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Sustainable Energy Authority of Ireland

National Energy Research, Development & Demonstration Funding Programme

FINAL REPORT TEMPLATE

SECTION 1: PROJECT DETAILS – FOR PUBLICATION

Project Title	Urban Building Energy Model
Lead Grantee (Organisation)	UCD
Lead Grantee (Name)	Gerald Mills
Final Report Prepared By	Gerald Mills
Report Submission Date	36 months

	Name	**Organisation**
Project Partner(s)		
Collaborators		

Project Summary (max 500 words)

Globally, the majority of energy use and related carbon emissions arise from cities, which occupy less than 3% of the planet's land area. While each city has a distinct economy, energy demand is split between buildings, industry and transport. Most research has focussed on each of these sectors independently to make them more efficient in terms of energy use however their spatial juxtaposition means that synergies are often overlooked. This research uses detailed building data to run an Urban Building Energy Model (UBEM) that examines building energy demand across the urban landscape. The UBEM will be used to explore the role of mitigation efforts that are focussed on behaviour changes, technical solutions or infrastructure change. This study constructs a detailed database on all the residential buildings in the Dublin city centre using a building typology allied with a Geographic Information System. Data on commercial buildings available from census data, tax records, rates data and information from Google Street View. The resulting database on the urban landscape will be used to simulate building energy use and carbon emissions that accounts for both spatial and temporal patterns. The UBEM will provide a spatial framework for planning interventions that may include renewable energy harvesting and/or fabric changes and/or district heating. It will also permit simulation of the outdoor effects of urbanisation including temperature (urban heat island) and wind effects that impact on building energy management. Although the focus of this work is Dublin city centre, the methodological approach can be directly applied to any city.

Keywords (min 3 and max 10)	Building Energy, Urban Climate, Energy Modelling, CO2 Mitigation, Policy, Renewable Technology

NB – Both Section 1 and Section 2 of this Final Report will be made publicly available in a Final Technical Report uploaded online to the National Energy Research Database.

In the following Section, please provide a clear overview of your project, including details of the key findings, outcomes and recommendations. The section headings below are provided as a guide, please update or add to these as best suits your project.

By submitting this project report to SEAI, you confirm you are happy for Section 1 and Section 2 of this report to be made publicly available. If you wish to request edits to this section in advance of publication, please contact SEAI at EnergyResearch@seai.ie.

SECTION 2: FINAL TECHNICAL REPORT – FOR PUBLICATION (max 10 pages)

2.1 Executive Summary

Anthropogenic climate change caused by human dependencies on greenhouse gas (GHG) economies is one of the fundamental challenges that global societies will have to address if predicted climate catastrophe is to be avoided. Cities are where most of these GHG dependent economies converge, and within these cities, buildings account for 40% of global energy consumption, which roughly equates to 33% of associated GHG emissions. Global urban populations are increasing, and with it, building stock, coupled with energy-inefficient ageing buildings, all of which exacerbate urban GHG emissions. Up until now, building energy policy underpinned by building energy modelling (BEM) has been limited in addressing the scale of rapid urbanisation and ageing building stock. Data and technological limitations have constrained BEMs ability to address energy modelling at a city scale. If aspirations of net-zero cities are to be realised within the next few decades, then building energy policy will need to address holistic emissions associated with urban buildings, which BEMs are ill-equipped to provide.

This research creates an urban building energy model (UBEM) to simultaneously simulate multiple buildings and large-scale energy saving measures (ESM) towards net-zero-carbon cities. In doing so, three objectives are identified and addressed by this body of work; the first creates a novel building database using building archetypes that meet the critical data criteria to run a UBEM successfully; the second objective converts and tests the validity of these data in a functional UBEM against real-world examples; and the third objective trials the capabilities of a functional UBEM in addressing climate policy and the prospect of a net-zero carbon urban neighbourhood.

Key findings demonstrate that it is possible to create a state-of-the-art functional archetype driven UBEM that is not limited by previous data and technological constraints affiliated with BEMs. This UBEM can harness energy saving opportunities afforded by the geographical context of buildings which, up until recently, policies supported by BEM risked overlooking. The UBEM can address real-world scenarios centred around reducing carbon dependencies in cities. Moreover, the method and data generated by this research

highlight existing biases and errors associated with data that underpins current building energy policy. Ultimately, the objectives set out by this research addressed the research question and generated a UBEM that simulated a net-zero carbon urban neighbourhood.

2.2 Introduction to Project

2.2.1 Climate Change and Cities

Anthropogenic climate change caused by greenhouse gas (GHG) emissions will likely be one of the most critical and defining issues for the 21st century. Extreme weather events such as heat waves, droughts, and storms, as well as diminishing global flora and faunae ecosystems, are to name but a few of the impacts associated with the changing climate. If society wishes to maintain any resemblance of the current climate equilibrium that has provided stability for these global ecosystems, then GHG emissions will need to be net-zero by the middle of the century (IPCC, 2014a). These climate impacts are already being felt and are predicted to intensify over the coming decades due to human's current and historical relationship with GHG dependant economies. Each sector of our global economy contributes a considerable share of the overall GHG emissions, with transport accounting for 14%, miscellaneous and building energy 16%, Industry 21%, Agriculture 24% and final electricity and heat production accounting for 25% of all recorded GHG emissions (EPA, 2021b).

All these sectors have historically been linked to CO2 emissions from fossil fuel-based energy production, which holds the largest share of GHG related gases emitted by anthropogenic activities. However, classifying these sectors as separate entities without observing their juxtaposition is not a helpful exercise when considering that most of these sectors overlap in our cities. For example, sectoral CO2 generated from grid energy production and heating energy for buildings are accounted for to heating and electricity energy use in residential and commercial buildings (which cities have the largest share of) or agricultural and transport energy intersect with the transport of agricultural produce to urban areas. These overlaps can be leveraged and tangible interventions that curtail the overall sectoral GHG emissions, which can be applied to reduce net emissions. In this light, we can now consider energy being the largest contributor to global GHG emissions and thus focus on where these GHG energy-related emissions converge (IPCC, 2014; Roser and Ritchie, 2021).

Attaining net-zero emissions requires a complete decoupling of GHG reliant economies. However, in practice, this means that the entire grid must become 100% dependent on renewables and/or nuclear energy coupled with cessation of all GHG dependant anthropogenic activities. This cannot be achieved overnight and will take a combination of both decarbonising energy while transitioning towards GHG friending economies, all of which will be implemented over time to meet emission targets associated with future climate stability. Many initiatives outlined by international organisations and state actors envision a net-zero carbon society by the middle of the 21st century as the fundamental goal in preventing climate catastrophe. Focusing on cities, where most anthropogenic energy consumption takes place, will be key to decoupling societies dependency on carbon-intensive energy.

By nature, cities are regions that host a plethora of condensed anthropogenic activities and, as a result, consume far greater recourses per square meter than any other surface on the planet. Moreover, cities can be generally described as ecosystems with inputs and outputs, much like a metabolism that must consume resources to survive. Ultimately, these recourses create an ecological footprint that often dwarf the physical footprint or boundaries of the cities themselves (Newman, 1999; Rees and Wackernagel, 2008). Resources most commonly consumed by the urban metabolism are water, physical materials, nutrients and the above-mentioned energy (Kennedy et al., 2007). Even though urban areas only cover approximately 3% of global landcover, almost 67% of the world's energy consumption are linked to human activities in urban areas (Liu et al., 2014). Within this context, buildings are attributed with 40% of overall global energy use and 33% of total GHGs (Randolph et al., 2018; World Bank, 2010). Furthermore, Since 2008, the proportion of the world's population living in urban areas reached over 50% and could reach 70% by the year 2050; this translates to 1.6 million new urban inhabitants per week (UN, 2008; UN, 2018). Ultimately, cities are growing, and more buildings are needed to facilitate the needs and activities of these new urban inhabitants. To help transition towards sustainable cities which are also resilient in the face of inevitable climate change, a strategy of "mitigation and adaptation" must be applied (IPCC, 2018)

2.2.2 Mitigation, Adaptation and Resilience In Urban Buildings

The practice of "mitigation and adaptation" acknowledges that anthropogenic GHG emissions must be mitigated, but additionally, society should prepare for the inevitable impacts of historical GHG emissions on current and future climates (Vijayavenkataraman et al., 2012). Mitigation and adaptation now form core components of international treaties and efforts to overcome challenges brought on by anthropogenic GHG emissions (IPCC, 2014; United Nations, 2015). Both mitigation and adaptation come with variable degrees of challenges and costs, particularly in cities with long-established systems that cannot easily be mitigated or adapted without sizable political, economic, and expert intervention (World Bank, 2010).

Resilience often described as "bounce back ability", is a term that contributes to the overarching theme of a system's ability to deal with change (Meerow et al., 2016; Tyler and Moench, 2012). Resilience in urban buildings can have a plethora of connotations at temporal and system dimensions. Considering the dynamic temporal span of "socio-ecological systems" in urban buildings, such as the ability to retain structural integrity or continuing to function during acute weather events (storms and floods) which often last hours; to a buildings ability to keep occupants thermally comfortable during long heatwaves or cold snaps can last for periods days or even weeks (Meerow et al., 2016, p39).

Moreover, the context of resilience is further complicated when considering "socio-technical systems" which can improve an urban buildings resilience to food, water, and energy shortages by adopting technologies and behaviours that reduce dependency on outside actors over months, years, and even decades (Meerow et al., 2016, p39). In the latter, buildings become independent and thus resistant to change and/or disruption from external supply chains related to food, water, and energy. Ultimately, resilience depends on the context of the situation it is being applied to and what criteria the actors are applying to meet their resilience goals.

Buildings, and their systems, are ideally situated to tackle both mitigation needs (reducing GHG dependency) and resilience needs (adaptable to climate change and capacity to harvest resources). Moreover, they can reduce the risk of lock-in carbon if they are appropriately developed and retrofitted to consider carbon-friendly procurement and incumbent renewable technologies (Seto et al., 2016). Although carbon lock-in is not limited to buildings, it is a fundamental theme that must be considered in any evaluation of current and future energy performance, particularly in the context of large building stock.

Buildings have unique attributes when considering their contribution to GHG emissions. Their construction is both resource and energy-intensive, with materials such as concrete, steel, glass and wood having to be procured, refined, and transported before being assembled onsite. This means, before buildings become operational, they already have a significant embodied carbon footprint. Furthermore, if buildings are designed without considering their local climate, their operational energy use can be significant for both cooling and heating systems coupled with the compatibility of a system to use carbon-free energy, all of which influences the intensification of lock-in carbon. These attributes are further compounded when considering the average life cycle of a building can range from 30-65 years, with some regions between 80-120 years (Marsh, 2017; Ramesh et al., 2010; Seto et al., 2016).

Fundamentally, if the right materials and correct design are not implemented from day one, particularly in developing regions undergoing fast urban growth, the risk of a lock-in carbon scenario runs high. This risk is amplified across cities where the building fabric and system inefficiencies consume far more energy over their lifespan leading to higher carbon emissions (World Bank, 2010; Marinova et al., 2020).

To best apply ESMs for urban buildings, it is important not to dismiss buildings' sectoral profiles altogether as they still contribute vital information on the nature of sectoral energy loads. This approach captures the buildings form (physical context) and function (behavioural context), which are key attributes for building energy consumption.

Residential and non-residential buildings profiles are often given their own sectoral categories. These categories attempt to capture the nature of their energy demand at large spatial scales suitable for nation-states and associated regions. For example, industry, commercial, residential, and transport electrical energy consumption in the USA represents 27%, 35%, 37%, 0.2% respectively (EPA, 2021a). These figures highlight the USA's lack of electrification in its transportation network, which can be alleviated with policy-driven towards electric vehicles and/or regional electric rail networks. This is an important exercise in understanding the nature of energy demand at the national scale but ignores the sector spatial context. In buildings, these energy profiles are defined by their temporal and activity attributes, often resulting in building energy dichotomy, which intensifies segregation. However, the spatial nature of these sectoral energy profiles often shares the same locations or structures, which affords policy makers and stakeholders energy saving opportunities that are not so obvious using the sectoral energy approach.

Methods that fail to realise the juxtaposition of different anthropogenic activities run the risk of missing opportunities afforded by the inputs and outputs of these activities . For example, at a diurnal scale, residential buildings will have a larger energy share for domestic hot water (DHW) which is most notable in the morning and late evenings, while a non-residential (i.e., commercial offices) will generally have larger equipment loads during the day (EPA, 2021a; Howard et al., 2012; McLoughlin et al., 2015). Excess heat from equipment in commercial buildings is generally removed to maintain the buildings thermal comfort equilibrium and often expelled outdoors as waste heat. By observing the energy balance of these two sectors together, it is possible to use waste heat from one sector to unburden the energy load for heating DHW in the other sector. These sectors spatiotemporal phenomena can be leveraged, and ESM can be implemented with appropriate information and technology. However, all of this can only happen with meaningful policy backed up with hard science.

Recently, policy and initiatives created by state actors and stakeholders have attempted to tackle sectoral emissions by implementing mitigation strategies, and lately, adaptation strategies in their response to climate change. Some of these strategies, such as the European Union (EU) 2020 climate goals, have proven successful in reaching targets . However, future initiatives depict roadmaps for carbon-neutral economies which are underpinned by technological and policy-driven approaches, many of which have been historically difficult and slow to implement . Understanding the context of these climate initiatives serves as guide wires for implementing meaningful change in sectors intricately tangled in carbon dependencies.

2.2.3 Global Policy Response to Climate Change

Since the 2015 Paris Climate Accord, there have been over 190 countries committed to keeping the global average temperature below 2°C(United Nations, 2015). Although the accord is legally binding, it serves only as a voluntary pack and roadmap for the globe to achieve climate commitments rather than penalising countries that do not reach their commitments. Each nation draws up its own plans for reaching targets set out by the accords. For example, the USA has set out an agenda for the next 10 years focusing on reducing carbon emissions by 50% of 2005 levels by the year 2030, with some framework being discussed for carbon naturally . China will be launching its national carbon market initiative, with aims to hit peak emissions by 2030 and be carbon neutral by 2060 . The European Union has announced the European Green Deal, which sets out a 50-55% reduction in climate emissions based on 1990s levels with carbon neutrality across the EU by 2050, making it the first carbon-neutral continent on the planet (European Commission, 2019). All the above initiatives describe various degrees of equitable mechanisms for transitioning carbon economies towards a more sustainable carbon-neutral future; however, the EU Green Deal relates specifically to the study area and thus will be discussed in further detail below.

The EU Green Deal set out a roadmap for net-zero emissions by 2050 using various mechanisms and initiatives across all sectors (transport, food, infrastructure… etc.) of the European economy (European Commission, 2019, 2020a). The Green Deal is split into subcategories poised at sectors responsible for large shares of carbon emissions. Each sector is responsible for reducing carbon emissions in tandem with other sectors to achieve the ambitious 2050 goal. For example, transport is responsible for a quarter of EU carbon emissions and must decouple its carbon dependency by 2050. However, the EU green deal states that these emissions need to be reduced by 90% before the year 2050 to reach carbon neutrality which is a 100% reduction in emissions. Consequently, the transport sector will rely on other sectors to make up the difference in achieving overall net-zero emissions. To this end, the building energy subcategory is labelled The Renovation Wave, which will focus on updating old energy-inefficient building stock synonymous with Europe.

Within the EU green deal, the Renovation Wave Road Map has been drafted to account for sectorial energy use in buildings and, by extent, cities. This roadmap stipulates that buildings must cut 60% GHG related emissions by 2030 and become net-zero by 2050 using a combination of technical (building energy refurbishments, renewable technologies) and policy (financial endowments, carbon taxes) driven approaches relative to the field of building energy (European Commission Roadmap, 2020). The goals outlined by the renovation wave describe the time and cost-sensitive challenges that arise with the wholesale change to the techno-socio systems and fabric associated with European cities. To address these challenges, it is important to acknowledge and define the unique features of European cities and the adversities that need to be overcome to reach the outlined goals.

2.2.4 Climate Change Policy in Europe And Ireland

Europe as a region is highly urbanised and has above average urban landcover when compared with the total global average urban landcover (Liu et al., 2014). Moreover, energy and GHG breakdown in Europe's building sector is quite similar to global trends, with buildings responsible for 40% of energy use which translates to roughly 36% of its GHGs emissions (Zhao and Magoulès, 2012). Currently, more than half of European building stock surveyed under the EPC/2010 directive are built before energy regulations were introduced, which is synonymous with the 1970s global energy crises (Pérez-

Lombard et al., 2009; European Commission, 2021). This indicates that a majority of European building stock needs energy refurbishments to meet today's standards. Furthermore, building stock routinely undergoes upgrades with typical building life cycles of 50-60 years resulting in future refurbishment of current building stock (Davila and Reinhart, 2013).

If Europe as a region plans to mitigate building GHG emissions in line with the Green Deal goals, it will have to demolish or refurbish its poor-performing building stock within a relatively short timeframe. An added caveat to European cities is a trade-off situation caused by two factors when compared with global urbanised regions 1) its cities are extremely wealthy, giving them capital to change their form and function but 2) they are long-established with historical roots, making them very difficult to physically change due to cultural and building preservation initiatives. Generally, it is difficult to update ageing building stock when upgrades are limited by preservation policy, but not impossible to implement.

The Republic of Ireland is one of the smaller nations of the 27 EU member states with a population of little under 5 million people and a land mass of approximately 68,900 km² ( ). Geographically situated 53°North of the equator and off the western coast of Europe, it's primarily a heating climate with mild summers and cold, windy winters . Although the nation is small, its per capita gross domestic product (purchasing power parity) ranks one of the highest in the world and is 2nd only to Luxembourg within Europe . This small wealthy nation is one of the largest contributors of greenhouse gases (GHG) per capita in Europe, with 29% of its energy-related GHG attributed to the residential sector alone .

Dublin is its capital and the most densely urbanised region of the Island of Ireland. It is a historical city with origins dating back over a millennium and contains building stock that spans over the 8 centuries of architecture, some of which is still in use today. Dublin, being a European capital city, falls under the reemit of the EU Green Deal and the EU 2010 directive on building energy surveys. Most of the buildings (65%) in Dublin 15 km² city centre can be described as historical and built before the above 1970 (1978 for Ireland) threshold for energy standards. Given the complexity of energy flows within urban centres coupled with the behemoth challenges set out by the Green Deals Renovation Wave, the task of transitioning this European capital to net-zero carbon is an expensive and time-consuming endeavour that requires an intricate, but holistic approach to account for all the moving pieces.

2.2.5 Current Approach to Building Energy Policy

Up until recently, building energy policy has focused on enforcing high energy performance standards on newly developed individual buildings. This approach has seen incremental improvements in the energy performance of building stock across Europe, with energy standards introduced in the late 1970s . Over time, technology and policy have developed to enable near-zero energy buildings (NZEB) (passive homes); nevertheless, these passive homes mostly represent contemporary building stock with much older and more energy inefficient buildings still in use today.

Getting these older buildings close to NZEB by using a combination of fabric upgrades and localised renewable energy sources is part of the EU's new Green Deal. However, incentivising their energy upgrades has proven challenging over the past few decades and has resulted in 1% incremental energy upgrades per annum, significantly below the quantity needed to attain ambitious carbon goals and one of the only goals missed by the EU 2020 carbon initiative (European Commission, 2020a).

There have been substantial partial energy upgrades implemented over the past two decades, which has seen an increase in energy efficiency. For example, 58% and 45.2% of windows and roofs have been upgraded respectively while in the same period only 25% and 16% of boilers and walls have been upgraded respectively (Hanratty et al., 2015, p 17). This is evident across many EU member states which have carried out state-funded and/or independent energy refurbishments from wall installation to energy-efficient light bulbs (Hanratty et al., 2015). However, these refurbishments fell short of the standard of energy performance needed to achieve NZEB status.

Currently, building energy policy (particularly 2020 goals) has failed to achieve energy refurbishment objectives set out for both the EU and Ireland for ageing building stock, which in some cases results in finical penalties . For the most part, much of the poor uptake can be explained by a lack of incentives both financially and environmentally, as payback periods on energy refurbishments are often long with considerably high upfront costs for stakeholders. Moreover, these stakeholders are often ill-informed and lack the technical expertise to identify energy-saving opportunities with their own individual buildings and likewise finical endowments that may be available to them (BPIE, 2011). The above financial and dissemination issues are further compounded when building energy policy is targeted at energy refurbishment endowments which do not account for all poor performing building stock.

Beginning in 2002 (introduced in Ireland 2007 and brought into force in 2009), energy performance certificates (EPC) have become mandatory in Europe under the Energy Performance of Buildings Directive (EPBD) (EU, 2010). In Ireland, this directive is enforced by buildings that are built, sold, or rented after the year 2009. However, this overlooks cohorts of building owners who have not met this criterion and who often reside in older energy-inefficient buildings. Moreover, buildings that fall within the criteria of historic structures are exempt from mandatory EPC surveys, which skews data further towards contemporary buildings sampled for building energy policy. As a result, EPC data covers more recent building stock that was either constructed after 2009 or has undergone substantial energy refurbishments, which are systematically more energy efficient, creating a bias in the data coverage gaps. Ultimately, a combination of sectoral approaches and data gaps have resulted in missed opportunities and miss guided energy policy that must be addressed if ambitious climate change goals are to be realised.

A new approach must be applied which changes the perspective of building energy from the individual standalone building to the collective array of neighbouring buildings. To date, energy policy has been ill-equipped to tackle previous carbon-reducing initiatives in the built environment. The reduction of building GHG dependence will hinge on our ability to tackle energy demand which is intricately embedded into our urban landscapes. Using a geographic approach to assessing energy demand could afford the opportunities needed to address these challenging goals, which have often been overlooked by the myopic categorisation of human activities.

By treating an entire neighbour as one energy entity, energy-saving and harvesting opportunities become more obvious and thus easier to disseminate for integration into policy and real-world applications at the city scale towards net-zero carbon goals. Furthermore, data representing the true nature of building stock is essential in avoiding coverage pitfalls associated with current data procurement. Building energy policy that considers the geographic context of buildings stock, particularly at the building level rather than regional or national level, can provide guidance and incentives that are better equipped for simulating the net-zero carbon agenda described by the EU Green Deal.

By observing building stock in its entirety (not sectoral or standalone) and simulating all internal and external influences on energy use intensity (kWh/m²/year, EUI), this research provides a method that circumnavigates some of the systemic errors associated with models and data that currently underpins the underperforming building energy policy in

Europe. Furthermore, disseminating these opportunities is further enhanced with 3D render digital twin approach, which is an intuitive method of disseminating complex scientific ideas.

2.2.6 Research Context

This research uses a novel method of simulating the exchanges between the indoor and outdoor climates of multiple buildings, their local climate, and the simultaneous influences that these buildings have on each other ,producing current and future building energy demand rapidly. This method is known as Urban Building Energy Modelling (UBEM) and is an emerging field of energy studies that utilises several disciplines of computer science, geography, and building energy. By simulating these complex interactions of the individual building and its outside environment across large quantities of the neighbouring building stock, this research enables the application of various ESM quickly. These simulations not only reduce both the time and costs associated with applying ESM but can also test ESM effectiveness at hitting EU green Deal goals.

Originally, statistical methods were used in supporting building energy policy for large quantities of building stock at national and city scales. However, these statistical methods depend on large amounts of historical data, and static calculations, which are unable to consider future technological and physical changes. This static nature makes them ill-equipped for modelling net-zero carbon cities of the future. To appreciate the added value and contribution made by this PhD thesis, it’s first important to understand the mechanisms that support policy related to building energy.

Building energy policy is often underpinned by building energy models (BEM), which simulates the energy performance of a standalone building, generally ignoring its spatial context. Weather files, usually from local airports situated miles from the urban centres, are used to simulate the impacts of the outdoor environment on an individual building. In practice, this approach assumes an urban building is situated alone in an open airfield and omits all influences from neighbouring buildings that have substantial impacts on the building’s internal and external climate. This practice not only feedbacks inaccurate energy performance but also ignores the opportunities afforded by the neighbouring buildings and geographical features such as additional roof space for photovoltaic (PV) panels or cooling potential of nearby bodies of water.

Up until recently, if multiple buildings in a region needed to be simulated, then a representative building (archetype) from a cohort of buildings is simulated alone, with the resulting energy performance aggregated across the related buildings under observation. Again, this ignores the building stocks spatial context and requires multiple highly detailed building archetypes to adequately capture the nature of energy performance in the region.

By simulating the energy performance of multiple urban buildings in their actual environment, it is possible to account for external influences and connect the energy efficiency dots between demand and supply across urban geographies. This research will highlight that this method is better for guiding building energy policy on local and national scales. Understanding the local environment of buildings, their geometric and thermophysical properties that form the urban fabric is key to capturing the nature of energy flows between them.

2.2.7 The Urban Fabric

Generally, cities (particularly older European cities) will contain a diverse range of dense urban neighbourhoods that regulate their own indoor climate. A block of buildings acts as an artificial layer of concrete, brick, wood, and glass that separates the outdoor climate from the indoor. Each of these buildings is designed to keep a consistent indoor temperature that is thermally comfortable for the building occupants; to achieve this, most buildings will use appropriate materials for their envelope (building fabric) and heating, ventilation, and air conditioning (HVAC) systems which artificially influences and control the internal climate. Depending on the climate (hot, cold, combination of both), buildings will leverage fabrics and HVAC systems to regulate the internal climate in response to external climate, using energy to make up for the difference. The more energy an indoor climate needs to keep a consistent temperature is directly determined by the divergence of the outdoor temperature and the efficiency of the building systems and fabric. Building energy models simulate the performance of existing and conceptual building stock by calculating the thermophysical process associated with keeping a single structure thermally comfortable throughout a calendar year.

To this end, UBEMs capture the energy performance of multiple buildings in a region, all of which, store an indoor artificial climate, then using a dynamic energy modelling engine, UBEMs calculate the interactions between indoor and outdoor climates over time. This method requires both powerful hardware, intricate software, and detailed building data to create a digital twin of the city or neighbourhood under investigation. Moreover, detailed building fabric and system data is a prerequisite to capture the complex physical interactions of heat and mass flows around multiple buildings. Consequently, creating a detailed building database isa critical step in the development of city-scale UBEM. Moreover, a detailed building database is useful for other related energy analysis endeavours. When fully operational, UBEMs provide a platform for testing various technological and/or policy-driven measures towards future net-zero carbon cities. Key to the overall approach is the geographic nature of UBEM, which can highlight opportunities for neighbourhood-based ESMs such as harvesting, sharing, and refurbishments.

Energy harvesting utilises environmental sources of solar, hydraulic, and wind energy to meet local energy needs. The UBEM applied by this research often relies on solar energy; however, hydraulic and wind sources can be considered once appropriate data is applied. The ability to offset building energy demand can be improved by utilising incidental solar radiation that would otherwise be dissipated and lost to the urban fabric. Accounting for building orientation and shading, UBEM captures relatively accurate PV performance over a calendar year which offsets the amount of grid energy demand needed. Furthermore, the spatiotemporal nature of this energy modelling allows for the analysis of both energy supply and demand, highlighting the opportunities and shortfalls associated with temporal energy fluctuations based on diurnal and monthly profiles.

Using a geographic approach coupled with temporal profiles unlocks energy sharing between blocks of buildings from different sectors and diverse temporal profiles. Buildings function generally determines its occupant schedule and thus determine most likely diurnal energy flux. Some buildings profiles generally work inverse to one another, i.e., residential and office buildings with diverging energy fluxes, while others maintain a stable energy profile throughout the day, such as a convenient store. These temporal profiles can be spatially mapped, and, if suitably close, energy flows can be connected to help unburden the diurnal grid energy loads. Reflecting back on a previous example in this thesis of residential and non-residential diurnal energy loads, sharing excess heat waste generated throughout the day, commercial buildings can provide heating needs for local residential buildings during diurnal peak loads. Consequently, as peak demand is often supported by carbon-intensive energy generation, mitigating peak loads substantially reduces grid-related carbon emissions.

Finally, the geographic approach can be packaged towards a community energy refurbishment initiative for multiple neighbouring buildings. Community refurbishment projects which utilise the above approaches can leverage shared fabric upgrades for terraces, and multifamily homes (apartments) can make use of the economy of scale, which reduces the cost associated with deep energy refurbishments. This can better pitch financial endowments and related energy policy towards communities who wish to better improve the energy standards of their properties.

Avenues of community energy sharing, harvesting, and refurbishment can aid policy, which to date has failed to address uptake in Europe's much-needed building energy refurbishment quotas. By treating the entire neighbourhood as one energy entity and illustrating its spatiotemporal profiles, UBEM driven policies can disseminate these complicated community-based ESMs towards improving uptake and utilising policy and/or technological opportunities that present themselves at the city scale.

2.2.8 Choosing Urban Modelling Interface -UMI-

To date, there are few software package's capable of large scale physical UBEMs, some are free to use, but most are restricted by pay-walls. At the time of this research, open-source software choices were limited to the Tool for Energy Analysis and Simulation for Efficient Retrofit (TEASER) and Urban Modelling Interface(UMI)(Sola et al., 2020). As UMI had the advantage of considering outdoor climate (using radiance), which TEASER lacked, it was favoured for use in this research. In addition, UMI was chosen due to its capabilities, insightful visualizations, and state-of-the-art approach to energy simulations (Figure 12 and 16).

UMI is designed and created by the Sustainable Design Lab (SDL) at MIT for use in Rhinoceros 3D (Rhino) an industry-standard computer-aided design software package. Rhino facilitates both geometric information for buildings and EnergyPlus simulation engine, which are key components for energy modelling both at standalone and multiple building scales (Crawley et al., 2001; McNeel, 2021; Reinhart et al., 2013). Furthermore, Rhino facilitates custom plugins making it a versatile platform for integrating various adaptions and add-ons to the existing UMI framework allowing for new simulation packages to be added (Benis et al., 2017; Letellier-Duchesne and Nagpal, 2021; McNeel Grasshopper, 2021)

2.2.9 UMI Development

The georeferenced Tabula budling archetypes are stored in GIS shapefile (shp.) format containing all the geometric (height, floor area and volume) and non-geometric (building envelope u-values, HVAC systems) properties. However, building energy modelling software cannot process the information in this file format, and thus, the shapefiles must be converted into industry-standard energy modelling file formats (idf.).

To do this, building energy modelling (BEM) software is used to incorporate all the relevant data from Tabula building archetypes and produce a functional building template in an idf. file format appropriate for use in UMI. This requires extensive knowledge of building energy-related proficiencies usually based in CAD software packages coupled with energy modelling engines. These skills are often confined to fields of architecture and building engineering, which normally observe urban buildings at a standalone scale, which limits the scope to the context of the individual building. Once the templates have been converted to appropriate file format, they are then uploaded into the UBEM software, becoming UMI building templates.

Using the EUI for each Tabula archetype as a benchmark, the new UMI templates energy performance can be evaluated. Furthermore, these evaluated EUIs are compared with EPC data which contains real-world EUI samples of the building stock under observation . Finally, as all the UMI templates are georeferenced, they can now adequately depict the context of each building under observation and consider the influences buildings have on each other. These small but key evaluation steps ensure the new UMI templates fall within an acceptable level of energy performance and depict the physical reality of the building stock under observation.

2.2.9 UBEM Application

The third and final objective applies the newly created UBEM to a real-world scenario with a focus on attaining a net-zero carbon neighbourhood that is often the overarching gaols of international climate initiatives. It is worth recapping the skill sets associated with generating data and applying it to a UBEM, as they are often affiliated with different disciplines observing the urban landscapes at different scales. This objective highlights the need for a multi-disciplinary approach towards energy simulations related to the urban landscape, which is intricately intertwined with climate-related issues. Furthermore, this objective demonstrates how taking a geographical approach to reducing carbon dependent economies is fundamental in addressing carbon reduction quotas as this method fosters initiatives that are often outside the scope of building energy-related disciplines.

The project objectives revolve around generating appropriate data for the application of dynamic building energy models at city scale. Most recent building-related studies lack appropriate building scale data for UBEM and, in the case of Ireland, is generally dependent on statistically driven energy models to assess the performance of building energy at city resolution (Ali et al., 2019; Hanratty et al., 2015; Gartland, 2015). As already stated, statistical models lack the capabilities to trial ESM towards net-zero carbon cities outlined by the EU Green Deal. This lack of data and, and by extension, lack of advanced energy modelling, provided an opportunity to address three research objectives in urban energy-related fields:

1) Create a database to rapidly develop an inventory of building information data that adequately describes the physical reality of building stock

2) Adapt this data to function in a state-of-the-art UBEM

3) Assemble an UBEM designed to simulate net-zero carbon cities based on current policy

General Data Protection Regulation (GDPR) laws and pay-walls prohibit the use of datasets and software needed for UBEM related studies. As a result, the research goals are aimed towards open-source information and software to facilitate replicability of this study by interested parties. Moreover, these limitations are a common theme across Europe and other developed regions. Some nations and regions cover a considerable amount of building information at the individual building scale, most notably Switzerland and Holland who have published building stock databases online (BFS, 2021; waag, 2018). However, more often than not, these data lack the critical information needed for generating UBEMs and building energy management (Monteiro et al., 2018). Furthermore, the method becomes more applicable to bridging similar data gaps in developing nations as data in these regions is either limited in coverage or none existent (Marinova et al., 2020).

UMI novel approach to calculating dynamic city-scale energy is still in its infancy, resulting in bugs and errors that must be overcome. Furthermore, UMI has been designed for use in North America with datasets that are more readily available there than other parts of the world. This research will be the first to integrate European building templates into UMI and evaluate their performance using publicly available building data while contributing to the UMI project in terms of testing and development. The three objectives are mapped in Figure 1, which illustrates this research's framework, beginning with creating the database, developing and evaluating the database capabilities in a UBEM, and finally testing net-zero carbon scenarios.

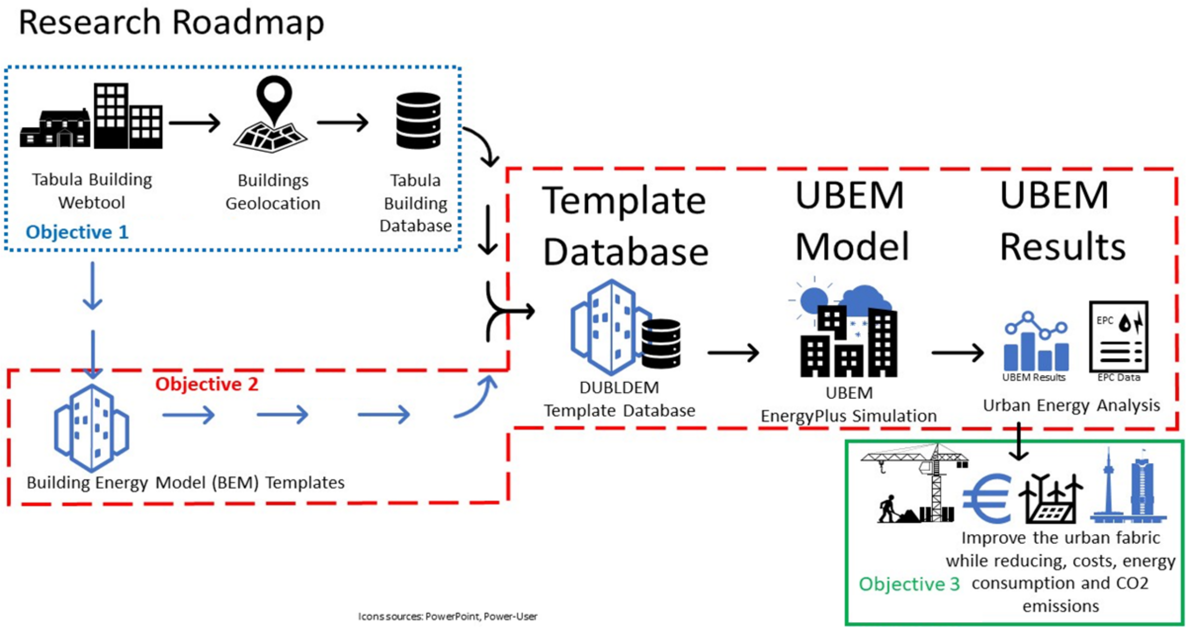

Figure 1 Objectives workflow

2.3.1 Intellectual Development and Knowledge Gaps and Data Generation

To develop and implement a physics-based UBEM using building information intended for steady-state modelling, various skill sets from several disciplines are needed to produce a UBEM of the study area. These skill sets are not often associated with anyone school of thought or discipline; however, they generally fall within the scope of urban-related studies.

Data procurement relied on Geographic Information Systems (GIS), which generated, processed, and managed all relevant data. Multiple levels of geographic information had to be procured and processed before being integrated with building information that is suitable for dynamic energy modelling. Skills needed to operate and navigate GIS software are fundamental to the development of the database and would be difficult to replicate using other systems, although not entirely impossible, as some studies have shown (Nouvel et al., 2013; Issermann et al., 2021). GIS skills are often affiliated with disciplines of geography, environmental policy and planning, which usually observe buildings at the scale of cities.

For this objective, GIS-based approach was chosen as the preferred approach as it is both intuitive and accessible by most operators who are familiar with interactive maps. Alternative approaches, such as point cloud and data mining, depended on extensive computer-aided design (CAD) and/or computer science skills which are generally less accessible and not often affiliated with the larger levels of geographic data. Fundamentally, the information critical for a functional UBEM is often in file formats best managed within a GIS framework and thus one of the key reasons for choosing this kind of data generation and management in this project.

Creating the data for a UBEM was derived from Tabula building webtool, which is available across 21 European nation-states. Tabula is an openly available source of residential and non-residential building information that provides detailed descriptions of buildings sufficient for calculating their EUI (kWh/m^2/year) and critical data needed for UBEMs. Tabula is part of EPISCOPES Intelligent Energy Europe project, which set out to make energy-saving measures related to European housing stock more transparent for its citizens (EPISCOPE, 2016). Moreover, Tabula is the only dataset publicly available that can easily convey building archetypes based on visual cues and brief descriptions, making it accessible for non-experts. For Ireland, Tabula provides residential building information which spans over three centuries of building archetypes coupled with the most probable HVAC systems. However, Ireland's Tabula data has no examples of non-residential building archetypes, which is key in simulating commercial buildings. This barrier can be overcome using commercial building archetypes benchmarked against the Charted Institutes of Building Service Engineers (CIBSE) guide F (2012).

GIS data which describes building footprints in Dublin's city centre, is integrated with Tabula archetypes using a visual observation process. Each building footprint is identified, categorised, and logged using relevant archetypes associated with the building footprint under observation.

2.3.2 Objective One

The methodology applied to address objective one utilises several databases, including the national census and national postal directory (Geodirectory), to derive what is termed as a "composite" database of building information in Dublin (Kitchin et al., 2015, p8). This composite data adopted the semantical terminologies and structures provided by the national census, thus making the database malleable with comparative and/or unrelated databases associated with the same geography. This enables the cross-reference of existing databases such as the national EPC database to make up coverage gaps or the vacant housing database for materials, and vice versa. Furthermore, DUBLD can support and evaluate building relevant data within the national census data domain while also acting as an independent data domain for Dublin city centre itself. By exploring interdependencies, DUBLD highlights biases and errors in existing databases that may have otherwise been missed or ignored due to the segmented nature of their creation.

For example, EPC data has covered just over 50% of the Irish national building stock due to its integration policy . Further to this, policy dictates that protected structures (almost always pre-1930 historic building stock, which is systematically energy inefficient) are exempt from EPC data regulations, and data related to these structures are stored in separate databases. As a result of the segregation of historical databases and the implementation policies, the EPC coverage is weighted towards more energy efficient building stock (SEAI, 2010).

A study by Cachia (2018) attempts to overcome this coverage gap by merging EPC data with local census data. However, census household data is particularly prone to human errors and coverage gaps, particularly in relation to historic building stock, which building occupants often find difficult to estimate (Monteiro et al., 2018). Current local building databases that are accessible inadequately depict the nature of building energy performance and are incapable of supporting UBEM models.

Up until recently, Ireland had no alternative databases that sufficiently described the nature of building stock at the critical level of detail needed to support a physics-based dynamic UBEM. Objective one's original contribution to knowledge is the formation of a highly detailed building information database suitable for energy management and state-of-the-art UBEMs. This database is replicable in nature and can be assembled in all 21 Tabula participant member states representing 90% of European building stock (Loga et al., 2016).

Currently, in addition to building inventory, objective one can also consider the most likely building occupants most susceptible to energy poverty. By cross-referencing the DUBLD database with census population data (which is less prone to census household inaccuracies) enables the identification of specific building stock at high risk of fuel poverty. A similar method was applied by Gartland (2015) spatial energy study, which is dependent on the BER database to identify poor performing building stock merged with census data, both of which have errors and biases outlined above. Objective one can build on the spatial energy approach by adding to the granularity of building stock under review and may even uncover areas that might have been overlooked by previous research. However, this added granularity can be hindered by neighbourhoods with heterogeneous building stock and occupants (Fabbri, 2015). Ultimately, objective one highlighted how energy policy overlooked low-socioeconomic occupants of the historic building stock, which is reflected in energy refurbishment schemes. Currently, new energy policies target energy-poor households with free upgrades; however, these upgrades are only available to homes built after 1940 . This appears to neglect the historic housing stock and possibly some of the more vulnerable building occupants susceptible to fuel poverty. Nevertheless, the methodology in objective one is not without its own limitations with an ever-evolving building stock; it is challenging to capture internal structural properties and new developments.

2.3.3 Objective Two

Objective two set out to test if a) steady-state Tabula archetypes perform sufficiently as dynamic UMI templates and b) could these UMI templates sufficiently real-world model buildings in line with goals in the EU Green Deal. The process of converting the Tabula archetypes into UMI Templates produces EUIs as a by-product. These EUI's were used to measure the performance of the new UMI templates against the respective Tabula archetypes. Although there were some minor deviations with the older building stock, the results demonstrated that UMI templates could sufficiently capture the thermophysical properties of their Tabula counterparts. Following this, when compared with EPC data in the study area, UMI templates demonstrated a correlation with the thermophysical performance of real-world buildings situated within the study area.

Overall, objective two original contributions to knowledge proved that it is possible to convert steady-state Tabula archetypes into dynamic UMI templates which adequately simulate the heat and mass flow around buildings. Moreover, when UMI templates are then evaluated against the EPC data of their real-world counterparts, they adequately portray the energy performance of the entire neighbourhoods under observation. Further to this, A UBEM using these UMI templates can be used to evaluate the credibility of applying ambitious Green Deal goals, using a small study area. Although the study area is made up of predominantly homogenous building stock, the UBEM proved versatile enough to demonstrate the advantages of using buildings juxtaposition with the application of community retrofits. However, using the methods described in this above is not without some drawbacks resulting in some limitations that were unavoidable.

2.3.4 Objective Three

With a functional UBEM, objective three assessed the application of UMI towards a net-zero carbon neighbourhood by evaluating its scope and affiliated plugins. The study area was chosen based on its urban geography with a canal, river, and rail network adjoining its borders and its diverse range of buildings and residents within. Moreover, the study area was synonymous with most urban regions found throughout the Island of Ireland and across Europe with its multifaceted energy needs.

Objective three's original contribution to knowledge is that it is the first UBEM of its kind that successfully implemented to test a net-zero carbon neighbourhood using the archetype approach described by both objectives one and two. This objective tested various ESMs towards a net-zero carbon neighbourhood in Dublin city centre using UMI. These measures consisted of community retrofits, solar harvesting, energy sharing with two additional plugins that simulated DHC and CEA impacts on the study area. The ESMs applied are geared towards energy equity as its core principle, ensuring that the most vulnerable residents are protected first. When these ESMs worked in tandem with each other, they dramatically reduced local carbon dependency and, in some cases, decoupled carbon dependent energy altogether.

The combination of retrofitting the entire neighbourhood coupled with PV panels on public infrastructure facilitated two key components for carbon neutrality in buildings: 1) converting inefficient energy homes to NZEB buildings; and 2) meeting the remaining NZEB homes energy demand with a local renewable supply. The renewable PV supply for the SFH neighbourhoods is substantial enough to meet energy demand in the winter months, when both diurnal and monthly energy demand peaks, but inversely PV potential is at its nadir. Contrariwise to this, energy yields would far exceed summer demand due to the lack of residential space heating needs coupled with the abundance of solar energy resulting in an energy surplus. This surplus can be utilised elsewhere, which demonstrates the versatility of UMI. Various scenarios were tested, from energy sharing with a local rail network that maintains a consistent energy profile over a calendar year to using surplus energy towards summertime commercial cooling loads or a combination of both. However, there are some limitations in the cost-benefit analysis and some minor limitations in general data gaps that can be addressed moving forward.

2.3 Summary of Key Findings/Outcomes

Describe how your project has furthered the current state-of-the-art, current knowledge or current practice. Clearly highlight the degree of novelty and innovation demonstrated by your project.

Address each innovation in a bullet point below. Add as many bullet points as you need:

- Innovation 1: Using building archetypes to develop templates for energy simulations.

  Summary: This was the first work to use building archetypes (associated with the Tabula database) to generate the information required by energy models to simulate energy demand. The use of archetypes that are linked to building images is an efficient way of acquiring information on large building stocks.

- Innovation 2: Applying an Urban Building Energy Model (UBEM) to Dublin.

  Summary: The archetype approach was combined with other databases to create the fundamental database of Dublin's building stock that could be incorporated into a UBEM. These models can be used to explore policy options for energy management at neighbourhood scales.

- Innovation 3: Developing a EU wide methodology

  Summary: The use of an EU database (Tabula) combined with a geographic information system provides a pathway to the application of UBEMs across Europe and provides a 'proof of concept' for the efficient acquisition of urban data relevant for climate modelling.

2.4 Project Impact

The UBEM can support several established needs in the Irish energy sector including:

- Opportunities for retrofit (e.g. ReHeat and Greener Homes Schemes). The UBEM database currently categorises the residential building stock using the TABULA scheme which describes houses as built; typically, this stock is organised into distinctive neighbourhood types that are related to historic building practices. These data can be used alongside BER data to identify the likely retrofit that has taken place to this point and the opportunities for further intervention. Census data can be used to establish the likely household structure in different neighbourhoods to evaluate the efficacy of spatially directed interventions.

- The potential for renewable energy generation at building/neighbourhood scales (e.g. Renewable Energy Feed-in Tariff scheme, Small and Micro generation and Part L of Building Regulations). The potential for generating renewable energy at a micro-scale in cities is limited by the urban landscape itself, which generates shadows and generates turbulence. To assess the solar potential for example, the useful roof space, including its aspect and slope are required. The UBEM database includes these roof attributes and can be used to establish the potential in the city for small scale energy capture and utilization.
- Meeting national energy efficiency goals (e.g. National Energy Efficiency Action Plan). The UBEM allows a systems approach to the management of energy by including commercial and residential energy demand within a spatial-temporal framework. This provides the opportunity to test the best approach to improving energy efficiency at urban scales, for example to decide the appropriate balance between retrofit, renewable energy generation, district heating options and behaviour changes.
- Meeting climate change goals (e.g. National Policy Position on Climate Action and Low Carbon Development (2014) and the Climate Action and Low Carbon Development Act 2015). The state is legally committed to reducing carbon emissions, much of which arise from building energy demand. The UBEM can be linked to residence-work/school commuting patterns to inform the best overall strategy of achieving carbon neutrality at the urban scale. Moreover, as UBEM has a detailed geographic framework, it can be linked to models of air and water quality and to climate adaptation strategies (e.g. urban greening).

Clearly position the impact of your project with reference to the needs of the Irish Energy Sector, national and international policy objectives, and SEAI's remit.

Discuss the key impacts of your project: societal, economic, technological or otherwise. Clearly identify and highlight the value of your project in the wider context.

2.5 Recommendations

2.6.1 Energy Efficiency and Costs

By focusing on energy efficiency at the core of any policy, planning, development and investment decisions, several of the key principles can be captured by using a wholesale energy first approach (European Parliament, 2018). Energy first reduces the costs associated with keeping a dwelling thermally comfortable and thus reduces the risk of energy poverty (discussed in further detail later). The key principle outlined in the renovation wave discuss the affordability of energy-efficient homes (i.e., the cost of purchasing and renovating houses). This means that energy refurbishments and renewable systems also need to be considered affordable in the carbon transition of the existing building stock. UBEM simulations demonstrate a policy in the economy of scale, or community retrofits, where an entire block of households are refurbished as one entity. This reduces costs associated with carrying out energy refurbishments on individual households while also increasing coverage of efficient building stock.

As ESMs have positive impacts on the mitigation of carbon emissions, they reduce the costs associated with the upcoming carbon tax increase, which is already in practice in the study area (McCarthy, 2019). This further unburdens the costs associated with carbon-intensive grid energy for the consumers, but in turn, also reduces the grid demand. The combination of renewable energy supply and ESS can reduce peak energy demand which decouples the need for carbon-intensive energy boost from inefficient power plants that serve as back up for peak energy demand (Ang et al., 2020; Taşcıkaraoğlu, 2018; Yekini Suberu et al., 2014). This has an overall impact on the decarbonising of the grid and additional costs incurred by carbon taxes.

In 2018, approximately 67% of Irish energy was imported in the form of fossil fuel at the cost of €5 billion (Byrne Ó Cléirigh, 2020). Ultimately, Irish national grid energy is carbon-intensive (above the EU average) but also susceptible to fluctuations in the international energy market. Harvesting local energy in the form of wind, hydrology, and solar in tandem with energy efficiency and storage systems will ultimately decuple Irelands dependency on carbon-intensive fuels (mitigation) will make the state more resilient to international energy shortages and tariffs (adaptation).

2.6.2 Operational and Embedded Carbon

Using the IDF standard file format coupled with an embodied carbon database for materials, this research can estimate the impact of embodied carbon relative to building materials used for construction (Circular Ecology, 2021a). The fabric of buildings stock can be upgraded to consider their overall performance and embodied carbon contribution over the building's life cycle. This format informs the user on best-fit materials for energy refurbishment or new construction. This is best exemplified by objective threes study, which utilised this tool when deciding the optimal amount of PV panels to implement in the study area . For example, if all available roof space was utilised for PV panels in objective three, the payback period for both energy production and carbon mitigation of operational use is estimated at 18 years. However, when embodied carbon is considered in the estimations, then the payback increases to 27 years due to the current embodied carbon affiliated with PV panels. Considering the average life span of PV panels is 25 years, covering all available roof space in the study area would have backfired (Circular Ecology, 2021b; Sorrell, 2009).

This tool goes beyond the boundaries of managing existing, and future building stock as the carbon intensity of extracting, refining, and constructing buildings is often hidden in the primary sector energy emissions. When considering the DUBLD database is essentially a stock take of building fabrics and systems, then the circular system can be considered using a process called Urban mining.

2.7.10 Digitising and Communicating Green Deal Complexities

Cities and wider regions often depend on indicator data which abstracts information on a variety of systems related to urban centres (i.e., gross domestic product as an indicator of a region's productivity). These often come in the form of tables, graphs, workflows, and maps which abstracts the system related to these data, informing decision-makers and stakeholders on the nature of the system under observation. These abstractions are sometimes referred to as city dashboards and, when used responsibly, can be insightful tools for managing the performance of urban systems (Kitchin et al., 2015). However, the volume of data, generally, as a by-product of the internet of things (IoT), coupled with the added complexity of day-to-day urban life, more multifaceted models which can facilitate and communicate real-time data are required.

With the advent of digital twins, these data and their related systems can now be modelled across space and time (Issermann et al., 2021; Kitchin, 2014; Kitchin et al., 2015). These spatiotemporal models support the abstraction of real-time data and functions of urban systems, which serve as the brain and neural network of smart cities, or within the context of energy follows, smart grids (Qian et al., 2019). Both IoT and smart grids can work in tandem with UBEMs to better estimate current and future demand response for regional grids (Ang et al., 2020; Taşcıkaraoğlu, 2018). This works both ways as UBEMs can estimate demand response for future grids based on building profiles, which are calibrated using historical data from smart metering, which in turn feedbacks information to the smart grid. Furthermore, with the recent wave of IoT (particularly in relation to environmental sensors) coupled with UBEMs, real-time monitoring and response to the environmental changes and other related activities in our urban areas are now possible (Issermann et al., 2021). Currently, the literature positions both digital twins and IoT as key digital tools in modelling and managing city energy and alternative systems for the improvement of day-to-day life (Kitchin et al., 2015; Monteiro et al., 2018).

Smart cities, smart grids and the IoT share a symbiotic relationship with UBEMs which can produce a digital twin illustrating the abstraction of urban energy flows, which is generally more intuitive to the wider public (i.e., 3D renders of the city and systems being abstracted). Both objectives two and three illustrate how UBEMs can relay complex information and system process to both expert and non-expert users using 3D renders of the study areas. However, in their current static format, these 3D renders are limited by their instructiveness but can be interacted with using online web tools that are currently in development . This is beneficial for tackling a well-known phenomenon associated with sectoral approaches to large complex problems known as “silo mentality” (Bento et al., 2020, p2).

Silo mentality is a socio-technical phenomenon that arises throughout the information structures of public offices and departments that is considered a negative occurrence in contemporary organisations. Silo mentality can be described as clusters of information and/ or policies created by one entity in an organisation, institution, or governing body that is segregated away from other internal/ external respective entities, which would have otherwise benefitted by sharing information with each other and vice versa (Bento et al., 2020). In the context of Ireland and, by extent, the study area, a recent report released by the environmental protection agency (EPA, Ireland) interviewed experts and stakeholders on how they would describe environmental policy integration (EPI) in Ireland. A majority of the interviewees referenced the phrase “silo” mentality and, in some cases “silos within silos” in Irish institutions, governing bodies and related fields (Flynn and Ó Huiginn, 2019, p8).

To remedy such issues a platform for sharing information on data and associated policies is vital to ensure that data is not duplicated and policies do not run counter to one another. The Flynn and Ó Huiginn (2019) report set out a checklist of key instruments in negating the impacts of silo mentality. Some of the key instruments used to remedy this ongoing phenomenon are “design” and “communicate” both “data domains” and “communicating complex and quality scientific findings” respectively (Flynn and Ó Huiginn, 2019, p15). Considering the silo-mentality and the dissemination of complex scientific research, objective one has generated a data domain where a plethora of geographically related data can be merged to address alternative urban systems and scenarios. Also, as objective one adopted the same semantics as the national census, it makes the database more accessible to alternative causes, increasing its integration abilities. Moreover, objective two created UMI templates that will be publicly available on MIT’s UBEM.io website enabling other researchers to recreate and disseminate their own UBEMs related to other urban centres in Ireland. Objective three demonstrates UMIs versatility with regards to plugins that simulate alternative urban systems. Finally, objectives two and three demonstrate the power of using 3D digital twin renders as a communication tool as a medium of communicating complex scientific findings and systems to non-experts. All of this furthers the case of UBEMs being (preferably open source) platform for multidisciplinary urban simulations, which is open for use by interested parties.

2.7.11 Fuel Poverty and Historical Preservation

Dissemination of complicated energy policy will be key in tackling fuel poor households in Europe, which is important in improving occupants physical and mental health (Fabbri, 2015; Pye et al., 2015). Fuel poverty occurs in regions with the following triggers: poor building energy performance, low-socioeconomic building occupant, and regional fuel costs all combine to create energy-poor trifecta. Given the socio-technical complexities of where the fuel poor trifecta intersect, UBEMs are adequately positioned to capture the key triggers that result in energy poverty. Considering the building performance coupled with local energy prices and occupant profiles are integrated into the calculations and results of UMI, areas at high risk of fuel poverty can be illuminated. Furthermore, the technical specifications for addressing such fuel poverty (i.e., energy refurbishments) sometimes further compound the health implications (often unintentionally) for fuel poor occupants. This is best exemplified in historical homes where certain refurbishments exacerbate mould issues, which in turn impacts the occupants' physical health, which is discussed further below (Collins and Dempsey, 2019).

Policies maintaining the historical integrity of streetscapes and related aesthetics is a common theme in most European cities. However, keeping within limits assigned by policies, particularly related to the aesthetics of building facades and glazing, is a tricky proposition in the context of energy refurbishments. For example, upgrades to Georgian buildings in Ireland must not jeopardise or impact the historical aesthetics of building brick façade while undergoing energy refurbishments. This is partially difficult as 35% of the building's heat is lost through the solid masonry façade. Furthermore, insulation can only be applied to the internal or external walls of Georgian buildings, as the facade lacks cavities to insulate. Moreover, these solid masonry walls carry with them various ramifications if the correct refurbishment measure is not considered accordingly, i.e., mould issues (Arnold, 2013).

Conveniently, the methodology in objective one uses both the chronological identifiers from the Tabula webtool and national census, which helps to identify buildings that fall within the historical criteria covered by the above policy. Further to this, the technical properties of protected buildings can also be estimated by this methodology (with some of the limitations outlined in this discussion), which is best illustrated when considering the role masonry brick walls often play in the breathability of historical buildings. If incorrect refurbishment measures are implemented, they can not only diminish the aesthetics of the historical building but also prohibit the buildings' ability to regulate moisture leading to mould and/or damp damage to the interior. This not only has consequences for the building physical appearance but serious health implications for the building's occupants (reflecting on energy-poor occupant). Choosing the correct refurbishment systems appropriate to addressing such policy (i.e., internal dry lining insulation) will maintain the facades historical aesthetic values but also maintain the moisture regulation function of the walls while improving the U-value (kW/m²K) of the building envelope (Arnold, 2013; Collins and Dempsey, 2019; Hall et al., 2013; Loga et al., 2016).

2.6.5 Final Recommendations

Ultimately, UBEMs and UBEM related data are poised to tackle the overwhelming depth and complexities associated with energy-related policy and sustainable approaches related to urban systems. These complexities often disenfranchise non-experts and experts alike, all of whom are vital in hitting net-zero carbon goals. Both mitigation and adaptation measures will be vital in society response to climate change. UBEM could not only be an effective tool for disseminating these measures but also a tool for testing their resilience in the face of a constantly changing environment.

The methodology used to create DUBLD, discussed above, can be a painstaking and time-consuming task depending on the urban morphology of the area under observation. This task involved visually categorising building stock in the study area using remote sensing, which is a tedious endeavour amongst homogeneous urban fabric but would prove to be quite time consuming when categorising heterogeneous urban fabrics (city centres filled with a mix of old, new, and mix-used building stock). Fortunately, Google Street photo imagery was used to categorise relevant building stock, and the process can be streamlined using machine learning. The current DUBLD information can serve as training data for machine learning to home in building classification accuracy using google earth/ street view or alternative platforms to extract data (Szcześniak et al., 2021). This could produce DUBLD quality data for the entire region with the potential to be expanded to other regions that participated in the Tabula project.

National building archetypes cannot give exact information on specific buildings; they generalise the building parameters to match the collective attributes of the national building type; this makes them quite coarse for building-by-building analysis. Ali et al., (2019) suggest that national archetypes create too much uncertainty for local level UBEM analysis due to their coarseness. However, Ali et al., (2019) approach was statistically driven and depended on accurate archetypes at building scale to capture energy demand. The method applied by this research uses a physical approach that calculates the influence geometric features have on shading and outdoor/ indoor ambient temperatures. Nevertheless, this does not totally prevent the (p)rebound effect. In order to remedy this phenomenon, better data on both physical building elements and metered energy is needed to calibrate the model for accurate energy analysis of urban areas (Sunikka-Blank and Galvin, 2012; Sokol et al., 2017). Currently, EPC data could be merged with the existing DUBLD to further reduce uncertainty in building fabric and systems real-world performance. A combination of both metered and EPC data would alleviate the (p)rebound effects that plague current building energy analysis.

The geometric information affiliated with the current research is limited to basic geometric shapes that roughly capture the volume of the building stock under observation. This is often referred to as 2.5D data, which often neglects finer geometric details affiliated with building stock (i.e., gabled roofs, eaves & overhangs, sky bridges, balconies, etc.). Although the omissions of these finer details have minimal impact on calculating final energy demand, the inclusion of this information could only serve to improve the accuracy of the models (Rosser et al., 2019). Furthermore, these finer details would improve the calculation of potential solar yields as orientation and shading impact PV performance (Camacho et al., 2012)

An unintended consequence of creating DUBLD could potentially have a role to play in circular economies and, more specifically, urban mining. Urban mining is a practice of extracting raw materials such as rare metals, glazing, stone etc. from anthropogenic waste. This practice is often more economical and environmentally friendly than extracting new raw materials from the earth, thus making an economy for repurposing elements towards the end of their life cycle (Cossu and Williams, 2015; Koutamanis et al., 2018; Marinova et al., 2020). As DUBLD roughly takes stock of the volumetric properties of each building and the archetypal features associated with each building (fabric, system), it is, therefore, possible to estimate the number of materials each building contains. This is a helpful exercise in taking inventory of current materials that are in use but could be considered “Anthropogenic Stock Materials” at the end of the buildings life cycle, which can contribute to future material flow cycles of new, carbon-friendly, building stock (Cossu and Williams, 2015, p2)

Please highlight any implications/opportunities/recommendations for Ireland (e.g., for policy makers, for the research community, for industry) based on the work carried out in the project.

2.6 Conclusions and Next Steps

UBEM ability to address a diverse range of challenges that span across multiple disciplines makes it difficult to discuss with any single viewpoint. This discussion will approach UBEM as not only being a tool for energy management but rather a tool for urban system management. Moving forward, rather than focusing on its obvious applications as a large-scale building energy modelling tool it is more appropriate to think of UBEM as a digital twin.

Although the themes discussed in this report are firmly embedded in building energy, it is best discussed in the field of geography. Geography provides an appropriate platform for the inputs and outputs of this research as it is fundamentally the “study of places and the relationships between people and their environments” (National Geographic, 2021, p1). By exploring these relationships using the insights provided by the UMI and DUBLD, the scope of this research connects the dots between building physics, energetics, climatology, and human behaviour, to address climate change mitigation and adaptation challenges in the coming decades. The broader themes and challenges highlighted by this research by exploring the benefits, limitations, and next steps for objectives one, two and three followed by overall findings of this research.

2.7.1 Objective One Limitations and Next Steps

A major limitation in objective one was the methodologies inability to account for the internal properties of the buildings under observation. DUBLD could only describe details about the entire building exterior but could not distinguish the internal properties or the number of households (dwellings) inside the structure. This particularly proved problematic when validating multi-dwelling buildings in the database. This limitation was overcome using the An Post (Irish national postal service) Geodirectory database, which described the amount of dwelling attributed to each structure; however, this could not account for recent upgrades to the urban morphology. Due to the nature of using remote sensing (Google Earth), the database was limited to new developments that have been recently surveyed by Google Earth. Although, given the quantity of buildings under observation, this lack of updated data has little impact on the overall energy demand of a city and can be easily remedied by field inspections in smaller areas under observation.

Further to this, the task of creating the database is a laborious undertaking taking over six months to categorise 61 archetypes across 28,000 buildings in Dublin city. Person power and the geography of the building stock (homogeneous or heterogeneous), to which this method is applied, will determine the time it can take to categorise the buildings under observation. However, the method applied is easily replicable and would significantly increase coverage and reduce the time associated with data procurement by employing more personnel or utilising the benefits of machine learning to grow the existing database. Moreover, DUBLD can be utilised as training data for machine learning which improves the overall accuracy of this approach and reduces time and costs associated with hiring personnel.

Ultimately, objective one outputs an effective database that has highlighted pitfalls and biases associated with existing databases which underpin energy policy in Ireland. Also, it could prove useful in future research in waste management such as urban mining, which is discussed in further detail later. Objective one succeeds in creating a database that adequately depicts the physical reality of building stock on the ground, which plays a fundamental role in the formation of a UBEM.

2.7.2 Objective Two Limitations and Next Steps

Once again, objective one’s limitations were echoed in this study’s ability to secure accurate information on the actual internal building properties. In addition to dwellings, renovations and updated HVAC systems could not be accurately accounted for, all of which are not obvious from external examination. Further to this, the lack of EPC coverage and also proved to be challenging when evaluating the viability of the UBEM with the existing EPC database. A considerable number of neighbourhoods lacked a sufficient sample of EPC surveys to adequately represent the current state of building stock resulting in their omission. Moreover, the EPC framework, much like the census, surveys individual households were the Tabula archetypes sample individual buildings. The issue was inconspicuous with building stock dominated by SFH, but MFH buildings with multiple households (apartment blocks) proved difficult to evaluate. Unfortunately, this issue could not be remedied by merging the national postal database as it only described the number of dwellings in a structure, which made no reference to the dwellings current energy performance status. Also, the current EPC data is only available at a neighbourhood scale which prohibited attributing the data to the individual buildings and thus rendered the EPC database too coarse to remedy the issue.

Moving forward in improving the data, these limitations could be overcome by merging building scale EPC data with the UBEM database (DUBLD) described by this research. Although the EPC database was used in this case to evaluate the performance of the UBEM, it could also prove useful resources towards resolving the internal properties blackspots that both objectives one and two highlights. Fundamentally, the outputs of this study adequately addressed the challenges posed by objective two. Again, this study can be replicated across all 21 Tabula participant countries and regions with equivalent archetype data. This unlocks the potential of using the UBEMs to address ambitious climate policy with bespoke neighbourhood scale energy policy across Europe.

2.7.3 Objective Three Limitations and Next Steps

Cost-benefit analysis is possible using the current UMI platform, but data related to costs are difficult to procure and are restricted to vague estimations and sources. Costing related to energy refurbishments for individual households are the most accessible, as these costs are most relevant to the public domain. However, aggregating these same costs into an entire neighbourhood of multiple buildings would decrease due to the economy of scale. To capture the economy of scale, a reasonable discount was used to estimate the overall cost-benefit of refurbishing several hundred households at once. This was also a factor in addressing the costs for large scale PV and ESS systems which were remedied by using alternative sources from both the UK and USA, respectively. Most notably, costs associated with the DHC plant proved most challenging, with very few examples of this technology in Europe. DHC related expenses relied on academic papers to generate the costs associated with systems of this nature. Lastly, all EPC and energy-related simulation data make generous assumptions on the true energy demand of each household as GDPR laws prohibit the access and use of metered energy data. This means that the model runs a high risk of (p)rebound effect, which makes ambitious carbon goals more elusive to attain.

Moving forward and resolving both limitations, data must be made more available by relevant stakeholders, which does not run the risk of undercutting the sustainability market or jeopardising the inviolability of GDPR rules. The cost associated with major public infrastructure works related to this study could be made publicly available in EU member states which would help other national and local governments better incorporate the cost-benefit analysis emphasized by UMI. Further to this, anonymised metered energy could be disseminated at the neighbourhood scale, which would enable UMI to calibrate appropriately, reducing the risk of (p)rebound effects.

2.7.6 All Three Objectives and The EU Green Deal

The EU Green Deal is pumping €1.25 trillion into the decarbonization of the European Union over the next 10 years (originally €500 billion but an additional €750 billion was added to help with the covid recovery, Green Recovery). The overall budget to fully decarbonise the EU by 2050 is at €2.8 trillion; however, the aim of upfront funding is to incentivise private investment to unburden 60% of the carbon transition budget for the European economy (European Commission, 2020b). Two major pillars of the Green Deal involve decarbonizing the EU's energy supply and digitizing the EU's economy; within these pillars are subcategories focusing on various sectors within the EU. The EU Green Deal Renovation Wave can benefit greatly from UBEMs which will play a key role in the decarbonization of European building stock and related systems by facilitating the transition as a digital information tool (European Commission, 2020a). Objectives one, two, and three can facilitate the digitization of European building assets and simulation of complex systems, which are in line with the key principles stipulated by the renovation wave. These Renovation Wave criteria are discussed in their broader themes with references to the relevant support provided by outputs from objectives one, two, and three.

Note - Both Section 3 and Section 4 of this Final Report are required for SEAI review purposes only and will not be made publicly available.

SECTION 3: COMMUNICATION & DISSEMINATION (max 3 pages)

3.1 Communication, Dissemination and Exploitation

Please provide details of all dissemination activities undertaken throughout the project, providing references and links where applicable.

Dissemination Summary Tables

Please list details of any scientific publications in Table 3.1 on the next page. Please mention papers published in peer-reviewed journals or papers disseminated at conferences (e.g. on the conference website, etc.).

Please list details of all dissemination activities in Table 3.2 on the next page (e.g. publications which do not fall under Table 3.1's scope, conferences, workshops, websites/applications, press releases, flyers, articles in press, videos, presentations, exhibitions, thesis, interviews etc.).

3.2 Intellectual Property Management & Exploitation

If applicable, please provide details of any patents or IP generated as a result of this research award, or patents/IP which you think may eventuate as a result of the project.

Table 3.1 – List of Scientific Publications

Title	**Main Author**	**Journal Title**	**Number, Date or Frequency**	**Publisher**	**Year of Publication**	**Is/Will open access be provided? If you marked "will", provide an estimate of the date**	**Peer-reviewed (Y/N)?**
Using urban building energy modelling (UBEM) to support the new European Union's Green Deal: Case study of Dublin Ireland.,	Buckley	Energy and Buildings	Energy and Buildings Volume 247, 15 September 2021, 111115	Elsevier	2021		Yes
Designing an Energy-Resilient Neighbourhood Using an Urban Building Energy Model.	Buckley	Energies	*Energies* **2021**, *14*(15), 4445; **https://doi.org/10.3390/en14154445**	MDPI	2021		Yes
An Inventory of Buildings in Dublin City for Energy Management	Buckley	Irish Geography	May 2020Irish Geography 53(1) DOI:10.2014/igj.v53i1.1408	Geographical Society of Ireland	2020		Yes

Table 3.2 – List of Dissemination Activities

Type of Activity	**Main Leader**	**Title**	**Date/Period**	**Location**	**Type of Audience***	**Size of Audience**
Generating urban-scale building data to support climate modeling	Mills	American Meteorological Society Annual Meeting	*2020*	Boston US	*Academic/professional*	50
Conference	*Niall Buckley*	*UBEM of Dublin's Docklands*	*10-12 May 2019*	*Dublin*	*Scientific Community, Industry, Civil Society, Medias and Policy makers*	80-100

Conference	*Niall Buckley*	*Developing a database to support an urban building energy model: A case study*	15-18 May 2019	NUI Galway	*Scientific Community*	20+
Presentation	*Niall Buckley*	*UBEM of Dublin's Docklands*	*22nd May 2019*	*Dublin Docklands Office, Custom House Quay, Dublin 1*	*Civil Society*	*50+*
Conference	*Niall Buckley*	*International Conference on Urban Climatology*	*5th August 2018*	*City University of New York, NYC*	*Scientific Community*	*80 - 100*

**Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).*