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RESEARCH ARTICLE

Sustainability's Three Principal Dimensions Versus Climate Change Act 2008: A Retrospective Numerical Modelling

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Abstract

Sustainability continues to be a key field of study, encapsulating three principal dimensions: social, economic and environmental, which are also found within the context of climate change. However, there appears to be limited literature drawing upon the between sustainability and climate change. relationship, particularly in connection to

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carbon emissions and energy management. These issues have already been the subject of legislation in different countries, though still, predominantly individually rather than from an integrated perspective. The Climate Change Act (2008) provides a platform through which the relationship between sustainability and climate change can be considered. This paper establishes this relationship aspects of this relationship by employing the increased use of insulation within the UK housing stock to contribute to achieving the carbon reduction set by the Act. Taking a retrospective view through theoretical numerical modelling, this paper demonstrates that CO_2 reductions were achievable. The results demonstrate that links can be drawn between sustainability and climate change and identifies that significant CO_2 savings, through robust energy management of the UK housing stock, these results can be achieved. It is also suggested that the theoretical mole developed can be reproduced to consider climate change targets and provide benchmarks, not only in the UK but in other countries.

Keywords

Energy Efficiency; Energy Management; Sustainable Development; Climate Change Act 2008; Carbon Emissions

INTRODUCTION

BACKGROUND

Greenhouse Gases (GHGs) are considered to be an influential anthropogenic activity associated with Climate Change and one of twelve sustainable development indicators in the United Kingdom (UK) (DEFRA, 2013). The generation of Carbon dioxide (CO_2) is one of the most significant GHGs, produced during the combustion of fossil fuels during the exothermic chemical process (Butt, Giddings and Jones, 2012). Since the industrial revolution in the 1900's, the production of CO_2 has continued to increase (CDP, 2010; Butt, Giddings and Jones, 2012). The realisation of this led the UK to implement the Climate Change Act in 2008, in an effort to reduce GHG emission to net zero by 2050 (DBEIS, 2021a). Figure 1 below illustrates this increase and demonstrates how, by 1985, the safety limit was exceeded and, since then, has continued to increase and, by June 2023 had broken through the 420.2 ± 0.5 ppm and was, as such, significantly above the anticipated concentration. (CO2.Earth, 2023).

The Green House Gass effect can be described as the accumulation of Carbon dioxide in the atmosphere and trapping heat near the Earth's surface to cause warming (Li, et al., 2021) and is closely associated with climate change (Aresta and Dibenedetto, 2021). The relationship between sustainability and the climate change is therefore closely linked to carbon emissions.

Sustainable Development Indicators (SDIs) represent a collection of metrics that demonstrate the extent of advancement towards a more sustainable economy, society, and environment. Within the UK's sustainability framework, there exist 12 primary indicators. Among the principal 12 indicators is the assessment of greenhouse gas emissions and CO_2 generation linked to energy consumption. One of the key indicators relate to UK CO_2 emissions by sector, including the residential sector. The energy efficiency of the UK's residential sector therefore serves as a key indicator, covering existing and new housing developments (DEFRA, 2013; ONS, 2015). Recent policy developments have concentrated on programs which enhance domestic energy efficiency, are economically feasible, curtail emissions, and tackle issues such as fuel poverty (Katris and Turner, 2021).

As Zuo and Zhao (2014) suggest, buildings contribute to GHG's emissions and, as such, contribute to global warming. It is estimated that buildings contribute to approximately one third of global greenhouse gas emissions, predominantly through fossil fuel-based energy generation (Huovila, et al., 2009) It is

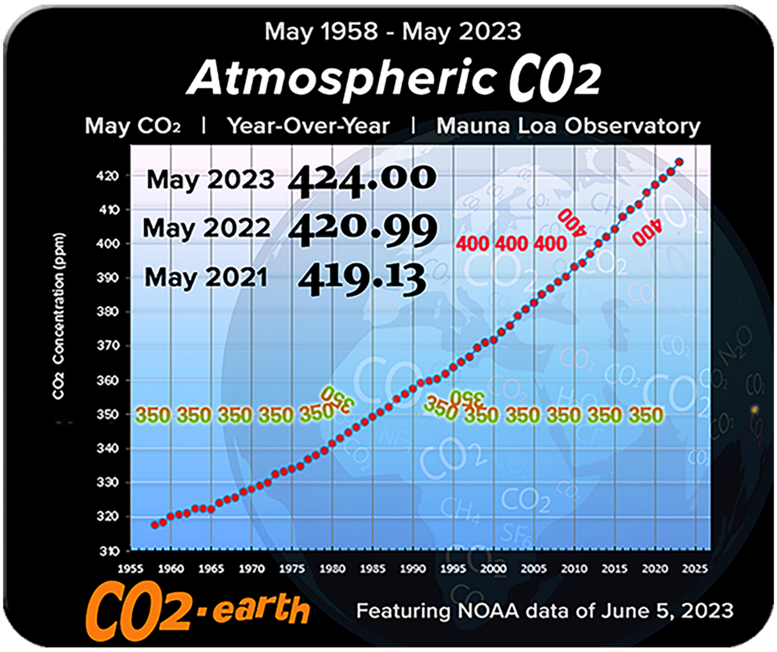


Figure 1. Atmospheric CO_2 Concentration (CO2.earth, 2023)

therefore suggested that it becomes imperative to evaluate the influence of the UK housing stock on climate change and its sustainable development strategy in reducing energy consumption in buildings (Janda, 2011).

The Climate Change Act (2008) (CCA) established a legislative framework to reduce GHG's emissions by setting targets for carbon reduction and promoting actions that mitigate atmospheric emissions (UK Government, 2008). The formulation of the CCA targets is grounded in the Kyoto Protocol and worldwide efforts to ensure the global warming threshold remained below 20C (CCC, 2015; Giddens, Latham and Liddle, 2009). The three key targets set for the reduction in UK carbon emissions were: compliance with the 1997 Kyoto Protocol to achieve a target reduction of 12.5% by 2012; Setting an interim goal of a 34% reduction by 2020; and a 100% reduction by 2050 (DBEIS, 2021a). These targets reference the baseline year of 1990 when UK carbon emissions amounted to 778 million tonnes (Beales, 2014). These targets continue to serve as key performance indicators in monitoring the UK's progress in reducing carbon emissions (DECC, 2015). As part of the CCA they hold legal status and must be considered in all energy efficiency enhancement projects related to UK properties (Curtis, 2010).

Sustainable development is typically conceptualized across three primary dimensions: social/ethical, economic, and environmental (Moldan, Janoušková and Hák, 2012). There is a lack in literature on the relationship between sustainable development and climate change along these three dimensions individually and yet simultaneously (i.e., in one single study) while specifically focusing on mapping sustainability implications to the legal targets of the Climate Change Act (see literature matrix below). This knowledge gap is the focus of this study.

AIM AND OBJECTIVES

Based on the implications of energy-saving/energy efficiency, carbon-cuts, cost-savings, pay-back periods of a typical insulation technology; the study aims to produce and apply an innovative and numerical conceptual model of energy to map the links between the sustainability philosophy and climate change at social/ethical, economic and environmental fronts. Thereby, this study specifically employs the UK housing sector as a use-case and using the legal carbon cut targets of the UK Climate Change Act (2008) as benchmarks for the year 2020 in a retrospective context. This aim is managed via the following key objectives:

1. Establish group types and the size of each group type of dwellings in the UK, as well as energy consumption/losses in them.
2. Calculate the corresponding potential savings in energy and cost for a typical insulation technology, if applied to each of the group types of the housing stock.
3. Map the calculated potential savings of energy on to the legal carbon cut targets of the Act, and estimate how far these legal targets could be achieved in the residential/housing sector, while considering the period 2016-2020, in retrospect; and
4. Overlay the findings from Objectives 2 and 3 on the three individual principal dimensions of the sustainability philosophy to establish mutual implications between the concepts of sustainable development and climate change.

RESEARCH METHODOLOGY AND LIMITATIONS

The research methodology is depicted via a flowchart in figure 2 below. A literature review is carried out based on not only refereed academic journals but also government reports and legislation documents. This leads to establish knowledge and secondary quantitative data around existing housing stock and characterisation, global and UK energy situation, domestic energy demand and typical heat losses, typical insulation technology and application formats, and cost implications. The literature review also assisted in more clearly identify and determine knowledge gaps to refine the problematisation. Benchmarks also established, particularly from the Climate Chage Act to inform the quantitative estimation and evaluation of the potential carbon footprint reduction in the existing UK housing stock. A numerical model is developed to simulate the potential impact of increased insulation on the achievement of carbon-cut targets in retrospect for 2020. The model considers various parameters such as the diversity of UK housing types, different insulation methods, potential energy savings, associated carbon emission reductions, and alike. In the scenario analysis of the model, multiple limitations and characteristics are considered as follows:

- Out of a several insulation types, a typical one is considered.
- For benchmarks, Climate Change Act targets are considered, i.e., a 34% reduction at the base level of 1990.
- Residential housing stock in the UK is divided in five types of dwellings i.e., Detached, Semi-detached, Mid terrace, Bungalow, and Flat).
- The focus is retrofitting potential of insulation, so, operational energy is counted for, not the embodied energy.
- The geographic remit is only the UK.
- All the three principal dimensions of sustainability philosophy are included – social, economic, and environmental.

LITERATURE REVIEW

THE UK HOUSING STOCK

It is estimated that 50% of the total energy consumed in UK is by buildings in use (Fathi, et al., 2020; Cotgrave and Riley, 2012) with the UK housing stock alone responsible for 29% of the total UK CO_2 emissions (Green, et al., 2020; ONS, 2018; DECC, 2013). The construction of new homes has contributed to the reduction of these emissions as building regulation requirements in terms of energy efficiency have

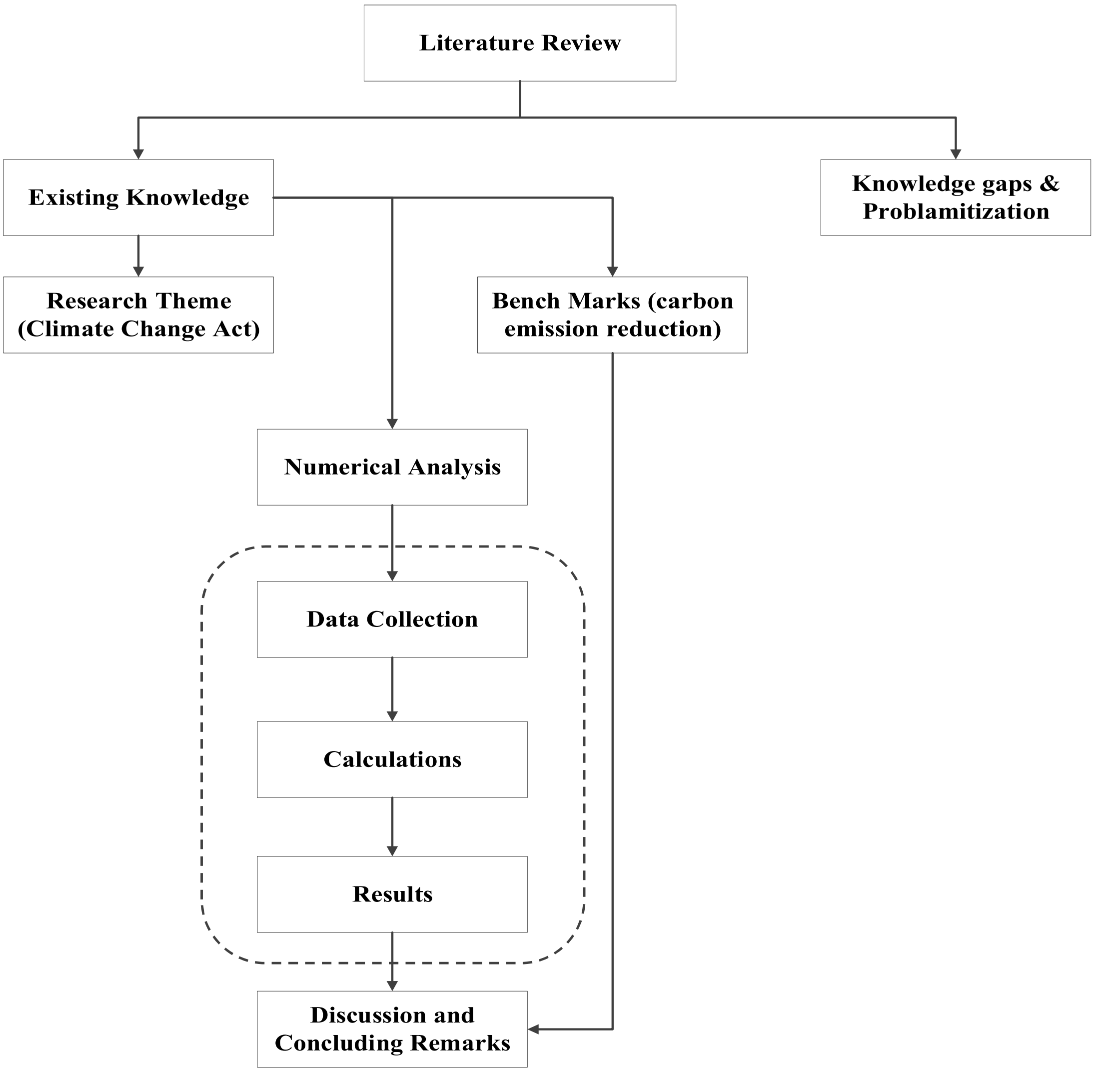


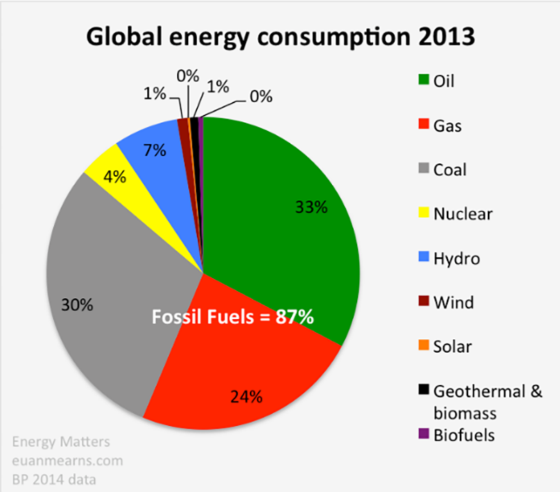
Figure 2. Research methodology flowchart

tightened. Part l of the Building Regulations state that heat loss through the fabric of a building should be limited (Cotgrove and Riley 2013). However, a large proportion of the UK population still live in older, less efficient homes. It has been estimated that between 70% and 86% (Baeli, 2019; Gillott and Spataru, 2010; Milner, 2008) of the current housing stock will still exist in 2050. Therefore, the onus of carbon emissions control appears to lie more with the existing housing stock rather than the new.

Approximately 40% of the UK housing stock was built before 1945 (EHCS, 2009), with 28% built before 1919 (IHBC, 2019), when energy efficiency was much less of a concern. Therefore, as Baeli (2019) identifies, there are a substantial number of the UK housing stock which can be considered less energy efficient than the newer built stock. As a result, to address and improve energy efficiency and reduce energy usage and CO_2 emissions, there is a substantial retrofitting programme required (Giesekam, et al., 2014).

ENERGY CONSUMPTION - FOSSIL FUELS AND NON-FOSSIL FUELS

The demand for energy has significantly increased to meet the growing population needs worldwide (IEA, 2020; EIA, 2019; EIA, 2020). It is argued that even were all the renewable resources deployed, they would still not meet the worldwide demand for energy and, as such, there is still a reliance on fossil fuels (WEC, 2013). Figures 3a and 3b below show the percentage distribution of global energy consumption.



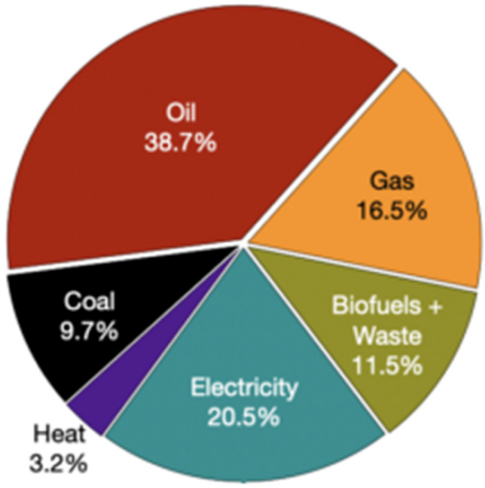
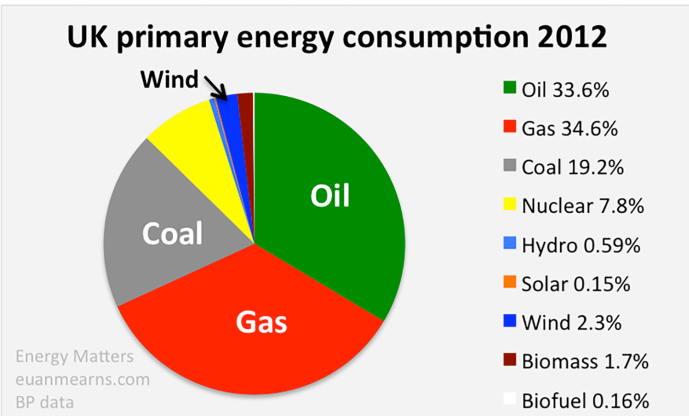


Figure 3a. Global energy consumption 2013 (Mearns, 2014)

Figure 3b. Global energy consumption as of June 2023 (WED, 2023)

While the UK still reflects the global perspective, with 85% of total energy consumption being derived from fossil fuels, it has made significant progress in reducing the use of fossil fuels by a move towards more renewable energy (see Figures 4a and 4b below).



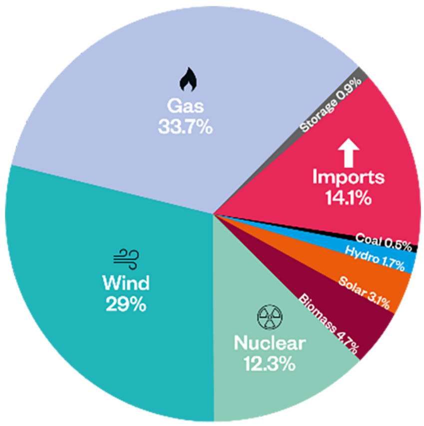


Figure 4a. UK energy consumption 2014 (Mearns, 2013)

Figure 4b. UK energy consumption 2023 (Mackenzie, 2023)

Whilst this change is welcomed, the use of fossil fuels for heating remains the largest consumer of energy consumption within the UK housing stock. To address this issue, it is argued that this can be tackled by improving insulation in homes. Of the UK energy consumption in various sectors, the domestic sector is the second largest at around 40 million tonnes of oil equivalent, as shown below in Figure 5.

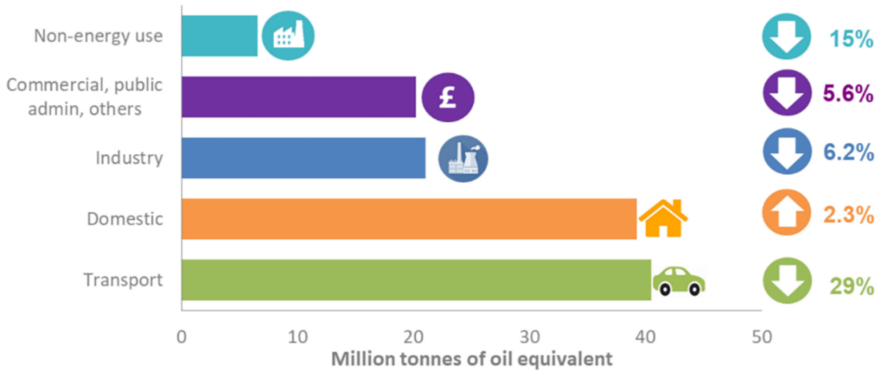


Figure 5. UK energy consumption by sector, 2020 (DBEIS, 2021b)

By focusing on this sector would address a significant percentage of the UK housing energy consumption. Figure 6 identifies the areas in where energy is consumed in a typical domestic setting and shows space heating as being the largest energy consumer, contributing to over a half of the total energy used in a typical dwelling.

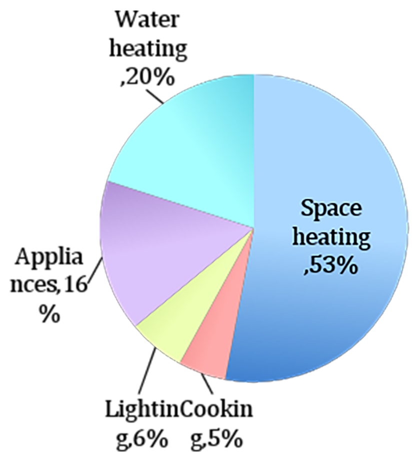


Figure 6. Energy use breakdown of a typical house (DCLG, 2006)

By addressing the energy use in this area will have a positive, direct impact, not only on energy use and cost savings but also on achieving the targets set by the Climate Change Act. A current trend in building construction is to move towards zero energy buildings, in an attempt to reduce the total energy consumption and so the impact on the environment buildings have over its lifecycle (Syngros, Balaras and Koubogiannis, 2017). As such, this paper focuses on heat losses in the domestic residential sector in connection to space heating.

DOMESTIC HEAT LOSS

Heat moves from a warmer space to a cooler space, with this movement taking place through heat transfer in three forms: conduction (heat transfer through a solid), convection (heat transfer through fluid or gas), and radiation (heat transfer through empty space) (Janna, 2009). One method of reducing this heat transfer is in the placement of the insulation, installed as a continuous barrier within, the building envelope to act as a barrier between the interior and exterior of the property. The building envelope includes the flooring, walls, windows, doors and the roof. The approximate heat loss from these elements is shown in figure 7 below.

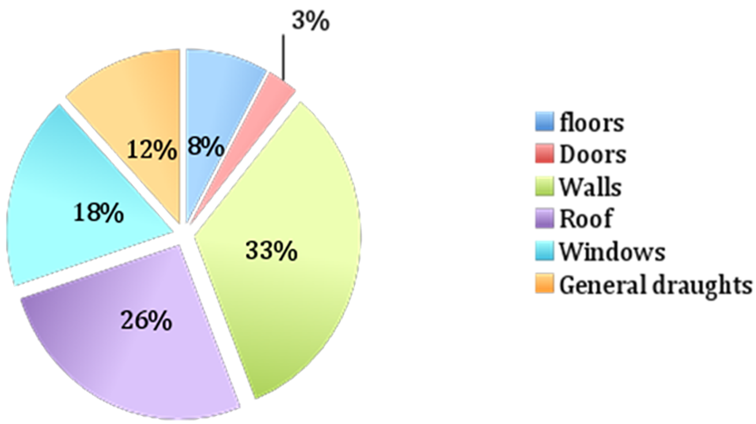


Figure 7. Building elements through which energy is lost in space heating (Anderson and Kahya, 2011)

This study is specifically focused on wall insulation and heat transfer through the walls of a house. There are different types of insulation including rigid foam and spray foam; however, the most used insulation in domestic properties is fibreglass batt insulation and injected insulation. A property, once insulated and heated, will experience a significant reduction in the amount of heat lost It is also important however, when insulating properties that a degree of ventilation is provided to maintain air quality and to ensure that a build-up of condensation does not occur and cause potential damage the building structure.

SUMMARY OF RELEVANT STUDIES

Table 1 summarizes the literature review in a matrix that demonstrates that the closest possible matches to the scope of this study. The marked cells demonstrate that there are literature focusing either on Climate change (such as Crawley, 2008; Šimko, et al., 2018), sustainability (such as Baeli, 2019; Cvelbar and Dwyer, 2013; Moldan, Janoušková and Hák, 2012; Eakin, Lemos and Nelson, 2014), Energy Distribution and Consumption, and Carbon Foot-print (Goodchild and Walshaw, 2011), Residential (Çomaklı and Yüksel, 2003). Whereas there is a lack of literature which is ticking all the boxes. In other words, no evidence has been found of literature which integrates all these angles together under one umbrella in which the insulation technology could be used to relate to climate change adaptation and mitigation, simultaneously and yet focusing on the residential, space heating, carbon footprint, fossil fuel and renewable energy. This knowledge gap is the focus of this study.

CONCEPTUAL MODEL & CALCULATIONS

BACKGROUND DATA

The UK housing stock falls into five categories as shown in Figure 8 below. Using the theoretical numerical model, the average energy-saving and carbon-reduction in each of the five categories is shown in Table 2. This is for two ways of the application of a typical wall insulation i.e., external, and internal. Average values are employed in the study in terms of size, shape, orientation, materials, location, and those that are gas heated and completely un-insulated. (EST, 2016).

Table 1. Literature Matrix

KEY LITERAURE/ PUBLICATION		Sustainability			Fossil Fuel Energy	Renewable Energy Generation	Energy Distribution	Energy Consumption	Carbon Foot-Print	Residential/Housing Sector	SDGs	Space Heating		Climate Change		Brief Remarks
Author	Year	Environment	Economical	Social								Insulation (Wall)	Others	Mitigation	Adaptation	
Baeli	2019	X	X	X	-	X	-	-	X	X	-	-	-	-	-	This paper covers Carbon footprint and Residential however Climate change and Space heating is not covered.
Šimko, et al.	2018	-	-	-	-	X	X	X	-	X	-	X	X	X	X	This paper covers Energy, Space Heating using Insulation, Climate Change and Residential however other sustainable aspects are not covered.
Eakin, Lemos and Nelson	2014	X	X	X	-	-	-	-	-	-	X	-	-	X	X	This paper covers Sustainable aspects, SDG and Climate change, However Energy, Space heating is not covered.
Giesekam, et al.	2014	X	X	-	-	-	-	-	X	X	-	-	-	X	-	This paper covers Sustainability in terms of Environmental and Economical, Residential however Space heating is not covered.
Cvelbar and Dwyer	2013	X	X	X	-	-	X	X	-	-	-	-	-	-	-	This paper covers Sustainable aspects and Energy however Climate change and Space heating is not covered.
Moldan, Janoušková and Hák	2012	X	X	X	-		-	-		-	-	-	-	-	-	This paper covers Sustainable aspects and Energy however Climate change and Space heating is not covered.
Goodchild and Walshaw	2011	X	X	X	-	X	X	X	X	X	-	-	-	X	X	This paper does not cover Fossil Fuel Energy, SDH and Space heating.
Bilen, et al.	2008	X	X	X	X	X	X	X	-	-	-	-	-	-	-	This paper covers Sustainable aspects and Energy however Carbon footprint, Climate change and Space heating is not covered.
Crawley	2008	X	X	X	-	X	X	X	-	X	-	-	-	X	X	This paper covers Energy, Space Heating using Insulation, Climate Change and Residential however other sustainable aspects are not covered.
Çomaklı and Yüksel	2003	-	-	-	X	X	-	X	-	X	-	X	-	-	-	This paper covers Energy, Space Heating via Insulation walls and Residential however other sustainable aspects are not covered.

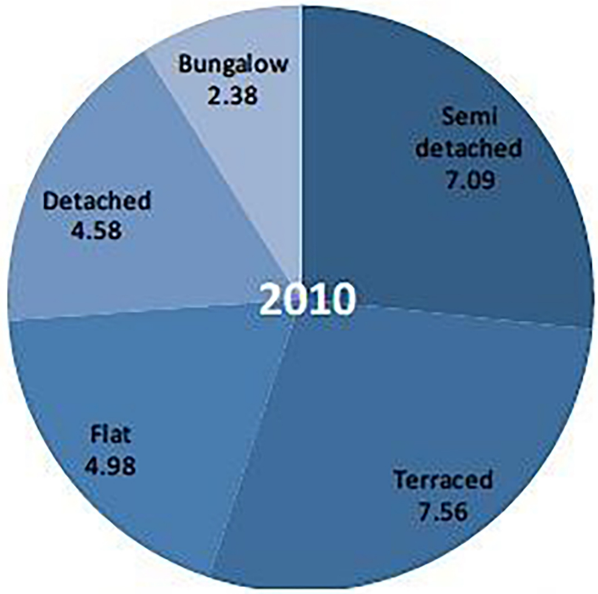


Figure 8. Housing group types in the UK residential sector in millions (DECC, 2012)

Table 2. Estimated figures based on insulating a gas-heated home (EST, 2016)

	Detached	Semi-detached	Mid terrace	Bungalow	Flat
Carbon dioxide cuts (kgCO²/year)	1,900kg	1,100kg	720kg	740kg	610kg
Fuel bill savings (£/year)	£455	£260	£175	£180	£145
Typical insulation cost	Internal wall insulation: £3,000 to £14,000; avg. = £8500 External wall insulation: £5,000 to £18,000; avg. = £11500				

CARBON CUTS

Based on Table 2 and Figure 7, potential of carbon cuts is calculated as shown in the box below for each of the five group types of the UK housing stock:

Carbon cut = Number of dwellings X Carbon cut per year for each dwelling type (kg/year)	
Detached	
Carbon cut = 1,900 X 4,580,000 = 8.702x109 KgCO2/year	8,702 MtCO2/year
Semi-detached	
Carbon cut = 1,100 X 7,090,000 = 7.799x109 KgCO2/year	7,799 MtCO2/year
Mid terrace	
Carbon cut = 740 X 7,560,000 = 5.594x109 KgCO2/year	5,594 MtCO2/year
Bungalow	
Carbon cut = 750 X 2,380,000 = 1.785x109 KgCO2/year	1,785 MtCO2/year
Flat	
Carbon cut = 610 X 4,980,000 = 3.037x109 KgCO2/year	3,037 MtCO2/year
Total carbon cut of the residential sector = 26,917 MtCO2 / year	

Table 3. The UK and residential emissions and percentage reduced from baseline (DECC, 2015)

Year	UK total Emission (MtCO2e)	Residential (MtCO2e)
1990	777	80.0
2010	598	89.0
2015	550	74.0
2020	435	67.0
2035	352	73.0

FIVE YEARS SCENARIO – 2020

The calculations are based on 5-year temporal window stretching between 2015 and 2020 i.e. starting from 01/01/2016 and ending at 31/12/2020

Without insulation:

Carbon emissions in 5 years = 74 X 5 = 370 MtCO2 Eq A1

The value 74 comes from table 3 presuming it remains the same from 2015 to 2020, especially when the carbon emissions are going to creep back to nearly the same value in 2035 as table 3 suggests.

With insulation:

Carbon emissions in 5 years = 26.917 X 5 = 134.59 MtCO2 Eq A2

Carbon cut in 5 years = Eq A1 – Eq A2 = 370 – 134.59 = 235.41 MtCO2

Carbon emissions in percentage = Eq A1 – Eq A2/Eq A1 X 100 = 370 – 134.59/370 X 100 = 63.6 %

This figure is almost double the carbon cut target of 34% by 2020 by just applying the wall insulation technology alone. These calculations regard a retrospective scenario of 2020 temporal target of the Climate Change Act 2008. The period considered is from January 2015 to December 2020 i.e., five years, as if the insulation was applied to entire the residential sector at the start of the duration. Irrespective of this, it is demonstrated that in 5 years, the legal climate change target is achievable. So still, if this wall insulation approach was applied, even then the 2020 target could have been achieved by 2 years or so late.

If this is supported further by insulations of other area such as roofs and floors, the carbon cut could be increased. The numerical model presented in this study also indicates the potential that in addition to the introduction of insulation, by applying in-situ renewable technologies such as solar panels and micro wind turbines, the reduction in carbon emissions can be significantly increased. By applying energy efficiency measures such as insulation and renewable energy generation on site, it is possible to achieve carbon neutral or zero carbon footprints in future.

COST ANALYSIS

The advantage of internal wall insulation is its overall cost-effectiveness. However, a drawback is that it reduces the internal space of the existing property or the room where it is applied. As it would be applied to all four walls of a given room, reduction in the space of the room would be twice as much on either side, that is both length and breadth. On the positive side, internal insulation remains protected from external environmental factors, contributing to its longevity. On the other hand, external wall insulation is more expensive, resulting in a longer payback period. However, it does not reduce the internal room space as it is applied externally. The trade-off is that external insulation is exposed to external weather conditions, UTS ePRESS

potentially leading to damage over time. The increased expense of external wall insulation is partly due to the need for more resilient materials to withstand weather conditions, as well as the larger quantity of materials required for external application as opposed to the internal one. Further research would be required to explore various materials, application methods, and other implications. However, such detailed investigations are beyond the scope of this study.

Table 4. Cost Analysis of Wall Insulation Scenarios (Referring Table 2)

Solid wall insulation			Detached	Semi-detached	Mid terrace	Bungalow	Flat
Fuel bill savings (£/year per dwelling)			£455	£260	£175	£180	£145
Internal Walls	Typical insulation cost (£)	Min.	£3,000	£3,000	£3,000	£3,000	£3,000
	Payback period (years)		*6.59	11.54	17.14	16.67	20.69
	Typical insulation cost (£)	Avg.	8,500	8,500	8,500	8,500	8,500
	Payback period (years)		18.68	32.69	48.57	47.22	58.62
	Typical insulation cost (£)	Max.	£14,000	£14,000	£14,000	£14,000	£14,000
	Payback period (years)		30.77	53.85	80.00	77.78	96.55
External Walls	Typical insulation cost (£)	Min.	£5,000	£5,000	£5,000	£5,000	£5,000
	Payback period (years)		10.99	19.23	28.57	27.78	34.48
	Typical insulation cost (£)	Avg.	11,500	11,500	11,500	11,500	11,500
	Payback period (years)		25.27	44.23	65.71	63.89	79.31
	Typical insulation cost (£)	Max.	£18,000	£18,000	£18,000	£18,000	£18,000
	Payback period (years)		39.56	69.23	102.86	100.00	124.14

*Note: The formula applied is as follows: Typical insulation cost (£)/Fuel bill savings (£/year) = 3000/455 = 6.59 years. In the same manner, other payback periods are calculated for other scenarios in the table.

SUSTAINABILITY AND THE CLIMATE CHANGE TARGETS – ANALYSES AND SYNTHESES

Based on the results above, this section of the paper maps the legal climate change targets on various aspects of the sustainability philosophy along each of its three principal dimensions (Getvoldsen, et al., 2018):

SOCIAL ASPECTS

The legislative framework of a nation constitutes a social and ethical concern, as it stems from the public through democratic processes within the parliament. Consequently, adhering to the established laws of the country holds both social and ethical significance. This fact is quantitatively illustrated in the "Theoretical Model and Calculations" section, wherein it is shown that by focusing on insulating just the walls of UK residential properties, the potential exists to move towards the requirements of the Climate Change Act 2008.

Predictions relating to climate change indicate a potential annual temperature rise of 1 to 3.5 degrees Celsius in the coming decades. In addition, due to the concentration of industrial infrastructure, buildings, and transportation, urban heat islands are becoming more prevalent (Hulme, et al., 2002; Crawley, 2003, 2008). The issue of energy efficiency, GHG emissions, carbon reduction and addressing fuel poverty, are crucial social facets relating to climate change, explicitly addressed within the UK's national sustainability strategy. Using the theoretical model presented in this paper, it is argued that progress across key sustainability indicators and measures can be made., including the specific sustainability objective of conserving energy and reducing reliance on fuels.

The issue of human comfort relating to indoor air quality, humidity levels, and ventilation within a dwelling relates specifically to the social facet of sustainability with the insulation of housing effectively enhancing this comfort. Heat naturally flows from warmer to cooler areas, but insulating properties will slow the rate of heat transfer from warm, interior parts of a property to the colder exterior. Similarly, in warmer weather, insulation can reduce the entry of external warmer air into the cooler interior of the property (KdB Insulation Ireland Ltd., 2013). In this context, insulation can contribute to maintaining a comfortable indoor temperature (a social aspect of sustainability) during both extreme cold and extreme heat, without requiring excessive energy consumption for either space heating or air conditioning. (WEC, 2013).

ECONOMIC ASPECTS

Affordability in the maintenance and operation of a household can be recognized as an economic dimension within the sustainable development paradigm, specifically encompassing expenditure on gas and electricity. These costs continue to rise, bringing more households into fuel poverty. It is therefore argued that widespread insulation of the UK residential sector can contribute to a reduction in gas and electricity bills and help alleviate financial hardships, a key economic metric in the national sustainability agenda (DEFRA, 2013).

Households with lower incomes are often found to reside in less energy-efficient homes. As such, access to Government subsidy initiatives for residential insulation projects can help address this issue. For instance, in England and Wales, eligible homeowners had access to a total of £540 million in financial assistance for several years (Straus, 2014). Certain households could even qualify for up to £7,600 to enhance their energy efficiency, with an additional £500 available for those who had moved within the last 12 months (Straus, 2014). Financial incentives in the form of tax credits, rebates, and grants provide innovative solutions that remove barriers to implementing energy efficiency upgrades. Such outcomes can contribute to shaping policies and aligning with national sustainability objectives.

The widespread application of insulation technologies and techniques (for instance, across the entire housing sector of the UK) can usher in fresh economic opportunities within the country, thereby contributing to the Gross Domestic Product (GDP). This, in turn, directly aligns with the sustainability headline measure of Economic Prosperity (DEFRA, 2013). A case in point is the passive house standard, which relies on advanced insulation to regulate housing thermal performance. By 2010, more than 15,000 buildings in Europe had been constructed or retrofitted to meet the passive house standard. This approach, characterised by airtight construction and intelligent insulation, reduces energy loss, operational expenses, and benefits the environment (Brindle, 2011).

ENVIRONMENTAL ASPECTS

Fossil fuels offer a range of valuable products and services, with energy generation being the foremost and most substantial contribution. The combustion of fossil fuels for energy production yields significant quantities of undesirable CO_2 emissions, thus playing a pivotal role in global warming. This leads to a number of effects, including extreme weather events, heightened frequency and intensity of rainfall, droughts, glacier melting, acid rain, ocean acidification, and rising sea levels (Butt, Giddings and Jones, 2012; CCC, 2015). HR Wallingford (2014) predict that the UK will experience significant increases in heatwaves, floods, and water shortages that could damage infrastructure in the years to come. This underscores the pressing need to curtail anthropogenic CO_2 emissions. Consequently, the control of greenhouse gas (GHG) and carbon emissions, particularly within the housing sector – known for its significant contributions – has been recognized as both headline and supplementary indicators in the national sustainability strategy.

In 2011, fossil fuels accounted for approximately 83% of the world's energy consumption. Global carbon dioxide emissions reached a record high in 2012, totalling 34.5 billion tonnes (McGrath, 2013). While many European Union countries were lowering their emissions, the UK witnessed an increase in energy emissions in 2012 compared to the previous year, prompting concerns within the UK government about securing a low-carbon future (Evans, 2017). This study underscores the substantial potential of residential sector insulation to facilitate sustainable energy consumption, thereby reducing carbon emissions – an essential measure for mitigating climate change.

Air quality and human health are not only key components of sustainability but are also closely intertwined. In the realm of air quality, carbon emissions, regardless of their source, stand out as significant contributors that compromise air quality. Poor air quality adversely impacts human health, safety, well-being, as well as associated ecological systems, habitats, and biodiversity (DEFRA, 2013; CCC, 2015). The reduction of carbon emissions from the residential sector can substantially contribute to the overall decrease in GHGs and specifically in carbon emissions in the atmosphere, constituting an environmental sustainability measure. This, in turn, can slow down the pace of global warming, a primary manifestation of climate change. Moreover, carbon reduction efforts would also effectively contribute to the mitigation of other threats to environmental sustainability such as glacier melting; adverse effects on ecological systems both habitat and species like polar bears; rising sea levels; increase in mobility of pollutants of contaminated sites due to water regime changing; acid rain; ocean acidification; geographical and temporal changes in precipitation patterns in term of intensity, duration, and frequency; increased frequency and intensity of flooding; and alike.

DISCUSSION AND CONCLUDING REMARKS

Through the lens of energy use and CO_2 Production, this paper has explicitly explored and presented the high degree of multi- and inter-disciplinarity of sustainability and climate change, drawing links between the two. It has presented the idea that they can be tackled and managed simultaneously, rather than individually in the context of energy use. To demonstrate this, an innovative, numerical, theoretical model has been designed, developed and applied by employing a practicable and visualize-able' case study. The case study used is the existing housing sector in the UK in a retrospective manner. Whereas the residential sector is a main contributor and constituent of the built environment, it is argued that the innovative model presented, can be extrapolated in future studies to address other sectors of the built environment e.g. commercial buildings and infrastructure.

In terms of benchmarks, legal carbon reduction targets set by the Climate Change Act 2008 have been employed. The calculations in the model are founded on the temporal targets to the year 2020, which in future can be expanded both temporally (e.g. 2030, 2050, and 2090) and geographically in other countries around the globe. This will further add an 'internationalisation' aspect to the research with 2030 being the global development agenda, 2050 the climate change act agenda and 2100 as one of the projections of IPCC (Collins, et al., 2013). The climate change projections predicting the future from the worst-case scenario through a range of average and most-likely scenarios. can be considered and the model presented in this paper applied to various countries to draw country-specific results. This demonstrates the flexibility and reproduceable nature of the numerical model.

The paper has distinctly identified a range of headline and supplementary indicators and measures within the national sustainability agenda, which directly align with the mandated carbon reduction targets set by the Climate Change Act. The paper has concisely presented several innovative insights and implications on how these sustainability measures can be aligned with climate change considerations, specifically focusing on carbon emissions. Moreover, the paper has undertaken this alignment across each of the three primary dimensions of the sustainable development framework.

Adhering to legal obligations signifies the fulfillment of the social facet of sustainable development. Enhancing comfort in the face of extreme weather events through insulation also constitutes a social benefit. The reduction of energy consumption not only fosters societal comfort but also decreases the UK's reliance on energy, thereby aiding in addressing energy demand, security, and scarcity concerns.

Realizing savings on energy bills directly translates into economic advantages for the UK population, especially amid substantial energy price escalations over the past two decades. Energy conservation, such as through insulation as explored in this study, results in reduced oil imports, yielding positive economic effects for the UK. From an environmental standpoint, reduced energy consumption leads to lower carbon emissions, contributing to a healthier atmosphere for both humans and other species. This, in turn, curbs GHG emissions and the subsequent greenhouse effect, which can be seen as an approach to climate change mitigation. Additionally, the control of global warming, achieved through energy conservation in part via insulation as proposed in this study, can have a positive impact on numerous environmental aspects, such as the preservation of habitats, ecological systems, and biodiversity.

The innovative mathematical model developed and presented in this paper addresses the UK housing sector only. However, it is recognised that the model can be used in other areas of the built environment. It has included factors such as energy savings and carbon reduction as well as cost savings and pay-back periods. Finally, the three studies can be amalgamated to estimate potential impact of the idea of the current study for the whole of the UK's built environment. Further studies are also required to recognise adverse environmental impacts, if any, for the retrospective application of the insulation technology on the massive scale of entire UK residential and other sectors. This may include waste arisings due to 'reconstruction;' transport; and other factors of the life cycle of the insulation materials.

This study has not only combined sustainability with climate change in an overall manner, but also integrated along a number of other facets or layers such as temporal deadlines of sustainability and climate change mitigation, numeric/calculations, legislative implications e.g. legal carbon cut targets, air quality, etc. This way, both, the study itself and model produced as a main output, are multi- and inter-faceted. However, further and future studies can be carried out on methods and technologies of energy conservation and management, other than the insulation approach employed in this study to demonstrate the application aspects of the model. This can be enhanced even further by employing technologies and techniques regarding digital engineering of construction which can assist to carry out and/or informed cost analyses of insulation scenarios. These scenarios include internal or external wall insulation options cavity wall insulation and the thermal mass of insulation material. In summary, the Industry 4.0 has potential waiting to be unlocked in order to contribute to the delivery of net zero carbon agenda, thereby more effectively decarbonize both the existing built environment and the future one as well.

Note: There are no Human Research Ethics Clearance (HREC) issues to report at all. Furthermore, no direct involvement of human participants occurred, and data were obtained from publicly available sources. Concepts and ideas presented in this paper may not necessarily represent those of the employer organisations of the authors.

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