Defining and identifying complex-to-decarbonise homes and retrofit solutions

Research report

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Glossary

Table 1 Glossary of report terms

Term	Definition
ASHP	air source heat pump
BEIS	Department for Business, Energy and Industrial Strategy
CCC	Committee on Climate Change
CTD	complex-to-decarbonise
CWI	cavity wall insulation
DESNZ	Department for Energy Security and Net Zero
ECO	Energy Company Obligation
EHCS	English Housing Condition Survey
EHS	English Housing Survey
EWI	external wall insulation
HEED	Homes Energy Efficiency Database
HTD	hard-to-decarbonise
HTH	hard-to-heat
HTR	hard-to-reach
HTT	hard-to-treat
HUG	Home Upgrade Grant
IWI	internal wall insulation
LAD	Green Homes Grant Local Authority Delivery
LSOA	Lower Super Output Area
MEV	mechanical extract ventilation
MVHR	mechanical ventilation with heat recovery
NEED	National Energy Efficiency Data framework
Ofgem	The Office of Gas and Electricity Markets
ORP	Optimised Retrofit Programme, Wales
PAS	Publicly Available Specification
PCM	phase-change material
PDR	permitted development rights
PV	photovoltaic cell
RER	rapid evidence review
RQ	research question
R4tF	Retrofit for the Future programme
SHS	Scottish Housing Survey
WHCS	Welsh Housing Condition Survey

Executive summary

Research purpose

This research was commissioned by the Department for Energy Security and Net Zero (DESNZ). Its purpose was to develop a definition for housing stock for which the presence, and combination, of attributes and contextual factors can add complexity to improving energy efficiency and utilising low carbon heating solutions. Central to this is the development of a methodology identifying and measuring this stock, to simplify the upgrading of homes that may be at risk of being left behind in the transition to Net Zero.

This study introduces complex-to-decarbonise (CTD), terminology which has emerged from the rapid evidence review of existing published evidence and extensive engagement with key stakeholders. The term CTD, which is used throughout this report, draws on and improves existing language such as ‘hard-to-treat’, ‘hard-to-heat’ and ‘hard-to-decarbonise’.

Methodology

This study is composed of several research methods:

- Rapid evidence review to assess what evidence exists to identify CTD homes.
- Data survey to identify other literature that may not be publicly available.
- Interviews to explore the challenges of CTD homes and approaches to retrofit.
- Case studies to explore in detail some retrofit projects on CTD homes.
- Synthesis of findings from across the study to answer the research questions.
- Development of an identification framework for CTD homes using Python.

Findings

A new definition

We propose new terminology of complex-to-decarbonise (CTD) homes and a definition:

> Complex-to-decarbonise (CTD) homes are those with either one, or a combination of, certain physical, locational, occupant demographic, or behavioural attributes that prevent the effective decarbonisation of that home until they are addressed. These attributes might constrain the design and delivery of measures to improve energy efficiency, decarbonise heating, or realise occupant benefits (e.g., increased comfort and affordability of domestic heat and energy).
>
> These effects may be amplified by one or a combination of numerous system-level factors including financial (e.g., feasibility and affordability of measures), economic (e.g.,

supply chain and materials availability), and/or organisational capacity and capability (e.g., workforce skills).

For example, a home with solid wall construction may be CTD to an extent, whilst a solid wall home in an area subject to wet weather conditions, lacking internal space to install a heat pump, and with low-income occupants, would be more CTD. Alternatively, a home (solid wall or otherwise) which can accommodate a heat pump without the presence of physical, social or behavioural CTD attributes, would not be considered CTD as it can be functionally decarbonised without complexity.

This new terminology attempts to tackle limitations with existing definitions, which are set out in Finding 1 in this report. Ultimately, the CTD definition broadens previous definitions to include a range of attribute types and moves away from binary categorisation of CTD homes and towards CTD as an index.

Overall findings

Defining and identifying CTD homes

- **Finding 1**: There are limitations to previously used terminology (such as HTT/HTD) and their associated definitions.
- **Finding 2**: CTD homes can be usefully identified and analysed at both the stock level and the individual dwelling level.
- **Finding 3**: Cost and cost effectiveness is a key element for identifying and retrofitting CTD homes.
- **Finding 4**: Existing information and data sets are limited or are not being effectively used to comprehensively map and understand CTD homes, the CTD Identification Framework helps to address this.

Understanding the attributes of CTD homes and the challenges to retrofitting them

- **Finding 5**: There is limited and dispersed expertise and skills availability for some aspects and types of CTD homes.
- **Finding 6**: There is an extensive set of physical attributes of CTD homes identified which the CTD Identification Framework reflects and further develops.
- **Finding 7**: The policy environment can be inconsistent and challenging for CTD homes, the CTD definition and CTD Identification Framework can help address this.
- **Finding 8**: Social, economic and behavioural attributes can exacerbate the complexity of treating CTD homes and the challenges to retrofitting them.

Evidence of approaches to retrofitting CTD homes

- **Finding 9**: Case by case approaches that recognise the unique characteristics and challenges of CTD homes are key to deliver effective retrofit.
- **Finding 10**: PAS 2035 has brought important improvements, but it could go further.
- **Finding 11**: There are innovative approaches for installing effective energy efficiency and low carbon heating for CTD homes, but more solutions are needed.
- **Finding 12**: Listed properties and those in conservation areas can be effectively and appropriately retrofitted.
- **Finding 13**: Social barriers are being effectively addressed by some organisations across various CTD homes.
- **Finding 14**: Monitoring and evaluation is critical, and lessons learned for CTD homes can be better captured and disseminated.

The CTD Identification Framework

- **Finding 15**: A wide array of datasets may be used to identify CTD homes.
- **Finding 16**: The CTD Identification Framework should be flexible for use at both the stock level and the individual dwelling level, where the CTD terminology is not binary.
- **Finding 17**: The CTD Identification Framework should recognise and support a wide array of analysis use cases: (1) policymakers and asset-owners, for macro-assessment of the scope of the challenge; (2) industry, for identifying CTD elements within stock; and (3) civil society, providing information.

Conclusions

Complex-to-decarbonise (CTD) provides a new unifying terminology designed to better articulate the multifaceted nature of homes which are difficult to decarbonise using standard approaches. Using the developed CTD Identification Framework, the physical, locational, occupant demographic and behavioural attributes can be effectively presented, analysed, and used both at the stock and individual dwelling level.

The CTD definition and CTD Identification Framework provide a starting point from which to improve practice. Firstly, they support better identification, monitoring and sharing of effective and ineffective practices for CTD homes across the industry to support continuous improvement. Secondly, CTD can help support the provision of clear advice and guidance for both suppliers and consumers, and their support organisations and can help to build trust and interest in home decarbonisation efforts.

The research has also demonstrated that innovative and effective approaches to energy efficiency and low carbon heating are being deployed for CTD homes, as exemplified by the case studies. A key factor for success is in clearly identifying and understanding these homes at the earliest point in the retrofit project lifecycle.

Introduction

Research purpose

One of the UK's most significant challenges to achieving Net Zero greenhouse gas emissions by 2050 is the decarbonisation of heat in buildings, which accounts for 468 MtCO2e, or 37% of UK annual greenhouse gas emissions.[1][2] Understanding complex properties that are difficult to decarbonise is vital to tackling two key national priorities: achieving Net Zero and mobilising the decarbonisation effort in the built environment as identified in the Heat and Building Strategy.[3]

This research was commissioned by the Department for Energy Security and Net Zero (DESNZ) to develop a definition for housing stock for which the presence, and combination, of attributes and contextual factors can add complexity to improving energy efficiency and utilising low carbon heating solutions. Central to this is the development of a methodology identifying and measuring this stock, to simplify the upgrading of homes that may be at risk of being left behind in the transition to Net Zero.

The domestic retrofit challenge

To reach net zero emissions by 2050 approximately 29m UK homes will need to be retrofitted.[4] A significant portion of these homes are estimated to be more challenging to decarbonise due to higher costs, barriers that are more difficult to overcome, or solutions that are more complex to implement. The scale of the issue is considerable; a previous attempt to quantify this issue (a previous definition of CTD of homes hard-to-decarbonise (HTD)) found that, over 25% of all direct residential sector emissions are from HTD homes in the UK (Foster et al., 2019). The CTD definition incorporates more than just HTD homes, meaning this is likely higher for CTD homes. Although an estimate, which is limited due to the use of the existing definition and available data, these homes remain an important priority in the built environment's response to the climate crisis, and more work is required to identify and map the distribution of these homes. From a policy perspective, the UK Fifth Carbon Budget identified CTD homes[5] as an area where options to reduce emissions were more challenging[6], and the Climate Change Committee (CCC)'s 'Net Zero 2019' report similarly recognised them as a priority. From an occupant-perspective, many who live in these properties are in fuel poverty (including 'Hard-to-Reach' energy users who are typically either locationally underserved, excluded through social or demographic factors, or hard to engage or motivate). Furthermore, research suggests that in

[1] BEIS. Clean Growth: Transforming Heating. Department for Business, Energy & Industrial Strategy; 2018.
[2] CCC. Net Zero: Technical Report. Committee on Climate Change; 2019.
[3] BEIS. Heat and Buildings Strategy; 2021.
[4] Bankers for Net Zero. Tooling up the Green Homes Industry: Financing the Retrofit Supply Chain; 2022.
[5] Using an existing definition of CTD as those that are hard-to-decarbonise (HTD) or hard-to-treat (HTT).
[6] CCC. Sectoral scenarios for the Fifth Carbon-Budget Technical report. Committee on Climate Change; 2015.

the future these occupants are more likely to be at risk of both fuel poverty and climate vulnerability.[7]

The need to address this challenge by installing energy efficiency and low carbon heating measures that improve the environmental and energy performance of homes is reflected in recent policy priorities, including the Heat and Buildings Strategy.

There are several challenges in understanding and tackling complex-to-decarbonise homes. Despite the increased policy interest, relatively little is known about CTD homes, rendering them a significant area of uncertainty. Multiple definitions exist and are used to different extents across policy and industry. The limited attempts to study segments of UK housing where it has been more challenging to decarbonise have thus far mostly focused on CTD homes with uninsulated solid and non-standard cavity walls where 'staple' cost-effective fabric measures are difficult to install.[8] Several knowledge gaps have been identified in this study's rapid evidence review (RER):

- **There is relatively little knowledge about many of the physical and locational attributes that render a home to be CTD**. Existing knowledge largely stems from case study research that investigates a single CTD home typology. Therefore, sources of such data at national and regional levels have limited representativeness and scope with regards to potential CTD attributes.
- **The socio-economic and behavioural characteristics as well as the preferences, habits and routines of CTD households are also poorly understood**. While these are a main determinant of the types/impacts of decarbonisation solutions that can be applied in these homes, they have yet to be fully understood.
- **CTD homes are not adequately represented in existing building stock models or datasets.** These are essential analyses to understanding the built environment, explore trajectories and assess the impacts of installing retrofit measures and deploying decarbonisation solutions. Policy measures guided by these existing models carry a high risk of under-performance.

Study objectives

This research was undertaken to develop knowledge and evidence of approaches to upgrading underperforming and technically difficult to treat housing[9]. The study objectives were:

- **Study objective 1**: Identify the technical (including physical, material and technological), regulatory and social challenges to improving the energy performance and decarbonising CTD homes, taking account of spatial variability across the UK.

[7] Raslan R, Ambrose A. The Potential of Hard to Decarbonise Homes as a Pathway to Energy Equity. Making Decarbonisation Fair-Third Engager-Cost Conference, 2021.
[8] BRE, EST, A study of Hard-to-Treat Homes using the English House Condition Survey. 2008
[9] Readers should note that originally these homes were referred to as 'hard-to-treat' in the study's objectives and research questions. However, for ease of readership, this has been updated to 'complex-to-decarbonise' (CTD), to reflect the updated terminology resulting from the study's findings.

- **Study objective 2**: Document and review the evidence on existing approaches to retrofitting CTD homes, including reviewing international policies, considering the costs to implement retrofit upgrades and implications for future retrofit schemes.
- **Study objective 3**: Develop a framework/definition, which identifies a spectrum of technical, physical, and material attributes that make a home CTD from a whole house retrofit perspective.
- **Study objective 4**: Identify potential data and/or sources of information that could be used to identify CTD homes for both energy efficiency and low carbon heating.
- **Study objective 5**: Review, compare and propose best-practice methods and approaches for identifying CTD homes.

These objectives were also used to determine a set of 12 research questions:

- RQ1: How can CTD homes be defined?
    - RQ1a: What definitions/frameworks for CTD buildings are currently being used, and what are the merits and drawbacks of these?
    - RQ1b: What is the range of different technical, physical, and material attributes that make a home CTD, from a whole house retrofit perspective?
- RQ2: How can we identify CTD homes?
    - RQ2a: What datasets and/or variables can we use to identify CTD homes?
    - RQ2b: What analytical methods can we use to identify CTD homes?
    - RQ2c: How does a change of building use affect the identification of CTD homes?
- RQ3: What are the current estimates for the number of CTD homes in the UK?
- RQ4: What is the regional/spatial distribution of CTD homes?
- RQ5: How do regulations (UK and international) on homes consider CTD homes?
    - RQ5a: What regulations apply to different CTD properties?
- RQ6: What are the technical challenges associated with improving the energy performance and decarbonising CTD homes?
    - RQ6a: What are the risks to the fabric of the building with retrofitting energy efficiency measures and moving to low carbon heating in CTD homes?
    - RQ6b: What geographic/spatial factors need to be considered?
- RQ7: What are the regulatory considerations and challenges for retrofitting CTD homes?
    - RQ7a: What are the legal/regulatory/planning barriers?
    - RQ7b: What regulations apply to different CTD properties?

- RQ8: What are the social challenges associated with improving the energy performance and decarbonising CTD homes?
    - RQ8a: What socio-economic factors should be considered?
    - RQ8b: What distributional demographic (spatial) aspects need to be considered?
    - RQ8c: What occupier and/or owner behaviours and lifecycle considerations should be considered?
- RQ9: What practical approaches could be applied/adapted to retrofitting CTD homes?
    - RQ9a: For CTD homes that are unsuitable for conventional insulation, what are the options to decarbonise and improve their energy efficiency?
    - RQ9b: When, in the lifecycle of a building, should retrofit interventions be implemented?
    - RQ9c: How effectively do the risk pathways under PAS 2035 consider CTD homes?
    - RQ9d: How can this translate into consumer advice for owners and occupiers?
- RQ10: What are the cost implications for the different approaches to retrofitting and installing low carbon heating, in different types of CTD homes?
- RQ11: Does the evidence suggest that CTD homes should be considered differently from other homes by policies on energy efficiency and heating (incentives, informational etc.) and regulations (minimum standards, bans of heating types, and their enforcement)?
- RQ12: What are the implications for future retrofit schemes and regulations?

Annex A presents the RQs mapped against the level of evidence availability and quality from the research streams. These can be categorised into three research question groupings (RQ) groups: (1) defining and identifying homes; (2) understanding the challenges of retrofitting CTD homes; and (3) evidence on existing approaches to retrofitting CTD homes.

New terminology

This study introduces complex-to-decarbonise (CTD), terminology which has emerged as a result of the rapid evidence review of existing published evidence and extensive engagement with key stakeholders. The term CTD, which is used throughout this report, draws on and improves existing language such as hard-to-treat, hard-to-heat and hard-to-decarbonise. Evidence for the definition is detailed in the findings section.

Methodology

We deployed multiple methods in this study, and we synthesised these through analysis to respond to the study's research questions. The section below details the methods in turn. More information on each method and their limitations can be found in Annex A: Technical Annex.

Rapid evidence review

Prior to this study there was little clarity of how to define, measure and identify CTD homes in the UK with regards to both energy efficiency and low carbon heating. We undertook a rapid evidence review (RER) to review existing evidence. We collected and critically analysed the current knowledge on CTD homes, to inform the definition of what is considered to be CTD (i.e., to learn what attributes are associated with these homes and/or their owners/occupants) and we scoped existing knowledge regarding retrofitting these homes. Over 400 articles were analysed as part of the RER.

Here, we also identified remaining evidence gaps, for example missing or incomplete datasets, themes with limited coverage through existing case study research. To inform both the subsequent framework development and the case study analysis, we:

- Identified key datasets that may be utilised in the development of the framework.
- Informed the development of case study selection criteria.
- Highlighted evidence gaps that may be informed through illustrative case studies.
- Used this to inform the new CTD terminology and definition, including CTD attributes.

Data survey

A data survey was undertaken as part of our wider stakeholder engagement exercise, to identify other current industry literature that may not be publicly available (also acting as a recruitment path for later interviews). The survey asked participants their views on identified CTD attributes, and for any additional sources of evidence they could provide.

Qualitative interviews

We conducted 50 qualitative in-depth interviews to explore evidence of the elements of the CTD terminology and existing approaches to treating these homes. Participants were from either industry organisations, third sector and civil society organisations, or academic and regulatory bodies and a list of those participating is given in Annex A. These interviews complemented evidence sourced through the RER and highlighted potential gaps and opportunities for further investigation.

Identification Framework development process

A data-driven framework was developed to enable the identification of CTD homes at: a) the individual dwelling level to determine if that dwelling is CTD; and b) the housing stock level to determine the number of CTD homes in a housing stock of a given size.

Case studies

A set of ten deep-dive case studies were developed to explore in detail practical examples of CTD projects and retrofit activities delivered by a variety of actors from across industry. Case studies were developed to bring to life elements of the identification framework and ground our analysis with examples that can help readers understand the practical opportunities and challenges related to tackling CTD properties.

Synthesis

The research streams were used together in synthesis to answer a set of 12 research questions (presented in full with their evidence mapping in Annex A) and to meet the five study objectives. We assessed data from across the research streams to identify the key findings a presented in this report. The synthesis methodology is set out in Annex A.

We used the synthesis to develop the CTD Identification Framework, which is discussed in the findings section and presented in full in Annex B.

Findings

Overview

The following presents the key findings by the three groupings of the project research questions: (1) defining and identifying CTD homes; (2) understanding the challenges of retrofitting CTD homes; (3) evidence on existing approaches to retrofitting CTD homes; and (4) a set of findings for the CTD Identification Framework. Annex A presents the mapping of evidence availability and quality to each research question.

This section begins with findings on how to define and identify what have previously been termed ‘hard-to-treat’ and ‘hard-to-decarbonise’ homes. We have proposed new terminology of complex-to-decarbonise (CTD), as detailed below.

The attributes of CTD homes and challenges to retrofitting them are discussed, followed by evidence on effective approaches to their retrofit. The CTD Identification Framework and its use cases is then set out in response to the findings.

Defining and identifying CTD homes

Complex-to-decarbonise (CTD) homes are those with either one, or a combination of, certain physical, locational, occupant demographic, or behavioural attributes that prevent the effective decarbonisation of that home until they are addressed. These attributes may constrain the design and delivery of measures to improve energy efficiency, decarbonise heating, and realise occupant benefits (e.g., increased comfort and affordability of domestic heat and energy). These effects may be amplified by one or a combination of numerous system-level factors including financial (e.g., feasibility and affordability of measures), economic (e.g., supply chain and materials availability), and/or organisational capacity and capability (e.g., workforce skills).

For example, a home with solid wall construction may be CTD to an extent, whilst a solid wall home in an area subject to wet weather conditions, which lacks internal space for the installation of a heat pump, and has low-income occupants, would be considered more CTD. Complexity may increase further due to additional system-level factors, for example where there is a limited local supply chain of PAS certified installers. Alternatively, when a home (solid wall or otherwise) could accommodate a heat pump without the presence of physical (e.g., high heat loss or spatial constraints), social (e.g., low affordability) or behavioural (e.g., willingness) CTD attributes then this home would not be considered CTD as it can be functionally decarbonised without complexity.

Annex C sets out a series of real-life examples of properties with CTD attributes, with how these attributes were addressed with the installation of retrofit and low carbon heating measures and supporting interventions.

The CTD definition is informed by evidence which recommends several improvements on existing terminology, which is further detailed in the findings below. These include:

- Recognition that CTD housing requires careful consideration, planning and defined/standardised approaches for successful improvement.
- Simplified terminology with a clearer description of attributes and influencing factors to improve understanding and promote intervention.
- Incorporating well defined and up-to-date terminology adopted across policy and industry contexts, with a focus on decarbonisation, in line with recent publications by the CCC[10] (see Finding 1 below).
- Acknowledging the system-level nature of housing decarbonisation: e.g., the design and delivery of measures is influenced by the context in which decarbonisation is occurring and the stakeholder/actors influencing it.

This new terminology is in response to limitations with existing definitions, which are set out in Finding 1 below. Some feedback and evidence on existing definitions was contradictory, meaning the new terminology is inevitably imperfect. For example, a few interviewees mentioned limitations with the term decarbonisation in previous definition as they felt it was confusing. However, decarbonisation has been more fully adopted across policy and industry contexts, and also reflects the CCC's position on keeping decarbonisation as the focus of these works.[11] The CTD definition has also been broadened to include other attribute types and moves away from binary categorisation of CTD homes and towards CTD as an index.

The attribute types included in the CTD definition are further detailed in the CTD Identification Framework (Annex B: Framework Report). Attributes are either primary and fundamental to CTD, which can alone or in combination mean a home is CTD. There may also be secondary attributes, such as those that are more system-level factors, which may add further complexity to retrofit projects. Users can prioritise, or weight, attributes with the presented framework.

For example, where homes can accommodate heat pumps – and without the presence of related CTD attributes (such as spatial constraints and low affordability) – then other CTD attributes may be excluded or weighted less as the home can be decarbonised effectively. Alternatively, if there is high heat loss and insulation is required before a heat pump can be installed, then the CTD attributes relevant to insulation (such as disruption and accredited supplier availability) may be heavily weighted when using the CTD Identification Framework.

The optimal weighting and relationships between attributes is an area for future consideration and research, as set out in Annex B and Annex D.

[10] CCC, 2019a. Net Zero-Technical report. Committee on Climate Change.
[11] Ibid.

The CTD definition was developed using the following design principles, which are in addition to those which informed the development of the CTD Identification Framework:

1. Evidence-based: Drawn from the best available evidence and complemented through deep qualitative interview techniques to validate viewpoints and surface outliers.
2. Objective language: Removing reference to ‘hard’ or ‘difficult’, instead articulating priority and effort required.
3. Multi-stakeholder: Drawn from multiple viewpoints across industry, academia, policy, and civil society.

The CTD Identification Framework accompanies the new CTD terminology and its definition, by bringing together the CTD attributes, referred to in the definition, in one place.

Below we detail the findings which have informed the development of the CTD definition.

Finding 1: There are limitations to previously used terminology (such as HTT/HTD) and their associated definitions.

The RER identified several terms in use across academic, policy and industry contexts (Table 2). The definitions are subject to several limitations, e.g., HTT may be considered less occupant centric, HTH as too heat centric, and HTD as too focussed on decarbonisation, to the detriment of other factors. These are further detailed in Table 2.

Table 2 Existing definitions from published sources

Definition	Detail
Hard-to-treat (HTT)	"Homes that for a variety of reasons cannot accommodate 'staple' energy efficiency measures offered under schemes such as Warm Front in England"[12] "(HTT homes are) those requiring, for example, remedial work to rectify faults, such as cracks in the building fabric or damp issues, ahead of energy efficiency measure installation."[13] "(HTT homes are) ones that, for whatever reason, cannot accommodate 'staple' or cost-effective fabric energy efficiency measure"[14] "(For HTT homes) you are unable to improve energy efficiency with lower-cost measures – such as cavity wall insulation – due to the age of the property or nature of its construction"[15]
Hard-to-decarbonise (HTD)	"'Hard-to-treat' [HTT/HTD] and/or do not have cost-effective options for low carbon heating."[16]
Hard-to-heat (HTH)	"(HTT homes are those) that were hard-to-treat (or more accurately expensive to heat or treat) with the issue of fuel poverty given that these homes are often difficult and costly to heat to a comfortable level for those who live in them."[17]

Definitions from the RER were tested through the interview phase to surface potential issues and benefits of existing definitions, and draw out opportunities to refine and improve language and terminology. Interviewees were asked to consider different definitions and share if and how they use language such as HTD or HTT. This provided a practical perspective on existing terminology.

There are however limitations to these definitions which drive the need for the CTD definition. Interviewees were asked to consider different definitions and share if and how they use language such as HTD or HTT.

Decarbonisation as a term was considered by some as overly specific to heat and heat decarbonisation, to the detriment of other factors:

> *"I would say hard-to-decarbonise was a physical problem to do with the building. I probably could say the same hard-to-treat. But I suppose we are trying to get a behavioural and demographic dimension and so if the definition could have both*

[12] EST, 2004. Hard to Treat Homes Guide. Energy Saving Trust
[13] BEIS, 2022a Guidance: Energy Security Bill factsheet: Enabling the Hydrogen Village trial, Department for Business, Energy & Industrial Strategy
[14] BRE, EST, DEFRA, 2008. A study of Hard-to-Treat Homes using the English House Condition Survey-Part I: Dwelling and Household Characteristics of Hard-to-Treat Homes (Energy Analysis Focus Report).
[15] CSE, 2010. Somerset West hard-to-treat homes. Centre for Sustainable Energy
[16] CCC, 2019a. Net Zero-Technical report. Committee on Climate Change.
[17] ACE, 2002. Affordable Warmth in Hard to Heat Homes; finding a way forward'. Association for Conservation of Energy

> *hard to engage – we talk about willing to pay, able to pay, vulnerable so perhaps that language. The sustainable warmth strategy has some of this in there." (Local authority/hub).*

This was similarly echoed by a trade association respondent who noted that whilst HTT is a term commonly used, it does not promote a holistic view of the property and promotes a potentially detrimental prioritisation of measures over other factors:

> *"Hard-to-treat is the one that everybody uses. But the approach is wrong. We systematically do a measure-by-measure approach, driven by government policy, rather than looking at each home and looking at it holistically." (Trade association).*

Some strongly expressed caution with labelling some homes as 'hard to...', feeling this may be detrimental to their inclusion in retrofit, may overstate the issues, or may disregard the point that many or most homes can be HTT/HTD from one or more attributes:

> *"Hard is quite off-putting as language: whereas if you call something constrained, it's not to say that it's not possible… I'm a bit against the language of hard-to-treat to be honest." (Small industry).*

Others in industry regarded developing a unified definition as counterproductive given the complexity and heterogeneity of UK housing stock, and the influence of occupant behaviours:

> *"We wouldn't consider a hard-to-treat home any differently to any other home in that it's unique in the way it's built, in the way that it's been changed since it was built and the way that the occupant uses it. Whilst there might be particular challenges to renovating hard-to-treat buildings, they're the same challenges that are applied to any building." (Large industry)*

Contrastingly, others argued to move away from standard definitions and binary terminology:

> *"I think you then get into a severity scale that says if something is hard-to-treat… That's why I've struggled with a standard definition." (Local authority/hub).*

Recognising complexity was also noted by an industry participant:

> *"Every building has a completely different set of circumstances, and it depends on everything from who the procuring body is, to who the residents are, whether they have ownership of the homes etc. It is so complicated. I think you need to have a really holistic approach." (Small industry).*

Others argued against the language of HTT, instead opting to adopt constraints to recognise the existence of solutions and the barriers to deploying and scaling them, in reference to language used in the LETI Climate Emergency Retrofit Guide:

> *"We have the solutions; we know it's possible technically and practically to deliver this but we're just not doing it at the scale. I think as soon as the scale increases*

then this hard-to-treat definition sort of goes away. I think that's why I prefer the LETI definition of constraints, rather than calling it 'hard'." (Small industry).

The RER also recognised the Sustainable Building Traditional Buildings Alliance responsible retrofit wheel, which has informed some of Publicly Available Specification (PAS) 2035. A comprehensive classification of attributes was also noted by others who highlighted that the behaviour and demographics of occupants is a missing element of existing HTT and HTD definitions.

Table 3 Summary of limitations arising from study evidence

Definition	RER limitations	Stakeholder interview limitations
Hard-to-treat (HTT)	Does not holistically consider attributes. Less occupant centric.	Divisive or contentious language. Considered simplistic/generic. Infers a binary categorisation; many consider a spectrum. Any property may have an attribute considered HTT; not specific enough. Fabric focused; limited social focus
Hard-to-heat (HTH)	Focuses on heating as main energy use. Ambiguousness on definition of staple energy efficiency measures	Does not provide holistic understanding or perspective of the wider issue. Not in wide use. No reference to wider factors (e.g., social factors)
Hard-to-decarbonise (HTD)	Emphasis on decarbonisation as the main goal, to the detriment of other outcomes (e.g., thermal and home comfort)	Broad use across stakeholders with no unified/common understanding. Not practical/accessible to industry. Net Zero focus: does not consider comfort. Existing definition still references HTT. Emphasis on installations, no embodied carbon. 'Cost-effective' is broad and considered variable and subjective.

Finding 2: CTD homes can be usefully identified and analysed at both the stock level and the individual dwelling level.

The attribute lens of the CTD terminology supports deeper analysis of stock and their complexity. This research shows that physical and fabric related technical challenges can be understood at the cross-home (or by-type) or individual home level. This identified a range of CTD home types, including some that may not typically be considered as such under previous definitions (e.g., HTT/HTD), such as homes built in the 1960s to 1980s, modern flat blocks and homes with modern higher-spec materials.

Evidence on identifying CTD homes from an individual home perspective emerged from the interview and case study analysis. A common theme from these was that any home can have constraints, and that similar properties in terms of age, form, street location and structure can still differ in their baseline and retrofit needs. These differences may be due to previous renovations, maintenance and usage history.

Previous renovations and maintenance were a common issue raised by interviewees:

> *"And generally, what I would say is every single existing building that we work with, is constrained to some extent. Because of the nature of doing piecemeal retrofit we're finding the least constrained still have some level of constraints." (Small industry).*

These may not be assessed initially by those instigating works and can cause a property to deviate from what its EPC or form may suggest and for which comprehensive survey(s) may be needed.

Additional elements which led to issues included: a lack of renovation guidance and regulation, covered ventilation, poor cavities, and wall tie issues (e.g., wall tie corrosion or incorrect installation) uncovering of dangerous, unsuitable or materials that are no longer recommended, and the uncovering of damp and/or mould.

Elementary retrofit was also raised as sometimes causing issues, where earlier work now needed to be addressed or had caused issues such as thermal/cold bridging and where the whole house and fabric system had not been well considered. Physical attributes are also covered below as part of Evidence of Existing Approaches.

Finding 3: Cost and cost effectiveness is a key element for identifying and retrofitting CTD homes.

The RER found that cost's significance has become increasingly evident in identifying and tackling CTD homes. Cost can be both a cause and effect of a property being CTD. Firstly, CTD homes can be more expensive to address, and secondly the very nature of being more expensive to treat often makes the home CTD. The latter is especially dependent on the occupant demographics and tenure type (e.g., income levels).

A number of interviewees raised the importance of cost-effectiveness as an element that can make a home CTD. Cost-effectiveness here refers to costs to both suppliers and households, and in costs across the life cycle. Life cycle costs include high heating costs driving intervention need; higher capital costs of the intervention itself; higher cost uncertainty, increased ancillary costs and more likely unexpected costs; and the risk of higher running and maintenance costs post intervention. All phrases except post intervention maintenance and running costs were cited as key considerations when understanding the consequences of new measures.

Cost-effectiveness is also referenced alongside pre-retrofit activities, such as repairs or remedial works, demonstrating its importance across the lifecycle. This is considered in the

ECO4 consultation. This is verified by the interviews as a need that is pertinent, but which is also not commonly considered ahead of work planning. This is a key risk given the potential for high ancillary costs at the pre-retrofit stage. The RER noted high costs at this stage, for example: (1) Planning Permission delays, in particular for heritage or conservation area homes; (2) delays in the approval processes for the use of specific materials/techniques; (3) specific material or supplier requirements to do specialised work including heritage, conservation area homes or specific property features; (4) specific detailing work and working with period features such as in external wall insulation (EWI) and window replacement for heritage or conservation area homes; (5) increased costs of pipework and ducting when required; and (6) the recent inflation environment has only heightened the importance of cost-effectiveness throughout the end-to-end process. End-to-end costs are further identified by the RER, such as: (1) need for careful monitoring before, during and after, often using technology; (2) costs arising from limited grid capacity or delays with Distribution Network Operators (DNOs); (3) increased engagement with occupants to build buy-in and provide support.

A key element of the considerations of cost-effectiveness was affordability, concerning household types and income, with fuel poverty a common consideration that was raised across interviews. This link is reflected with the hard-to-heat terminology. Interviews also recognised that cost effectiveness differed according to occupant demographics, for example where households are not able to pay and therefore are at greater risk of fuel poverty, for example, or renting from landlords who were not incentivised or able to retrofit their homes.

Our co-occurrence analysis found that cost-effectiveness was a particular barrier to deploying low carbon heating. This was often due to high upfront or running costs of the measure, and/or from the requirement to take a ‘fabric first’ approach to establish thermal efficiency before low carbon solutions such as heat pumps can be installed. The importance of cost-effectiveness as a barrier is reflected with the inclusion of occupant demographic attributes and financial system-level factors within the CTD definition, including the affordability of measures. This means that homes with fuel poor occupants, or occupants who struggle to afford their existing heating system or low-carbon heating solutions, may be CTD to an extent, as the affordability of operating the low carbon heating solution for the occupants may affect the choice of measures installed alongside the heating, and the complexity of those measures may make the property CTD.

‘Fabric first’ was widely recognised as the right approach to take in advance of low-carbon heating solutions, though it may create longer timelines and cost outlays to get homes to the target outcomes. However, it was also recognised that some homes can accommodate low carbon heating solutions such as heat pumps without significant barriers. These homes would be able to be decarbonised effectively and affordably, so would not be considered as CTD.

The RER and interviews identified other elements that impact cost-effectiveness, with additional costs associated with requirements including: (1) the need for scaffolding and additional works needed to access walls or lofts; (2) more extensive wall work where the cavities are part filled or in poor condition; (3) more extensive roof work where it is insufficient to support solar or needs repairing; (4) more expensive underfloor insulation using technology

where floor voids are narrow; (5) however, the RER also identified that cost effectiveness of low carbon heating is not explicitly referenced in HTT definitions.

Upfront and comprehensive assessments of CTD homes are vital, otherwise there is increased risk for costly repeat visits. Participants noted that the risk of needing repeat visits is increased by pressures to deliver work to particular timescales and with limited incentives for suppliers to do more detailed upfront assessments after they have been appointed. This issue is referenced in three case studies (Case Studies 3, 8, and 10). Some interviewees suggested it could be beneficial to receive separate upfront grants to assess properties thoroughly before then bidding for and using delivery grant funds.

These time and cost requirements cause an acute challenge in a policy and funding framework which specify delivery timescales. Some industry and housing associations expressed the tension between addressing small numbers of high-cost homes but at increased timescales, with tackling large numbers of low-cost homes which require fewer complex works, and can be more readily addressed. Some admitted avoiding retrofitting these more difficult homes, especially when they have less experience of funding mechanisms and large scale retrofit programmes.

Finding 4: Existing information and data sets are limited, or are not being effectively used to comprehensively map and understand CTD homes. The CTD Identification Framework helps to address this.

Current models, datasets and methods may not be best suited to understand CTD homes. For example, issues pertaining to the quality and coverage of the datasets were identified by interviewees. Further, data gathering approaches used in studies focused on CTD homes may not be sufficient to achieve strong analytical study designs.

Interviewees identified a challenge with the poor accuracy and completeness of EPC and SAP modelling, with impacts identified across the project lifecycle. Other information gaps (or perceived gaps) for identifying or assessing CTD homes included a lack of:

- Recording of previous works and upgrades to the home as well as more general home maintenance and repairs.
- Detailed housing and site surveys, in preparation for retrofit to identify physical attributes (explored in Finding 6) or areas for detailed design consideration or alternative measures.
- Socio-economic, demographic, and behavioural context information to better understand the nature and needs of identified homes, such as deprivation, health issues and potential occupant behavioural factors.
- Locational information, needed to better understand the nature and needs of identified homes, such as DNO capacity, weather patterns and building orientation.

The RER, data survey and CTD Identification Framework however identify some datasets and evidence on locational factors which meet some of the evidence gaps raised, including

exposure (impacting EWI), remoteness (impacting supply chain access), hazard mapping and spatial constraints of a property. This demonstrates that such information may not always be known or used, highlighting a potential use of the CTD Identification Framework. Interviewees also often mentioned issues related to off gas grid considerations, alongside barriers related to funding considerations and the interpretation of conservation Planning Permission (as per Finding 7). These interpretations have been found to vary across, or even within, geographies and permitted development rights may relate to spatial constraints and hinder retrofit leaving behind some CTD homes.

Academic and policy interviewees also considered locational attributes relative to climate change management and mitigation, while this was considered less so by other interviewees. The lack of embedding climate adaptation into CTD approaches was identified as a risk to future-proofing homes across the UK and according to any more specific local changes (e.g., areas becoming wetter and warmer):

> *"Certainly, when you go to coastal regions, particularly over the west side of the UK, where the wind-driven rain is far more prevalent and there's more rain and wind-driven rain, they are typically more hard-to-treat properties because you've got to consider those prevailing weather conditions and not install a measure that will prevent that property being able to deal with those." (Trade/sectoral association)*

Across literature, limited evidence was found that supports a comprehensive economic evaluation of retrofit measures. Data on costs and savings resulting from energy efficiency measures are relatively limited and, in many cases, highly uncertain as they are based on self-reported information from installers. There is also little robust evidence on the roles of wider actors and the value provided by and to different stakeholders, such as with wider benefits realisation, in retrofit delivery.

Interviewees highlighted the value of monitoring and evaluation approaches beyond economic impact assessments, with uses in guiding and informing the design and deployment of future interventions. Interviewees gave examples of projects measuring on-going impacts of the work and sharing best practice approaches. Some interview examples and case studies (Case Studies 1 and 6) acted as testbeds for emerging approaches ahead of scale up across larger stock. Consumer satisfaction, wellbeing and home comfort were also frequently recognised as important measures of success.

Furthermore, some interviewees mentioned that some projects that they or others in the sector have delivered have not had monitoring for long enough for evaluation and best practices to be captured and shared. This includes developing an evidence base for how retrofit and low carbon heating impact running costs. Interviewees also referred to a culture for failed work to not be shared and discussed openly, which could prevent others making mistakes when retrofitting in CTD homes.

The CTD Identification Framework demonstrates the existing datasets that can be used to source, or as proxies for, the included CTD attributes (as detailed in Annex B). The framework

more generally is data-agnostic. As a result, it can incorporate new datasets to ensure it remains up-to-date, and can be customised or linked to further datasets to suit the array of analysis needs highlighted by stakeholders.

Understanding the attributes of CTD homes and the challenges of retrofitting them

The RER, qualitative interviews, and case study research streams enabled extensive analysis of attributes and challenges, which informed the development of the CTD Identification Framework. This section brings together attributes to identify CTD homes across a stock or to identify CTD elements for an individual home. It sets out the key attributes of CTD homes, across physical, locational, occupant demographic and behavioural attributes, and the challenges to retrofitting them.

Finding 5: There is limited and dispersed expertise and skills availability for some aspects and types of CTD homes.

The synthesis process illustrated key barriers across the UK that prevent retrofit at scale. Though there is much knowledge and best practice evidence for retrofitting CTD homes, there is not always sufficient depth of expertise or skilled workers through the supply chain, and the knowledge base is often dispersed. The domestic retrofit supply chain, and more specifically the CTD homes retrofit supply chain, is not yet a mature market and its (lack of) resilience can be a challenge.

A number of local authority, industry and social organisation interviewees raised concerns with a lack of knowledge and expertise across suppliers concerning the specific needs of CTD homes. Some also raised concerns with suppliers' care and sensitivity when working with difficult heritage features or with vulnerable residents, noting that these were skills to be developed, and areas where regulation may need to be more consistently enforced to ensure quality of work (detailed in Finding 9).

There are a range of skill gaps and skill areas with poor resilience identified by the RER and more so by the interviews. Some are broader than CTD homes, but their adverse impacts can be more acute for those homes:

- An insufficient supply of workers to fill important traditional construction and site jobs.
- Established small businesses and an ageing workforce in parts of the built environment and heating sectors that may not be interested in training for or switching their focus towards low carbon heating solutions.
- Expertise and skills shortages in wall insulation, especially for early and damaged cavities.
- A lack of expertise and people that are working in heat pump design and installation that is suitable for CTD homes.

- An insufficient depth of training and expertise on CTD homes in the wider industry, meaning that certified organisations may not have staff with all the skills needed for work on these specific types of home.
- PAS-2035 has been important for improving quality of work, However, in some areas the level of training available is insufficient, which can result in a lack of available qualified retrofit assessors, coordinators and installers for more challenging projects such as CTD homes.

Interviewees who procured work often raised challenges to find good suppliers:

> *"I have led tenders on a number of retrofit projects and trying to get knowledgeable contractors who are able to tender fully understanding what they're tendering against is very difficult." (Policy/standards body)*

Geographical disparities were apparent, with amplified skill shortages in rural areas and in parts of South West England and Wales. However, bottlenecks and high demand peaks are noted across the UK, due to the scale and timing of government funding and procurement in concentrated time frames. The inability for some areas to use and develop local suppliers and skills, and instead bring in firms from elsewhere, is seen as a missed opportunity to build local knowledge, resilience and capture economic benefit. Case studies illustrate where suppliers were difficult source and procure, or where suppliers changed at a later date due to a lack of resource or capability (Case Studies 1, 3, and 10).

There are also behavioural and cultural challenges identified within the supply chain. We have identified through the research streams, and qualitative research analysis, a key role for installers as the face of the work and in being householders' key points of contact. In turn, engaging with contractors and their installers on Net Zero and specific measures may be required, so they can competently and sympathetically support, advise, and engage residents. Some interviewees also suggested limited incentives to up-skill:

> *"There's a real absence of retrofit designers, architects and surveyors with the right skills to do that, or just a slight reskilling. And it's not generally such lucrative work as new builds or major refurbishments." (Trade association)*

Finding 6: There is an extensive set of physical attributes of CTD homes identified which the CTD Identification Framework reflects and further develops.

Physical attributes, non-traditional archetypes, and property age were identified as significant factors in both the RER and qualitative interviews, complemented with further attributes such as those concerning solid walls, cavity walls, flat roofs and lofts. The research enables the CTD Identification Framework to bring together an extensive set of physical attributes of CTD homes in one place.

The physical attributes identified across the research streams have been used to develop the CTD Identification Framework. This enables CTD identification and analysis across a stock of housing and for an individual home. The CTD Identification Framework is composed of the

following principal categories and sub-categories for physical attributes. One of these attributes alone or in combination with other attributes, or by being amplified by system-level factors (as presented by the definition), may mean a home is CTD.

The CTD Identification Framework is not prescriptive to the extent to which different attributes mean homes are CTD. The purpose of this research is to provide a foundational evidence base for understanding more complex stock, to provide clarity and to inform solutions. Users of the CTD Identification Framework apply their judgement and expertise to determine appropriate weights for each attribute according to the purpose of their analysis and its context.[18] For example, where a home can accommodate a heat pump without insulation then the insulation related CTD attributes will be of low importance and may be weighted less or excluded.

The physical attributes are presented here and the supporting findings from the research are then set out below.

- Insulation
    - Non-fillable cavity wall
    - Infeasible loft insulation
- Space
    - Internal wall insulation
    - Heating/energy storage
    - Low carbon heating/energy
- Heating source
    - Off gas grid
    - Off heat network
- Construction
    - External wall insulation
    - Poor maintenance history
    - Non-standard construction
    - Other additional work

The interviews raised many instances where CTD homes are more nuanced than archetypes or where there may be incorrect assumptions being made. For example:

> *"For historic and traditional reasons there can be a bit of myth that they [heritage properties] are HTT/HTD, when you do have a good base of materials and skills.*

[18] The nature of attribute weights and interactions should be the subject of future research with users of the CTD Identification Framework.

> *For example, other properties in the 1960s, 1970s can be difficult." (Policy/standards body).*

Interviewees often mentioned that issues arise from historical work and maintenance, as these can change the quality of the property from that recorded in its EPC, and this is an important addition to the framework. In the case of poor maintenance this can have a detrimental effect, creating a CTD property that is hidden from view if assessed through EPC data alone.

Case Study 3 provides a good example of the impact of this when identifying and retrofitting homes as part of the Social Housing Decarbonisation Fund (SHDF):

> *"Overall, the job became bigger as the work continued and more design detailing, remedial works and installation needed to be carefully thought about.... Some structural remedial work was also needed given the property age such as additional roof braces (following Solar PV engineering reports), bringing chimneys down where they were leaning and not in good condition, and re-roofing the property." (Social housing provider, Case Study 3).*

Case studies also identified defects and further physical complexities through initial property survey work (Case Studies 1, 4, and 6).

Ventilation was frequently reported by interviewees and in case studies as a critical, and often unexpected, factor. Furthermore, knowledge and awareness of the impacts of the building having inadequate ventilation was found to be low, particularly for newer properties (e.g., those build post 2000). Water ingress, dampness, mould, and condensation were consistently discussed by interviewees as common consequences of poor ventilation. The presence of these issues caused by inadequate ventilation can make a property CTD. Where any of these issues are identified the retrofit of these homes must include the installation of suitable ventilation alongside any other building upgrades to ensure these issues are resolved. This was highlighted by an interviewee from an academic institution:

> *"I am particularly worried about the build-up of moisture and heat because we were really not very good at dealing with that and ventilating our homes and those important things around exchanging air even in the winter." (Academic Institution)*

Spatial dimensions of properties were also assessed by the qualitative research to be a primary factor for identifying CTD homes. These reflect constraints to internal wall insulation (IWI) and wall to floor junctions, where rooms are already space limited, as well as the internal and external space requirements[19] for heat pumps. External layouts and access are also critical, such as for blocks of flats. Case Study 6 referred to the spatial constraints for demonstrator work including solar PV, air source heat pump (ASHP) and mechanical ventilation with heat recovery:

[19] For example, to install heat pumps, internal space may be needed for radiator re-sizing, water storage, pipework and ducting, and external space is needed for the heat pump itself including permitted development rights (PDR).

> *"There were spatial challenges for where the battery storage could go. The loft was considered but it provided a fire hazard and the transporting and maintenance access of the battery was also important and there was not clear guidance here. In the end, a number of cupboard spaces were used for both hot water cylinders and battery storage." (Large industry, Case Study 6)*

Interviewees also referenced issues where different parts of a home need different treatment, which need to be well-linked in either sequencing them appropriately or applying different techniques. For example, differences in front and back walls, extensions, and architectural features, which need extra care and consideration, and difficult wall to floor junctions.

Finding 7: The policy environment can be inconsistent and challenging for CTD homes, the CTD definition and CTD Identification Framework can help address this.

The RER reviewed the regulatory landscape and planning permission requirements, finding regulatory gaps, such as a lack of formal definition related to CTD homes in current UK building regulations, and where planning policy influenced the viability of measures such as external wall insulation, solar PV, heat pumps and window replacements. This was verified by many interviewees who discussed challenges with a range of specific policy and regulation areas in terms of a lack of coverage and clarity or of poor understanding about them and their interactions.

Several interviewees and Case Study 7 considered the challenge to relate to the interpretation and application of conservation planning permissions at the local level (e.g., Local Authority), adding project delays and divergence in what measures can be used; and permitted development rights, where the current limits mean heat pump and solar PV measures often have to gain planning permission instead, which is inefficient.

Interviewees referred to a lack of cohesive regulatory guidance and advice, which they saw as dispersed across government. For example, off gas grid homes and their treatment are incorporated in some building regulations, and the decent home standards has some elements related to CTD. Many interviewees suggested there was a lack of standards to focus on for CTD homes, which has led to confusion over the actions to take and standards or practices to adopt. Both industry and third sector/civil society organisations identified a benefit to clarifying and signposting relevant policy and regulations and steps to their application, as demonstrated in the CTD Identification Framework use cases (further below) and reflected in the following interview excerpts:

> *"When we started this project, it was really hard to understand all the existing regulations around process, funding streams… and it took months if not a year to just define all of this and understand it all. Any comprehensive document that gives us an understandable step by step approach or best practice measures and essentials to go to a it would be welcomed." (Third sector/civil society organisation)*

> *"Having those standards in place is a key thing. I think if you can get everyone working towards the same core standards that would help the sector a lot." (Trade/sectoral association)*

Interviewees also noted the inconsistent policy environment can lead to adverse impacts across tenure types – the social housing, private rented and privately owned sectors – due to them being separated with differing regulations and levels of enforcement. This means that CTD homes may have different prioritisation, treatment and outcomes according to their tenure type or funding eligibility, which also leads to streets or groups of homes having varied retrofit work. This is exacerbated by wider challenges of limited expertise and a lack of due care within the supply chain (Finding 6), enhancing the potential risks of poor thermal comfort and high energy costs for CTD homes that do not fall under clearer standards requirements.

The enforcement of standards is needed to set consistency and norms in the industry and hold suppliers to principles and responsible for their work. Interviewees, especially trade/sectoral associations and social organisations, noted that poor enforcement is strongly related to issues with consumer protection in the private sector with examples of poor consumer experiences in being left with poor work, work delays or high costs. Interviewees related this to impacting wider consumer trust in retrofit and a need for education for consumers in protecting warranties and where to go for help. The Minimum Energy Efficiency Standards (MEES) were identified as being important but infrequently enforced, leaving behind some CTD homes. MEES was contrasted to housing health and safety regulations, such as the 2004 Housing Act (like the Housing Health and Safety Rating System (HHSRS) tool). The latter was perceived to be better enforced by and embedded within local authority housing departments.

A useful definition and identification of CTD homes can support the effective design and application of regulation and standards for retrofitting these homes. This is an element of the policy-based use case for the CTD Identification Framework.

Finding 8: Social, economic, and behavioural attributes can exacerbate the complexity of treating CTD homes and the challenges to retrofitting them.

The RER identified that there are limited datasets for considering socio-economic barriers, their impacts, and any distributional aspects for CTD homes beyond datasets on household characteristics and income. The RER also identified limited evidence on social and behavioural barriers. However, the interviews and case studies identified and provided examples for a range of socio-economic factors that should be considered for CTD homes. These research streams also provided a large number of potential behavioural factors for households (occupiers and owners) that matter for retrofitting CTD homes, which go beyond the more typical home behaviours and usage considerations. These attributes can be understood within households' user journey of retrofit: the design process, engagement and buy-in, work delivery, and post-work use and maintenance. These stages may also be longer or more complex for CTD homes, requiring more care, time and/or cost, whilst the decanting of residents (moving people out of their homes for the work) and work disruption to daily lives are critical factors to retrofit uptake and effectiveness. These attributes also matter in understanding how delivering

a just-transition may be limited and the households and residents that could be left behind in decarbonisation.

All interviewees identified cost and funding barriers for CTD homes, across all types of tenure, this is itself a barrier and also impacts motivation to retrofit these homes. A secondary barrier was also often identified related to motivation to retrofit CTD homes, which has wider elements, both intrinsic (attitudes, knowledge, ability, disruption concern) and extrinsic (incentives, benefits framing) motivation.

Interviewees consistently reported that much more retrofit was currently being done and possible in social housing due to local authority funding. However, the increased time and cost needs for CTD homes meant that they could be left out of funding applications. Alternatively, these homes may need to be addressed alongside homes that are simpler and cheaper to retrofit, to meet average spend per home requirements, which also leads to less CTD homes being included. With CTD social housing in particular, there is still a need to consider the running costs for residents thereafter, where fabric first measures are key to reduce heat demand. The main factors that improve motivation for work involving social housing tenants were the need to mitigate or limit disruption, and provide suitable knowledge and advice (e.g., in an accessible format and describing good post-retrofit practices in the home). These factors may be more important for CTD homes though they are important across all homes.

In the private sector, as well as a lack of funding, owner incentives and motivations, there is some reluctance from industry stakeholders to take forward work that could have a higher cost or could leave them liable if anything goes wrong. Despite efforts, the research team were unable to source case studies from the private rented sector, indicative of the challenge of influencing this cohort.

Interviewees recognised that being an owner occupier does not necessarily equate to ability to pay, especially for those in CTD homes. Interviewees perceived gaps in current grant schemes, regulations and forward-looking funding models to progress retrofit in this sector and it was seen to be the most challenging tenure type.

Though an outlier point, a couple of interviewees also referred to the idea of ‘social archetypes’ for identifying CTD homes. The following excerpt captures some of the socio-economic and motivational elements that could form such archetypes:

> *“The hard-to-treat home very often also comes with fuel poverty, with vulnerable households, with households that already find they have health issues related… Another issue is that many people don’t understand what it means to them, other people understand it as a cost, other people understand it as a comfort, so it needs a very different communication tool that you need to use to understand the urgency to improve their building... to use different tools depending on the group of people that you need to work with.” (Academic Institution)*

A broader information issue relates to overcoming resident resistance and developing effective engagement approaches. Myths may need to be dispelled by providing consumer advice and

information developed by trusted organisations. This has been reported by interviewees and in case studies, and is further detailed below in the evidence of approaches to CTD homes.

There is also recognition of more 'system-level' factors that the CTD attributes may interact and be amplified by, as part of the presented definition. This includes the willingness of installers to approach retrofit design and delivery, and its engagement, in best practice ways to support residents in their uptake and in helping residents to have a positive experience before, during and after the works. Further, the willingness of residents to have retrofit works undertaken in their home (and the level of resistance to it) may be impacted by how much trust there is in both the need for the work and the organisations involved in the work.

The CTD attributes have been used to develop the CTD Identification Framework, enabling CTD identification and analysis across a stock of housing and for an individual home. These include the following principal categories and sub-categories. One of these attributes alone or in combination with other attributes, or by being amplified by system-level factors (as presented by the definition), may mean a home is CTD. Users of the framework apply their judgement and expertise to determine appropriate weights for each attribute according to the purpose of their analysis and its context.[20] For example, if a heat pump can be accommodated and the household can afford and are willing to have one installed, then the property may not be CTD and other attributes may be weighted less or excluded.

- Willingness
    - Self and fellow occupants' resistance
    - Self and the landlord resistance
    - Self-resistance
- Affordability
    - Low affordability
- Disruption
    - Disruption to neighbours
    - Disruption to self

Overall, the key challenges to retrofitting CTD homes remain under-evidenced, and where evidence exists quality is a potential concern.

There is substantial discussion of the challenges to retrofitting CTD homes from all the research streams including with detailed insights from interviewees. There is less discussion of locational challenges and the social and behavioural challenges. Insights from the qualitative fieldwork, literature review and individual case studies highlight that these challenges exist in

[20] Users of the CTD Identification Framework apply their judgement and expertise to determine appropriate weights for each attribute according to the purpose of their analysis and its context. The nature of attribute weights and interactions should be the subject of future research with users. The framework is not prescriptive to when and the extent to which different attributes mean homes are CTD. The purpose of this research is to provide a foundational evidence base for understanding more complex stock, to provide clarity and to inform solutions.

practice. However, there is limited evidence on their prevalence and severity without evidence from systemic reviews or observational studies.

We developed the CTD Identification Framework considering these challenges to retrofitting CTD homes, and the attributes of defining CTD homes that reflect them. The case studies and the following section demonstrate that these challenges can be, and are being, effectively addressed and that being CTD does not mean that these homes cannot be retrofitted efficiently. Rather, these homes may require more care and consideration in their planning, design and delivery.

Evidence on existing approaches to retrofitting HTT

The RER, interviews and case studies highlight that successful retrofit of CTD homes tends to involve: the use of well-established or more innovative technologies, such as new insulation materials or those that overcome spatial limitations (height, underfloor depth, internal space); scaling up approaches that improve roll out and economies of scale; suites of ongoing monitoring approaches, such as indoor temperature data and metered consumption before and after retrofit, which achieve better outcomes and provide opportunities for learning; and occupant-centric approaches that improve occupant engagement and satisfaction.

Finding 9: Case by case approaches that recognise the unique characteristics and challenges of CTD homes are key to deliver effective retrofit.

Evidence from practical case studies have demonstrated that sufficient understanding of the existing building and its configuration, with more detailed surveys early on is a factor for success. This was demonstrated with several case studies in particular (Case Studies 1, 3, 4, and 6):

> *"The dwelling assessment was key and was done early in the retrofit process though the initial information was basic. This was a challenge and three different levels of surveys were then undertaken. We ended up doing borescope surveys, wall tests to see how strong the structure was to hold EWI weight. Structural engineering reports showed where there was roof spread and cavity wall failure ties. There was quite a lot of intrusive and in-depth surveys for the properties…. "(Social housing provider, Case Study 3)*

Effective case by case approaches to CTD homes also involved:

- Explicit project objectives and clear responsibilities that are facilitated by collaborative decision-making and subject to quality assurance throughout the supply chain.
- Due consideration given to the resident's needs and specific context, by tailoring the communications and work delivery, and to giving resident's points of choice where possible.
- Sensible coordination throughout the project stages, with dedicated retrofit coordinators.

- Careful professional detailing for the building junctions and installations, to mitigate the risks for CTD homes.

The CTD Identification Framework has been developed to enable CTD attributes to be identified for an individual home, which can help plan and design its retrofit in a bespoke way, and to identify a particular attribute across a stock of homes to again consider in their retrofit or to replicate a best practice approach for those homes.

Finding 10: PAS 2035 has brought important improvements, but it could go further.

The Publicly Available Specification (PAS) 2035 details best practice guidance for domestic retrofit projects, through a whole house retrofit approach, and must be used in conjunction with PAS 2030. PAS 2030 is a standard which sets out robust and uniformly applicable technical specifications for the installation of energy efficiency improvement measures. PAS 2030/2035 were introduced in response to a key recommendation in the Each Home Counts review, to introduce a technical code of practice and conduct for the installation of home energy efficiency measures. PAS 2035 is mostly used in government funded retrofits, there is no requirement to use it elsewhere, PAS 2030/2035 incorporates the requirements of the entire building, considering both technical requirements and factors such as occupancy comfort. There are currently three PAS 2035 retrofit pathways (A, B, C) and of particular relevance to CTD homes are its Pathways B and C (higher risk, complexity and/or scale), however changes to this are currently being consulted on.

Many interviewees were positive about PAS 2035, including about its pathways approach and its consideration of staging work as this aligns well to the principle of ‘no regrets’ in retrofit work and also encourages more upfront assessment of the home:

> *“I think that’s why staging and pathways is so important, especially with those HTT homes, where you might not be able to do certain measures. Getting in a plan and a staged approach to what measures go in and when is even more vital.” (Trade association)*

Some interviewees reported they were already meeting PAS 2035 standards, but that it raised the minimum standard of other suppliers. However, interviewees also suggested that some suppliers still fall below appropriate quality levels to meet PAS 2035 standards. Interviewees also recognised that compliance with PAS 2035 drives increased costs and work requirements. This was seen to deter others in the industry from addressing CTD homes, which may have other factors that increase work costs and timelines (as per Finding 3).

Interviewees including local authorities, housing associations and trade associations raised that there is a lack of suppliers who are sufficiently qualified in PAS 2035 alongside a lack of retrofit assessors and coordinators. This can in turn create a bank of CTD homes in areas with deficiencies in PAS 2035 expertise and qualification. Case Study 3, an SHDF 1930s property whole house retrofit, identified a lack of qualified suppliers as a challenge.

Another reported limitation to the application of PAS 2035 is the potential to only undertake monitoring and evaluation for a short period. The impacts, or missed opportunity, of this may be heightened for CTD homes as understanding what works and how measures performed is even more valuable for improving future practice for CTD homes.

There also remain some measures which are constrained by PAS 2035, or where further complexities for CTD properties remain outstanding that PAS 2035 cannot alone address. Those raised by interviewees included: where PAS 2035 retrofit assessment of the home was still insufficient to pick up the necessary building insights to design the approach. For example, sustainable streetscape retainment and re-using materials for EWI work is not a PAS 2035 compliant measure. Furthermore, they noted a need for deep expertise to consider heritage needs and PAS 2035 together, as reflected with the following excerpt:

> *"It is also worth noting that not everything covered in PAS 2035 will be applicable to traditionally constructed buildings and careful design and application of retrofit measures in such buildings will be required over and above any requirements in the PAS. "(Policy/standards body, Case Study 1)*

There was a notable call from a range of interviewees for PAS 2035's scope to be widened, or at least used as a basis for other sectors under it as a 'PAS-lite' type of approach. It was felt that this could support the standard of work in the private rented and owner occupier sectors and to encourage a market response to upskill:

> *"So, you almost want a PAS-lite… which is what we're, kind of doing for non-funded [work]... in the company we're auditing ourselves to make sure that we're following the processes. But I think it should be across both sides of the delivery." (Large Industry).*

The TrustMark Licence Plus is such an example of extending the PAS 2035 scope to non-government funded work.

A large number of the case studies used PAS 2035 (Case Study 3, 8, 9, and 10) or aligned to many of its principles where they were pre-PAS 2035 or for private homes (Case Study 1, 2, 6, and 7). Case Study 5 differed in that it was focused on failed retrofit repair and acknowledged a potential gap here:

> *"Most of the regulations and especially PAS 2035 don't account for this repair work situation and to comply would have been too expensive. For this project to be PAS 2035 compliant, the project team would have had to remove the failed installation, repair the fabric, and then restart the project from scratch. This journey for the householder is extremely disruptive and for the managing agent it is prohibitively expensive." (Third sector/civil society organisation, Case Study 5).*

Finding 11: There are some innovative approaches for installing effective energy efficiency and low carbon heating for CTD homes, but more solutions are needed.

Both the RER and interviewees suggested that fabric-first approaches were the most appropriate for CTD homes. Considering the whole property system is a successful approach for decarbonisation and means issues like thermal/cold bridging and poor air flow can be avoided. The RER also noted the importance of monitoring devices for ensuring the right fabric – heating measures and their interactions, and to reduce risks to fabric.

Examples from the interviews and case studies also illustrates that installing some measures into certain homes often mean they are no longer CTD. This is a really encouraging finding that homes, with CTD attributes, can be effectively and meaningfully decarbonised.

For example, homes with narrow floor voids, which have underfloor insulation with innovative robotic tools (Case Study 6); bungalows being effectively and affordably retrofitted with fabric first approaches and low carbon heating (Case Studies 8 and 10); and high-rise flat blocks, including innovative external insulation (Case Study 9). Similarly, when other heat sources are constrained infrared wall panels may provide an innovative alternative intervention.

However, there are gaps in the availability of solutions and measures that can effectively treat CTD homes. The RER identified limited availability of materials including diverse specialist products for specific detailing, and emerging insulation materials that may perform better and improve the performance of CTD homes more easily but require testing and approval. Interviewees also noted a lack of viable low carbon heating alternatives for many homes when heat pumps are too costly or are not suitable due to spatial barriers, or where roofs are not able to accommodate solar PV.

The CTD Identification Framework is necessarily flexible to incorporate new solutions that emerge whereby certain attributes become less relevant in making a property complex to retrofit, so can be removed or be given with less weight, as detailed in the CTD Identification Framework section below.

Finding 12: Listed properties and those in conservation areas can be effectively and appropriately retrofitted.

The RER recognised the scale of the heritage sector (listed status, located in conservation areas, and traditionally constructed buildings), that makes up a significant proportion of the UK stock of CTD homes. Elements such as Planning barriers, technical constraints, and risks to damaging heritage value, particularly for breathability and aesthetic protection, matter here.

Interviewees recognised the complexity and challenges of retrofitting listed CTD properties and those with heritage features or in conservation areas. While they identified effective methods and approaches of retrofitting, the outstanding challenge may be the cost and scale at which these homes can be retrofitted given limited financing and expertise. Interviewees emphasised the importance of strategies including:

- Installing IWI instead of EWI.
- Assessing and protecting natural ventilation.
- Carefully applying appropriate infill materials.
- Replacing window-panes while retaining heritage frames.
- Improving fabric and insulation through the use of traditional materials to preserve character.
- Enabling the reinstatement of traditional finishes and details.

This research, including the case studies show that these homes can be successfully retrofitted but that there are complexities that may often be costly to address and which require due care and knowledge to be applied in the retrofit.

Case Studies 1 and 2 detail how successful outcomes were delivered for unique and complex listed properties. Other case studies also adapted their approaches given heritage and conservation elements of the properties (Case Studies 3, 6, and 7). Heritage solutions tended to also actively consider long-term climate impacts on the home, to future proof and embed adaptation to their design, as demonstrated by this insight from Case Study 1:

> *"A key principle was to work with the building as a whole. We have our own hierarchy and guidance that we follow for such properties. Another key principle was in ensuring compatibility with the fabric, where delivering effective ventilation was really important and improving the indoor air quality. We also promote the need to reduce waste where you can – recognising the materials that are vapour permeable and naturally derived where possible such as hemp as an alternative to wood fibre. Construction has a key role in the project's carbon impact, where much can be embodied at this stage." (Policy/standards body, Case Study 1)*

Finding 13: Social barriers are effectively addressed by some organisations across various CTD homes.

The interviews and case studies were highly consistent in highlighting the importance of resident engagement at early stages and in the post-work period, with transparency with residents on what will be done and how through the work planning and delivery. This is especially the case for CTD homes where disruption may be higher and there are more existing barriers. The RER however found limited evidence on social barriers and addressing them.

Interviewees noted that there are information and advice services being used across local authorities, civil society and the third sector. However, advice is disparate and signposting can be challenging to find for those facilitating and supporting work for households. There is a critical gap in the provision of consistent advice and clear and simple guidance from a trusted source for households.

Many interviewees suggested that occupant-centric approaches are necessary to improve the effectiveness of interventions to tackle CTD homes, and these form a key factor in the success

of several of the case studies. These approaches to design, engagement, delivery, and monitoring differ by tenure and resident type and according to the work needs and potential disruption. As noted, there is a lack of retrofit evidence from the PRS sector. However, interviewees identified the influential power dynamics between landlords and tenants that can leave homes with poor energy efficiency.

Interviewees, from the social housing sector in particular, highlighted the importance of regular and consistent engagement through drop-in-sessions, or one-to-one engagement in the form of home visits with trained personnel. However, many interviewees also mentioned reducing the number of home visits in balance with the need to actively engage and inform households. This is especially so for social tenants where disruption and the burden should be limited. This requires clear planning, efficient work, and efficient communication. Social housing sector interviewees were also attuned to the importance of closely engaging with vulnerable occupants:

> *"Keeping people engaged with what we were doing. Did they understand retrofit? Did they understand the impacts and the benefits it would have to them and the building, and then talking to them about how they use the building post retrofit. So, we didn't have any unintended consequences." (Social housing provider)*

Mixed-tenure properties were noted as very complex to retrofit, with limited evidence on how to approach these. Case Study 2 provides useful lessons learned where bespoke engagement and facilitation methods were used for a heritage mixed-tenure flat building. Several case studies focus on occupant-centric engagement and delivery, including mitigating risks of resident decanting; aligning retrofit work to other home upgrade works; and to identify the benefits, and co-benefits, that matter to different residents and where possible provide areas of choice (Case Studies 3, 4, 8, 9, and 10). Case Study 4 also delivered an effective street-level approach, realising quality of place improvements, and using a resident drop-in/demonstrator site.

Finding 14: Monitoring and evaluation is critical, and lessons learned for CTD can be better captured and disseminated.

The RER found that the use of various quantitative and qualitative methods can inform the design of retrofit strategies and assess the outcomes of retrofit. These included:

- Monitoring indoor temperature data.
- Analysis of metered consumption.
- Air permeability tests, building envelope thermal imaging.
- Occupants' qualitative insights and feedback before and after retrofit.

This can inform the design of retrofit strategies and assess the outcomes of retrofit. Interviewees also frequently mentioned the above methods found in the RER as well as:

- Humidity and temperature tests.

- Moisture checks.
- U-Value testing.
- Smart monitoring devices.

These technologies and approaches helped organisations to better understand issues and gaps in advance of starting work, and to see how measures improved properties once installed. This was also relevant as part of ongoing work to see if any other measures, or more extensive application of currently installed measures, were needed given the home's live monitoring. Interviews and case studies raised examples where monitoring usefully informed the direction of ongoing and future work. Furthermore, some of the case studies were used as live demonstrators and an opportunity to test and monitor measures for their wider stock or for others in the industry.

Across the research streams, findings suggest that there is insufficient monitoring of retrofit in CTD homes, nor are good practice, failures limitations, or evaluation outcomes adequately shared.

Interviewees recognised that monitoring and evaluation was often not done sufficiently as: a) funding requirements allowed only short time periods for this and with perceived low incentives for landlords and suppliers to do more; b) clients did not want to pay extra for it; or c) there were wider funding or time constraints. Some interviewees also noted the need for clear industry goals and the outcomes to focus on.

Consumer satisfaction, wellbeing and home comfort is being increasingly included in evaluation. Some interviewees and case studies reported using dedicated social researchers for evaluations, which may be particularly important for CTD homes, particularly those with vulnerable residents.

Ongoing monitoring is also valuable in increasing understanding of how people are using new systems, technology or adopting new practices or behaviours. This can in turn identify areas where people may need further support, or to flag potential maintenance requirements.

CTD Identification Framework

We developed the CTD Identification Framework by drawing on data from across the research programme. The framework accompanies the new CTD terminology and its definition, by bringing together the CTD attributes referred to in the definition (physical, locational, occupant demographic, and behavioural attributes) and ways to analyse CTD in one place. This section's three key findings reflect its development. Annex B sets out the framework in detail, including the following important points.

A pivotal outcome of this research and the CTD Identification Framework is a shift in identifying CTD homes, from a simple binary (yes/no) to a relative complexity indicator (a CTD index). This reflects the consideration that many homes are, to varied extents, CTD. The high-level use cases for the framework, detailed below, recognise the value in understanding the level of CTD attributes across a stock of housing. To estimate numbers of CTD homes relevant to a

particular analysis application, the process described in Annex B would need to be applied by users of the CTD Identification Framework to incorporate thresholds, attributes, and attribute weights reflective of their priorities and analysis scope. This should be informed through stakeholder inputs and the use of relevant and appropriate datasets.

Users of the framework apply their judgement and expertise to determine appropriate weights for each attribute according to the purpose of their analysis and its context. The framework is not prescriptive to when and the extent to which different attributes mean homes are CTD. The purpose of this research is to provide a foundational evidence base for understanding more complex stock, to provide clarity and to inform solutions. The nature of attribute weights and interactions should also be the subject of future research with users, as reflected in Annex B and D.

Finding 15: A wide array of datasets may be used to identify CTD homes.

Our dataset analysis highlighted the range of datasets (e.g., housing stock data, EPC data, heritage and spatial data) that are available to support the identification of CTD homes, and the subsequent variability in the data variables within each. Appendix 1 of Annex B presents a mapping of available datasets to the CTD attributes. We designed the framework to be data/dataset-agnostic[21] to allow interaction with this wide array of datasets. This approach ensures it is versatile, not dependant on specific databases, and so may be customised to suit the varied stakeholders' needs. The framework can also incorporate new data that emerges, as issues raised in Finding 4 on current data limitations are overcome. Overall, the framework brings the different attributes of the CTD definition and dataset use into one place, enabling more comprehensive mapping and understanding of CTD, which was identified as a need (Finding 4).

Finding 16: The CTD Identification Framework should be flexible for use at both the stock level and the individual dwelling level, where the CTD terminology is not binary.

We asked interviewees and case study participants about how an identification framework could support their work going forward or have supported completed projects. This drew together a series of recommendations for framework content and suggested use cases (as per Finding 17 and presented in Annex C) and established a clear rationale for a framework.

These findings suggested an approach that does not explicitly categorise a CTD group and a non-CTD group, which instead looks at the specific home(s) in question, to understand the physical, locational, occupant demographic or behavioural attributes that could make it CTD. We therefore developed the framework to reflect this with a CTD index, to support the mapping of the scope of the challenge (detailed in Annex B). Furthermore, there are a range of attributes and challenges identified in this research such that it is useful to be able to weight attributes differently to reflect whether they are fundamental and primary or secondary and

[21] A system in which the format of data transmission is irrelevant to its function. This means that the system can receive data in multiple formats or from multiple sources, and still process that data effectively, whereby it can work with information received from heterogeneous databases, i.e., databases with dissimilar data formats.

'amplifying' in a particular context. The framework does this with the CTD Index (e.g., the relative possibility of CTD, where some attributes enhance the possibility or impact of CTD and/or in combination with other attributes).

The usefulness of having two levels of analysis is reflected with suggestions from interviewees, for example for the stock level of analysis:

> *"A framework would certainly be useful – as there are more loose terms and not clear definitions. This should be clearer for architects, social landlords, housing providers – to understand where their stock falls." (Small industry, Case Study 7).*

> *"A predictive model of where hard-to-treat properties might be in our stock database would be useful to help understand where to pay attention, and where there could be some properties that slip through the net." (Housing Association, Case Study 10).*

As well as for analysis at the individual dwelling level:

> *"It is important to reflect that every home is bespoke, so it can't just do a sweeping 'every one needs this' and you have to look at what the biggest issues are with the house. There would be so many questions that you could go down a big tick list." (Large industry, Case Study 6)*

Finding 17: The CTD Identification Framework should recognise and support a wide array of analysis use cases.

We identified a number of 'use cases' through analysis of the qualitative interview insights and in consultation with DESNZ stakeholders. This guided our development process and understanding of how the framework may be used by stakeholders. We highlighted three high level use cases:

1. Policymaker and asset owner: Mapping – macro-assessment of the scope of the challenge.
2. Industry: Diagnostic – to help industry to identify CTD elements of individual homes or within a stock of housing, and steer industry to guidance and to select practical solutions.
3. Civil society and representative organisations: Knowledge and information – illustrate the nature of the problem and how it affects their stakeholders.

We asked interviewees and case study participants how a definition and identification could support their work or have supported their project; this drew together a series of suggested uses and recommendations for framework content. Annex C includes the case study insights and suggestions for the use cases. The qualitative analysis also determined some common use suggestions as follows, supported with some illustrative stakeholder suggestions:

- Signposting and providing steer on the guidance, standards and regulations that should/could be followed.

  "When we started this project, it was really hard to understand all the existing regulations around the processes, funding streams, how to dos and how to deliver this." (Third-sector/civil society organisation, Case Study 5)

- Identifying potential risks or key considerations given property and context details, perhaps in a checklist form, and through the home's project lifecycle.

  "To have something that sets out what physical issues/potential issues you might expect given the property characteristics – a checklist almost. A bit of a map to follow would be really useful, for what you need to consider and when and what follows if X is true etc. The support it could give is to identify the types of measures that are more standardised for these homes, and these ones are trickier." (Housing Association)

- Supporting consistency across suppliers, especially in 'able-to-pay' markets, and to help address work quality issues by raising the profile of a range of attributes that can make a home CTD, with supporting examples of how to address them (such as the case studies presented in this research).

  "A framework should also reflect the needs and challenges of stakeholders and suppliers, such as the hassle factors, how to best engage and what the specific material needs are." (Housing Association, Case Study 4)

- Consumer advice, as a simple guide for residents to better understand what their home may require and why.

  "It could be something that is filled out, not by the homeowner themselves but by a skilled person who can go through a tree diagram structure for the questions and resulting considerations… To get the residents involved and to not exclude them in decision making and support their home understanding and use. A framework could also be an opportunity to dispel some myths." (Large industry, Case Study 6)

- Supporting resident and community agents to navigate challenges and manage contractors.

  "A framework could also have a useful role in dissemination, of what works and of the solutions that are out there – in a way that people and organisations could trust." (Small industry, Case Study 9)

Identification Framework: current development

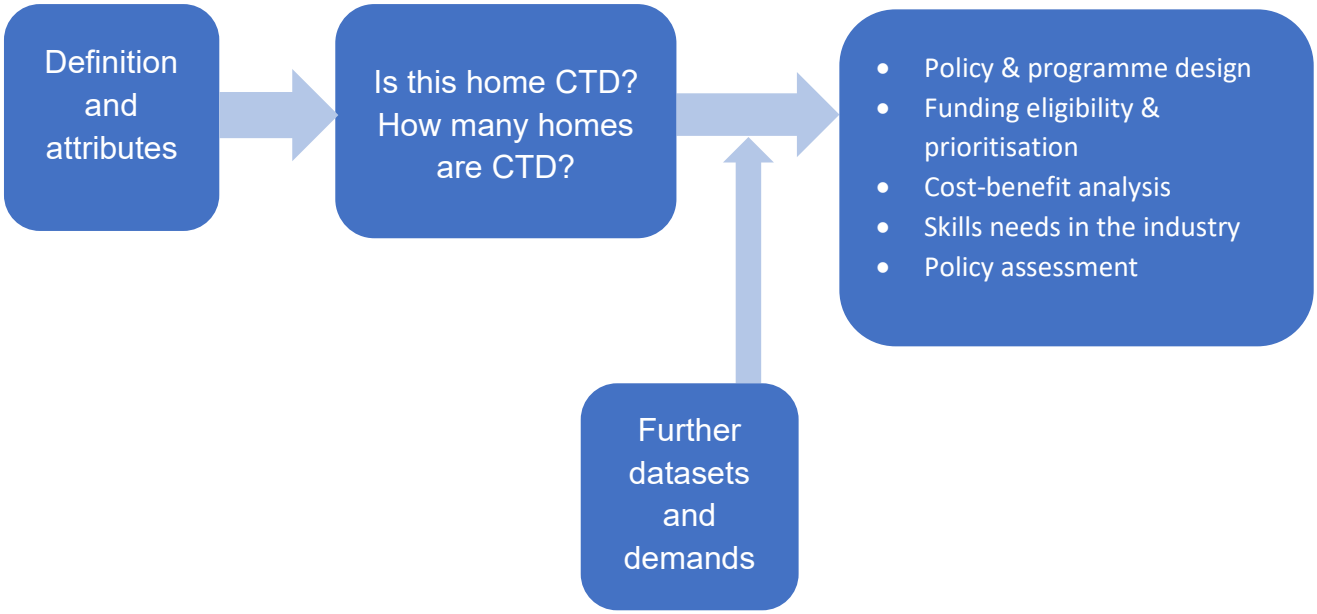
Given the scope of the project, Use Case 1 ('*Policymaker and asset owner: Mapping – macro-assessment of the scope of the challenge*') was prioritised for the development. This defines the attributes of CTD, to enable a user to use the framework to answer: 'is this home CTD?' and 'how many homes are CTD, or have particular attribute(s)?'

Further research is suggested to take forward Use Cases 2 and 3, where these will be suitably informed by Use Case 1 and there may be a role for the policymaker and wider stakeholders to drive and shape the advice and framework that is developed for industry and consumer group use in being well-evidenced, well-trusted and with supporting guidance.

The framework responds to recommendations from the research to have the ability to both (a) identify the relative possibility of CTD (CTD Index) and CTD attributes for an individual dwelling, and to determine the degree of relative difficulty associated with its retrofit; and (b) for a stock of housing, where various datasets are 'layered' to determine the incidence of CTD at the defined scale.

The current framework may be used (subject to the availability of suitable datasets) through 'soft-linking'[22] to support number of Use Case 1 applications[23] identified by DESNZ Stakeholders. This is set out in Figure 1.

Figure 1 The application of Framework outputs



Annex B provides a set of illustrative uses for individual dwelling assessment and Lower Super Output Area (LSOA)/regional distribution. Annex B also presents further applications of the framework outputs, including cost of retrofit, skills needs and eligibility.

[22] A soft link is similar to a shortcut, as a file whose purpose is to point to a file or directory in any file system by specifying a path in a data or computing system.
[23] Use cases define the function(s) the framework through the applications it may be used for and, where relevant, the interactions of intended users with it.

Conclusions

This research introduces the complex-to-decarbonise (CTD) definition, a new unifying terminology designed to better articulate the multifaceted nature of homes which are difficult to decarbonise. This brings together archetypes/typologies and a wide set of attributes of these homes in one definition. The definition has also supported the development a of a powerful CTD Identification Framework and set of use cases for mapping CTD attributes and their prevalence. In doing so, this report provides an opportunity to bring clarity and consistency through language that conveys the critical importance of decarbonising challenging UK housing stock.

The research outputs of the CTD definition and the CTD Identification Framework respond to Study Objective 3 (*'to develop a framework/definition, which identifies a spectrum of technical, physical, and material attributes that make a home HTT from a whole house retrofit perspective'*). These outcomes bring together the challenges specified in Study Objective 1 ('*to identify the technical, regulatory, and social challenges, taking account of spatial variability across the UK'*) with review and evidence gathering. This evidence has considered existing approaches and presented some of these with ten deep-dive case studies (meeting Study Objective 2 on demonstrating existing and effective approaches).

Defining CTD homes: The lack of a unifying definition of HTT/HTD homes led to an uncertainty across stakeholders interviewed. Without such a definition, many interviewees offered mixed perspectives and approaches for how to address these homes and the regulations that need to be considered, where CTD homes were often at risk of being left behind. Going forward, the terminology of 'hard-to-treat' may also become a limiting factor on the market when there are few clear, trusted, and certified solutions and products. These limitations demonstrate that there is an advantage with the CTD definition in suggesting considered and holistic approaches, and greater understanding of multiple attributes and their relationships.

The CTD definition and CTD Identification Framework provide a starting point from which to improve practice. Firstly, they support better identification, monitoring and sharing of effective and ineffective practices for CTD homes across the industry to support continuous improvement. They also encourage stakeholders to identify areas of complexity, through a wider consideration of attribute types, and to demonstrate how they then address these complexities. Secondly, the CTD definition and framework can support the provision of clear advice and guidance for both suppliers and consumers and their support organisations. This can help to build trust and interest in home decarbonisation efforts, particularly for those properties which are difficult to address.

The research has also demonstrated that innovative and effective approaches to energy efficiency and low carbon heating are already being deployed for some CTD homes, as exemplified by the case studies. A key factor for success is in clearly identifying and understanding these homes at the earliest point in the retrofit project lifecycle. This can provide a starting point for capturing and sharing best practice, with transparency on the challenges of

CTD homes, and with the building of capability and capacity, where required, to effectively tackle these homes.

The definition:

> Complex-to-decarbonise (CTD) homes are those with one of a combination of certain physical, locational, occupant demographic, or behavioural attributes which may constrain the design and delivery of measures to improve energy efficiency, decarbonise heating, and realise occupant benefits (e.g., increased comfort and affordability of domestic heat and energy).
>
> These effects may be amplified by one or a combination of numerous system-level factors including financial (e.g., feasibility and affordability of measures), economic (e.g., supply chain and materials availability), and/or organisational capacity and capability (e.g., workforce skills).

Utilizing the CTD Identification Framework to view homes through a multi-attribute lens: The CTD Identification Framework provides a practical way to introduce varied attributes into mapping processes. Using the framework, the physical (for example non-fillable cavity walls or poor maintenance history); locational (for example off gas grid or rainfall); occupant demographic (for example low affordability); and behavioural (for example disruption or self-resistance) attributes can be effectively presented, analysed, and used both at the stock level and at the individual dwelling level. The CTD definition and CTD Identification Framework also consider the retrofit project lifecycle, from historic work and maintenance, through early engagement, planning and design, delivery, and post-intervention, with the relevance of different physical, locational, occupant demographic and behavioural attributes.

CTD as a term recognises the complexity inherent in the combinations of physical, locational, occupant-level and behavioural attributes. Furthermore, the CTD Identification Framework offers a useful prompt for stakeholders to consider the importance and weight of these, allowing a more nuanced or holistic approach through the framework and CTD analysis. This meets needs identified by many interviewees, as a use case of the framework, and in response to Study Objective 5- *to review, compare and propose best-practice methods and approaches for identifying HTT/HTD homes.*

There are notable dataset limitations and gaps to support such a comprehensive understanding and identification of these homes, which the CTD definition partly addresses, and the CTD Identification Framework offers a route to solving through the development and improvement of datasets (meeting Study Objective 4 '*to identify potential data and/or sources of information that could be used to identify HTT homes for both energy efficiency and low carbon heating')*. This should also encourage more comprehensive home assessment in advance of work design and planning. An important part of future research may be to develop understanding on the attribute combinations and interacting impacts for CTD homes, and using this to develop the CTD Identification Framework.

Other areas for further research and development of the CTD Identification Framework include: evidencing suitable attribute weights and interactions under different conditions; developing a

framework diagnostic use for industry; and providing complementing guidance for use by a range of stakeholders.

Annex D sets out research suggestions across industry stakeholders, policy-makers and consumer-based stakeholders, as well as areas for further research and development.

Prompting action and investment: An emergent theme from the interviews was the long-term consequences of not retrofitting CTD homes, which could raise issues for landlords, owners, and occupants. For example, limiting the ability to deliver a just-transition, leaving some homes and their occupants behind in decarbonisation and accessing its co-benefits (such as health benefits, home and place quality improvements, and labour market outcomes).

A key barrier in retrofitting CTD homes is not being able to utilise economies of scale. These cannot be reached with the current regulations and funding environment, particularly given the relatively immature nature of the CTD home retrofit market. This creates inefficiencies and reduces incentives to suppliers and for up-skilling. This is made more pertinent by key elements of CTD including the social, economic, and behavioural factors for occupants across different tenures but also for wider stakeholders in their financial means, views and motivations for home decarbonisation. The role of the installer is highlighted as critical to the retrofit process, often being the main point of contact or face to the work. There is often a need to upskill and support this ‘middle actor’ engagement to better provide advice and steer to residents in retrofit choices, uptake and post-work usage and maintenance.

The CTD definition and CTD Identification Framework brings clarity to the attributes that make homes CTD and their potential relationships. In the future this could help to support critical actors in the supply chain to build their knowledge and understanding of how to retrofit complex homes. This will usefully be supported by examples of effective approaches to CTD homes, such as the case studies developed for this research (and presented in Annex C).

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