

Title

1 100 unintended consequences of policies to improve the energy efficiency of the UK housing
2 stock

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4 **Short title: 100 unintended consequences of policies to improve the energy efficiency:**

5 **Shrubsole et al**

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Key words

Built environment, Climate change, Complexity, Housing, Policy, Unintended consequences

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8 **Additional data to accompany this study available at <http://bit.ly/HEW-100-unintended->**
9 **[consequences](http://bit.ly/HEW-100-unintended-consequences)**

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Abstract

As a major sector contributing to the UK’s greenhouse gas (GHG) emissions, housing is an important focus of Government policies to mitigate climate change. Current policy promotes the application of a variety of energy efficiency measures to a diverse building stock, which will likely lead to a wide range of unintended consequences. We have undertaken a scoping review identifying more than 100 unintended consequences impacting building fabric, population health and the environment, thus highlighting the urgent need for Government and society to reconsider its approach. Many impacts are connected in complex relationships. Some are negative, others possibly co-benefits for other objectives. While there are likely to be unavoidable trade-offs between different domains affected and the emissions reduction policy, a more integrated approach to decision making could ensure co-benefits are optimised, negative impacts reduced and trade-offs are dealt with explicitly. Integrative methods can capture this complexity and support a dynamic understanding of the effects of policies over time, bringing together different kinds of knowledge in an improved decision-making process. We suggest that participatory systems dynamics (PSD) with multi/inter-disciplinary stakeholders is likely to offer a useful route forward, supporting cross-sectorial policy optimisation that places reducing housing GHG emissions alongside other housing policy goals.

Introduction

European and domestic legislation motivated by (GHG) reduction concerns aims to substantially improve energy efficiency in both new and existing UK homes in the coming decades [1]. Existing dwellings are likely to represent 70 - 80% of the 2050 stock [2, 3]. Through a number of policy mechanisms [4], these existing dwellings are likely to undergo extensive retrofitting with a range of measures that will increase air tightness, insulation,

40 glazing improvements and the efficiency of heating systems in order to help meet the UK's
 41 ambitious GHG reduction targets (80% of 1990 emissions by 2050) [5]. The summary of
 42 relevant legislation and national policy in Table 1 demonstrates the Government's approach to
 43 GHG reduction involving the housing sector; with policies seeking to improve energy
 44 efficiency, reduce the carbon intensity of energy generation and change the energy related
 45 behaviour of building occupants [4, 6].

46 **Table 1** Summary of primary UK legislation, policies and incentives currently used to promote
 47 the decarbonisation of the housing stock.

Legislation	Description
Climate Change Act 2008	Requires emissions reductions of 80% by 2050, introduces legally binding carbon budgets and sets a legal framework for climate change adaptation.
Energy Bill 2012	Electricity Market Reform including predictable incentives for investment in low-carbon generation (Contracts for Difference) and ensuring adequate supply (Capacity Market).
Building Regulations and associated technical guidance	Includes legislative requirements for energy efficiency and GHG emissions from new buildings as well as requirements for retrofitting existing buildings.

Policies and Incentives	Description
Renewables Obligation	Requirement for electricity suppliers to source an increasing proportion of electricity from eligible renewable sources or pay a penalty. Suppliers buy certificates from generators and present them to the regulator or buy-out their obligation.
The Green Deal	The main national incentive for retrofitting existing dwellings, includes a loan scheme covering loft and external wall insulation (including solid and cavity walls); boiler upgrade or replacement with heat pump; renewable energy generation (solar panels or wind turbines); double glazing and draught proofing. Expected financial savings must be equal to, or greater than, the costs. Loans are attached to property utility bills.
Energy Company Obligation (ECO)	Requirement for Energy Companies to fund energy efficiency improvements under three obligations: (i) provision of insulation to low income households in specific target areas; (ii) provision of heating and insulation for beneficiaries in private tenure and (iii) installation of less cost effective measures not meeting the financial savings requirement of the Green Deal (e.g. solid wall

insulation). Energy companies are expected to respond to these obligations by increasing energy prices.

Feed-in Tariff (FITS)

Guaranteed payment from electricity suppliers for surplus electricity from small-scale (less than 5MW), low-carbon generation – under review.

Domestic Renewable Heat Incentive (RHI)

Proposed future extension of the non-domestic RHI to houses, providing financial support for installation of eligible technologies (e.g. biomass boilers, ground source heat pumps, solar thermal).

48

49 The need to consider the linkages that exist between buildings, human wellbeing, local and
50 wider societal, and environmental impacts when forming these policies has been noted
51 previously [7]. In this paper, with a focus on housing, we aim to illustrate the complex nature
52 and range of possible unintended consequences arising from policy framing and
53 implementation that is limited to a focus on climate change mitigation. This initial scoping
54 study makes no claims to be a systematic review - rather we aimed to exemplify and categorise
55 the broad range of possible unintended consequences that may arise as a result of proposed
56 energy efficiency measures. We further suggest the need for a broader approach to policy
57 decisions that integrates multiple objectives about housing and includes consideration of a
58 wider range of outcomes and involves multiple stakeholders in decision-making so that co-
59 benefits may be optimised, negative impacts reduced and trade-offs made more explicit.

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61 **Methods**

62 *Definition of Unintended Consequences*

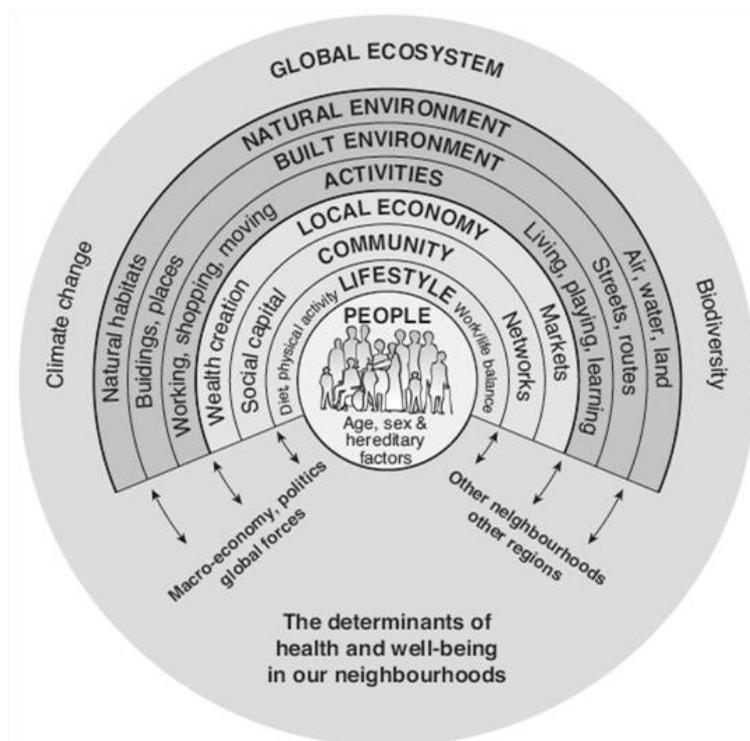
63 For the purpose of this study, unintended consequences were defined as outcomes that arise
64 unintentionally as a result of policy, development or implementation. Multiple direct and
65 indirect consequences can occur. They can be broadly grouped into two categories: (i) an
66 unexpected benefit or negative effect (or a combination of both), which may occur in addition
67 to the desired effect of the policy or action; (ii) an effect contrary to the original intention that

68 undermines the intention and even makes the problem worse [8]. The complex interdependence
69 of many of the consequences is discussed in detail below.

70

71 *Framework*

72 In the absence of a specific structure for the potential relationships between housing, people
73 and nature, we used a broad exploratory framework (Figure 1) to define domains of possible
74 consequences [9].



75

76 **Figure 1** Holistic framework of health and wellbeing [9] adapted from [10]

77

78 This framework was originally designed to illustrate the relationships between health and
79 wellbeing in neighbourhoods and the physical, social and economic environment, but we
80 considered it a valuable holistic model. It provided a useful structure that directed the areas for
81 literature search by revealing the multiple domains of consequences of policies to improve
82 energy efficiency.

83

84 *Search Methods*

85 We used the framework described above to undertake a scoping search of the literature across
 86 the following disciplines: building physics; construction technology and practices; health and
 87 wellbeing; and social sciences. We searched the following electronic databases: Web of
 88 knowledge (including citation reports which were further investigated via Scopus); Google
 89 Scholar; Index of Theses; Science Direct; Social Science Research Network and PubMed. Grey
 90 literature investigated included the Open Grey data base, European Union and UK Government
 91 legislative and policy documents, technical data sheets and specifications, published textbooks,
 92 reports from NGO's involved in the retrofitting process, recognised websites (for example from
 93 construction organisations) and newspaper articles. We used the grey literature to identify
 94 further peer-reviewed studies.

95 Using the framework domains, an initial set of keywords were developed for each energy
 96 efficiency intervention and further used in combination with outcomes relevant to that
 97 intervention, for example human health. An example is shown below in Table 2. The full range
 98 of search terms are shown in the web appendices accompanying this study, available at
 99 <http://bit.ly/HEW-100-unintended-consequences>. Additional terms and combinations revealed
 100 by the literature search were also investigated.

101
 102 **Table 2** Example of keywords used in the literature search
 103

Policy Impact	Initial Keywords	Domain combination	Additional Revealed terms
airtightness	permeability, airflow, air change rate, indoor air, indoor air quality, airtight	health, well-being, consequence	mental health, physical health, psychological well- being, child development

104
 105 The impacts of the range of interventions on dwellings were considered independently so as
 106 reveal the pathways of their individual consequences. Themes emerged from the literature
 107 which lead to specific interventions being investigated including: increasing airtightness,
 108 purpose provided ventilation (PPV); insulation (including double glazing) and impacts related

109 specifically to ‘traditional built’ structures as opposed to new builds due to their constructional
110 differences [11]. Additional areas of investigation include the implications of the policy
111 funding structure under the Green Deal; the UK Coalition Government’s flagship carbon
112 emission reduction policy for domestic properties [4], as well as the potential effects of changes
113 to design, construction and manufacturing processes that may result from current policy.

114

115 *Selection Criteria and Analysis*

116 The search was limited to studies in English published from 1990-2013. We included studies
117 that made a direct connection between an intervention to reduce GHG emissions from, or
118 improve the energy efficiency of, dwellings and an impact on one or more domains described
119 in the framework above. Studies that failed to meet these criteria were considered not relevant
120 to the scoping review and were rejected. We used the findings of included studies to group and
121 characterise described relationships between interventions and outcomes. We tabulated these
122 relationships, summarising the short pathways described in the studies between the impacts on
123 buildings, people and the natural environment. Where there was unresolved debate about the
124 direction of effects of an intervention on an outcome, we included both theories. Although we
125 placed greater emphasis on systematic reviews of particular effects of interventions on housing
126 our aim was not to assess the quality of the evidence, nor to report on relative effect sizes or the
127 strength of relationships.

128

129 **Results**

130 We identified nearly 1600 potentially relevant studies. Of these, 436 had content relevant to
131 this study, and of these 206 met the inclusion criteria. 119 unintended consequences were
132 highlighted, representing the impacts related to the application of the investigated energy
133 efficiency policy measures. However, many individual consequences further impact on
134 multiple domains resulting in a total of 196 possible outcomes reported across the studies. The

135 papers reported impacts across many of the domains identified by our framework (figure1)
136 including the built environment, life style, and activities, community, local economy, the
137 natural environment and the wider global ecosystem. We also identified some intervention
138 effects that did not fit well within the holistic framework, including new legal ramifications and
139 impacts on household-level economics. These have been included in the results and indicate
140 potential future additions to the framework.

141
142 The included studies described the effects of interventions that could be categorised as impacts
143 associated with:

- 144 • increasing dwelling airtightness;
- 145 • replacing uncontrolled ventilation with purpose provided ventilation;
- 146 • insulating properties and raising indoor temperatures

147 A further set of unintended consequences have been reported that relate to current options for
148 funding interventions and to the way that such interventions are being implemented. Within
149 these categories, many studies also explored the particular impacts on older/traditional houses
150 compared with more modern ones due to their constructional differences. The term ‘traditional’
151 is generally used to define a structure built prior to 1919 with solid walls constructed with
152 moisture-permeable materials [11, 12]. Such buildings are estimated to represent almost a
153 quarter of the current UK housing stock. They have specific issues different from the rest of the
154 built stock for example; heat loss and moisture movement in solid walls [11, 12]. Both current
155 regulations and the Green Deal and related policies do not take these differences into account
156 when applying efficient technologies [11], although work is currently underway to address
157 some of these issues.

158 Due to the substantial range of consequences uncovered, it has not been possible to capture
159 individual impacts in any depth within this article. However, the following sections
160 demonstrate the level of detail that exists for some known consequences.

161

162

163

164 *Impacts associated with increasing dwelling airtightness*

165 Studies described the airtightness impacts of a range of measures including for example; draft-
166 proofing, the provision of double glazing, insulation of loft spaces and the filling of cavity
167 walls. For these interventions a range of both positive and negative impacts on a range of
168 domains were described. Increases in airtightness of dwellings should result in reduced
169 ventilation heat loss through lowered air change rates potentially leading to reduced energy
170 consumption and GHG emissions [13]. The quieter environment created by these measures can
171 have further impacts, such as a more peaceful atmosphere and the accompanying sense of
172 security, which has a positive impact on mental health and psychological wellbeing [14, 15].
173 Improvements in child development in the spheres of physical, social and emotion health as
174 well as behavioural outcomes are reported [16]. These positive impacts have been attributed to
175 the ‘reduction’ in noise [17]; conversely it has been emphasized that the ‘absence’ of sound
176 (e.g. sounds from nature) may lead to negative mental health impacts [15, 17]. For some
177 individuals this can lead to anxiety from both real and perceived threats [18] and a possible
178 sense of isolation and disconnection having further impacts on social cohesion. Increased
179 window opening to compensate for lack of natural sounds could lead to increases in ventilation
180 heat loss working against GHG emission reduction [19].

181 External sealing of the building envelope to increase airtightness was found to have the
182 additional benefit of making properties more watertight and is recommended as a climate
183 change adaptation measure thereby reducing possible future impacts from excess rainfall and
184 the likelihood of water damage and mould/rot risk [20]. However, other authors have described
185 links between lower air change rates and a rise in relative humidity (RH), leading to increases
186 in house dust mites, mould, severity of asthma and allergies [21, 22] and in fabric decay in

187 existing properties, particularly traditional buildings [11]. Further rises in RH are produced
188 when clothes are dried indoors and have been linked to increased exposure to microbiological
189 pathogens and infectious diseases [23]. In new builds, with tighter construction drying out
190 times for ‘wet trades’ are extended leading to higher RH over a prolonged period during initial
191 occupancy [24].

192 Other changes in indoor air quality have also been identified as a further consequence of the
193 lower air change rates, beyond those associated with increased humidity. Whilst a reduction in
194 pollutants from external sources such as PM_{2.5} which has known negative health impacts is
195 noted [5], an increase in exposure to indoor sourced pollutants such as PM_{2.5}, volatile organic
196 compounds (VOCs) and environmental tobacco smoke (ETS) may occur [5, 25, 26] There is
197 also emerging evidence for a population-wide increase in cancer risk from increased exposure
198 to radon indoors (an airborne pollutant known to be carcinogenic [13, 27]).

199 These relationships between increasing airtightness and human and environmental wellbeing
200 are summarised in Table 3; which demonstrates the method used to map the pathways
201 described between interventions and individual unintended consequences.

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215 **Table 3** Examples of unintended consequences arising from the application of energy efficiency measures; airtightness

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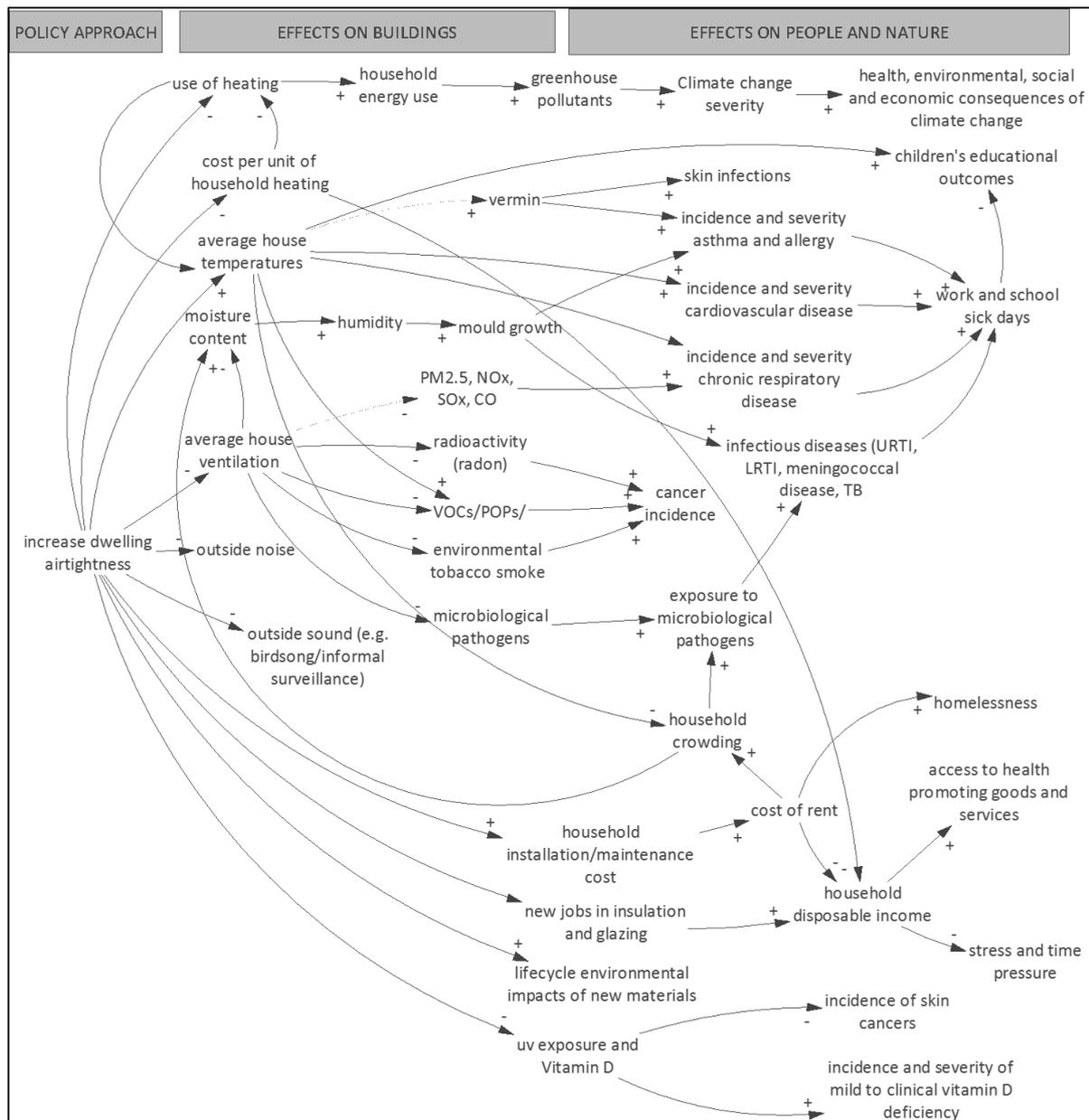
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A	B	C	D	E	F	G	H
No	Policy Impact on Buildings			Impacts on People/ Nature		+/-	Reference
				Unintended Consequence	Domain		
1	Airtightness		Quieter Environment	Peace/Wellbeing / Security	Mental Health Psychological Well Being	+	14, 15 D,E,F
2	Airtightness		Quieter Environment	Isolation/ Disconnection	Mental Health Psychological Well Being	-	18 D,E,F
3	Airtightness		Quieter Environment	Anxiety: real and perceived threats	Psychological Well Being	-	18 D,E,F
4	Airtightness		Quieter Environment	Reduction in Noise	Mental Health	+	15, 17 D,E,F
5	Airtightness		Quieter Environment	Absence of sound	Mental Health	-	15, 17 D,E,F
6	Airtightness		Quieter Environment	Improvements in physical health; social, emotional, and behavioural outcomes	Child Development	+	16 D,E,F
7	Airtightness	Lower air change rate	Increased RH Timber decay	Increase in HDM and mould, severity of asthma and allergies.	Physical Health	-	21,22 B,C,D,E,F
8	Airtightness	Lower air change rate	Increased RH Clothes drying issues	Increase in and exposure to microbiological pathogens. And infectious diseases	Physical Health	-	22, 23 B,C,D,E,F
9	Airtightness	Lower air change rate	Drying out times (wet trades) Increased RH	Mould-microbiological growth	Physical Health	-	24 B,C,D,E,F
10	Airtightness	Lower air change rate	Changes in indoor air quality (IQA)	Increased exposure to indoor sourced pollutants. Decrease in external sourced pollutants (e.g. PM _{2.5}).	Physical Health	+/-	5, 25, 26 B,C,D,E,F
11	Airtightness	Additionally More water tight	Prevention of impacts from excess rainfall	Mitigation benefits, less water damage, mould risk	Physical Health	+	20 B,C,D,E,F

218 As illustrated in Table 3, some interventions have a cascade of consequences from their direct
219 effects on the building to effects on human wellbeing and the environment (nature). Columns
220 B-D represents the flow of impacts caused by the application of airtightness policy on
221 buildings. The resulting unintended consequences are seen in columns E and the domain
222 affected in column F. Column G shows the direction of the impact; whether positive, negative
223 or both. Column H shows the literature source and whether this refers to the whole flow or an
224 aspect of it by indicating the columns to which the literature source refers.

225 A full version of this table with all the unintended consequences described in the included
226 studies and additional references used are available at [http://bit.ly/HEW-100-unintended-](http://bit.ly/HEW-100-unintended-consequences)
227 [consequences](http://bit.ly/HEW-100-unintended-consequences).

228
229 A more complete consideration of the complex inter-relationship between airtightness and its
230 unintended consequences is shown in Figure 2, illustrating the limitations of considering each
231 impact pathway in isolation. The level of complexity seen raises a number of issues which are
232 dealt with under the *Summary of impacts* and *Discussion* sections below.



233
 234 **Figure 2** The complex links arising from the policy of promoting airtightness in the domestic
 235 stock and the impact on buildings, people and the wider environment.
 236

237 *Impacts associated with purpose provided ventilation*

238 A key approach to dealing with the potential negative impacts of increasing the airtightness of
 239 dwellings is to accompany these interventions with purpose provided ventilation systems.
 240 However, a number of modelling studies reported that the addition of purpose provided
 241 ventilation to airtightness had its own wide ranging effects. Generally, a reduction in most
 242 indoor sourced airborne pollutants (mould, PM_{2.5} and environmental tobacco smoke (ETS))
 243 was reported, which yielded health benefits [5, 26, 28]. However, in practice many ventilation

244 systems do not perform to their designed standards, with poor installation and maintenance
245 cited as reasons for further reductions in capacity [29]. Increased ventilation without heat
246 recovery could lead to energy efficiency gains being offset by ventilation heat losses with GHG
247 emission increased or remaining unchanged and increased fuel bills, especially so if systems
248 are not understood by end users [30, 31].

249 In addition, increases in outdoor sourced pollutants could occur if systems are not filtered or are
250 not working correctly [26]. The application of Mechanical Ventilation with Heat Recovery
251 (MVHR) systems with filters, although proposed as a solution to these problems also has
252 reported impacts, for example disturbed sleep resulting in systems being switched off [32].
253 Poor installation and lack of maintenance of MVHR systems has also been linked to increases
254 in indoor pollution and microbiological growth [32, 33] and failure to achieve the energy
255 savings anticipated from design data. On the other hand, studies have demonstrated that
256 correctly functioning systems provide good air exchange and a quieter environment resulting in
257 a reduction in household accidents and a general increase in mental alertness [34]. However,
258 current MVHR systems may not be appropriate for the majority of existing properties requiring
259 retrofitting due to the extensive duct work required [35].

260

261 *Insulation and the consequences of higher indoor temperatures*

262 The assumption of reduced energy demand as a result of better insulated buildings will be
263 affected by, for example, comfort take-back thereby potentially undermining policy objectives
264 [7, 36, 37].

265 Warmer environments and higher average indoor temperatures resulting from insulation can
266 have a range of positive and negative impacts across a range of domains. The potential benefits
267 of warmer indoor winter temperatures are well described [25]. Much attention in the literature
268 has been given to the potential reduction in winter mortality [36, 38]; but more recent research
269 has highlighted the potential for summer time overheating, especially in the context of expected

270 future climate change coupled with increases in urban heat island effects [6,39,40]. Top floor
271 apartments appear to be particularly at risk [6]. An emerging consequence of overheating is the
272 risk of legal action by residents if homes become uninhabitable due to poor design or lack of
273 adaptation to a warming climate [41]. Higher indoor temperatures can also lead to changes in
274 indoor air quality through an increase in concentrations of indoor sourced pollutants;
275 specifically volatile organic compounds (VOCs) and a balance needs to be struck between
276 airtightness to prevent ventilation heat loss for GHG reduction policies and the need for a
277 healthy air change rate [5, 26, 28]. Warmer environments could give greater room availability
278 resulting in changes in occupant patterns and family dynamics and shifts in home/work
279 relationships and the concept of home which could be either positive or negative [14, 15].
280 Increased time spent in a more pleasant indoor environment might lead to sedentary behaviour
281 and weight gain [42, 43] and a possible reduction in social cohesion. Alternatively, it was noted
282 that warmer environments led to a reduced cold induced 'comfort' food intake, a reduced level
283 of energy required to maintain body temperature and an increase in the frequency of eating
284 breakfast at home [44]. Infant weight gain and developmental status has been shown to be
285 improved by higher temperatures [45]. Increases in the severity of skin infections and reaction
286 to allergens may occur with increases in temperature [22], as well as the attraction of pests and
287 vermin, spreading disease [46]. Conversely, an increase in immunity and decreases in
288 multiplication of common colds, less time off work and higher productivity are seen with
289 higher indoor temperatures and greater mobility/dexterity for arthritis sufferers [47, 48] and
290 reductions in high blood pressure [49]. Reductions in injuries in the elderly or infirm resulting
291 in reduced hospital admissions have also been reported [47]. Increases in bedroom
292 temperatures are linked to improved mental health across life time [50] and an improvement
293 specifically in adolescent mental health [51, 52].

294 If cost savings are made as predicted under the Green deal, possible outcomes include
295 increased financial control and reduced stress, which was considered the most important mental
296 health benefit under the Warm Front Scheme [53]. Other consequences relate to the use of any
297 savings. For instance, extra disposable income may be used to purchase quality food increasing
298 micronutrient levels [44]. On the other hand, increased consumption of ‘goods’, while possibly
299 providing economic benefits, could increase carbon emissions in other sectors such as
300 agriculture or manufacturing, undermining GHG reduction targets [54].

301
302 For more traditional structures, the introduction of internal insulation to achieve the low U-
303 values specified ($0.3 \text{ W/m}^2\text{K}$); in the building regulations; is likely to lead to an increased risk
304 of moisture build up and fabric damage in areas of driven rain and exposed masonry; also
305 specific risks of thermal bridging and mould on reveals and party walls [11]. Currently it is
306 perceived that an over estimation of the U-values of solid walls is occurring, resulting in over-
307 engineered/non-optimal applications (see BR443; EN ISO 6946, 1997). This is in part due to a
308 lack of in-situ U-values for traditional wall construction prompting the need for alterations to
309 BR443 and RD299v 9.91 Appendix S, 2012 in order to provide better modelling conventions.
310 A disconnection exists between best research and current guidance leading to inappropriate
311 material specification and/or application; or almost complete lack of available data/research
312 e.g. thermal bridging/thermal mass [11], heat loss via pre-1919 floors [55] and ventilation heat
313 loss [56].

314 In historic buildings the current use of BS5250, 2011 for moisture risk; the “Glaser method”,
315 makes no allowance for hygroscopic sorption, liquid transport or rain [57]. Increases in
316 moisture ingress and differing coefficients of thermal expansion produced in building elements
317 have been reported leading to thermal cracking [11] and possible loss of envelope integrity
318 resulting in ventilation heat losses. Moisture ingress and movement within the structure leading

319 to interstitial condensation and mould/microbiological growth has also been reported [21] and
320 could exacerbate the severity of asthma and allergies [22]. Furthermore, any refurbishment
321 would require further resources (with additional carbon emissions) to repair subsequent
322 damage.

323 Similar problems have been noted with external wall insulation (EWI) systems [58] with
324 inappropriate survey practices leading to poor design/application and subsequent thermal
325 bridging noted [59]. EWI is also associated in the literature with damage to, and loss of, the
326 appearance of our cultural heritage [60]. High relative humidity (RH) and mould have been
327 reported where the underfloor space is thermally sealed from the dwelling with the possible
328 ultimate danger of collapse of structural elements in this ‘unseen’ area [61]. The current lack of
329 consistency in planning policies for historic buildings where energy efficiency is the main
330 driver of change, could lead to the inappropriate application of these measures and damage to
331 heritage assets resulting in disconnection from our sense of history and affecting psychological
332 wellbeing [60,62].

333

334

335

336 *Impacts associated with current models of funding and implementation of policies*

337

338 Implementation mechanisms and funding strategies influence the success of any policy.

339 Effective marketing, the current economic uncertainty and loans offered at higher interest rates
340 than could be obtained elsewhere, are all issues that influence the success of policies to
341 improve the energy efficiency of housing. Current cash back schemes offered as a means to
342 encourage take up of energy efficiency products are very limited when perhaps a subsidy on
343 base material cost would be more effective [63]. It would appear there is a reliance on
344 voluntary public engagement ‘altruism’ which could lead to an increase in fuel poverty and the
345 gap between the better-off and poor, with the neediest not benefiting from the policy [7, 54]. If
346 this is not addressed, policy failure might ultimately result in failure to curb GHG emissions

347 from much of the existing housing stock [64]. The scope of finance offered is limited with
348 necessary façade and fabric repairs currently excluded from the scheme [11]. Damage to fabric
349 and contents may occur if such a scheme is implemented as it stands, leading to possible failure
350 to achieve the energy savings expected and possible issues with moisture ingress and health
351 impacts [7, 12]. Additional costs needed may cause delays or a decision not to proceed with a
352 scheme.

353 Holistic policies which tackle the issues of ventilation, indoor air quality (IAQ) and behaviour
354 could help avoid multiple negative consequences from airborne pollutants [26, 54] and impacts
355 such as mould on building elements and contents [65]. Schemes can have on-costs such as
356 increased installation/maintenance costs, reducing disposable income and creating stress. In
357 extreme circumstances this could lead to a “heat or eat” situation and a social determination of
358 comfort [11, 38]. With current housing shortages, upgrades of dwellings in the rented sector
359 could see increases in rents possibly resulting in overcrowding and increased exposure to
360 pathogens and infectious diseases and could impact social cohesion and mobility [66, 67]; with
361 long term effects on future socio-economic wellbeing and status [68].

362 Negative impacts on child development [16]; increase in sudden infant death syndrome (SIDS)
363 and additionally rents become untenable; a risk of an increase in homelessness [69].

364 Should public uptake of schemes driven by energy efficiency policies prove successful, there
365 are clear economic benefits led by the need for new designs, equipment, materials and
366 specification with resulting economic growth, potential growth of UK based manufacturers,
367 supply chains, specialist designers, contractors and general employment [4]. However, as
368 previously discussed, it is essential that this growth is sustainable and does not simply add to
369 the carbon burden [70]. There is the opportunity for increasing the skill set of the current
370 construction work force to ensure buildings reach specification[71, 72] and increase partnership
371 working [73,74] improving business prospects nationally and abroad.

372 *Summary of impacts*

373 A summary of the downstream impacts on domestic properties caused by the application of the
 374 various energy efficiency measures investigated are shown in Table 4. In addition the directions
 375 of the unintended consequences as seen in the literature search are shown. As previously noted
 376 this has been adapted from the framework in order to clarify specific impacts on domestic
 377 properties.

378
 379 **Table 4** Downstream impacts on buildings related to the application of the investigated energy
 380 efficiency measures and their direction of influence
 381

Downstream impacts on buildings	Direction of influence			Totals
	+ve	-ve	+/-ve	
Noise levels	4	4	2	10
Air change rates/Indoor air quality	9	6	9	24
Indoor temperatures	18	13	4	35
UVB, UV and UVA reception	2	9		11
Energy use		4	8	12
Fabric/Structural components	2	25		27
Totals	35	61	23	119

386
 387 A summary of the total impacted domains discovered are shown in Table 5, which illustrates
 388 how unintended consequences translate into impacts that affect people, buildings, society and
 389 the environment, with many single consequences impacting multiple domains.

390 **Table 5** Domains of impact and their direction of influence
 391

Domain	Direction of influence			Totals
	+ve	-ve	+/-ve	
Physical health	16	47	13	76
Mental health	4	4		8
Psychological wellbeing	9	5	2	16
Child development	1	1		2
Social cohesion		3		3
Social inequalities		1		1
Social mobility		2		2
Occupant behaviour		1	2	3
Household finances		2	1	3
General economic	9	1	2	20
Building fabric	1	17	2	20
Legal		3		3
Environmental	7	31	9	47
Totals	47	118	31	196

398 It should be noted that the totals seen in Tables 4 and 5 demonstrate where the attention of
399 previous research has focused, rather than necessarily the relative importance of a particular
400 influence on unintended consequences. Tables 3-5 highlight the individual routes to
401 consequences for clarity and in order to achieve the objective of this study in scoping the range
402 and domains impacted by policies to apply energy efficiency measures to the domestic stock.
403 However, this method, although useful, hides the complexity and interconnections that exist
404 between the different domains. Using the example of increased dwelling airtightness seen in
405 Table 2, Figure 2 shows that when taken together, the linkages identified in the literature form
406 complex and dynamic inter-relationships between the individual components.

407 **Discussion**

408 We have undertaken a scoping, cross-disciplinary literature review to identify, enumerate and
409 characterise what is already known about the unintended consequences of current interventions
410 to reduce GHG emissions from the UK housing stock. Guided by a holistic framework for
411 potential impacts we found more than one hundred consequences across a range of domains of
412 human wellbeing, including physical, mental, social, environmental and economic wellbeing.

413
414 For the examples we have outlined in detail, there are some individual solutions suggested in
415 the literature. For example, in response to growing understanding of the risk of overheating,
416 several authors have recommended specific solutions: a more flexible approach to design;
417 increasing the thermal mass of buildings and providing reflective roofs [39, 40]. In addition,
418 some argue that the risks of overheating may also be reduced by increasing the availability of
419 air conditioning. However, this would lead to additional GHG emissions undermining any
420 energy efficiency gains achieved through insulation [11]. In contrast to these single focus

421 solutions, which are likely to have further unintended consequences, we have demonstrated
422 with our investigation of airtightness that when taken together, the linkages identified in the
423 literature form complex inter-relationships between various domains, suggesting that more
424 holistic, multi-disciplinary approaches are needed to formulating and implementing policies
425 about housing.

426
427 The study of unintended consequences in the built environment, and indeed in other areas of
428 society and policy, is, as yet, underdeveloped. This is the first time that a holistic attempt has
429 been made to characterise the effects of policies to reduce end-use housing energy demand. It
430 builds on previous work to integrate a range of physical and mental health impacts of policy
431 options to reduce GHG emissions of the housing sector, significantly broadening the scope of
432 impacts considered. The review is limited to an initial characterisation of consequences by the
433 broad but non-systematic approach taken. We were therefore unable to draw conclusions about
434 the size of intervention effects, or their relative importance. In addition, there are almost
435 certainly likely to be a greater range of ‘unknown’ unintended consequences, which the current
436 approach to research, is not able to reveal and requires new methodologies to enable
437 investigation.

438
439 However, some limited conclusions for policy can be drawn from the review. Possible
440 unintended consequences are related both to faulty policy formulation and to problems with
441 implementation. In complex systems such as housing, policy formulation processes that focus
442 on a single objective, while taking inadequate account for the complex and dynamic inter-
443 relationships between objectives and outcomes, are vulnerable to policy failure and negative
444 unintended consequences. On the other hand, a more integrated policy formulation process has
445 the potential to achieve co-benefits across a range of objectives. This requires a different set of

446 policy formulation methods that can bring a wide range of stakeholders together in a
447 collaborative learning process about dynamic system complexity. Furthermore, it was clear
448 from the review that choices relating to funding mechanisms for policies can either support or
449 undermine policy objectives. Incorporating considerations about funding mechanisms into
450 policy formulation could improve these choices.

451

452 **Conclusions and recommendations for further work**

453 In order to explore the issues raised here further, we argue that there is a pressing need for an
454 approach such as ‘Participatory Systems Dynamics’ (PSD) which would require the
455 involvement of multiple stakeholders from a variety of disciplines to investigate these issues
456 holistically [75, 76, 77]. By utilising the findings of this study and understanding the stocks,
457 flows, feedback and reinforcing loops occurring in the system, the use of PSD could help to
458 highlight key issues and ensure that regulatory measures are framed to achieve policy goals
459 without unduly jeopardising general health, well-being and the damage to building fabric,
460 contents and the environment that is otherwise likely to occur. To avoid policy failure and
461 possible liabilities, there is an urgent need for processes that ensure regulatory measures are
462 framed to achieve multiple realistic objectives, including those of high community priority.
463 Part of this process will be the acceptance that multiple trade-offs (for example between
464 emissions reduction and public health) will occur if the current policies are rigidly enforced as
465 they stand.

466 Furthermore, systematic reviews of the links between aspects of housing and a wide variety of
467 outcomes are also needed. Such reviews need to use a holistic framework that includes
468 potential outcomes across a range of domains, including physical, mental, social,
469 environmental and economic wellbeing.

470

471

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480
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