Enabling a just transition: A composite indicator for assessing home-heating energy-poverty risk and the impact of environmental policy measures

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A B S T R A C T

Home-heating energy-poverty risk presents both challenge and opportunity for policymakers, businesses and communities. Effective measurement and management of this risk requires an evidence base that accounts for characteristics of the householder, building, and heating system. A composite index utilising 10 indicators refined to Small Area level is created to deliver spatially refined analysis of home-heating energy-poverty risk. The index is used to assess home-heating energy-poverty risk across 18,641 Small Area clusters in Ireland. This risk index is a scalable and internationally transferrable methodology that can be extended to cover other energy uses. Importantly the index is also dynamic and offers the capacity to analyse changes in energy-poverty risk associated with specific policy intervention proposals, including major contemporary environmental policy transitions such as residential fabric retrofit, residential heating system changes, energy price changes and carbon taxation. The application of the index to the Irish case affords refined insight into the impact and incidence of various market, technology and policy driven interventions such as fuel price changes, retrofit strategies and carbon tax increases. Risk and impacts vary geographically, and this index is designed to inform targeted policy interventions to mitigate home heating energy-poverty risk and thereby support ambitions for a 'just transition'.

1. Introduction

Policy actions and interventions to reduce climate and air pollutant emissions may affect fuel prices, energy efficiency requirements and fuel choices. At a time of such substantial change it will be necessary to assess not only emission outcomes, but also the shifts in energy poverty risk associated with a given change. This is important in terms of delivering a 'just transition' as part of efforts to address global environmental and societal goals. However, this also requires tools that provide a dynamic and granular assessment of energy-poverty risk.

The definition of fuel poverty as being where a household must spend more than 10% of disposable income (Boardman, 1991) on energy costs is a simple and static method for defining an important societal issue. Whilst simple to understand, and likely a reasonable aggregate indicator of home heating energy poverty, it offers no information on the underlying reasons for expenditure representing more than 10% of disposable

income. Thus, the information provided is limited in terms of effectively guiding decisions on the most appropriate interventions to mitigate or manage that risk. A further challenge relates to measurement of home heating energy poverty in this manner at an aggregate level in broad geographic terms. Whilst Eurostat reports estimates of total household expenditure and shares of expenditure on "electricity, gas and other fuels" – this metric is aggregated at a national scale. Examining the European data for 2017, no country in the EU28 reports having an average national expenditure on "electricity, gas and other fuels" above 10%. The EU Energy Poverty Observatory[1] offers a broader range of indicators and resources related to energy poverty. However, they are individual indicators and include many blank data sets, mismatched age of indicators (e.g. 2010 and 2018) and so forth. These data gaps and issues are understandable given the constraints on resources to generate routine and detailed data for energy poverty across the region. They also highlight scope for improvement where there is a shift to a broader

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integrated composite index derived from more reliable, routine and accessible data.

Whilst it is possible to survey households and individuals to generate more refined estimations of energy poverty, such surveys are both time-consuming and costly. More importantly they normally provide a subjective assessment by the household of their own fuel-poverty risk, health characteristics and/or the energy characteristics of the home, and furthermore there are considerable challenges when seeking to elicit detailed household income and expenditure data as part of such a process.

Fizaine and Kahouli (2019) argue that, despite several studies utilising composite indices to measure energy poverty in various countries, there is still scope for advancing energy poverty measurement methodologies in order to address existing drawbacks such as the limitation on their applicability to other countries and the possibility of over-simplification associated with combining variables and their reduction into a single measure (Nussbaumer et al., 2012; Fizaine and Kahouli, 2019). Moreover, from a societal and policy perspective, energy poverty is something that is ideally considered at a fine spatial scale. Aggregate and average data may mask issues at the margin and, as such, a better method for identifying energy poverty risk is necessary to guide the policy system towards designing targeted policy instruments that result in better energy poverty outcomes.

This paper contributes to addressing these challenges by developing a dynamic and evidence-based spatial energy-poverty risk index system that can evaluate, on a fine scale basis, shifts in home heating energy poverty risk associated with specific interventions. We apply this system to an analysis of home heating energy poverty risk in Ireland. The overall objective is to provide a decision-support tool to support energy-poverty alleviation and a just transition.

The remainder of this paper is structured as follows. Section 2 discusses approaches to measuring energy poverty, with Section 3 focusing on energy policy and energy poverty in our Irish case study. Section 4 provides a rationale for the indicators selected and the methodology employed in the development of the Home Heating Energy Poverty Risk Index (HH-EPRI). Section 5 details the final outputs of the HH-EPRI and related sub-indices while also highlighting the potential of the index for scenario modelling. Section 6 discusses areas for future consideration. Section 7 presents concluding thoughts.

2. Approaches to home heating energy poverty measurement

A fuel-poor household is one that cannot afford to keep a home adequately warm at a reasonable cost. The World Health Organisation (2007) defines an adequate standard of warmth as 21 °C in the living area and 18 °C in other occupied rooms. Whilst energy poverty is often seen to be caused by low household income, poor energy efficiency of dwellings, and high energy prices, there is no consensus on the definition, nor the measurement, of energy poverty among the increasing number of researchers in the field. Various indicators have been suggested in the energy poverty literature (Boardman, 1991; Healy and Clinch, 2002; Fabbri, 2015; Nussbaumer et al., 2012; Thomson and Snell, 2013; Hills, 2011, 2012). The approaches for measurement of energy poverty can be classified into three categories (Fizaine and Kahouli, 2019):

2.1. Objective approach

The indicators under the objective approach are based on measurable and observable criteria. The income/expenditure-based indicators, which have commonly been used in the energy poverty studies, are the main examples of the objective approach. Building upon the economic theories that explain consumption, this approach looks at the relationship between household income and domestic energy expenditures and often identifies a threshold beyond which a household is considered energy poor. The most prominent example of these indicators is the 10%

indicator, where a household is deemed fuel-poor if it spends more than 10% of its disposable income on energy to maintain an adequate level of warmth inside the dwelling. Despite its widespread application, this indicator has been criticised by many researchers for its drawbacks. The 10% lacks a theoretical foundation and was initially calculated by doubling the median energy expenditures based on the 1988 Family Expenditure Survey for UK households (Boardman, 2012). More importantly, it does not take into account restricted expenditures, heating restriction practices, nor the income level of affluent households. Another example of these indicators is the Low Income High Cost (LIHC) indicator suggested by Hills (2012). The LIHC indicator uses a combination of a national income threshold and fuel-cost threshold. Using this indicator, a household is considered energy poor, if it exceeds both thresholds. This approach has also been the subject of critique, as it is not based on the constrained income and does not take into account heating restriction behaviour practised in some households (Robinson et al., 2018; Fizaine and Kahouli, 2019). It also excludes some low-income, single person households (Middlemiss and Gillard, 2014; Walker et al., 2014).

2.2. Subjective approach

Indicators developed using the subjective approach are based on a household's self-assessment of its living conditions and circumstances. Based on survey respondent's personal opinions, interpretations, and judgments, these indicators examine whether, or not, householders feel able to afford adequate heating. In order to collect information regarding energy poverty using this approach, researchers ask households questions such as: Are you able to heat your home adequately? Have you had difficulty in paying your utility bills over the past year? Are you satisfied with your heating facilities? Some studies show that there is a considerable mismatch between the results of objective factual indicators of home-heating energy poverty with those based on subjective self-declared indicators (Hills, 2011; DETR, 2000; EPEE, 2006; Mckay, 2004; Healy, 2003). Given that the needs, preferences and circumstances of different householders can vary widely, the results of the subjective indicators should be interpreted with caution (Waddams Price et al., 2012).

2.3. Composite approach

This approach acknowledges the complex and multidimensional nature of energy poverty and, therefore, aims to move away from narrow, one-dimensional indicators by integrating a set of sub-indicators. The approach enables several indicators to be combined to create composite and easy-to-interpret metrics (Thomson and Snell, 2013). Several studies have utilised composite indices to measure energy poverty in various countries (Fabbri, 2015; Thomson and Snell, 2013; Charlier and Legendre, 2016; Okushima, 2017; Berry et al., 2016; Walker et al., 2013). Walker et al. (2012) suggested a Small Area energy poverty risk index for Northern Ireland using a composite approach. This index consists of three main categories of indicators, namely, built environment vulnerability (20%), heating burden (40%), and social vulnerability (40%). Heating burden comprises two elements: the heating demand associated with the outdoor temperature and the costs of heating oil. Dwelling size (floorspace) is used as a proxy for energy efficiency concerning built environment vulnerability. Social vulnerability includes several social and dwelling characteristics, such as the percentage of families with children and disabled populations that live in a Small Area. Charlier and Legendre (2016) work is another example of a composite index approach and comprises three main elements: disposable income to account for monetary constraints, energy consumption as a measure of energy efficiency, and indoor temperature to capture heating restrictions.

Fizaine and Kahouli (2019) and Nussbaumer et al. (2012), argue that, despite a considerable number of composite measures being

presented, there is still scope for advancing energy-poverty measurement methodologies to address their drawbacks such as their lack of applicability to multiple nations and the over-simplification associated with combining variables into a single measure.

3. Policy context

In order to demonstrate the application of the Home Heating Energy Poverty Risk Index (HH-EPRI), we take an Irish case study. Nearly two decades ago, energy poverty in homes in Ireland was first acknowledged by the academic community as a significant policy challenge in terms of environmental impacts, health outcomes and thermal comfort standards (Clinch and Healy, 2000a, 2000b, 2000c, 2003). In the last decade, policymakers have begun to consider the energy poverty challenge motivated, in particular, by the impact of rising energy costs coinciding with the 2008–10 recession. This led to the publication of two key strategy documents related to affordable energy and energy poverty. Published in 2011, Warmer Homes: A Strategy for Affordable Energy in Ireland (DCNER, 2011) represented Ireland's first affordable energy strategy. Its central concern was the affordability of energy for low-income households. Currently Ireland's households are defined by the Government as energy poor if more than 10% of their disposable income is spent on energy costs. However, the report highlighted issues relating to that measurement methodology and recommended an improved methodology be developed. This recommendation was repeated in the new Strategy to Combat Energy Poverty in Ireland (DCCAE, 2016) released in February 2016. The delay in generating a new methodology was blamed on using limited resources for programme delivery rather than developing new methodologies. However, despite this acknowledgement Ireland continues to use the income-based method.

Ireland is currently embarking on an "energy transition" (DDCAE, 2015; Halligan and Lawlor, 2018). In 2018 the Government outlined its commitment to transition Ireland to a low-carbon and climate-resilient society through Project Ireland 2040 which comprised a New National Planning Framework and National Development Plan 2018–2027. €21.8 billion funding has been committed (€7.6 billion Exchequer/€14.2 billion non-Exchequer) to achieve this with some of the measures proposed including investment in energy efficiency such as retrofitting homes, increasing the number of electric vehicles on the road and phasing out oil exploration and the use of coal and peat. In 2019, the Irish Government published its Climate Action Plan (CAP) (DCCAE, 2019; JCCA, 2019). The CAP outlined a series of cross-sectoral measures to reduce Ireland's carbon emissions by 30% (relative to 2005 levels) by 2030 in line with European Climate commitments. The CAP will have wide ranging implications for the power and residential sector including a rise in the national carbon tax, increased reliance on renewable energy for 70% of electricity by 2030, the retrofitting of 500,000 homes to a B2 building energy rating[2] (BER), and the retrofit installation of 400,000 heat pumps.

These environmental and energy related goals will necessitate dramatic change in technologies, legislation, policies and behaviour. In the built environment sector, there are many examples of where such policies may have an impact on energy poverty risk. Proposed increases in the Irish carbon tax, for example, will affect the cost of heating a home with fossil fuels, with the overall cost influenced by the specific fuel type, the heating system efficiency, and householder characteristics. On the demand-side, such an intervention could be expected to increase home heating energy poverty risk if introduced without poverty proofing measures. On the supply-side, a state led support scheme to retrofit social housing would improve the energy performance of those buildings, and this improved efficiency should reduce heating-related energy poverty risk in those homes.

Ireland's is not an isolated case. Across the globe, policymakers are faced with difficult choices when implementing instruments to address the challenge of climate change and improving air quality. Such instruments can cause shifts in energy poverty risk and it is crucial that tools are available to provide an assessment of energy-poverty risk and an indication of the likely impact of such policy measures on that risk.

4. Methodology – Home heating energy poverty risk index – Evidence base

The complex composition of energy poverty presents a challenge to the formation of a single internationally accepted metric. However, a wide range of proxy indicators have been used in previous studies to assess and monitor energy poverty (Healy and Clinch, 2004; Pye et al., 2015; Herrero, 2017; Fizaine and Kahouli, 2019). When employed cumulatively, and appropriately, these indicators are useful for analysis. However, they require careful selection and structure based on relevance and measurability while also reflecting the multi-dimensional nature of energy poverty (Nussbaumer et al., 2012; Pye et al., 2015). Furthermore, any energy poverty index is likely to be constrained by limited data sources (Nussbaumer et al., 2012; Jones and Kammen, 2014; Min et al., 2010).

Our HH-EPRI, as applied to the Irish case, combines a set of proxy indicators of home heating energy poverty, based on both relevant literature and publicly available Irish datasets, including 2016 Census data and the Building Energy Rating (BER) database. Similar data sets are available across EU Member States and in most developed countries. The Index builds upon similar research undertaken in Northern Ireland (Walker et al., 2012) and represents the creation of a uniform measure of home-heating energy poverty that can provide a consistent way of assessing and comparing energy-poverty risk at a fine scale to examine a variety of dynamic drivers of change. The analysis was undertaken using GIS software at Small Area (SA) level. In total, there are 18,641 SAs in Ireland each containing, on average, 80 to 120 households.

The HH-EPRI is comprised of 10 indicators which, together, inform three weighted categories related to:

1. Heating requirements of the building;
2. The building's physical characteristics;
3. Householder characteristics.

Due to the necessarily arbitrary nature of weight assignment (Nussbaumer et al., 2012; Fizaine and Kahouli, 2019), reaching a consensus on the relative importance of our 10 indicators and 3 categories proved challenging. Indeed, the indicator selection process, even without weightings, is a value judgment based on available and relevant evidence (Nussbaumer et al., 2012). However, in the case of home heating energy poverty in Ireland there is convincing evidence to indicate that not all indicators are of equal importance (Healy and Clinch, 2004; Scott et al., 2008; Watson and Maitre, 2015). For instance, Walker et al., (2012) and Walker et al., (2013) consider 'oil price' and 'heating demand' as more important indicators in determining energy poverty vulnerability, compared to other indicators such as the energy efficiency of buildings or the socio-economic characteristics of households.

As indicated in Section 3, Ireland is currently undergoing an energy transition with the expected introduction of a range of interventions that may affect current and future levels of energy poverty. The HH-EPRI developed in this paper aims to offer the capacity to model the impact on energy poverty rates at both national and local level of changes to heating technology, heating efficiency, fuel price, and housing efficiency. The HH-EPRI is thereby designed to facilitate the exploration of how specific changes in particular variables will affect energy-poverty risk rates. For example, if the energy efficiency of homes in a small town is improved a number of grades on the building energy rating scale, how does this intervention affect energy demand and associated energy poverty risk? Conversely if the price of a selected fuel increases

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[2] https://www.seai.ie/home-energy/building-energy-rating-ber/.

Table 1

Energy poverty risk categories and indicators.

Categories	Indicators	Data Source[a]	Weighting	
Heating Requirements	Heating system (Type of fuel)/ Fuel cost	Domestic Fuels Comparison of Energy Costs – (SEAI) Census 2016 Theme 6 Table 5 Permanent Private Households by Central Heating Type (CSO)	15%	40%
	Domestic energy efficiency	Building Energy Rating Certificate (BER) Dataset (SEAI)	20%	
	Temperature	Temperature data from Met Éireann	5%	
Building characteristics	Number of rooms	Census 2016 – Theme 6 – permanent private households by number of rooms (CSO)	10%	20%
	Year built	Census 2016 – Theme 6 – permanent private households by year built (CSO)	10%	
Householder characteristics	Tenure status	Source 2016 Census Theme 6 Housing – Permanent private households by type of occupancy (CSO)	7.5%	40%
	Age dependency	Census 2016 Theme 1 Population aged 0–19 by sex and year of age, aged 20 and over by sex and age group (CSO)	5%	
	Employment status	Census 2016 Theme 8: Principal Status - Population aged 15 years and over by principal economic status and sex (CSO)	10%	
	Lone Parent	Census 2016 Theme 5: Private households by type Table 1 (CSO)	7.5%	
	Social Class	Census 2016 – Theme 9 - Persons in private households by socio-economic group of reference person (CSO)	10%	
Overall Energy Poverty Risk Index			100%	

[a] Data Sources: SEAI - Sustainable Energy Authority of Ireland: Domestic Fuels Comparison of Energy Costshttps://www.seai.ie/publications/Domestic-Fuel-Cost-Comparison.pdf; Building Energy Rating (BER) Data: http://maps.seai.ie/giswiki/maps/heat-map/domestic-sector-datasets/CSO – Central Statistics Office:Census 2016: https://www.cso.ie/en/census/census2016reports/census2016smallareapopulationstatistics/.

Table 2

Energy Poverty Risk Index Nine Categories of Risk according to index score range.

Category		Value Range
Highest Risk (Reds)		
1.	Higher Red (this is highest risk category)	6.45–6.90
2.	Medium Red	5.90–6.44
3.	Lower Red	5.35–5.89
Median Risk (Blue)		
1.	Higher Blue	4.80–5.34
2.	Medium Blue	4.25–4.79
3.	Lower Blue	3.70–4.24
Lowest Risk (Green)		
1.	Higher Green	3.15–3.69
2.	Medium Green	2.60–3.14
3	Lower Green (this is lowest risk category)	2.05–2.59

(e.g. via an oil price or carbon tax change) how does this affect energy poverty risk? The overall HH-EPRI, and the publicly available variables included within it, has been structured in a manner that can accommodate such recalibration and analysis to provide a useful decision support tool for policy. The following section provides an overview of the three weighted categories and the 10 indicators within them (Table 1).

4.1. Category 1: Heating requirements

The heating requirements of a household have a major influence on energy poverty risk. Three key indicators were selected for use in our HH-EPRI: the cost of heating the building (Healy and Clinch, 2002; Charlier and Legendre, 2016; Liddell et al., 2011; Walker et al., 2013); the energy efficiency of the building (Healy and Clinch, 2002; Thomson, and Snell, 2013; Charlier and Legendre, 2016; Walker et al 2012, 2013); and the heating demand of the building due to ambient outside temperature (Morris and Liddell, 2011; Barry and Chorley, 2001; Walker et al., 2012).

A key issue is how changes in fuel prices over time may impact upon risk of energy poverty in different types of households (Fahmy et al., 2011; Morris, 2007; Oreszczyn et al., 2006). Price changes can be affected by factors such as levels of taxation, supply costs and whether prices are regulated. The fuel type and fuel cost of a dwelling were calculated using Census 2016 data and Sustainable Energy Authority of Ireland (SEAI) domestic fuel price comparison sheets. An average fuel

cost value was calculated for each SA based on the total number of houses using a particular fuel for their central heating system (obtained from Census, 2016 data) and the average delivered cost of that fuel type in c/kwh (obtained from SEAI domestic fuel price comparison). Seasonal efficiency ratings were also factored into the calculation. The average fuel cost ranged from a minimum of 9.02c/kwh to a maximum of 18.02c/kwh 2. An Index Risk value between 1 and 10 was attributed to each SA based on its Average Delivered Energy Cost ranging from 1 (Lowest "Fuel Cost" Decile: 9.02c/kwh-9.92c/kwh) to 10 (Highest "Fuel Cost" Decile: 17.12c/kwh – 18.02c/kwh).

Housing stock in Ireland is given a Building Energy Rating (BER) Assessment to review its energy performance. A Building Energy Rating (BER) certificate measures the efficiency of a dwelling by calculating the CO_2 emissions and KWh/m2/yr of the property. The BER label has a scale of A - G, with A-rated buildings the most energy efficient (lowest BER score <50) and G the least energy efficient (highest BER score >450). A BER geocoded dataset containing an average BER Score for each SA level was released for the first time in October 2019. However, this new dataset contains geocoded information on only 33% of the total Irish residential stock. Therefore, the number of surveyed dwellings within some SAs was a relatively small proportion of the total or in some cases none at all. For the purpose of this research an arbitrary threshold of at least 20% of all dwellings in each SA being BER registered was applied.

Prior to the release of this dataset original BER data included only county level geographic information on the location of the dwellings. To derive SA level spatial distribution of residential BERs, we previously linked census data from individual households with BER profiles of dwellings built, based on the characteristics of houses such as counties, dwelling types, fuel types, and years of construction (Kelly et al., 2016; Fu et al., 2014). The outputs of this methodology show a strong correlation[3] with the new dataset, and so this prior method was used to calculate an average BER rating for those SAs falling below the 20% threshold level. An Index Risk value between 1 and 10 was assigned to each SA based on its average BER score ranging from 1 (Lowest "BER Score" Risk: 0–50) to 10 (Highest "BER Score" Risk: 450+).

The external annual average ambient temperature provides an indication of the home heating requirements to maintain an indoor temperature of 21 °C in the living area and 18 °C in other occupied

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[3] The two BER datasets are highly correlated, with a spearman rank correlation coefficient of 0.827 at the 1% level of significance.

HH EPRI - Building Characteristics Index
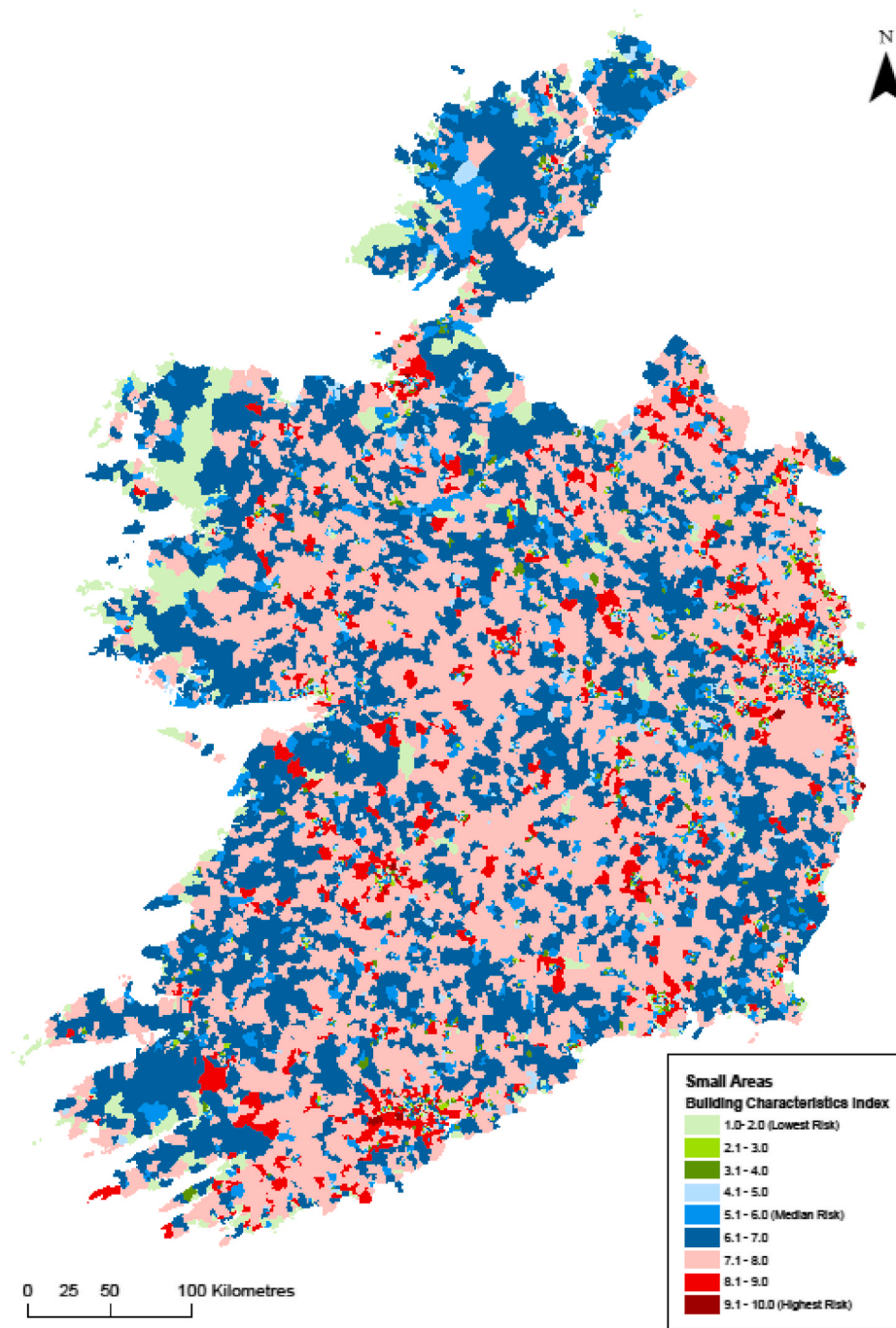
Map 1. Building characteristics index category.

rooms (WHO, 2007). The temperature distribution across Ireland was sourced from Met Éireann's temperature grids. Average temperatures from temperature grids were added to the SA data based on the closest method used in ArcGIS (Fu et al., 2014). Average Temperature per SA ranged from a minimum of 7.00 °C–11.39 °C. An Index Risk value was attributed to each SA based on its average ambient ranging from 1 (Highest "Average Temperature" Decile: 10.95 °C–11.39 °C) to 10 (Lowest "Average Temperature" Decile: 7.04 °C–7.44 °C).

4.2. Category 2: Building characteristics

Although there is a degree of overlap between them, the building

characteristics category offers information that relates more directly to the absolute size of the home, and therefore influences the scale of the heating requirements category. Two key indicators were selected for use in our HH-EPRI: Number of rooms per dwelling (Hong et al., 2006; Thomson, and Snell, 2013) and Year built (Healy and Clinch, 2004; Fabbri, 2015; Fizaine and Kahouli, 2019). When the BER ratings data eventually become more robust, the variables included in this section will no longer be required. Until then, the proxy variables included offer complementary measurement of relevant building energy characteristics and, the inherent risk of energy poverty.

All else being equal, apartments will typically have lower heat loss than detached houses. In addition, the total number of rooms in a
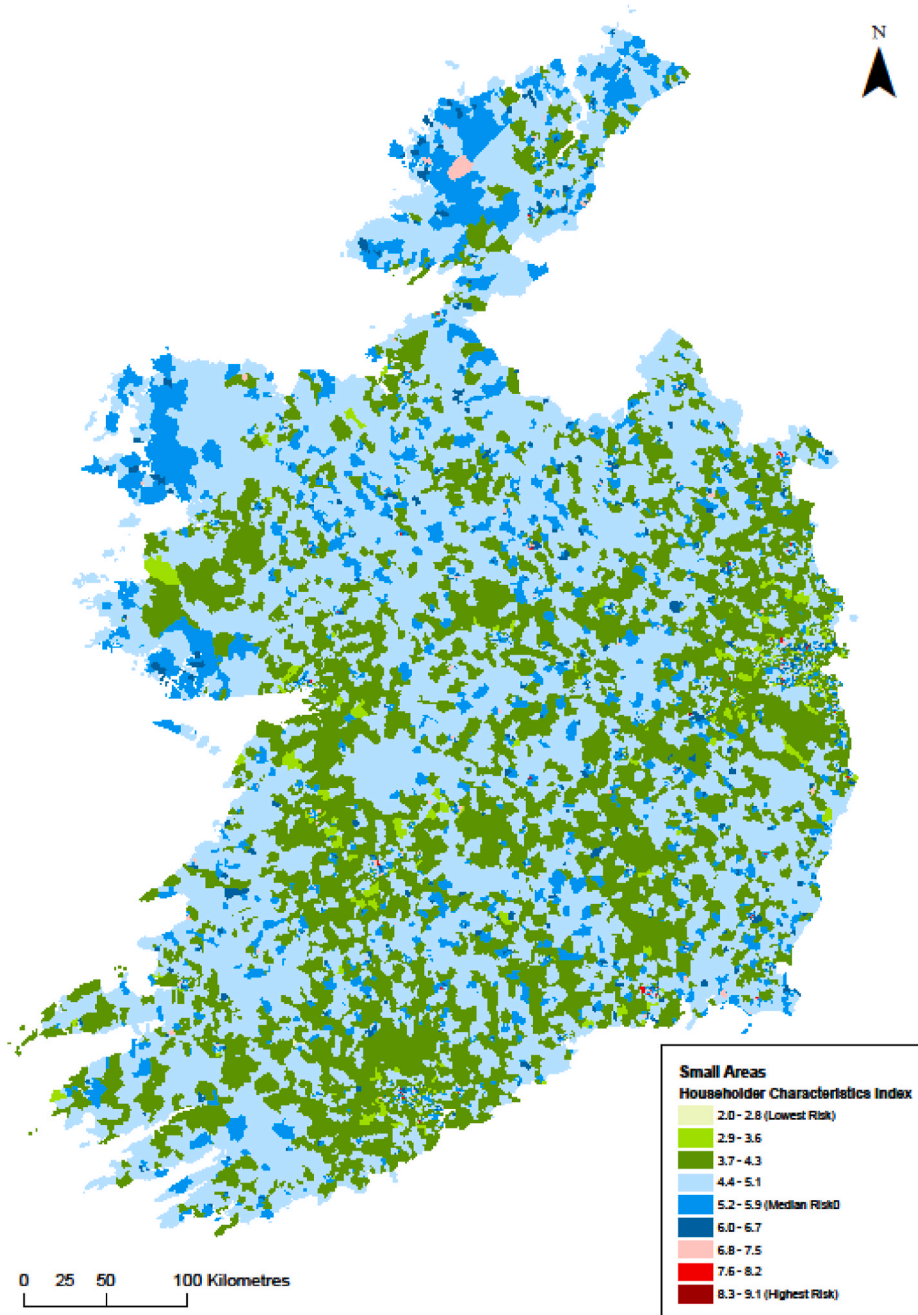
HH EPRI - Heating Requirements Index
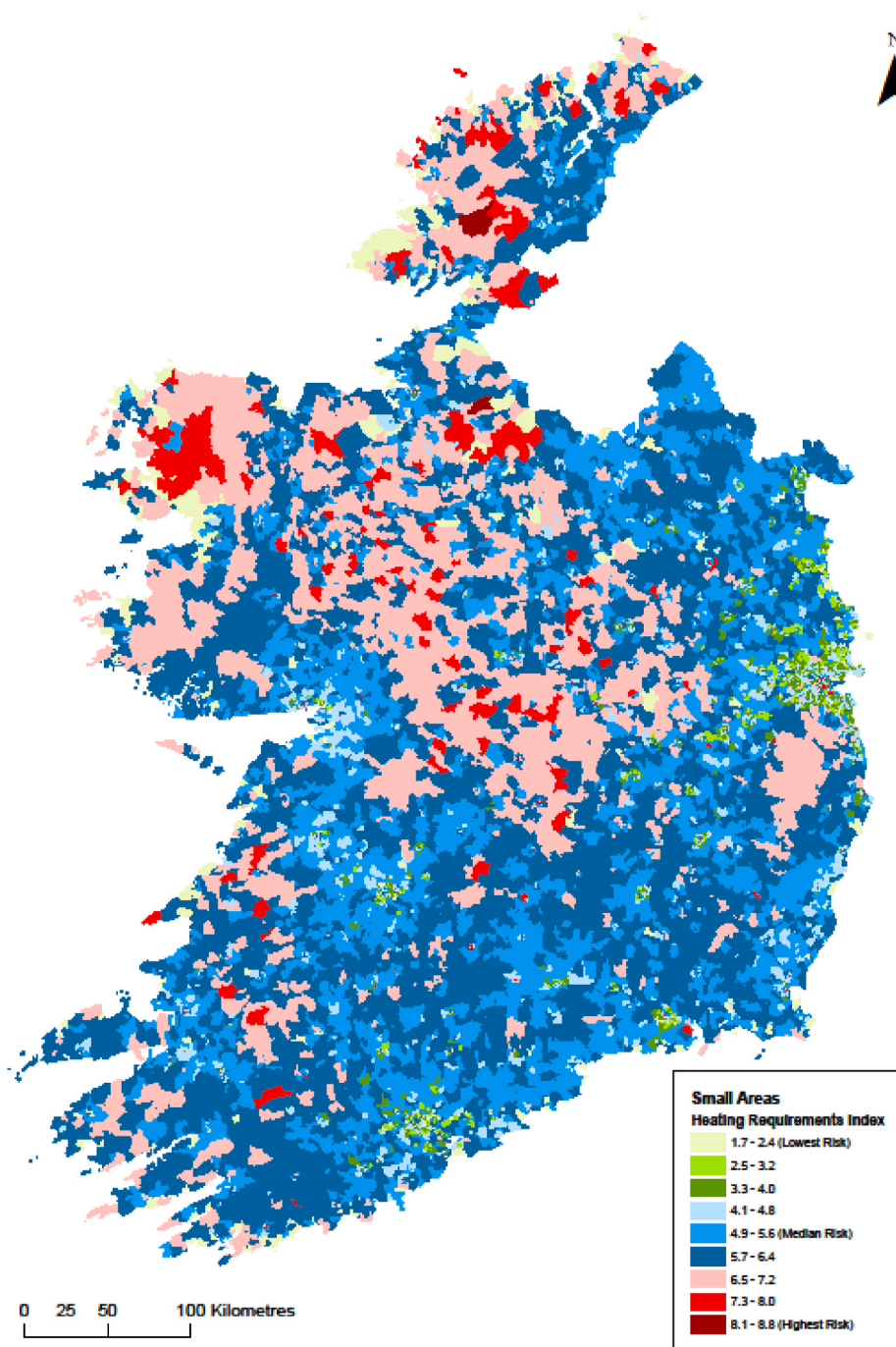
Map 2. Heating requirements index category.

dwelling requiring lighting and heating will also affect energy requirements. In Ireland the average number of rooms in a detached house is 6.3 (Census 2011). Using 2016 Census data, the percentage of homes in each SA with 6 rooms[4] or more was calculated. This ranged from a minimum of 0% to a maximum of 100%. An Index Risk was attributed to each SA ranging from 1 (Lowest "6+ Rooms per SA" Decile: 0–10%) to 10 (Highest "6+ Rooms per SA" Decile: 90%–100%).

The age of a dwelling has also been cited in numerous studies as an important home energy-poverty indicator, mainly because newer homes tend to be more energy efficient (Kavgic et al., 2010; Fracastoro and Serraino, 2011; Fabbri, 2015). The first mandatory Building Regulations in Ireland which explicitly addressed conservation of fuel and energy in buildings were issued in 1992. Again, using 2016 Census data, the percentage of homes in each SA which were built post 1991 was calculated. This ranged from a minimum of 0% to a maximum of 100%. An Index Risk value was attributed to each SA ranging from 10 (Lowest "Post, 1991 Housing" Decile: 0–10%) to 1 (Highest "Post, 1991 Housing" Decile: 90%–100%).

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[4] The Census does not count bathrooms, toilets, kitchenettes, utility rooms, consulting rooms, offices, shops, halls or landings, or rooms that can only be used for storage such as cupboards.

HH EPRI - Householder Characteristics Index

Map 3. Householder characteristics index category.

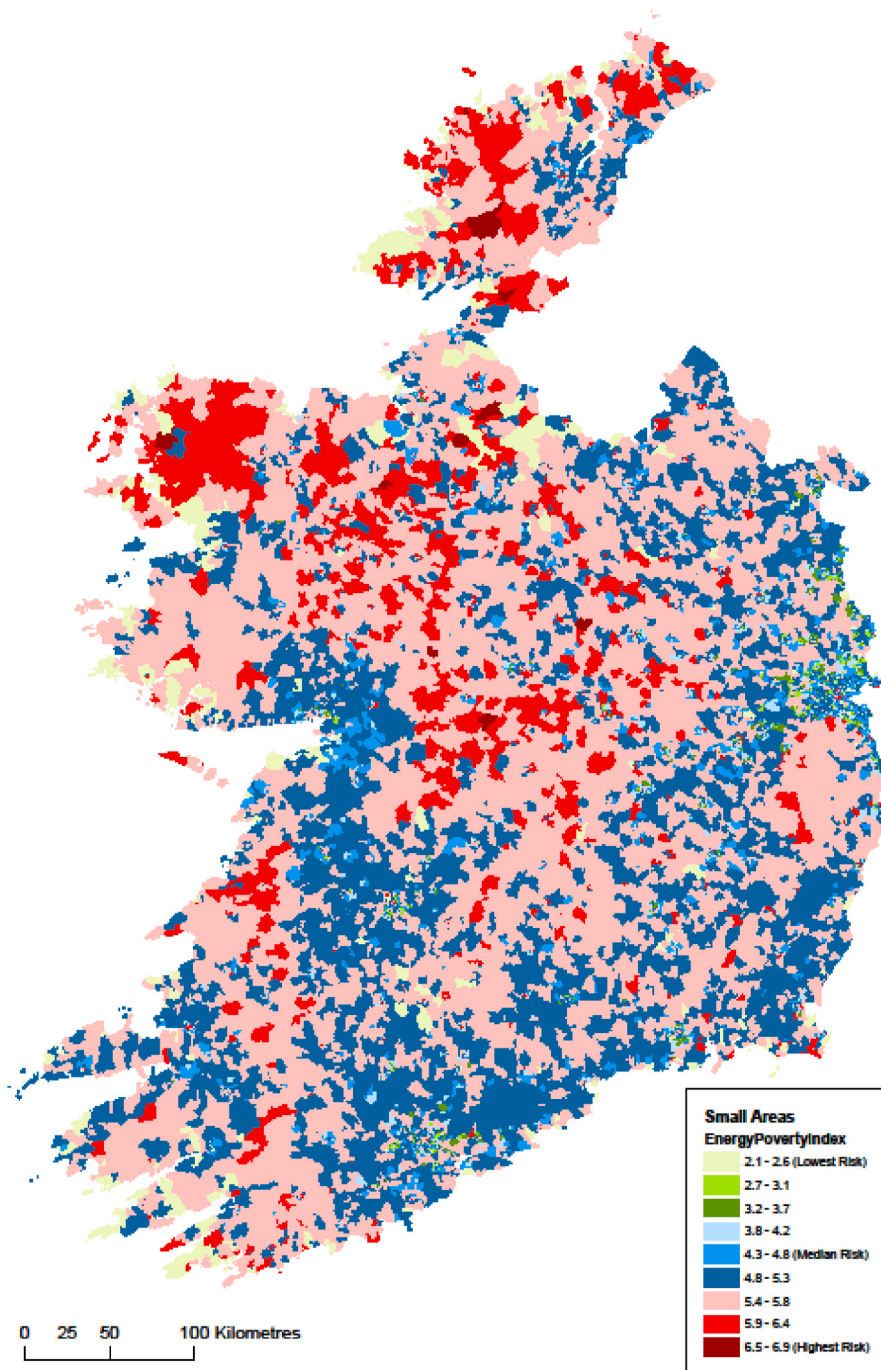## 4.3. Category 3: Householder characteristics

Tackling energy poverty requires a knowledge of householder characteristics as vulnerable households often display specific socio-demographic features (Preston et al., 2014). These features are more wide ranging than simply income (Healy and Clinch, 2002). With this in mind, five demographic ratios were calculated using Census 2016 data for each SA for use in our HH-EPRI: Tenure status (Whyley and Callender, 1997; Boardman, 2010; Thomson, and Snell, 2013); Employment status (Fabbri, 2015; Healy and Clinch, 2004; Scott, 1997; Fizaine and Kahouli, 2019); Age dependency (Fizaine and Kahouli, 2019); Single Parent Households (Healy and Clinch, 2004; Fizaine and Kahouli, 2019); and Social Class status (Fabbri, 2015; Scott, 1997; Fizaine and Kahouli,

2019).

Recent research in Ireland has shown that households living in rented accommodation experienced disproportionately higher levels of energy poverty compared to owner occupied households (De Bruin and Yakut, 2018). It was hypothesised that, all else equal, owner occupied dwellings are less likely to experience energy poverty than rental (other) dwellings. Tenure status was calculated using an Own House Ratio which shows the ratio of households who own their house compared to the total number of households. An Index Risk value was attributed to each SA ranging from 1 (Lowest "Tenure Status" Decile: 0–10%) to 10 (Highest "Tenure Status" Decile: 90%–100%). Based on the literature it was also hypothesised that people living in pensioner households or households with a large number of children are more likely to

HH EPRI - Overall Energy Poverty Risk Index

Small Areas EnergyPovertyIndex

- 2.1 - 2.6 (Lowest Risk)
- 2.7 - 3.1
- 3.2 - 3.7
- 3.8 - 4.2
- 4.3 - 4.8 (Median Risk)
- 4.8 - 5.3
- 5.4 - 5.8
- 5.9 - 6.4
- 6.5 - 6.9 (Highest Risk)

0   25   50   100 Kilometres

Map 4. Energy poverty risk index.

experience energy poverty (Healy and Clinch, 2004; Fizaine and Kahouli, 2019). An Age Dependency Ratio was calculated which shows the ratio of the number of dependents aged zero to 14 and over the age of 65 to the total population aged 15 to 64. This ranged from a minimum of 0% to a maximum of 85.7%. An Index Risk value was attributed to each SA ranging from 1 (Lowest "Age Dependency" Decile: 0–8.57%) to 10 (Highest "Age Dependency" Decile: 77.14%–85.7%).

Households where the head of household is not in work are more likely to be vulnerable to energy poverty (Healy and Clinch, 2004; Fizaine and Kahouli, 2019). Employment status was calculated using an 'At Work Ratio' showing the ratio of the number of people at work aged 15 years and over to the total population aged 15 years and over. This

ranged from a minimum of 0.58% to a maximum of 93.11%. An Index Risk value was attributed to each SA ranging from 1 (Lowest "Employment Status" Decile: 0.58–9.84%) to 10 (Highest "Employment Status" Decile: 83.85%–93.11%). In addition, it was hypothesised that households whose head of household was categorised as being either Professional or Managerial were less likely to experience energy poverty (Fabbri, 2015; Scott, 1997; Fizaine and Kahouli, 2019). A 'Social Class Ratio' was therefore calculated which shows the ratio of the number of

Table 3
Number of Small Areas identified as Spatial Outliers and Spatial Clusters based on Local Morans I.

Sample Small Area/ Surrounding Small Areas Category	Building Characteristics Index	Heating Requirements Index	Householder Characteristics Index	Overall Energy Poverty Risk Index
Not Statistically Significant	15,596	13,174	16,138	16,448
High-High Clustering (Hot Spot)	1263 (+3.49)[a]	2321 (+3.79)	1558 (+4.37)	560 (+2.56)
Low-Low Clustering (Cold Spot)	1595 (+6.18)	3015 (+4.16)	726 (+4.64)	1327 (+5.76)
High-Low (Spatial Outlier)	80 (−2.92)	90 (−2.94)	120 (−3.28)	132 (−3.19)
Low-High (Spatial Outlier)	107 (−3.11)	41 (−2.96)	99 (−5.74)	174 (−5.58)

[a] Mean Local Moran's I Z-score value is shown in brackets. A high positive Z score for a Small Area (SA) indicates 'clustering' i.e. surrounding SAs have similar index scores. These clusters can either be High-High for a statistically significant (0.05 level) hot-spot of high index scores or Low-Low for a statistically significant (0.05 level) cold-spot of low index scores. Conversely a low negative Z score for a SA indicates a statistically significant (0.05 level) 'spatial outlier'. These spatial outliers can either be High-Low if the SA has a high index score and is surrounded by SAs with low index scores or Low-High if the SA has a low index score and is surrounded by SAs with high index scores.

households whose reference person is classified as professional or manger compared to the total number of households.[5] This ranged from a minimum of 0% to a maximum of 100%. An Index Risk value was attributed to each SA ranging from 10 (Lowest "Social Class" Decile: 0–10%) to 1 (Highest "Social Class" Decile: 90%–100%).

The final vulnerable group included in the HH-EPRI were lone-parent families. According to research undertaken by ESRI lone parents in Ireland stand out as a group experiencing high rates of fuel poverty using both the subjective and official expenditure measures (Bercholz and Roantree, 2019). A 'Lone Parent Ratio' per household was calculated showing the ratio of the number of one-parent households compared to the total number of households per SA. This ranged from a minimum of 0% to a maximum of 100%. An Index Risk value was attributed to each SA ranging from 1 (Lowest "Lone Parent" Decile: 0–10%) to 10 (Highest "Lone Parent" Decile: 90%–100%).

4.4. Compiling the energy poverty risk index

The three categories (Heating Requirements; Building Characteristics; Householder Characteristics) were combined and weighted to produce the overall HH-EPRI as described in Eq. (1).

We follow a similar methodology to that employed by Walker et al. (2012, 2013). This methodology acknowledges that the allocation of weights is somewhat arbitrary and based on *a priori* assumptions. However, the tool we have developed makes the weightings easily modifiable as more empirical evidence emerges to support them.

For illustration of the use of the HH-EPRI, the three indicators

comprising the Heating Requirements (HR) category were allocated a combined weight of 40%. Table 1 details the percentage applied to each indicator. The five indicators comprising the Householder Characteristics (HC) category were allocated a weight of 40% with the Building Characteristic (BC) category (2 indicators) allocated the remaining 20%. The final HH-EPRI ranged from 1 (Low Energy Poverty Risk) to 10 (High Energy Poverty Risk) was then mapped at SA Level.

$$HH\text{-}EPRI = (HR*0.4) + (BC*0.20) + (HC*0.4) \qquad (1)$$

HR = (Average Fuel Cost (15%) + Domestic Energy Efficiency (20%) + Average Temperature (5%))

BC = (Number of rooms (10%) + Year built (10%))

HC = (Tenure status (7.5%) + Age dependency (5%) + Employment status (10%) + Lone Parent (7.5%) + Social Class (10%))

4.5. Clusters and outliers of risk

In this study, Anselin's Local Moran's I statistic[6] (Anselin, 1995) was used to identify spatial clusters and spatial outliers for each of the three component indices (Building Characteristics; Heating Requirements; Householder Characteristics) and the overall HH-EPRI at the significance level of $p < 0.05$.[7] The Cluster and Outlier Analysis tool available in ARCGIS was used to calculate a local Moran's I value, a z-score, a p-value, and a code representing the cluster type for each feature.

In terms of spatial clusters, a statistically significant positive value of the Local Moran's I for a SA indicates that the surrounding SAs have similar Index rates. A SA with a high Index score surrounded by SAs which also have high Index scores was coded as high-high while a SA with a low Index score surrounded by SAs which also have low Index scores was area coded as low-low. With regard to spatial outliers, a statistically significant negative value of the Local Moran's I for a SA indicated that this SA had a different Index score from surrounding SAs. A SA with a high Index score surrounded by SAs which have low Index scores was coded as high-low area while a SA with a low Index score surrounded by SAs which have high Index scores was coded as a low-high area.

### 5. Results – Home heating energy poverty risk index maps for Ireland

The HH-EPRI has been graded into a 9-point scale for ease of interpretation and to provide for structured decision-making by policy makers (See Table 2). The use of a scale offers an advantage for policy makers over Ireland's current 10% income-based criterion which offers only a binary judgement.

The HH-EPRI can also be represented in absolute numerical format to facilitate more explicit inter-country comparisons. Of course, this will be dependent on the availability of comparative datasets. The absolute HH-EPRI values generated in this study provide a representation of the current situation across Ireland and a baseline upon which future versions of the index can be compared. This allows for modifications in the weightings and other assumptions based on future research. The approach applied on the national scale for Ireland is to divide the HH-EPRI scale into three shades each of red, blue and green. This approach can be used for not only the overall HH-EPRI but also its three weighted component categories: heating requirements of building; building's physical characteristics; and householder characteristics. The

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[5] In the 2016 Census the entire population is classified into one of seven social class groups, ranked on the basis of occupation of the person in the family on whom they are deemed dependent. The social class ranks occupations by the level of skill required on a social class scale ranging from 1 (highest) to 7 (lowest).1. Professional workers 2. Managerial and technical 3. Non-manual 4. Skilled manual 5. Semi-skilled 6. Unskilled 7. All others gainfully occupied and unknown.

[6] Provides a measure of the spatial autocorrelation for each given SA with surrounding SAs.

[7] The null hypothesis is that there is no association between HH-EPRI scores in nearby SAs.

HH EPRI - Building Characteristics Index
Local Moran's I Results
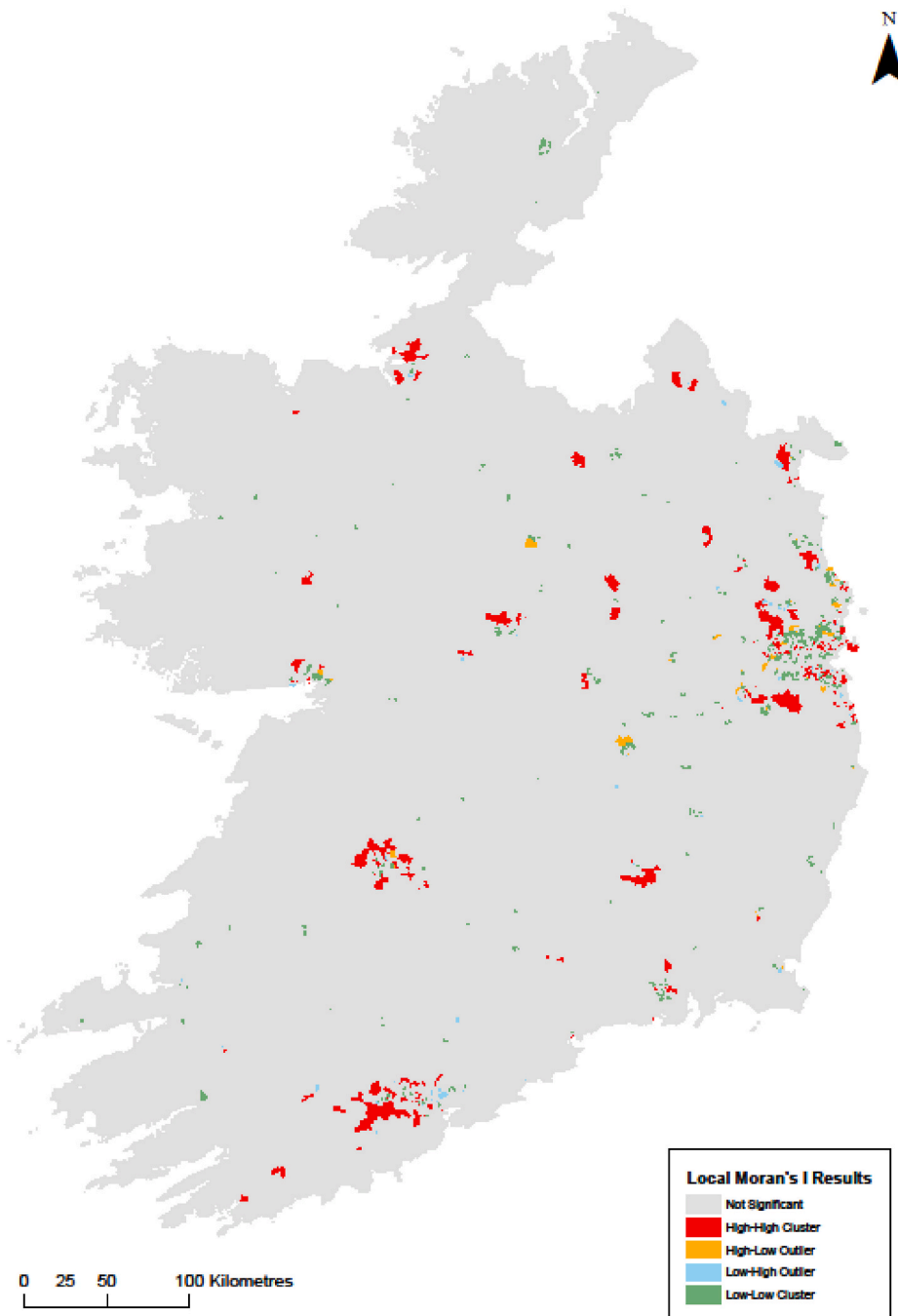
Map 5. Building characteristics index category.

darkest red represents the highest energy-poverty risk category, whilst the lightest green represents the lowest risk category (See Maps 1-4). Policymakers can set their own energy poverty line and select which risk categories (population) would most benefit from a specific policy intervention. In addition, they can model its impact across the HH-EPRI and its three key components.

5.1. Spatial distribution results

Mapping of the Building Characteristics Index component at SA level reveals the majority of the SAs are either in the median or high-risk categories. There are small pockets of low risk SAs on the North Western and Western Coastal areas. However, concentrations of low risk SAs are mainly located either in the Dublin region or other major urban areas. Indeed, urban areas demonstrate a wider range of this particular component's categories than rural areas which primarily range from medium to high risk only.

Examination of the map of the Heating Requirements Index component demonstrates a clear spatial pattern of higher heating requirements of SAs located in the Midlands region, the Mid-West region and North Western areas of the Border region. Similar to the Building Characteristics Index component, the SAs with the lowest risk factor are

HH EPRI - Heating Requirements Index
Local Moran's I Results

Local Moran's I Results

- Not Significant
- High-High Cluster
- High-Low Outlier
- Low-High Outlier
- Low-Low Cluster
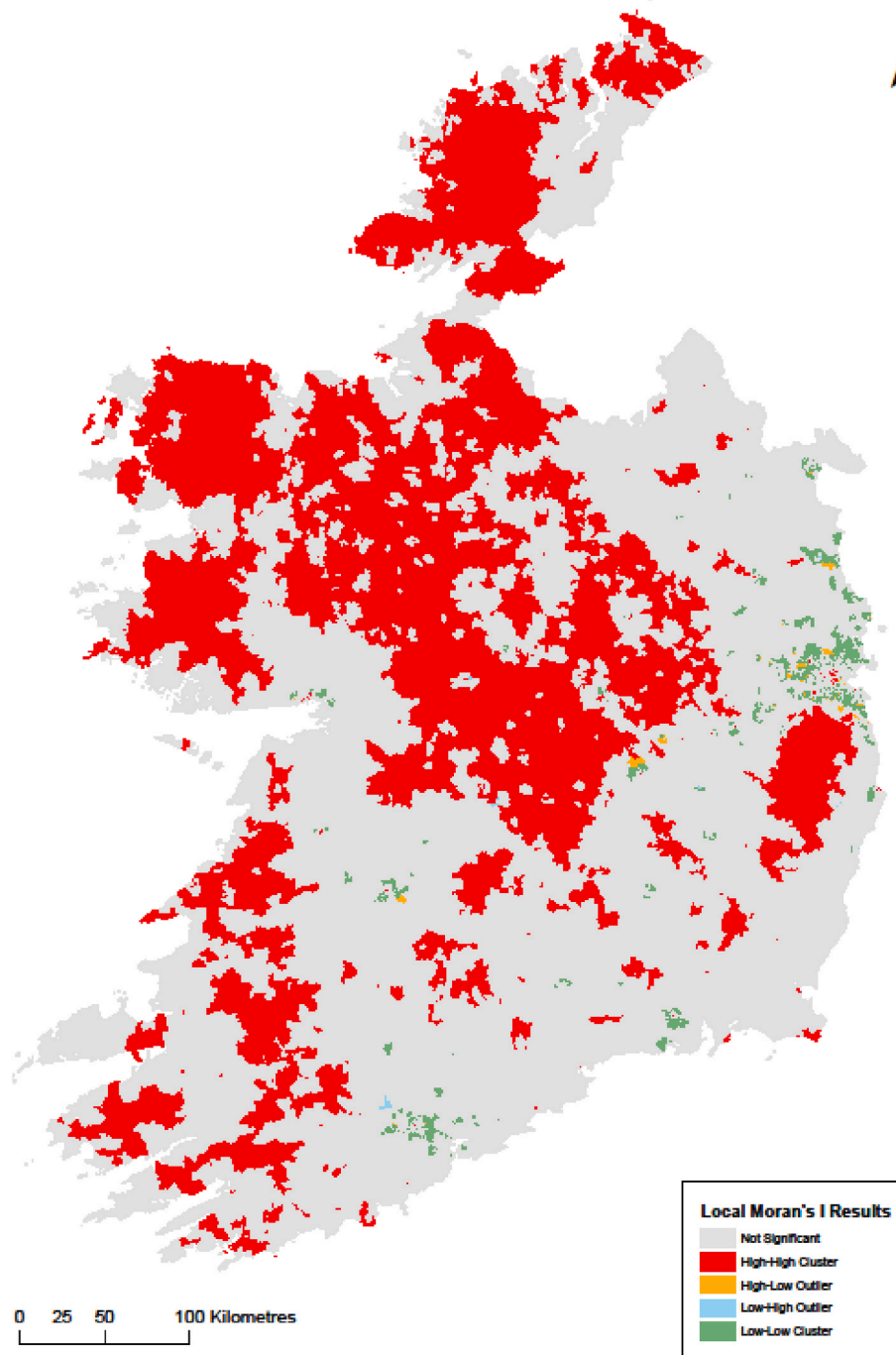
Map 6. Heating requirements index category.

located mainly in the Dublin region, in particular, and other urban areas (See Map 2).

As we move onto the Householder Characteristics Index component, the risk distribution has changed in as much as the higher risk SAs are concentrated in the Dublin region and other major urban areas. Conversely the lower risk SAs are concentrated in surrounding commuter areas on urban peripheries with the risk appearing to increase with the move towards more rural locations (See Map 3). This is not surprising as similar spatial patterns are demonstrated by the HP Pobal Deprivation Indices 2016 (Haase and Pratschke, 2016). Outside of urban

areas, the highest risk SAs are located on the Mid-Western and North-Western coastal areas.

Map 4 details the spatial distribution of the composite Home Heating Energy Poverty Index scores at SA level across Ireland. The majority of the SAs are either the high-end of the median risk to low end of the high-risk category. The highest concentration of low risk areas is found in the Dublin region and other major urban areas. The greatest concentrations of high-risk areas are in the West, Midlands and Western parts of the Border regions.

Sensitivity analysis of these HH-EPRI scores were conducted to assess

HH EPRI - Householder Characteristics Index
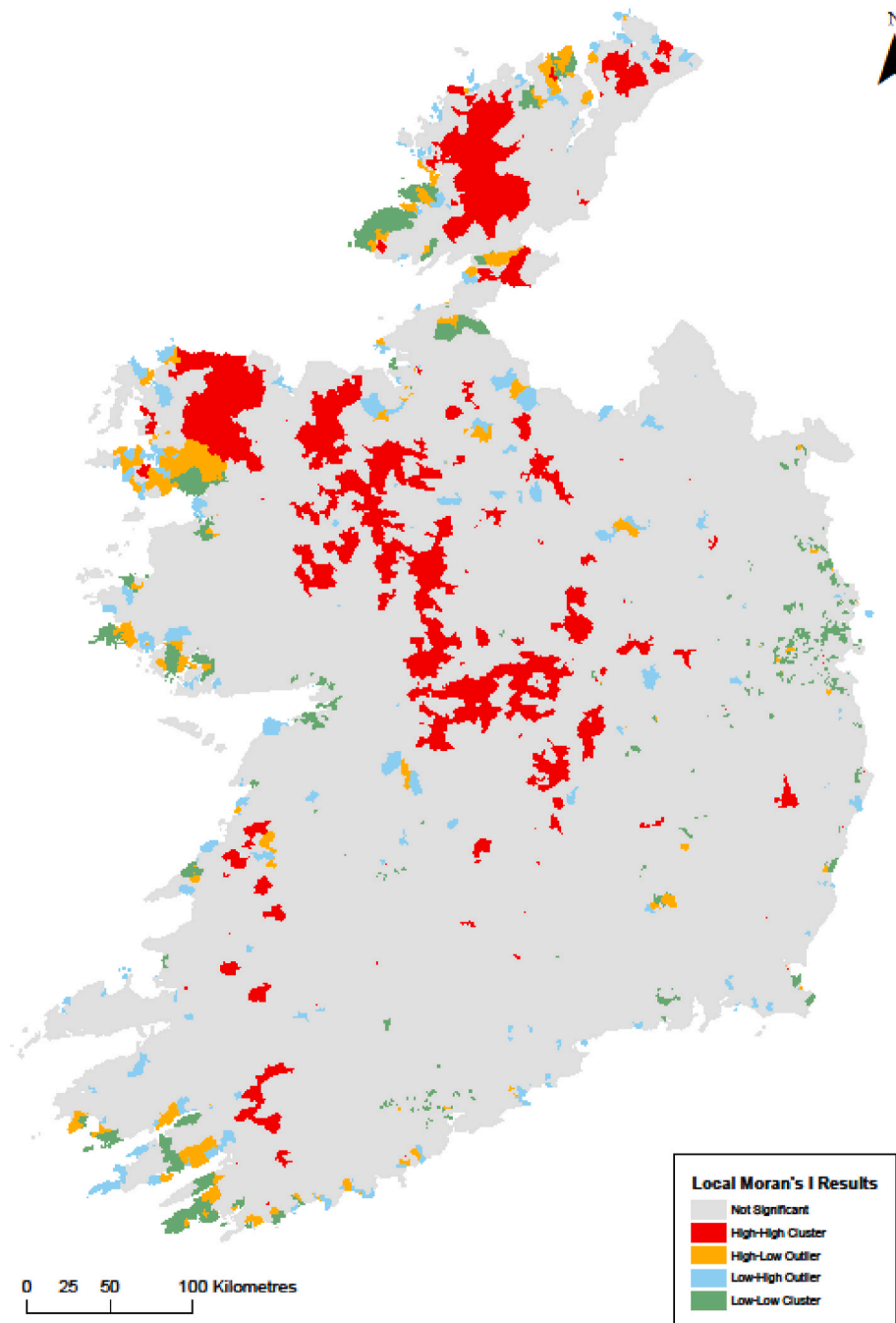## Local Moran's I Results
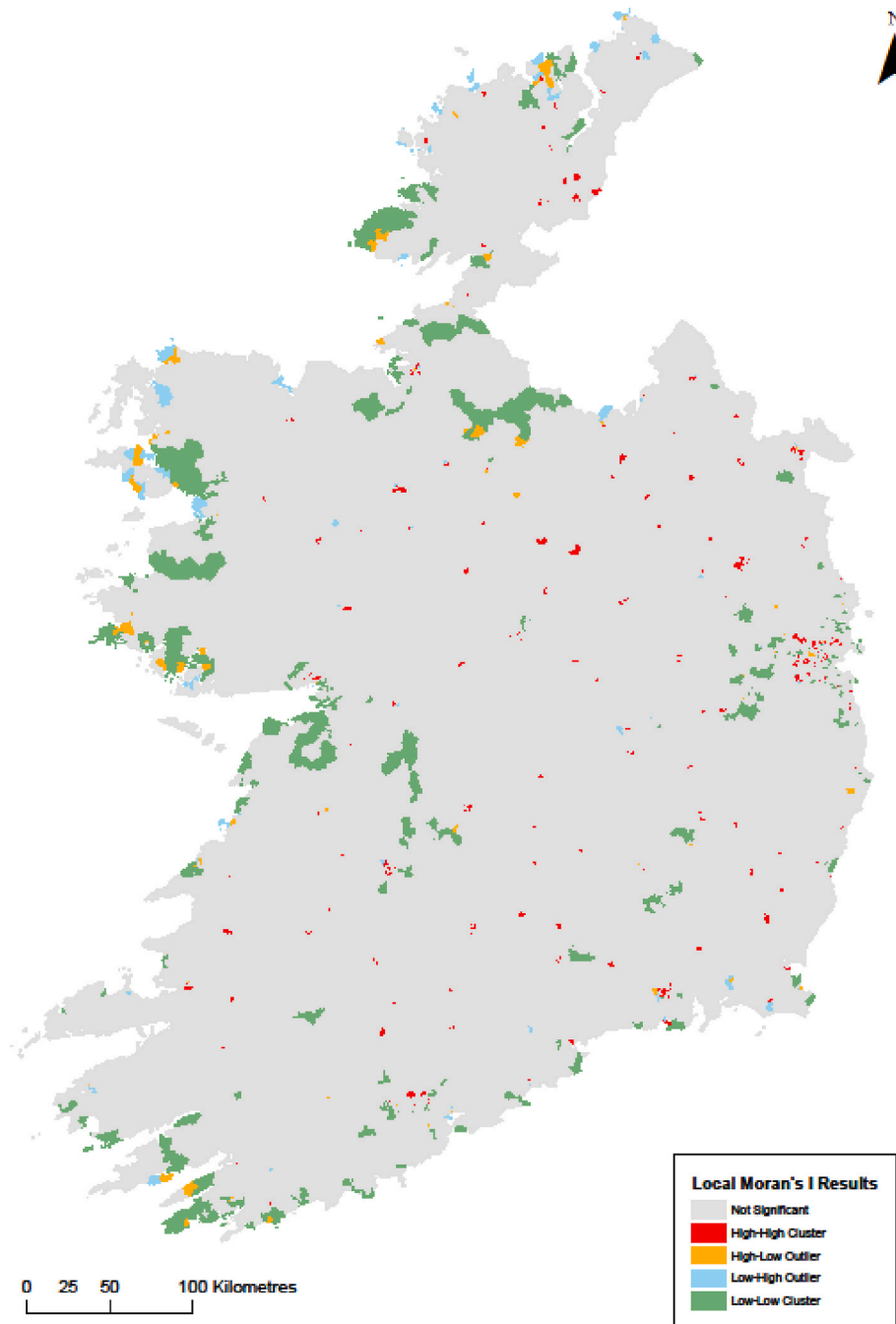
Map 7. Householder characteristics index category.

the sensitivity of the mapped index outputs to the assumptions made on the index weighting. Specifically, we examined the impact on overall HH-EPRI from 3 alterative weighting schemes presented below. The mean HH-EPRI under the current weighting was 4.96 (SD = 0.71):

1. Current weighting vs. removal of BER Proxy Sub Index: In this scenario the two Building Characteristics (BER Proxy) Indicators were removed (Number of Rooms 10%; Age of Dwelling 10%) and the Average BER Score Indicator weighting was increased from 20% to 40%. The mean HH-EPRI decreases slightly in this scenario to 4.88 (SD = 0.79).

2. Current weighting vs. Equal weighting across individual indicators level; In this scenario all ten individual indicators were weighted at 10%. The Sub-Index weightings however remained the same as the Current Weighting (Heating Requirements Sub Index 40%; Building Characteristics (BER Proxy) Sub Index 20%; Householder Characteristics 40%). The mean HH-EPRI increases slightly in this scenario to 5.20 (SD = 0.70).

3. Current weighting vs. Equal weighting at Sub-Index level: In this scenario all ten indicators remained at current weighting. Each Sub-Index weighting however was changed to 33.3%. The mean HH-EPRI increases slightly in this scenario to 5.23 (SD = 0.76).

HH EPRI - Overall Energy Poverty Risk Index
Local Moran's I Results

Map 8. Energy poverty risk index.

5.2. High- and low-risk HH-EPRI clusters

Table 3 details the Local Moran's I results for the three component indices and the composite HH-EPRI. The spatial distribution of clusters and outliers for each of the different indices are illustrated in Maps 5-8. Focusing on the composite HH-EPRI results, the Local Moran's I analyses indicate that only 3% of all SAs (N 560) form statistically significant high-risk clusters. The mean Local Moran's I Z-score for these SAs was +2.56 (p < 0.05). These clusters are distributed across the country in non-urban areas but are particularly prevalent in the Midlands. Conversely, 7% of all SAs (N 1327) form statistically significant low-risk

clusters (mean Z-score + 5.76, p < 0.05). These are primarily located in the larger urban areas particularly Dublin and Cork. The small number of significant outliers (or 'pockets') of high risk (N 132, 0.07%, mean Z score −3.19, p < 0.05) are generally located in the midlands and along the west coast. Low-risk outliers (N 174, 0.13% mean Z-score −5.58, p < 0.05) present the same spatial distribution.

5.3. HH-EPRI scenario modelling – Oil price increase simulation

The HH-EPRI analysis, as outlined in Sections 5.1 and 5.2, is essentially static. However, a key dimension of energy poverty concerns the

vulnerability of households to fluctuations in fuel price and/or changes in policy. The HH-EPRI therefore incorporates a dynamic element that can examine the local and national impact on energy poverty risk of changes in exogenous factors both nationally (e.g. policy changes) and internationally (e.g. changes in oil prices).

Ireland has the highest percentage (38.1%) of oil and petroleum products for final energy consumption in the residential sector in Europe. Furthermore, it is the only EU Member State in which oil represents the main energy carrier for the residential sector, with most others relying mainly on natural gas and electricity to meet their residential energy needs. Space (Table 4) and water heating make the most significant contribution to final household energy use; Ireland's consumption of oil for space and water heating is the second highest in Europe in terms of market share (EUROSTAT, 2017a; EUROSTAT, 2017b).

With such high dependency on oil for space and water heating, price level and volatility are serious issues for many households. Although household oil prices in Ireland during the 1990s were relatively constant averaging €311 per 1000 L (€/kl), since 2000 they have been more volatile peaking at 1121 €/kl in Q3 of 2012 (168% above the 2000 price) before falling back to 512 €/kl in Q1 of 2016 (SEAI, 2018).

The average fuel price (for each SA) is one of the ten indicators included in the composite HH-EPRI. Consequently, the HH-EPRI can model the impact of oil price changes (or other fuel price changes). For illustration, the following scenario illustrates the impact on the HH-EPRI scores at both a national and regional level of a 25% increase in oil prices without any increase in income.

5.3.1. Relative HH-EPRI impact of oil price increase - national level

Fig. 1a and b illustrate the distribution of total HH-EPRI scores for all SAs with and without the 25% increase in oil prices. As expected, the mean HH-EPRI score increases with a 25% oil price increase. It is also evident from the graphs and the associated standard deviations that the increase in oil prices affects the distribution of scores at SA level with a greater number of SAs falling into the highest poverty risk score categories.

5.3.2. Relative HH-EPRI impact of oil price increase - local level scenario

The spatial impact on HH-EPRI scores becomes more evident at a local level. Maps 9 and Map 10 present the impact of the oil price index

in a small town in the Midlands region of Ireland. This town is comprised of 12 SAs containing a total of 1075 households. The 25% increase in oil price will result in 43% of all households in the town moving into Category 8 - Highest Risk (Medium) (Table 5).

### 5.3.3. HH-EPRI as policy decision making tool – Carbon tax increase simulation

In Ireland, a carbon tax of 26 euro per tonne of CO_2 is levied on the use of fossil fuels including oil, gas, coal and peat. In 2018, the Government's Climate Change Advisory Council (CCAC, 2018) recommended that the tax should be set at 30 euro per tonne and increase to 80 euro per tonne by 2030 as part of the national climate action strategy. Whilst a carbon tax will incentivise greater energy efficiency and fuel switching, there remain barriers to change for some households (e.g. inertia, access to capital, transactions costs and behavioural factors (Kelly et al., 2016)), thus the intervention has the potential to increase energy poverty risk in the absence of supporting actions. The HH-EPRI offers a decision support methodology that can guide policy makers in respect of the impact of policies on home heating energy poverty risk rates and performance in relation to "just transition" goals. Specifically, the methodology could be applied to test a range of potential carbon tax increases on relative and total HH-EPRI scores.

In contrast to standard measures of energy poverty, the HH-EPRI offers a high-resolution spatial dimension, that equips policy makers to undertake targeted analysis and action. An exploration of how this spatial dimension can be applied is presented in Map 12. Ireland has one

Table 4
Percentage of households using different type of fuels for Central Heating in Ireland.

Coal	5.2%
Peat	5.4%
Oil	41.5%
Gas	34.3%
Electricity	8.8%
Wood	2.1%
Other	1.3%
No Central Heating	1.4%

Source 2016 Census.: Based on 1,654,577 homes surveyed in the 2016 census who stated their Central Heating type.
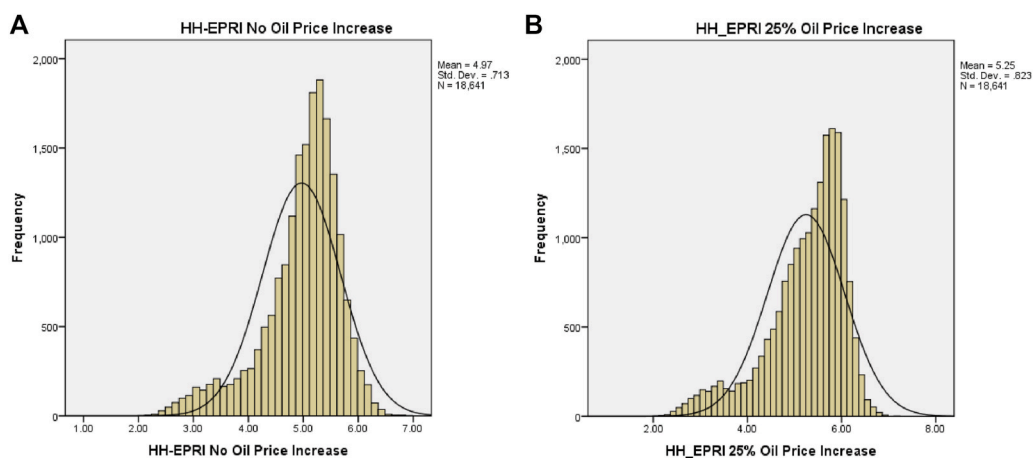
Fig. 1. a Distribution of fuel poverty risk scores with 0% oil price increase (mean 4.9685 s.d. 0.712). Fig. 1b Distribution of fuel poverty risk scores with 25% oil price increase (mean 5.24 s.d. 0.823).
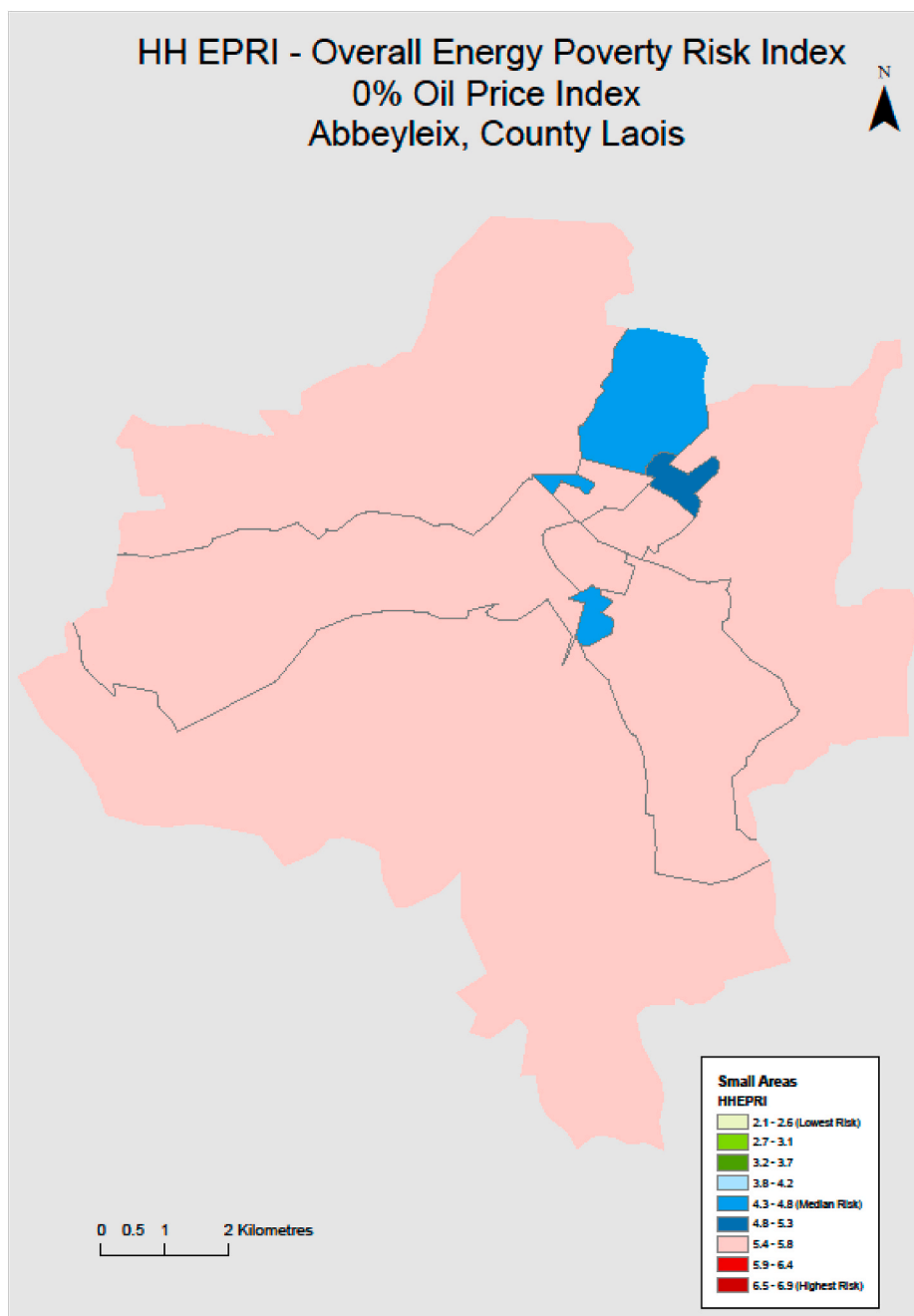
Map 9. Spatial distribution of EPRI in Abbeyleix before 25% oil price increase.

of the highest dependencies on coal and peat for residential space heating purposes in the E.U with a market share of 10.6%.[8] Map 11 presents the percentage of households which use peat and coal for Central Heating purposes at SA Level. It is evident that such fuel use is most prevalent in the Midlands and on the West Coast of Ireland. Use of natural gas has lower emissions than both coal and peat, with relatively low emission factors of NO_x, CO_2 and black carbon, and only fractional emissions of other air pollutants such as $PM_{2.5}$, SO_2, NMVOC and CO. However, natural gas use is constrained by access to the gas distribution network, as shown in black lines in Map 11.
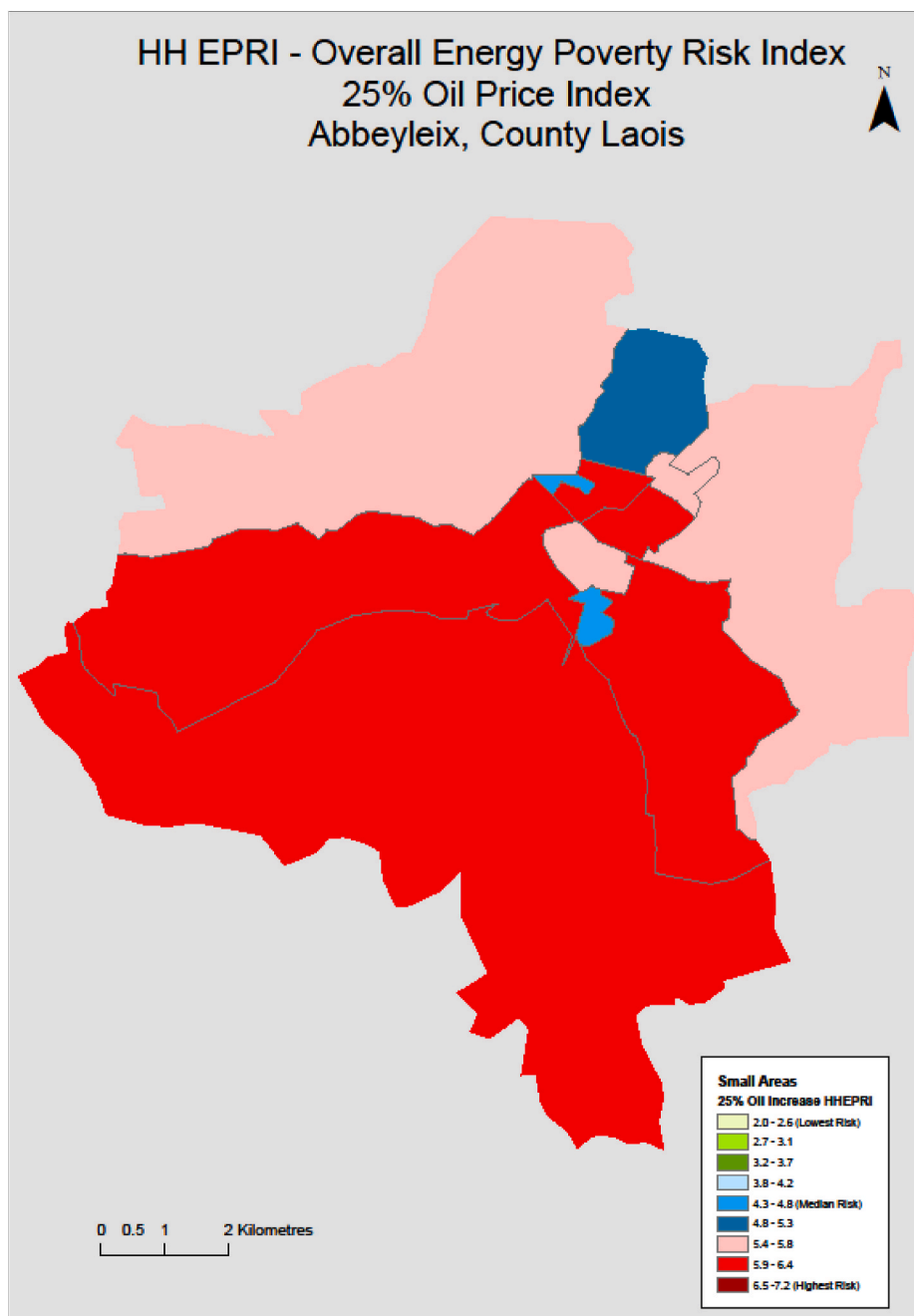
In Map 12 the HH-EPRI system has been calibrated such that all

households which currently use coal and peat for space heating purposes, and lie within 13 km of the gas pipeline, switch their central heating system to gas. The outcome of this is that Energy Poverty risk rates within that 13 km catchment area show a marked decrease from the rates exhibited in Map 4. This scenario is just one example of how such targeted spatial analysis could be undertaken for policymakers prior to the implementation of future policies that would be anticipated to impact on home heating energy poverty risk (e.g. heat pumps, community retrofit programs, fuel bans, carbon tax changes).

6. Discussion

In this work we have focused on a framework to address home heating energy poverty risk. The complexity and multi-dimensional nature of the concept of energy poverty has resulted in a lack of

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[8] Of 1,654,577 homes surveyed in the 2016 census who stated their Central Heating type. 5.2% declared as using coal fired central heating, 5.4% declared as using peat fired central heating.

Map 10. Spatial distribution of EPRI in Abbeyleix after 25% oil price increase.

Table 5
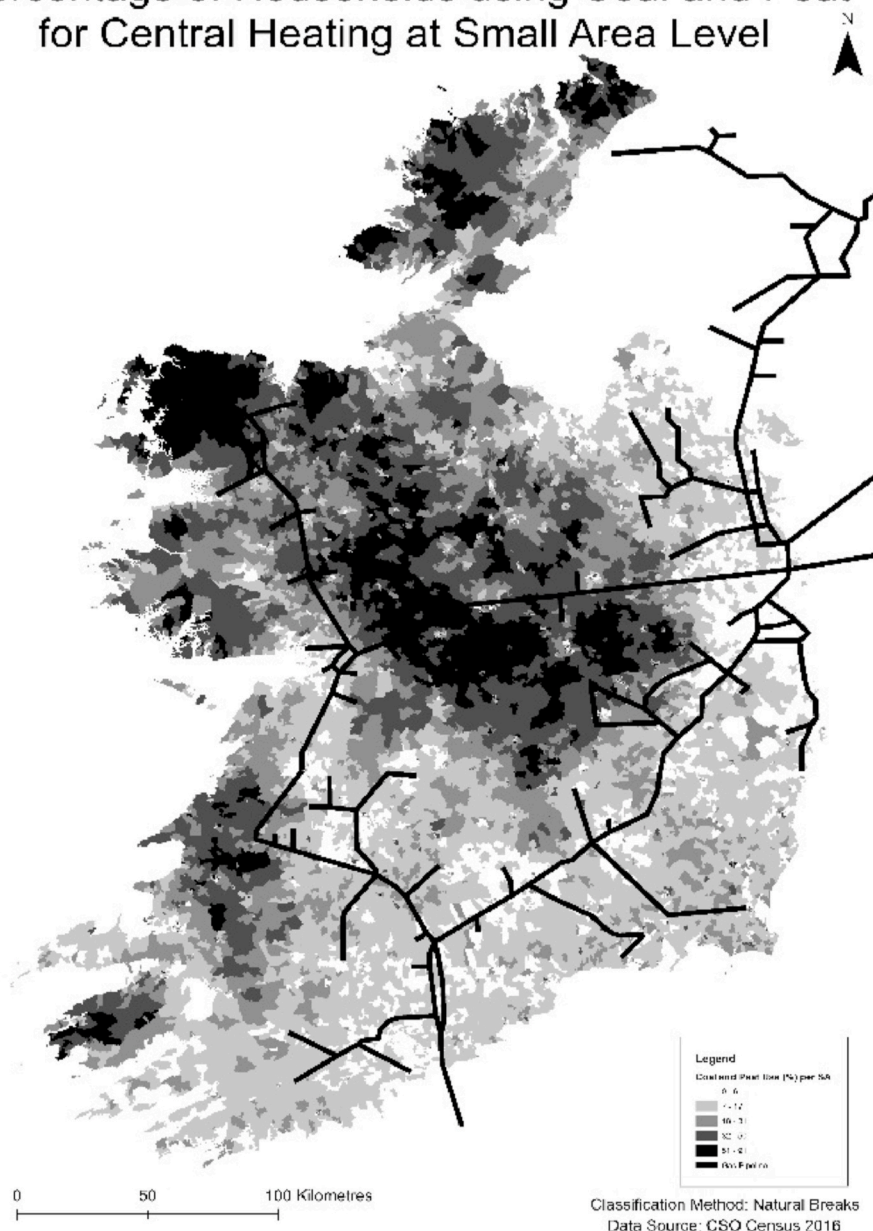Impact of oil price increase at local level (Abbeyleix, Co Laois).

EPRI Category	0% Oil Price Increase		25% Oil Price Increase		Percentage Change after Price Increase
	Small Areas	House Holds	Small Areas	House Holds	Households Only
Median Risk Medium	3	237	2	132	−44%
Median Risk High	2	179	1	105	−41%
High Risk Low	7	659	4	378	−42%
High Risk Medium	0	0	5	460	N/A
Total	12	1075	12	1075	

consensus in both its definition and measurement. As such we are explicit with the scope and focus of the HH-EPRI.

In a broader sense, the undertaking of regular nationwide household-level surveys could improve the accuracy of estimates of the number and distribution of households in regard to all forms of energy poverty. However, such routine and detailed assessments are not generally considered financially feasible. In the absence of such detailed data, current approaches to measuring energy poverty can be classified into three main categories: Objective; Subjective; and Composite. The composite approach, outlined in this paper, can best address the multi-dimensional nature of energy poverty and offers a better instrument to complement, and potentially replace, the most utilised and criticised income-based method. Moreover, from a societal and policy perspective, energy poverty is something that is ideally considered at a fine spatial scale. Aggregate and average data mask issues at the margin and so a

Map 11. Spatial distribution of peat and coal use for central heating at small area level.

better spatial method for identifying energy poverty risk is necessary to guide the policy system towards designing policy instruments that result in better energy poverty alleviation outcomes.
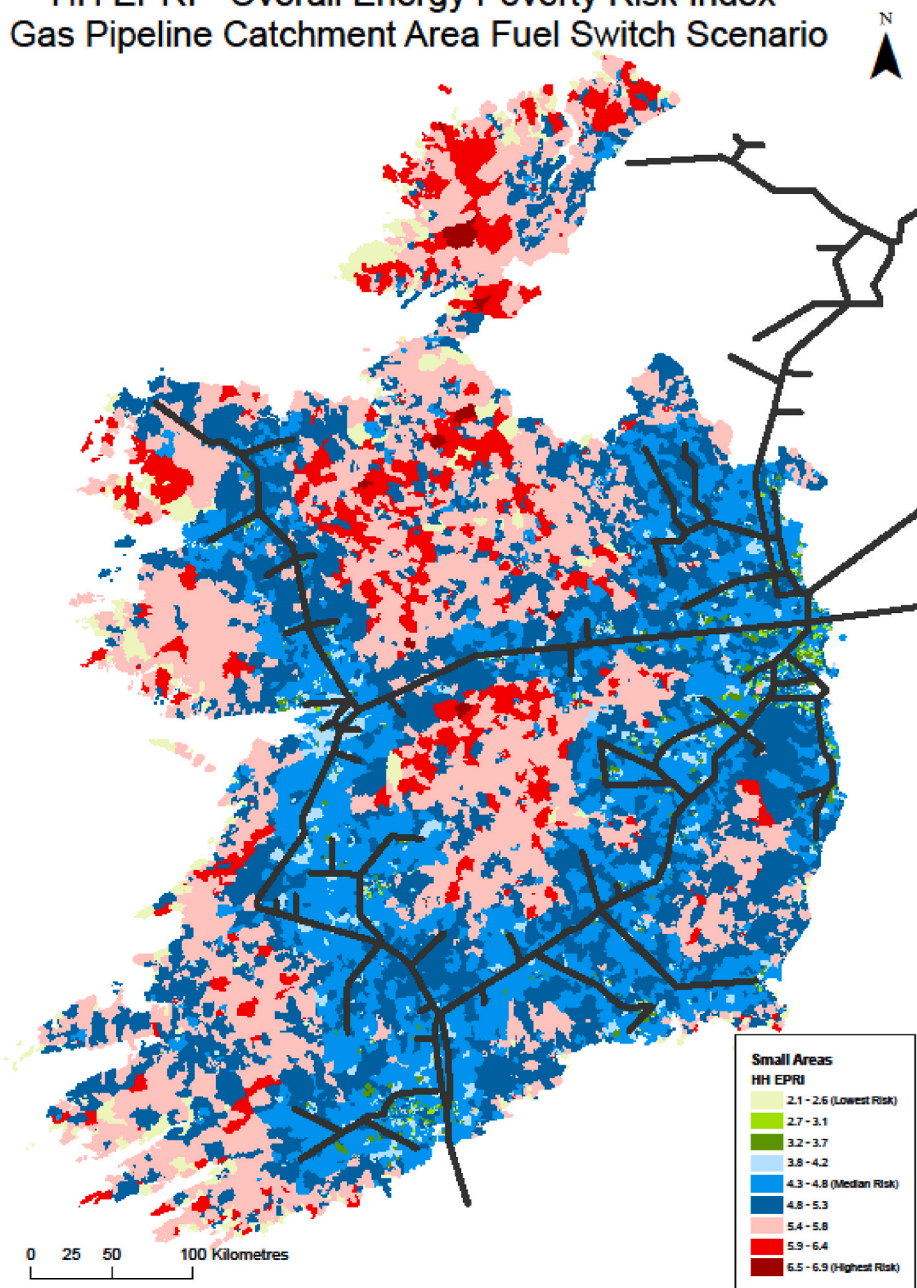
The methodology and its application outlined in the development of the HH-EPRI is capable of further refinement. The choice of parameters and the indicators selected for this analysis are believed relevant and robust, however, we acknowledge the scope for replacement variables where improved data becomes available. For example, development of the index was constrained by lack of access to complete Building Energy Rating data, and BER data itself can also be improved over time. The BER dataset at SA level contains information on 33% of the total Irish residential stock. Until the BER dataset has greater national coverage we must continue to supplement the index with proxy indicators.

Similarly, whilst the HH-EPRI is, by definition, focused on residential home heating, the system could be extended to incorporate other residential energy uses. Residential transport energy demand is something that could be developed as a further module and further work is ongoing

in this regard. Appliance energy use is then another source of residential energy demand that can influence the overall energy poverty risk rating. The appliance element was excluded from the home heating index so as to maintain a more direct focus on home heating, and also due to the absence in our Irish case study of adequately refined spatial data on energy use let alone appliance energy use, by household. Indeed, a challenge in an Irish and European context is the difficulty in sourcing regular spatial meter data by household, a task made more complicated by European General Data Protection. Where utilities can share these data, and where smart metering becomes more prevalent, we would anticipate drawing on alternative international methods (e.g. Min et al., 2010) to extend the EPRI to include an appliance module that moves us closer still to a full scope residential energy poverty index.

As with all indices, the reliability of an overall composite figure for home heating energy poverty is determined by the weighting process. We have been clear that the allocation of weights is somewhat arbitrary and based on *a priori* assumptions. However, the tool we have developed

HH EPRI - Overall Energy Poverty Risk Index
Gas Pipeline Catchment Area Fuel Switch Scenario

Small Areas
HH EPRI
- 2.1 - 2.6 (Lowest Risk)
- 2.7 - 3.1
- 3.2 - 3.7
- 3.8 - 4.2
- 4.3 - 4.8 (Median Risk)
- 4.8 - 5.3
- 5.4 - 5.8
- 5.9 - 6.4
- 6.5 - 6.9 (Highest Risk)

0   25   50   100 Kilometres

Map 12. Spatial distribution of EPRI under gas Pipeline catchment area fuel switch scenario.

makes the weightings and other variables readily modifiable as more empirical evidence emerges to support them. Thus, the HH-EPRI can be adapted, and the assumptions updated, as required.

The index may also be calibrated to enable its use in regions with alternative energy use demand profiles. As an example, the relationship between air conditioning and energy poverty risk would be relevant in warmer regions and, where similarly disaggregated spatial energy data were available, this form of energy use could be readily incorporated into the index. In developing countries, the residential energy demand mixes could see fuel used for cooking as a particularly relevant item in the basket of a broader energy poverty risk index. Once again, this energy demand could be included in the basket, however, the substantial challenge in that regard would be access to reliable spatially-disaggregated data with which to compile the index.

7. Conclusion and policy implications

The HH-EPRI developed and presented in this paper offers an adaptable and transferrable method for assessing energy poverty risk at a fine spatial scale. The resolution of the index to small housing clusters allows for localised identification of energy-poverty risk and an assessment of the likely effect of changes in exogenous factors. Importantly in this regard, the HH-EPRI has been designed with a relevant basket of indicators that allows analysis of how, and where, home heating energy poverty risk may change in response to specific policy interventions such as tax changes, fuel bans or a building fabric retrofitting program. At a time when nations across Europe and the world are developing, implementing and incentivising such actions to reduce energy use and curtail greenhouse gas and air pollutant emissions, the HH-EPRI provides a valuable tool for designing better policies that can deliver the necessary

changes, as well as identifying targeted supporting actions that can mitigate or manage any excessive rise in energy poverty risk amongst the vulnerable. Specifically, the HH-EPRI can support fine scale assessment of the impact of carbon taxes on home heating fuels and associated energy poverty risk; it can help to identify which communities at national or local scale require greater supports in terms of building retrofit programmes; and it can inform targeted actions to enable just transitions where specific fuels (e.g. peat and smoky coals) or methods of home heating (e.g. open fires) are discouraged or denied into the future.

This fine scale spatial analytical capacity is needed, as many approaches for energy poverty and energy poverty risk definition are somewhat static, narrowly focused and identify risk on an aggregate scale. In practice, only certain subsets of the market in certain locations may be affected by a given change. The issue with highlighting "general risk" but failing to indicate where the risk falls, and what could be done to mitigate that risk in those communities, is that energy poverty risk can then serve as a barrier to necessary environmental policy transitions. Given the scale of transitional changes required in energy use and heating systems across Europe over the next decade, it is vital that viable national policy interventions are not derailed by generic risks of energy poverty but, rather, that policy is supported in targeting complementary solutions. The HH-EPRI can be adapted to match societal preferences and priorities such that localised risks can be identified and managed, whilst broader national goals are advanced in a just transition.

CRediT authorship contribution statement

J. Andrew Kelly: Conceptualization, Methodology, Formal analysis, Writing - original draft, Resources. **J. Peter Clinch:** Conceptualization, Methodology, Writing - review & editing. **L. Kelleher:** Methodology, Data curation, Formal analysis, Writing - original draft. **S. Shahab:** Investigation, Writing - original draft.

Declaration of competing interest

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

Acknowledgements

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