Household carbon emission research: An analytical review of measurement, influencing factors and mitigation prospects

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Household carbon emission research: an analytical review of measurement, influencing factors and mitigation prospects

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Abstract

Greenhouse gas (GHG) emissions are simultaneously exhausting the world's supply of fossil fuels and threatening the global climate. Despite energy efficiency improvements, total carbon emissions are still increasing alarmingly. A large proportion of energy consumption and associated carbon emissions is from the household sector. The UK's residential sector, for example, is responsible for approximately 30% of all its carbon emissions – mainly due to high household energy consumption. In many developing countries, where energy demand has been typically lower, the significant improvement in living standards in recent years due to the accelerating development of their economies has resulted in a disproportionate increase in household energy consumption. Therefore, a major reduction in household carbon emissions (HCEs) is essential if global carbon reduction targets are to be met. To do this, major OECD states have already implemented policies to alleviate the negative environmental effects of household behaviors and less carbon-intensive technologies are also proposed to promote energy efficiency and reduce carbon emissions. However, before any further remedial actions can be contemplated, though, it is important to fully understand the actual causes of such large HCEs and help researchers both gain deep insights into the development of the research domain and identify valuable research topics for future study.

This paper reviews existing literature focusing on the domain of HCEs. This critical review provides a systematic understanding of current work in the field, describing the factors influencing HCEs under the themes of household income, household size, age, education level, location, gender and rebound effects. The main quantification methodologies of input-output models, lifecycle assessment and emission coefficient methods are also presented, and the proposed measures to mitigate HCEs at the policy, technology and consumer levels. Finally, the limitations of work done to date and further research directions are identified for the benefit of future studies.

Key words: household carbon emissions (HCEs), influencing factors, quantification methodologies, measures

Highlights

- The factors influencing HCEs under the themes of household income, household size, age, education level, location, gender and rebound effects are analyzed
- The main quantification methodologies of input-output models, lifecycle assessment and emission coefficient methods are presented
- Measures to mitigate HCEs at the policy, technology and consumer levels are proposed
- The limitations of work done to date and further research directions are identified for the benefit of future studies

Introduction

Greenhouse gases (GHG) have an adverse impact on both natural and socio-economic systems in the atmosphere, and the huge quantities now being emitted worldwide is accepted by many as a major cause of climate change (IPCC, 2007). The continuous and increasing production of GHG is therefore a matter of global concern, and many countries have set ambitious longer term GHG emission reduction targets (UNFCC, 2009, 2011). The UK, for example, aims to reduce its GHG emissions by at least 80% of 1990 levels by 2050 (HM Government, 2008); the U.S. to lower carbon (CO_2) emissions by 17% and 83% below 2005 levels by 2020 and 2050 respectively (The White House, 2009); China to abate emissions per unit of economic output to 40-45% of 2005 levels by 2020; India to bring down its emission intensity by 20-25% by 2020; and Brazil to reduce emissions by 38-42% of 'business-as-usual' (BAU) levels by 2020.

How these very ambitious targets are to be achieved is far from clear. Previous studies, however, point to a large proportion of energy consumption and associated carbon emissions being from the household sector. The UK's residential sector (excluding transport), for example, is responsible for approximately 30% of all its carbon emissions – mainly due to high household energy consumption (Palmer et al., 2006). In many developing countries, where energy demand has been typically lower, the significant improvement in living standards in recent years due to the accelerating development of their economies has resulted in a disproportionate increase in household energy consumption. In China, for example, approximately 26% of total household energy consumption and 30% of CO_2 emissions are due to residents' lifestyles and related economic activities (Wei et al., 2007); in Greece, now classified as of near developing country 'emerging-market' status (MSCI, 2013), a 44% increase in household expenditure between 1990 and 2006 was accompanied by a 60% increase in CO_2 emissions (Papathanasopoulou, 2010); and India, with CO_2 emissions from household consumption of goods and services increasing by 66% between 1993-94 and 2006-07 (Das and Paul, 2014). Therefore, a major reduction in household carbon emissions (HCEs) is essential if global carbon reduction targets are to be met. To do this, the IPCC (2001) propose changes in consumption patterns, and major OECD states have already implemented policies to alleviate the negative environmental effects of household behaviors (Geyer-Allely and Zacarias-Farah, 2003). Less carbon-intensive technologies are also proposed to promote energy efficiency and reduce carbon emissions.

Before any remedial actions can be contemplated, though, it is important to fully understand the actual causes of such large HCEs. What is needed is a review of the literature relating to HCEs to date. Despite the large amount of literature involved, few reviews have been forthcoming although, as Tsai and Wen (2005) and Flanagan et al. (2007) point out, they do help researchers both gain deep insights on the development of the research domain and identify valuable research topics for future study. This paper therefore fills this gap by providing a comprehensive review of the most relevant articles to explore the factors that influence HCEs, identify the most commonly used quantification methodologies and the various mitigation measures proposed to date. In doing this, the next section provides the background of HCEs, followed by the methodology of the study, classification of the reviewed studies, summary of the articles themselves, their limitations and further research directions.

Background of HCE research

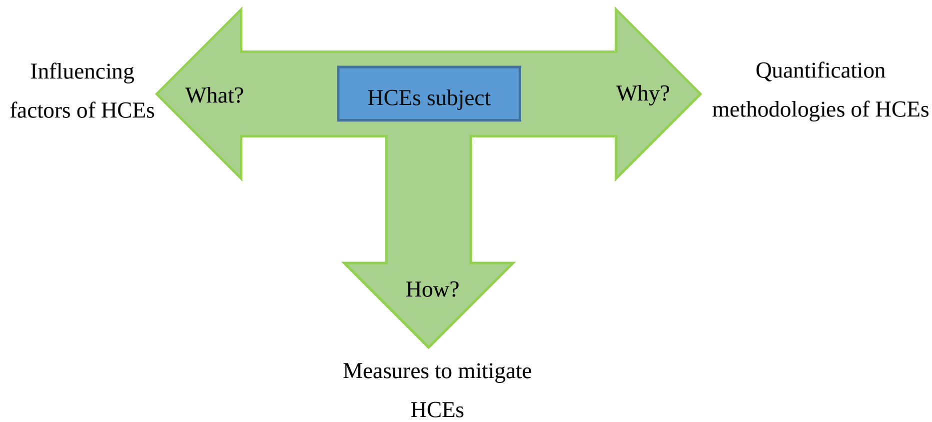

Figure 1 Research framework

There has been a growing awareness of the impact of HCEs, as evidenced by the increasing number of studies published in recent decades. The analysis of household consumption and related environmental effects, for example, is one of the most popular topics in sustainability research. This paper reviews these studies to identify the critical factors that influence the generation of HCEs and the quantification methodologies used to gauge their level of impact. Measures that could effectively mitigate HCEs are also reviewed. Fig. 1 illustrates the research framework involved.

The terms used to described HCEs include household carbon footprint (e.g. Fan et al., 2012; Shigetomi et al., 2014; Shirley et al., 2012; Weber and Matthews, 2008), household carbon dioxide emissions (e.g. Büchs and Schnepf, 2013; Golley and Meng, 2012; Lee and Lee, 2014) or just HCEs (e.g. Qin and Han, 2013; Revell, 2014). Another term is the embedded carbon footprint of a household, defined by Fan et al. (2012) as "the CO_2 emissions resulting from the whole life cycle of products and services for the household including those associated with their manufacturing and eventual breakdown". Qu et al. (2013), on the other hand, are more focused on the human element, defining household CO_2 emissions as "the emissions of individuals or their families in order to meet the demands of their existence and development under certain socio-economic conditions, which includes both direct and indirect emissions". Direct emissions are understood to be those related to direct household fuel use, such as electricity, heating, gas and other liquids. Indirect emissions, on the other hand, are those that arise in the production and distribution processes of goods and services for households, such as emissions that occur in the manufacture of food, clothes, furniture and services.

Since the 1990s, a starting point increasingly used for developing strategies for environmental preservation has been the reduction of HCEs (Boxall, 2006). This has inspired a voluminous HCE research literature, one of the more outstanding features of which is that indirect emissions are much higher than direct emissions. In the U.S. for example, indirect carbon emissions account for 77% of total emissions (Jones and Kammen, 2011). Similarly, more than 60% of the energy requirement in the household sector in Korea is indirect (Park and Heo, 2007).

Most studies analyze HCEs from a consumption perspective, which considers all the emissions supporting household consumption in one country, whether they occur in that country or abroad. Hertwich and Roux's (2011) investigation of the climate implications of the use of household electric and electronic equipment (EEE), for example, shows TV sets and other EEE to have significant lifecycle GHG emissions. Panzone et al. (2013), on the other hand, have designed an index to measure the environmental sustainability of household food consumption based on consumer preferences and scanner data provided by a UK food retailer. In contrast, the production perspective takes account of emissions produced within one country, regardless of where the consumption of final products and services occurs. The difference between these two methods is the CO_2 embodied in trade (Druckman and Jackson, 2009).

A good way to investigate CO_2 emissions due to household consumption is to check associated expenditures. Meier and Rehdanz (2010), for example, point out that heating expenditure accounts for the largest proportion of total household energy expenditure in the UK, implying that the emissions from heating are considerable in such regions of the world.

Methodology

This paper employs Wu et al's (2014) approach of collecting papers relating to construction and demolition waste from two world renowned indexed databases: the SCI database and the EI database, to successfully summarize existing waste quantification methodologies through the analysis and comparison of selected papers and presentation of current research limitations and further research directions. The worldwide publications indexed by these two databases are peer reviewed and of high quality. Therefore, HCE related papers were collected from the same databases. Three steps were then taken to identify relevant studies. First, the term "household carbon emissions" and time span "from 1990 to 2014" was used to search for potential related journal articles. This produced over 200 results. Second, the titles and abstracts of the collected papers were scanned to filter those outside the research scope (such as papers on city or industrial emissions). This resulted in 75 papers remaining for further analysis. For the third step, the full text of each article was carefully scrutinized for relevance and a further six papers were omitted. For the final set of 69 papers, Fig. 2 shows the number published each year and the increasing trend in HCE research interest over the years.

<Insert Figure 2 here>

Table 1 lists the papers together with their major distinguishing features of location, quantification methodologies, influencing factors of HCE and mitigation measures. These latter issues are explained in detail in the remaining sections of this paper.

<Insert Table 1 here>

Quantification methodologies

The adoption of different quantification methodologies to estimate carbon footprints is likely to produce different results (Dias and Arroja, 2012; Plassmann et al., 2010). Various approaches have been used to analyze household consumption activities, with a view to addressing the resulting environmental effects in different countries and regions. Input-output models, life cycle assessment and emission coefficient methods are all popular approaches to quantifying HCEs. Consumption data from consumer expenditure surveys is also often used to quantify consumption-induced emissions. The analysis of the reviewed methodologies follows. Table 2 summarizes the advantages and disadvantages of the quantification methodologies involved.

Table 2. Advantages and disadvantages of the quantification methodologies

	Advantages	Disadvantages
IOM	• provides a standard method of analysis that can be updated or applied to different populations in a uniform manner • could be easily combined with other methods	• lacks reliability when forecasting long-run effects • assumes a fixed technology coefficient which cannot reflect technological improvements and elasticity
LCA	• reflects the effects of the entire life cycle	• data intensive and time consuming
ECM	• presents an easy calculation process	• the coefficient is difficult to estimate
CLA	• has considered the interacting factors that influence consumers • combines the advantages of IOM and ECM	• the model application is complicated

Input-output model (IOM)

Input-output modelling was first proposed by Bicknell et al. (1998) as a method for estimating ecological footprints. They claim that the primary advantage of IOM is that it provides a standard method of analysis that can be updated or applied to different populations in a uniform manner. Several subsequent papers employ this technique in calculating the carbon emissions of particular products or services in countries such as France (Hawkins and Dente, 2010) and Norway (Larsen and Hertwich, 2011). Based on this original model, other developed models include the United Kingdom Quasi-Multi-Regional Input–Output (QMRIO) models (Druckman and Jackson, 2009, 2010) and the Norwegian Environmentally Expanded Input-Output models (Larsen and Hertwich, 2011) to widen the scope. The U.S. Multi-Regional Input-Output model is particularly useful for determining the location of various production factors (such as pollution, employment, energy, etc.) in the production of goods and services, which standard IOM cannot achieve alone (Weber and Matthews, 2008).

Kok et al. (2006) describe three methods based on input-output analysis to assess the energy requirements and related carbon emissions of households in the Netherlands, namely, input-output energy analysis based on national accounts (IO-EA-basic), input-output energy analysis combined with household expenditure data (IO-EA-expenditure) and hybrid energy analysis combining input-output analysis with process analysis (IO-EA-process). The results obtained by using these methods are very similar, with less than 4% differences. Kok et al further point out that each method can be used at different levels, with IO-EA-basic being more suitable for describing and explaining the effects of household consumption, and IO-EA-process is better for searching household consumption pattern changes. The most often used is IO-EA-expenditure for a variety of practical reasons.

As can be seen in Table 1, IOM is the most commonly used carbon quantification method, especially in China where relevant data can be accessed from the Energy Statistical Yearbook and Household Expenditure Table published by National Bureau of Statistics of China. Many studies employ IOM to evaluate the indirect environmental influences of household consumption. Bin and Dowlatabadi (2005) in the United States and China's Qu et al. (2013) and Golley and Meng (2012), for example, use IO-EA-expenditure while Liu et al. (2011) adopt IO-EA-basic to calculate the indirect carbon emissions of residential consumption. The popularity of IOM in the calculation of indirect carbon emissions in China is most likely due to IOM reflecting the impact of changes in one industry on other industries, or the effects of government, foreign suppliers and consumers on the economy, making it appropriate for studying the indirect emissions of households (Zhu et al., 2012).

IOM does have some limitations, however. First, the energy input-output tables are static, while the real production and consumption system structure changes over time - so it lacks reliability when forecasting long-run effects. Second, the input-output model assumes a fixed technology coefficient, which implies that technologies are constant in a particular period, and does not address technological improvements and elasticity (Liu et al., 2009).

Life cycle assessment (LCA)

Life cycle assessment is a tool to assess the environmental impact of product systems and services, accounting for emissions and resource uses during the production, distribution, use, and disposal of a product (ISO, 1997). The global leaders agreed at the 2002 Johannesburg World Summit for Sustainable Development that LCA should be used to enhance world sustainable production and consumption patterns. LCA consists of three distinct analytical steps: (1) determination of the processes involved in the product life cycle, (2) determination of the environmental pressures (emissions, use of resources, etc.) produced in each of these processes, and (3) assessment of the environmental impact and aggregation of impact indicators (Hertwich, 2005). Commonly used life cycle approaches include process-based LCA, input-output LCA and hybrid LCA. Process-based LCA is a bottom-up model describing each constituent process of a supply chain in terms of its material inputs and environmental outputs. Input-output LCA is a top-down approach considering the resource and waste emission implications in producing particular goods and services, while hybrid LCA combines the advantages of all these methods and incorporates their distinctive useful features. Applications include Zhang et al.'s (2013) hybrid LCA to evaluate the carbon reduction potential of a typical Chinese household biogas system.

Consumption-based LCA provides a complete picture of GHG emissions due to consumer expenditure and is thus suitable for development of consumer-induced carbon management tools. Saner et al.'s (2013) LCA model, for example, is used to assess the emissions of household consumption of housing and transportation in Switzerland; Alfredsson (2004) uses LCA to calculate the energy and CO_2 intensities of Swedish household consumption to obtain the total energy requirements and CO_2 emissions of each household; and Shirley et al (2012) also use consumption-based LCA to evaluate GHG emissions during the extraction, processing, transport, use and disposal stages of different commodities and related consumption to establish carbon footprint levels in the U.S. Virgin Islands.

Emission coefficient method (ECM)

ECM is based on the method used by IPCC (2006), in which CO_2 emissions from commercial energy (fossil fuels) are:

$$E_R = \sum_{i=1}^{n} EF_i \times C_i \tag{1}$$

$$EF_i = CEf_i \times NCV_i \times OR_i \times 44/12 \tag{2}$$

If CO_2 is emitted through ways other than fossil fuels, the emission factor can be adjusted according to the IPCC reference. However, due to diverse technologies and production conditions, it is difficult to estimate the coefficient, so the results are uncertain. This method has been adopted in such studies as Liu et al. (2012, 2013) and Kadian et al. (2007). Fan et al. (2013) comment that changes in carbon emission coefficients have an inconspicuous and yet overall negative effect on changes in residential carbon emission intensity, which partly offsets the increase in carbon intensity.

Consumer lifestyle approach (CLA)

CLA was first proposed by Bin and Dowlatabadi (2005) to explore U.S. consumer-oriented energy use and related CO_2 emission activities. The term *Consumer* in CLA refers to the entity that purchases and uses products and services for the purpose of individual or household consumption. *Lifestyle* is a way of living that influences, and is reflected by, an individual's consumption behavior. CLA provides an integrated assessment framework that explicitly acknowledges the interacting factors that influence consumers, namely, external environmental variables, individual determinants, household characteristics and consumer choices and consequences.

CLA combines ECM and IOM to calculate all carbon emissions and ECM is used to assess direct carbon emissions, while IOM is employed to evaluate indirect carbon emissions. As Table 1 indicates, this method is used by Wei et al. (2007) and Wang and Yang (2014) in China and by Feng et al. (2011) in the UK.

Influencing factors

There are many factors affecting household energy consumption and CO_2 emissions, such as socio-economic factors, household characteristics and geographic factors, all of which are identified in the combined sample of papers examined. These are summarized here in terms of household income, age, size, education level, location, gender and rebound effects.

Household income

The role of household income has been widely discussed in the literature. All the studies worldwide conclude that HCEs rise with income. In Ireland, for example, direct emissions per person fall gradually as household income increases, whereas indirect emissions increase sharply with income (Lyons et al., 2012); in Spain, there is a positive relationship between average CO_2 emissions and household income levels for both direct and indirect emissions (Duarte et al., 2010); while Chancel's (2014) comparison of carbon emissions in France and United States households indicates that the richest 10% of the population in both countries emit around three times more direct carbon dioxide than the poorest 10%.

Research results in China are similar, with Peters et al. (2007) structural decomposition analysis of economic input-output data showing that the increase in CO_2 emissions from household consumption is driven by a combination of increased urban household expenditure and urbanization for, as household income in most regions continues to rise, more money is spent on recreation activities, education, transportation, communication services, etc.; Zha et al. (2010) and Han et al. (2014) find income to have the greatest association with the rise of CO_2 emissions in both urban and rural areas; Liu et al. (2011) find that indirect CO_2 emissions per capita for households with the highest income are 6.7 times and 3.8 times higher than those of the lowest income household in urban and rural regions respectively; Fan et al.'s (2012) study of the embedded carbon footprint of urban household related activities, such as food, transportation, communication, education, recreation, health and hygiene shows that total carbon emission intensity rises when an individual's expenditure is higher than 10 000 Yuan; and, according to Golley and Meng (2012), poorer households in China are more emission intensive in their direct energy consumption because of their heavy dependence on coal, with richer households being more emission intensive in their indirect energy consumption.

Higher HCEs associated with higher income levels, therefore, seems to reflect richer households' desire for more goods and services due to their higher income. They are more likely to pursue larger houses, more luxurious vehicles, more comfortable indoor environments and recreational activities, which are all significant carbon emission sources.

Age

How the age of household members affects HCEs has been a popular topic in the literature to date. Household age composition has an impact on energy use and carbon emissions. The percentage of children in Chinese households, for example, affects HCEs significantly (Golley and Meng, 2012), with young people and children emitting more HCEs than adults Han et al. (2014). A commonly held view also is that older people are likely to generate more carbon emissions in some domains than others. For example, Chancel (2014) found French 1930-1955 cohorts to be the highest carbon emitters; older people in the U.S. and UK are be less likely to adopt carbon-saving technologies (Murray and Mills, 2011; Wrapson and Devine-Wright, 2014); and UK heating expenditure increases with the average age of household members as older people are more sensitive to indoor temperatures (Meier and Rehdanz, 2010). The results in China are similar, with the percentage of older people (age $\geqslant$65) positively influencing all emissions as a result of the longer time seniors spend at home (Golley and Meng, 2012). Interestingly, though, emissions begin to decline when older people reach their later years. UK household heating expenditure, for example, shows a downward trend when the average age of households reaches around 80 years (Meier and Rehdanz, 2010). In terms of overall emissions, the turning point seems to be at around 74 years for home energy use.

The income of older people, however, also tends to decline in their later years and, as already noted, the less wealthy create less HCEs – suggesting that it might be income instead of age that is responsible for the declining HCE generation among the elderly. For example, the employed in China emit more than persons who are unemployed or retired (Han et al., 2014) and Chancel's (2014) study found no similar French cohort 1930-1955 effect in the United States, possibly due to the income inequalities of different generations in the United States being weaker than in France. There seems to have been little effort made to date to disentangle these effects in the U.S., households in different age groups simply having been linked with different income and consumption patterns, and that these differences have implications for carbon emissions, both directly and indirectly (Dalton et al.'s (2008). Research in the UK is more conclusive, with Büchs and Schnepf (2013) finding households with a relatively high percentage of older people have higher direct and indirect CO_2 emissions, after controlling for income.

Household size

Household size has been shown to influence household carbon footprints (Jones and Kammen, 2014) and is an important contributor to larger consumption-related carbon footprints in suburbs of the U.S. (Jones and Kammen (2014). Meier and Rehdanz's (2010) study of the factors affecting residential heating expenditure in the UK, also shows that heating expenditure increases with household size and the number of children in a household. The number of rooms occupied rises with household size, which may explain why heating expenditure is higher for larger households. Emissions per capita, however, decrease with family size. Lyons et al.'s (2012) calculations of the direct and indirect carbon emissions of households in Ireland, for example, reveal that although one and two person households emit roughly the same amount of methane per person indirectly, a one-person household emits more directly than any other household size, indicating per capita direct emissions to be generally lower for larger households. Studies in China confirm this, with larger households also having less indirect emissions (Qu et al., 2013).

However, household size is not the most important source of HCEs, with many studies showing that household income has a relatively stronger relationship with emissions (e.g., Zha et al., 2012; Lyons et al., 2012)

Education level

Studies on the impact of the education level of household members on carbon emissions have produced differing results. Some claim a higher education level leads to higher emissions, while others believe more schooling is helpful in reducing household-based pollutants. Golley and Meng (2012), for example, suggest that more educated households in China are more aware of the adverse consequences (health and environmental) of direct energy consumption, especially in the use of coal, and are therefore more likely to adopt improved direct energy consumption patterns, contributing to low carbon practices. Dai et al.'s (2012) study also reveals that China's "education level influences consumption attitudes and spending habits". However, Büchs and Schnepf (2013) believe that UK education is positively related to transport, indirect and total CO_2 emissions, suggesting that higher education alone is unlikely to account for HCEs as more the educated tend to consume and travel more as part of their identity. Liu et al. (2013) also find higher educated households in China to have higher emission levels, possibly because households that are better educated pursue a higher living quality. They also indicate that better educated households prefer more modern and convenient energy sources to traditional biomass, resulting in more HCEs. A similar situation exists in the U.S., where carbon dioxide emissions from electricity use and home heating rise with education (Lee and Lee, 2014). As Han et al. (2014) point out, what is really needed in education to bring about significant changes in consumption behavior is a greater emphasis on environmental philosophy.

Household location

Location is an extremely important factor affecting household energy use and associated HCEs in the UK (Druckman and Jackson, 2008), as many studies find different segments of people have differing consumption patterns based on their socio-economic characteristics. Research in the U.S. also shows the size and composition of HCEs to be significantly different between and within geographic regions due to basic demographic characteristics, with “households in some locations contributing far more emissions than others” (Jones and Kammen, 2014). The average carbon footprint per capita in the U.S. Virgin Islands, for example, is roughly 35% less than the average U.S. value (Shirley et al., 2012). This is because “regions may have different energy-saving characteristics or propensities to purchase Energy Star appliances”, with California, New York and New England regions, for example, having a higher tendency to buy Energy Star labeled appliances (Murray and Mills, 2011).

Studies in China also indicate regional differences. For example, Feng et al.’s (2011) analysis of household energy use and HCEs in different regions in China indicates that energy consumption structures and related CO_2 emissions have regional differences that are mainly reflected in the amount of energy consumed. Qu et al. (2013) also observe noticeable differences in HCEs between regions in China, with highest HCE values being over 68 times more than the lowest emission values. Being a socially diverse nation, significant differences also exist between China’s rural and urban regions in many respects, including household energy consumption (Wei et al., 2007). Recent work by Wang and Yang (2014), for example, in analyzing the impact of indirect energy consumption on the energy ecological footprint (EEF) in China based on the Consumer Lifestyle Approach and Net Primary Productivity, shows that EEF of indirect energy use is rising for urban residents but declining for rural residents.

Although most studies of the association between geographic location and HCEs focus on China and the United States, there are many other nations or regions where there are regional inequalities in the world such as Russia (Fedorov, 2002), India (Das et al., 2010) and Brazil (Santos et al., 2013). In Ireland, for example, urban households have been found to emit more per capita by indirect means than that emitted by rural households, with this pattern being reversed with direct emissions (Lyons et al., 2012).

Gender

Gender is a factor influencing indoor energy consumption (Streimikiene and Volochovic, 2011). Studies in the UK, for example, have found female-headed households to have higher direct CO_2 emissions than male headed households (DEFRA, 2008), emit higher home emissions, indirect and total CO_2 emissions and lower transport emissions (Büchs and Schnepf, 2013). According to Druckman et al. (2012), this is because UK women generally spend more time at home while men spend more time at work outside the home. Men, on the other hand, generate more leisure and recreation activities-based carbon than women do: the proportion of carbon footprint allocated to leisure being 26% and 22% for men and women respectively. Murray and Mills (2011), on the other hand, believe that gender does not significantly affect awareness of the U.S. Energy Star classification, although males are more likely than females to be conscious of appliance labels.

Rebound effects

The rebound, or take-back, effect refers to behavioral responses that tend to offset the beneficial effects of new technology or other measures taken. In terms of energy efficiency improvements, the rebound effect accounts for the gap between engineering assessments of potential energy savings (PES) after accounting for shortfall, and actual energy savings (AES) (Thomas and Azevedo, 2013).

Household energy efficiency improvements, therefore, can bring about rebound effects that make practical energy and emissions savings less than anticipated. For households, these are divided into direct and indirect rebound effects. Direct rebound effects are generated by rising consumption of the, now cheaper, energy services such car travel, heating or lighting, whilst indirect rebound effects stem from increased expenditure on other goods and services (e.g., leisure and clothing) that also involve energy and GHG emissions (Chitnis et al., 2013). These effects may lead to *increased* overall energy consumption in the long term - a phenomenon known as “backfire” (Brookes, 2000; Saunders, 1992).

Several estimates have been made of these effects involved in household energy efficiency improvements. Druckman et al. (2011), for example, estimate the rebound effects for the combined three carbon reduction behaviors to be around 34% in the UK, with re-spending on low carbon-intensive goods and services reducing this to around 12%, while re-spending on high carbon-intensive goods and services results in backfire; Chitnis et al’s (2013) estimates of the rebound effects of 7 energy efficient measures in UK households range from 5% to 15% and mostly derive from indirect effects; while Thomas and Azevedo (2013) also estimate an indirect rebound of 5-15% in primary energy and CO_2 emissions for U.S. households.

Mitigation measures

Since the realization that they significantly contribute to GHG emissions, households have been targeted in the search for appropriate carbon reduction measures (Streimikiene and Volochovic, 2011). As energy users, central government and energy suppliers are the main actors in the development of emission reduction policies (Parag and Darby, 2009) and their combined efforts are needed to achieve global carbon reduction goals. In China, it is believed that reductions in rural CO_2 emissions can be achieved from both the demand and supply sides (Liu et al., 2013). From the demand side, the adoption of more efficient technologies and green energy sources for space heating have a considerable potential for achieving low carbon households in older regions. From the supply side, in contrast, domestic CO_2 emissions can be effectively reduced by making renewable and green energy sources and technologies available to householders. Measures for carbon abatement have been proposed at the policy, technology and consumer levels as follows.

Policy level

City planning

The impact of urban form on GHG emissions in the household sector has been recognized in many studies. Lee and Lee (2014), for example, note the mitigating effects of compact and transit friendly cities in the United States, while Saner et al. (2013) consider the emissions of household consumption of housing and transportation (excluding air travel) in Switzerland, revealing a 4.30

tonnes CO_2 emission equivalent per person per year. In China, Dai et al. (2012) point to the need for more careful design of Chinese city layouts to reduce unnecessary transport service demand; Qin and Han's (2013) studies confirm that higher building density, mixed land-use patterns, proximity to public transport and jobs-housing balance are important HCE reducing planning parameters; while Ye et al (2013), after eliminating socio-economic factors, find HCEs are reduced by green spaces and water bodies – a result that needs to be taken into account in urban planning, especially in coastal cities. In general, therefore, the emphasis is on reducing the use of transport (and hence emissions caused by transport) by better planning, while providing increased green and water spaces.

Environmental protection policies

The barriers to reducing HCEs are typically the investment (and sometimes maintenance and operation) costs involved and lack of interest or information (Hamamoto (2013)). The main policies exercised by governments for environmental protection to overcome these barriers are interventions in the form of financial incentives and disincentives, mandatory standards and the provision of guidance information. Financial incentives can take the form of loans and tax credits. Zhao et al. (2012), for example, find high investment costs to be the major factor hindering Chinese homeowners' selection of energy-efficient and renewable energy (EERE) products, and that tax credits are much more attractive than interest-free loans, indicating that reasonable tax credits should be provided to encourage residents to buy EERE products.

Financial disincentives can be provided by increasing the cost of emissions. Hamamoto (2013), for example, suggests that a high carbon price is needed in order to incentivize consumers to adopt energy-consuming durable products that can reduce CO_2 emissions in Japan. Liu et al. (2011), on the other hand, believe the government should implement environmental policies involving the imposition of a HCE tax by which carbon-intensive commodities bear high levies. Similarly, Feng et al. (2010), investigate the distributional effects of climate change taxes imposed on Chinese households with different income and lifestyles, indicating that housing-related carbon emissions constitute the largest proportion of CO_2 tax payments for low income groups and that the government should provide compensation for the losses involved. They also compare the effects of a multiple GHG tax and a CO_2 tax in the UK in terms of the cost efficiency and distributional effects, and find a multi GHG tax to be more efficient than a CO_2 tax. In this way, therefore, the high investment costs of reducing HCEs can be offset by incentives such as tax credits or marginalized by increased carbon prices and other interventions.

For mandatory standards, Kadian et al. (2007), for example, compare India's energy-related household emissions and energy conservation (EC) in different scenarios, with various energy conservation technologies, policies for emission reduction and the replacement of energy-intensive appliances by efficient and less energy-intensive technologies. Similarly, Boardman (2004) explores new directions for household energy efficiency in the UK, proposing that the combined efforts of manufacturers and consumers are needed and policies should encourage manufacturers to produce more efficient products and provide motivational feedback to consumers. Niemeier et al. (2008), on the other hand, argue that a downstream GHG cap and trade program is needed to provide opportunities to engage households in California in GHG reduction. They propose a household carbon trading system with four major components: a state allocation to households, household-to-household trading, households to utility company credit transfers, and utility companies to government credit transfers. This system is considered more equitable than an upstream cap and trade system and carbon taxes.

Government provision of guidance has been shown to be beneficial to householders, especially those of higher income levels, on changing their consumption to less carbon-intensive products and services (Liu et al., 2011). In addition to information such as standards, costs, incentives and payback periods the government may implement environmental policies such as green labeling (Liu et al., 2011). Yet another approach is typified by the UK home energy visit program which, according to Revell's (2014) analysis has seen an average 3% reduction in annual household emissions, the greatest carbon savings being as consequence of installing easy energy saving measures.

Technology level

The importance of technological changes in reducing the carbon footprint is emphasized. Since emissions from heating accounts for a large proportion of total emissions in colder climates, low carbon thermal technologies such as biomass, heat pumps and solar technologies provide consumers with significant green alternatives. Monahan and Powell's (2011) comparison of four different energy typologies, found that UK households with active solar technologies (thermal and photovoltaic) provide most benefits in terms of both energy demand and CO_2 emissions, while ground source heat pumps provide the highest annual primary energy demand and carbon emissions. India is also promoting the adoption of solar home systems (SHS) to meet household lighting requirements and help abate GHG emissions (Chaurey and Kandpal, 2009).

Zhang et al. (2013), on the other hand, propose the stable running and maintenance of household biogas systems as an effective method of carbon reduction in China, indicating the need to be used for at least 1.8 years in order to make the required reduction savings offset-related CO_2 emissions in the life cycle. Biogas has also been shown to be very effective in China by Dhingra et al.'s (2011) in finding that biogas households have 54% lower GHG emissions than non-biogas households.

The indications are, therefore, that solar and biogas technologies have the most potential for GHG reduction. However, as Druckman et al. (2012) point out, technology alone is unlikely to meet climate change objectives in countries such as the UK, as behavioral change is also an essential requirement.

Consumer level

Changing consumer behavior in both the composition and volume of products and services consumed is generally regarded as an option for reducing GHG emissions (UNEP, 1995). Since expanding lifestyles are significant factors in driving UK HCEs, shifting consumption to lower GHG intensive categories is important (Druckman et al., 2011). Druckman and Jackson (2010) , for example, describe a Reduced Consumption Scenario in the UK, assuming that a 'minimum income standard' can help households achieve a decent life, and show that 37% of average household GHG emissions in the UK could be reduced if such a scenario was implemented.

In China,Wei et al. (2007) suggest that people should transform from luxurious to more frugal consumption activities, such as in less use of air conditioning, purchasing low gasoline consumption and emission cars, and using more energy conserving and environmentally friendly home appliances. Dai et al.'s (2012) studies also indicate that low carbon consumption can save large quantities of energy and CO_2 emissions in China, advise people to adopt low-carbon consumption patterns, such as reusing and recycling cloths and furnishings and using vehicles that use renewable energy, in order to save both direct and indirect energy. Moreover, as per capita emissions decrease with household size, it seems that large and extended Chinese families living together may offer a promising way for saving energy and reducing CO_2 emissions (Qu et al., 2013). For the individual, therefore, it is clear that some inconvenience is inevitable. As the population in many countries continues to increase in wealth, there needs to be a concomitant increase in environmental responsibility. It is in countries such as China, where this increase in wealth is developing most rapidly, that people are having the greatest difficulty in adjusting their life aspirations from one of ensuring the survival of the family unit to one entailing a broader environmentally responsible

In summary, to effectively reduce HCEs requires the integrated efforts of the government, households and manufacturers with each assuming their environmental responsibilities. The government's leading role is emphasized in reducing HCEs by issuing corresponding policies and regulations, as well as offering information, incentives and interventions to encourage the use of green products. Households are instrumental in adopting a low-carbon living pattern in sympathy with the needs of the environment, while technological changes also play an important role by providing green technologies and equipment.

Limitations and further research directions

- Data reliability is essential in the quantification of carbon emissions. However, obtaining detailed and accurate data in practice is problematic, especially in developing countries. In China, the energy data provided by Chinese national statistics is believed to be under-reporting coal consumption, and economic data is also questioned by several authors (e.g., Peters et al., 2007). This clearly affects the accuracy of the results. Due to the lack of authorized up-to-date datasets for the UK Environmental Input-Output model, all the years after 1995 have to be modelled using the 1995 Leontief Inverse and Imports Use Matrices (Druckman and Jackson, 2009), which may have a considerable impact on extant results. These existing data shortcomings need to be improved in the future.
- As can be seen in Table 1, previous studies of HCEs are largely restricted to China, the United Kingdom and the United States while HCEs in other countries or regions have received little or no attention to date. Admittedly, these three countries are large emitters of carbon emissions, accounting for 28%, 16% and 2% of gross emissions respectively all over the world and research into these countries can provide useful suggestions for global carbon reduction. However, other regions constitute almost half the total carbon emissions, and therefore attention in these areas is also needed.
- Existing research often analyzes the indirect carbon emissions of households using the input-output model. However, the data and results cannot provide a comprehensive explanation in terms of household lifestyles. Indirect emission sources are major contributors to pollution for most emissions (Lyons et al., 2012). Further research is needed to adopt hybrid methods to investigate indirect carbon emissions in order to obtain detailed information concerning the description of household consumption activities.
- The significant impact of rebound effects on household emission reductions has been

identified in several papers. However, the current understanding of rebound effects is still very limited and an analysis is needed of a wider scope rather than simply limited to several actions or countries. In addition, rebound effects have significant implications in the design of carbon reduction measures, and are in need of further development.

- Consumers are an important target group for reducing household-induced carbon emissions, and various policies are trying to raise the public awareness of environmental protection. However, the extent to which people are willing to reduce HCEs is still unknown. Further studies are needed to explore people's tendency to reduce HCEs, from which corresponding policies can be developed.

Conclusions

As household CO_2 emissions keep increasing, and climate change becomes increasingly serious, more forceful measures are needed to diminish the environmental burden involved and various countries across the globe have set ambitious targets in order to reduce their emissions. However, although energy efficiency has improved, total emissions are still increasing. Family households, as important GHG emitters, are receiving widespread attention, as they have a huge potential to reduce consumption-induced carbon emissions. This critical review can help interested scholars, and especially new researchers, gain an in-depth understanding of the field, and is of value for exploring new research topics concerning the role of HCEs in GHG emissions worldwide.

The review summarizes current work relating to HCEs in terms of the most commonly used quantification methodologies, factors that influence HCEs and the various mitigation measures proposed to date. Of the quantification methodologies, the four main ones are the input-output model (IOM), life cycle assessment (LCA), emission coefficient method (ECM) and consumer lifestyle approach (CLA). Each has its own different attributes, with. IOM, for example, providing a standard method of analysis that can be updated or applied to different populations in a uniform manner and easily combined with other methods, but lacks reliability when forecasting long-run effects and assuming a fixed technology coefficient that is unable to reflect technological improvements and elasticity. LCA, on the other hand, reflects the effects of the entire life cycle but is data intensive and time consuming; while ECM has an easy calculation process but entails a coefficient that is difficult to assess. In contrast, CLA considers the interacting factors that influence consumers by combining the advantages of IOM and ECM but is complicated to apply.

The main factors influencing HCEs are household income, household size, age, education level, location, gender and rebound effects. Of these the most important in household income, as this has a considerable effect on spending on such household related activities as food, transportation, communication, education, recreation, health and hygiene - reflecting richer households' desire for more goods and services due to their higher income and increased likelihood of pursuing larger houses, more luxurious vehicles, more comfortable indoor environments and recreational activities, all of which are significant carbon emission sources. The effect of age seems to be complicated, with young people and children emitting more HCEs than adults and older people less likely to adopt carbon-saving technologies but that, beyond a certain age, HCEs appear to reduce. The role of income in this pattern is unclear as yet, however, and seems likely to have a confounding effect with age. HCEs also increase with household size due to greater occupancy of rooms, etc., but decreases per capital, prompting the intriguing conclusion that the Chinese tradition of the extended family has positive implications in HCE reduction. The confounding effect of income also occurs with education level, as the better-educated are generally the better paid, although education with greater emphasis on environmental philosophy would seem to offer better prospects for the future. Geographical location is said to be an extremely important factor, with substantial differences between regions even in the same country due to different energy-saving characteristics or propensities to purchase energy-saving appliances. Of particular interest is that China, by far the world's largest GHG emitter, has significant differences between its rural and urban regions, the EEF of indirect energy use rising for urban residents but declining for rural residents. Finally, in the section it is noted that one of the most influential, but least studied, factors is the 'rebound effect', where improvements in money-saving energy-saving technologies, for instance, are accompanied by greater expenditure on energy-expending technologies. Estimated to be around 34% in the UK, it is clearly time for some serious research into this area.

Mitigation factors occur at the policy, technology and consumer levels, with city planning and environmental protection policies being the most salient policy issues – city planning emphasizing the need to reduce the use of transport by better planning, while providing increased green and water spaces. Environmental protection policies are perhaps the key to successful mitigation, involving government interventions in the form financial incentives (loans and tax-credits) and disincentives (tax imposition and levies) mandatory standards (e.g., on the use of energy-efficient produces, GHG caps and carbon trade programs) and the provision of guidance information on standards, costs, incentives, pay-back periods, labelling and through home visit schemes. The main technological contributions at the household level are biomass, heat pumps and solar technologies, with the latter providing most benefits in terms of both reduced energy demand and CO_2 emissions. Recent work on biogas, however, indicates that biogas households in China have 54% lower GHG emissions than non-biogas households – suggesting the need for further research in this area too. Finally, in this section, is another little-researched issue of householder willingness to pay for HCE reduction measures. At the present time, it appears that increased prosperity in many parts of the world, especially China, is having a counterproductive effect. As noted earlier, income is the most dominant factor affecting HCE levels and, in the absence of suitable interventions, seems set to continue indefinitely into the future.

Finally some major limitations and future directions are identified in terms of data reliability; the need for more studies outside China, the United States and the United Kingdom; and need to develop improved methods of HCE measurement.

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