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Reducing household greenhouse gas emissions from space and water heating through low-carbon technology: Identifying cost-effective approaches

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ABSTRACT

Reducing fuel use for the heating of houses is key to meeting greenhouse gas emission reduction targets. This study constructs Marginal Abatement Cost Curves (MACC) of different technologies for space and water heating of houses in the county of Gwynedd in Wales, UK, and uses information provided by energy certificates to correctly assess the energy requirements of a house. This approach allows us to accurately predict energy consumption and identify potential ways to reduce demand. We then explore the costs and savings of a switch from systems using conventional heating fuel (e.g., gas, electricity, oil, LPG, and coal) to low-carbon technology such as PV, biomass boilers and heat pumps. Solar PV was the low-carbon heating technology found to be most cost-effective per tonne of emissions abated (£/t CO_2). A reduction in capital costs of low-carbon technologies could potentially make technologies such as heat pumps be cost-effective. Without any policy intervention, low investment and fuel cost of gas would make replacement with any low-carbon technology uneconomical. Emission savings in Gwynedd over 30-year period could be between 3.494 and 5.289 Mt CO_2 if appropriate measures which cater towards reducing capital costs and/or incentivising the uptake of technology are adopted.

1. Introduction

Energy use in households for space and water heating is responsible for a large portion of greenhouse gas (GHG) emissions. For example, Wales, UK, has 1.4 million homes, that account for 27% of the nation's total energy usage, producing 15% of national GHG emissions [65]. Under the Environment (Wales) Act 2016, the Welsh Government is required to reduce GHG emissions in Wales by 80% by 2050 (compared to 1990 levels) [65]. Key to meeting this target is to reduce the energy usage associated with households.

Even before the introduction of the Environment (Wales) Act 2016, the Welsh and UK governments had introduced a variety of programmes to reduce the contribution of buildings to GHG emissions, by incentivising the renovation of existing homes to improve energy efficiency, and by financing renewable energy solutions. For instance, in 2009, the Retrofit for the Future Programme was launched, aiming to improve energy efficiency in existing housing stock and to reduce their overall annual carbon emissions by 80% [36]. Then in April 2010, the UK government introduced the Feed-in-Tariff scheme (FiT) to promote the uptake of renewable and low-carbon electricity generating technology. Under the FiT scheme, households were able to gain payments for every kilowatt-hour they generated from domestic-scale systems such as solar photovoltaics (PV). The Green Deal was introduced in 2013, which paid towards improvement in the energy efficiency of a home though replacing windows or doors, installing secondary glazing, insulating walls, upgrading heating systems, as well as generating renewable energy from wind and solar power. The domestic Renewable Heat Incentive (RHI) was introduced in 2014, through which households were able to receive payments for renewable heating technologies such as biomass boilers, solar water heating and heat pumps. More recently, the UK government announced vouchers of up to £5000 for households in England to improve their home insulation [14]. In parallel over this time, there has been considerable investment in decarbonising the electricity grid through reducing reliance on fossil fuels, moving towards more renewable sources and increasing the share of low-carbon power [20]. In light of all these measures, the UK's emissions due to housing has fallen more than one-fifths from the 1990s, despite an increase in the number of homes [7]. Residential energy consumption has also fallen in the past 20 years due to a combination of policies such as prohibition on non-condensing boilers in 2004

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and improvement in boiler efficiency and higher gas prices [16]. The Supplier Obligation programmes placed responsibility on energy suppliers to meet carbon emissions reduction targets by improving energy efficiency in the residential sector. The policies were aimed to reduce household emissions through removing barriers regarding the uptake of efficiency measures such as cost of insulation, heating and lighting [26]. Such polices have helped lower energy costs through reduced demand, which then potentially enables households to invest in measures that further reduce energy usage, such as floor, wall or cavity insulation [52,26]. Evidence shows that such policies contributed towards the growth of energy efficiency market by increasing the production capacity of low-carbon technology and insulation measures [26].

The energy efficiency of the UK's residential buildings ranks the lowest amongst EU countries [16]. Further potential exists to decrease residential emissions, however, there are often challenges associated with regards to the housing stock. For instance, in Wales, approximately three-fourth of the houses were built before the 1980s [64], meaning that, compared to the rest of the UK, Wales has a higher proportion of solid-wall homes that are more difficult and expensive to insulate, as well as more properties not connected to the gas grid [19]. Thus, inefficient building stock, coupled with low refurbishment rates has presented a challenge in improving environmental efficiency.

Low-carbon heating systems could play an integral part in reducing GHG emissions associated with households, especially for houses that are difficult to insulate. However, adoption of low-carbon technology has been relatively lower in Wales (and the UK) than the rest of Europe [22,60]. The share of low-carbon technology is expected to rise as they are expected to play a large role in reducing emissions in the future [44]. Countries such as Sweden and Norway have a much higher heating demand than the UK due to cold climates, but they mainly depend on electricity from renewables and heat derived from waste, thus having lower emissions associated with household energy use [16]. Jalil-Vega [40] assessed the cost of heat networks of a UK city (Bristol) against that of low-carbon technologies, and found that the electrification of heat can be a cost-effective option if the heat generated through district heat pumps is distributed through a heat network rather than having individual building heat pumps. They found that that the cost for improving distribution and transmission of electricity supply to cater for higher electricity demand due to individual heat pumps would be higher than the cost of setting up a district heat network. However, heating homes only by using electricity from the grid would result in higher electricity demand that the current grid or distribution systems may not be able to handle without expansion. It would require reinforcement of electricity transmission and distribution and disuse of gas networks, thus increasing costs further [16].

The generally higher cost of low-carbon heating systems relative to conventional heating systems has proven to be a hindrance in gaining market share [22]. Furthermore, new heating systems are mostly only bought when the current system has reached the end of their working life as there is not a strong enough incentive to replace existing working systems.

Natural gas has been the widely used for residential space heating in the UK [16]. Gas heating systems have low upfront, running and maintenance costs, which makes them more desirable for households [2,20,6]. To become a viable alternative to conventional heating systems such as gas, low-carbon heating systems need to be financially attractive to households, which will need significant government investment in incentives and/or generate sufficiently attractive savings on energy bills for households.

Focusing a case study area of Gwynedd, a county in north-west Wales, the aims of this paper are two-folds: firstly, to use information from household energy certificates and MACC to assess the cost-effectiveness of potentially suitable low-carbon technologies for households; and secondly, to explore 'what if' scenarios which may influence the GHG emission savings potential and cost-effectiveness of such low-carbon technologies.

Studies have shown that low-carbon technologies such as heat pumps (air and ground source pumps), PV and biomass boilers have had a great impact in reducing emissions, however economic drivers are key components in an individual's decision making [66,57,29,38].

The difference in cost-effectiveness of technologies may arise due to the fuel used by houses for heating purposes [61,44], different energy costs [38] and emission factors as well installation costs [63]. When comparing factors that influence the economic viability of Ground Source Heat Pumps (GSHP) in four cities in Canada, Le Dû et al. [45] found that the cost of energy and its source had the greatest impact, however, subsidies on GSHP did not improve its economic attractiveness. Esen et al. [29] found that in Turkey, GSHP were economical compared to other heating systems such as coal, oil, and liquid petroleum gas, however, it was less cost-effective than systems using natural gas due to the relative low cost of natural gas.

Until recently, PV systems were used to generate electricity only for the grid, however with increasing energy prices, electricity generated through PV systems is becoming more attractive for individual homes [42]. The optimal size of PV for individual homes has been dependent on the buying and selling price of electricity as well as energy demanded by the property [38]. So if the selling price of electricity was sufficiently higher than the buying price, then it would be beneficial for the property to install the maximum size of PV system [48]. Yu [66] studied the economic attractiveness of PV systems combined with lithium batteries for the French residential sector and predicted that such a system would become profitable before 2030. Their study also emphasised the importance of a steady transition to PV systems as rapid growth in the market impacted price competitiveness, in turn leading to slower growth of the technology. Slower integration of technologies would also provide an additional benefit of lowering costs of a technology due to competition and improvements over time.

Biomass boilers have the potential to reduce heating costs and associated GHG emissions and increase energy independence especially in remote locations that do not have access to natural gas for heating [58,53]. Carpio et al. [17] found that the use of biomass boilers in heating promoted economic savings and improved the energy ratings of a building. Furthermore, the use of woodchips and wood pellets as fuel for biomass boilers led to an 88% and 70% cost saving compared to gasoil, respectively, showing that savings would depend on the type of biomass used.

This study focuses on low-carbon technologies deployed individually in houses. The economic and environmental performance of hybrid systems such as PV combined with heat pumps was not evaluated in this study, but Cui et al. [23] found that such systems can be cost-effective and payback is received as early as 4.15 years in their 25-year lifespan. A similar study by Allouhi, Rehman and Krarti [3] showed that a hybrid photovoltaic/biomass system reduced costs by 25% and carbon emissions by 47% compared to the conventional system, hence improving energy efficiency of rural houses significantly. We did not include hybrid systems in our study as we wanted to focus on the implications of replacement of a single fuel heating systems with an individual low-carbon technology.

The importance of this paper stems from the uniqueness of the method of estimation of energy consumption which is calculated from the energy certification of houses. The energy consumed by a household is influenced by factors such as floor area, the type of fuel use, and the degree of insulation [41].These factors may make it difficult to estimate the energy consumption of individual homes without conducting a through survey which may be time consuming and/or costly. Energy certificates are determined according to a recognised framework by the regulating body and are conducted by a professional assessor who is suitably qualified and has had relevant training and experience [25] (see Section 2.1). Using energy consumption data from energy certifications would allow us to accurately calculate households' energy demand and should enable useful and realistic recommendations to be made.

To achieve the aims of this paper, we use information from the energy certificates together with Marginal Abatement Cost Curve (MACC) assessment to determine cost-effectiveness of low-carbon heating systems. MACC have been used by policy-makers to show the economic cost-benefits of climate change mitigation methods by plotting the marginal abatement cost and the total carbon emissions abated [43]. MACC can aid in decision-making by identifying interventions that are most cost-effective per unit of CO_2 equivalents abated [32,67,16,37]. For this to be done accurately, there is a need to assess all the expected potential costs associated with the low-carbon technology, such as operating, maintenance and other costs across its expected lifetime.

However, the use of MACC for informing policy comes with certain caution. Due to the static nature of MACC, adoption of one measure may potentially change the cost-effectiveness of another measure. Negative abatement costs of a measure indicates that the project would yield positive returns and save money, while positive abatement costs show that the project would lose money [62].

In this paper, we use the energy consumption data calculated from the energy certificate, together with MACC, to examine the cost-effectiveness of replacing systems using conventional heating fuels like gas, electricity, oil, LPG, and coal with low-carbon technologies like PV, heat pumps and biomass boilers for houses in Gwynedd. A 30-year time-period (2018–2048) was selected to construct MACCs to allow, at least once after its installation in 2018, the replacement of all low-carbon technology after it has come to the end of its life. The marginal abatement costs were calculated to show the cost or savings associated by the reduction of per unit of emissions by the households if they replaced their current heating system with low-carbon technology.

2. Methodology

2.1. Sourcing of data

The data collected for this study was taken from the Energy Performance Certificate (EPC) website for the houses in Gwynedd over a 10-year period (2008–2018). EPCs are calculated according to Standard Assessment Procedure (SAP), which standardises the assumption for occupancy and behaviour to facilitate comparison between dwellings.

In the UK, an EPC assessment is mandatory at the initial stage when deciding to purchase or sell a house [25]. The EPC's primary focus is on energy losses in a home due to heat losses. Hence, a good rating may be achieved if the home has good roof, wall and floor insulation as well as double-glazed windows [55]. EPC also evaluates the impact of heating systems used in a dwelling.

An EPC rating is determined following an on-site audit by an assessor. This includes an evaluation of the structure of the house, insultation, heating systems and other aspects of a home. The experts can assess heat losses which may be otherwise missed, such as those from chimneys or ineffective air tightness of the home.

The inspection is carried out in segments, and for each segment a score is given depending on how efficient that segment is calculated according to the SAP [15]. SAP is a methodology set up by the UK Government to show that a property complies with the current building regulations. The scores given are based on construction material of the property, the efficiency of heating systems, levels of insulation, the fuel use for space and water heating, energy costs, air leakages and renewable technology available on the property. Once the SAP scores are calculated, it is used to form an EPC. The final score is calculated by summing the individual score of the segments and the highest value it can take is 100. The SAP scores are then categorised into 7 EPC bands: Band A to Band G. Band A represents the most efficient band where the energy costs are the least and Band G represents higher energy costs thus, being the least energy efficient band.

The EPC has been used as a method to bring about improvements in the energy efficiency of homes. In April 2018, Minimum Energy Efficiency Standard (MEES) came into effect under which landlords were unable to renew leases for homes which fell under Bands F and G, until the property's energy rating was improved to a minimum of Band E. It is expected that the standard will further tighten so that properties fall under Band B as a minimum by 2030 [13].

For this paper, we use information from the EPC as a guideline to calculate energy consumption of selected houses and ignore the EPC band, as it is not important in the context of this paper. Using the energy consumption data generated from the EPC allow us to accurately calculate the consumption trends in homes in Gwynedd, although we are cognisant that the data might not reflect the trends in energy consumption in the rest of Wales. A random sample of 9526 houses from the EPC was selected to estimate the energy consumption of households in Gwynedd. The sample was carefully selected to represent only houses using a single fuel type. EPC characterises a house as a property which has heat losses from ground floor and an exposed roof. A property without heat loss from floor is not considered a house, but a flat or a maisonette [15]. Flats and maisonettes were omitted from the sample as energy demand for such properties are different and low-carbon interventions may have different savings compared to savings in houses.

The demand for energy in housing would vary according to the floor area, the type of fuel use and insulation of the house [41]. To consider variations in energy demand, the sample was selected to represent energy consumption due to different heating fuels and house size. Houses already using low-carbon heating systems such as heat pumps, solar PV or biomass boilers were omitted from the study as they already had interventions to improve energy efficiency of the property.

Due to lack of availability of insulation data, the sample size could not be further classified according to houses' insulation, which is known to affect energy demand. The number of houses belonging to each fuel category varied according to the fuel's popularity, availability, and ease of access. The number of houses using gas or electricity were more than the houses using alternative fuel such as LPG, oil, or coal. A minimum of 17 houses in 25 categories of fuel type and house size were selected to assess the average annual space and water heating energy consumption.

The emissions abatement potential from switching to low-carbon heating systems was then calculated for the 54,241 houses in Gwynedd [51]. Due to the lack of availability of data on houses in Gwynedd that have low-carbon technology, it was assumed that all these houses used conventional fuels for heating. As expected, households used different kinds of fuel for space and water heating, with the most prevalent fuel used for heating being gas (71%), followed by electricity (15%), then oil (8%), LPG (5%), and lastly, coal (1%). Although gas does remain the prevalent fuel in Gwynedd, proportionally fewer properties are connected to the gas grid in Gwynedd than the rest of the UK due to it being rural area of lower housing density, which made it costly to connect individual houses. Gwynedd, therefore, has a higher proportion of homes heated by electricity, oil, LPG, and coal.

Energy consumption in homes will also differ due to factors such as the presence of teenagers [41], household income [28], number of bedrooms [5] and time spent at home during weekdays [5]. Furthermore, energy consumption differs according to house size, with larger houses demanding more energy. For instance, it is known that energy consumption patterns vary from rural to urban populations, with homes in urban areas generally being smaller than those in rural regions such as Gwynedd, and so tend to be more energy efficient [28]. Determining the consumption of energy per m^2 floor area may allow extrapolation of data according to the distribution of different house sizes, however, this is problematic as larger houses have a larger floor area that may not all be heated. Using energy consumption per m^2 as an indicator of energy demand for larger houses may not be precise and may show much lower energy consumption per m^2 than smaller houses. In order to differentiate between energy consumed by smaller and larger houses, EPCs divide household energy consumption into five different categories, based on their size [25].

This paper only focuses on energy required for space and water heating. However, energy consumption data provided by the EPC is the total energy used in the households, as opposed to a breakdown by categories such as space heating, water heating, lighting, and appliances. The EPC does, however, also provide information on the cost of space heating, water heating and appliances, separately, along with the type of fuel used. Using the energy costing data for households provided by the EPC, for a single type of heating fuel, energy consumption in kWh was calculated.

Table 1 presents the calculated annual average energy consumption (kWh) according to the fuel type and households' size category in Gwynedd. The average annual energy consumed for heating was thus calculated by dividing the cost of space and water heating with the unit cost of heating fuel, given in equation below.

$$Average\ Annual\ Energy\ Consumption\ (kWh) = \frac{Total\ household\ annual\ energy\ cost(£)}{Unit\ cost\ of\ heating\ fuel(£/kWh)} \quad (1)$$

The energy costs of heating fuel (£/kWh) used for energy consumption calculations are given in the Supplementary Material (Table S1).

The data given by the EPC included details on the type of fuel used for a specific purpose in a house. The average annual energy consumption for space and water heating allowed us to determine the size and capacity of low-carbon technology required to fulfil the needs of the household.

The average annual energy consumption ranged from 8003 kWh to 76,864 kWh and varied according to house size and fuel type. For example, smaller houses consumed almost twice as much as energy from gas and oil as compared to houses of similar size using standard tariff electricity, most likely due to the lower efficiency of gas and oil powered boilers [15]. Households using coal as primary fuel consumed three times as much energy as houses of similar size using electricity. This may reflect the fact that electricity-based systems have a higher efficiency than gas, oil, LPG and coal-based heating systems [15]. Furthermore, due to coal having a lower calorific value than the rest of the fuels used for space and water heating, a higher kWh of coal is consumed to fulfil heating demands [12].

2.2. MACC

MACC can be classified according to the underlying methodology – with either a top-down or a bottom-up approach used to construct a MACC. The top-down approach uses economic models to explore the impact of economic issues like energy prices or emission policies whereas the bottom-up assess the mitigation measures and rank them according to their cost-effectiveness [67].

Expert-based MACC is used in this study that uses bottom-up approach to assess the cost and carbon-reducing potential of single abatement measures. Expert-based MACCs are sometimes called "technology cost curves" as they are built upon the carbon mitigation potential from a single technology [43]. An explanation of Expert-based MACC is given in the Supplementary Material (Fig. S2).

Yue et al [67] derived MACC based on Irish TIMES energy system model where they included scenarios to capture more details about mitigation technology that reflect the interaction between the technologies. Although MACC provided more robust policy insight than the conventional scenario analysis, they were highly reliant on the model assumptions.

Timilsina et al [59] developed a MACC for the building sector in Armenia and Georgia. The measures for emission reduction included structural changes like improvement in floor, wall and window insulation and replacement of inefficient light bulbs and appliances. They found that penetration rates of the measures had a strong effect on the emission abatement potential: the higher the penetration rate of measures, the lower the potential emissions reduction, as the decline in emissions had already been realised.

Hamamoto [37] constructed MACCs to assess the emissions reduction in houses through behavioural measures. They found that to promote energy saving, and in turn, emission-saving behaviours, a higher carbon price is required. Using regression analysis, they also found that larger houses, houses with fewer occupants, and lower income houses had higher costs savings from energy-saving measures than their counterparts.

The construction of MACC requires an establishment of a baseline scenario that reflects the present situation. Due to market imperfection, market barriers, irrational behaviour of agents and incomplete information, it is important to construct MACCs with extreme caution [47]. MACC were constructed using the methodology given by Ibrahim and Kennedy [39]. The cost-effectiveness of a mitigation technology is calculated by:

$$CE_{MT} = \frac{NPC}{Emissions_{MT}} \quad (2)$$

where:

CE_{MT} = Cost-effectiveness of mitigation technology, £/t CO_2

Table 1
Average annual energy consumption according to fuel type (kWh) and household size in Gwynedd.

	Fuel Type (kWh)				
House size (m^2)	**Electricity**	**Gas**	**Oil**	**LPG**	**Coal**
1–55	8003	17,986	18,747	10,639	23,266
55–70	9928	19,236	23,926	12,185	25,909
70–85	11,170	21,074	22,687	13,758	32,420
85–110	12,564	24,889	27,034	13,559	37,200
>110	21,585	37,253	47,826	22,495	76,864

NPC = Net Present Cost, £
$Emissions_{MT}$ = Emissions saved through the implantation of mitigation technology, t CO_2

The NPC is calculated as the sum of all costs subtracted by savings due to the mitigation technology, and then discounted.

$$NPC = CC_{MT} - CC_{RT} + \{(OC_{MT} - OC_{RT}) - ES + CE_{AF}))\} * \frac{(1+r)^t - 1}{r(1+r)^t} \quad (3)$$

where:

CC_{MT} = Capital Cost of mitigation technology, £
CC_{RT} = Capital Cost of reference technology, £
OC_{MT} = Operating and maintenance cost of mitigation technology, £
OC_{MT} = Operating and maintenance cost of reference technology, £
ES = Energy cost Savings calculated by multiplying energy saved with the unit price of fuel, £
CE_{AF} = cost of alternative fuel, £
r = discount rate, %
t = lifetime of the mitigation technology, years

The energy cost savings (ES) is calculated by multiplying energy saved with the unit price of fuel.

$$ES = (EC_{RT} - EC_{MT}) * UP_{RF} \quad (4)$$

where:

EC_{RT} = energy consumption of reference technology, kWh
EC_{MT} = energy consumption of mitigation technology, kWh
UP_{RF} = unit price of baseline fuel, £/kWh

In addition, the cost of alternative fuel (CE) is calculated as:

$$CE_{AF} = EC_{AF} * UP_{AF} \quad (5)$$

EC_{AF} = alternative fuel consumption, kWh
UP_{AF} = unit price of alternative fuel, £/kWh

Lastly, $Emissions_{MT}$ is calculated as:

$$Emissions_{MT} = [(EC_{RT} - EC_{MT}) * EF_{RF}) - EC_{AF} * EF_{AF}] * t \quad (6)$$

where:

EF_{RF} = Emission factor for reference fuel, kg CO_2/kWh
EF_{AF} = Emission factor for alternative fuel, kg CO_2/kWh

The mitigation technology is implemented as a replacement of an existing method or it is replaced when the existing baseline reference technology has expired. If we assume that the reference technology is in working order and is being replaced before the end of its lifespan, then in the investment cost of the mitigation method, we would need to factor in the residual cost of the reference technology being replaced or the cost of disposal of the reference technology. To overcome this problem, we assume that the households are replacing the reference technology when it is at the end of its lifespan [22]. Households would therefore have two choices: either to substitute the reference technology with mitigation measures such as PV, or substitute the reference technology with the same technology but with higher efficiency due to a newer model.

2.3. Scenarios

Different 'what if' scenarios were constructed to estimate the direct or indirect effect of policy changes on the emission abatement potential and cost savings for houses in Gwynedd.

2.3.1. Baseline scenario

The *Baseline Scenario* is constructed for Gwynedd to reflect residential demand for energy consumption. In the *Baseline Scenario*, it was assumed that the consumer's uptake of the technology is without any policy intervention.

The initial investment costs, installation, maintenance, and operating costs of mitigation technologies have been gathered through extensive market research as there are different makes, models, sizes and quality for low-carbon technologies. Costing data was taken from studies and reports such as NERA [50], DCLG [24] and CCC [18]; supported by more recent data obtained through online resources (e.g. boilerguide.co.uk, screwfix.com and greenmatch.co.uk) to allow for accurate market representation. The costing of low-carbon technologies allows for changes in size and capacity of the technology according to the energy demanded by the households and is presented in the Supplementary Material (Table S3). The costs of low-carbon technologies have been calculated keeping in mind the size of the house and the energy demand. The costs of low-carbon technologies are adjusted for inflation according to the rates given by the Bank of England and reflect the prices in 2018 to make cost comparison easier between the technologies. The cost assumptions are subjected to uncertainties as they reflect the maturation of the technology [44].

The market penetration rates have been determined based on the historic trend of share of mitigation technology in the residential sector [11]. The emission factors and unit price of fuel is based on the rates provided by the UK government and are presented in the Supplementary Material (Table S1) [8,11].

2.3.2. Mitigation scenarios

Three alternative emission mitigation 'what if' scenarios were constructed to capture the effect of policy changes that may influence a mitigation technology's investment costs, the market penetration of the technology, and improvement in energy efficiency.

Low-Carbon mitigation measures

PV: Photovoltaics technology converts daylight directly into electricity through the interaction of sunlight with a semiconductor material inside the PV cell. The cost of PV ranged from £7402 (for a 4 kW installation size) to £14,187 (for a 13 kW installation size) based on the size of the house [9,8,11]. The electricity generated from PV was calculated using the formula below, provided by SAP [15].

$$Electricity\ produced\ by\ PV = 0.75 * kWp * S * Z_{PV} \quad (7)$$

The electricity produced by PV depends on the installed peak power (kWp) of the PV module, the solar radiations (S) and the overshading factor (Z_{PV}). The installed peak power was determined by assuming that the PV cells have power density of 0.125 kWp/m^2. Annual solar radiations were calculated using SAP guideline which considered solar radiations in Wales over a 12-month period, including seasonal variances in production potential [15].

The assumptions made regarding the angle of PV and orientation were taken in line with the SAP guidelines set by the government for calculation of energy ratings [15]. In accordance to the SAP guidelines, if some values were not known due to missing data, then it should be assumed that the PV installation was done at a 30° angle with South orientation.

The SAP assumes that the overshading factor takes the value of 1 in case of none or little overshading, the value of 0.80 in case of modest overshading, the value of 0.65 in case of significant overshading and lastly the value of 0.50 in the case of heavy overshading. In accordance to SAP guidelines, where data is not available for the calculation of electricity produced by PV, overshading factor should take the value of 0.8 which implies modest shading [15].

The performance of PV is known to be affected by something as small as a shade of a chimney, tree, building or an antenna on the PV panel [33,46]. Approximately 69% of all urban tree canopy coverage in Gwynedd is due to non-woodland trees which represents the individual or group of trees along the streets, gardens, carparks and other urban private and public open spaces [31]. Compared to Gwynedd, the average percentage cover of the non-woodland trees was lower in the rest of Wales, implying higher shading due to tree cover in Gwynedd. Thus, it was assumed for this study that Gwynedd had a greater overshading factor of 0.65.

Currently, there are 2106 domestic solar PV installation in Gwynedd, covering 4% of housing stock in the region [10]. The total annual energy generated by PV may not be able to cater to the total annual final demand of households, so it was assumed that the shortfall of energy required for space and water heating would be covered by the conventional heating fuel. Where PV produced a surplus, any additional energy generated by households was fed back into the grid with households receiving the standard rate for electricity.

Biomass boilers: Biomass boilers work in the same way as conventional gas boilers, but burn woodchips, wood pellets or wood logs to produce energy for space and water heating. For this study, we explored MACC for biomass boilers using woodchips or wood pellets as a source of fuel as both these sources have different unit price and emission factors. The capital cost of biomass boilers ranged from £15,510 (for 15 kW installation size) to £25,850 (for 25 kW installation size), based on the size of the house and their heating demands [34].

ASHP: Air Source Heat Pumps use external air to heat the homes. ASHP work best in homes with a good level of insulation and underfloor heating. The performance of heat pumps is measured in terms of coefficient of performance (COP). It was assumed that COP for ASHP was 3, so three units of heat was produced by using a single unit of electricity, thus making ASHP cheaper to run than the normal boilers.

GSHP: Ground Source Heat Pumps absorb heat from within the ground and use it to heat homes. GSHP have a higher COP than ASHP, implying that they may be less expensive to run than ASHP. The COP of GSHP used in this study for space and water heating was 4.

Gas and electric boilers: Gas and electric boilers are not considered as low-carbon technology but have been included in the mitigation scenarios for two reasons. Firstly, to determine the cost-effectiveness of prevalent heating fuel which hinder the adoption of low-carbon technology. Secondly, to obtain the potential emissions abated from the replacement of old boilers or replacement of other conventional boilers like oil, LPG, and coal to gas or electric boilers.

Technological Scenario

The *Technological Scenario* assumes that over the years, the production efficiency of the mitigation technologies would increase, thus leading to reduction in their costs. Since the costs of technologies tend to change as they mature over time [44], we assumed a potential reduction of 20% in the costs of technology over the 30-year study period which would increase market share of the technologies. The assumed 20% reduction in cost was based on the study by the CCC [21], which looked at the impact of a 20% fluctuation in cost on the uptake of low-carbon technologies. We also assumed that with the increase in market share of these mitigation technologies, the market share of gas as an energy source would decrease in parallel.

Energy Efficiency Scenario

The *Energy Efficiency Scenario* assumes that over the years, the trend of increase in energy prices would continue. The expected future fuel prices have been taken from the estimation provided the UK Government [8]. Furthermore, the *Energy Efficiency Scenario* assumes that the emissions from electricity would reduce considerably due to decarbonisation of electricity supply.

Technological-Energy Efficiency Scenario

It is widely believed that one measure may not be enough to reduce household emissions significantly – a combination of policies would aid in reducing emissions significantly. As well as the doubling of market share assumed in the *Technological Scenario*, this scenario further assumes an increase in fuel prices and a decrease in emissions due to electricity.

3. Results

3.1. Baseline **S**cenario

The *Baseline Scenario* assumed that there had been no policy interventions and the uptake of technologies was according to past trends [11]. In that case, the total emissions from space and water heating of 54,241 residences in Gwynedd [51] was 0.302 Mt CO_2 in 2018, which may potentially be reduced to 0.189 Mt CO_2 per year by 2048. If the existing trend of uptake of mitigation technology continues without any policy changes, then 3.4 Mt CO_2 could be saved over the 30-year period. The baseline MACC is presented in Fig. 1.

Although gas boilers were not considered as low-carbon technology, their implementation in homes with other (less efficient) sources of fuel would save about 0.054 Mt CO_2 per year, with a cost of abatement of −1194 £/t CO_2. The results of cost efficiency (£/t CO_2) and emissions abated (t CO_2) for all 'what if' scenarios are given in Supplementary Material (Table S4).

After replacing conventional systems with more efficient gas boilers, the most cost-effective mitigation technology was PV, which resulted in a reduction of 0.015 Mt CO_2 at a cost of abatement of −160 £/t CO_2. The lowest emissions savings was from ASHP (0.002 Mt CO_2) and GSHP (0.002 Mt CO_2), based on the lack of uptake of these technologies thus far in the UK. Biomass boilers would also contribute significantly to the reduction in emissions (0.039 Mt CO_2), however due to their high installation costs, the cost per tonne of CO_2 emission abated would be the highest, ranging between £382 to £597.

Although electric boilers were included as a mitigation measure, their installation would increase emissions and so they have been omitted from analysis under the *Baseline Scenario*.

3.2. Mitigation scenarios

Fig. 2 presents the MACC for the *Technological Scenario* where it was assumed that the penetration rate of the mitigation technology has doubled from the *Baseline Scenario* and the capital cost of the technology had reduced by 20%. The total emissions savings in this scenario would increase to 0.16 Mt CO_2 per year in Gwynedd.

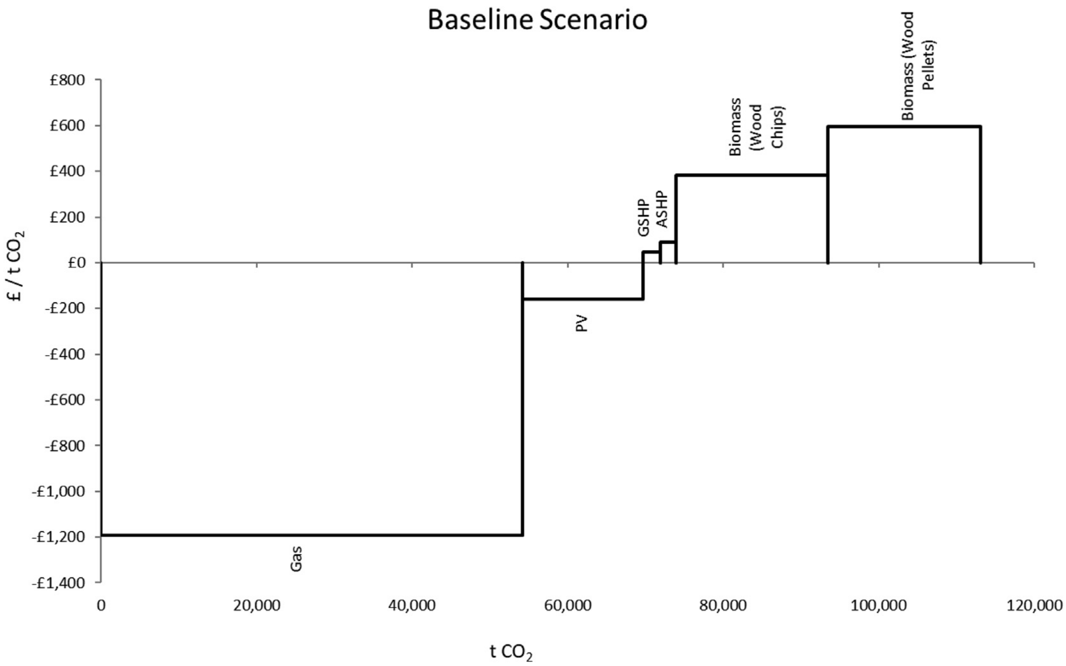

Fig. 1. MACC of Baseline Scenario for space and water heating for households in Gwynedd.

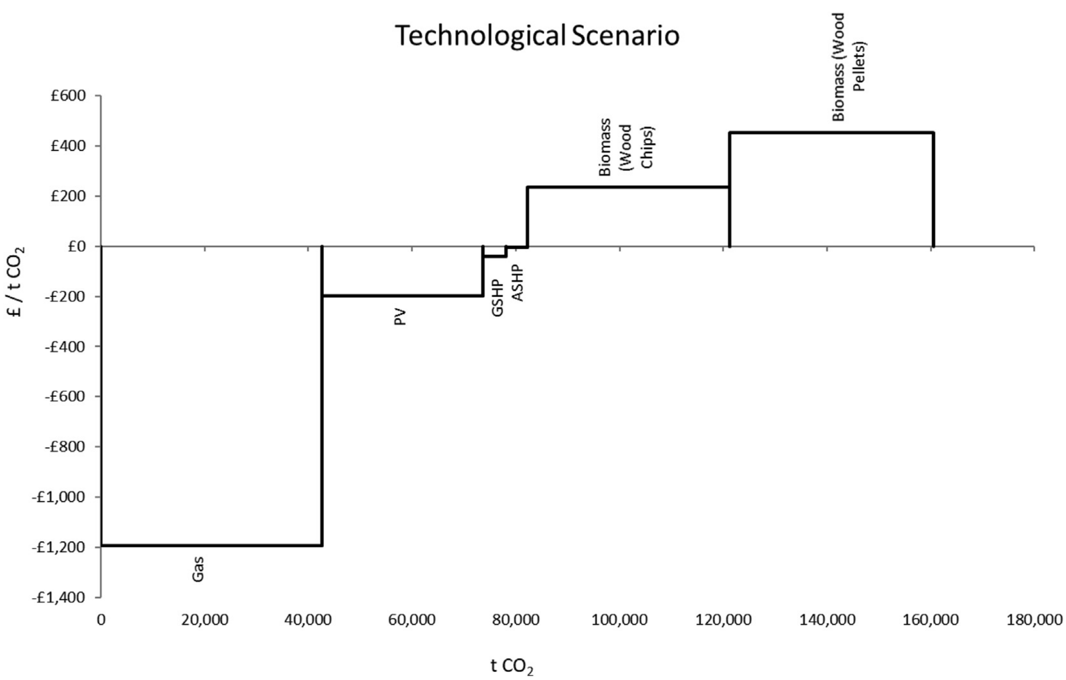

Fig. 2. MACC of Technological Scenario for space and water heating for households in Gwynedd.

Gas and PV remained the most cost-effective solutions, generating savings per unit of emissions abated. The emission savings from gas declined from the *Baseline Scenario* to 0.043 Mt CO_2 as the share of gas as fuel reduced due to an increase in share of other heating systems. The uptake of PV would then potentially save 0.03 Mt CO_2 per year. The switch to GSHP and ASHP could potentially result in total emission savings from heat pumps of 0.008 Mt CO_2 at a cost of 39 £/t CO_2 and 6 £/t CO_2 abated, respectively. Despite the assumed reduction in the cost of technologies, biomass boilers remain cost-ineffective due to being more expensive than other heating systems.

Fig. 3 presents the MACC for the *Energy Efficiency Scenario*, which assumes that the previous trend of increase in fuel prices would continue. Moreover, the emissions from electricity would decrease due to decarbonisation of electric grid. The total emissions abated in a year under this scenario was 0.116 Mt CO_2.

Gas, PV and heat pumps, like in the *Baseline* and *Technological* scenarios, remained the most cost-effective system in the *Energy*

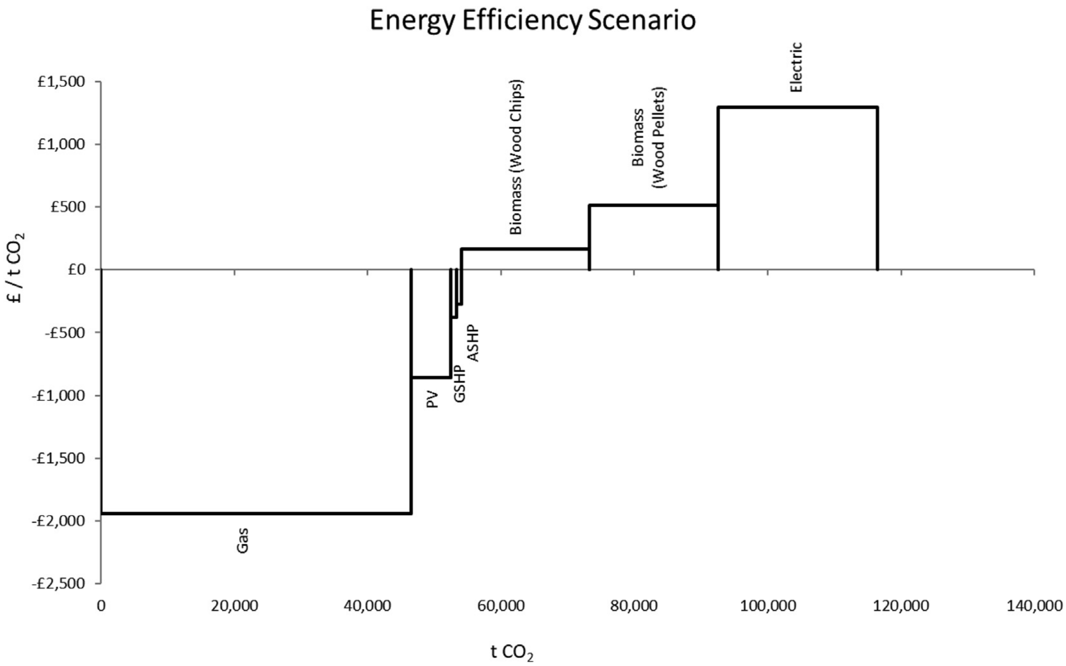

Fig. 3. MACC of Energy Efficiency Scenario for space and water heating for households in Gwynedd.

Efficiency Scenario. Under the *Energy Efficiency* scenario, it was assumed that the emissions due to electricity use would decline in the future. The results showed that the use of electric boilers would lead to a decrease of 0.024 Mt CO_2, however, it was the least cost-effective option after biomass boilers.

Fig. 4 presents the combination of *Technological-Energy Efficiency Scenario*. The total emissions abated in a year rise significantly to 0.176 Mt CO_2 per year with all mitigation measure becoming cost-effective apart from biomass boilers using wood pellets as fuel (due to much higher cost per kg than woodchips). This suggests that a combination of policy measures that cater to changes in emissions, energy use, cost of low-carbon technology and increase in their market share would result is the most reduction in emissions. Our results show that biomass boilers may become cost-efficient if their cost decreased by 20%, however, the cost of type of fuel used for biomass boilers was also important.

In all scenarios, we see that gas boilers and PV remained the most cost-effective heating technology. Although gas boilers would not be considered as low-carbon technology, their low costs show why gas has continued as a preferred fuel for space and water heat-

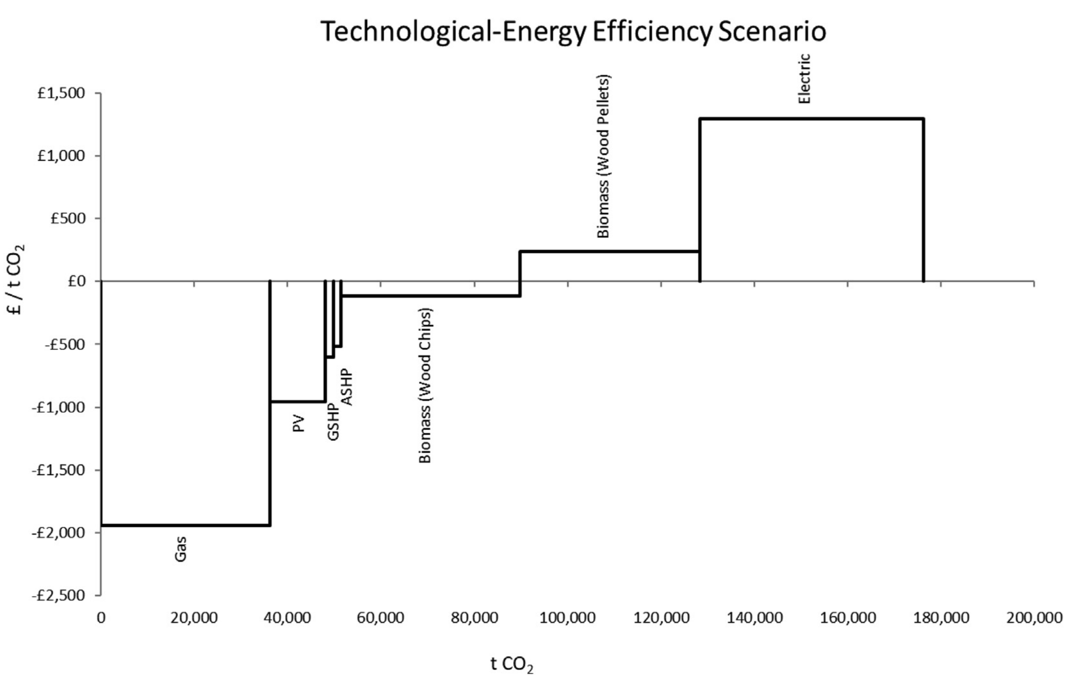

Fig. 4. MACC of Technological-Energy Efficiency Scenario for space and water heating for households in Gwynedd.

ing systems. Therefore, decarbonisation of the gas grid through hydrogen and biomethane [35] and switching to it from other fuel sources could still yield a significant reduction in emissions.

4. Discussion

Households are becoming more aware of their carbon footprint and are increasingly concerned about the environment [27]. This has created a great potential for emissions abatement from household energy use, so long as it is affordable to implement.

In this study, we aimed to introduce a variety of measures that may be implemented to shift from conventional to low-carbon heating technologies in the homes of a case study region of Gwynedd, a county in north-west Wales. As explained earlier, several variables influence energy demand and its use in households, as well as the availability/suitability of different technologies, which will in turn influence the CO_2 emissions per unit of energy used. Extrapolation of results from one case study region to others, or a national scale, should therefore always be done with caution. Nevertheless, the findings of this work could still help inform discussions around energy policy and on the abatement potential and associated costs, as many of the same challenges, and indeed answers, will apply to other regions.

We found that without any intervention, and under continuation of the current trend in the uptake of heating technologies, gas boilers remain the most cost-effective heating system, followed by PV, providing largest emission savings. Though gas boilers are not considered as low-carbon technology, the decarbonisation of gas grid through hydrogen and biomethane [35] and replacement of fuels like coal, oil and LPG with gas would yield higher emission saving in the future. Even by reducing the investment costs of low-carbon technology by 20%, we saw that gas boilers remained more cost-efficient than any other heating systems. The low capital cost of gas boilers allows them to compete with low-carbon technologies such as biomass boilers.

The percentage of decline in costs was assumed, however, it may be possible that this may differ between technologies due to competition, innovation or maturation of technology [27,44]. This study assumes a blanket reduction in costs to show that low-carbon technologies, such as heat pumps, which were not previously cost-effective, can become attractive.

Without policy intervention, it is more likely that the conventional heating systems would remain in place and their integration in the infrastructure would slow down the deployment of low-carbon technologies [44]. As shown in studies such Kozarcanin et al. [44], Vicente and Alves [61], Hartner et al. [38] and Esen et al. [29], the reduction in investment costs has allowed low-carbon technologies to become more cost-effective. This, coupled with the continuing trend of increasing fuel prices, mean that low-carbon technologies like PV and heat pumps become more desirable. However, similar to Esen et al. [29], low-carbon technologies such as GSHP would be unable to replace gas systems due to its relative inexpensiveness. If the 'what if' scenarios were to be implemented, the emission saving in Gwynedd over 30-year period due to *Technological Scenario* was 4.816 Mt CO_2, *Energy Efficiency Scenario* was 3.494 Mt CO_2 and *Technological-Energy Efficiency Scenario* was 5.289 Mt CO_2. Hence, the largest emissions savings was achieved through a combination of policy measures that influenced energy costs, emissions factors and the market share of technologies.

Similar to Le Dû et al. [45], we found that cost of energy had a great impact on the economic attractiveness of a heating system. Biomass boilers only become cost-effective in when using woodchips as fuel as compared to wood pellets, which are more expensive. Thus, it may be possible that a technology be cost-effective only when using a fuel with lower costs.

Policy-makers agree that without any policy intervention, the UK will continue to use natural gas for home heating, which would counteract the climate policy goals [30]. Renewable electricity and heat networks can lessen the dependence on gas. Urban heat networks have the ability to reduce costs and emissions especially when supplied with low-carbon electricity. Similarly, electrification combined with biomass has the potential of increasing energy efficiency of residential buildings. Thus, implementing one measure may not be enough for households to switch to low-carbon technologies. Even though a measure is cost-effective and has potential to reduce emissions, it may still not be implemented due to technical and institutional barriers. Unfamiliarity with newer technologies also presents a challenge to overcome wider adoption of low-carbon heating. Policies with environmental causes would more likely motivate households to adopt newer and innovative technologies [27].

The transition towards low-carbon heating systems would require changes to the majority of homes and so would require government interventions to achieve strong public engagement. To overcome these barriers, programs such as RHI and FiT have been introduced; however, implementation of these programs themselves has been challenged by administrative barriers, management issues, as well as concerns about funding mechanisms [49].

The payments made to households under RHI was funded by the government through general taxation rather than placing a levy on energy bills [49]. It was argued that placing a levy on fossil fuels and funding RHI through energy suppliers would be rather difficult and time-consuming for the government, whereas funding RHI through general taxation seemed a much simpler solution [49]. Furthermore, energy suppliers argued that it was difficult to determine the fossil fuels on which levy was to be placed and concerns were shown on placing a levy on natural gas which may potentially penalise the use of gas which had lower emissions than other fuels like oil and coal. These examples demonstrate how programs fostering adoption of low-carbon heating systems face challenges from all stakeholders including public, institutional and regulatory bodies, energy providers and more. Such points need consideration by policy-makers and provides a challenge for devising future incentive schemes for households.

Such programs have the potential to increase public participation in installing low-carbon heating. With the 13% reduction in average cost per kW of small scale solar PV between 2013 and 2018, the installation numbers only increased significantly when FiT was accepting applicants [9,8,11]. So, even with solar PV being the most cost-effective low-carbon technology, the uptake has been slow and programs such as FiT motivate and encourage households to adopt such technologies. Even with the introduction of these programs, limited academic research has evaluated their economic and environmental impacts.

Comprehensive studies are needed which examine all aspects of emission reduction in houses. As well as what was studied here, the renovation of existing buildings should also be considered along with the implication of the cost of renovation. For example, a 15% reduction in emissions was achieved in Swedish homes by replacing conventional design with low-carbon designs without increasing existing costs of a building [4]. Others suggest a more draconian approach; e.g., limited studies conducted by Snape [56] and Abu-Baker [1] suggested that to increase the uptake of technology, higher energy tariffs are required, so that households are pressured (as opposed to incentivised) to adopt energy-saving measures.

This study focuses on the energy consumption in households using a single kind of fuel for space and water heating purpose.

Households have been known to use at least two different fuel for their energy requirement (wood and oil, for instance). Future studies need to be conducted to analyse whether higher emissions savings can be potentially achieved through either utilising more than one fuel source in a house (e.g., using both gas and electricity for space and water heating), or by switching to a single source of fuel which is more efficient and produces less emissions.

The replacement of conventional heating systems would also result in emissions due to their disposal as well as those from the embedded energy in the materials and production of low-carbon systems. So, the choice of materials used in replacement systems can influence this. For instance, Schestak et al. [54] conducted a LCA study on heat recovery systems for kitchen drains in commercial kitchens. They found that replacing components of a heat exchanger made up of recycled copper with one made from polypropylene-graphite (PP-GR) with polyethylene pipework reduced the environmental impact for seven categories by 80–99% compared to the components made out of 35% recycled copper. With the energy savings from PP-GR based system, the burden of all seven assessed environmental impacts were paid back within two years while the payback for copper-based systems took 10 years.

Improvement in energy efficiency of buildings would not only reduce emissions but would also save energy and reduce energy costs. Through better insulation and installation of low-carbon heating systems, the households would raise their energy efficiency. This, together with the availability of funding streams (similar to FiT and RHI), would influence adoption of low-carbon heating and facilitate the shift towards renewable energy as opposed to fossil fuels like gas and oil.

Integrating Life Cycle Assessment and MACC studies would provide an accurate estimation of the different environmental impacts and associated cost-savings resulting from these technologies and policy changes either singularly, or in combination.

5. Conclusion and policy implications

The aims of this study were to use information from both household energy certificates and MACC to assess the abatement potential of measures introduced to reduce household GHG emissions arising from energy use from space and water heating for Gwynedd, Wales. Household energy consumption is known to be driven by factors such as insulation, house size, and heating system fuel type: information captured within the EPC used within our study to calculate energy consumed for space and water heating through different fuels including natural gas, oil, LGP, electricity and coal.

Compared to the rest of the UK and even Europe, Wales has had a relatively low adoption of low-carbon technologies. This is a result of factors including higher cost of low-carbon technology and lower alternative fuel costs such as gas and electricity. As a result, Welsh houses are less energy-efficient, leading to higher energy costs and higher GHG emissions.

We also investigated ‘what if’ scenarios to predict future gains due to changes to the cost of technology or energy costs and efficiency. The cost of each tonne of CO_2 abated by implementation of low-carbon technology was calculated using MACC. It was found that the most cost-effective low-carbon technology was PV, however, if we considered gas-based heating systems as a mitigation technology, it remained cost effective in all scenarios.

Low investment and running costs of gas systems along with its vast distribution network has made it the most sought after heating system. However, with plans of banning the installation of gas heating systems in newer homes, the share of gas systems would see a decrease in the future. Our analysis suggests that if energy prices continue to rise, as they have in the past, combined with decarbonisation of electric grid, heat pumps may become cost-effective. Furthermore, without decarbonisation of grid electricity, replacement of various heating systems with electric heating would produce more emissions.

There has been a great deal of uncertainties in energy and low-carbon technology costs, energy efficiency of fuels as well as future policies and regulations regarding the deployment of low-carbon heating solutions like PV, heat pumps and biomass boilers. These uncertainties would no doubt influence household’s energy demand and the uptake of mitigation measures in the future. Programs need to be introduced that provide financial aid to increase the uptake of this technology. Policy development to encourage the utilisation of low-carbon technology is important and can have economic, environmental, and social consequences. The policies should cater toward benefitting the consumer so that uptake is maximized and therefore targets are achieved.

Policies that cater towards reducing capital costs of the technologies and/or incentivising their uptake through subsidies or taxes would facilitate more consumers to make a shift towards low-carbon technologies. In turn, this would grow the choice of technology options available, which should foster competition and further reduce costs.

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.

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Appendix A. Supplementary data

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