Report
May 2022

Green Gas

The Green Economy under our feet.

The Green Britain Foundation

ecotricity

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Foreword

by Founder of Ecotricity, **Dale Vince**

Seven years ago we published our first green gas report. In it, we flagged the amazing opportunity that gas made from grass offers us as a nation.

Essentially we believed that it was possible to make all the gas we need to heat Britain's homes, right here in Britain, from a new approach using a proven technology - grass fed anaerobic digesters.

Our desktop study told us there was enough grassland in Britain to do this, that we could create 100k jobs and a £10 billion annual contribution to the rural economy. We would end our use of fossil gas for home heating - worth some 15% of our carbon emissions and since domestic use of gas is 2/3 of our national total - it would be a big step towards Energy Independence.

We struggled to get traction for some reason, while we also struggled to build our demonstration project, for lots of reasons - planning, patchy government support, a pandemic followed by an energy crisis followed by a war in Europe - all complicated the picture.

But we finally started work on that demonstration project, the same day we launched this new report.

We commissioned this second green gas report to validate our first one, or not - as the case may be.

We also wanted a deeper dive into the data, to look more closely at the availability of land and grid connections, the economics of green gas, the job creation potential - the whole works really. And we wanted the impact that an independent and academic voice could add to this.

Because to us gas from grass is an amazing opportunity - right beneath our feet.

This new study doesn't just validate our original position - it shows that the opportunity is even bigger than we said it was seven years ago.

The key findings for me are these;

There is enough grassland to make all the gas Britain's homes use - without taking any land out of food production.

In the process we would create 160k jobs and a £15 billion contribution to rural economies.

If we model in changes to our diet, the reduction of animal consumption and therefore farming - the opportunity gets even bigger, green gas from grass could actually power the whole country's homes and businesses.

In fact by 2050 we could be making nearly twice as much gas this way as we currently get from the North Sea.

Green gas made this way would have almost 90% less greenhouse emissions when compared to north sea gas and synthetic fertiliser use - green gasmills produce natural fertiliser as a by product.

With process improvements it looks possible to achieve an emissions reduction of 99%, compared to North Sea gas and current fertiliser production.

These are stunning findings. We could be Energy Independent in gas, freeing us from the global commodity markets that set prices beyond our control - and from our dependency on unreliable or unethical sources of fossil fuels, such as Russia and the Middle East.

Making all the gas we need from the grass we have an abundance of is the perfect complement to making all the electricity we need from the wind and the sun - which we also have an abundance of.

In combination we can achieve complete Energy Independence and enormously strengthen our economy, which pre the energy crisis was depleted by £50 billion every year - that's how much we spent to bring fossil fuels to Britain just to burn them. £1 billion each week. That's like the lie on the side of Johnson's Brexit bus (£350m per week for the NHS if we exit the EU) - but three times bigger and real.

In the process we can create an enormous amount of new sustainable jobs here, help farmers diversify from animal agriculture, save ourselves a shedload of money every year - and do what we have to do, to avoid the worst of the climate crisis into the bargain - get to net zero carbon.

It's a plan with no downsides. It even creates habitats for wildlife, on a vast scale - over and above those that exist on grassland now.

The second part of this new report looks for the first time in depth at the government's alternative plan - a national air source heat pump program. The key findings for me are these;

It will require the scrapping of tens of millions of existing devices, gas cookers and boilers.

The scrapping of our national gas grid.

A tripling of renewable energy generation to make the electricity to power nearly 30 million heat pumps. And a massive grid upgrade to deliver that extra electricity.

A home that uses a heat pump will have annual energy bills that are higher by over 40% - than the same home using a gas boiler.

Heat pumps won't work in 20% of our homes without significant home upgrades - while for another 20% they won't work full stop.

A national air source heat pump program will cost six times as much as a green gas program - almost £300 billion versus £50 billion.

These are also stunning findings.

This report could not be more timely - we're deep into an energy security crisis that has exacerbated an existing energy price crisis - while we urgently need to deal with the role of energy in the climate crisis anyway. The answer is not to throw away our national gas grid and the tens of millions of appliances that use it, imposing vast costs on the public - the answer is simply to change the gas we put into the grid. And carry on as normal.

Green gas is cheaper, faster and far less wasteful than a switch to heat pumps. And it will work for every home - no exceptions. It will give us a more balanced and diverse outcome in terms of energy supply, and form an essential part of the smart grid we need - with gas and electricity grids supporting each other, sharing the energy load of the country.

Today we announced a new gas field 'discovered' in Britain - this report shows that Britain's grassland could actually be be our new North Sea - but with a significant difference - it will never run out.

Dale Vince

Dale Vince
Founder, Ecotricity

Part One

Green Gas – The opportunity for Britain

An independent report by Dr Gbemi Oluleye and Dr Semra Bakkaloglu of Imperial College London

Imperial College London
Consultants

Green Gas – The opportunity for Britain

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Executive Summary

The UK Government's new Net Zero Strategy[1] , UK Heat and Building Strategy[2] and British Energy Security Strategy[3] lays out for the first time how the government plans to cut UK emissions in half in less than a decade and eradicate them entirely by 2050, while also ensuring the UK can be largely independent of changes in global fuel prices. It is a feasible proposal that will bring employment, investment, and broader advantages to the UK. However, as the UK Climate Change Committee pointed out, there are significant gaps between these ambitions and a clear policy and delivery pathway. A number of key decisions have yet to be made, with aspects of this pathway relying on ongoing studies (low carbon hydrogen) and technology yet to be developed (new and advanced nuclear power), let alone brought to the market.

The Government has proposed deployment levels of low-carbon options. Recognising that future demand for gas will decline[4] as we decarbonise implies that the gas system will need to change to meet net zero targets. This will allow us to identify how the gas market will need to develop to guarantee that the required market and regulatory signals are in place to provide the requisite level of investment and maintenance during the transition.

A new Green Gas Support Scheme (GGSS) has been introduced to encourage the injection of biomethane from anaerobic digesters (AD) as well as investigate the development of commercial-scale gasification and the replacement of the GGSS with a long-term biomethane support scheme.

To get there, we are going to have to work on a new frontier – to remove the carbon emissions from our nation's heating. Ecotricity believe that they have found a solution that could play a significant part in this: Green Gas Mills.

Through the process of Anaerobic Digestion, Ecotricity's Green Gas Mills will use species rich herbal leys as fuel to produce biomethane (or 'Green Gas'). The big benefits of Green Gas are that it is a fuel source that will never run out, it's low carbon, it reduces the need to import fossil fuels from overseas or frack the countryside, and it uses existing infrastructure such as the gas grid (there is no need to upgrade the gas grid to stop hydrogen leaking from the old pipe network) and household heating systems. Grass/herbal ley biogas/biomethane is a viable solution for meeting renewable energy targets in the UK in terms of available technology, energy balance, greenhouse gas (GHG) savings, and policy constraints.

Green Gas Potential in the UK

Green Gas can immediately contribute significantly to meeting the UK's Net Zero target. We assessed that the UK has **6.46 million hectares** of suitable grassland. This is enough suitable grassland for around **5,400 Green Gas Mills** to be built. This would provide up to 236.5 TWh - enough energy to heat 98.8% of British homes if made energy efficient - while also boosting the rural economy by **nearly 162,000 jobs** and generating £16 billion for the rural economy.

Green Gas Mills also save **nearly 87% of greenhouse gas (GHG)** emissions when compared to usage and generation of natural gas and synthetic fertiliser, as business-as usual scenarios, which could be further reduced with proper automation and well monitored systems by 2050 to emission saving up to **99%**.
We are now working on the second phase of the green gas mill project with Ecotricity to assess the Life Cycle Analysis (LCA) of green gas mills. This will be completed when the plant at Reading is operational in 2023/24.

The above assumes Green Gas Mills with 5MW capacity, and requiring 1200 hectares of land each in line with current technology. Total energy output could be increased further if Green Gas Mills become more efficient. If this was not a constraint, the gas potential of herbal ley species on the suitable UK grassland itself is 247.2 to 482.5 TWh, with an **average of 288.5 TWh**. This green gas potential could be increased to 579.2 TWh by adding seaweed and even 923.1 TWh by 2050 if diet habits also change, allowing for more grassland to be used for green gas generation on top of the use of seaweed. This significantly exceeds UK gross natural gas production from the North Sea (438.3 TWh).

According to various studies we have reviewed, an additional 6.86 million hectares of land would be available if the total population became vegan. Assuming that just 10% of the population adopts a plant-based diet now, we could re-purpose 664 thousand hectares of current grazing land to produce 318.2 TWh energy per year on average. Even without changing diets, with seaweed addition the UK's suitable grassland could meet up to **71.6% of total current natural gas demand** including industrial use. There is potential to produce more than enough biomethane to supply every household in the UK and replace the need for natural gas for our domestic gas needs. If 20% of hydrogen is blended into the gas grid, 76.5% of total natural gas demand could be offset.

The price of a unit of Green Gas is expected to be around £70 per MWh, but this can be reduced to **£54 per MWh** with technological advancements and the addition of seaweed, which is half the cost of current natural gas prices. Given the cost of heat pumps and the electrification of the entire gas grid (which includes all heating and hot water requirements), Green Gas is a safe and cost-effective solution to the current energy price crisis.

Benefits of Green Gas

Green Gas Mills can help us decarbonise our heating and contribute to the fight against climate change. They also provide additional benefits, including the following

- Boosting rural economies: each Green Gas Mill will generate approximately 30 jobs and £3 million in annual feedstock contracts for farmers.
- Increasing food productivity: when grass feedstocks are grown in rotation with crops on arable land, soil health is improved.
- Supporting wildlife and biodiversity by providing a pollen and nectar-rich habitat for bees and other insects in areas growing feedstock species, such as rich herbal leys.
- Weaning the UK off reliance on imported gas as North Sea production declines, thereby eliminating the need for fracking.
- Utilising existing gas infrastructure: This enables us to easily switch from fossil fuel to grass-based gas.

Green Gas Mills are the antithesis of fracking: they are low carbon, a truly renewable source of indigenous gas, provide an infinite, rather than limited, supply, and boost local economic benefits without jeopardising water supply, air quality, local communities, or climate targets. Indeed, Green Gas Mills have a sizable environmental benefit.

We are aware of concerns about 'energy crops,' which are another method of producing biomethane; if the incentives are not right, farmers may abandon food production on arable land in favour of crop production for biogas production. This is a legitimate concern – the farmland in the UK is valuable and must be protected.

The other frequently discussed method of producing green gas is from food waste. While this method presents its own set of complications such as the need of source segregation, it will clearly need to be part of the plan for future energy security.

In the United Kingdom, we are developing another method of producing green gas - from species rich grassland, known as herbal ley. It has none of the drawbacks associated with food waste, energy crops, or fracking, but it has significant advantages over all three. This is a significant opportunity for the UK.

How can the UK support Green Gas Mills?

Green gas mills are a relatively new technology. We believe they have tremendous potential, but in order to get started and demonstrate what they are capable of, they will require policymaker support. As a priority, we hope the government will:

- Maintain support for biomethane producers through the Green Gas Support Scheme (GGSS).
- Clarify the regulation and classification of permitted feedstocks under the Green Gas Support Scheme to ensure that feedstocks such as herbal leys that do not threaten food production are supported.
- Avoid duplicating the regulations already in place for biomethane injection with additional rules under the Green Gas Support Scheme.
- Provide additional clarity on targets post-2035.

The next major challenge in our quest to become a Green Britain is decarbonising the gas network and providing carbon-neutral heating and hot water systems. Green Gas Mills, we believe, can play a critical role in meeting that challenge.

Introduction: The new frontier for decarbonisation

The Prime Minister, Boris Johnson, has made further pledges to ensure that the UK remains at the forefront of the green industrial revolution over the next decade[5]. He unveiled a ten-point strategy for a green industrial revolution in 2020 to make the UK a global leader in renewable energy generating employment, reducing emissions and increasing exports. The target is to power the country with 100% clean energy sources by 2035. The announcement is part of the government's pledge to achieve net zero emissions by 2050, and it will sustain 60,000 jobs.

But the UK is now approaching the next chapter of this challenge: decarbonising heating.

Heating accounts for 37% of total energy consumption in the UK and is responsible for the majority of residential emissions, which account for 16% of the UK's annual greenhouse gas emissions (Figure 1). It's straightforward: unless and until we can decarbonise our heating and hot water, we will never achieve Green Britain.

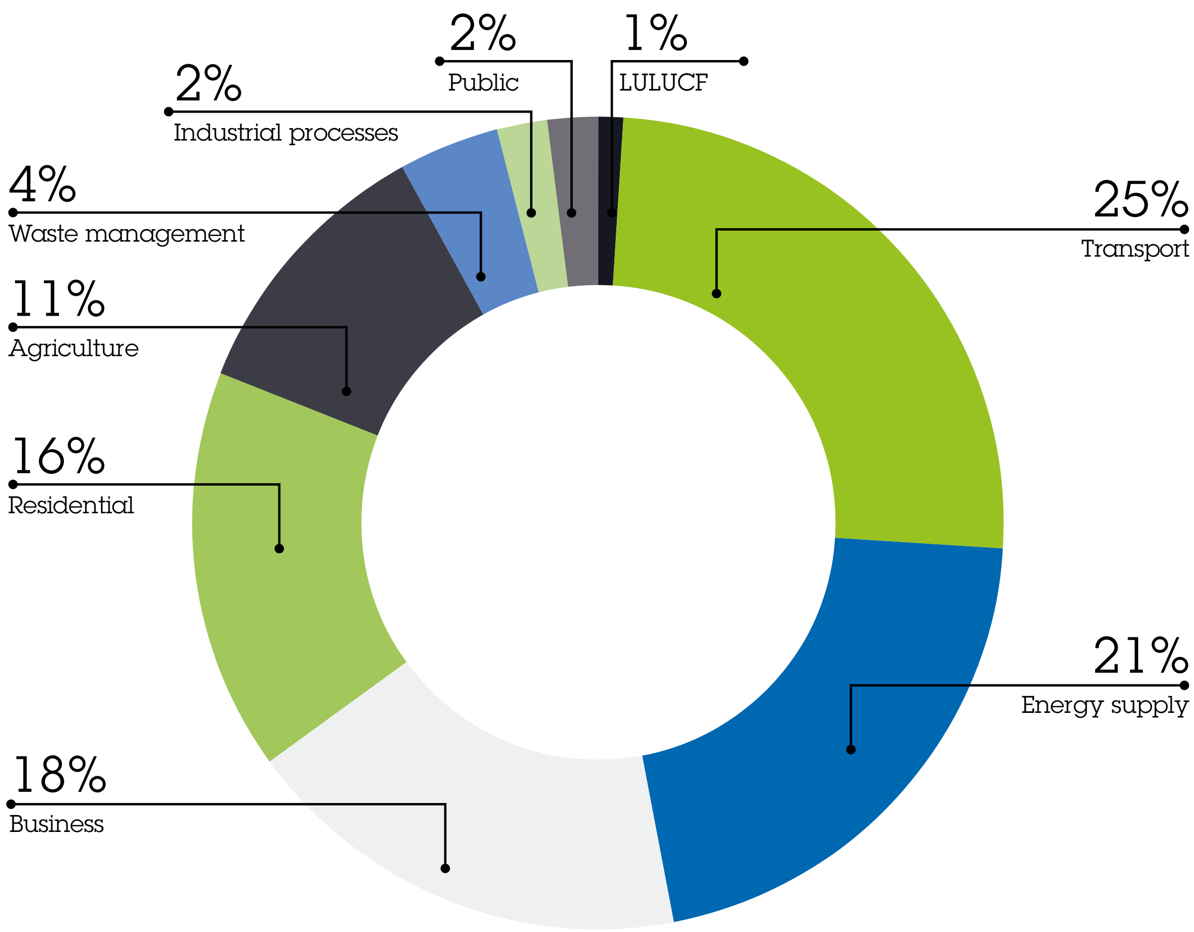


Figure 1. Final UK greenhouse gas emissions for 2020[6]
Note: LULUCF is land use, land use change and forestry

A beginner's guide to the Green Gas Mill

Ecotricity have been working on Green Gas Mills for a while now, and are not the only ones. These Green Gas Mills are potentially revolutionary: using herbal leys as fuel they produce biomethane (Green Gas), which is both renewable and virtually carbon-neutral but can be used just like natural gas, replacing gas from the North Sea, Saudi Arabia or even Russia. The big difference is that biomethane recycles existing carbon in the atmosphere which has been absorbed by the grass within the last year, rather than fossil fuel gas which releases carbon when it is burned after being safely stored underground for at least 65 million years, and methane (CH_4) from incomplete combustion or fugitives from venting and flaring events.

The way the Green Gas Mills work is pretty simple. They can be fuelled with organic feedstocks - in Ecotricity's case species rich grassland known as herbal leys - which bacteria then break down in an oxygen-free environment through a process of Anaerobic Digestion (AD). From the process of AD, we get two main outputs: biogas and a 'digestate' which isn't actually wasted at all, but can be used as a rich source of organic fertiliser.

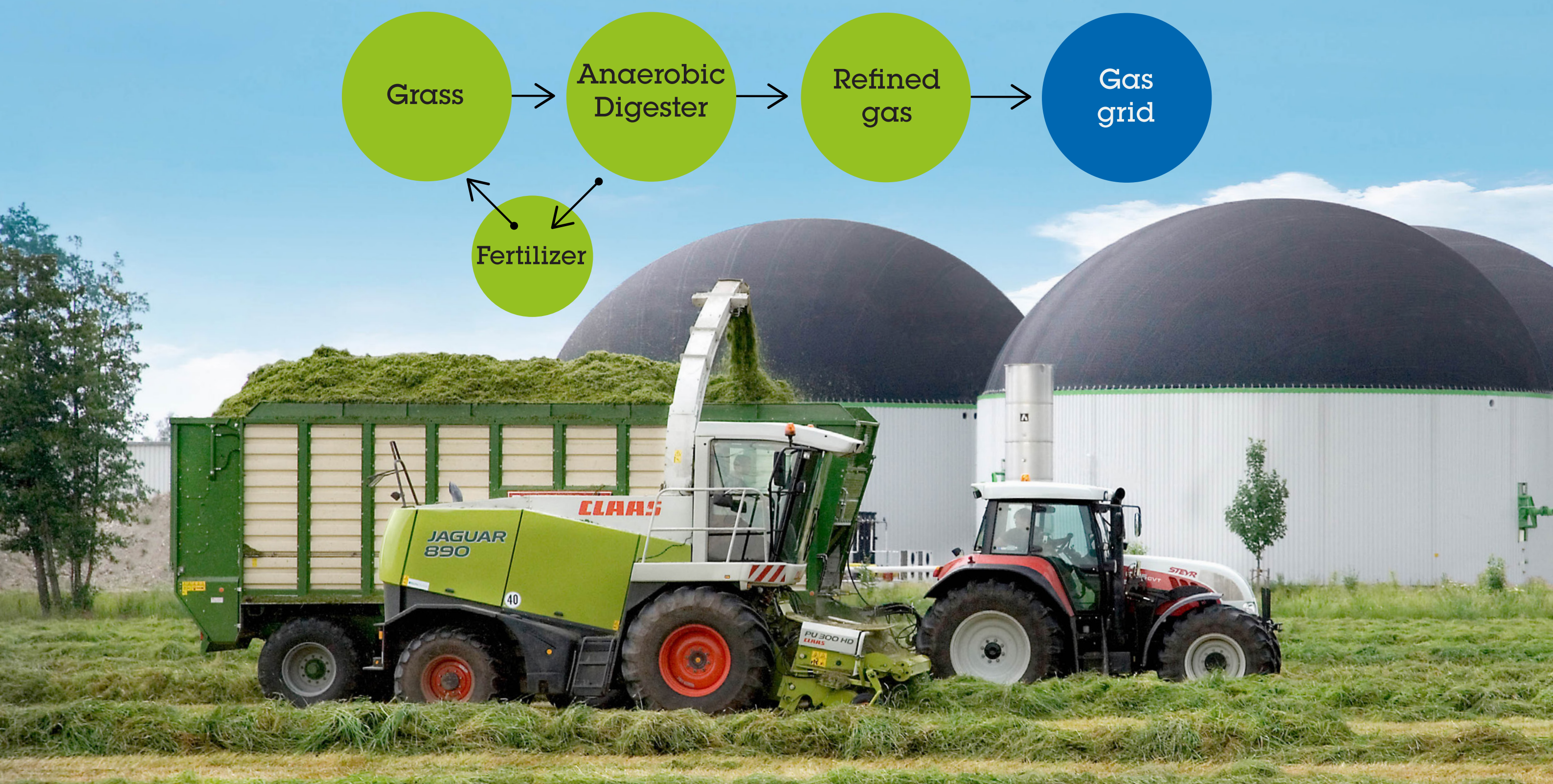
In many ways the process is just like a cow: the grass goes in one end, and gas and fertiliser come out the other. But in this case, rather than the gas 'escaping' like it does from cows, it is collected and used to replace natural gas.

Some people use the biogas directly in gas boilers for heating or burn it in an engine to generate combined heat and power (CHP). Our Green Gas Mills go one step further. Once we have the biogas it is then 'upgraded': purified and brought up to the UK's high environmental and safety standards as biomethane. After being upgraded to biomethane, it can be fed directly into the national gas network to be used for heating in gas heating boilers, cooking on a standard gas hob, or even as vehicle fuel.

That's one beauty of the Green Gas Mill concept: you can be cooking on Green Gas, and you won't even notice.

Grasslands are found across large area of the UK ranging from natural upland grassland, through lowland hay meadows, semi-improved grasslands to intensively managed single species grasslands cut for silage or intensive cattle grazing. Grasslands also contribute to a region's cultural heritage and recreational benefits, as well as providing a vital regulating ecological function and supporting biodiversity and cultural services[7]. Grassland is a significant carbon sink[8] as well as a feedstock for renewable energy generation in the form of grass biomethane. It also has other benefits (e.g., long persistency of high dry matter yield, intercropping potential with legumes and subsequent reduction in fertiliser application rates[9], protection of soil from erosion, and groundwater formation[10-13]).

Ecotricity believes that "green gas from grass" will provide the UK with a new type of low-carbon, sustainable energy.



1. How much grassland is available?

The first crucial question is not how much land one Green Gas Mill will require, but how much land will be required across the UK to replace natural gas for home heating and hot water with "green gas from grass." There are many different land types, but not all of them are suitable for green gas generation.

There is a total **17.46 million hectares** of agricultural land in the UK. This consists of arable and horticultural land, improved grassland, neutral grassland, calcareous grassland, and acid grassland areas (see Figure 2 and Table 1).

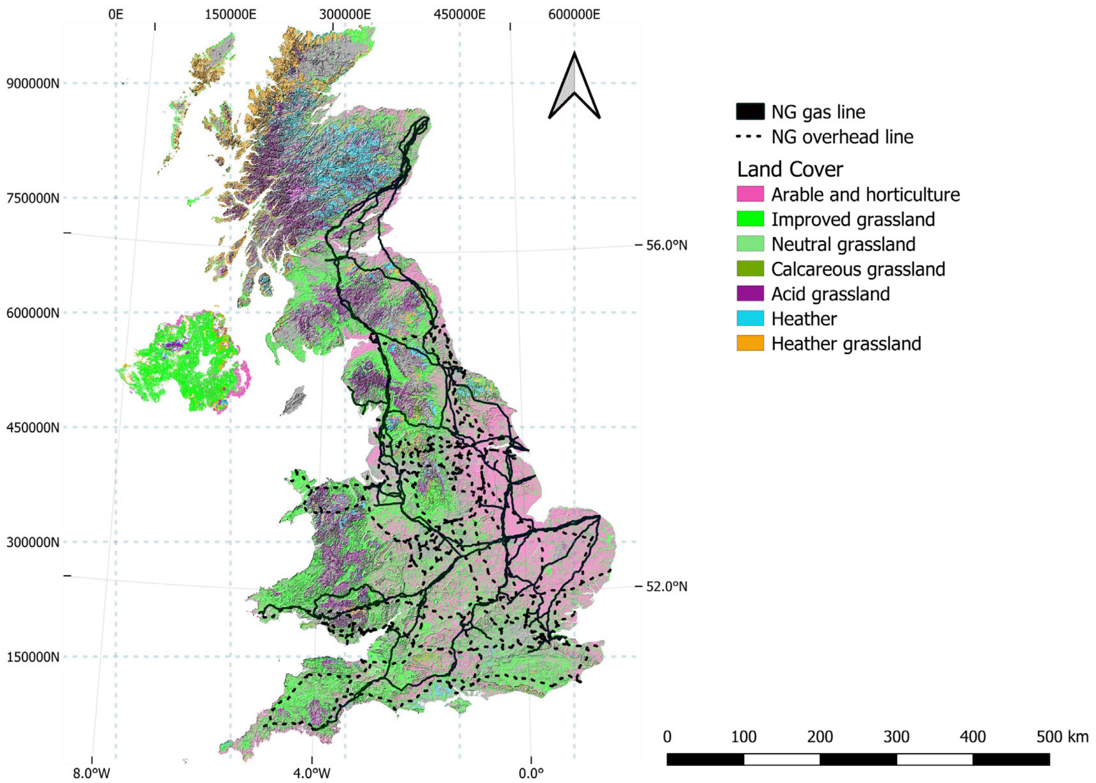


Figure 2. This represents available grassland in the UK[14]. Surface hill shade demonstrates the steepness of surface[15], which can vary in local areas[16]. Because soil characteristics are influenced by the slope of the surface, acid grasslands are found on more steeply sloped areas. Solid and dashed black lines show the natural gas (NG) pipeline (© National Grid UK, 2022)[17]. See Appendix A1 for details of the UK land cover, Appendix A2 and A3 for the steepness of the surfaces.

Table 1. The UKCEH Land Cover class and area for UK in 2020[16]

UKCEH Land Cover Class	Area (million hectares)
Arable and horticulture	5.38
Improved grassland	7.10
Neutral grassland	0.27
Calcareous grassland	0.13
Acid grassland	2.21
Upland heather moorland	1.03
Heather grassland	1.35

Excluding land used for food production and horticultural activities, the total of potentially available grassland area in 2020 would be **12.08 million hectares**.

1.1 How much grassland is suitable?

However, not all of the potential 12.08 million hectares of grassland would be harvestable or close enough to a suitable gas grid connection.

The slope of the surface is critical for determining the type of equipment that can be used in a given area, identifying areas that are more susceptible to surface runoff, and even determining the feasibility of green gas generation in that area. There is approximately 2.16 million hectares of acid grassland and 1 million hectares of upland heather land in Great Britain that exceeds a 12-degree threshold[17], making it unsuitable for harvesting, leaving an area of **8.92 million hectares** of potentially suitable grassland. Furthermore, the majority of Scotland's heather grassland (1.26 million hectares) is located outside the gas grid, and thus is excluded.

Of the remaining **7.65 million hectares**, a significant area is used for common grazing (1.19 million hectares of grassland based on agricultural statistics for the UK in 2020[18]) and therefore also considered unsuitable. Thus, it is estimated that a maximum **6.46 million hectares of grassland** can potentially be used to produce green gas (see Appendix A4 for details). This would of course exclude any permanent species rich grassland nature reserves or Sites of Special Scientific Interest (SSSI) .

1.2 Biomethane potential of suitable grassland

Anaerobic digestion (AD) is a technique for producing biogas from biomass (i.e., grass, legume and herbs for Green Gas Mills), which can then be upgraded into biomethane of the same quality as natural gas. Biomethane, which contains 97% CH_4, 2% CO_2, and some minor constituents, plays a significant role in providing renewable energy as biomethane and natural gas can be mixed and interchanged. Green Gas Mills are designed to produce biomethane, which is used to replace natural gas in the gas grid.

The UK has a high potential for green gas, with temperate climates and a high proportion of grassland. There is growing interest in utilising grassland for bioenergy generation in Europe and North America[19], focusing on various grass species[20,21]. Despite this, methane yield from grass species is generally modest due to them containing relatively low and imbalanced nutrients[22]. Herbal ley mixtures can improve methane yield by including diverse chemical compositions, such as concentrations of structural and non-structural carbohydrates, as well as mineral nutrients (e.g., nitrogen, N)[23-25], which are linked to biomass digestibility in Green Gas Mills. Recent studies[21,26] indicate that some deep-rooting herb species such as chicory are rich in macro and micronutrients (potassium, sulphur, zinc and boron) because of absorption from deeper soil layers, which is significant for the health of microorganisms in Green Gas Mills, whereas legume species (i.e., white, red clovers) are high in nitrogen in plant tissues. Anaerobic digestion of grass, herb and legume with complementary nutrient composition has potential to increase methane generation[27]. Hence, Ecotricity have decided to feed Green Gas Mills with herbal leys, made up of grass, legume and herbs or wildflower species, by working with farmers (see Appendix A5 and A6 for details). Ecotricity will also conduct ecological surveys so as to maintain herbal ley mixture quality and increase the biodiversity of the land. The herbal ley mixture is suitable for medium to light soil types with a pH of 6-8[28] and the UK's climate conditions, and is thus a good fit with the UK's 6.46 million hectares of grasslands identified above.

The yield and quality of biomass from herbal leys for Green Gas Mills can be improved by land management practices such as cutting period, harvest time and frequency[25-27]. Recent studies reported that a two-cut strategy in a year for multi-species grass, legume and herbs mixtures can increase biodiversity and methane yield[27,29], while also lowering cost and energy inputs[30]. Ecotricity aim to apply the two-cut strategy for Green Gas Mills. Although the methane yield per hectare may vary from field to field and year to year due to difference in species composition (and yearly rainfall[31]), the aim is to obtain a range of methane yield of herbal species which would be the main feedstock for Green Gas Mills (see the Appendix A6 for the details of herbal species mix to be used).

Table 2 depicts the UK's biomethane potential from suitable grassland. Based on 6.46 million hectares of suitable grassland potential and 13 tonnes of dry solids yield per hectare of herbal ley mixture in a year, 84 million tonnes of dry solids and 75.6 million tonnes of volatile dry solids could be the feedstock of Green

Gas Mills. The average methane yield of a herbal ley mixture is 375 m^3 CH_4 per tonne of volatile dry solids (see Appendix 5 for more information), which can produce **47.2 billions m^3 of biogas that is further refined into 28.3 billion m^3 of biomethane from AD**. Before injecting this produced gas into the gas grid, it should be upgraded. The biomethane loss from upgrading processes such as pressure swing adsorption (PSA), membrane, chemical and water scrubbing processes, and chemical absorption systems ranges from 0.001 to 5.5% of gas generation[32]. Due to the high technology of Green Gas Mills, we assumed that methane slips would be in the lower range. According to recent studies, PSA technology can result in the highest methane loss, and chemical absorptions[32,33] can yield lower methane loss from upgrading systems; therefore, Ecotricity will consider using chemical absorption for biogas upgrading systems in order to minimize methane loss from the system, resulting in lower methane emissions and thus lower GHG emissions. So, we assumed 0.5% of methane slip from the biogas upgrading facility on average. As a result, before considering the capacity of Green Gas Mills themselves, the UK's suitable grassland could in theory generate **288.5 TWh (ranging between 247.2 and 482.5 TWh)** energy per year based on biomethane higher heating value. Because these calculations are based on 6.46 million hectares of suitable grassland, the biomethane yield from per hectare of grassland would be **160.8 GJ per hectare on average**, ranging from 137.8 to 268.9 GJ ha^{-1} per year (see Appendix A7 for the details of these calculations).

The estimated biomethane from the current AD under construction by Ecotricity is 65,538 kWh per hectare (235.75 GJ ha^{-1}), and falls within this range, although this does include the addition of seaweed extract (Ascophyllum Nodosum) to boost methane production. If this method were applicable across the board, it would result in **482.5 TWh from 6.46 million ha**, which is near the upper end of the range estimated in Table 2. Also, Shin et al.[34] reported that adding seaweed to anaerobic digestion of food waste and sewage sludge enhances anaerobic digestion performance and increases methane yield by 24% and 20% respectively, at high substrate concentrations. We assume that seaweed addition to Green Gas Mills may improve biomethane yield by 20%. Thus, the UK's suitable grassland has a great potential to generate **296.6 to 579 TWh of biomethane per year, with an average of 346.2 TWh**.

Table 2. The biomethane potential of the UK

	Unit	Average	Min	Max
Grassland	million ha	6.46	6.46	6.46
Herbal leys yield[a]	t DS/ ha/y	13	13	20
Annual Feedstock	t DS/ y	8.40 $\times 10^7$	8.40 $\times 10^7$	12.92 $\times 10^7$
Herbal leys yield[b]	t VS/ t DS	0.9b	0.9b	0.9b
Volatile dry solids yield	t VS/ y	7.56 $\times 10^7$	7.56 $\times 10^7$	11.63 $\times 10^7$
Methane yield of herbal leys[c]	m^3 CH_4/ t VS	375	340	408
Methane production	m^3 / y	28.3 $\times 10^9$	25.7 $\times 10^9$	47.4 $\times 10^9$
Biogas production[d]	m^3/ y	47.2 $\times 10^9$	42.8 $\times 10^9$	79.1 $\times 10^9$
Biomethane loss in upgrading[e]	%	0.5	1	0.1
Biomethane after upgrading[f]	m^3/y	27.49 $\times 10^9$	23.56 $\times 10^9$	45.97 $\times 10^9$
Biomethane energy yield	GJ/y	839.6 $\times 10^6$	275.6 $\times 10^6$	1670.2 $\times 10^6$
Biomethane energy yield	**TWh/ y**	**288.5**	**247.2**	**482.5**
Biomethane energy yield	**GJ/ ha/ y**	**160.8**	**137.8**	**268.9**
Biomethane yield after seaweed addition[g]	**TWh/ y**	**346.2**	**296.6**	**579.0**
Biomethane energy yield by 2050[h]	**TWh/ y**	**460.0**	**394.2**	**769.3**
Biomethane energy yield by 2050 after seaweed addition[i]	**TWh/ y**	**552**	**473.0**	**923.1**

[a]Herbal ley mixture yield per hectare was obtained from the Cotswold Grass Seed webpage which states that herbal ley yields 13 tonnes of dry matter (DM) per hectare[28]; [b]It is assumed that 0.9 total volatile dry solids (t VS) in total dry solids (t DS)[35]; [c]Methane yield was derived from the literature; more information can be found in Appendix A5 and A6; [d]Biogas includes 60% of methane; [e]Different biogas upgrading technologies have varying gas loss rate[36],[37], but we assume methane slip from Green Gas Mills would account for no more than 1% of total biomethane production; [f]97% CH_4 in biomethane was assumed[38]; [g]Seaweed addition increase biomethane yield by 20%; [h]Additional 4.18 million hectares of land will be available by 2050; [i]A 20% increase in biomethane yield is assumed.

Notes: $Methane_{HHV}$: 38.1 MJ/ m^3; 1 MJ: 0.000278 MWh

According to the Committee on Climate Change (CCC) analysis[39], **22% of the land** currently used for agriculture (the total UK agricultural area is 17.46 million hectares39) will be available by 2050 due to a variety of factors, including increased sustainable crop productivity and livestock grazing intensity, decreasing beef, lamb, and dairy consumption, reducing food waste, and moving horticulture production indoors. Therefore, an additional **3.84 million hectares of land** will be available for use in green gas generation, resulting in an **additional 146.9 to 286.8 TWh** energy capacity per year.

To sum up, **the green gas potential of the UK's suitable grassland could reach 769.3 TWh** without seaweed addition by 2050 (see Table 2), and **923.1 TWh by 2050 (ranging from 473.0 to 923.1 TWh, with an average of 552.0 TWh**) with the addition of seaweed and future land availability in the UK (see Figure 4).

In this study, it is assumed that Gas Mills have a capacity of 5MW and require 1200 hectares of land each. This means that with current mill technology and efficiency, **5,400 Green Gas Mills** could be built on the 6.46 million hectares of suitable grassland identified above, providing up to **236.5 TWh of green gas**. At present, Green Gas Mills have capacities ranging from 3 MW to 6 MW, requiring around 1000 hectares of feedstock growing land. Ecotricity has the most recent technology and efficiency to further utilise the UK's green gas potential.

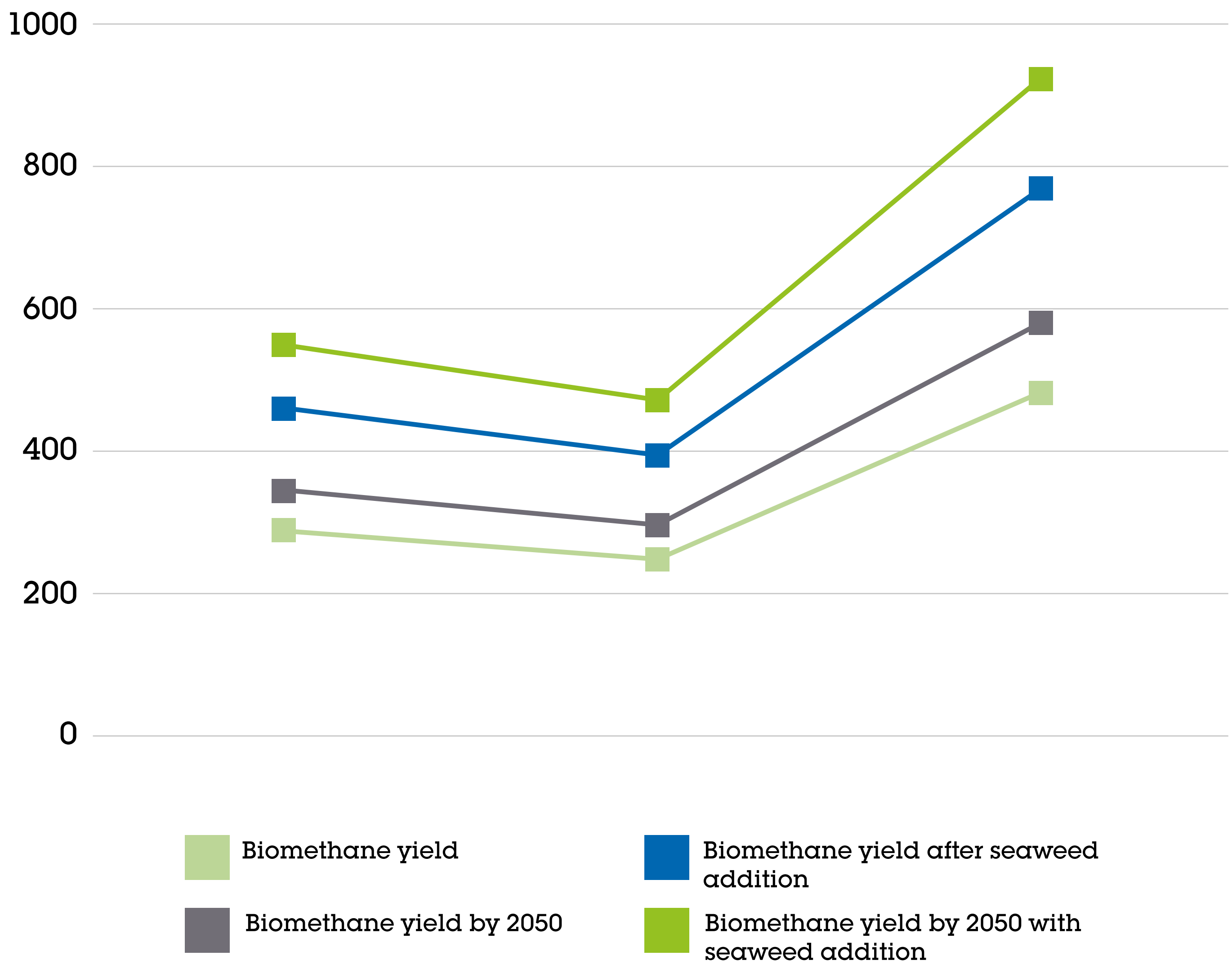


Figure 3. Green Gas potential of the UK (TWh). It is assumed that the addition of seaweed increases methane yield by 20%. Figure 3 represents that grey line is 20% higher than pale green line; and bright green line is 20% greater than blue line.

2. Is Green Gas capable of meeting the UK's natural gas demand?

Based on BEIS data (2021)[40], the UK's total natural gas demand was 808.7 TWh in 2020 (Table 4),a 6% decrease from 2019 due to reduced activity across the economy during the Covid-19 restrictions.

Of this 808.7 TWh of gas, 231.6 TWh was used to generate electricity of which approximately 29% is for domestic electricity demand (90 TWh) and 61% for business and industry electricity demand (141 TWh).

In 2020, domestic house gas demand for heating and hot water was 299.3 TWh, and 189 TWh was used by business.

Table 3. UK Natural Gas demand, TWh[40]

	2019	2020
Electricity generators	272.3	231.6
Energy industries	91.2	88.6
Industry	108	99.3
Domestic	294.9	299.3
Services	93.2	89.6
Transport	0.2	0.3
Total	858.9	808.7

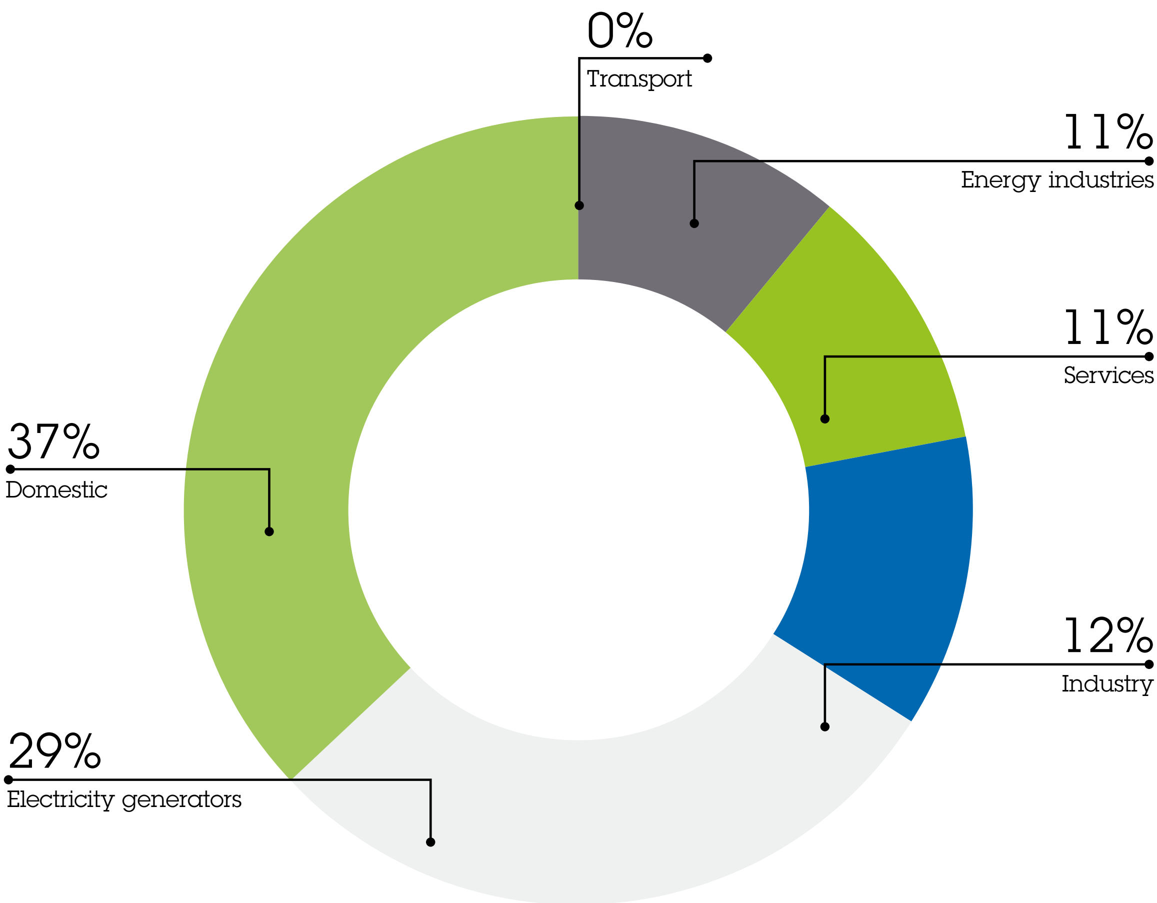


Figure 4. Natural gas demand percentage for each sector, adapting from Table 3.

Green gas from the UK's suitable grasslands has the potential to meet between **30.6 and 59.7%** of the UK's total natural gas demand in 2020 (37.1% to 71%.6 of total natural gas demand if seaweed is added to AD). If an additional 1.19 million hectares of common grazing areas are used for grassland production, biomethane production could reach 292.7 to 571.3 TWh, replacing 36.2 to 70.6% of natural gas demand, depending on herbal ley biomass yield per hectare of grassland and gas production unit loss.

2.71, 5.41, and 10.8 million hectares of grassland respectively would be required to meet 25%, 50%, and 100% of the UK's total demand for natural gas (see Table 5). Currently, suitable grassland cannot replace 100% of natural gas demand; however, shifting to vegan diets will reduce meat and dairy demand, affecting the land requirement. The researchers[41] estimate that if the entire world adopted a vegan diet, our total agricultural land use would fall from 4.1 billion to 1 billion hectares (a 75% reduction in land use)[42]. If we apply this ratio to the UK's agricultural land (so 75% of the 17.46 million hectares of agricultural land will become available for green gas production), **we get 13.1 million hectares of land available for green gas production**, which can yield twice as much biomethane as the present estimate. As a result, all the natural gas demand could be met with green gas.

Table 4. Minimum area of grassland required to meet UK's total natural gas demand

% UK total natural gas demand	UK natural gas demand, TWh (2020)	Min. required grassland, million hectares (without seaweed addition)
25%	202.18	2.71
50%	404.35	5.41
100%	808.7	10.8

In 2020, UK gross natural gas production from the North Sea was 438.3 TWh; however, 51 TWh was used by the extraction industry and 105 TWh was exported, resulting in 282.3 TWh being injected into the grid, with further 6.3 TWh biomethane injection[43]. A minimum of **1.1, 2.2 or 4.6 million hectares of grassland** could compensate for 25%, 50% or 100% of North Sea natural gas production without industrial extraction, respectively (see Table 5).

Table 5. Minimum area of grassland required to meet the UK's North Sea natural gas production.

% UK total North Sea gas production (minus amount required for extraction) and assuming no exports	UK North Sea gas production, TWh (2020)	Min. required grassland, million hectares (without seaweed addition)
25%	83.3	1.1
50%	166.7	2.2
100%	333.3	4.6

The UK's Green Gas potential can also meet the domestic natural gas demand if **at least 1, 2 or 4 million hectares of grassland** were used to meet 25%, 50% or 100% of domestic natural gas demand, respectively (See Table 6).

Additionally, according to the UK Government's Net-Zero Strategy[40], heat and building energy demand is expected to fall by 15-20% by 2050 as a result of energy efficiency measures such as improving homes to meet Minimum Energy Efficiency Standards to EPC band C and building new homes with a high standard of energy efficiency. The British Energy Security Strategy aims to go further with "as many homes to reach EPC B and C by 2035". Therefore, when compared to the 2020 domestic natural gas demand in Table 3, the energy requirements for domestic consumption in 2035 would range between **239.4 and 254.4 TWh**, requiring a minimum of **3.21 to 3.41 million hectares of grassland**.

Table 6. Minimum area of grassland required for UK's domestic natural gas demand

% UK domestic natural gas demand	Domestic natural gas demand, TWh (2020)	Min. required grassland, million hectares (without seaweed addition)
25%	74.8	1.0
50%	149.7	2.0
100%	299.3	4.0

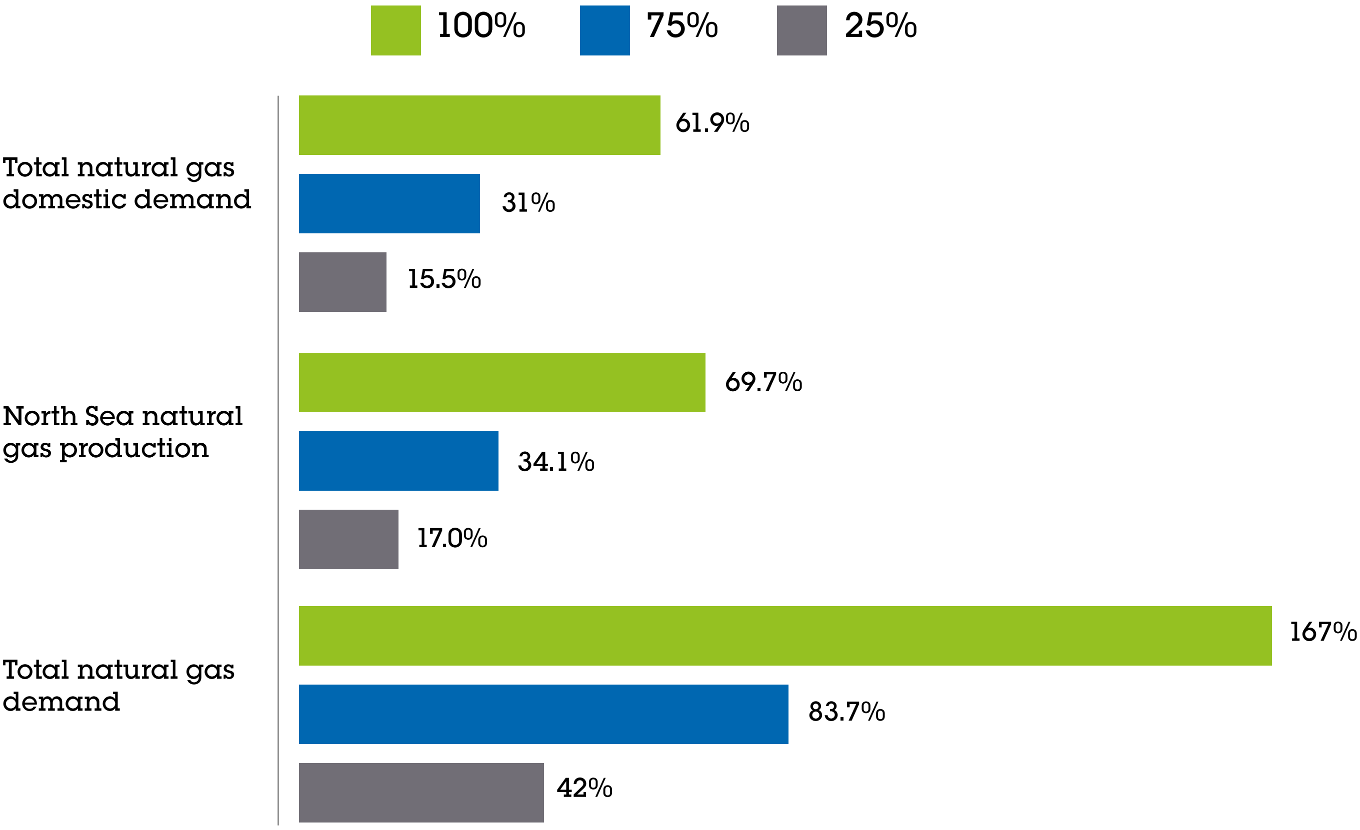


Figure 5. The minimum % of suitable grassland (6.46 million hectares) required to meet the 25%, 50% and 100% natural gas demands

The Prime Minister announced a Ten Point Plan for a Green Industrial Revolution in November 2020 and stated that the government will "work with industry to complete testing necessary to allow up to **20% blending of hydrogen into the gas distribution grid** for all homes on the gas grid" by 2023[44]. We also analysed the minimum land requirement for Green Gas production assuming hydrogen is blended into the gas grid at a rate of 20%. As shown in Table 4, the natural gas demand for 2020 is 808.7 TWh, which equates to 72.9 billion m^3 natural gas (assuming the higher heating value of natural gas is 11.1 KWh per m3). 20% of this volume could be compensated by hydrogen, which is approximately 14.6 billion m^3. With hydrogen's higher heating value of 3.55 KWh per m^3, this 20% hydrogen blending can offset 51.7 TWh of energy. Therefore, the demand of natural gas would be **reduced to 757 TWh**, requiring a **minimum of 10.1 million hectares of grassland to replace natural gas with a green gas** (Table 7).

Table 7. Minimum area of grassland required to meet UK's total natural gas demand (2020) if 20% of hydrogen is blended into the gas grid

% UK total natural gas demand	UK natural gas demand, TWh (2020)	Min. required grassland, million hectares (without seaweed addition)
25%	189.3	2.53
50%	378.5	5.06
100%	757	10.14

According to the CCC's analysis of the most cost-effective strategy for meeting the UK's 2050 emissions goal, natural gas consumption in industry, buildings, and electricity may decline from approximately 700 TWh in 2030 to around 370 TWh in 2050 (290 TWh based on CCC central scenario[45]). If efficient enough Green Gas Mills were built in sufficient number, this demand for **green gas in 2050 could be easily met by utilizing 76.6% of currently suitable grassland without changes in diets or adding seaweed.**

3. How economic is green gas?

Grass from the previously identified suitable grassland has to be converted into biomethane. Anaerobic digestion plants have to be built, and the grass must be collected and transported to the plants. The production of biomethane depends on the geographical location and the type of grass available to produce biomethane.

The cost of biomethane production is an important pillar because it affects the competitiveness of the energy vector. The cost of biomethane relies on the following components:

- Feedstock costs include feedstock collection costs and costs of transporting the feedstock from the collection location to the conversion location.
- Operating expenses (OPEX) including conversion and upgrading costs.
- Capital expenditure (CAPEX) including conversion, upgrading and injection costs.

3.1 Feedstock cost

The average cost of the simple herbal ley mixture was estimated to be around £6.47 per kg (£194 per hectare)[46] although this will vary from year to year.

3.2 Feedstock transport cost

Typically, herbal leys for biomethane production are collected and transported to the conversion plant. It is assumed that herbal ley will be transported over a maximum of 5 miles from a Green Gas Mill to grassland and back. The haulage rate per mile for an 18/27 tonne vehicle is £2.5[47]. However, in most new Green Gas plants the aim will be to harvest as much as possible from the farm where the Green Gas Mill is located and neighbouring farms.

3.3 Biomethane production cost

Bioenergy costs, efficiencies, and emission intensities can change over time, but they are not expected to change across scenarios. The full cost data for biogas and biomethane production are adapted from CCC analysis[48].

The cost of biogas production from anaerobic digestion is forecast to be £29 per MWh in both 2020 and 2050; biogas upgrading to biomethane technology costs £38 and £35 per MWh in 2020 and 2050, respectively. The total cost of producing biomethane from the feedstock would be **£67 per MWh in 2020 and £64 per MWh in 2050**. However, with development of technology and the addition of enzymes to boost biomethane, costs are expected to fall considerably, with some estimates for new plants to be commissioned this year already suggesting **£54 per MWh**.

3.4 Price per unit of biomethane

Table 8 shows the total costs associated with utilising the entire biomethane potential of the UK. The price of a unit of biomethane was calculated based on the average biomethane potential of the UK.

Table 8. The total costs of if UK's biomethane potential is fully utilised

	Unit	Costs, £ billion
Feedstock cost	£194 / hectare	1.25
Grass to biomethane conversion technology cost	£67/ MWh (£64/ MWh for 2050) (£54/ MWh for enzyme addition)	19.3 (18.5) (15.6)
Transportation cost	£2.5 / mile for 27 tonne truck	0.039
Total cost		**20.6**

The total grassland area is assumed to be 6.46 million hectares, with a herbal ley yield of 13 tonne DS/year.

Assuming that the average UK's biomethane potential is 288.5 TWh/ year (see Table 2), the price unit of biomethane would be **£71.4 per MWh**, which could fall to **£69.5 per MWh by 2050**. The unit cost will be reduced to **£58.5 per MWh** through the development of new technology and the addition of seaweed enzymes.

According to the IEA World Energy Outlook report extract on prices and affordability[49], spot natural gas prices have been steadily rising around the world, reaching their highest levels in Europe during the second half of 2021. Natural gas prices fell significantly during the pandemic but have recently climbed dramatically (see Figure 6). In 2021, the EU's natural gas price is around £42.6 per MWh (15.8 USD/MBtu, one USD is currently worth around £0.79 on April 26, 2022). As shown in Figure 6.b, natural gas prices soared to around 45 USD/MBtu (£121 per MWh)[50] in 2022, more than twice the unit price of green gas because Russia's invasion of Ukraine has added further pressure and uncertainty to energy prices.

According to the IEA[51], annual upstream investment in natural gas supply will be around 240 and 125 billion USD (2020) for Net Zero Emissions by 2050 and Stated Policies scenarios (STEPS), respectively. The IEA also warns that demand uncertainty caused by the energy transition, global pandemics, and investor pressure to diversify away from fossil fuels could result in higher prices. Under these circumstances, as illustrated in Figure 6, the future natural gas unit price cannot be easily predicted. On March 20, 2022, the IEA announced a 10-point plan to reduce reliance on Russian natural gas[52], which encourages the replacement of natural gas with alternative sources such as green gas and gas grid electrification[52]. However, electrification of the gas grid has its own challenges with high associated costs.

Element Energy Limited and E4tech conducted a cost analysis of future heat infrastructure options for the National Infrastructure Commission and discovered that low carbon heating will be more expensive than fossil fuel heating today[53]. The cost of decarbonising the UK's heating and hot water is estimated to be between £120 and £300 billion under their central cost assumption, and between £100 and £200 billion under their best-case assumptions. They also stated that in 2050, the average cost of heating per home would be £100-300 higher. The CCC also estimates in its Sixth Carbon Budget report that £250 billion investments will be needed to fully decarbonise homes[54]. The decarbonisation of heating and hot water system includes different technologies such as heat pumps and direct electric heating. According to the Element Energy Limited and E4tech study[53], the electrification using heat pump requires upgrades to the electricity distribution network and the transmissions network, for a mid-case range total of £44 billion.

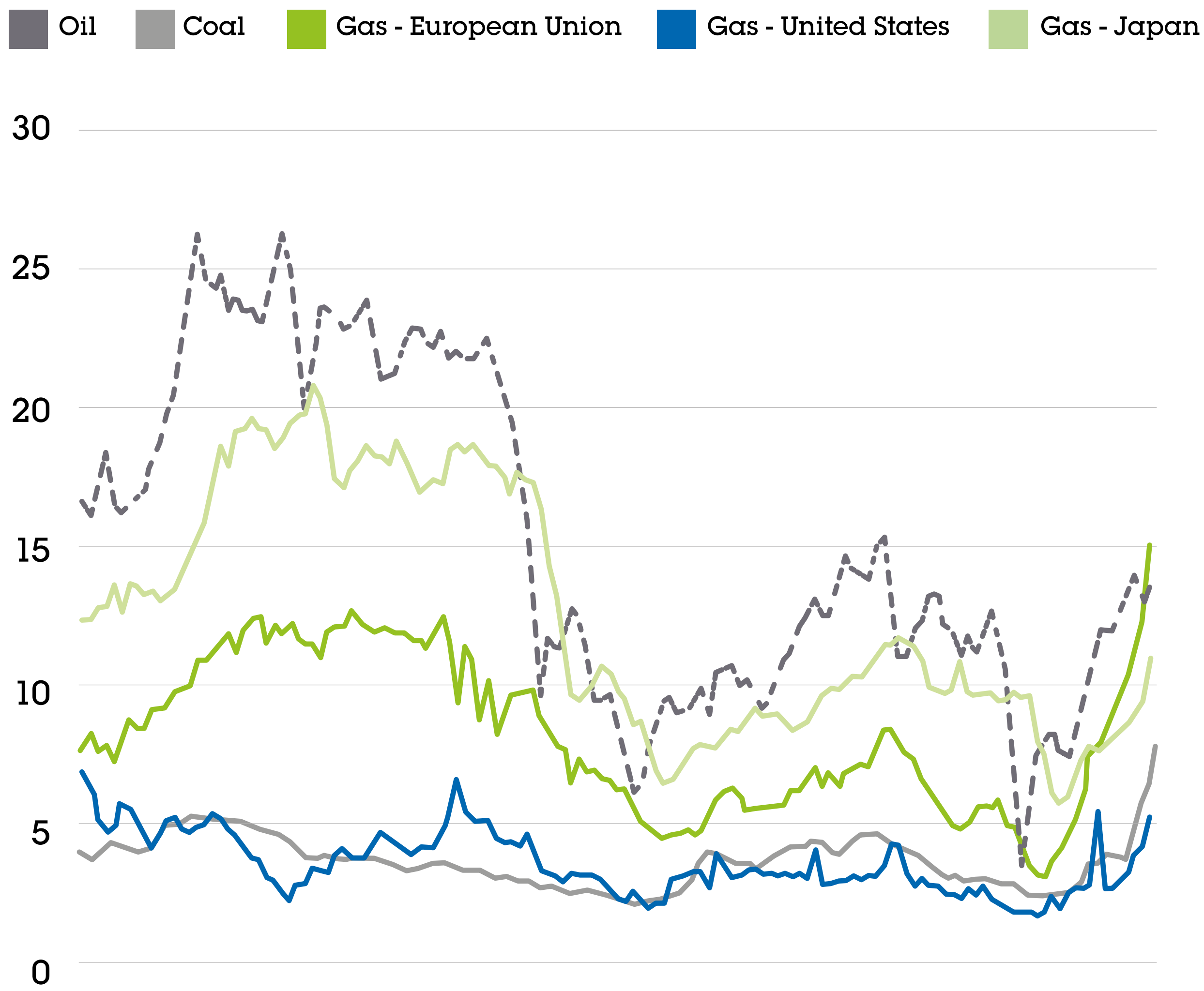


Figure 6a. Oil, natural gas and coal prices by region from 210 to 2021 in terms of USD per million BTU obtained from IEA[49].

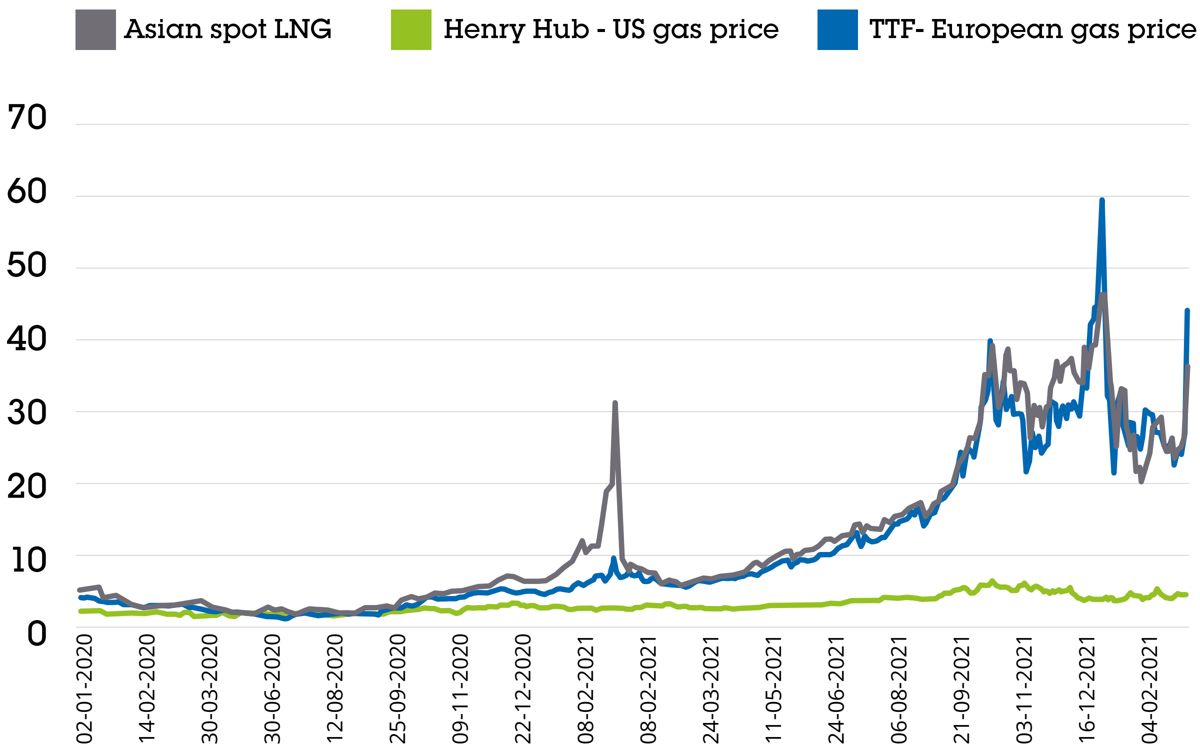


Figure 6b. IEA estimation of natural gas prices in Europe, Asia and the United States[50].

These high energy prices indicate that supply is struggling to keep up with demand. Green Gas is a simple and straightforward solution to address the high cost of electrification and the unexpected cost of natural gas prices.

3.5 Employment opportunities from green gas

Green Gas Mills have a large economic impact on rural regions. Each Green Gas Mill will generate around 30 jobs in agriculture and feedstock collection, operation and maintenance, and site management. We predict that each Green Gas Mill will provide £3 million per year, to the local agricultural economy via contracts for grass feedstock. This would provide a significant boost to rural towns at a difficult time.

The first Green Gas Mill, with a capacity of 5MW, requires on average 1,200 hectares (3,000 acres) of grassland (see Table 2 for average energy production), and costs £11.3 million to heat **3,600 homes** in the UK (The median gas consumption per meter in 2020 is 1.39 kW /12,145 kWh[55]). That equates to 0.33 hectare (0.82 acres) per house. That is less than one acre per household.

By 2050, energy efficiency is expected to reduce heat and building energy demand by 15-20%[40], implying that 0.27 hectares (0.67 acres) of grassland would be required per home. Thus, a typical Green Gas Mill could heat **4,500 homes** efficiently.

Nearly **5,400 (5,383) Green Gas Mills** could be built in the UK's 6.46 million hectares of suitable grassland, providing enough energy to heat 24.3 million homes (98.8% of British households) with well-insulated systems, or 19.5 million homes without energy efficiency modifications. As a result, the rural economy would gain nearly **162,000 jobs and £16 billion in annual investment**.

To heat the entirety of the UK's 29 million homes[56] (87% or 25.4 million residential buildings are currently connected to the gas grid; the remaining 13% or 3.8 million rely on oil, or liquid petroleum gas (LPG) or coal)[57]. In 2020, the median domestic gas consumption per meter in 2020 is 12,145 kWh[55]. Considering the total domestic gas demand in 2020 (299.3 TWh), 24.6 million homes would be heating by natural gas demand. The remaining homes (756,000) would be heated by heat pumps or biomass heating, which requires approximately 5,500 (5,466) Green Gas Mills would need to be built. We believe that by adding seaweed or shifting to a vegan diet by 2050, Green Gas Mills will be able to heat all homes in the UK if they are insulated for energy efficiency.

3.6 Reducing our reliance on fossil fuel imports

Natural gas prices have risen sharply in the last year, causing the British government to struggle to reduce the impact of energy prices on citizens' energy bills. Ofgem announced a 54% increase in the energy price cap from April 2022 due to a spike in wholesale gas prices affected by the war in Ukraine, and a further increase is expected in October 2022[58]. However, rapid biomethane scaling-up could provide both a short-term and long-term solution.

While the UK's overall gas usage is decreasing, the quantity imported is increasing as the North Sea depletes (Figure 6). According to the UK Oil and Gas Authority, the UK's natural gas imports could rise to nearly 70% by 2030. As a result, rather than benefiting the British economy, more and more of the money we spend on importing fossil fuels will be spent overseas, making us larger clients for the Netherlands, Norway, and Qatar. Rising costs for fossil fuel imports have led in recent years to a current account deficit, which narrowed to £11.4 billion (1.9% of GDP) in Quarter 4 2021, from £26.1 billion in the previous quarter[59].

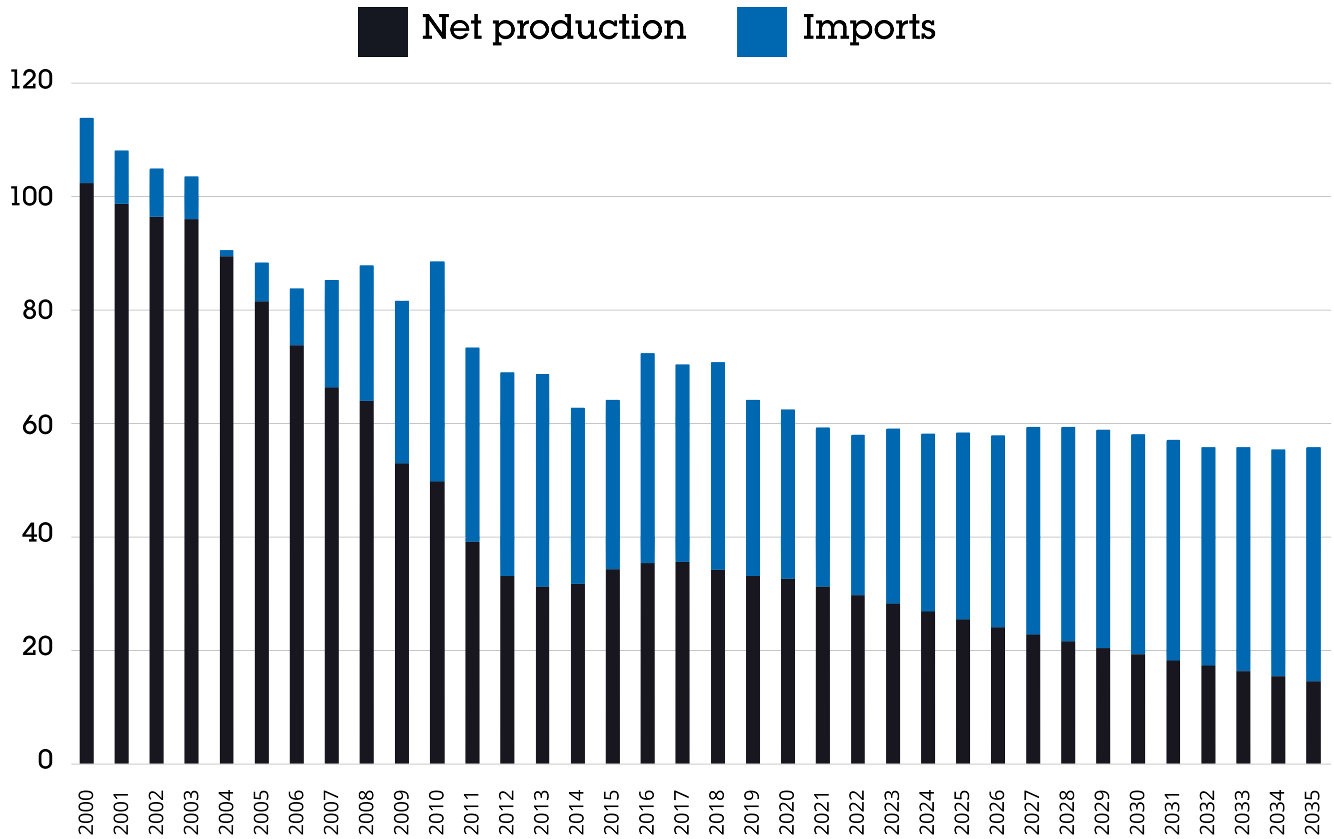


Figure 7. The UK gas consumption by source (million tonnes of oil equivalent) [60]

Biomethane produced in Europe is currently 30% cheaper than natural gas[61] and can reduce the UK's energy dependency on external suppliers. Capable of being produced from £58.5 per MWh of biomethane, (with cost expected to decline, in addition to being a cheaper alternative, biomethane could provide the steppingstone to green hydrogen, which requires more time and cost to adequately scale-up[61]. The ongoing Russia-Ukraine crisis has prompted the UK's decision to phase out Russian imports (less than 4% of its natural gas supply, 32 TWh)[62]; biomethane could very quickly replace these imports and help stabilise rising gas prices in the UK. It would take just 430 thousand hectares of grassland and 358 Green Gas Mills to replace all the gas imported from Russia.

Green Gas Mills can not only get us on the road to a greener Britain, but they can also aid our farmers, increase food yield, create employment, protect wildlife, and reduce our dependency on fossil fuel imports.

4. Biodiversity gain

According to the House of Commons report "Biodiversity in the UK: bloom or bust?", the population sizes of birds, mammals, amphibians, reptiles, and fish have declined by 68% since 1970. The UK is one of the world's most environmentally devastated nations with 15% of UK species on the verge of extinction. Among the G7 nations, the UK has the lowest amount of biodiversity surviving63. At the very least, the UK has failed to reach 14 of the 19 Aichi biodiversity objectives, which are global environmental goals that the UK agreed to meet by 2020[63]. The reason for the dramatic decrease in biodiversity could be the intensification of both arable land and monoculture grasslands; additionally, the UK lost nearly 2 million acres of grassland due to urban area expansion[64].

The House of Commons report recommends that an urgent revolutionary change is necessary to reverse the trajectory of biodiversity loss[63], which cannot be addressed simply by better using natural resources. In 2020, the UK Government unveiled the Ten Point Plan for a Green Industrial Revolution, with the ninth point focusing on the protection of our natural environment[44]. The UK government allocates funding to create more green jobs, with a £40 million second round of the Green Recovery Challenge fund to improve biodiversity and tackle climate change[44].

Ecotricity's vision is to plant herbal ley species not only to generate green gas but also to address the UK's biodiversity crisis. Herbal ley mixture species do not require agricultural land, so they do not compete with food production. They do, however, provide specific added environmental values, such as promoting biodiversity and soil fertility. Herbal leys on grasslands even have the potential to enhance biodiversity[65,66] and to provide additional benefits such as increased carbon capture from the atmosphere and food production for pollinators like bees, butterflies and hoverflies [66-69].

4.1 Enhancing the soil health and structure

Herbal leys, which are composed of grass, legumes, herbs, or wildflowers, have numerous advantages for improving soil health and structure. Plants like grass, legumes, herbs, and wildflowers provide energy, protein, and minerals, as do plants like sainfoin, chicory, or bird's-foot-trefoil[70]. Legumes do add nitrogen to the soil, which can reduce the need for synthetic N fertilizer[71]. Additionally, they absorb more carbon from the atmosphere and store it in the soil as organic matter.

When used in crop rotation cycles, the varieties of native grass species we use in our Green Gas Mills can increase food productivity on arable farmland and improve soil health while breaking disease and fungal cycles that can persist in the soil[72] because herbal leys build soil carbon, fix nitrogen and mobilise phosphate for the following crop, all of which benefit soil fauna. Deep-rooted grassland has the ability to create and restore healthy organic matter to the topsoil in a way that cannot be duplicated by adding organic topsoil or manures alone, as they can reach water deeper in soil. Also, growing herbal leys creates an absorbent layer on the surface, which has the benefit of impeding rainfall runoff, thereby providing greater community benefit from reduced flood risk.

Digestate as a biofertilizer

Ecotricity's Green Gas Mills will contribute not only to renewable energy but also to renewable fertilisers. Green Gas Mills produce a digestate as a by-product, which may influence water, land and biodiversity. Converting digestate into biofertiliser can provide economic benefit as well as increase microbial biomass and activity in soil [73,74].

Digestate biofertilisers can also boost herbal leys growth. According to an Irish study, the quality of biofertilisers varies significantly depending on the feedstock used [75]. The development of biofertilisers from digestate is becoming increasingly important for Green Gas Mills in order to meet regulatory requirements and generate additional revenue.

Green Gas Mills have the necessary technical performance and infrastructure to recover nutrients from digestate which can be marketed as a biofertiliser. Digestate from Green Gas Mills will be accredited to the standard of PAS 110[76] which ensures safe and reliable organic fertilisers while also eliminating methane emissions, as it requires closed digestate storage.

4.2 Creating habitats for wildlife

It is estimated that Britain has lost 97% of its species rich grassland with only isolated pockets remaining since 1930[77]. This has caused the decline of many species of farmland bird and insects, particularly bees, which play a vital role in the ecosystem.

Green Gas Mills can enhance the wildlife values of land by replacing intensive monoculture grasslands with species rich herbal leys. Green Gas Mill feedstocks, herbal leys, contain a greater diversity of species, including herbs and wildflowers such as chicory, ribgrass, clovers, sainfoin, and lucerne, which provide pollen and nectar-rich habitats that can help slow or halt the decline in pollinating bee populations and species in the UK[78]. Herbal leys will support a much higher density of insects, bees, and other pollinators than any intensively managed grassland because of the lack of use of synthetic pesticides or agrochemicals. Those insects and insect larva offer food for voles, shrews, and mice, which are prey for mammalian predators such as weasels and stoats, as well as birds of prey such as kestrels, buzzards, harriers, and owls and a variety of other species. Additionally, insectivorous birds such as skylarks, yellow wagtails, whitethroats and grey partridges, as well as bats would benefit from herbal leys as a food source.

To summarise, the UK's 25 Year Environment Plan, published in 2018[79], highlights the threats posed by long-term trends in water quality, air quality, GHG emissions and biodiversity. This represents a great challenge to British agriculture. However, the development of successful Green Gas Mills coupled with enhanced nutrient management planning represents an excellent opportunity to reset and refine our systems to deliver better environmental outcomes at a local and national level.

5 Greenhouse gas savings

The Climate Change Committee (CCC) recommends that the UK set its Sixth Carbon Budget to require a 78% reduction in emissions by 2035 compared to 1990[54]. Net Zero Strategy: Build Back Greener lays out policies and proposals for decarbonising all sectors of the UK economy in order to meet our net zero target by 2050[1]. The decarbonisation of the British gas network strategy covers the future injection of biomethane and potential hydrogen blending. The availability of UK grassland potential for biomethane generation and displacement of natural gas in the current gas grid would make biomethane a more viable solution for decarbonising the gas grid than hydrogen, which requires more cost and energy to produce and store.

The main emissions from green gas generation are methane emissions from anaerobic digesters, biogas upgrading units, digestate storage and transmissions, distribution and storage of green gas, and nitrous oxides from digestate handling stages. The emissions can come from fugitives, leaks on pipes, tanks, vents or pressure relief vales. Methane emissions are the main concerns of biomethane production due to higher 100-year global potential of 27.2 ±11 based on latest IPCC report[79]. Nitrous oxide (N2O) has an even higher 100-year global warming potential of 273 ±130[79] than CO2 which can also be emitted by incomplete combustion of engine and flare. Life cycle emissions should be thoroughly investigated in order to generate sustainable green gas. In order to quantify GHG emission savings, total life cycle emissions of Green Gas Mills should be compared to the alternative scenario of business as usual (BAU). The stages associated with GHG emissions from the Green Gas Mills and the BAU alternatives are categorised in Table 9 below. The end-use emissions from natural gas and green gas are not included.

Table 9. Stage of life cycle emissions (LCE) from Green Gas Mills and BAU

	Green Gas Mills – GHG emissions	**BAU Alternatives – GHG emissions**
Upstream emissions	A) Emissions saving from grassland, as feedstock	1) Land used for grazing, or grassland uses business as usual
On-site emissions: gas production, transmission, distribution and storage	B) Biomethane production and utilisation on site: emissions from supply chain • Biogas production • Biogas upgrading: Biomethane production • Transmissions, distribution and storage	2) North Sea emissions from domestic gas production, pipeline distribution and LNG shipping
Downstream emissions: Fertiliser application	C) Digestate transport and spread-ing on land	3) Life cycle emissions of synthetic fertiliser production and spreading on land
Total LCE	A+B+C	1 + 2 + 3

The GHG saving (%) can be calculated as the ratio of the differences between alternative scenarios and total LCE of Green Gas Mills compared to the alternative scenarios:

$$\frac{\text{Total LCE from BAU alternatives (1+2+3) - Total Green Gas Mills LCE (A+B+C)}}{\text{Total LCE from BAU alternatives (1+2+3)}}$$

5.1 Upstream GHG emissions

If the available grassland is not used for Green Gas Mills, the land would be used for grazing.

According to the UK National Atmospheric Emission Inventory (NAEI, 2022), the UK's emissions from grazing are 1,037 kilotonnes of $CO_{2\text{-eq}}$ for 2019[80]. The total grazing land in the UK in 2019 is 5.09 million hectares, including rough and common grazing land. Therefore, emission intensities in 2019 would be **203.7 kg CO2-eq/ha**. The emissions would be higher if methane emissions from manure management and nitrous oxide emissions from agricultural soils were included. We aim to assess the lowest possible range of GHG emissions savings by operating Green Gas Mills.

The grassland emission savings are 1,100 kilotonnes $CO_{2\text{-eq}}$ for 2019[80]. Given the UK's total grassland area of 12.08 million hectares, the grassland emission intensity in 2019 would be **-91.1 kg $CO_{2\text{-eq}}$/ha**.

5.2 Average emission intensity of the UK Natural Gas Supply (On-site emissions – 2)

Green gas, as an Ecotricity goal, has the potential to replace natural gas. As a result, natural gas emissions from the production, transportation and distribution stages should be compared to Green Gas Mill emissions under the BAU conditions. The emission factor for natural gas assumed in the Ofgem Carbon Calculator is 67.59 g CO2-eq /MJ **(243 kg CO2-eq /MWh)**[81] for the EU mix with 4000 km of transport distance and combustion emissions.

5.3 Downstream GHG emissions

Synthetic fertiliser is an alternative for biofertiliser obtained from Green Gas Mills. The Ofgem GHG calculator is utilised to estimate GHG emissions from fertilisers[81]

Table 10. Lifecyle emission intensities from fertiliser production[81]

Parameters	Emission intensity	Unit
Fertiliser production LCE, N	4.57	kg $CO_{2\text{-eq}}$ / kg N
Fertiliser production LCE, P_2O_5	1.18	kg $CO_{2\text{-eq}}$ / kg P_2O_5
Fertiliser production LCE, K_2O	0.64	kg $CO_{2\text{-eq}}$ / kg K_2O

These parameters are combined with the amount of digestate (kg or tonnes) to calculate the fertiliser counterfactual's GHG emissions. In 2020, the fertiliser consumption given in Table 10 was used to estimate total GHG emissions from fertiliser utilisation (see Table 12).

Table 11. Overall fertiliser usage on grassland per hectare in Great Britain for 2020[82]

Nitrogen usage	53	kg N/ ha
P_2O_5 usage	8	kg P_2O_5 / ha
K_2O	11	kg K_2O / ha

Table 12. Total emissions from fertiliser production and utilisation in Great Britain for 2020

Nitrogen fertiliser	242.21	kg $CO_{2\text{-eq}}$ / ha
P_2O_5 fertiliser	9.44	kg $CO_{2\text{-eq}}$ / ha
K2O fertiliser	7.04	kg $CO_{2\text{-eq}}$ / ha
Total emissions from fertiliser production and utilisation	**258.69**	**kg $CO_{2\text{-eq}}$ / ha**

5.4 Lifecycle emissions from biomethane production (A, B, C)

According to the DEFRA GHG conversion factors, lifecycle emissions of anaerobic digestion plants with biomethane upgrade for the gas grid would account for **65 kg $CO_{2\text{-eq}}$/ MWh** in 2020 and **6 kg CO2-eq/ MWh in 2050**[83]. Green Gas Mills have been operating with advanced technology, so we believe methane emissions from such facilities will be in the lower range. However, 6 kg $CO_{2\text{-eq}}$/ MWh may be too ambitious, so we decided to use an average GHG conversion factor for 2020 and 2050, which is **35.5 kg $CO_{2\text{-eq}}$/MWh** for Green Gas Mills. As these are the default emission factors (which do not represent a specific grass type), future research will be able to assess the comprehensive lifecycle emission estimate for a typical Green Gas mill. We are now working with Ecotricity to assess the Life Cycle Analysis (LCA) of green gas mills. This will be completed when the plant at Reading is operational in 2023/24.

5.5 GHG emission savings from Green Gas Mills compared to business-as-usual emissions

BAU (i) Grassland is used for

- Upstream emissions from grazing, **(136.7 tonnes CO2-eq/ y for 1200 hectares land)**
- On-site emissions from natural gas **(10,643.4 tonnes CO2-eq /y for 5 MW energy production)**, and
- Downstream emissions form chemical fertiliser utilisation (**314.1 tonnes CO2-eq/ y for 1200 hectares land)**

Total LCE emissions would be **11,094.2 tonnes $CO_{2\text{-eq}}$ per year**.

BAU (ii): Grassland is utilised for

- Upstream emissions as a native grassland **(-110.6 tonnes CO2-eq/ y for 1200 hectares land)**,
- On-site emissions from natural gas is used for energy **(10,643.4 tonne CO2-eq / y for 5 MW energy production)**, and
- Downstream emissions from chemical fertiliser utilisation **(314.1 tonne CO2-eq/ y for 1200 hectares land)**.

Total LCE emissions would be **10,846.9 tonne $CO_{2\text{-eq}}$ per year**.

How about the LCE emissions from Green Gas Mills?

One Green Gas Mill needs 1,200 hectares which saves 109.3 tonnes of $CO2_{\text{-eq}}$/y. Green Gas Mills with a capacity of 5 MW generate 1,554.9 tonne $CO_{2\text{-eq}}$/y from biogas production to biomethane generation. Downstream emissions for digestate would be zero[81]. Each Green Gas Mill will produce **1,445.6 tonnes of $CO2_{\text{-eq}}$/y** in total, although this is the upper end of the emission range for Green Gas Mills. We believe that with proper automation and well monitored systems, these emissions will be significantly reduced. These emissions will be reduced further to **153.5 tonne $CO_{2\text{-eq}}$/y** by 2050 using the DEFRA 2050 GHG conversion factor[48].

In comparison to the above-mentioned alternative use of grasslands with natural gas supply, Green Gas Mills provides GHG savings ranging **around 87%**, which could account for **up to 99% of GHG saving by 2050**.

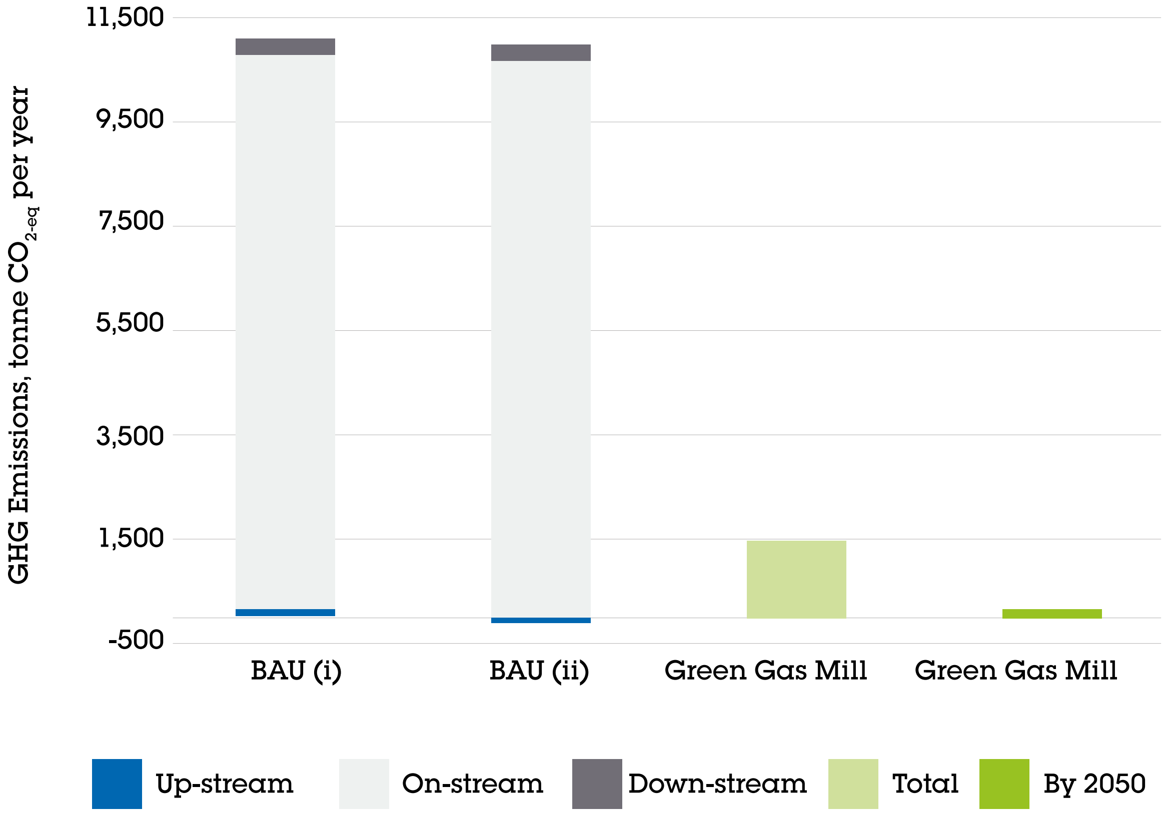


Figure 8. GHG from the Green Gas Mill and business as usual (BAU) scenarios

Green gas recycles atmospheric carbon and does not release any additional fossil carbon into the atmosphere as the carbon contained in biomethane is biogenic and part of the carbon cycle. As a ready to use technology, biomethane needs to be an urgent priority to ensure that we can cut emissions as much as possible, as soon as possible. This needs to be done by Green Gas Mills.

6 Achieving Our Green Potential: summary of becoming Green Britain

The UK has tremendous potential for green gas generation to be used not only to decarbonise heating and hot water, but also to meet its net zero emission commitments. Additionally, green gas can serve as a form of seasonal energy storage and provide support for other low-carbon electricity sources. The rise in energy prices following the pandemic and the energy crisis caused by the Ukraine war have prompted the world to look for suitable energy sources, one of which is Green Gas, readily available in the UK.

We believe that Green Gas Mills can directly contribute to the UK's need for energy independence and decarbonisation. Although low-carbon heating technologies such as heat pumps will also be critical, and the National Grid's 'Leading the Way' scenario includes a mix of hydrogen and electrification for heating[84], these will necessitate significant societal changes as well as significant investment in overall system infrastructure. We believe that Green Gas Mills can be easily adapted to the current natural gas grid without incurring significant costs, and that they can contribute to the UK's net-zero goal.

To demonstrate how, we've created three scenarios (low, medium and maximum ambition represents 25%, 50% and 100% of total green gas production, respectively) that illustrate theoretically how far we could go in decarbonising our heating by 2035 through the use of Green Gas Mills (Table 13). Green Gas Mills are more than eight times less expensive than heat pump options, with up to £16 billion in revenue and 162,000 jobs created, as well as a 52 million tonne $CO_{2\text{-eq}}$ GHG savings. These are not predictions. They have nothing to do with what we believe is probable. They are about what is possible, ranging from what we think is a bare minimum to the very ambitious. Ultimately, these scenarios are intended to demonstrate how far we can go and to set the stage for a discussion about the potential benefits of Green Gas Mills.

Table 13. Green Gas Mills 2035 scenarios

	Low ambition	Medium ambition	Maximum Green Gas
Green Gas Mills	1350	2700	5400
Green gas generated (TWh)[1]	59.1	118.3	236.5
UK energy-efficient households supplied (%)	24.7	49.4	98.8
Estimated carbon saving (million tonne $CO_{2\text{-eq}}$)	13	26	52
Revenues generated (£mn)	2025	4050	8100
Employees	40500	81000	162000
Green gas roll-out costs (£bn)	14	28	56.1
Heat pump roll-out costs (£bn)[2]	65	130	260

Notes: [1] It is assumed that each green gas mill has 5 MW capacity. [2] The total cost of heat pump replacement for 29 million homes is interpolated to the number of homes (24.6 million) heated by Green Gas Mills.

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Part Two

Domestic Heat Pumps in the UK – The implications of a wholesale switch to heat pumps and the potential for interface with Green Gas

Independent analysis by NRS Griffiths

Domestic Heat Pumps in the UK – The implications of a wholesale switch to heat pumps and the potential for interface with Green Gas

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Introduction

The UK Government's Heat and Buildings Strategy (October 2021) rests on the Clean Growth Strategy (2017), the 2050 Net Zero commitment, and the Prime Minister's Ten Point Plan for a Green Industrial Revolution (2020).

The Heat and Buildings Strategy sets out a path for decarbonisation of heating, but there are significant challenges along the way. This Strategy correctly recognises that demand reduction is needed as a first step. Demand reduction ultimately reduces the need for new sources of low carbon energy production to be built. All new construction has a carbon impact of its own - embodied carbon - as well as other environmental impacts, so it is essential to minimise these impacts and not to rely on the single metric of "carbon emissions from buildings in use" during the decision-making process.

A further significant challenge is that the targets for demand reduction are framed in terms of a building's headline score on the Energy Performance Certificate (EPC). The problem is that the headline EPC score is an estimate of energy cost, not a measure of carbon emissions. Replacing gas central heating with a heat pump, for example, in order to reduce carbon emissions, will increase running costs for consumers and is therefore unlikely to improve the EPC score[1]. The Heat and Buildings Strategy includes a commitment to rebalance the relative price of gas and electricity to address this issue, but serious concerns remain about EPCs and hence their use as a policy tool[2].

The Strategy sets out 5 policy areas to be developed during the next decade:

- **Energy efficiency in buildings**
- **Heat pumps**
- **Hydrogen**
- **Heat networks**
- **Bioenergy**

The optimal path to net zero requires a mix of technologies and approaches - sustainability is the art of the possible, making best use of what we have got. It is clear from the Heat and Buildings Strategy that there is to be a heavy reliance on heat pumps as the optimal or only solution to the decarbonisation of heating in many or most circumstances. For the purposes of comparison only, this brief analysis sets out the costs and implications of a wholesale or partial switch to heat pumps as the primary source of space heating and hot water in domestic buildings.

2. The Capital Cost Implications of a switch to Heat Pumps

There are 3 elements to the capital cost of switching to heat pumps:

- cost of installation in each property;
- cost of upgrade to the local electricity distribution grid;
- cost of increasing renewable electricity production.

2.1 The costs of installation

The cost of installing a heat pump of course varies according to the property - principally according to the peak demand which the pump will be called upon to meet. The Heat and Buildings Strategy quotes a cost of £7,000 - £14,000 for the cost of installing a domestic air source heat pump (ASHP), depending on building size and fabric efficiency. Some buildings may of course be suitable for a ground source heat pump (GSHP), but the mass market is likely to be for ASHPs as there are constraints to GSHP installation in so many locations.

We cannot simply take an average of these figures and multiply by the number of dwellings in the UK to derive an overall capital cost - for a number of reasons:

a. Some dwellings are already heated by heat pumps;

b. There are more smaller dwellings than larger ones, so the median cost will be lower than the average;

c. The costs of installation may be expected to fall as market size increases;

d. Boilers need to be replaced on average every 15 years in any case, so the cost of the replacement boiler should be deducted.

e. In some cases, the switch from a gas boiler to a heat pump will require replacement of the heat distribution system to allow for the lower temperatures which heat pumps require to operate efficiently.

To examine each of these factors in detail:

a) Market size

The current English domestic building stock is approximately 25.2m dwellings[3], 1.4m in Wales[4] and 2.6m in Scotland[5], making a total of 29.2m homes in the UK excluding Northern Ireland. In 2020 it was estimated that 200,000 heat pumps had been installed in UK homes. This leaves a net total of 29m homes where new heat pumps could in theory be deployed - in England, Scotland and Wales.

b) Costs of heat pumps

The cost of £7,000 - £14,000 for the cost of installing a domestic ASHP quoted in the Heat and Buildings Strategy (P86) needs some interpretation. According to the BRE's analysis of UK dwelling types, less than 20% of properties are detached, the majority being semi-detached, terraced, bungalows or flats. In other words, we can realistically conclude that average costs will be at the lower end of this cost spectrum. Indeed, some small social housing units for example are heated by very small heat pumps which cost considerably less than the lower estimate[6]. On this basis, it is safe to assume an average cost of £8,000 per property, based on current prices.

These costs relate to air-water heat pumps - where water is the heat distribution system - as is the norm in the UK with gas and oil boilers. Air distribution is of course common in non-domestic buildings as a component of air conditioning systems, and used in housing in other countries, but rare at present for dwellings in the UK. Costs for air-air heat pumps are lower but this would require a completely new distribution system (air) to be installed. The additional cost of distribution would compensate for the lower cost of the heat pump, so the total cost of a replacement air-air system is likely to be similar to an air-water system using at least part of the existing distribution system.

c) Savings from volume roll-out

The 2016 report[7] "Potential Cost Reductions for Air Source Heat Pumps" derives a figure of 20% for expected reductions if ASHPs are rolled out at mass scale. Similar reductions have been achieved in other areas of technology in recent years, so we should therefore apply this reduction across the board to the total figures derived.

d) Natural replacement cycle

If a machine of any type is replaced before the end of its life - this creates a "wasted asset". The impact of wasted assets, and their embodied energy is completely missed in policy terms. If we replace boilers before they have reached the end of their life, then we increase carbon emissions more than is necessary.

To minimise such wasted assets and their embodied carbon emissions, heat pumps should therefore be introduced according to the "natural replacement cycle" of boilers, and not before. The exception to this may be the introduction of hybrid heat pump/boilers - where an existing boiler can sometimes be retained - see the Section below on Hybrid Systems.

If the installed cost of a replacement gas boiler is taken on average to be £2,500[8], this should be deducted from the cost of the air source heat pump installation - as a heating system will be required in any case.

In the UK, 87% of domestic properties are on the gas grid. Of the remaining 13%, we may assume that those on oil or coal would be replaced by a heat pump as this is demonstrably lower carbon. There would be no point replacing biomass heating with electric heating until the grid is fully decarbonised, as biomass would be both lower carbon and lower in running costs, but only a small percentage of domestic buildings are currently heated by biomass. Oil boilers have a similar (or slightly higher) installed cost to gas boilers.

e) Heat distribution system replacement

Heat pumps work best with low temperature distribution systems. This is because they have to raise the temperature of the heat by a lower amount, and can thus run more efficiently. It is perfectly possible to run a heat pump with higher distribution temperatures but the efficiency level drops, so the carbon intensity increases, as does running cost[9].

Unless major thermal improvements are being made to the property at the same time as heat pump installation, a lower temperature distribution system will be required. In most retrofit situations it is impractical to fit underfloor distribution so in practice this means increasing emitter (radiator) sizes so that they can deliver the same comfort temperatures while using a lower temperature distribution system.

The cost of increasing radiator sizes of course depends on the size of the property, and not all properties will require distribution system replacement, but it is realistic to add an average of £1,000 per property to allow for this.

Conclusions on heat pump roll-out costs

Taking into account the costs set out in (b) to (e) above, we can derive the following average cost per property for the switch to ASHPs:

	Add	Subtract	Total
Average cost of Domestic ASHP			£8,000
Distribution system upgrade	£1,000		£9,000
Replacement boiler cost		£2,500	£6,500
Volume discount		20%	£5,200
Net Total			**£5,200**

Applying this average unit cost across the housing stock for England, Scotland and Wales, we can derive the following costs:

	No of dwellings	Total cost
25% of dwelling stock	7.25m	£38Bn
50% of dwelling stock	14.50m	£75Bn
100% of dwelling stock	29m	£151Bn

It is important to understand that the final figure in this table is **purely notional** as it would be impractical to replace all heating systems with an ASHP. Firstly, there are lower carbon heating systems (biomass, biogas, waste heat) already in use and their use should be expanded. Secondly, some properties will be suitable for a GSHP. Thirdly, there are constraints to the deployment of heat pumps, as many buildings are not suitable for heat pumps, and cannot be made to be suitable in a cost-effective and environmentally sustainable manner.

2.2 The costs of upgrade to the electricity distribution grid

The government recognises that a large scale switch to electric heating will require "significant additional network capacity", including a massive upgrade to the low voltage network which provides the connection from local substations to dwellings.

No formal attempt has yet been made to quantify these costs, but the UK Government states that "We have been engaging with distribution network operators (DNOs) and the Energy Networks Association to understand the potential scale of the need for local network reinforcement and preparations for electrification of heat. For these reinforcements to be carried out effectively, we need to ensure that DNOs can make strategic investments that reduce the need for network upgrades, investing ahead of need, where possible and useful. DNOs were due to submit their final business plans to Ofgem in December 2021, setting out their proposed projects and actions for the 2023-2028 price control, RIIO-ED2.[10]"

These business plans clearly need to be analysed and summed. However, they do not contain the full figures required because 100% electrification of heating has not been proposed and the DNOs are not allowed to include costs for speculative investment - they can only respond to proven levels of demand. Furthermore, the demand will also be increased by the planned switch to electric vehicles, which will add significantly to the requirements for electricity grid capacity. By contrast, smart grid management should reduce overall costs somewhat.

100% heat pump deployment would require replacement of whole grid system components - including provision of 3 phase power at local level - as many buildings have a larger heat demand than can be met by a 240V heat pump. It is possible that (carefully selected) 25% heat pump deployment could impose demands on the grid that can be met with only partial grid reinforcement, so it is conceivable that grid costs for 100% deployment would be greater than they would be if scaled up from 25% (i.e. more than 4x greater).

According to the Element Energy report "Cost analysis of future heat infrastructure options" (2018) the worst case scenario (based on reduced heat pump efficiency and sub optimal consumer behaviour) is that "This leads to total discounted distribution and transmission reinforcement costs of £62 bn.

2.3 The costs of increasing renewable electricity production

Electrification of heat will require a huge investment in renewable electricity production, in addition to the loads already to be imposed by decommissioning of fossil-fuel power plants, and the switch to electric vehicles.

The key to working out supply costs is an assessment of peak demand. Peak domestic demand for gas is currently 170GW, though according to other calculations referenced the peak demand may be more than double this[11].

Based on a coefficient of performance (CoP) of 2.5 (which an ASHP is unlikely to achieve in mid winter), if this peak demand were to be replaced by heat pumps, we would need 170GW/2.5 = 68GW of additional electricity generating capacity. This ignores the potential impact of energy storage systems but as the CoP in mid winter will be lower than 2.5 the peak demand on the grid is likely to be higher.

Note that solar cannot be used to provide this power for space heating - as it is not available when heat demand is at its highest. In terms of low carbon electricity, we are therefore reliant on nuclear, wind power, hydro , geothermal or tidal power (if this is ever introduced, which it should be).

The installation cost of offshore wind power is recorded by BEIS at £1.3m per MW[12] in 2030, excluding transmission costs. This equates to £1.3Bn per GW.

On that basis, to add 68GW of further capacity would cost 68 x £1.3Bn = £88Bn, with no allowance for transmission costs. Economies of scale may well bring this figure down, so we may crudely estimate a further £88Bn in capacity costs for the supply of additional renewables capacity to provide complete electrification of domestic heating via heat pumps.

2.4 Total capital costs of heat pump installation

Based on the analysis of individual heat pump costs set out above, it is necessary to add the costs of increasing renewables capacity to meet this additional demand.

At present, good data is not available, and there are other sectors of the economy (such as transport) where a switch from fossil fuels to electricity is envisaged, so it is difficult to isolate costs. Nonetheless, it is essential to include an estimate, so that the cost is recognised - and this estimate can be refined as better data becomes available.

Based on housing stock for England, Scotland and Wales:

	Heat Pump installation estimate	Grid upgrade Estimate*	Renewables capacity estimate	Total cost estimate before grid upgrade
25% of dwelling stock	£38Bn	£11Bn	£22Bn	£71Bn
50% of dwelling stock	£75Bn	£22Bn	£44Bn	£141Bn
100% of dwelling stock	£151Bn	£44Bn	£88Bn	£283Bn

* https://nic.org.uk/app/uploads/Element-Energy-and-E4techCost-analysis-of-future-heat-infrastructure-Final.pdf

As previously stressed these figures are purely notional as 100% switch to heat pumps is not proposed.

These figures suggest that the cost of heat pump deployment could be doubled by the costs of grid upgrade and the costs of providing additional renewable electricity generation capacity to meet the increased demand.

2.5 Other environmental costs

Ultimately, sustainability is about the kind of tomorrow we want to leave to the next generation. This is the key message of the famous Brundtland definition of 1987 that sustainable development is:

> *"development which meets the needs of current generations without compromising the ability of future generations to meet their own needs."*

We therefore need to think carefully about the implications of our different options and carry out a much fuller cost-benefit analysis before making decisions about the future of heating and electricity supply in the UK.

There is a tendency to measure carbon emissions solely at the point of use. This serves an industrial agenda as it tends to promote the maximum amount of change - i.e. switch from A to B and the emissions will fall. This ignores the carbon cost of making the change - the embodied carbon. When considering a wholesale switch to renewable energy this impact will be very significant indeed, and it will take some time simply to pay back the carbon cost of making the change. In other words, decarbonisation of heating will actually increase carbon emissions in the short term, so we need to be careful how this is done.

Capital costs are not the only costs. Resource scarcity is an issue and all change has an impact. If we are developing vast new capacity of low carbon generation plant, be it nuclear, tidal or wind power, this all consumes resources and certain resources are constrained - especially metals. Land use is a further cost which does not easily translate into financial values despite the efforts of economists.

Decarbonisation is also not the only environmental priority. Many people have been reminded through the pandemic that we value both our natural and built heritage, and time spent outdoors is vital for mental and physical health. New sources of low carbon energy have an impact on our landscape, and this has to be weighed against the decarbonisation aim. Regeneration should deliver not only a low carbon future, but one where communities thrive, employment is available, heritage is enhanced, flood risk is reduced, and where we re-green and protect our natural environment

3. Constraints on heat pump deployment

3.1 Building typology

Heat pumps work best in well insulated and airtight buildings but many existing buildings cannot be retrofitted to modern thermal standards. There are many details on buildings which make insulation very difficult at reveals and junctions between walls/floors and roof structures, meaning that heat will continue to escape at these points - via unavoidable thermal bridging. Added to this, the way that some buildings are constructed makes it very hard to prevent air leakage, so they will continue to have a high heat demand - you can't retrofit an air tightness membrane, it needs to be built in from the word go.

Low temperature distribution systems such as underfloor heating cannot be installed in many buildings because there is no insulation in the floor slab and the floor level cannot be raised, or because not all suspended floors can take the required insulation and pipework. In such buildings, all other things being equal (i.e. heat demand not reduced), the radiator sizes will have to be increased, taking up more internal wall space, but delivery temperatures will also be higher than when underfloor heat distribution is used, making heat pumps run less efficiently. At least 20% of the UK's dwellings are of traditional construction[13] - i.e. solid walled, and these are not ideally suited to the low temperatures delivered by heat pumps.

There comes a point where the impact of the insulation and airtightness work to reduce space heat demand (i.e. the embodied energy & emissions) becomes so great that in carbon (and cost) terms it is better to insulate up to a certain point only, and accept that some buildings will always have a significant residual heat demand. Only when the electricity grid is fully decarbonised and gas is no longer in use to make electricity would it make sense to switch these buildings to a heat pump. This is explored further in the section on hybrid heat pumps.

Approximately 20% of UK dwellings are flats (there is some limited crossover with the 20% traditional construction mentioned above, but most flats were constructed after 1919). Many would not be suitable for individual heat pump installations because it would not be possible to install ASHPs on the exterior of these buildings at height. However, flats can be heated by a communal heat pump - with the heat being piped through the building. Many large office blocks and other non-domestic buildings are already heated by heat pumps, so this is not necessarily a barrier. Heat can be metered just as easily as gas and electricity, so individual dwellings can still be responsible for their actual heat use. This would require a new distribution network to be installed within each block, which is not impossible, but could be costly. In some blocks of flats, there may not be sufficient space to install the ASHP even at ground level. Planning barriers might also apply.

3.2 Impact of domestic hot water demand

As fabric insulation standards improve and space heating demand falls, hot water for washing and bathing becomes a much more significant proportion of domestic energy use. We also take more showers than we did 50 years ago.

Domestic hot water is delivered at around 50ºC (and raised to 60ºC for periodic sterilization), much higher than the ideal space heating distribution temperatures when a heat pump is in use (30-40ºC). A heat pump is therefore less efficient at delivering domestic hot water than space heating as it has to do more work to raise the temperature of the delivery medium to a higher level.

The net effect is that the heat pump will be running at lower efficiencies for a greater percentage of its operation time. This increases both the carbon emissions and the cost of running the heat pump. When considering the costs of running heat pumps, the percentage of hot water load as opposed to space heating therefore needs to be taken into account.

3.3 Running costs & fuel poverty

As things stand, changing from a gas boiler to a heat pump won't save consumers any money. In fact, it will almost certainly increase bills. Given the recent doubling of fuel prices across the UK, the percentage of households in fuel poverty is climbing rapidly so this is a serious concern.

The ratio of the kW of heat energy produced by the system to the kW of electrical energy needed to power the pump is known as the "Coefficient of Performance" (CoP). If the system runs at a CoP of 3, this means that it produces 3 units of heat energy for each unit of electricity input. When summed over an entire heating season, the ratio of total energy input to total heat output is known as the Seasonal Performance Factor or SPF.

Good quality independently verified data on heat pump performance is scarce. The heat pump trials from the Energy Saving Trust (already a decade old) put the SPF at around 2.5 for ASHPs[14] . A very limited study of installations under the Renewable Heat Premium Payment scheme[15] put the figure slightly higher, but the sample size was small. SPFs quoted by manufacturers are usually much higher than what is achieved in practice - it is the actual performance of the whole system over a year which matters. Good quality metered data for electricity input and heat output has been collected under the Non-Domestic Renewable Heat Incentive from 2016 onwards, but for some reason this data has not been analysed and published. The Electrification of Heat Demonstration Project is ongoing and this should provide some more robust data soon.

At the time of writing, the capped prices are 28.34p/kWh for electricity and 7.37p/kWh for gas - and these are the rates that most domestic customers are paying. Electricity is therefore roughly 4 x the price of gas per kWh.

Based on an SPF of 2.5, over a year you might get an average of 2.5 units of heat for each unit of electricity used by an ASHP. If electricity is 4 x the price of gas, then by simply switching from a gas boiler to an ASHP, and allowing for - say - 90% efficiency of gas boilers, you would currently increase your bill for heating space and water by 4/2.5 x 0.9, which is a 44% increase.

Switching to a heat pump on top of a doubling of energy prices will add a significant further cost to space and water heating, which is clearly unsustainable, and will increase fuel poverty yet further.

The demand for space heating can be reduced by insulation measures, but these have already been installed in many properties - double glazing, loft insulation and cavity wall insulation all have very high percentage penetration across the UK. There is a limit to what can be achieved by further measures - insulation suffers from the law of diminishing returns - a little insulation goes a long way and it takes a lot more insulation to do only a little more work. None of this will affect demand for domestic hot water.

Even for hybrid heat pump/boilers, the savings are not obvious. The Freedom Project (2018) which tested out hybrids in Bridgend, South Wales[16], concluded that “it is rarely cost-effective to operate the heat pump; and even in the scenario that gas prices increase by 50%, it is only worthwhile for the heat pump to take 40–50% of the heat load.”

4. Hybrid heat pump/boilers

ASHPs perform less efficiently when the temperature of the heat source (i.e. the external air) is low. Unfortunately this coincides with the time of peak demand for space heating - i.e. in mid winter. This has led to growing interest in hybrid heat pumps.

In simplest terms, hybrids include a backup boiler (gas, LPG or oil) which takes over when the air temperature is low - the system controller automatically selects which is the most efficient mode to use. In this case, the ASHP component would be used mostly during the “shoulder months” of the heating season - i.e. at either end of winter when the air temperature is warmer, and the backup boiler would be used in the coldest periods.

The hybrid approach has numerous advantages:

- ASHPs can be sized smaller, reducing installation costs;
- Existing boilers can be retained - avoiding a wasted asset;
- Energy security is improved, as a backup is in place (since the main current sources of renewable electricity are notoriously intermittent);
- Running costs can be slightly lower;
- Peak demand on the electricity grid is far lower - resulting in:
  - less cost to upgrade the distribution network;
  - less cost of installing new renewable generation plant.

We already have a very effective gas distribution network in place to 87% of the UK’s homes, so it makes practical and economic sense to make use of this at least while we progress towards decarbonisation of both the electricity and gas grids.

4.1 Running cost effectiveness

As an ASHP is less effective in mid winter, it follows that it is more effective when the air temperatures are warmer, and the COP should be well above 2.5. If used correctly as part of a hybrid system, an ASHP can deliver not only carbon savings but also cost savings on space heating, when it’s not too cold outside. At current prices, and ignoring time of use pricing, an ASHP would deliver a saving when the COP is above 4.

During the coldest months, the backup boiler takes over and the consumer is at least no worse off than they are already. Over the course of a whole heating season the hybrid therefore produces a small net saving.

Hybrid systems can be used in a much more sophisticated way if the controller is linked to variable time-of-use pricing, enabling the householder to make best use of low priced electricity when available, and simultaneously benefiting the grid by load spreading. This is explored in much more detail in the Freedom Project[17] which concluded in 2018.

4.2 Reduced capital costs of installation

In a hybrid system, the heat pump does not have to provide the full peak space heating demand. This means that the heat pump can be sized smaller - to meet demand at lower levels and when the air temperature is warmer - so that it can run more efficiently. A smaller heat pump is going to cost less than a large heat pump, so the capital cost of installing the heat pump side of the hybrid system can be reduced.

Some hybrid heat pump/boilers are sold as a package, but others can make use of the existing gas (or oil, LPG) boiler as the backup system. This means that relatively new boilers, which have not reached the end of their working life, can continue to be used. This of course significantly reduces the capital cost of the hybrid system, as only a heat pump and a new controller need to be installed.

4.3 Reduced impact on the electricity grid and generation costs

By reducing peak demand on the electricity grid, smart optimised hybrid systems (as trialled under the Freedom Project) will substantially reduce the costs of electricity grid upgrade. If peak demand is not so high, the local and national transmission networks will require less investment to reinforce them, and there will be greater capacity for electrification of vehicles - if managed correctly.

Although the cost of energy storage is falling rapidly, electricity storage still adds cost, and batteries have other environmental impacts; they also lie idle much of the time. The gas grid already has capacity to store significant quantities of gas by means of “linepack” - i.e. increasing the pressure within the distribution network - as already occurs. This means that the gas grid can more easily take care of sudden surges in demand, while predicted peaks can be reduced in any case by smart use of heat pumps to pre-heat dwellings.

Lastly, a reduction in peak electricity demand reduces the total generation capacity that will be required, so substantially reduces the capital cost of providing renewable power. As it is accepted that renewables are intermittent and backup systems will need to remain in place, it makes not only economic sense but also environmental sense to plan for a lower total generation capacity - as all new generation capacity has an environmental impact of its own.

4.4 Interface with green gas

The backup boiler element to hybrid heat pumps currently uses fossil fuels, in most cases.

For installations off the gas grid, the most common backup boiler will be oil or LPG. However, oil can now be replaced with biodiesel, and LPG with bioLPG, so there is no reason why a hybrid heat pump/boiler should have any carbon emissions other than the electricity component still produced using fossil fuels.

For on-gas-grid installations (87% of the dwelling stock), the situation is evolving. There are increasing sources of hydrogen and biogas which can be injected into the gas grid, thus decarbonising the gas grid to a degree.

The Pathfinder project[18] is a full system analysis tool developed by Wales & West Utilities and this kind of tool holds the key to predicting demand and optimising the grid to deliver lowest cost and carbon, evolving over time. This simulation clearly concludes that the gas network is essential to delivering a low carbon energy network at reasonable cost, based on smart use of hybrid boiler/heat pumps. As new sources of biomethane or other low carbon biogas become available, the gas grid can decarbonise further, providing the balance to a decarbonising electricity grid.

5. Conclusions

Full electrification of domestic heating and delivery via heat pumps makes no sense in environmental, economic or social terms - the three original pillars of sustainability. The capital cost is likely to exceed £300Bn even before provision for grid upgrade costs, and consumers will face significantly higher running costs - a burden that cannot be acceptable given current high levels of fuel poverty. There will be very significant embodied carbon costs of grid reinforcement and of providing the required new supplies of renewable power.

By contrast, partial electrification of heating and the intelligent deployment of hybrid heat pump/boilers can deliver better levels of energy security, lower running costs, and greatly reduced infrastructure costs. This also allows change to happen gradually and be better managed, prevents wasted assets and makes best use of the existing gas grid, which is also able to decarbonise. At reduced demand for gas, the proportion of gas coming from renewable and low carbon sources will be even higher, offering a cost-effective route towards decarbonisation over a realistic timescale.

Straight heat pumps will work effectively in new buildings which are airtight and highly insulated, so have low space heating demand. There should be minimal concerns over fuel poverty for occupants of such buildings - even if the unit cost of heat is high, consumption will be very low. For existing buildings which are not so well insulated, hybrids are the optimal solution in many cases, and at the very least an important interim step on the path to full decarbonisation.

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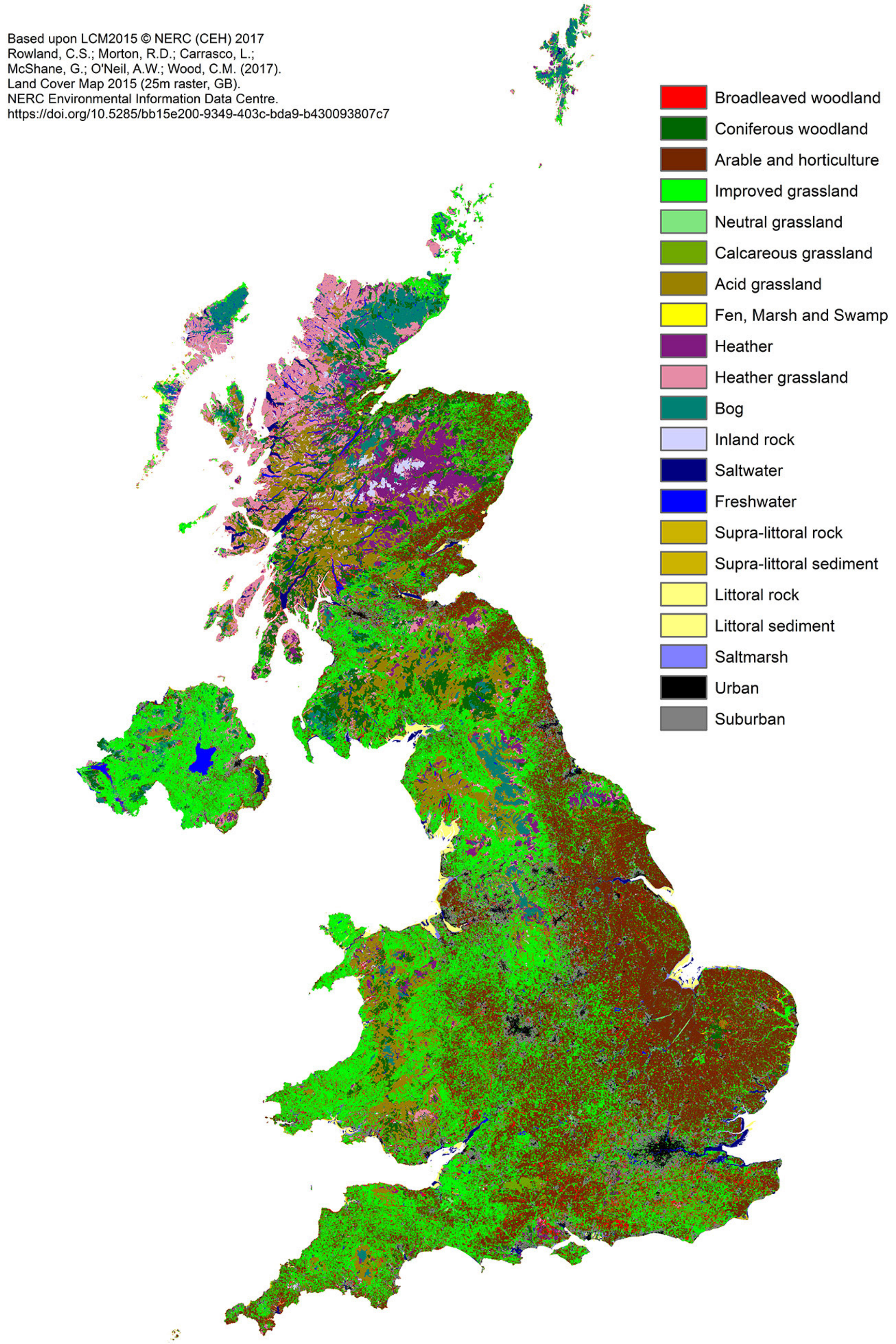
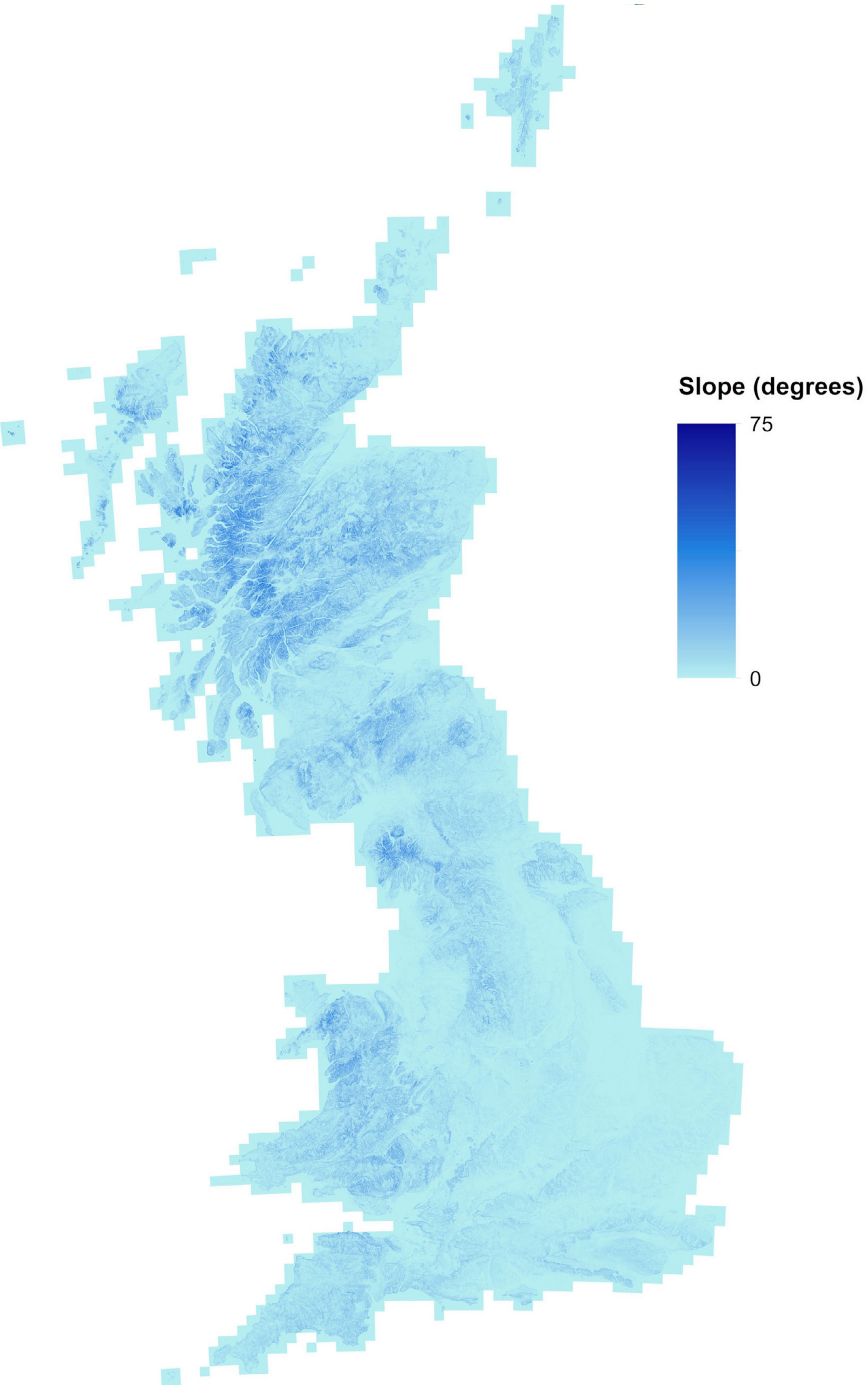
Appendix for Green Gas – The opportunity for Britain

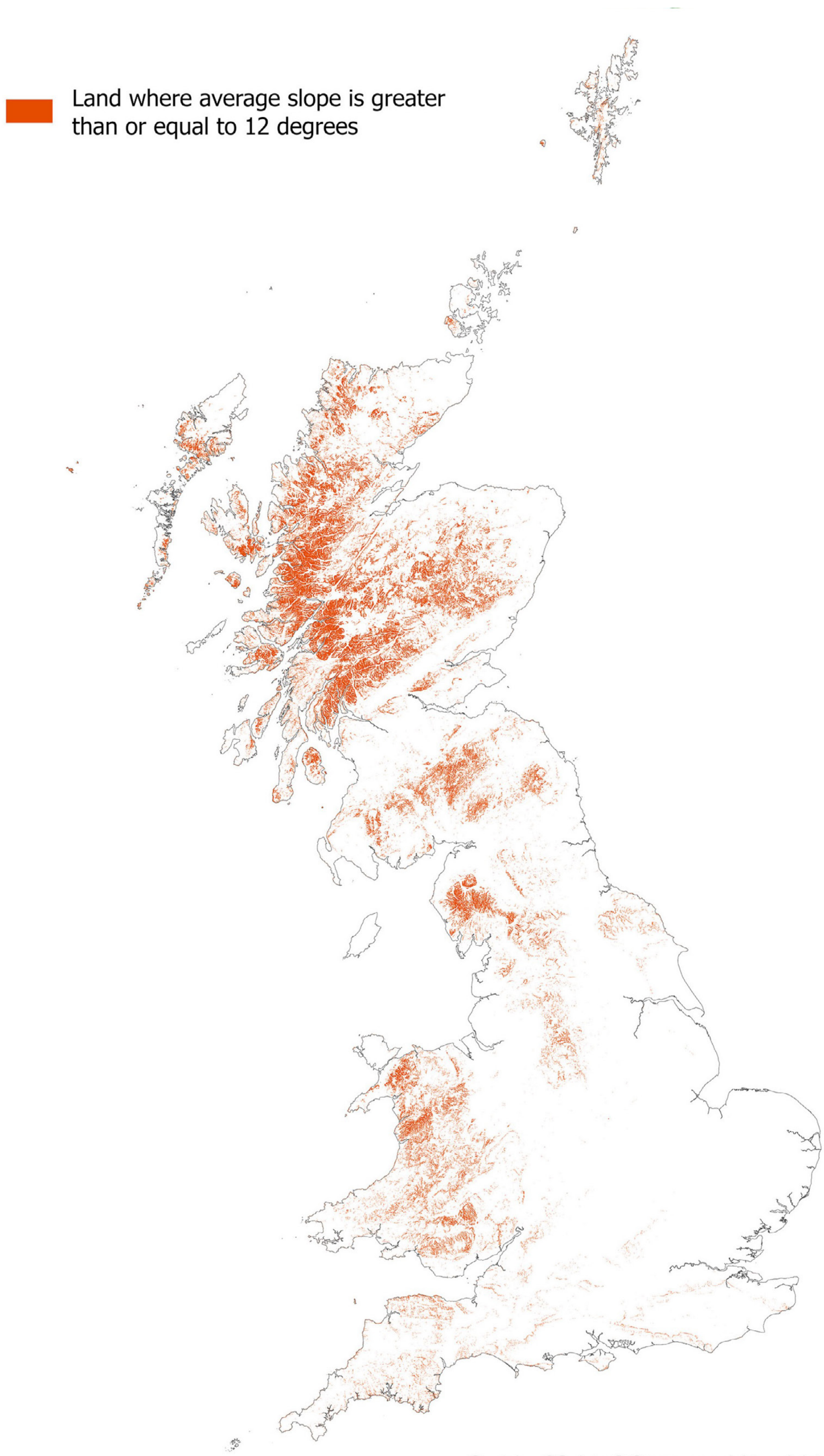
Appendix item A1 - UK Land Cover details



Appendix item A2 – OS Terrain 50 – Slope[17]



Appendix item A3 – Surface slope (12 degree threshold)[17]



Appendix item A4 – The UK Land Cover details[14] in million hectares were obtained from QGIS raster data

	Great Britain	Ireland	UK
Deciduous woodland	1.79	0.10	1.88
Coniferous woodland	1.32	0.06	1.38
Arable	5.25	0.13	5.38
Improved grassland	**6.47**	**0.62**	**7.10**
Neutral grassland	**0.14**	**0.13**	**0.27**
Calcareous grassland	**0.13**	**0.00**	**0.13**
Acid grassland	**2.16**	**0.05**	**2.21**
Fen	0.02	0.00	0.02
Heather	**1.00**	**0.02**	**1.03**
Heather grassland	**1.26**	**0.08**	**1.35**
Bog	0.89	0.09	0.97
Inland rock	0.23	0.01	0.25
Saltwater	0.20	0.02	0.22
Freshwater	0.25	0.06	0.31
Supralittoral rock	0.06	0.00	0.06
Supralittoral sediment	0.08	0.01	0.09
Littoral rock	0.06	0.00	0.06
Littoral sediment	0.24	0.01	0.25
Saltmarsh	0.12	0.00	0.12
Urban	0.40	0.01	0.41
Suburban	1.44	0.05	1.49

Appendix item A5 – Mimimum, maximum and average methane yields of various types of grass, legumes and herbs consisting of herbal leys mixture, in m^3 CH_4 kg^{-1} VS

	Type	Min	Max	Average	References
Chicory	Herb	0.245	0.326	0.336	Wahid et al[26]
Clover	Legume	0.140	0.558	0.298	Zhang et al [85]
Cocksfoot	Grass	0.291	0.446	0.369	Tilvikiene et al[86]
Cow parsley	Herb	0.135	0.412	0.274	Kosse et al[87]
Fescue	Grass	0.259	0.446	0.354	Zhang et al [85]
Festulolium	Grass	0.381	0.464	0.423	Kandel et al[25]
Grass lay	Grass	0.250	0.307	0.279	Lfl[88]
Lucerne	Legume	0.265	0.432	0.349	Kaiser et al[89]
Meadow foxtail	Grass			0.310	Mähnert et al[90]
Meadow grass	Grass	0.290	0.322	0.320	Zhang et al [85]
Pasture grass	Grass	0.307	0.322	0.315	Lfl[88]
Red clover	Legume	0.236	0.344	0.290	Zhang et al [85]

Ribwort plantain, ribgrass	Herb	0.273	0.296	0.285	Wahid et al[26]
Ryegrass	Grass	0.390	0.409	0.400	Zhang et al [85]
Sainfoin	Legume	0.267	0.292	0.280	Lfl[88]
Tall fescue	Grass	0.401	0.428	0.415	Kandel et al[25]
Timothy	Grass	0.308	0.365	0.337	Zhang et al [85]
White sweet clover	Legume	0.162	0.183	0.173	Huňady et al[91]
Yarrow	Herb	0.265	0.290	0.278	Kosse et al[87]

Appendix item A6 – According to the Cotswoldseed, the methane yield of typical herbal ley mix to be utilised in Green Gas Mill, in m^3 CH_4 kg^{-1} VS.

Type	Percentage in the mixture, %	Min	Max	Average
Festulolium	20.8	0.079	0.097	0.088
Ryegrass	40.3	0.157	0.165	0.161
Cocksfoot	8.3	0.024	0.037	0.031
Timothy	12.5	0.039	0.046	0.042
Fescue	6.7	0.017	0.030	0.024
White clover	4.2	0.007	0.008	0.007
Red clover	2.1	0.005	0.007	0.006
Alsike clover	1.3	0.002	0.007	0.004
Chicory	2.5	0.006	0.008	0.008
Ribgrass	1.3	0.004	0.004	0.004
Total	**100**	**0.340**	**0.408**	**0.375**

Herbal ley yield is reported to be 13 tonne dry matter per hectare (0-20 t DM ha^{-1}) and chicory yield is reported to be 10 t DM ha^{-1}. The percentage values in the herbal ley mixture (Cotswold mix23- Simple Herbal ley[45]) are multiplied by the minimum, maximum, and average values given in Table A5.

Appendix item A7 – Details of Table 2 calculations

The average biomethane potential was calculated as shown below. The same calculation was performed for the maximum and minimum biomethane potentials, taking into account the maximum and minimum values in Table 2.

Available grassland: 6.46 $x10^6$ hectares

Herbal ley yield: 13 tonne dry solids per hectare

Annual feedstock become 83.98 $x10^6$ dry solids (6.46 $x10^6 \times 13 = 83.98\ x10^6$)

Volatile dry soils yield is assumed as 0.9 in total dry solids. The total volatile dry solids become: 83.98 $x10^6 \times 0.9 = 75.58\ x10^6$ volatile dry solids

The average methane yield for herbal ley species is 375 m^3 CH_4 in volatile dry solids.

Therefore, methane production from 75.58 $x10^6$ volatile dry solids become 28.3 billion m^3 methane (75.58 $x10^6$ VS × 375 m^3 CH4 VS^{-1} = 28.34 $x10^9$ m^3 CH_4).

Methane in biogas is assumed as 60%; therefore, biogas amount will be 47.24 billion m3 (28.34 x109 m^3

CH_4 ÷ 0.6 m^3 CH_4 biogas-1= 47.23 $x10^9$ m^3 biogas)

During the biogas upgrading process to biomethane, it is assumed that 0.5% of produced gas is lost. Therefore, the biomethane amount become 27.49 billion m^3.

(28.34 $x10^9$ m^3× 0.005 = 27.49 $x10^9$ m^3 CH_4)

Biomethane energy yield:

27.49 $x10^9$ m^3 × 37.78 MJ m^{-3} (CH_4 energy content) × 0.00027778 MWh MJ^{-1} × 10^{-6} TWh MWh^{-1} = **288.5 TWh**

288.5 $x10^3$ GWh ÷ (6.46 $x10^6$ hectares) ÷ 0.0002778 GJ GWh^{-1} = **160.8 GJ / ha**

Appendix 2 – Biographies

Dr Gbemi Oluleye

Dr Oluleye is an Assistant Professor (Lecturer) in the Centre for Environmental Policy and a member of the Sargent Centre for Process Systems Engineering with over 15 years combined experience in academia and as a consultant for the process industry, and innovations to support decarbonisation. She has a BSc in Chemical Engineering from the Obafemi Awolowo University, Nigeria in 2008, completed an MSc in Advanced Chemical Process Design at the University of Manchester in 2010, worked as a Process Engineer before beginning her PhD in 2012. Dr Oluleye research is centred on developing frameworks to support modelling, integration, assessment (both economic and environmental) and adoption of low-to-zero carbon innovations including alternative fuels and technologies.

Dr Oluleye is working with Ecotricity on an independent basis capacity via Imperial Consultants.

Dr Semra Bakkaloglu

Dr Semra Bakkaloglu is a Research Associate at the Sustainable Gas Institute with over 10 years of combined academic, industry and consultancy experience. Dr Semra double majored in Environmental Engineering and Chemical Engineering at Middle East Technical University (METU) in 2011 and 2012, respectively. She attended Clemson University as a Fulbright Scholar, where she earned a master's degree in Environmental Engineering & Earth Science in 2014. She completed her PhD at Royal Holloway University of London as a Marie Curie Early-Stage Researcher. Dr Bakkaloglu's research focuses on environmental process engineering, life cycle assessments, and modelling of biomethane production, as well as methane and hydrogen emissions from its supply chains.

Dr Bakkaloglu is working with Ecotricity on an independent basis capacity via Imperial Consultants.

Nigel Griffiths

Nigel Griffiths is a sustainability and energy efficiency expert in the built environment with over 25 years' experience as a practitioner, project manager, author and consultant. As Director of the Sustainable Traditional Buildings Alliance, he works at the cutting edge of sustainability for heritage buildings. As a Principal Consultant with Ricardo, he provided practical energy efficiency, renewable energy and sustainability strategies for numerous buildings and large property portfolios. He has also worked extensively on policy development in this sector in the UK and overseas. He continues to inspect Renewable Heat installations on behalf of Ofgem, and is a lead technical expert to BEIS on the Social Housing Decarbonisation Fund. He is the author of several books including the Haynes Eco House Manual, writes for the Build-it monthly self-build magazine and is the resident sustainability expert at their UK exhibitions.

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