The potential for carbon neutral advanced biofuels in UK road transport

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ABSTRACT

As a result of anthropocentric climate change, there is an urgent need to decarbonise the supply of energy. Organic biomass, referred to as feedstock, can be converted into biofuels that have the potential to decarbonise transport. However, biofuels are typically not carbon neutral, as the preparation of feedstocks and the production of biofuels requires energy currently supplied by fossil fuels, which involve carbon emissions. This work aims to bring biofuel research up to date with current UK policy of net zero carbon emissions by examining the volume of carbon neutral advanced biofuels that could be produced from sustainable feedstocks generated in the UK. By analysing relevant data it is estimated that between 667 and 1791Mltr of carbon neutral biodiesel equivalent could be produced with the energy content of 22.7 – 60.9PJ, corresponding to 8.1 - 21.7% of current diesel consumption by heavy goods vehicles in the UK.

INTRODUCTION

The UK has recently committed to a legally binding target of net zero emissions by 2050 (BEIS 2019). As a result, there is an imperative need for decarbonisation of the energy supply. In 2019, the CO_2 emissions from the transport sector accounted for 33% of all CO_2 emissions in the UK (BEIS 2020b; BEIS 2021), and 91% of this figure related to road transport, i.e., cars, taxis, Heavy-Goods Vehicles (HGVs), light vans, buses/coaches and motorcycles (DfT 2019a). Additionally, transport is the only sector with significant CO_2 emissions, which has experienced a mere 4% of

CO_2 reductions since 1990 (BEIS 2021; BEIS 2020a), as opposed to other sectors like Energy Supply and Business that have recorded 63% and 42% reductions, respectively.

In 2014, the UK government set up the Transport Energy Task Force in order to develop policy for decarbonising transport. The Task Force reported that electrification should be the primary method for decarbonisation, whilst recognising there is a role for biofuels in achieving greenhouse gas (GHG) savings in modes of transport that are challenging to decarbonise, such as HGVs (Transport Energy Task Force 2015; DfT 2019a) due to their high-energy consuming requirements. Currently, biofuels supply over 3 times the amount of transport energy than electricity (BEIS 2020b), although this will change with plans to outlaw the sale of conventional engine and hybrid cars in 2035.

The use of biofuels in the UK became mandatory for transport (and non-road mobile machinery) in 2007 through the Renewable Transport Fuel Obligation (RTFO), in an effort to maximise the desired decarbonisation (UK Secretary of State for Transport 2007). This mandates transport fuel suppliers to ensure 4.75% (by volume) of fuel originates from renewable sources (BEIS 2020a). As a result, fuel suppliers currently provide E5 petrol, containing 5% bioethanol and B7 diesel with 7% biodiesel. Therefore, it is not surprising that these are the two most common biofuels in UK road transport (DfT 2019b). Conventional biodiesel, fatty acid methyl ester (FAME), is produced from crops with a high oil content, such as oilseed rape, by mixing the oil with methanol and triggering a chemical reaction called transesterification. Bioethanol is produced by fermenting crops with a high sugar content such as sugar beet, or a high starch content such as wheat.

However, limitations related to the supply and capability of biofuels have challenged the aspired outcomes. Social and environmental concerns regarding feedstock production for conventional biofuels has led to the promotion of advanced biofuels produced from non-edible feedstocks with particular emphasis regarding municipal waste and residues from agriculture and forestry. The advantage of utilizing these resources, as well as not competing for land, are low cost of feedstock and achieving the waste management goal of a circular economy. Reports published by bioenergy consultants (Scholes et al. 2017; E4tech (UK) 2017) have analysed the potential of sustainable feedstocks generated in the UK and building on previous analyses reached similar conclusion to the current status of the resources this work covers. However, these reports were not commissioned to examine the fossil fuel consumed from converting waste to fuel or the efficiency of the conversion process. A recent report by the Royal Academy of Engineering (Azapagic et al. 2017) did address fossil fuel consumption by reviewing a significant quantity of published works. The findings from this literature review, regarding what that report classified as second generation biodiesel (which is synonymous to advanced biofuel), are the basis for this work's ratio for MJ of fossil fuel consumed for MJ of biofuel produced.

A number of researchers (Leibbrandt et al. 2013; Rafati et al. 2017; Snehesh et al. 2017) have modelled the biomass to liquid fuel (BtL) conversion efficiency in various ways producing a range of different efficiencies. However, in the current work, the BtL conversion efficiency produced by the National Renewable Energy Laboratory (NREL) of the US Department of Energy was utilised (Dutta et al. 2015).

This work focuses on the technical potential for biofuel production using waste generated exclusively in the UK. Waste generated abroad has not been considered for import and has equally the same potential for carbon neutral biofuel production. Statistics on waste production in the UK compiled by the UK Department for the Environment, Food and Rural Affairs has been the main source of data used in the current work to estimate the availability of sustainable feedstocks. The objective of the current work is to determine the net volume of carbon neutral advanced biofuels available for the transport sector in the UK, with an emphasis on HGV.

The approach followed for the carbon neutrality aspect of this study is an original approach in the field of biofuel research and is achieved by considering a system whereby all the energy required processing the feedstock and producing the biofuel was supplied not by fossil fuel but by some of the advanced biofuel being produced from waste feedstocks. Fuel produced in this self-sufficient system would be carbon neutral and therefore assist in meeting the UK's net zero carbon emissions policy. The current work brings biofuel production research up to date with the revised governmental policy (which is currently oriented to net zero carbon emissions) and examines their potential without the need for any carbon capture, as opposed to previous works which had only addressed biofuels potential to reduce emissions in line with previous emission reduction policy. It is highlighted that the production of carbon neutral advanced biofuels from organic waste, as proposed in the current work, is distinctly different from *development fuels*, which have recently emerged as a potential alternative *sustainable fuel*. *Development fuels* will not be discussed in the current study, since they are permitted to utilise non-biological waste (such as plastic) as feedstock (DfT 2018). The combustion of fuel derived from such feedstocks can actually enhance climate change (Reijnders and Huijbregts 2008), thus jeopardising the efficiency of other climate change mitigation approaches.

The concept of producing carbon neutral biofuels in a self-sustaining system examined in this article concerned the UK exclusively; however this goal of carbon neutral biofuels is applicable to any country that chooses to utilise biofuel production as a waste management strategy. For the purpose of this study, data concerning UK origin feedstock was examined for the year 2016, solely because this was the most recent year that extensive statistics regarding waste has been published by the UK government. Yet, the extension of the proposed approach for ensuing years is straightforward.

DEFINING ADVANCED BIOFUELS

The term advanced biofuel is synonymous with and has largely replaced second generation biofuels, although currently, there is no internationally agreed definition for what constitutes an advanced biofuel (IEA 2017; IRENA 2016). Amongst the various definitions, some qualifications are common, others are not. In the current work, first, an attempt is made to identify all these characteristics for which there appears to be a consensus in the various definitions. Additionally, some attributes are attached, which although they are not shared among the whole range of the individual definitions, it is believed they enable a coherent, comprehensive and integrated definition of advanced biofuels.

Amongst current definitions, there is a consensus regarding the following necessary qualifications of an advanced biofuel:

- The production pathways are capable of converting lignocellulosic biomass (e.g., (Cheng and Timilsina 2011; Morone and Cottoni 2016)). There are several different approaches for breaking the lignocellulosic bonds to facilitate this biomass's conversion into biofuel. Biochemical methods use acid or enzymes to hydrolase polymers to release fermentable sugars (Andrews and Jelley 2013), while thermochemical methods crack the bonds of the polymers and the sugars using heat, to produce bio-oil or generate simple molecules, that can be synthesised into fuel (Twidell and Weir 2006). The latter can be applied to all carbon-based materials increasing the number of potential feedstocks. Both can break the bonds in cellulose and hemicellulose but the only the latter (i.e., the thermochemical) can break the bonds in lignin.
- The biofuel should involve significant GHG emission reductions (e.g., (Ullah et al. 2018)). Biofuels are not truly carbon neutral. There are numerous processes made apparent during life-cycle assessments that require energy (more details for this in the next section), the majority of which is supplied by fossil fuels, resulting in GHG emissions. For biofuels to mitigate climate change, it is imperative that these supply chain emissions are sufficiently less than those released by the equivalent volume of fossil fuel. The EU Renewable Energy Directive II (RED II) (European Union 2018) dictates that biofuels should have from 2021, at least 70% lower GHG emissions than what is released by the equivalent volume of fossil fuels (Azapagic et al. 2017).
- The feedstock should be non-edible and therefore not cause land use change (e.g., (Oh et al. 2018; Stephen and Periyasamy 2018; Callegari et al. 2020)). Production of feedstocks for conventional biofuels raises both social and environmental concerns, as cultivating agricultural land for feedstocks results in less land being available for food production. Unmoderated, this land use change would lead to increases in food prices and cause food poverty, disproportionately affecting the world's poorest people (Mortimer 2013). Furthermore, the destruction of uncultivated natural habitats to provide land for feedstock production would have detrimental environmental effects. Deforestation would not only diminish biodiversity

but reduce natural mechanisms for CO_2 absorption. In addition, the cultivation of wetlands or peatlands would induce the release of carbon stored within the soil. The negative effect of the land use change would be to negate the GHG savings gained by biofuel use and potentially exasperate climate change. By converting agricultural land for feedstock cultivation, the risk exists that the displaced food production would then be grown on uncultivated land, and this indirect land use change would have the same negative effects as direct land use change (Wicke et al. 2012).

Amongst advanced biofuel definitions, the aspects that generate disagreement, yet, are included in the current work's definition, are as follows:

- The production pathway is not fully commercialised. The point in development a technology has reached from a conceptual idea, through research and development (R&D) to commercialisation is evaluated and allocated a Technology Readiness Level (TRL). The values start at 1 for a concept and run through to 9 for fully commercialised. Worldwide the TRL of the thermochemical pathways are 6-8 for gasification and 5-6 for pyrolysis (Landälv et al. 2017), although in the UK there are no developers at TRL 6 or above for either (E4tech (UK) 2017).
- The employed feedstocks are sustainable (e.g., (Landälv et al. 2017)). Although all edible feedstocks are disqualified, there is ambiguity as to what nonedible feedstocks qualify as sustainable for an advanced biofuel. It is unanimously accepted that municipal waste, as well as residues from agriculture and forestry qualify for sustainable feedstocks. However, there is lack of consensus around used cooking oil (UCO), animal fat and energy crops (Azapagic et al. 2017).
- The biofuel is a 'drop in' fuel (e.g., (IRENA 2016)). A drop in biofuel can be used in 100% concentrations in current vehicles' engines without requiring any modifications unlike conventional biofuels which can only be blended up to a ratio of 10% and 30%, for bioethanol and biodiesel, respectively, before modifications are required (Landälv et al.

2017).

SUSTAINABLE FEEDSTOCKS FOR ADVANCED BIOFUELS

The UK policy regarding waste is currently determined by the EU Waste Framework Directive (WFD) (Directive 2008), which created the hierarchy for waste management. According to WFD, waste prevention is the most favoured option as shown in Fig, 1, while energy recovery is only considered an option better than disposal. Therefore, of the waste appropriate for conversion only a limited volume is available as feedstock, as some volume will be processed by alternative methods such as recycling and reuse.

While biofuel production through waste is considered as a form of energy recovery, one could argue that the transformation of organic waste into a biofuel can also be viewed as the recycling of carbon into another material form and should rightfully be given the equivalent status of recycling and recovery in the waste hierarchy. This detail highlights the significance of the biofuel production's place in the waste hierarchy. If it is classified as energy recovery, then waste being recycled is unavailable for biofuel production, while if it is classified as recycling then waste that is currently recycled could be diverted to biofuel production and the volumes of potential waste available would increase significantly. The individual forms of sustainable feedstocks that will be considered in the analysis are briefly described next.

Municipal waste

Of all types of municipal waste, only the biogenic component, such as food, wood or paper are suitable sustainable feedstocks. It is estimated that the UK sent 7.4Mt of biogenic waste to landfill in 2017 (DEFRA 2020). This volume includes household or similar waste from businesses, as well as vegetal, animal and mixed food waste arising from food preparation and production. The biogenic fraction of household waste is incorporated with an assortment of other waste materials that are unsuitable feedstocks and requires separating prior to biofuel production (Barampouti et al. 2019).

Agricultural residue

Agricultural residues are the plant material remaining after a crop is harvested, such as straw from wheat crops, although it is necessary to leave some behind to prevent soil erosion, as well as loss of nutrients and soil carbon (Whittaker et al. 2014). Other commercial uses limit the availability of this feedstock, such as composting for nutrient recovery, straw as animal bedding, or feedstock for anaerobic digestion (AD) (DEFRA 2020).

Forestry residue

Similarly to agricultural residue, forestry residue is the section of crop that is not collected at harvest, such as branches, and for good land management purposes some residue should be left (Thornley et al. 2009), although there are no competing uses to reduce its supply.

Forms not considered

Opinions vary whether fuel produced from the feedstocks discussed below are eligible for advanced biofuel. In 2018, 236 million litres of conventional biofuel were produced from edible food crops grown in the UK (DEFRA 2020). Energy crop feedstocks for advanced biofuels are nonedible and they lead to the rapid production of lignocellulosic biomass. They include the perennials Miscanthus (Sinensis), which is harvested annually, and willow (Salix spp.) and poplar (Populus spp.), which are short rotation crops harvested every 2 to 3 years. Over 40,000 tonnes of these crops were grown in the UK in 2018, mainly for heat and power, none of which was used for biofuel production (DEFRA 2020). Only the above-ground biomass of energy crops is harvested, leaving the roots undisturbed, allowing cultivation on marginal sloping land where food crops could not be grown without risk of soil degradation. With intact root systems some carbon sequestration is guaranteed and as a result of the annual leaf fall, the carbon content of soil can be increased, providing opportunity for bioenergy with carbon capture and storage (BECCS). Lack of machinery designed for the cultivation, harvesting and processing of non-edible energy crops has the consequence that these feedstocks are relatively more expensive than edible crops to grow and at current biomass prices deliver low economic returns for farmers (Aylott and McDermott 2012).

Due to land use change concerns, RED II set a crop cap, a maximum percentage of renewable transport energy permitted to come from biofuels derived from crops cultivated as feedstocks (Landälv et al. 2017). The UK has set the crop cap lower than the 7% recommendation by RED II, at 4% in 2020, decreasing to 2% in 2032, in order to incentivise the use of waste-based biofuels. Energy crops are exempt from the crop cap and being the only feedstock discussed which are not dependent on other industries represent the only means whereby the supply of feedstock could be increased unilaterally.

Used cooking oil (UCO)

UCO is cooking oil that is no longer fit for human consumption after being used for commercial cooking, such as takeaways, restaurants or factories. The disposal of UCO is tightly regulated and costly, consequently it has negative costs as a feedstock (Phillips and Tomkinson 2019). UCO is converted to biodiesel via transesterification, as with virgin oils. The previous use of UCO (through cooking) can result in higher water content and hydrolysis of triglycerides to free fatty acids, which reduces the options for catalysts that can be used for transesterification (Enweremadu and Mbarawa 2009). From April 2017 to April 2018, the most commonly used feedstock in the UK was UCO, producing 85% of the biodiesel consumed, equivalent to 682 Mltr. The majority of UCO was imported from China, with 18% originating from the UK, producing 126 Mltr of biodiesel (DfT 2019b). UCO is not included in the current analysis because it does not meet the “*not fully commercialised production pathway*" qualification for the advanced biofuels.

Animal and Food waste (meat)

The animal fat (tallow) in abattoir waste requires a hydrolysis process to prepare it for use as a feedstock (Rezania et al. 2019). This is normally achieved by rendering the fat in water of at least 95°C for up to 2.5 hours to release free fatty acids (Chen et al. 2018). These can then be converted to biodiesel by conventional transesterification. However, it leads to biofuel production with no drop in quality.

Other potential feedstocks excluded are animal manure and waste treatment sludge because of their high moisture contents, with animal manure 75-92% water (Callegari et al. 2020). This makes them unsuitable feedstocks for gasification or pyrolysis, as the drying process would consume too much energy. Synthesis of biogas by anaerobic digestion (AD) provides an alternative energy recovery method for these feedstocks (Slorach et al. 2019).

ANALYSIS

The key assumptions made in the analysis were the following:

- All available generated waste is collected and processed into advanced biofuels.
- The volume of fossil fuels consumed for the production of biofuels considers the processes: waste collection, transport, drying, grinding, and processing.
- The BtL conversion efficiency is calculated from a system of homogenous feedstock.
- The comparison of the potential carbon neutral biofuel production against the HGVs fuel needs is performed on the basis of biodiesel.
- Only biodiesel is produced from the biofuel production processes analysed.

The first step in the process is the determination of the available mass of the different sustainable feedstocks generated in the UK. To determine the availability of feedstocks the following sources used were:

- For municipal waste, the UK government's Statistics on Waste (DEFRA 2020). It is noted that the latest UK statistics on waste (first published in 2019) are for 2016 and are not expected to be fully updated earlier than 2021 (DEFRA 2020). This demonstrates the complexity of gathering data from the sources used to compile the statistics. Data collected from individual local authorities, relevant to household waste, can be assumed to offer a high degree of accuracy. In contrast, commercial and industrial waste data have a lower level of accuracy, as they are collated from companies self-certifying.
- For agriculture and forestry residue, the work of *Searle & Malins* was considered (Searle and Malins 2016). There is, in fact, limited literature published regarding agricultural and forestry residues generated in the UK and the reports published by bioenergy consultants (e.g., (Scholes et al. 2017; E4tech (UK) 2017)) may have overestimated residue availability. On the other hand, it is believed that the baseline figures published in the work of *Searle*

& Malins (Searle and Malins 2016), constitute more realistic approximations.

The aforementioned statistics on waste include figures for the total waste produced, broken down into different categories, e.g., household, wood, paper etc., and include data regarding how this waste is processed by different methods of waste treatment. These methods include:

- Energy recovery, incineration for power or heat generation
- Incineration, without energy recovery
- Recovery/recycling/reclamation, composting
- Backfilling, filling of old mines and quarries, and landscaping
- Landfilling, the disposal and burial of waste on land.

For the purpose of calculating the availability of waste as a feedstock, current waste treatments were examined and only waste being disposed by burial or incineration without energy recovery was considered as available biomass. This approach was selected because, as already mentioned, the waste hierarchy puts waste treatment in preferential order, and in the current work it is assumed that biofuel production is energy recovery and so waste processed by alternative methods was unavailable for biofuel production.

Table 1 summarises the total mass and energy content for each individual type of waste in the UK, for 2016, using statistical data published in (DEFRA 2020; Searle and Malins 2016). It is noted that for the calculation of the total energy content of the available feedstocks, the energy densities of individual feedstocks were identified in the literature, as follows:

- Biogenic household: 8.9 MJ/kg (Slorach et al. 2019)
- Paper & cardboard: 14.0 MJ/kg (Agarwal et al. 2014)
- Animal & mixed food: 6.3 MJ/kg (Melikoglu et al. 2013)
- Wood: 18.3 MJ/kg (DEFRA 2014)
- Agricultural residue: 17.6 MJ/kg (Rosillo-Calle and Woods 2012)
- Forestry residue: 18.9 MJ/kg (Rosillo-Calle and Woods 2012).

The above values are averages for each feedstock category, as within a category there exist variations in energy densities between different members of the same category. Additionally, the actual content of waste mixtures varies seasonally and geographically (Slorach et al. 2019) and energy densities are also affected by moisture content (Twidell and Weir 2006). Finally, an energy density for vegetal waste was not found in the literature, so the value for animal and mixed waste was applied. Although vegetal waste would be expected to be lower, the small volume of this stream will not be detrimental to overall accuracy.

Table 1 shows that in 2016, 16,359 kt of sustainable feedstocks were available for biofuel production, only 24% of the total amount of the generated waste. The largest part of the total available feedstock relates to biogenic household waste (46%), while paper and cardboard waste along with agricultural residue share the same contribution (17%). Forestry residue and wood waste have negligible contributions of $<$ 1% and 2%, respectively. It is worth noting that the two largest contributors to the total generated waste are the biogenic household waste and the agricultural residue, with contributions of 41% and 30%, respectively. However, only 27% and 14% of the total amounts of these types of waste are considered as available feedstock because the largest part is processed for reuse or recycle, thus, indicating a great potential to increase the availability of these feedstocks.

In terms of energy content, the total mass of 16,359 kt of sustainable feedstocks has an energy content of 180 PJ, which is merely the 21% of the energy content of the total amount of generated waste, therefore, making 79% of energy content unavailable for biofuel production. The greatest contribution of the energy content available originated from household waste (37%), followed by agricultural waste (27%) and paper and cardboard waste (22%).

Having the total energy content of all available feedstock, the next step is the calculation of the gross energy content of the biofuels that could be produced, by applying a biofuel to liquid (BtL) conversion efficiency. The biofuel production pathways taken into account in the current work are the gasification with Fischer-Tropsch synthesis and pyrolysis with upgrading. They are both well researched technologies (Tippayawong and Tippayawong 2017) and show the potential of becoming fully commercialised for biofuel production, with large industrial and governmental investment taking place over the past recent years. Gasification is an established technology for reducing carbon-based feedstocks, such as natural gas or coal to produce syngas, a combination of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2) and methane (CH_4). Worldwide most hydrogen is produced by this process or else the syngas is used in Fischer-Tropsch synthesis, another mature technology, to produce ammonia and methanol (Ahmad et al. 2016). The use of these technologies combined to convert waste biomass into biofuels remains a novel technology (IEA 2017). Pyrolysis is is another process resulting in the thermochemical decomposition of biomass, the key difference with gasification is that the reaction occurs in an oxygen free atmosphere. Also, the reactor residence times can be shorter, from between less than a second to several hours and the usual temperature ranges from 500°C to 800°C (Akhtar and Amin 2012). The pyrolysis products; bio-oil, gas, and biochar, a carbonous solid are later separated. Bio-oil a combination of phenolic tar and pyroligneous acid has high viscosity, oxygen and water content and with a greater energy density (22MJ/kg) than the feedstock, it is usually burnt for heat and power (Twidell and Weir 2006). As an energy dense intermediate, bio-oil is finally refined by standard techniques to produce transport fuels.

Biochemical pathways composed of hydrolysis followed by fermentation are not considered in the current work because the products, ethanol or butanol, are gasoline substitutes. However, the focus in this work is biodiesel because HGV transport, which is challenging to decarbonise, predominantly consumes diesel. Furthermore, the hydrolysis of lignin does not release sugars necessary for fermentation, so this biomass is unexploited, making biochemical methods unsuitable for woody feedstocks with a high lignin content (Barampouti et al. 2019). In addition, the heterogeneous composition of municipal waste is more efficiently converted by thermochemical methods compared to biochemical methods (IRENA 2016).

The values used for the BtL conversion efficiency were produced by the US Department of Energy's National Renewable Energy Laboratory (NREL) (Dutta et al. 2015). The efficiency for the two pathways considered in the current work - pyrolysis with upgrading and gasification with

F-T synthesis - are 56.4% and 33.2%, respectively. This means that the pyrolysis with upgrading pathway is 70% more efficient compared to gasification with F-T synthesis. It is noted that, the efficiencies produced by the NREL consider that part of the biomass is used to power the conversion process, thus making the process carbon neutral (Dutta et al. 2015).

The gross energy content of the biofuels that could be produced, when applying the BtL conversion efficiency ratio to the 180 PJ energy content of the available feedstocks, is shown in Table 2. The pyrolysis with upgrading pathway with a greater conversion efficiency is capable of producing biofuels with an energy content of 101.5 PJ, 70% more than the respective value of the gasification with F-T synthesis pathway (59.7 PJ).

The net energy content of the biofuels was determined by subtracting the energy required in processing the feedstocks from the gross energy content to create a value for carbon neutral fuel that could be produced from available feedstocks.

Calculating the amount of energy consumed in collecting, transporting, and processing the feedstocks is an important requirement for calculating the net volume of carbon neutral biofuels that can be produced. This part of the analysis is characterised by high level of uncertainty, due to a number of unquantifiable factors, such as the energy for feedstock transportation over undefined distances, the energy required for drying and reducing the particle size of the feedstock to that required for biofuel production pathways, which is feedstock dependent and would vary seasonally and geographically. Determining accurate figures would require lifecycle assessment of each individual feedstock and include logistical planning, both of which are out with the scope of the current work.

Instead, in the current work, average figures were employed for the fossil energy consumed and embedded in the feedstock by using the ratios of fossil fuel consumption reported in Ref. (Azapagic et al. 2017). For advanced biodiesel, the range was 0.4 - 0.63 MJ of fossil fuels consumed for every MJ of biofuel produced and considering all the papers researched, a mean ratio value of 0.48 MJ/MJ was employed (Azapagic et al. 2017). This range of values was used to create best, mean and worst case scenario outcomes as it will be shown next. It is noted that according to the EU definition post 2020 that makes 70% reduction in GHG emissions compulsory, any ratio greater than 0.3MJ/MJ would discount a biofuel for qualifying as advanced.

In order to calculate the net energy content available to produce carbon neutral biofuels, the gross energy content (see Table 2) was reduced by the energy required in preparing the feedstocks, using the fossil fuel consumed to biofuel produced ratios (0.4, 0.48 and 0.63 MJ/MJ). The results from this step of replacing the fossil fuel consumed with a corresponding proportion of the advanced biofuel, are summarised in Table 3. It is shown that the range of energy available for carbon neutral biofuel production with pyrolysis is estimated at 38.6 - 60.9 PJ (a mean of 52.8 PJ) while for gasification with F-T synthesis the corresponding figures are 22.7 - 35.8 PJ (a mean of 31.0 PJ). The aforementioned figures can be easily translated to the carbon neutral biodiesel production, given the energy density of 34 MJ/ltr that can be assumed. Thus, as shown in Table 3, the carbon neutral biodiesel that could be produced ranges between 667.2 and 1791.2 Mltr, depending on the production pathway.

According to the latest available data from government sources, the total yearly road transport fuel consumption (taking into account all types of road transport) is estimated at 37,928 Mltr for 2018, while the respective figure for diesel consumption in HGVs is estimated at 7,812 Mltr (BEIS 2020a). Considering an energy density of 36 MJ/ltr for conventional diesel and gasoline (European Union 2018), the total yearly road transport fuel consumption corresponds to 1,365.4 PJ while the respective estimation for the HGV diesel consumption is equal to 281.2 PJ. These figures are compared to the three scenarios for carbon neutral biofuel production (Table 3) on the basis of the two production pathways.

Table 4 shows that depending on the production pathway, the potential of the yearly contribution of carbon neutral biofuels to the UK can vary between 1.7% and 2.6% of the overall road transport in the case of the gasification with F-T synthesis pathway and between 2.8% and 4.5% in the case of the pyrolysis with upgrading pathway. If all the produced carbon neutral biofuel was to be used for HGV transport, it could cover their needs with a significant contribution ranging between 8.1% and 21.7% depending on the production pathway.

DISCUSSION

The most important factors that determine the viability of the system to produce carbon neutral biofuels are feedstock availability and process efficiencies.

The availability of sustainable feedstocks is the primary constraint on biofuel output. As already discussed, 37% of feedstock energy content originates from the biogenic household waste sent to landfill. However, biogenic waste is often contained in or combined with plastics or tin foil upon collection, so its separation from these other fractions of waste is required, therefore the full resource may not be completely released. Also, as it shown in Fig. 2, biogenic waste volumes have been decreasing, a trend that is predicted to continue in line with government policy (Searle and Malins 2016), so this feedstock's availability is expected to reduce in the future.

With only 24% of potential feedstocks available (out of a total of 68,656 kt of generated waste), there are opportunities to increase the supply for biofuel production. In 2018, the UK exported 4.81 Mt of paper waste (WRAP 2020) with an estimated energy content of 67PJ (assuming an energy density of 14 MJ/kg). This mass is 68% of the total paper and cardboard waste generated and considered in the previous analysis. Applying the efficiencies for the two production pathways (see Table 2) and the ratios of the fossil fuel consumption for the biofuel production (see Table 3), the net carbon neutral energy for biofuel through pyrolysis with upgrading ranges between 14.4 and 22.7 PJ (mean of 19.6 PJ) and between 8.4 and 13.3 PJ (mean of 11.6 PJ) for the gasification with F-T synthesis pathway. The aforementioned figures translate to 3.0% - 8.1% of the HGV transport needs on a yearly basis (depending on the production pathway).

Although fairly different estimates for municipal waste and agricultural and forest residues have been published in the literature, it is believed that the figures employed in the current work are reasonable approximations. Table 5 displays estimates for available municipal waste, as well as forest and agricultural residues published in various works. Available municipal waste is considered the sum of the available biogenic household, paper, animal, food, vegetal and wood waste shown in column 2 of Table 1. The average of the four referenced estimates shown in Table 5 is 14.43 Mt, i.e., 7% greater than the current work's estimate, thus confirming that the report's estimate was a reasonable approximation. It is noted that the Green Investment Bank used data from 2012 (Green Bank 2014), which partly explains their higher estimate, as volumes generated have reduced since then. Anthesis' estimate is also greater than the figure reported in the current work (Scholes et al. 2017), but it included waste being processed through energy recovery methods, which the current work omitted.

There are greater apparent discrepancies regarding agricultural and forestry residues. These discrepancies originate from the fact that it is considered absolutely essential to leave some agricultural/forestry residue behind for soil quality, but there is no consensus on the quantity that should be left. Searle & Malins (Searle and Malins 2016), estimated considerably less residue available than other sources. However, their original estimate for the volume generated was 20.3Mt and greater than other estimates, but it proposed a larger amount, 10.3Mt, should be left for environmental reasons.

According to the conversion efficiencies reported by NREL (Dutta et al. 2015) for the two production pathways (Table 2), pyrolysis is a better thermochemical option than gasification, capable of producing 70% more biofuel for the same mass of feedstock. However, pyrolysis requires a feedstock with a lower moisture content compared to gasification, and this leads to higher energy consumption during pre-treatment of the feedstock. Yet, this extra energy would be considerably less than energy related to the 70% extra biofuel produced by pyrolysis, so pyrolysis would still produce more carbon neutral biofuel. In addition, the NREL results were obtained on the assumption of a homogeneous feedstock of wood, while heterogeneous waste would lower the efficiency. The feedstock would be a mix of materials of varying qualities, so operating parameters would be difficult to optimise as for a specific feedstock. Certain types of waste also contain contaminants increasing the energy required cleaning the syngas or bio-oil products, e.g., wood waste which derived from the construction and demolition sector can be contaminated with paint or fixings.

Less apparent in the calculation is that the ratio used to calculate the energy required in feedstock preparation was the same for all feedstocks. However, some feedstocks require less energy than others, making them more viable for efficient conversion and producing greater volumes of carbon neutral biofuel. Opportunities for BECCS exist in biofuel production with the production of biochar during pyrolysis, which has proven resistance to degradation and ongoing research efforts examine its potential for carbon sequestration (Dissanayake et al. 2020). This would allow for some fossil fuels to be used in the production pathways and still achieve net zero emissions. This would increase the potential volume of carbon neutral biofuel produced or else the carbon credits attained could lower the cost of production. Both the conversion efficiency and the fossil fuel consumed to biofuel produced ratio can be considered quite conservative values. The NREL efficiencies used in the current work are lower than other published values and the EU RED II (European Union 2018) assumes GHG savings of 70% are attainable, so only 0.3MJ of fuel consumed per MJ of production is realistic. Therefore, the amount of carbon neutral biofuel obtainable may be greater than calculated.

It is commonly accepted that the potential contribution of advanced biofuels for road transport will be influenced by factors such as the price of fossil fuels, competition for feedstocks and for the advanced biofuels produced. The economic profitability of sustainable advanced biofuels is a primary constraint on their development (Correa et al. 2019) and may determine whether advanced biofuels become commercialised. Currently biofuels cost more and are uneconomical compared to direct competition from fossil fuels (IEA 2017). This could change by disincentivising fossil fuel consumption through taxation, in order to promote decarbonisation. In addition, waste management is problematic and costly for society and therefore, feedstocks can have negative costs as biofuel producers are currently contracted for their collection. This can be seen as an attractive reason to develop biofuels, as it will reduce production costs.

Biofuel production by thermochemical processes is currently a novel technology requiring R&D as well as capital costs. NREL estimated the construction cost of a 730,000 tonne/annum pyrolysis plant at £469 million (Dutta et al. 2015). BTL Bioliquids with the largest pyrolysis plant in Europe (40,000 tonne/annum) had an estimated cost of £18 million (Delta 2018). Using NREL's estimate, to convert the 16,359 thousand tonnes of feedstock revealed as available by the current work would require 23 plants and a total cost of £10.8 billion. In comparison the BTL model would require 409 plants at a cost of £7.25 billion. Therefore, there is a considerable difference between these two systems regarding the cost and number of plants required. NREL offers a financial estimate with a margin of error. It is reasonable to assume that economy of scale should have actually made building fewer plants cheaper, as the technology for the two systems will be similar. The building of more plants would reduce transportation distances for feedstocks with consequent fuel cost reductions.

To encourage investment and development of advanced biofuels, the government must develop policy involving long term commitments. Without these interventions potential investors are dissuaded by the risks associated with a novel industry and potential changes in policy (IRENA 2019). The current net zero carbon emissions target does, however, provide continuity of policy.

Furthermore, biofuel production is in direct competition with other industries that use the same sources of available sustainable feedstocks. For instance, incinerating municipal waste for electricity has existed in the UK for 100 years (Herbert 2007), in fact has had a recent renaissance in waste management. The UK Energy from Waste (EfW) sector has increased the quantity of municipal waste it processes 350% in 10 years, from 3.3Mt to 11.49Mt. In 2018, there were 42 EfW fully operational, 5 being commissioned, 15 under construction and more being planned (Tolvik Consulting Ltd. 2019).

Anaerobic digestion (AD) is another competing energy recovery process where biogenic feedstocks with any moisture content are digested by micro-organisms to release biogas. Energy output from AD has increased over 6000% in 10 years to approximately 1250 toe, equivalent to 1.48 million litres biodiesel (DEFRA 2019). Biogas (composed of 60% of methane) is normally used for heat and power, although it can be purified and the produced biomethane can be used as an alternative renewable transport fuel to biodiesel.

As a result of the growth in these technically proven sectors, the volume of feedstocks available for biofuel production will reduce before conversion technologies become fully commercialised. This will make the investment required for commercialisation riskier and consequently less probable.

Steps to increase carbon neutral advanced biofuel production

Government intervention is essential to increase biofuel production nationally, by actively encouraging biofuel development. Towards this direction, the publication of a roadmap would outline the necessary steps to be followed, therefore, creating long term certainty and confidence for investors and the industry.

Moreover, a national standardised waste management policy would maximise the supply of feedstocks. Currently, the absence of a national waste management policy results in local governments developing individual plans which exhibit significant differences. Thus restraining the maximising of the sustainable feedstock from households which accounts for 46% of the total feedstock. A national waste management policy, that mandates separate food waste and green waste collection, would increase the supply of sustainable feedstocks.

Energy crops are the only sustainable feedstock not a co-product of another industry, which could be specifically produced for biofuel production and represent the greatest opportunity for increasing the supply of sustainable feedstocks (E4tech (UK) 2017). In 2018, 31.6% of renewable electricity generated was derived from bioenergy, with 2,716,000 tonnes of oil equivalent from home produced plant biomass (BEIS 2020a). By using the best-case scenario for carbon neutral biofuels using pyrolysis, this biomass converted to biofuel represents 13.7% of HGV fuel consumption.

In addition, it is believed that the following recommendations will also promote considerably the availability of sustainable feedstocks for the development of advanced biofuels:

- Biofuel production should be defined as recycling in the waste hierarchy, thereby increasing the quantity of feedstock permitted for production.
- The export of paper and cardboard waste for recycling abroad is currently the preferred waste management option for this material. Prohibiting this trade, as previously demonstrated, would increase the availability of sustainable feedstocks.
- The biomass currently combusted for renewable electricity generation would be better utilised for biofuel production, considering that GHG emission-free electricity is achievable by numerous technologies, while transport is a more problematic sector to decarbonise.

- Lack of an internationally agreed definition for what constitutes an *advanced biofuel* necessitated the creation of a definition for the purposes of the current work. Whilst this definition was sufficient for the analysis presented above, a wider consensus is necessary for consistency amongst researchers and the creation of a framework for policy development. This is important as policy development may be significant to stabilising market investments in the biofuel industry. The current definition of advanced biofuels, which stipulates production from a novel technology, suggests the nomenclature is transitory raising the risk that biofuels on development might be disqualified from being marketed as advanced.
- An increase of carbon taxation and regulations concerning CO_2 emission that discourage the use of fossil fuels would make biofuels more competitive, as well as promote research and investment in the opportunity for carbon storage within biofuel production pathways.

KEY FINDINGS

The current computational study aims to quantify the technical potential for carbon neutral advanced biofuels production in the UK, on the basis of sustainable feedstock. Despite the inherent uncertainty (pertinent to the computational study of any nature), the estimates are believed to be accurate because: (i) the employed conversion efficiencies are all from well-reviewed reliable sources and (ii) aspects of the feedstocks' heterogeneity have been taken into consideration. A novelty of the proposed approach is the fact that it showcases the carbon neutrality without considering any carbon sequestration which is currently at a low TRL.

The major finding of the current study is that depending the production pathway (pyrolysis with upgrading versus gasification with F-T synthesis) and the energy required to prepare the feedstocks, the potential of the yearly contribution of carbon neutral biofuels to the UK can vary between 1.7% and 4.5% of the overall road transport 8.1% and 21.7% of diesel consumption by HGV transport. The largest part of the variations originates from the consideration of the two different production pathways with pyrolysis with upgrading being the most efficient pathway.

The above figures were calculated on the basis of the most updated (2016) published data on biogenic waste. The fact that a mere 24% of the generated biogenic waste could be available as feedstock for advanced biofuel production, suggests that there is plenty of room for increasing the available feedstock. The categories of feedstocks with the largest potential are the household biogenic waste and the paper/cardboard waste. The first can be effectively maximised mainly through the introduction of a national waste management policy while the latter could be significantly increased by minimising the paper waste exports which as of 2018 could result in 3.0%-8.1% of the HGV transport needs.

CONCLUSIONS

The necessity to decarbonise transportation and a continued requirement for high energy density liquid fuels creates an opportunity for biofuel consumption to expand. The development of conventional biofuels is constrained by the area of land available for the cultivation of feedstocks without resulting in negative consequences. Advanced biofuels unencumbered by these issues are promoted as a sustainable option using waste and residues as feedstocks. It has been demonstrated the supply of these feedstocks is equally constrained and diminishing due to waste policy and competing uses. Therefore, the only option for increasing feedstocks is to encourage the cultivation of energy crops on marginal land. However, caution and regulation are imperative for this approach to avoid the problems associated with land use change occurring from conventional biofuel production.

The current work examined an original concept of supplying the energy consumed in biofuel production solely with biofuels, thereby producing carbon neutral transport fuel, a necessary commodity for the UK decarbonisation policy. Key findings have identified the volumes of sustainable feedstocks for advanced biofuels generated in the UK and estimates 24% of these are available for biofuel production. It has been calculated these feedstocks could potentially be converted into the equivalent of 1,791Mltr carbon neutral biodiesel and supply 21.7% of HGV fuel demand. It has been demonstrated that due to a superior conversion efficiency, pyrolysis with upgrading is a better production pathway, capable of producing more biofuel from the available biomass, compared to gasification with F-T synthesis. However, it is noted that the TRL of pyrolysis is lower and will take longer to commercialise.

The benefit of supplying carbon neutral fuel is enhanced by the fact that the feedstocks utilised are waste that is costly to depose of by incineration or landfilling. A more sensible waste management policy would be converting this biomass into transportation fuel, thereby contributing to the government's policies of net zero emissions. The key findings presented herein demonstrate the potential of producing significant quantities of carbon neutral advanced biofuel (biodiesel), a key element for policy makers in deciding how best to achieve net zero carbon obligations.

More detailed research on the generated waste is required, concerning particularly the energy consumed and the economic cost of collecting, transporting, and preparing individual types of feedstock. This should include among others a quantification of the biogenic content of municipal waste that can be separated from non-biogenic content, the moisture content of different feedstocks, the energy consumed in the evaporation process, the geographical distribution of the waste and the geographical installation of the biofuel production plants.

DATA AVAILABILITY STATEMENT

- All data, models, and code generated or used during the study appear in the submitted article.

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TABLE 1. Mass and energy content for the individual categories of sustainable feedstocks in the UK for year 2016. Data obtained from Refs. *DEFRA 2020, Searle and Malins 2016*.

Categories of feedstock	Total waste generated (kt)	Available feedstock (kt)	Available feedstock (kt) / Total waste generated (kt)	Energy density (MJ/kg)	Energy content of waste generated (PJ)	Energy content of available feedstock (PJ)	Energy content of individual over total available feedstock
Biogenic household waste	28,028	7,517	27%	8.9	249.5	66.9	37%
Paper & cardboard waste	6,990	2,832	41%	14	97.9	39.7	22%
Animal & food waste	3,056	1,189	39%	6.3	19.1	7.4	4%
Vegetal waste	6,019	1,687	28%	6.3	37.7	10.6	6%
Wood waste	3,363	314	9%	18.3	61.5	5.7	3%
Agricultural residue	20,300	2,800	14%	17.6	357.3	49.3	27%
Forestry residue	900	20	2%	18.9	17.0	0.4	0%
Total	68,656	16,359	24%		840	180	100%

TABLE 2. The gross energy content of the biofuels that could be produced from the two pathways, using the total energy content of the available feedstock.

	Feedstock energy content (PJ)	Biomass to biofuel efficiency (%)	Energy content of biofuel (PJ)
pyrolysis with upgrading	180	56.4	101.5
gasification with F-T synthesis	180	33.2	59.7

TABLE 3. The net energy available for carbon neutral biofuel production and the net biodiesel that can be potentially produced, via the two production pathways. The gross energy values for the two pathways are shown in Table 2; 101.5 PJ for the pyrolysis with upgrading pathway and 59.7 PJ for the gasification with F-T synthesis pathway. For the produced biodiesel an energy density of 34 MJ/ltr was assumed.

		pyrolysis with upgrading		**gasification with F-T synthesis**	
Scenario	Ratio of fossil fuel consumed for biofuel produced (MJ/MJ)	Net energy available for biofuel production (PJ)	Net produced biodiesel equivalent (Mltr)	Net energy available for biofuel production (PJ)	Net produced biodiesel equivalent (Mltr)
Best	0.40	60.9	1791.2	35.8	1053.4
Mean	0.48	52.8	1552.4	31.0	913.0
Worst	0.63	38.6	1134.4	22.7	667.2

TABLE 4. Potential yearly contribution of carbon neutral biofuels to UK transport.

	pyrolysis with upgrading		**gasification with F-T synthesis**	
Scenario	% of road transport	% of HGV transport	% of road transport	% of HGV transport
Best	4.5%	21.7%	2.6%	12.7%
Mean	3.9%	18.8%	2.3%	11.0%
Worst	2.8%	13.7%	1.7%	8.1%

TABLE 5. Yearly available feedstock estimates in the UK.

Source	Municipal waste (Mt)	Agricultural residue (Mt)	Forestry residue (Mt)
The current work	13.54	2.8	0.02
Searle & Malins (Searle and Malins 2016)	10.27	2.8	0.2
E4tech (E4tech (UK) 2017)	7.3	3.4 - 5.1	1.1
Anthesis Consulting Group (Scholes et al. 2017)	19.35	10.6	1.6
Green Investment Bank (Green Bank 2014)	20.8	N/A	N/A

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Fig. 1. The waste hierarchy as outlined in the WFD.

Fig. 2. Yearly landfilled volumes of total vs biogenic waste.