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An assessment of the viability of alternatives to biodiesel transport fuels

Rebecca Kächele [1], Daniel Nurkowski [4], Jacob Martin [1,3], Jethro Akroyd [1,3], Markus Kraft [1,2,3]

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[1] Department of Chemical Engineering and Biotechnology
University of Cambridge
Philippa Fawcett Drive
Cambridge, CB3 0AS
United Kingdom
E-mail: mk306@cam.ac.uk

[2] School of Chemical and Biomedical Engineering
Nanyang Technological University
62 Nanyang Drive
Singapore, 637459
Singapore

[3] CARES
Cambridge Centre for Advanced Research and Education in Singapore
1 CREATE Way
Singapore, 138602
Singapore

[4] CMCL Innovations
Sheraton House, Castle Park
Castle Street
Cambridge, CB3 0AX
United Kingdom

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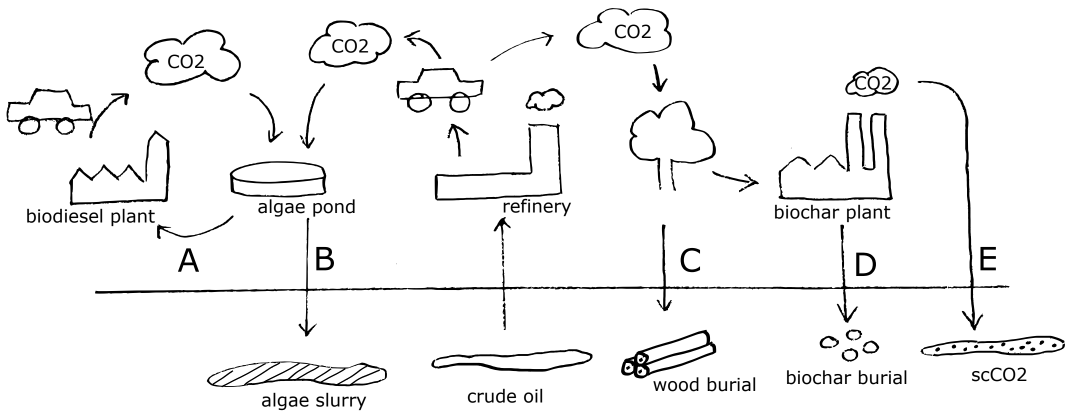
Edited by
Computational Modelling Group
Department of Chemical Engineering and Biotechnology
University of Cambridge
Philippa Fawcett Drive
Cambridge CB3 0AS
United Kingdom

E-Mail: c4e@cam.ac.uk
World Wide Web: `http://como.ceb.cam.ac.uk/`

Abstract

This work presents an economic feasibility study of using algae and biochar burial strategies to offset carbon emission from the use of conventional fossil-derived transport fuels. The economic feasibility is quantified on the basis that the final price of the decarbonised fossil-derived diesel that should be lower or equal to the price of biodiesel which is deemed as the next best alternative. The extra costs associated with the carbon capture/offset via algae and biochar burial are estimated for the most typical scenarios using the economic models developed as part of this work. In addition, High Dimensional Model Representation (HDMR) based global sensitivity analyses are performed in order to quantify an influence of key model parameters on the overall costs. It was found that using the algae burial strategy to offset carbon emission is at the moment not practical because it would at least double the current diesel price. This is mainly due to the high costs of pumping diluted algae slurry underground. The biochar burial approach, on the other hand, was found to be much more economically viable as it only increases the conventional diesel price by a small amount. This comparably low price is due to the revenue generated from selling the electricity produced from the pyrolysis by-products. In addition, the global sensitivity analysis revealed that the overall costs were the most sensitive to the wood price, as the wood feedstock may either be an income or an expenditure.



Highlights

- Economic feasibility study of using algae and biochar burial strategies to offset carbon emission from the use of conventional fossil-derived transport fuels.
- Costs associated with the carbon capture/offset via algae and biochar burial are estimated.
- The biochar burial approach was found to be more economically viable than the algae burial.

Contents

1 Introduction

Over the past century, there has been a significant increase in atmospheric concentration of carbon dioxide (CO_2) due to human activities [30]. There is near unanimous scientific agreement that uncontrolled emission of this and other greenhouse gases will change Earth's climate. This poses serious environmental threats, such as, ocean acidification [12], desertification [26] and sea level rise [16]. A rapid reduction in CO_2 emissions is then required to prevent further irreversible damage to the environment [15, 30].

Combustion of fossil fuels for energy is a primary human emission source of carbon dioxide. This consists of two main sectors: electricity production from burning coal, natural gas or various petroleum products and burning gasoline and diesel for transportation purposes (to fuel cars, trucks, ships or planes). It has been estimated that these two sectors contributed 30% and 26% to the total greenhouse gas emission in the US in 2016, respectively [36]. Whilst there are many options to decarbonise power generation systems, e.g. utilisation of solar, wind, and nuclear energy or CO_2 capture from the flue gases of coal-fired power plants, not many suitable "green" alternatives exist for the transport sector. Indeed, whereas good progress has been made on decarbonising the power sector, transport sector emissions are increasing [17].

A possible viable option to reduce the CO_2 emission in the transport sector is to utilise biomass-based fuels such as biodiesel from algae to provide a significant proportion of the fuel required for the transport activities [22]. The advantage of algal biodiesel is that, if produced using renewable energy, it can have a much lower carbon footprint compared to the conventional fossil-derived fuel. This is because the amount of CO_2 released during combustion of this biofuel is in part counter-balanced by its consumption due to the algal growth process when the fuel is produced. Taylor et al. [32] even studied an economic feasibility of an idealised case of carbon-neutral algal biodiesel. One of the main conclusions from this work was that such process is possible, but it would have very high energy requirements and high production costs associated with the algae cultivation and its transformation into usable liquid fuel. It has been estimated that the production of biodiesel is 2.5 times more energy intensive than production of the conventional diesel [29]. Such high energy demand poses difficulties to provide enough "green" energy supply to keep the whole process environment-friendly, which in turn raises capital costs and shifts production to much larger and not well-studied scales to be economically attractive or viable [32].

Because of the mentioned problems, biofuels are expected to play rather a complimentary role to the conventional fossil fuels in the short and mid-term future. It is anticipated that in Europe, green vehicles will be an important, but not dominant part of the transport sector [3]. Moreover, in the US the fossil-derived liquid fuels are predicted to be a key source of energy in transportation for the next 30-40 years [22] despite efforts to develop green synthetic fuels. It is then believed that at least in the short term a different and more realistic fuel decarbonisation strategy is required that would take into account not quickly diminishing importance of fossil fuels.

Figure 1 shows some of the possible carbon-capture strategies that could be applied to the transport sector. Option A corresponds to an idealised case of carbon-neutral biodiesel cycle. Options B-E show various fossil fuel related alternatives. They all rely on an idea that the conventional fossil fuel could be decarbonised by burying the same amount of carbon as is produced by extracting, refining, transporting and using the fuel. In case of option B this is achieved by absorbing CO_2 from the atmosphere via algal ponds. These ponds, depending on land availability, could be located either in close proximity to refineries or in other places with high CO_2 emissions. Such created algae biomass can then be transported to suitable places and buried in the ground, which is the most direct and simplest technological approach, giving some carbon credits to the utility. Cases C and D explore the possibility to sink carbon in a geologically stable form via either direct burial of a waste wood or its conversion and subsequent burial as a biochar. The last option (E) represents carbon dioxide trapping in rock deposits by injecting it underground in a supercritical form.

The wood burial and supercritical CO_2 sequestration techniques have been already investigated [27, 40, 41]. When it comes to the former, it was found that it is a viable carbon capture strategy at a small scale. Pursuing this option at larger scales, however, may pose various not yet properly researched strains on important ecosystems [40]. The latter option, on the other hand, has been found to be a feasible solution at both small and large scales. However, it was also concluded that injection of supercritical CO_2 into rock deposits involves much bigger risk of an uncontrolled CO_2 leak that would make this method completely ineffective and potentially dangerous. In addition to that, the long term impact of storing large amounts of supercritical CO_2 in rock deposits on the environment are not yet well understood [20]. Therefore in this work it was decided to focus on the two remaining carbon sequestration options which are algae and biochar burial.

It has to be also mentioned that the carbon offset strategies via algae and biochar burial can only be feasible if they fulfill two important criteria. Firstly, (i) the buried carbon must be permanently stored underground such that it is cut off from the atmosphere for at least several decates. Secondly, (ii) overall costs of fossil fuel production combined with a given carbon burial method should not be higher than the next best alternative, which in this paper is considered as an idealised case of carbon-neutral biodiesel cycle (A). Fortunately, the selected strategies naturally fulfill the first criterion as geochemical trapping of algae slurry in depleted oil fields successfully prevents carbon release from such deep voids [20] and biochar decomposition in soil requires milenia [18]. Therefore, the focus of the current work is to assess the economic feasibility of these approaches.

The **purpose of this paper** is to assess the economic feasibility of using algae burial (B) and biochar burial (D) to pre-offset carbon emissions from the conventional fossil fuels as an alternative to the biofuels in the short/midterm future of the transport sector. The paper is split into two main sections. The methodology section provides a detailed description of each process and sets out the criteria used to assess the economic feasibility of each option. The results section assesses the implications of the economic analyses and evaluates each option against the use of biofuel. A sensitivity analysis is performed to assess the robustness of the results to changes in the model assumptions. Conclusions are drawn and possible future work is identified.

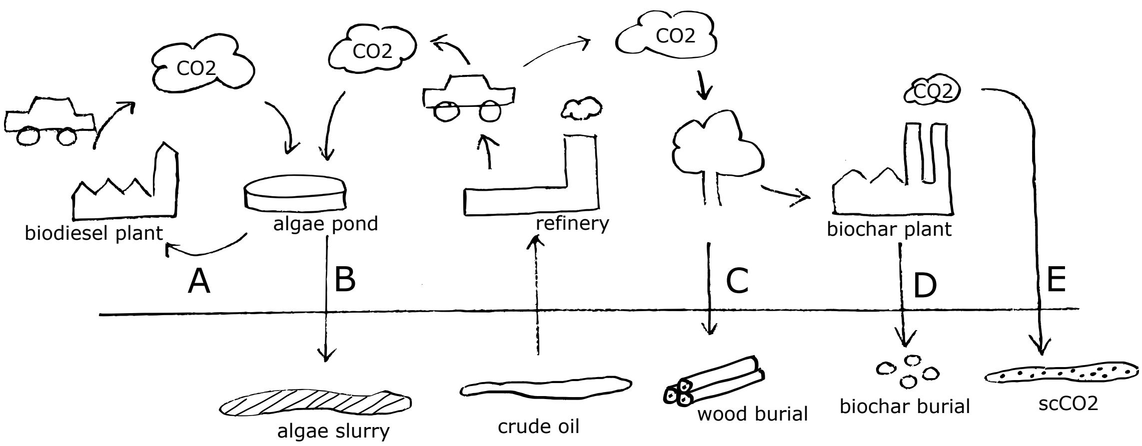


Figure 1: *Carbon-neutral options to provide fuel for the transport sector. (A) biofuel versus options to pre-offset carbon emissions from the use of conventional fossil fuel: (B) algae burial, (C) wood burial, (D) biochar burial and (E) underground storage of supercritical* CO_2.

2 Methodology

The economic feasibility of the algae and biochar burial strategies is quantified in this work as a difference between the price of carbon-neutral biodiesel which represents an idealised next best alternative and the final price of the decarbonised fossil-derived fuel. This can be written as follows

$$C_{\mathrm{B}} - (C_{\mathrm{D}} + C_{\mathrm{CPO}}) \geq 0 \tag{1}$$

where, $C_{\mathrm{B}} = 1.05$ £/l is the net price of a one litre of carbon-neutral algal biodiesel taken from techno-economic study of Taylor et al. [32], $C_{\mathrm{D}} = 0.58$ £/l is the current net price of one litre of the conventional diesel and C_{CPO} represents the costs of offsetting the carbon emission due to combustion of a one litre of the conventional diesel via algae or biochar burial. It can be seen from **equation** (1) that the decarbonised fossil-derived diesel can only be economically competitive if its final price ($C_{\mathrm{D}} + C_{\mathrm{CPO}}$) is either equal or lower than the price of the carbon-neutral biodiesel.

The costs C_{CPO} of burying carbon to compensate for the CO_2 emission generated by one litre of conventional fuel were calculated according to the following formula

$$C_{\mathrm{CPO}} = C_{\mathrm{C}} \times \theta \times \frac{12}{44} \quad [\text{£/l}] \tag{2}$$

where, C_{C} are the burial costs of a one kg of carbon, $\theta = 3.0514$ kg/l is an average CO_2 emission per litre of a conventional diesel [1, 19] and the $12/44$ factor accounts for the carbon mass content in the emitted CO_2.

Due to the number of used literature parameters and required assumptions, the costs for algae and biochar burial can only be approximated. However, the value is expected to be sufficiently accurate to assess the feasibility of this carbon offset approach. Additionally, a global sensitivity analysis of key parameters was conducted to elucidate the reliability of the calculated costs.

2.1 Costs of algae burial to offset CO_2 emission

Algae burial to offset CO_2 emission involves three main process steps (**Fig.** 2). In the first step (I) algae are cultivated in open raceway ponds similar to the algae system studied by [5]. In the second step (II) the algae content in the slurry is increased in a buffer tank using gravity sedimentation [21]. This is the most common method for biomass collection during waste water treatment and does not require additional resources [24]. In the final step (III), the produced algae-water-slurry is pumped into depleted onshore oil reservoirs or something equivalent. For the purpose of this rough estimate we assume a depleted onshore oil reservoirs is available.

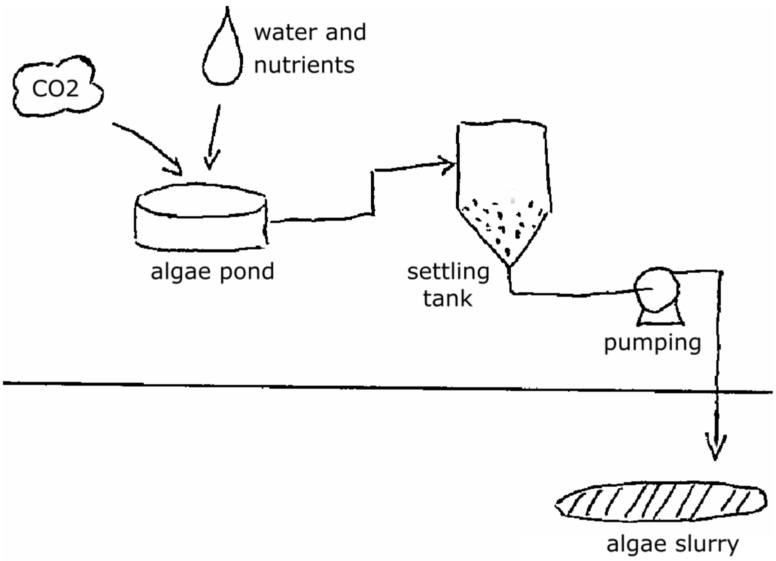


Figure 2: *Schematic of algae burial process.*

All parameters required for algae burial cost analysis are summarised in **Table** 1. Where necessary, the currencies are converted to £ and parameters are scaled to match our case size.

The capital expenditures (CAPEX) for algae cultivation include a paddle wheel, CO_2 injector, electricity supply and water delivery system. These costs are assumed to scale linearly from a 4820 acre pond assessed by Davis et al. [9]. Operational expenditures (OPEX) include maintenance, operating labour, laboratory cost, plant overheads, local taxes and insurance and were assumed to be 6.45% of the capital expenditures [35]. The required amount of fresh water was approximated by multiplying the amount of buried slurry with its water content. For a conservative estimate we assume that Water evaporation to be negligible. Furthermore, electricity is required for operating a paddle wheel to circulate the pond water. The bulk of electric power required by an algae pond is utilised by the paddle wheels [25], thus other electricity consumers were not considered. Nutrients and CO_2 are considered to be free of charge. Former is assumed to be part of the fresh water while flue gas from an adjacent power plant is used as CO_2 feedstock.

Harvest tanks are the only capital expenditure for the algae harvesting [21]. As gravity sedimentation is used for this process step, no additional operational costs have to be considered [23, 24].

Pumping of algae is assumed to be similar to the technology applied for supercritical CO_2 burial described by Metz et al. [20]. The capital expenditures are taken from the supercritical CO_2-storage project Sleipner in Norway. Operational expenditures are average costs for supercritical CO_2 injection into onshore oil fields. The expected additional costs for pumping slurry containing solid algae compared to supercritical CO_2 was accounted for by multiplying the operational costs with a factor $\alpha \geq 1$.

Table 1: *Key assumptions and model details for the algae burial model.*

Process data		
Plant type	Open raceway pond	
Growth area	1	ha
Plant life time	30	years
Yield Y of dry algae[a]	80	t/year
Average dry biomass content in pond	2	wt%
Average dry biomass content ϕ in harvest tank [a]	8	wt%
Major equipment costs		
Cultivation[b]	6665	£/year
Harvesting[c]	852	£/year
Pumping[d]	90	£/t_{slurry}
Operational costs		
Cultivation[e]	6.45% of equipment	
Water	0.06	£/m^3
Electricity	0.0936	£/kWh [10]
Pumping[f]	$\alpha \cdot 1.02$	£/t_{slurry}
Other data		
Pond mixing[g]	0.22	W/m^2
Average carbon content $x^a_{C,\text{algae}}$	54.8	wt%
Pumping algae factor α^a	5	-
Water density (25 °C)	997.1	kg/m^3 [34]

[a] Variable of model, given value is the base case

[b] Pond, paddle wheel, CO_2 injection, electrical system and water delivery [9]

[c] Harvest buffer tank assuming four times more biomass as in [21]

[d] Facility, other and total capital investment cost for industrial CO_2 storage project Sleipner in Norway [20]

[e] Includes maintenance, operating labour, laboratory costs, plant overheads, local taxes and insurance [35]

[g] Requirement of paddle wheel in baseline scenario [25]

2.2 Costs of biochar burial to offset CO_2 emission

CO_2 offset via biochar burial is considered to consist of three main process units (**Fig.** 3). A pyrolysis plant (I) converts biomass into biochar. The plant capacity is assumed to be $m_{\text{feed}} = 16000$ odt/year (oven-dry tonnes per year), similar to the work of Shackley et al. [28]. During the pyrolysis, syngas (H_2+CO) and methane (CH_4) form and are converted into electricity with a gas engine (II). Finally, the produced biochar is buried underground (III). The process details, assumptions and utilised literature values for calculating the cost of biochar burial are presented in **Table** 2.

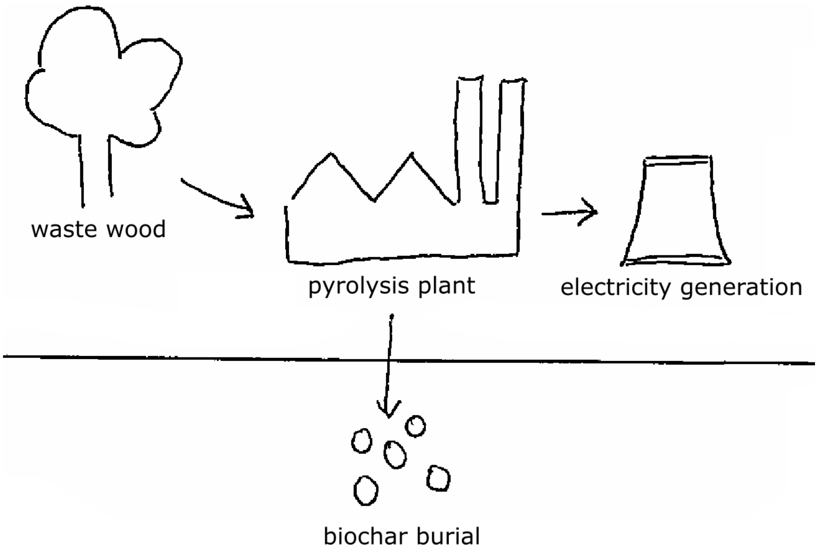


Figure 3: *Schematic of biochar burial process.*

The economic analysis is based on the work of Shackley et al. [28]. Capital expenditures for the pyrolysis plant include design, construction, civils and gas engine. Operating costs for labour, plant handling and natural gas to initiate the pyrolysis are adjusted to a biochar production of 5396 odt/year. The wood utilisation can generate income if process receives money for using the waste wood. This is known as the wood gate fee. If the wood has to be bought, the operational costs would increase. Here, wood is assumed to be free of charge in the base case while the wood feedstock will be an income or expenditure in the sensitivity analysis.

The remaining operational costs depend on the amount of produced biochar and syngas. These amounts are associated to operating conditions such as temperature, pressure, water and oxygen contents in the feedstock. The pyrolysis unit is modelled in Cantera [14] using a multiphase equilibrium process involving wood, treated as cellulose $C_6H_{10}O_5$, graphite, CO, H_2, CO_2, CH_4, H_2O and O_2. Thermodynamic properties of cellulose are calculated by applying raw data from Blokhin et al. [6].

The costs of biochar burial are calculated based on the price for wood burial given by Zeng [40]. The provided price per ton of carbon in wood is converted to £ per ton of carbon in biochar using the carbon content and density of wood and biochar.

To estimate the profit from electricity sale, the amount of energy stored in the pyrolysis products H_2, CO and CH_4 is computed according to its composition and lower heating values (LHV). A gas engine with a conversion efficiency of 35% [28] is used for the electricity generation. The LHV values are taken from Tasma and Panait [31] while the electricity price was assumed to be identical to the one used in the algae process.

Table 2: *Key assumptions and model details for the biochar burial model.*

Process data		
Plant type	Pyrolysis plant	
Plant life time	20	years
Average capacity	16000	odt/year
Temperature[a]	700	K
Pressure[a]	1	atm
Water mass content x_W in wood[a]	0	wt%
Oxygen-drywood-moles-ratio λ[a]	0	-
Major equipment costs		
Pyrolysis[c,d]	543660	£/year
Operational costs		
Pyrolysis[e,f]	642124	£/year
Price of wood[a]	0.0	£/t_{wood}
Biochar burial	4.73	£/t_C [10]
Sales of electricity	0.0936	£/kWh [10]
Other data		
Gas engine efficiency	35	% [28]
LHV of H_2	11.2	MJ/Nm^3 [31]
LHV of CO	13.1	MJ/Nm^3 [31]
LHV of CH_4	37.1	MJ/Nm^3 [31]

[a] Variable of the model, given value is the base case

[b] odkg - oven dry kg

[c] Includes design, construction, civils and commission costs and gas engine [28]

[d] Annulised with 8% interest rate

[e] Includes labour, plant, handling, natural gas and other operating costs [28]

[f] Calculated with an assumed biochar production of 5396 odt/year

[g] Requirement of paddle wheel in baseline scenario [25]

2.3 Global sensitivity analysis

A global sensitivity analysis is used to examine uncertainties corresponding to key model variables with respect to the carbon offset costs. The analysis was conducted with the High Dimensional Model Representation (HDMR) technique [2]. A brief summary of HDMR is given below while more detailed descriptions can be found in literature [5, 7].

The HDMR method approximates a complex multivariate response or target function as a hierarchical correlated function expansion in terms of the model input variables. The first term of the correlation function is a constant and represents the zeroth-order component or the mean response. The first-order terms represent an effect of the input variables acting alone whereas the second and higher order terms account for the cooperative effects of a group of variables upon the model output. In practical applications and in calculations performed in this paper, the HDMR function is truncated to second-order terms with negligible impact on accuracy [2]. Hereby, the computationally demanding complex multivariate target function is replaced by significantly more efficient approximation model. Besides the inherent uncertainties of the input parameters, the HDMR method accounts for potential non-linearities and contributions due to interactions between input parameters.

The selected algae burial model parameters for the HDMR analysis are presented in **Table** 3. The yield Y of dry biomass and the carbon mass content $x_{C,\mathrm{algae}}$ in algae were varied as different algae species could be used. The range of the two parameters are based on work of Azadi et al. [5] and Williams and Laurens [39], respectively. The harvesting efficiency is represented by the final solid algae concentration ϕ in the harvest tank. The minimum boundary is equal to the concentration in the cultivation pond while the maximum value represents the limit of a Newtonian fluid [24, 38]. As the the actual costs for pumping algae underground are unknown, the factor α was varied to assess the influence of different pumping expenditures.

In case of the biochar model five parameters are varied in the sensitivity analysis (**Table** 4). Two specify the input composition, two quantities affect the thermodynamic equilibrium and the fifth parameter is the price of wood. The water mass content x_w in wood and oxygen-wood-ratio represent the input composition. Parameters for the thermodynamic equilibrium (temperature and pressure) are chosen to vary within the most common pyrolysis conditions [8]. The costs of wood are varied in between avoided wood gate fees when wood waste is used [37] and the average price of harvested wood [28].

Table 3: *Input variables of algae burial model.*

Variable	**Min**	**Max**	**Unit**
Yield Y of dry biomass	60	100	t/year
Carbon mass content in algae $x_{C,\mathrm{algae}}$	53	60	wt%
Solid algae content ϕ after harvesting	2	8	wt%
Factor α for pumping algae	1	10	-

3 Results and discussion

3.1 Viability of carbon offset via algae burial

As an initial case the annual costs of algae burial based on an 1 ha open raceway algae pond were calculated using the base parameters listed in **Table** 1. The expenditure shares

Table 4: *Input variables of biochar burial model.*

Variable	Min	Max	Unit
Water mass content x_w	0	40	wt%
Oxygen-drywood-moles ratio λ	0	0.4	-
Temperature T	600	900	K
Pressure p	0.5	10	atm
Price of wood P_{wood}	-35.00	50	£/t_{wood}

of the process steps, that were annualised over the life time of the plant, as well as the required feedstock and products are presented in **Table** 5. The algae cultivation consumes 70.7% of the overall algae burial costs. The OPEX hereby amount to £12896 (60.2%) of the overall cultivation costs. Some saving might be possible when the plant size is increased (decrease in labour and laboratory costs) or certain tasks are automatised. In the calculations CO_2 and nutrients are assumed to be freely available. This however requires the algae ponds to be adjacent to a CO_2 emitting source (power plant, cement factory, etc.) and a nutrition rich water supply. Latter might be achieved by using waste water in which case water costs would be eliminated.

The dry biomass content in the algae slurry is increased from 2 wt% to 8 wt% in the harvesting step. The overall costs amount to only 2.8% as the sedimentation tank is the only expenditure. Nevertheless, the amount of algae slurry is decreased from 4000 t to 1000 t, significantly reducing the amount that needs to be pumped underground.

Pumping the algae slurry underground claims 26.5% of the overall algae burial costs. Due to the assumed carbon content in algae and dry biomass content in the slurry, the buried 1000 t of algae slurry amount to only 43.84 t of carbon.

For easier comparison with biodiesel, the price of algae burial per litre of compensated fossil diesel was calculated according to **Equation** 2 and is shown in **Fig.** 4. It can be seen, that the total algae burial costs to offset the emissions of one litre of conventional fuel are 0.57 £/l. Thus making fossil diesel CO_2 neutral would approximately double its net fuel price of 0.58 £/l [32]. The calculated price of algae burial is however dependent on numerous parameters that can only be approximated, motivating the sensitivity analysis.

The impact of the model input variables on the algae burial costs were assessed with a sensitivity analysis (**Fig.** 7). The solid algae content ϕ in the slurry has the largest effect on the overall costs (51.4%). This can be expected as a higher ϕ translates into decreased quantities of slurry that needs to be pumped underground. Thus the efficiency of the harvesting step is one key parameter in making the algae burial process more cost-effective.

The pumping factor α is the second most sensitive variable. This parameter is difficult to quantify as data regarding pumping costs of slurries into depleted oil fields are scare. Furthermore, α is expected to be influenced by the viscosity of the pumped fluid. Increasing ϕ might thus decrease the amount of algae slurry that needs to be pump underground but simultaneously increase α. The other model variables are only of minor importance and account to less than 21% of the global sensitivity.

Table 5: *Annual feedstocks, products and costs of algae burial based on a 1 ha open raceway algae pond.*

Process	**Feedstock**	**Products**	**Amount**	**CAPEX**	**OPEX**
Cultivation				£6665	£12896
	Water		920 t		£55
	Electricity		84.93 GJ		£1804
	CO_2		-		£0
	Nutrients		-		£0
		Algae slurry ($\phi = 2$ wt%)	4000 t		
Harvesting				£852	
	Algae slurry ($\phi = 2$ wt%)		4000 t		
	Gravity		-		£0
		Algae slurry ($\phi = 8$ wt%)	1000 t		
Pumping				£3005	£5008
	Algae slurry ($\phi = 8$ wt%)		1000 t		
		Stored carbon	43.84 t		

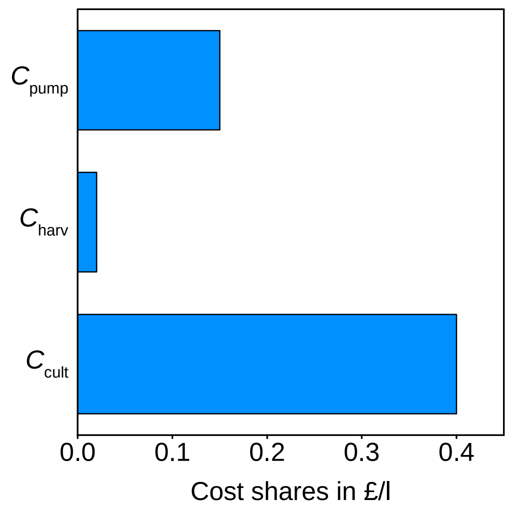


Figure 4: *Cost shares for storing carbon via algae burial per liter of fuel.*

The UK consumes $3.58 \cdot 10^7$ t/y of transport fuel, corresponding to an emission of $1.48 \cdot 10^8$ t/y CO_2 [11]. It would require $3.38 \cdot 10^6$ ha of ponds, which is 14% of the total UK land area [33], and $3.1 \cdot 10^9$ t/y of water, which is 38% of the annual fresh water withdrawal of the UK [4] in order to offset these emissions via algae burial using the suggested method.

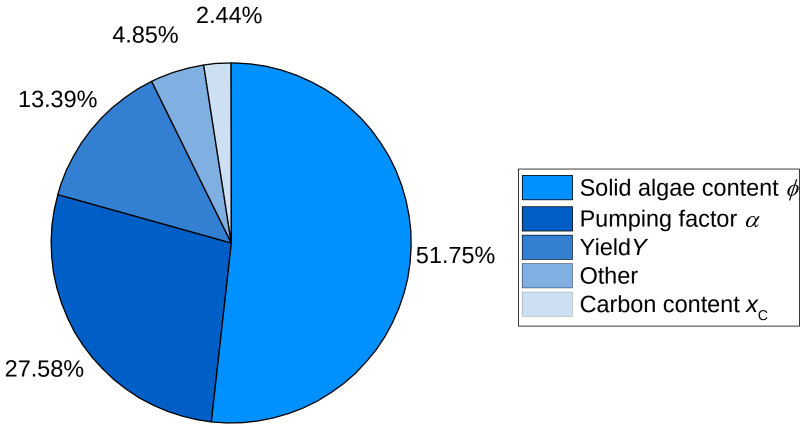


Figure 5: *Global sensitivity of input parameters with respect to carbon storage costs via algae burial.*

3.2 Viability of carbon offset via biochar burial

Annual costs for carbon offset via biochar burial were calculated for the base case using values presented in **Table** 2. The CAPEX value was annualised over the plant life time as per **Table** 2. Final results, spanning all process steps with expenditures, required feedstock and products are presented in **Table** 6. The pyrolysis unit is the most cost-generating step that 98.2% of the overall burial costs. The operational expenditures of the pyrolysis are 54.2% of the cultivation costs, and can potentially decrease with increasing plant size. In the present base case there are no operational expenditures for wood. However, revenue could be generated if waste wood would be used.

The concentrations of the pyrolysis products represent the ideal case of thermodynamic equilibrium. Here, 63.5% of the carbon in wood is converted to biochar which accumulates to 4514 t of biochar. The remaining carbon together with O and H in the cellulose (in the base case the water content was 0) forms the other pyrolysis products CO, CH_4, and H_2. These gases can be used as a feedstock for a gas engine to produce electricity and generate income. The ratio of formed biochar and pyrolysis gases depends on the reaction temperature and pressure and amount of water and oxygen in the system. Notably, an increase in pyrolysis gases would increase the revenue but simultaneously decrease the amount of biochar that can be buried. Thus optimisation of the process parameters could potentially further economise the overall burial costs.

The gases produced during the pyrolysis are converted to electricity using a gas engine. Within this process 9.08 GWh of electricity is produced, which can cover the typical power consumption of 1973 UK households [13]. Hereby, a revenue of -£850056 is generated, which compensates 70.4% of all expenditures. This revenue is highly dependent on the local electricity rates and rising prices would increase the feasibility of biochar burial.

The burial of the biochar accumulates to 1.8% of the total spendings. In the present scenario biochar was assumed to consist entirely of carbon. Thus compared to the algae burial relatively small quantities of biochar have to be buried to offset a certain amount of CO_2. This explains the relatively small share of biochar burial on the overall process costs compared to the algae pumping.

Table 6: *Annual feedstocks, products and costs of biochar burial based on a* m_{feed} = 16000 *odt/year pyrolysis plant.*

Process	Feedstock	Products	Amount	CAPEX	OPEX
Pyrolysis				£543660	£642124
	Wood		16000 odt		£0
		Biochar	4514 t		
		H_2	$16.68 \cdot 10^{10}$ l		
		CH_4	$19.82 \cdot 10^{8}$ l		
		CO	$90.56 \cdot 10^{6}$ l		
Gas engine					
	H_2		$16.68 \cdot 10^{10}$ l		
	CH_4		$19.82 \cdot 10^{8}$ l		
	CO		$90.56 \cdot 10^{6}$ l		
		Electricity	9.08 GWh		-£850056
Burial					£21351
	Biochar		4514 t		
		Stored Carbon	4514 t		

Similar to the algae burial process, the cost shares of biochar burial for compensating the CO_2 emission from one litre of fossil diesel were calculated (**Fig.** 6). The total costs are 0.07 £/l as a large fraction of the pyrolysis costs are compensated by the electricity sales. Compared to a fossil fuel price of 0.58 £/l, the CO_2 neutral fuel based on the biochar burial strategy will be only 12.1% more expensive.

Figure 7 presents results of the sensitivity analysis to assess the impact of the model variables on the biochar burial costs. it can be seen that with a share of 48.37%, the wood price P_{wood} has the largest effect on the total costs. In the analysis P_{wood} was varied between an average wood price of 50.00 £/t_{wood} [28] and an income due to avoided gate fee of -35.00 £/t_{wood}, which in turn translated into variation in feedstock price from £800000 to -£560000 for a base case capacity as specified in **Table** 2. A high sensitivity of this parameter is therefore not surprising. Additionally, it was found that in order to generate a profit in the base case scenario (**Table** 2) the price of the waste wood should be no higher (less negative) than -23.00 £/t_{wood} while keeping all other parameters fixed.

Leaving all other variables fixed this means that the case calculated in **Table** 6 would generate an overall profit if the process receives money for using the waste wood and if the unit price of this wood is no higher (less negative) than -23.00 £/t_{wood}. The total biochar burial costs are second most sensitive to the interaction of temperature T and pressure p (25.0%). These parameters combined define the pyrolysis reaction conditions and thus specify the ratio between produced biochar and pyrolysis gases. Amount of

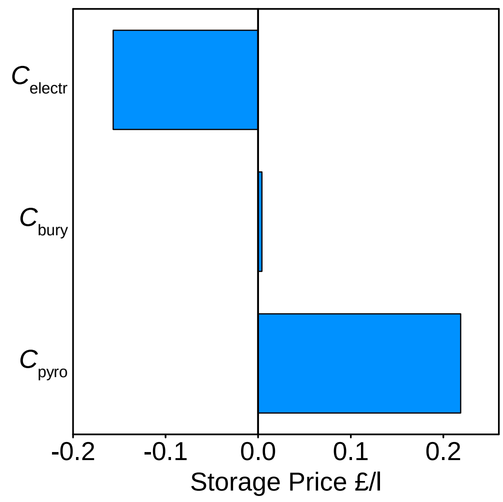


Figure 6: *Cost shares for storing carbon via biochar burial per liter of fuel*

biochar determines how much carbon for the burial is generated while the pyrolysis gases generate the main income of the overall process. Temperature and pressure alone have a minor impact on the total costs, shown by their small sensitivities values of 4.21% and 0.73%, respectively. All other variables and variable interactions are of minor importance and combined account to less than 22%.

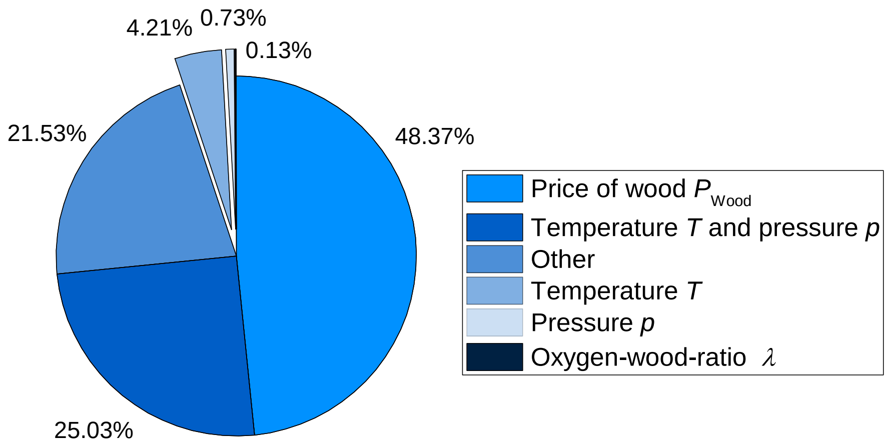


Figure 7: *Global sensitivity of input parameters with respect to carbon storage costs via biochar burial.*

It is estimated that the UK produces approximately $5.56 \cdot 10^6$ t tonnes of waste wood per year that could be available for pyrolysis biochar systems [28]. This would be sufficient to offset 3.6% of the $1.48 \cdot 10^8$ t/y CO_2 emissions from transport fuel in the UK. It is additionally estimated that the UK carbon sequestration potential from coarse wood debris is approximately 0.11 kgC/m^2/y [40], corresponding to 43% of the carbon emission from the transport sector.

3.3 Comparison of algae and biochar burial

Figure 8 shows the final comparison of the algae and biochar burial approaches to offset carbon emission from utilising fossil fuels. The data are in the form of cumulative costs per one litre of carbon-neutral diesel and are depicted as an addition to the current net diesel price C_D of 0.58 £/l . The model parameters used in the costs calculations represent the base case scenarios and are listed in **Tables** 1 and 2. Additionally, the algae and biochar data are benchmarked against the price of biodiesel which is considered as the next best alternative. Moreover, it was assumed that the production of biodiesel is carbon-neutral. This represents the ideal situation that was investigated by Taylor et al. [32] from which the final biodiesel price equal to 1.05 £/l was taken.

As shown in **Figure** 8 the final carbon neutral fossil diesel price for algae and biochar burial is equal to 1.15 £/l and 0.65 £/l, respectively. Conventional diesel combined with algae burial is thus 9.5% more expensive than biodiesel. Nevertheless, it would potentially be compatible if the pumping factor α would be reduced or the dry biomass content after harvesting ϕ would be increased. Both parameters were shown to have the biggest impact of the overall algae burial costs (**Fig.** 7) and are simultaneously difficult to quantify. Alternative harvesting techniques might significantly increase ϕ and α can only be approximated due to lacking literature data. Further work is also required in determining the interaction between the two parameters as an increase in ϕ is expected to increase α as well.

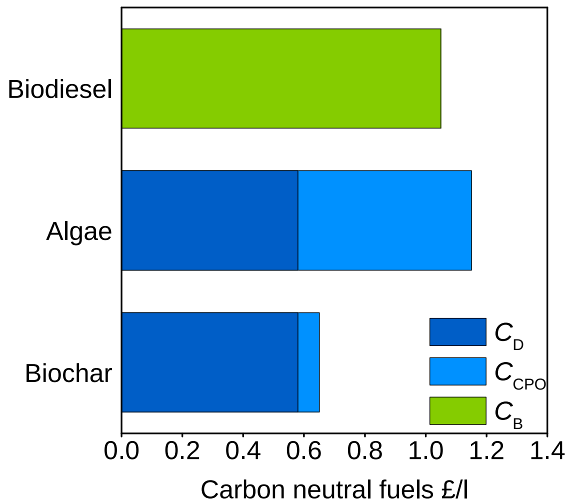


Figure 8: *Comparison of average costs per litre of carbon neutral fuel: Biofuel costs C_B, fossil diesel costs C_D and carbon pre-offset costs C_{CPO}*

The biochar burial approach leads to the cheapest carbon-neutral biodiesel among all the options presented in **Figure** 8. The main reason is the significant revenue that can be generated through the production and sales of electricity. It is important to note that the pyrolysis conditions have the biggest impact on the overall process as they determine the amount of produced biochar and pyrolysis gases for the gas turbine. Therefore, the process could be further optimised by balancing the electricity generation and biochar production. Biochar burial is further highly dependent on the wood feedstock expenditures. Ideally, waste wood should be used as revenues would be generated from saved gate fees.

In summary, both offset methods are potentially capable and feasible alternatives to biodiesel. There are however a number of variables such as the long-term price development of fossil diesel, biodiesel, and electricity or the availability of wood waste. Each of them may become a dominant factor in the near future thus shifting the most cost-effective approach from one to another.

4 Conclusion

The feasibility of algae and biochar burial to offset carbon emission from fossil fuels usage were studied with economic models developed in this work. The expenses of the two approaches were estimated for base case scenarios. The sum of conventional diesel and CO_2 offset costs were compared to biodiesel. A HDMR-based global sensitivity analysis was applied to elucidate the correlation between key model variables and the economic feasibility of the carbon offset method.

The total costs of algae burial to offset the carbon emission of conventional fuel are 0.57 £/l in the base case, which would double the assumed net fuels price. The global sensitivity analysis shows that algae burial costs are most sensitive to the solid algae content ϕ (51.75%) and pumping factor α (27.58%). Both are difficult to quantify due to lacking literature data and it is expected that ϕ influences α.

Total costs to offset the carbon emission of conventional fuel via biochar burial are 0.07 £/l. This comparably low price is attributed to the revenue from selling electricity produced from the pyrolysis by-products. The carbon offset costs are most sensitive to the wood price P_{wood} (48.37%), as the wood feedstock might either be an income or an expenditure. The second most sensitive variable is the interaction of temperature T and pressure p (25.0%), representing the pyrolysis reaction conditions. These determine the ratio of produced biochar and pyrolysis gases.

In our study conventional diesel combined with algae burial is 9.5% more expensive than biodiesel in the base case. Further reduction of costs might be achieved by reducing α or increasing ϕ. In the base case, the combination of conventional diesel and biochar burial is already cheaper and might further be optimised. Two improvement possibilities are the pyrolysis conditions to improve the biochar/electricity production ratio and the usage of wood waste. Thus, both approaches for offsetting carbon emission from conventional fossil fuels are economically competitive with biodiesel.

Neither of the methods would be suitable to completely offset the CO_2 emissions in the UK from transport fuel. Nevertheless, the biochar burial offset deserves more attention as it may be a promising technology to reduce the impact of transport on the UK carbon footprint at a reasonable cost.

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