A novel approach to assessing the commercial opportunities for greenhouse gas removal technology value chains: Developing the case for a negative emissions credit in the UK.

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*Title Page

A Novel Approach to assessing the Commercial Opportunities for Greenhouse Gas Removal Technology Value Chains: Developing the case for a negative emissions credit in the UK.

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Abbreviations (place in footholder of first page)

BECCS	bioenergy carbon capture & storage
BEIS	Department for Business, Energy and Industrial Strategy
BM	business model
CCS	carbon capture & storage
DAC	direct air capture
DECC	Department for Energy & Climate Change
GGR	greenhouse gas removal
GHG	greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
NERC	National Environmental Research Council
PPM	parts per million
VI	vertically integrated
VP	value pool

Highlights

- A novel bottom up model is developed to generate commercially relevant analysis for Greenhouse Gas Removal (GGR) innovation and deployment.
- It has generated decision centric data for GGR developers, investors and policy makers.
- GGR value chains can access value of £35.3bn to £36.9bn by 2050 in future scenarios developed.
- Electricity generation and carbon credit value pools are fundamental to scaling GGR.
- A distributed biomass-focused pathway to deployment enables greatest value capture and mitigates risk.
- The introduction of a negative emission credit mechanism for net CO_2 removal is essential.

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Abstract

In the UK the development of greenhouse gas removal (GGR) technologies at scale by 2050 is seen as an increasingly urgent imperative; necessary to ensure alignment of the UK's carbon targets with international efforts to limit the global temperature increase to 2°C or less. As such, GGR is an increasingly critical topic for UK climate policy. So far, GGR research has focused on top-down assessment of techno-environmental potential and carbon abatement costs - an approach which aids integrated assessment modelling but does not provide the commercially relevant analysis necessary to understand potential routes to market for this sector. This research reduces this knowledge gap by employing a novel bottom-up perspective to determine the financial opportunities available to GGR business models in Biomass heavy UK energy scenarios. This delivers results relevant to national and sectorial policy and decision making, by quantifying revenue opportunities from future GGR value chains, as well as business model performance. It also informs the innovation, policy, and regulatory environment required to ensure market development and resilience of different revenue streams. The work concludes that energy market policy - specifically access to a carbon credit mechanism - has by far the greatest near term opportunity to drive the negative emissions technologies we assess. This is because the values in this market far outweigh those in related supply chains such as: enhanced oil recovery, afforestation payments, biochar markets, and industry and commercial uses of captured carbon. This data shows that negative emissions technologies in the UK, should not be led by agricultural and land use policy, but should be integrated with energy policy. To do this, the development of a carbon storage credit mechanism analogous to the existing carbon price floor is key. As a proof of concept for a novel method to generate commercially relevant insights for GGR scale up, the research clearly demonstrates that the value pool method provides critical insights to assist GGR development and could form the basis of further work.

Keywords

- Greenhouse Gas Removal
- Negative Emissions
- Value Pool
- Business Models
- Energy Policy
- Commercial Delivery

Word Count: 8,830

1. Introduction

1.1 The International Challenge Ahead: Negative Emissions

Despite significant attempts to advance progress towards global greenhouse gas (GHG) emissions reduction, there is unequivocal evidence that more substantial action will be necessary in order to meet internationally agreed climate targets. This is observed in the disparity between the emissions pathways compatible with keeping global temperature change to well below 2°C such as the RCP 2.6 emissions pathway relative to other scenarios (Rogelj et al., 2016) - see Figure 1.

Eighty seven percent (101 of 116) models consistent with the 2°C target require net-negative emissions - the net withdrawal of CO_2 from the atmosphere - in the second half of this century (Fuss et al., 2014). Central projections suggest that 600 $GtCO_2$ need to be removed. This can only be achieved by the deployment of greenhouse gas removal (GGR) technologies on a scale equivalent to today's largest industries, such as the Oil and Gas sector, to capture and permanently store CO_2. To achieve this goal within an adequate time frame, these technologies will require development at an unprecedented rate of diffusion through research, policy support, and commercial investment at a global scale.

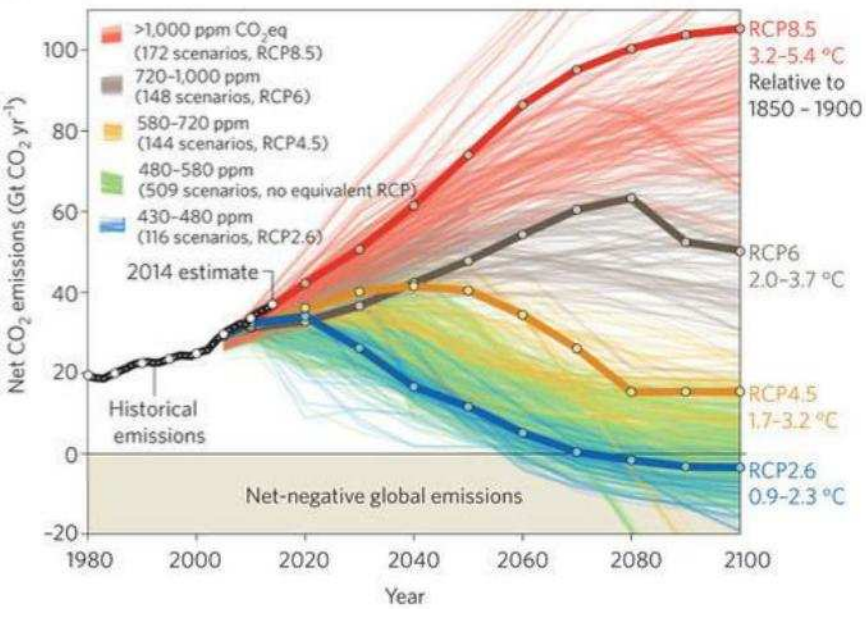

Figure 1: Graph showing IPCC Integrated Assessment Models (IAMs) and the requirement for net-negative global emissions to limit CO^2 equivalent to 480 ppm to keep temperature change to 2°C or less (Fuss *et al.*, 2014).

1.2 Greenhouse Gas Technologies: The UK Perspective and the significance of firms and investment

The prominence of greenhouse gas removal for UK policymakers reached a significant milestone in 2017. A report by the Parliamentary Office of Science & Technology (2017) concluded that net zero emissions may be difficult and more costly to achieve without GGR, whilst also underlining the absence of specific policy in this area. In addition, the Committee on Climate Change (2017) emphasised the requirement for further climate strategy development by the UK government, as a necessity for deeper emissions reduction beyond 2030. Greenhouse gas removal, as well as related areas of carbon capture and storage (CCS) and sustainable bioenergy, were highlighted as key areas requiring substantial and immediate progress to achieve the 2050 target of 80% reduction in emissions below 1990 levels - which require a reduction from 466 MtCO2e in 2016 to 120 MtCO2e in 2050.

The government response to the Committee on Climate Change report outlined a UK GGR strategic approach with two main elements (BEIS, 2017):

- A research programme, enabled through £8.6 million of funding for the National Environmental Research Council (NERC); coupled with a commitment to develop estimates of sustainable biomass resource available to the UK; and
- A study to consider the scope for removing barriers, strengthening incentives and introducing a policy framework to support GGR deployment, with the ambition for the UK to become a sector leader. Areas of interest include development of a carbon offset market and UK timber for construction.

It is in the context of these recent publications, and most specifically the second element of the government strategy that this work looks to advance: A better understanding of prospective GGR policy in the UK, and question whether more immediate measures can be taken using existing policy tools in established markets.

1.3. The implications of Greenhouse Gas Removal Technology Development in de-carbonisation

The development of negative emissions in the UK emissions reduction policy mix provides much flexibility to where decarbonisation innovation needs to be directed, and the allocation of energy carriers – especially biomass (Committee on Climate Change, 2011). In conjunction with Carbon Capture and Storage (CCS) development, biomass would be allocated very differently in 2050 compared to a future without CCS development – see figure 2, below.

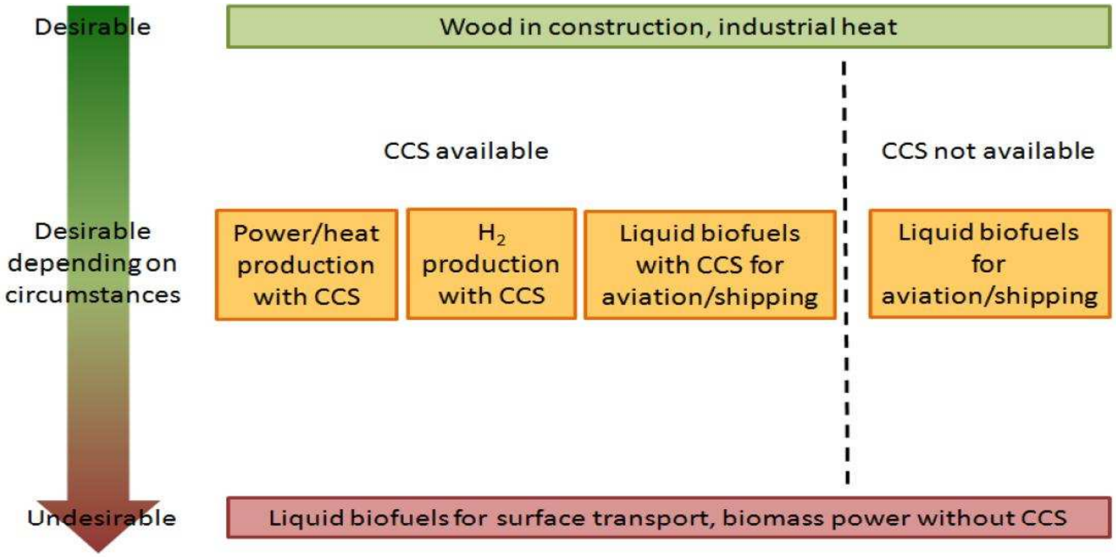

Figure 2: displaying the difference in the allocation of biomass in a UK energy system to 2050 with and without the development of Carbon Capture and Storage and therefore the ability to generate negative emissions (Committee on Climate Change, 2011).

In a 2050 UK future without CCS and negative emissions, biomass is allocated to the production of liquid transport fuels for aviation and shipping. There would also be the requirement for substantial breakthroughs in low carbon technology development in bioenergy such as biofuels from algae or changes in consumer behaviour e.g. diet and or travel behaviour. Whereas with CCS and negative emissions, biomass is instead allocated to electricity and heat production as well as hydrogen surface transport with as well as an allocation to biofuels for aviation and shipping. Thus the development of CCS is a critical branching point (Foxon et al, 2013) for negative emission technologies related to biomass utilisation and other dimensions of UK decarbonisation policy.

1.4. The Role of the Firm and Investment in Technology Transitions

The development of a greenhouse gas removal technology sector on the scale of that needed to address the worst effects of climate change will more than likely require the co-evolution of regulation, policy and the harnessing of private sector (innovation and investment) capacity to scale up (Geels, 2011). Therefore understanding relative size of revenue streams created by the development of a prospective GGR sector is important because in many developed nations, the main drivers of decarbonisation are taking place in liberalised markets - comprising private firms making decisions about how to compete in open markets (Wegner et al, 2017). Firm innovation is driven by profit expectations which are a function of the size of the market they are entering and the relative competition within it (Grant, 1991). In new markets, that are sensitive to wider system scenarios, the size of future financial opportunity is uncertain, weakening the ‘market pull’ for innovation. .

'The relative size of the markets created or destroyed by different future scenarios matters because firms undertaking future market analysis will likely select strategies that are compatible with their resource endowments, the potential size of the market opportunity that might develop, and its robustness across several possible futures' (Wegner *et al*, 2017 p.816). For the GGR sector, the development of innovation policy depends on understanding the future size of GGR revenue streams in different markets and which kinds of policy mechanisms may unlock which kinds of GGR technology by allowing them to access these revenue streams.

1.5. Previous Literature

Despite the salience of the likely role of the firm and investment community in GGR sector development, to date, research regarding GGR has predominantly focused on global level, top-down assessment of techno-environmental potential and economic viability via carbon abatement costs, as outlined in Figure 3.

Figure 3: Identifying the research gap addressed by this research: building on the foundation of technical and economic potential[1]

This approach is evident in GGR research such as McGlashan *et al.* (2012), McLaren (2012), Creutzig *et al.* (2015) and Smith *et al.* (2016), where technology-encompassing analysis has been undertaken to quantify technical limitations and economic viability of GGR methods. This has led to the definition of a possible global ceiling for deployment of leading GGR technologies, but other methods are needed to address how the GGR sector is to initiate growth through commercial delivery opportunities (Nemet et al., 2018). Additionally, the comparative carbon abatement cost element of current research may provide a broad guideline to cost-competitiveness of GGR methods (Ciais et al., 2013 and Sanchez et al., 2015); however, there are several drawbacks in this cost-centric approach to inform relevant audiences. Most notably, it is inherently difficult to predict the present or future cost of novel technologies (Gross et al., 2013). These are often best defined by technology developers themselves, and can be commercially sensitive or skewed to attract investment capital.

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[1] Based on Slade et al 2011 – Energy from Biomass: The Size of the Global Resource - p14.

Cost-centric data analysis based on techno-environmental assessments will likely fall short in advancing an agenda which requires urgent development. We argue that to catalyse and inform policy, a greater understanding of revenue opportunities and market potential that GGR commercial delivery platforms might access in possible future pathways will be required. Doing this allows an assessment of future opportunities without over-reliance on predicting future costs. This is also essential to better characterising the risk to the investment community, which has a critical role to play if large-scale GGR development is to be realised (Lomax, *et al* 2015). Furthermore, methodologically the characterisation of revenue opportunities, though still prone to uncertainty, is a more transparent way to parameterise existing and future revenue streams from publicly available data. This contrasts with the aforementioned difficulties in sourcing cost-based data.

1.6. Research Objective

This study seeks to assess the development of a novel method to reframe the discussion on negative emissions and GGR technology from one around techno-economic potentials to one around opportunity, value, and future markets. It does so by generating one part of the commercially-relevant data required to address the information asymmetry between techno-economic potential and GGR delivery business models. This will inform policy and regulation, market development possibilities, revenue opportunities, and investor decision-making from a bottom-up perspective (Lomax et al., 2015).

This is accomplished as follows:

- Develop a novel method to identify the financial opportunities that commercial developers might seek to access when developing GGR value chains to assess the viability of their business models in terms of access to stable and large pools of revenue.
- Use the UK as a case study to assess revenue generating opportunities available to GGR commercial developers for a limited number of GGR technology value chains within the present and anticipated UK policy and regulatory environment; and
- Use these insights to highlight policy and regulatory recommendations - in line with the second element of the UK GGR strategy - which would allow these revenue streams to become stable in a number of different possible futures.

Our approach fulfils these objectives by using the value pool modelling approach (Wegner et al., 2017) which determines the size of potential revenue in different markets accessible by GGR technology business models in a set of narrative-led UK future development pathways. Not all business models or revenue streams which GGR commercial developers will seek to access will be those which immediately or directly deliver negative emissions. Instead, revenue streams might be accessed to supplement or temporarily generate income whilst the GGR technology value chain scales-up and technology or process transfer can be achieved: such revenue streams can be termed `bridging revenue pools'. These revenue pools are useful technological and market niches (Geels, 2004) in which GGR processes can develop. The capacity for revenue capture across all markets is then assessed for various GGR business models (see Figure 4).

It is noteworthy that the method forms one part of a Human Centred Design approach (Brown, 2009) to assessing components of commercial development of GGR technologies. In this part of the research only the financial viability of different business models and the policy implications of realising that finance in the form of revenue is assessed. There are other aspects of commercial assessment which are not covered in the paper - these include but are not limited to: feasibility i.e. the maturity of the technological dimensions needed to realise the business models; the policy / regulatory risks to allow the business models to operate and access the revenues identified; and desirability i.e. the willingness of actors to purchase products and services which might be forthcoming from GGR value chains. All of these aspects would be an important requirement in assessing the risks that the business models face and the robustness of the revenue streams which they would seek to access. They would require substantial research effort in the GGR sector - see for example the summary of work undertaken in the Carbon Capture and Storage sector (Bui et al., 2018) and are considered important for future work - section 6.

2. Materials & Methods

The approach taken in this study required the creation of an innovative GGR value pool model, which focuses on potential revenue streams in the UK. This was partially founded upon the Department for Energy & Climate Change (DECC) - now BEIS - 2050 energy pathways calculator (DECC, 2013), due to the lack of relevant GGR-focused models available for the UK. From a government perspective, this task is complicated by the GGR sector transcending boundaries between energy, agriculture and industrial innovation. As outlined in Figure 4, the methodology consists of:

1) Selection of GGR technologies, which provided the basis to design the business model archetypes - see stage 4;
2) Creation of narrative-led development pathways, inspired by the DECC 2050 scenarios, and key interactions observed in the GGR space;

3) Selection of value pools (revenue streams in potential markets) accessible by GGR technology value chains, to be analysed for their performance in terms of market size in each pathway; and
4) Develop a set of GGR business models, specific to each technology value chain, and assess their revenue capture potential in each pathway.

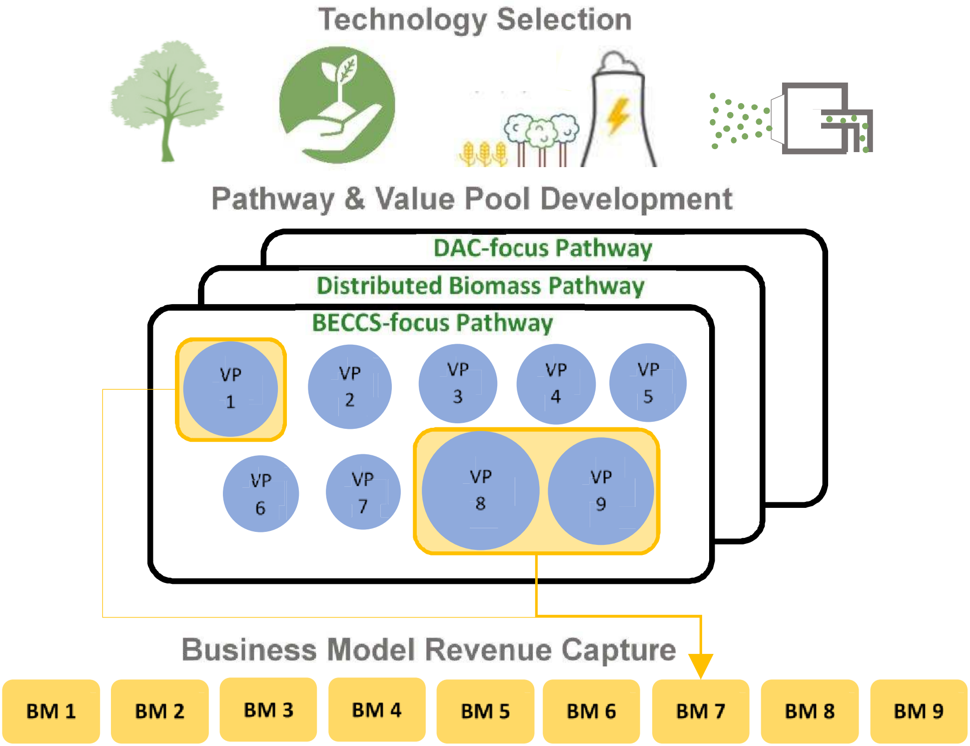


Figure 4: Overview of the value pool method with example business model revenue capture

Single trajectories are used on the basis that central values from papers and available data were selected, and where required, used to create reasonable assumptions. In the methodological supplementary information provided, further detail is given on model data sources, assumptions, calculations, structure and numerical results are presented for each constituent value pool. The narrative for each scenario, value pool and business model archetype is set out below before model results are presented. The scenarios parameterise financial opportunities a long way into the future or indeed where markets don't yet exist for GGR business models due to regulatory or policy barriers: the values are therefore highly uncertain. One of the reasons for the selection of the UK as a case study for the proof of concept of this novel method is the prevalence of UK government published data, peer reviewed papers and reports by companies and consultants which allow the scenarios to be parameterised to a greater level of fidelity than would have otherwise been possible. This allowed a large number of commodity costs to be accessed which are based on published UK government sources or advisory groups and were almost exclusively quoted as exact figures - see supplementary information in Appendix A. In line with the high-level resolution of this research to assess a novel method, drawing from data sources which largely also cite single figures the uncertainties of the values are taken as a given and therefore single value outputs. Most importantly the sensitivities around the uncertainties of the parameters are unlikely to detract from the insights method provides or conclusions drawn - though this requires verification - see Section 6.

2.1 Technology Overview

After assessing the present GGR technologies available and their current development, the four options selected for analysis were: (1) Afforestation; (2) Biochar; (3) Bioenergy with carbon capture and storage (BECCS); and (4) Direct air capture (DAC).

Though not an exhaustive set of GGR technologies and value chains which might be deployed in the UK (e.g. Smith *et al*, 2016) - this selection enables the study of biomass resource and land use prioritisation in the GGR landscape, with three of four technologies affected by these factors. Direct Air Capture is also included as one of the leading technologies requiring no biomass interaction. The key techno-environmental factors affecting these technologies have been summarised in Table 1.

Table 1: Summary of main techno-environmental concerns regarding each technology selected, based on Smith *et al.* (2016) Key: Green – No concerns | Orange – Moderate concerns | Red - Significant concerns.

<table>
<tr><th></th><th>Afforestation</th><th>Biochar</th><th>BECCS</th><th>DAC</th></tr>
<tr><td>Storage Vulnerability</td><td>🟥 Deforestation & Wildfires</td><td>🟩</td><td colspan="2">🟧 Geological Leakage</td></tr>
<tr><td>Ecological Impact</td><td>🟩</td><td>🟩</td><td>🟥 Biodiversity & Nutrient Removal</td><td>🟩</td></tr>
<tr><td>Land Use</td><td>🟥 Forestry Area</td><td colspan="2">🟥 Biomass Feedstock</td><td>🟩</td></tr>
<tr><td>Water Use</td><td>🟩</td><td colspan="2">🟧 Biomass Feedstock</td><td>🟩</td></tr>
<tr><td>Energy Intensity</td><td>🟩</td><td>🟩</td><td>🟩</td><td>🟥 Heat or Electricity Consumption</td></tr>
</table>

2.2. Pathway Development

Data from the DECC 2050 scenarios is utilised where possible in the pathways developed, listed in table 2. By building on this foundation, the UK's 80% GHG reduction target compared to 1990 emissions is also incorporated (BEIS, 2013).

The DECC: Higher CCS, More Bioenergy pathway was selected, due to the use of GGR via BECCS in the model. Furthermore, it is assumed that the biomass resource availability in this scenario is comparable with the maximum sustainable potential for the UK (both indigenous and import). This highlights the tension as to the prioritisation of biomass and land allocation between pyrolysis, BECCS and afforestation value chains. This issue is why we created two biomass focussed pathways BECCS-focus and Distributed Biomass - see Table 2. The DAC-focus pathway uses the DECC: Higher Renewables, More Efficiency pathway, exploring a future where imports of biomass are more constrained due to sustainability concerns. Consequently, the deficit in CO_2 removal is filled by DAC plants. Our analysis is therefore a maxima prediction in that we both report the maximum size of the vale pools, and chose energy scenarios which maximise bioenergy led negative emissions technologies and associated value chains.

Table 2: Summary of development pathways developed and their defining characteristics

Development Pathway	Description
Scenario 1 (Sc. 1) - BECCS-focus Pathway (DECC: Higher CCS, More Bioenergy)	• High land use for biomass production • BECCS prioritisation • Extensive CCS development with CO_2 EOR
Scenario 2 (Sc. 2) - Distributed Biomass Pathway (DECC: Higher CCS, More Bioenergy)	• High pyrolysis deployment • Extensive biochar market development • High afforestation & wood construction
Scenario 3 (Sc. 3) - DAC-focus Pathway (DECC: Higher Renewables, More Efficiency)	• Low biomass availability • High DAC deployment • Moderate pyrolysis development

2.3. Value Pool Assessment

The value pools were selected to create a representative overview of the existing and potential sources of revenues / markets accessible by business models relating to: (1) each GGR technology that are technologically feasible today; and (2) any avoided costs that might be generated by implementing cost savings along value chains. This was not an exhaustive study of the value pools possible for these technologies; however, this study also included a selection of existing markets which might not generate negative emissions in their own right but which business models would access as bridging markets on the way to scaling, as well as currently undeveloped markets in technologically proven areas, summarised by the Ansoff framework in Figure 5. This underlines the lack of developed markets with permanent carbon storage (the top right section of the matrix) required for GGR to gain traction.

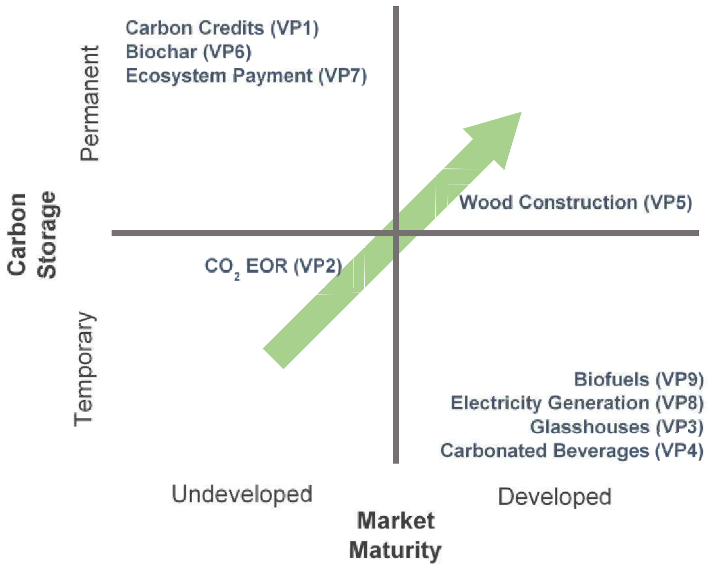


Figure 5: Matrix displaying carbon storage permanence and market maturity of value pools parameterised in this research.

Each UK Value Pool is characterised and parameterised as follows by this research:

Value Pool 1: Carbon Storage Credit assumes a payment structure exists for the net removal and storage of CO_2. It is also anticipated that the value of carbon storage credits will be equal to the projected cost of emitting CO_2 established by the Carbon Price Floor (CPF) system. We assume the this carbon payment to be priced at 'expected' carbon prices by the Committee on Climate Change, (2015) Apart from in 2020 where we expect the current freeze at £18 to be still in place.

In this study, each GGR technology obtains a credit for every tonne of CO_2 captured and stored. This is weighted in relation to each technology's particular process and vector for storage. Based on available data the following figures were used: $1.7tCO_2/tWood$ for construction (Forestry Commission, 2009), $2.2tCO_2/tBiochar$ for pyrolysis (Galinato et al., 2011), $0.033tCO_2/m^2$ for sustainably managed afforestation (Cannell, 2003), $0.28tCO_2/tWh$ for Biomass CCS, $0.17tCO_2$ for biogas CCS (DECC 2050 Model) and $0.095tCO_2/unit.yr$ for DAC (Lam, 2017) (Climeworks, 2017).

Value Pool 2: CO_2 Enhanced Oil Recovery (EOR) assesses the potential market for increased oil production by injecting CO_2 into petroleum reservoirs, based on scenarios proposed by Element Energy (2014) for a CCS hub in the North Sea. This report projects CO_2 EOR will peak in 2040, before declining to zero by 2050. The Distributed Biomass pathway utilises the Buzzard and Forties oil fields, while the BECCS-focus and DAC-focus pathways see the Fulmar, Beryl, Brae, Claymore, Ninian and Piper fields also developed. It is assumed that a recycling plant to capture and re-inject any CO_2 produced along with the oil is used throughout (Aycaguer *et al.*, 2001).

Value Pool 3: Glasshouses (or greenhouses) estimates the potential market size for concentrated CO_2 sold to increase crop yield of plants, as well as the Carbon Price Floor cost avoided for CO_2 displaced from fossil fuel sources. This is a revenue opportunity that has been utilised by the first commercial DAC plant, built by Climeworks (2017). Glasshouse area projection and CO_2 use is based on data from DEFRA (2016) and Kuroyanagi *et al.* (2014) respectively. Pathways retain identical market expansion due to lack of pathway influence.

Value Pool 4: Carbonated Beverages represents a similar market to the glasshouse opportunity outlined. The revenue opportunity for concentrated CO_2 use in carbonated drinks produced within the UK is estimated, as well as potential Carbon Price Floor costs avoided from displaced fossil fuel based CO_2 production. Projected carbonated beverage production in the UK is also anticipated to remain unchanged between pathways.

Value Pool 5: Timber-Framed Construction was identified as a potential market, based on two factors: the imminent necessity for the UK to embark on a major house building project (House of Lords, 2016), and the comparatively low levels of wood construction in the UK (specifically England) at present (Lippke *et al.*, 2011).

The BECCS-focus and DAC-focus pathways envisage that lack of meaningful afforestation policies results in low wood construction growth following UK Government (2017) extrapolated statistics. In contrast, the Distributed Biomass pathway - with its greater focus on forestry - sees high growth in wood construction for private and social house building.

Value Pool 6: Biochar focuses on two potential markets: agricultural use for large-scale fertiliser application as a replacement for lime to increase soil pH (Galinato *et al.* 2011), and smaller commercial sales by garden centres for domestic use at a high mark-up price. Currently, the commercial market dominates for biochar sales in the UK, though Manley (2014) suggests that only 827 tonnes have been sold to 2014.

For this value pool to become established, a development of the agricultural market is necessary, and occurs in growing amounts from BECCS-focus, to DAC-focus and then Distributed Biomass pathways respectively. Straw and wood residue resources are provisioned for biochar production via pyrolysis.

Value Pool 7: Ecosystem Services Payment is inspired by the increasing research into the undervaluation of ecosystems (such as forests) to society and the economy, due to inadequate quantification of that value (Costanza *et al.*, 1997). The growing interest in this area is exemplified by the UK government commitment to incorporating the value of natural capital into UK Environmental Accounts by 2020 (Smithers *et al.*, 2016). As part of this work, the value of flood-regulation services by forestry to the UK economy has been estimated for the first time, and therefore will be the focus in this study.

This valuation applied to the afforestation area in each pathway, assuming current forest upland proportion remains constant. This revenue is also adjusted for the expected rise in annual damage caused by flooding due to an increased number of properties (Ramsbottom *et al.*, 2012).

Value Pool 8: Electricity Generation is dependent on the total electricity demand in each pathway, as defined by the DECC model applied. This is combined with the wholesale electricity price, extrapolated from Ofgem (2017) data, to find the size of the value pool.

Value Pool 9: Biofuels explores the revenue opportunity for bio-oil produced by pyrolysis and sold for upgrading to biofuels. Similar to electricity generation, this value pool is defined by the UK biofuel market size for vehicle transport, defined by the DECC model in each pathway. This is combined with a price determined for the sale of bio-oil to a biorefinery.

2.4. GGR Business Model Archetypes

Using the finalists from the Virgin Earth Challenge (2017) and available literature, a selection of business model archetypes (BMAs) have been created. We use these business model archetypes to estimate how much of the value pools listed above can be captured by firms with GGR propositions. This is undertaken to enable a comparison of revenue capture potential for each BMA in each pathway, highlighting the most commercially attractive development scenario and business model combinations. The following business models are proposed, along with illustrative diagrams of the value chain elements owned. These are referred to by the corresponding letters in the description.

BM 1: Vertically Integrated BECCS (VI BECCS) is designed as a similar ownership structure to the current Drax bioenergy power plant business model (Drax, 2017), with the addition of CCS. Ownership of the value chain from feedstock production (a) through to carbon capture and storage (CCS) infrastructure and CO_2 EOR assets (d) is envisaged (see Figure 6).

By incorporating sustainably managed afforestation in the UK as a component of the biomass feedstock production owned by the business, revenues from forestry ownership activities are also enabled (outlined in BM 9). The BECCS plant (b) produces revenue via the sale of electricity at the wholesale market price. Ownership of the CCS infrastructure (c) allows additional revenue capture from industrial CCS and DAC CO_2 storage. The appropriate fraction of the CO_2 supply required will be used to meet the scenario demand of EOR activities, enabling revenue from additional oil recovery, while the remainder is stored without usage.

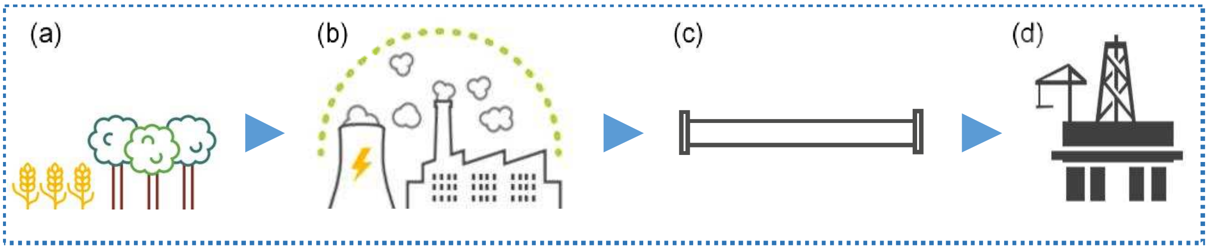


Figure 6: Diagram of value chain business ownership for Vertically Integrated BECCS

BM 2: BECCS & EOR assesses the ownership of a BECCS plant (b) and offshore oil and gas licensing area for CO_2 EOR activities (d). This company will operate in the presence of a CCS infrastructure hub development (c) in the North Sea, built and operated by a regulated monopoly – equivalent to the National Grid's operations for energy transmission (see Figure 7). The CCS Hub will be responsible for CO_2 transport proximal from BECCS and industrial sources to offshore oil and gas fields. At this end-point, a fraction of the CO_2 will be diverted to companies with EOR activities, while the remainder is stored by the monopoly. The structure of the CCS industry with this BMA is comparable to the UK electricity market, with generation (CO_2 producers), monopolised transmission (CO_2 transport), and end-users (CO_2 EOR operators).

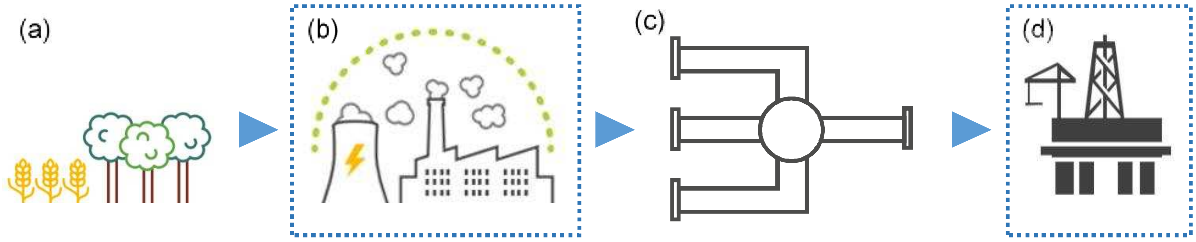


Figure 7: Diagram of value chain business ownership for BECCS & CCS Hub

BM 3: CCS Hub explores the value in operating CCS hub infrastructure (c), as outlined in the previous business model, as well as EOR activities (d) in the North Sea (see Figure 8). Revenue from storing CO_2 is shared equally with the CO_2 capture business, while oil production from EOR provides additional income. This highlights the proportion of the income in BM1: VI BECCS that could be captured by one business with the ownership of CO_2 transport infrastructure.

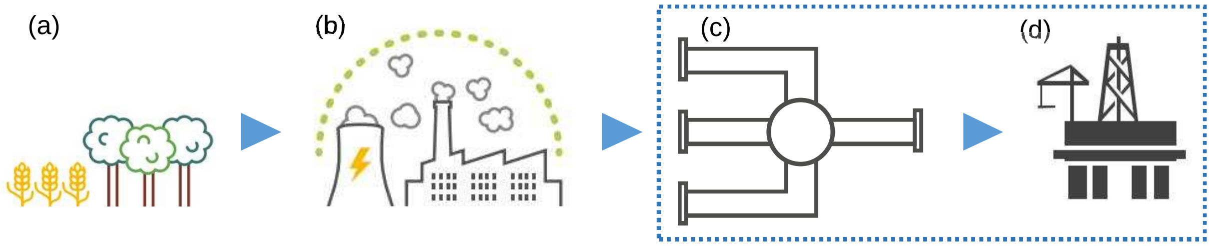


Figure 8: Diagram of value chain business ownership for CCS Hub monopoly

BM 4: DAC Utilisation implements a business structure inspired by the pioneering commercial DAC plant by Climeworks (2017). Ownership of a DAC plant (a) located strategically to enable value capture from nearby commercial greenhouses or carbonated beverage production plants (b) is implemented (see Figure 9). This is anticipated to enable revenue capture from the sale of captured CO_2 at an estimated market price, as well as a fraction of the CPF cost avoided by the CO_2 utiliser.

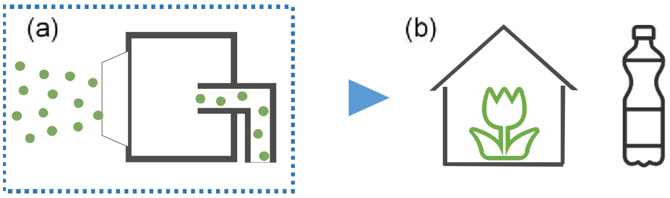


Figure 9: Diagram of value chain business ownership for DAC with CO_2 utilisation

BM 5: DAC Storage explores the deployment of direct air capture units (a) for geological storage of CO_2 (b) (see Figure 10). It is expected that such companies will not have the expertise to operate their own offshore CO_2 transport and storage; thus, the revenue from carbon storage will be shared between the capture and storage companies.

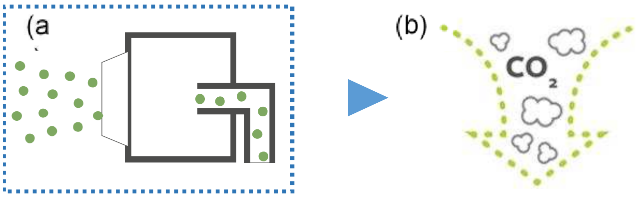


Figure 10: Diagram of value chain business ownership for DAC with geological storage of CO_2

BM 6: Decentralised Pyrolysis assesses the implementation of small-scale, distributed pyrolysis units (a) located at the source of waste biomass production - in this case farms to utilise straw and wood residue (see Figure 11). This enables farmers to produce biochar that is applied to soil on their land at zero feedstock and transport cost. Bio-oil and syngas co-products are used for on-site electricity generation and consumption, though an efficiency penalty is incurred due to the small size of the units.

Revenue is obtained through carbon storage credit received, as well as agricultural lime CPF cost avoided from biochar replacement. Additionally, electricity generated results in further avoided cost for the business, displacing the purchase of electricity at the retail price.

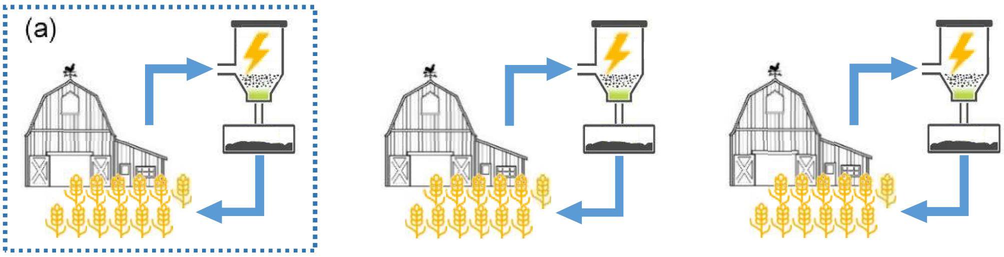


Figure 11: Diagram of value chain business ownership for decentralised pyrolysis on-site electricity and biochar production

BM 7: Pyrolysis & Electricity provides an alternative approach, whereby larger, centralised and independently owned units (c) export electricity to the national grid (d). Farmers (a) will utilize transport assets (b) to supply biomass feedstock to the strategically located plant, and return with biochar produced (see Figure 12). This business model enables similar revenue capture to the decentralized model; however, extra revenue will be gained from the sale of biochar to farmers. Furthermore, only a fraction of the carbon storage credit received by farmers at the point of application is shared with the pyrolysis plant owner.

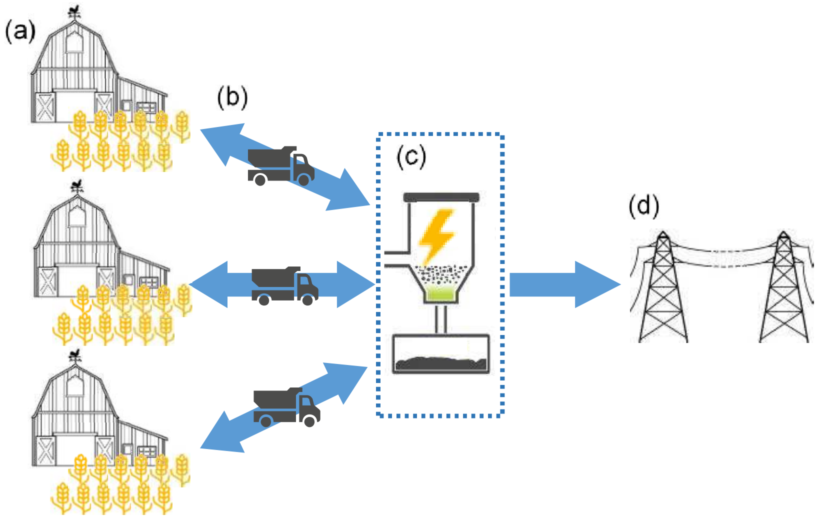


Figure 12: Diagram of value chain business ownership for pyrolysis electricity and biochar production

BM 8: Pyrolysis & Biofuels sells the co-product of bio-oil to produce biofuel, rather than producing electricity. This is likely to require fewer, larger pyrolysis plants to improve economic efficiency. Bio-oil is anticipated to be sold to a separately owned biorefinery (d) to produce biofuels, with the price of bio-oil determined by the difference between the biorefinery process cost and the biofuel price (see Figure 13). As observed in BM 7: Pyrolysis & Electricity, this is complemented by revenue captured from the sale of biochar and the incorporated carbon storage credit.

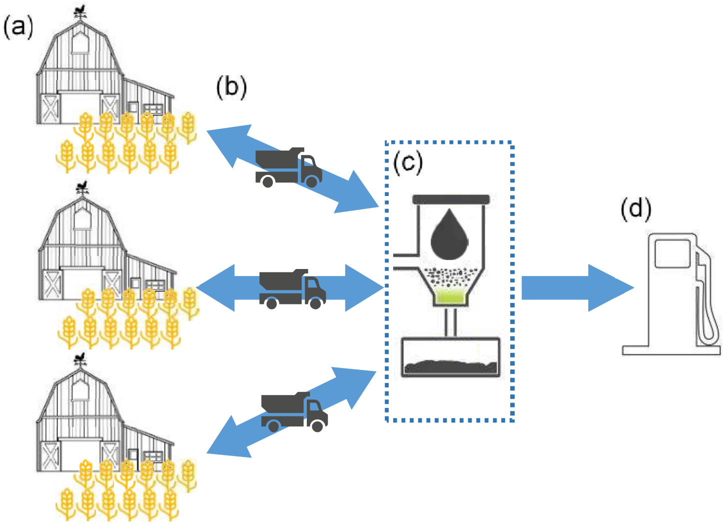


Figure 13: Diagram of value chain business ownership for pyrolysis oil and biochar production

BM 9: Sustainably Managed Afforestation explores the value capture potential for afforestation, proceeded by sustainable forest management of new woodland (a). Forest owners are able capture revenue from carbon storage credits, ecosystem services payment, and wood timber processed and sold for construction material (b) (see Figure 14). It is assumed that land afforested was previously grade 3-5 grassland for livestock and fallow, as categorised by the DECC 2050 model. Sustainably managed afforestation integration into other BMAs will also be able to benefit from the same revenue capture.

Figure 14: Diagram of value chain business ownership for sustainably managed afforestation

Value Pool – Business Model Relationship

Analysis of Table 3 shows that the VI BECCS business model enables revenue from the greatest number of value pools, while DAC Storage gains revenue from the fewest. Given that all business models resulting in net removal of CO_2 access the Carbon Storage value pool, this represents the most commonly accessed value pool, followed by the Electricity Market. This emphasises the importance of access to these revenue streams for the GGR sector.

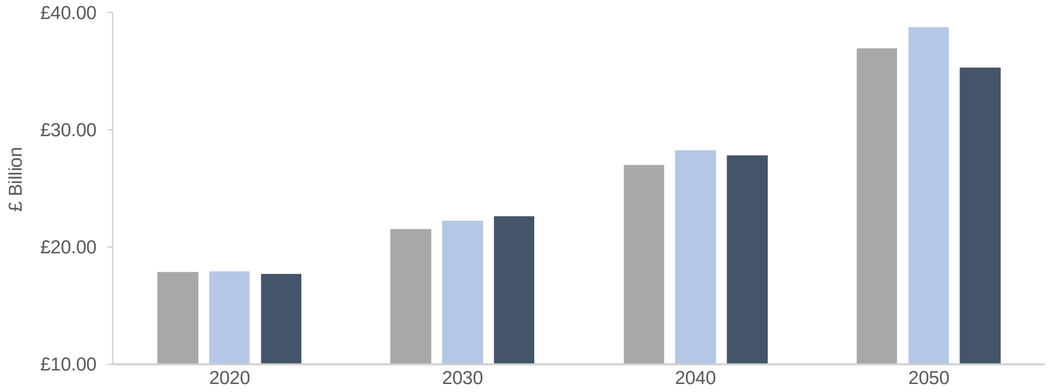
Table 3: Summary of value pools accessible by each business model.

	VP 1: Carbon Storage	VP 2: EOR	VP 3: Glass-houses	VP 4: Carbonated Beverages	VP 5: Wood Construction	VP 6: Biochar	VP 7: Ecosystem Payment	VP 8: Electricity Market	VP 9: Biofuels
BM 1: VI BECCS	✓	✓			✓		✓	✓	
BM 2: BECCS & EOR	✓	✓						✓	
BM 3: CCS Hub	✓	✓							
BM 4: DAC Utilisation			✓	✓					
BM 5: DAC Storage	✓								
BM 6: Decentralised Pyrolysis	✓					✓		✓	
BM 7: Pyrolysis & Electricity	✓					✓		✓	
BM 8: Pyrolysis & Biofuels	✓					✓			✓
BM 9: Afforestation	✓				✓		✓		

3. Results

3.1. Value Pool Analysis

The cumulative value accessible by GGR value chains in each pathway modelled totalled £35.3bn to £38.8bn in 2050, with the Distributed Biomass pathway exhibiting the highest potential value (see Figure 15). More than 99% of value originates from revenue potential, with costs avoided accounting for less than 1% of the total. The low avoided cost may be attributed to the undeveloped markets and business models analysed, resulting in less cost avoided than in established value chains.



	2020	2030	2040	2050
■ BECCS-focus	£17.88	£21.53	£27.00	£36.94
■ Distributed Biomass	£17.92	£22.26	£28.28	£38.75
■ DAC	£17.70	£22.61	£27.84	£35.31

Figure 15: Graph displaying cumulative value pool size in different pathways

The relative contribution of each value pool to the total identified varies substantially by pathway (Figure 15). Analysis of the 2050 results, exhibited in Figure 16, shows that:

- Electricity generation is the largest value pool by a significant margin across all pathways, at £26bn to £27.3bn in 2050. Electricity generation combined with carbon storage credits and biofuels constitute more than 95% of revenue opportunity across all pathways. Note, this is the size of the entire market, not what GGR business models can realistically capture which is the focus of the following section;
- BECCS-focus and DAC-focus pathways rely almost entirely on these three value pools;
- The Distributed Biomass pathway sees growth in the biochar market to a notable proportion of the total value at £1.5bn;
- CO_2 EOR provides 6% to 46% of other value in 2040, but declines to zero in 2050; and
- The carbonated beverages market contributes less than 1% of other value.

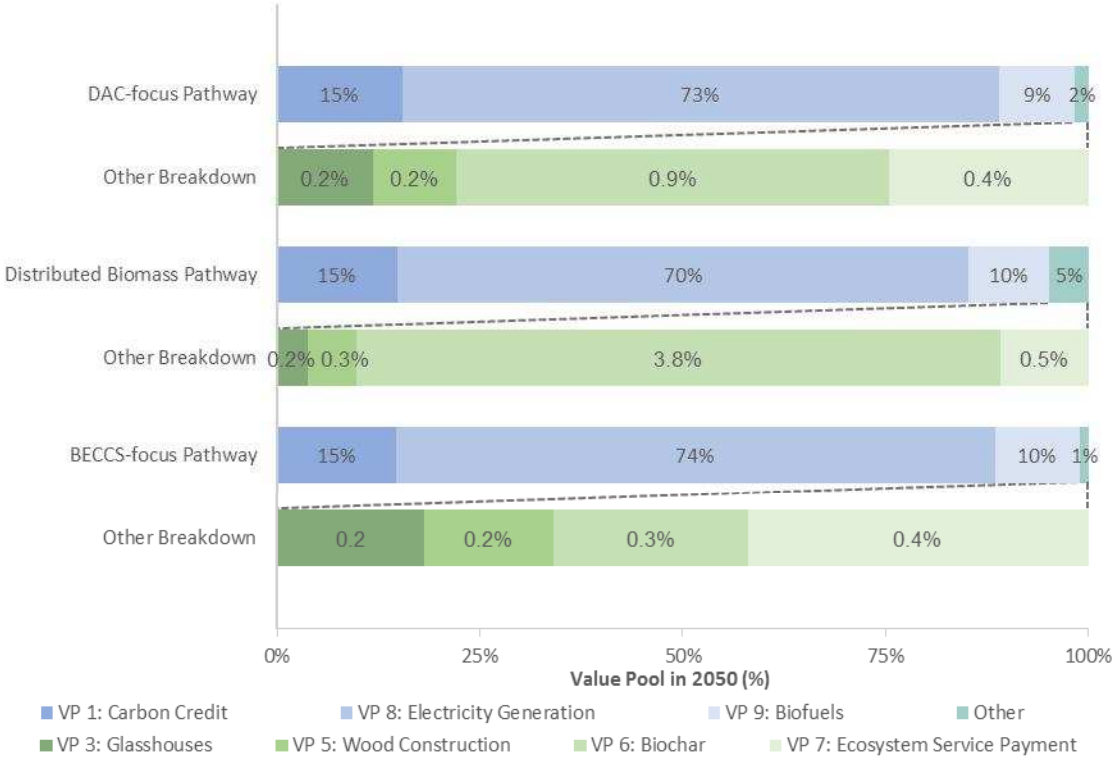


Figure 16: Summary of value pools as a proportion of cumulative value in 2050

The summary SWOT analysis undertaken by the authors based on the outputs of this research in Table 4 **Error! Reference source not found.**underlines that while considerably large value pool potential is possible (figure 15) - and in some cases already established - most markets will require substantial policy development to fulfill their potential (e.g. wood construction, CO_2 EOR) or to create a new mechanism for payment (e.g. Carbon Storage Credit, Ecosystem Services Payment). However, the pathways developed show that most value pools analysed are relatively resilient if GGR receives policy support. Despite perceived scenario resilience in this model, the transition to zero marginal cost electricity and distributed generation may evolve - how the value of electricity generation might be realised through innovative business models remains an open question. The potential for this to affect electricity generation revenue is not accounted for in this model, but the reliance on a sector going through a period of uncertainty is highlighted.

Those markets already viable represent the best targets for ‘first-mover’ GGR businesses, as well as policymakers looking for established markets and environmental credit mechanisms to enable GGR development. For example, the dominance of the wholesale electricity value pool, and the existence of familiar electricity generation credit and taxation measures in Feed in Tariffs, and carbon pricing, mean amendments to existing policy packages to allow GGR development may be the most administratively efficient and transaction cost reducing way of developing GGR business models.

Table 4: Summary of value pool performance and Strength, Weakness, Opportunities and Threat (SWOT) analysis across the different scenarios in the context of policy support required, present viability and resilience in different scenarios. Assessment undertaken by authors.

Value Pools	Sc. 1 Rank	Sc. 2 Rank	Sc. 3 Rank	Strengths / Opportunities	Weaknesses / Threats	Policy Support	Current Viability	Scenario Resilience
Carbon Storage Credit	2	2	2	Carbon Price Floor collaboration	Policy absence, Carbon accounting	🔴	🔴	🟢
CO_2 EOR	4 (2040)	7 (2040)	4 (2040)	Established industry in N. Sea	Short time window, Life Cycle Assessment emissions	🔴	🟡	🟡
Glasshouses	6	8	7	Established market	No growth potential, No CO_2 storage	🔴	🟢	🟢
Carbonated Beverages	9	9	9	Established market	Small market size, No CO_2 Storage	🔴	🟢	🟢
Wood Construction	8	6	8	New house building program required in UK, Faster construction	Insurance & mortgage market, Public perception	🔴	🟡	🟡
Biochar	6	4	5	Several potential benefits	Poorly quantified impact	🔴	🔴	🔴
Ecosystem Services Payment	5	5	6	Simple & low cost, Potential insurance company investment	Policy absence, Quantifying difficulty, Public perception	🔴	🔴	🟢
Electricity Generation	1	1	1	Developed market, New generation requirement	Transition period	🟡	🟢	🟢
Biofuels	3	3	3	Already large market (non-slow pyrolysis)	Air pollution, Market competition	🟢	🟢	🟡

Key:
Sc. 1 Rank = Value pool rank represents highest revenue generating year comparison (2040 for CO_2 EOR, 2050 for all others) for each of the three scenarios in Table 2. Sc. 1 - BECCS-focus pathway | Sc. 2 - Distributed Biomass Pathway | Sc. 3 – DAC-focus pathway.

Strengths / Opportunities and Weaknesses / Threats - are the salient upside and downside to risks relevant to each Value pool.

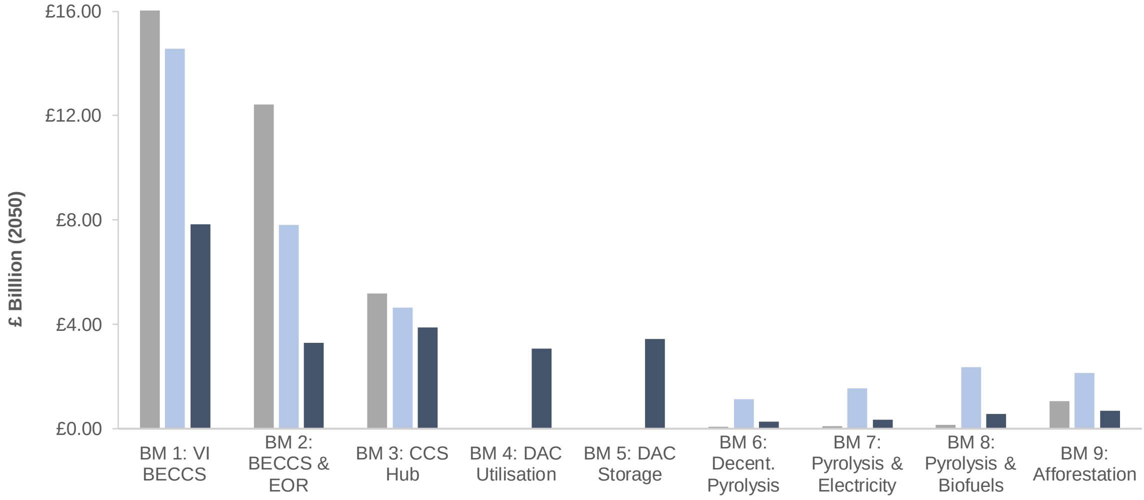
Colour Code assessment for **policy support** required for those value pools to be realised, their **current viability** based on the present policy framework and performance in different scenarios - **scenario resilience**: Green - No concerns | Yellow – Moderate concerns | Red - Significant concerns.

3.2. Business Models Analysis

Revenue capture by GGR business models showed varied performance throughout future pathways. Analysis of the results in 2050, as observed in Figure 17, highlights that:

- BM 1: VI BECCS achieves the highest value capture potential in all scenarios, resulting from the number of value pools accessed;
- BECCS related business models can achieve far higher value capture than through other technologies;
- Pyrolysis achieves the highest revenue capture through accessing the biofuels market; and

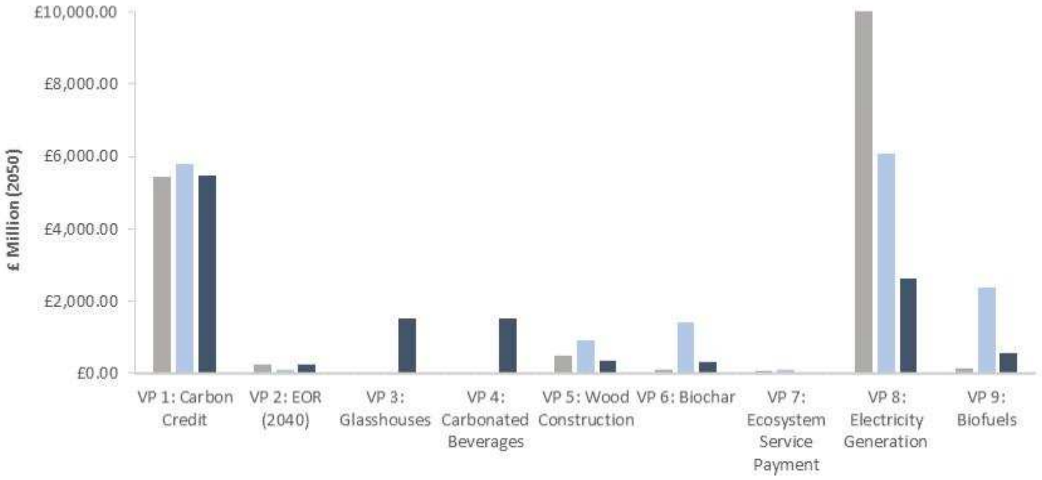
- Sustainably managed afforestation can achieve substantial value capture, either as a standalone business model or by integration into other activities.



	BM 1: VI BECCS	BM 2: BECCS & EOR	BM 3: CCS Hub	BM 4: DAC Utilisation	BM 5: DAC Storage	BM 6: Decent. Pyrolysis	BM 7: Pyrolysis & Electricity	BM 8: Pyrolysis & Biofuels	BM 9: Afforestation
■ BECCS-focus	£18.64	£12.43	£5.17	£0.00	£0.00	£0.07	£0.10	£0.14	£1.05
■ Distributed Biomass	£14.57	£7.81	£4.65	£0.00	£0.00	£1.14	£1.56	£2.35	£2.13
■ DAC-focus	£7.84	£3.28	£3.87	£3.06	£3.45	£0.26	£0.34	£0.55	£0.69

Figure 17: Graph displaying business model revenue capture in 2050 for different pathways.

The effect of the DAC-focus on the total value capture is evident in Figure 18, where overall value captured in relation to total value pool size is almost 10% lower than in other pathways analysed. This also underlines that as well as being the largest value pools, Carbon Credits and Electricity Generation provide the largest proportion of business model revenue.



	VP 1: Carbon Credit	VP 2: EOR (2040)	VP 3: Glasshouses	VP 4: Carbonated Beverages	VP 5: Wood Construction	VP 6: Biochar	VP 7: Ecosystem Service Payment	VP 8: Electricity Generation	VP 9: Biofuels	Overall Value Capture (%)
■ BECCS-focus	100%	100%	1%	59%	100%	95%	29%	37%	4%	**44%**
■ Distributed Biomass	100%	100%	1%	59%	100%	95%	43%	22%	61%	**43%**
■ DAC Focus	100%	100%	100%	100%	100%	95%	21%	10%	17%	**35%**

Figure 18: Graph showing value capture potential from each value pool in 2050. Table also displays (in bold) percentage of total value pool size captured for each pathway by the business models proposed.

The summary SWOT analysis undertaken by the authors based on the outputs of this research can be found in analysis in Table 5 highlights that whilst a similarly high policy risk exists to success for GGR business models, as for the value pools, there is additional uncertainty as a function of the lack of resilience present for these business models in different futures. This outcome from the model is likely a reflection of absent direction and UK strategy, which translates to greater uncertainty and risk for any potential business development and investors.

Table 5: Summary of business model performance and Strength, Weakness, Opportunities and Threat (SWOT) analysis across the different scenarios in the context of policy support required, present viability and resilience in different scenarios. Assessment undertaken by authors.

Business Models	**Sc. 1 Rank**	**Sc. 2 Rank**	**Sc. 3 Rank**	**Strengths / Opportunities**	**Weaknesses / Threats**	**Policy Support**	**Current Viability**	**Scenario Resilience**
VI BECCS	1	1	1	Other CO_2 sources transport revenue, Feedstock integration	High upfront cost	🔴	🟡	🟡
BECCS & EOR	3	3	4	Retrofit stranded assets, Contract for Difference & capacity market	Feedstock security, CO_2 supply security	🔴	🔴	🟡
CCS Hub	2	2	2	Efficient operation, Monopoly of market	High upfront cost, Significant degree of risk	🔴	🔴	🟢
DAC Utilisation	8	8	5	Few barriers to utilisation	Technology cost, Early development	🔴	🔴	🔴
DAC Storage	9	9	3	Can transition from utilisation to storage	Technology cost, One value pool accessed	🔴	🔴	🔴
Decentralised Pyrolysis	7	7	9	mature technology at small scale,	Electrical efficiency & load factor	🔴	🟡	🔴
Pyrolysis & Electricity	6	6	8	Higher efficiency generation	Large-scale pyrolysis less developed	🔴	🟡	🔴
Pyrolysis & Biofuels	5	4	7	Diverse revenue stream	pyrolysis oil issues, biofuel competition	🔴	🔴	🔴
Sustainably Managed Afforestation	4	5	6	Low cost & simple, Woodland Carbon Code	Land use requirement	🟡	🟢	🟢

Key:
Sc. 1 Rank = Business model ranked by 2050 results for each of the three scenarios in Table 2. Sc. 1 - BECCS-focus pathway | Sc. 2 - Distributed Biomass Pathway | Sc. 3 - DAC-focus pathway.

Strengths / Opportunities and Weaknesses / Threats - are the salient upside and downside to risks relevant to each business model.

Colour Code assessment for **policy support** required for those business models to be realised, their **current viability** based on the present policy framework and performance in different scenarios - **scenario resilience**: Green - No concerns | Yellow – Moderate concerns | Red - Significant concerns.

4. Discussion: Finding Solutions to the GGR Policy & Regulation Gap

Through the bottom-up approach taken in this research, it has been possible to highlight the substantial value accessible through GGR business models. Furthermore, this method has drawn attention to key areas of policy and regulation which will require development to enable this value to be realised through commercial delivery.

4.1. The Carbon Price Floor to a Carbon Storage Credit

The carbon price floor (CPF) system was introduced into the UK as part of a wider Energy Market Reform package. This package also included renewable energy subsidies and availability payments for flexible capacity in a capacity mechanism. It is therefore directly within the purview of UK energy policy to introduce carbon pricing for industrial/power system processes. There is no reason to suggest a positive carbon price (i.e. a payment) cannot be made to industrial operators that sequester as opposed to omitting carbon dioxide.

We have assumed this positive carbon pricing in our analysis and it is this payment that substantially expands the value pools available to negative emission business models. We applied the Committee on Climate Change's expected carbon prices to this reverse 'carbon payments' mechanism. current UK government policy is to freeze the CPF at £18/tCO_2 until 2021 (Delebarre, 2016). This has introduced policy risk for potential investors and resulted in further disparity between the expected market carbon price in the UK and the target consistent value.

While there is uncertainty over UK carbon pricing in the near term, using the Committee on Climate Change's expected carbon prices remains a conservative estimate of carbon price value pools as the higher 'target consistent values' were not used. If the carbon price were to be directly converted into a carbon storage mechanism by mirroring the taxation price with an identical credit per tonne of sequestered carbon; this carbon storage credit constitutes the second largest value pool accessible in the model, therefore its introduction in a functional manner is imperative to realising the value pool to GGR business models. In this study, each GGR technology obtains a different sized credit for the removal and storage of CO_2, depending on the life cycle assessment of negative emissions achieved. Businesses in the GGR value chain can exchange one credit (1 tCO_2 net sequestered) for a payment that is equal to the CPF, in a system that functions in a similar and familiar fashion. This system provides GGR businesses with a predictable revenue stream, which is protected from the uncertainty inherent in cap and trade systems. Currently, the Climate Change Levy (CCL), including the Carbon Price Floor, is forecast to obtain a consistent income of approximately £2.2bn per year to 2020 (Delebarre, 2016), which outweighs the carbon storage credit revenue per year projected up to 2030 in all pathways analysed (£1bn – £1.6bn). Therefore, a system whereby the CPF applied to polluters provides the funding for the carbon storage revenue may be suitable up to and beyond 2030, though this would require more hypothecation CPF taxation than is currently the case. The revenue potentials in the electricity wholesale market are presented in this model without credit. It would also have been possible to envisage a negative carbon credit mechanism for electricity generated by the GGR BMA's. However, given the benefits of predictability of a carbon storage credit, it's accessibility by non-electricity generating GGR business models, and the uncertainty surrounding electricity wholesale prices in the medium to long term, the carbon storage credit approach avoids systemic risk by separating the public good of carbon sequestration from the private good of wholesale electricity.

4.2. Regulating Biomass Resource Consumption to ensuring Sustainability

The model to generate the scenarios in this research anticipates 50 - 90% of biomass for CCS will be imported. This work re-iterates the potential issues related to use of unsustainable biomass and land management practices for GGR technologies which have been highlighted in the literature (e.g. Committee on Climate Change, 2011). The UK government's commitment to defining sustainable biomass resource available to the UK in its response to the Committee on Climate Change is a key development. However, implementing regulation will be required to avoid unsustainable consumption of biomass. This may include reducing the incentives for imported biomass use in GGR, based on higher life cycle emissions and unsustainable resourcing. Furthermore, only biomass with adequate certification for sustainable harvesting should be used, given the wide variability in biomass emissions based on forestry practise (Brown *et al,* 1995).

4.3. Prompt policy development to execute a CCS hub strategy in the North Sea

The work strongly suggests that prompt policy development is required to prevent missing the CO_2 EOR value pool window identified in the UK (Energy Research Partnership, 2015). The UK EOR Value Pool opportunity is based on the exploitation of fields in the mature North Sea Basin Oil Play by the establishment of a CCS CO2 transport hub - as articulated in Value Pool 3 - section 2.3 and in Business Model 2 - section 2.4. This may include re-introduction of funding for the CCS, specifically for co-fired or fully BECCS plants to provide GGR support.

Most significantly, the CCS Hub would provide opportunity for development of the most substantial GGR opportunities in that it underpins the value chains of a number of the more resilient BMAs which also capture the most revenue - Figure 18. It also allows other value pools to be developed with greater confidence in the knowledge that BMAs will be able to scale rapidly in the certainty that they will be able to access to an already established CCS network and substantial permanent CO_2 sink (Caldecott et al., 2015).

4.4. Carbon Storage Monitoring, Reporting and Verifying

Monitoring, reporting and verifying (MRV) is a prominent issue throughout the GGR space, including the carbon storage credit system and incentivising efficiency. The Woodland Carbon Code (Forestry Commission, 2018) has been identified as an exemplar method of MRV. This code of practise encourages a consistent approach to woodland carbon projects and carbon accounting, as well as achieving transparency and clarity by using independent verification of carbon sequestered in forests (Forestry Commission, 2017). It is suggested that this code be made compulsory for all forestry.

While other GGR sectors have additional, specific complexities that will require tailored MRV codes, the fundamental elements of the Woodland Carbon Code, of independent verification and consistent carbon accounting, may be replicated. Suggestions for geological storage are for collection of data at the point where CO_2 enters the transport stage, the point of injection underground, and continued monitoring of the sub-surface for leakage. Soil carbon storage via biochar prevents a greater to challenge to monitoring beyond the production and application stages, therefore a unique plan to account for dispersion out of soil must be developed.

4.5. Potential Future Investment Pools

Areas of the transport industry, such as aviation and shipping, represent some of the most difficult sectors to decarbonise. This presents an opportunity to access potential investment from the substantial profit-making incumbents in these sectors, who may want to maintain their business longevity through making their transition to a less carbon-intensive business model in a timeframe less disruptive to their investment cycles.

Another potential investment source is the insurance industry. Expected annual damage to properties by river and tidal flooding is estimated at £1.2bn for 2012, rising to £1.6-6.8bn in 2050 (Ramsbottom *et al.*, 2012). Furthermore, the number of properties at risk of flooding is expected to rise from 0.56 million to 0.8-2.1 million during the same period (Ramsbottom *et al.*, 2012). These figures are substantially larger than the ecosystem services payment quantified for flood reduction, and may act as an incentive to insurance companies to invest in the implementation of such schemes.

5. Conclusions

The recent announcement of the NERC £8.6 million programme for GGR research indicates a commitment from the UK towards including GGR technologies in future climate strategy. Further research is crucial, given that many GGR technologies remain in early development. However, to scale development will require insights relevant to private sector actors and commercial delivery mechanisms, as a force for technological advancement and increased deployment in the GGR sector.

The work has resulted in the following empirical findings:

- Total value capture potential is highest in a Distributed Biomass GGR pathway, in comparison to single technology focused approaches. This supports a portfolio approach to GGR development, with diverse biomass resource use. It also mitigates the reliance on a single technology such as BECCS which dominates current GGR modelling (IPCC, 2014).
- Electricity generation and carbon storage credit value pools present the most significant revenue capture potential. While, these larger revenue streams are somewhat uncertain, they place the onus on energy policy for the short to medium term development of a GGR economy in the UK.
- Carbon utilisation value pools are comparatively small by 2050, suggesting that opportunities provided by 'bridging markets' (glasshouses, carbonated beverages, CO_2 EOR) only have a niche role in advancing negative emissions.
- Sustainably managed afforestation provides a low cost, simple, high return option – thus presenting an attractive opportunity, as a stand-alone business or via integration into BECCS and pyrolysis business models to avoid costs and increase revenue.

A strategic level summary of this work, observed in Figure 19, concludes that without the creation of a dedicated GGR technology development strategy, as well as integration into the UK's existing energy policy framework, the risk for commercial developers is too substantial, and policy barriers too significant for value capture to be realised at present. This has consequential knock on implications for the optimisation of the allocation of biomass in the UK energy mix to 2050 and highlights the need for greater innovation effort for the decarbonisation of other sectors of the UK economy

This novel method assists in clarifying what is needed to realise these value chains and therefore the subsequent effect on broader UK energy innovation policy.

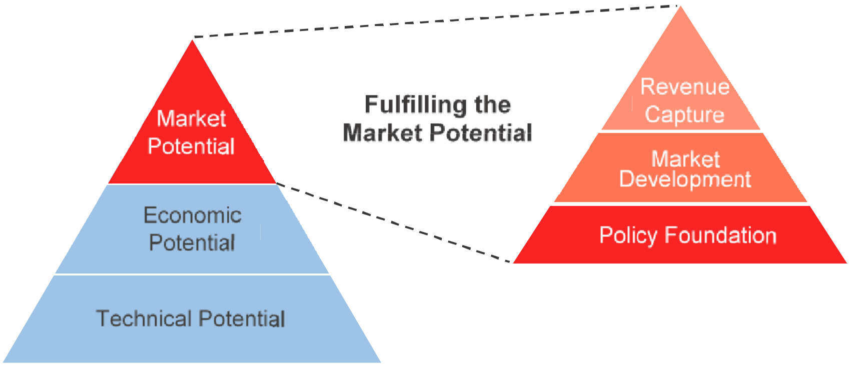


Figure 19: Graphic showing a breakdown of the stages to fulfilling the market potential outlined in the research.

6. Assessment of Method and Opportunities for Further Work beyond the UK

Finally, applying the research method of value pool modelling approach (Wegner et al., 2017) to the GGR sector has proved to be highly successful. The value pool modelling approach was undertaken due to its ability to rectify the over reliance on cost-benefit data being produced in present GGR research. The revenue-centric data generated provides better insights into possible business models by the reframing of decision-making by policymakers towards commercial opportunity and market development, rather than cost and current technical readiness. Furthermore, the data generated will enable the investment community to gain a better understanding of the revenue potential and risks associated in developing a UK GGR sector in possible future pathways. It is worth emphasising that this approach does not seek, nor claim, to offer highly precise valuations; this is in part due to poor data availability and a significant degree of uncertainty in novel pathway development. Instead, the value pool model enables a high-level comparative assessment of outputs, which are of adequate accuracy to inform decision making for both policy and investment communities in order to stimulate development of this technology (Lomax et al., 2015).

As stated in section 1.6, the method highlights only the financial opportunities available and the likely ability for business models to maintain financial viability for a limited number of value pools. There is considerable need for further work to be undertaken to better understand the commercial risks that commercial developers of GGR value chains would face – these include but are not limited to:

- Sensitivity analysis around the impact of different variables which make-up the value pools that business models can access and the impacts of new policies being enacted e.g. 45Q initiative in the US whereby \$50 per tonne is available for permanently sequestered CO_2 and \$35 per tonne is available for CO_2 which is utilised;

- The maturity of the technological dimensions needed to realise the business models across a broader range of GGR technologies and value chains;
- The policy / regulatory risks to allow the business models to operate and access the revenues identified both in the UK and in other national jurisdictions;
- The scale and interaction of the markets that are available for negative emissions generation which GGR commercial developers might be able to exploit and the extent to which negative emissions are needed to attain national and international carbon budgets; and
- Most importantly assessment of the willingness of actors to purchase products and services which might be forthcoming from GGR value chains.

All of these aspects would be an important requirement in better assessing the risks that GGR business models face and the robustness of the revenue streams which they would seek to access. These themes would require a substantial research effort, building on the analysis undertaken in this paper and are considered important for future work to generate greater understanding of the commercial risks and uncertainty that this potentially game-changing but little understood and as yet commercially untested technology.

Acknowledgements

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at [link to MS Excel Spreadsheet Model]

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Supplementary File

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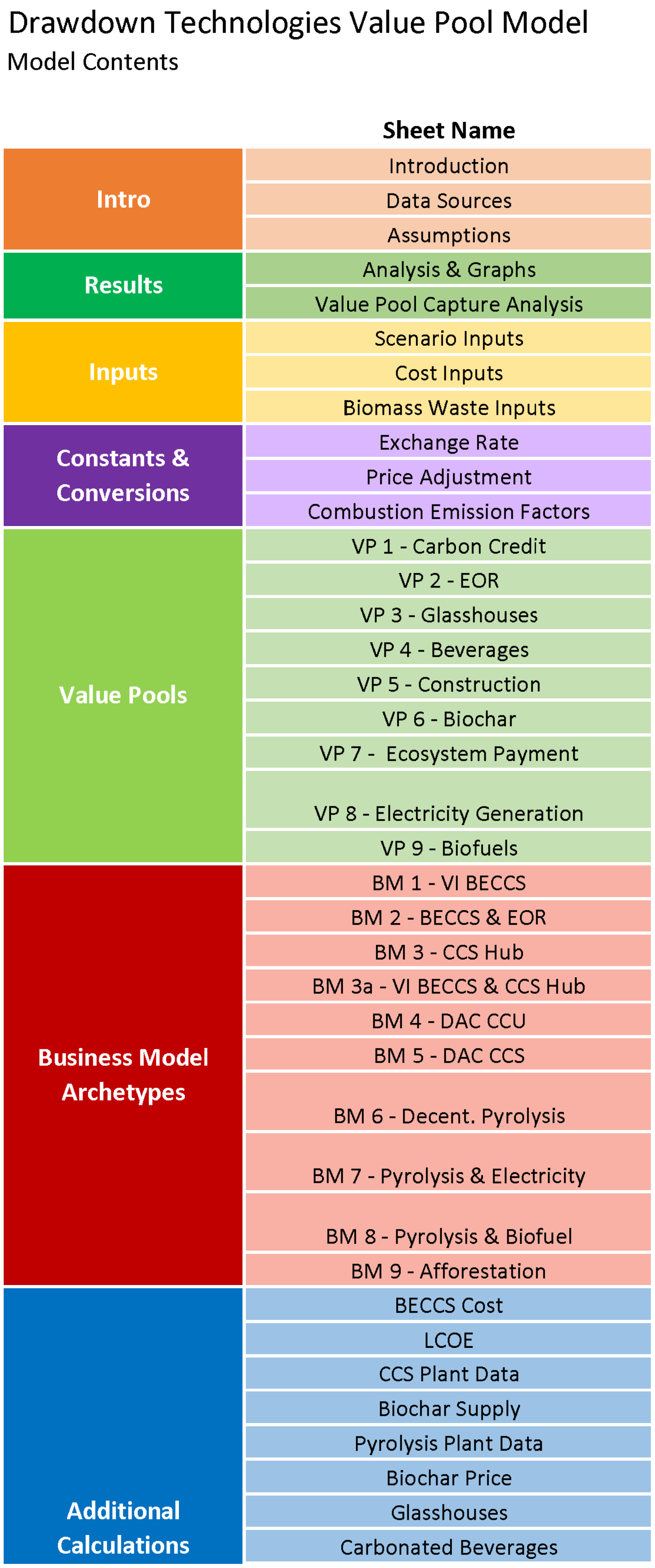

Drawdown Technologies Value Pool Model

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