UK Energy Research Centre

Biomass, afforestation and energy demand reduction: trade-offs in the route to decarbonisation

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Summary

- This paper tests the sensitivity of energy system decarbonisation pathways to the role of afforestation and reduced energy demands.
- Based on core assumptions, the model was unable to find a solution for a 1.5°C target.
- Large-scale afforestation (instead of energy crops) and reduced energy demands each reduced the CO_2 budget exceedance but both were required to allow the model to meet the 1.5°C target.
- Under the 2°C target, afforestation reduced the reliance on BECCS by 60%. Under the 1.5°C target, the system still used all of the biomass available.
- Given its key role, afforestation should be considered more in deep decarbonisation scenarios, as should lower demand scenarios.
- Further work should focus on factors affecting the carbon sequestration potential of afforestation, along with an interdisciplinary research agenda on the scope for large energy demand reductions.

Introduction

The stringency of climate mitigation targets set out in the Paris Agreement has placed strong emphasis on the role of carbon dioxide removal (CDR) over this century. Integrated Assessment Models (IAM) are used to examine pathways for decarbonisation of the energy system and wider economy, accounting for technological and societal change, behaviour of elements of the earth system and the use of CDR.

IAM scenarios consistently indicate that CDR is critical to achieving the long-term climate objectives of limiting the global temperature rise to 1.5°C or 2°C (Fuss et *al.* 2014, Rogelj et *al.* 2018). However, there are large uncertainties around the techno-economic viability and the environmental and social sustainability of large-scale carbon dioxide removal (CDR) (Smith et *al.* 2016, Anderson & Peters 2016). These are particularly significant for the key CDR options of bioenergy with carbon capture and storage (BECCS) (Vaughan & Gough 2016) and forestry (Brown et *al.* 2019). Furthermore, there may be trade-offs between BECCS and forest-mitigation due to their land-use requirements. The land-use emissions balance of these two options, as well as wider biodiversity and social impacts, lead many to warn against large upscaling of bioenergy, in favour of land-use for expanded forests (Roe et *al.*, 2017; Food and Land Use Coalition, 2019). A key driver of the level of CDR required is the size of the energy system and central scenarios of socio-economic development over the next century see a world with ever-increasing energy requirements (Riahi et *al.*, 2017). Uncertainty over the availability of biomass warrants further consideration of its role in decarbonisation pathways, alongside the degree to which demand reduction could reduce the requirement for NETs (van Vuuren et *al.* 2018, Grubler et *al.* 2018).

To support the Committee on Climate Change report *Net zero - The UK's contribution to stopping global warming* (CCC, 2019), the energy system model TIAM-UCL has been used to examine global decarbonisation pathways consistent with Paris Agreement goals. The research focuses on the potential for the UK and other developed countries to implement more rapid emissions reductions (Pye et *al.*, 2019). This UKERC briefing paper examines the sensitivity of these pathways to two key uncertainties: the allocation of land for bioenergy and afforestation, and future energy demand.

> **“Doubt over the viability of large-scale CDR has prompted a renewed examination of the extent to which the need for them can be offset by lowering demand.”**

BECCS (biomass for biofuel and hydrogen production, and heat and power generation, combined with carbon capture and storage) and forestry-based mitigation through avoided deforestation, reforestation and afforestation are two of the most promising land-based options for CDR (Smith et *al.* 2016, Fuss et *al.* 2018)[1]. IAM scenarios reviewed in the Intergovernmental Panel on Climate Change (IPPC) 5th Assessment Report and Special Report on 1.5 Degrees consistently indicate large roles for these CDR options (Huppmann et *al.* 2018). In scenarios consistent with the 2°C target, BECCS sequesters a median of 3.3 $GtCO_2$/yr by 2100, which requires 380-700 Mha of crop land globally (Harper

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[1] Reforestation refers to the restoration of degraded forest areas, while afforestation refers to the establishment of forest on land which was not recently forested.

[2] For reference, crop land currently covers approximately 1,600 Mha globally (Goldewijk et *al.*, 2017).

et al., 2018)[2]. For those consistent with the 1.5°C target, BECCS sequesters a median of 6-15 $GtCO_2$/yr by 2100, depending on the degree to which the models are permitted to overshoot the 1.5°C limit, and re/afforested land sequesters a median of up to 11 $GtCO_2$/yr in 2050 and 5 $GtCO_2$/yr in 2100 (J. Rogelj et *al.*, 2018). However, there remains significant uncertainty on the potential scale of BECCS and re/afforestation, and the allocation of land between them.

The sensitivity tests described in this paper examine the roles of afforestation and reduced energy demands. The afforestation scenario is motivated by an interest in its potential as an alternative to large-scale BECCS, with its arguably lower risk supply chains, and multiple co-benefits (Griscom et *al.*, 2017). The lower demand scenario tests the prospect for demand-side action that could again reduce dependency on BECCS. The two sensitivities modelled together generate insights about the feasibility of deep emission reductions to limit warming to 1.5°C.

Key Uncertainties

Key uncertainties on the potential for BECCS to fulfil this critical carbon mitigation role arise from multiple factors including: the availability of land for dedicated energy crops; the yields that may be expected from abandoned or degraded land; costs associated with improving degraded land; the availability of residues from agriculture and forestry, considering the changing production intensity of these sectors and demands on the residues for alternative uses; the potential build rate and cost of CCS; reliability of sequestration methods; the net GHG emissions from a BECCS supply chain; and social acceptability (Searle and Malins, 2015; Anderson and Peters, 2016; Fajardy et *al.*, 2019).

Uncertainties regarding the potential mitigation role of reforestation and afforestation include the availability of unforested or degraded forest land, the success of policies to incentivise or regulate land-use and land-use change, and forest carbon sequestration rates, which are affected by factors including landscape characteristics, species mix, management practices and changing climatic conditions (Bernal et *al.*, 2018; Brown et *al.*, 2019). Recent research examining these uncertainties indicates that due to GHG emissions arising from land-use change, afforestation could provide more effective carbon sequestration than growing dedicated crops for BECCS, but the knock-on impacts on the energy system must be considered for a full evaluation (Harper et *al.*, 2018).

Potential pathways for regional energy demand span a wide range of scenarios, as illustrated by the Shared Socio-economic Pathways (SSPs) implemented in IAMs (Riahi et *al.*, 2017)[3]. Key socio-economic drivers are population, education, urbanization, and economic development. Future demands depend on social trends and institutional changes as well as technological development, the modelling of which remains an important research agenda and requires understanding from several perspectives (Grubler et *al.*, 2018).

Aerial view of a planted eucalyptus forest in Brazil

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[3] The SSPs map a set of plausible scenarios of major trends in order to explore how the global socio-economic system could develop out to 2100. They include key socio-economic drivers and represent a range of challenges for climate change mitigation and adaptation (Riahi et *al.*, 2017).

Balancing supply and demand

It is widely considered that reducing energy demand is a vital component of climate change mitigation, with policies including minimum energy performance standards, utility obligations and incentives being extended and strengthened (IEA, 2018). Challenges for the success of efficiency policies to reduce demand stem from both the technical and social dimensions, such as the need for behavioural interventions, the links between energy demand and economic growth and the complexity of rebound effects (Sorrell, 2015). Doubt over the viability of large-scale CDR has prompted a renewed examination of the extent to which the need for them can be offset by lowering global energy demand. So far, studies differ on whether deep demand reduction can remove the need for CDR in 1.5°C scenarios (Grubler et *al.*, 2018; J. Rogelj et *al.*, 2018; van Vuuren et *al.*, 2018). In the 'Low Energy Demand' scenario described by (Grubler et *al.*, 2018), global warming is limited to 1.5°C without the use of CDR with a pathway reflecting strong demand reduction. This is achieved through rapid urbanization, uptake of novel energy services, increasingly engaged end-users and rapid improvements in information technology. It results in a global final energy consumption of 245 EJ/yr in 2050, almost the lowest of the scenarios consistent with 1.5°C, which span approximately 222-570 EJ/yr (Huppmann et *al.*, 2018).

The scenarios explored by van Vuuren et al. (2018) indicated that lifestyle change accompanied by significant supply-side transformation such as rapid electrification, roll-out of renewable generation, and reduction of non-CO_2 greenhouse gases (GHGs) can significantly reduce the need for carbon dioxide removal but not fully eliminate it.

Method

TIAM-UCL Model

The TIMES Integrated Assessment Model at University College London (TIAM-UCL) is a technology-rich global optimisation model (Anandarajah et *al.*, 2011; McGlade and Ekins, 2015; Pye et *al.*, 2016; Price and Keppo, 2017). With perfect foresight over the modelling period and all decisions driven by a least cost objective, a cost-optimal energy system is designed that will meet future service demands within technical, economic and policy constraints. The model is driven by demands for 43 end-use services across five economic sectors: residential, commercial, industry, transport and agriculture. It characterises the transformation of primary resources to end-use energy services through conversion technologies (refineries, generation plants, transmission) and energy carriers (fuels and electricity). The world is represented as 16 geographic regions, between which energy commodities can be traded. Further details of the model set up and a detailed summary of the key assumptions are given in Pye et *al.* (2019). Key elements for this study are described in the following paragraphs, focusing on biomass and emissions associated with land-use, land-use-change and forestry (LULUCF).

Biomass feedstocks are represented as six primary resources in the model. First-generation fuels are represented as bioliquids (bioethanol and biodiesel from crops, which might compete with food crops for land) and biomethane (gas captured from controlled landfill sites). Primary feedstocks for second-generation technologies are represented as four fractions: solid biomass, energy crops, municipal solid waste and industrial waste. Only solid biomass and energy crops can be used for BECCS in the model; the waste fractions are used directly in the residential and industrial sectors.

Solid biomass represents woody agricultural and forest residues. Assumptions of future availability are based on spatial modelling of the theoretical available potential, with the biomass fractions required for maintenance of soil quality and other uses subtracted (Daioglou et *al.*, 2016). Cost assumptions include elements such as harvest, operations, storage and drying, forwarding, chipping and transport (Daioglou et *al.*, 2016). Availability assumptions for dedicated energy crops are based on regional modelling of 'abandoned agricultural land' (Ricardo Energy & Environment, 2017) and so assume no competition for land with food crops or pasture. The most degraded and water scarce land is excluded (see Pye et *al.* (2019) for more details and data references). The land considered available for bioenergy crops globally thereby totals 199 Mha in 2020, 207 Mha by 2050 and is assumed constant up to 2100. For reference, 207 Mha is equivalent to 24% the land area of Brazil. Typical yields for perennial energy crops are applied for each region and a 1.3% yearly yield increase is assumed. This figure was estimated based on historic yield increases and a business-as-usual scenario regarding globalisation and investment (Ricardo Energy & Environment, 2017).

CO_2 emissions associated with land-use change for energy crop cultivation are included in the model, while the other biomass fractions are assumed to produce no land-use change. Emissions coefficients are applied for CO_2, CH4 and N2O depending on how the biomass is used. It is estimated that approximately 5% of the biomass carbon content is lost during storage, drying and transport. Net CO_2 emissions associated with other land-use and land-use change are represented by an emissions pathway, which is an input to the TIAM model (Pye et *al.* 2019).

Core scenarios

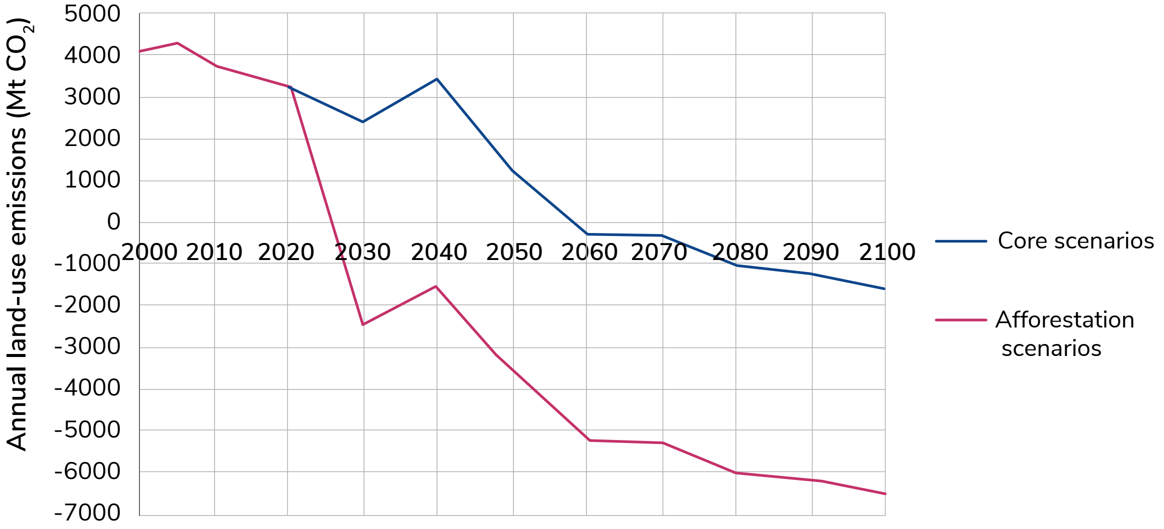
Two core scenarios are modelled, distinguished by their level of climate change mitigation ambition. Climate targets are modelled using global carbon budgets of 1170 and 420 $GtCO_2$ for a 66% probability of keeping the global mean surface temperature rise below 2°C and 1.5°C respectively. These are taken from the IPCC SR1.5 report (IPCC, 2018) and are defined from 2018 onwards. In addition, the model is constrained to meet the 2°C and 1.5°C targets in 2100 and ensure that the global temperature rise cannot overshoot 2°C at any point. The model allows for climate mitigation to occur from 2020 onwards, with earlier periods fixed to historical estimates.

In the core scenarios, future energy demands follow a pathway representing ‘middle of the road’ socio-economic development (SSP2).

Sensitivity tests

The first set of sensitivity tests explores the relative benefits of using abandoned agricultural land for bioenergy crops or afforestation. As noted by Harper et al (2018), the carbon balance of land-use for afforestation and bioenergy crops can be compared but the fossil fuel offsets in the energy system must also be considered in order to judge the relative benefits of each. For the afforestation case, it is assumed no dedicated energy crops are grown from 2025 onwards, and instead new forest is established on the abandoned land. Carbon dioxide removal rates for afforested land are derived for each geographic region from Bernal et *al.* (2018). The values, which range between 7.6 and 25.4 tCO_2/ha/yr, are applied to each region according to its most appropriate climatic description (boreal, temperate or tropical) and are assumed to be constant (see Pye et *al.*, 2019). The total annual CDR by the afforested land is calculated and subtracted from the pathway of land-use and land-use change emissions which is an input to the model (Pye et *al.*, 2019). These pathways are presented in Figure 1, showing land-use emissions are modelled as falling sharply, giving negative emissions from the start of the afforestation period. With these assumptions, afforestation sequesters 429 $GtCO_2$ over the period 2020-2100[4]. It is also assumed that residues could be extracted from this forestry by thinning trees, so while the availability of energy crops is assumed to be zero in the afforestation scenarios, the availability of solid biomass resource is slightly increased. A single residue retrieval factor of 16 PJ/Mha/yr is assumed. This is derived from data from a typical management regime of a southern Finnish forest stand, assuming clear cutting after 70 years (EUBIA; VTT[5]).

Figure 1: Global land-use CO_2 emissions for the core scenarios and afforestation sensitivity tests



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[4] This is consistent with the afforestation-based CDR in the 1.5C “Early CDR” pathway presented in Jia **et al.**, (2019) (Bertram **et al.**, 2015) and equivalent to approximately one third of the potential afforestation carbon stock calculated by Bastin **et al.** (2019). Estimates of the global mitigation potentials of forest expansion range from approximately 0.5 to 10 $GtCO_2$/yr (Arneth **et al.**, 2019).

[5] VTT Wood Energy Technology Programme, Finland, http://www.eubia.org/cms/wiki-biomass/biomass-resources/challenges-related-to-biomass/recovery-of-forest-residues/

The second set of sensitivity tests explores how lowering end-use energy service demand could reduce the size of the required energy system transformation by lowering the overall requirement for electricity, heat and fuels. For the low demand scenarios, energy service demands are driven by the regional population and GDP projections for SSP1, with calibration factors applied so that the final energy consumption falls within the plume of results from the IAMs for SSP1 (Riahi et *al.*, 2017). SSP1 characterises a future of green growth with high resource efficiency, sustainable production methods and investment in human development. For comparison, a scenario consistent with the SSP1 storyline and climate mitigation to 1.5°C results in a final energy consumption of approximately 424 EJ/yr in 2050, while the Low Energy Demand scenario presented by Grubler resulted in 245 EJ/yr (Grubler et *al.* 2018).

The third set of tests combines the low energy service demands with the higher afforestation assumptions to explore the extent to which lowering demand could trade-off with the use of CDR in stringent climate mitigation scenarios.

In summary, for each temperature limit, the model is tested with medium and low energy service demands and an allocation of the available land to either energy crops or afforestation: see Table 1. The resource potentials for each biomass fraction are summarized in Table 2. The global total primary biomass resource in 2050 is 112 EJ/yr in the energy crop scenarios and 100 EJ/yr in the afforestation scenarios.

Table 1: Scenario summary

Scenario		Warming limit in 2100	Global carbon budget (from 2018) $GtCO_2$	Demand level	Afforestation level
Core runs The carbon budget and 2100 warming level are limited to 2°C and 1.5°C	2C	2°C	1170	Medium	Low
	1.5C	1.5°C	420	Medium	Low
1. Afforestation As core but the land available for energy crops is instead used entirely for afforestation.	2C_Aff	2°C	1170	Medium	High
	1.5C_Aff	1.5°C	420	Medium	High
2. Low demand As core but the future energy service demands are in line with SSP1 rather than SSP2.	2C_LoDem	2°C	1170	Low	Low
	1.5C_LoDem	1.5°C	420	Low	Low
3. Combined: Low demand and afforestation As core with both the low demands and afforestation implemented.	2C_LoDem_Aff	2°C	1170	Low	High
		1.5°C	420	Low	High

Table 2: Biomass resources

Feedstock	Scenarios	Global potential (EJ/y)			
		2015	2030	2050	2100
Bioliquids	All	1.6	1.6	1.6	1.6
Biogas	All	8.0	8.0	8.0	8.0
MSW	All	9.9	12.3	19.1	20.3
Industrial	All	2.1	4.4	7.5	7.5
Solid biomass	Core and Low Demand	40.9	42.6	44.8	50.0
	Afforestation and Combined	40.9	44.1	48.0	52.7
Energy crops	Core and Low Demand	6.4	17.1	31.4	31.4
	Afforestation and Combined	6.4	0	0	0

Wood chip for pellet fuel

Results

Core runs

For full details of the core model runs and analysis of the potential for a high ambition coalition of regions to increase their rates of mitigation, see Pye et *al.* (2019). Key points relevant to the sensitivity tests described above are noted here.

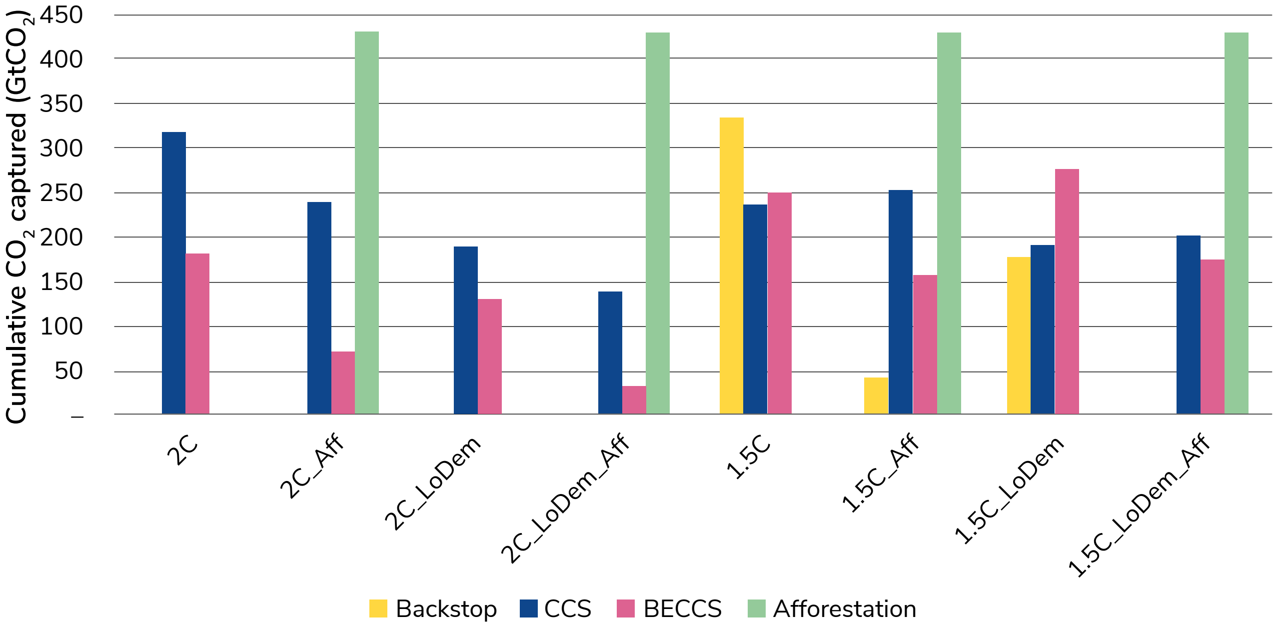
From the core scenarios with the assumptions used in this study, we find the model is not able to achieve the 1.5°C (66%) target without deploying a 'backstop' option, which is set to sequester CO_2 at a very high cost of $5000/ tCO_2. Reasons for why this is the case for TIAM-UCL but not other IAM scenarios is explained in Pye et *al.* (2019). The backstop does not represent a specific technology but is rather a modelling mechanism used to allow the model to solve even without sufficient mitigation options while representing the degree to which the global CO_2 budget is exceeded. Over the modelling period, the cumulative global budget of 420 $GtCO_2$ is exceeded by 332 $GtCO_2$. This is despite the model deploying substantial amounts of carbon removal by fossil fuel CCS and BECCS (9.3 $GtCO_2$ per year by 2100).

The capability of economic sectors to reduce their emissions varies significantly. Under the stringent 1.5°C climate target, by 2100 the agriculture sector becomes a carbon sink and residential and commercial buildings are completely decarbonised. However, emissions in industry, upstream and transport sectors are still 55%, 50% and 22% of their 2020 levels respectively, indicating these emissions are the most difficult to mitigate. In both core scenarios, there is a 6-fold increase in electricity generation between 2020 and 2100, primarily from solar and wind technologies. By 2055, no electricity is generated by fossil fuels without CCS in either core scenario.

Biomass use differs between the 2°C and 1.5°C core scenarios, indicating the pressure on the model to employ negative emissions in the energy system. Not all the available solid biomass and energy crops are used in the 2°C case but they are in the 1.5°C case. Under the 1.5°C case, total carbon capture is lower, but the capture with BECCS is higher, with the available biomass prioritised for use in BECCS. In the 2°C case, 496 $GtCO_2$ is captured between 2020 and 2100, of which 181 $GtCO_2$ is by BECCS, while in the 1.5°C case, 486 $GtCO_2$ is captured, of which 249 $GtCO_2$ is by BECCS, though an additional 332 $GtCO_2$ is also captured by the backstop. These figures are summarised for the core scenarios along with the sensitivity tests in Figure 2 (the sensitivity test cases are discussed later in this paper).

> **“The core model is not able to achieve the 1.5°C target… the global carbon budget of 420 GtCO2 is exceeded by 332 $GtCO_2$.”**

Figure 2: Cumulative CO_2 emissions captured 2020-2100



In the 2°C case, the marginal cost of CO_2 mitigation peaks at 435 $/t$CO_2$ around 2050, then falls to 214 $/t$CO_2$ in 2060, then plateaus (Figure 3). This indicates the large effort required to mitigate CO_2 sufficiently to avoid overshooting 2°C in the mid-century. Note, the marginal cost is not a useful indicator for the 1.5°C core case as this run required the backstop technology.

Under the 2°C target, geographic regions reduce their greenhouse gas emissions at different rates, according to their available technologies and demand assumptions. Under the 1.5°C target, almost all regions reach negative CO_2 emissions and net zero GHG emissions by 2080. Several developed regions achieve negative CO_2 emissions earlier (Canada by 2040, Japan and UK by 2045, Europe by 2050).

Sensitivity tests

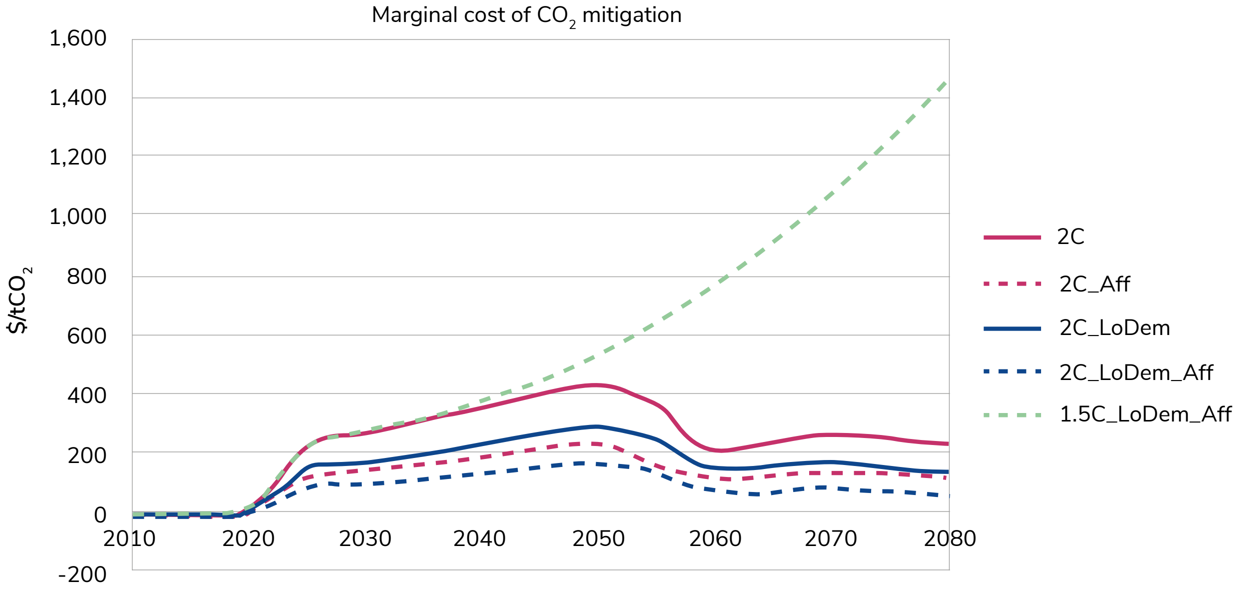
In this section, results are presented to show the sensitivity of these core scenarios to 1) afforestation, 2) lower demand and 3) lower demand and afforestation combined. The discussion focusses on the use of available bioenergy resources, the reliance on BECCS for carbon capture, changes in the global fuel mix and the marginal costs of mitigation.

Test 1: Afforestation

As mentioned above, in the core scenarios the mitigation options in the model are sufficient to stay within the 2°C limit but the model is not able to stay within the 1.5°C limit. When high afforestation is assumed on the abandoned land instead of energy crops, a higher level of CDR is achieved (5 GtCO_2/yr) than from BECCS in the core scenario (4 GtCO_2/yr). However, this large-scale afforestation is not quite sufficient to allow the 1.5°C case to solve without the backstop. In the 1.5C_Aff case, the model still exceeds the carbon budget by 39 GtCO_2 by the end of the century (see Figure 2).

Under both climate targets, afforestation increases the total final energy consumption. Due to the elastic demand feature of the model, demand decreases when fuel prices increase. A more stringent climate change target (smaller carbon budget and lower temperature limit) forces the model to use more expensive (lower-emissions) supply options. In the afforestation cases, more mitigation is done outside the energy system, effectively increasing the carbon budget for the energy system, allowing the model to choose slightly less expensive options. This leads to lower fuel and electricity prices compared to the energy crop scenarios, and so demand increases to a slightly higher level.

Figure 3: Marginal cost of CO_2 mitigation for runs with no backstop

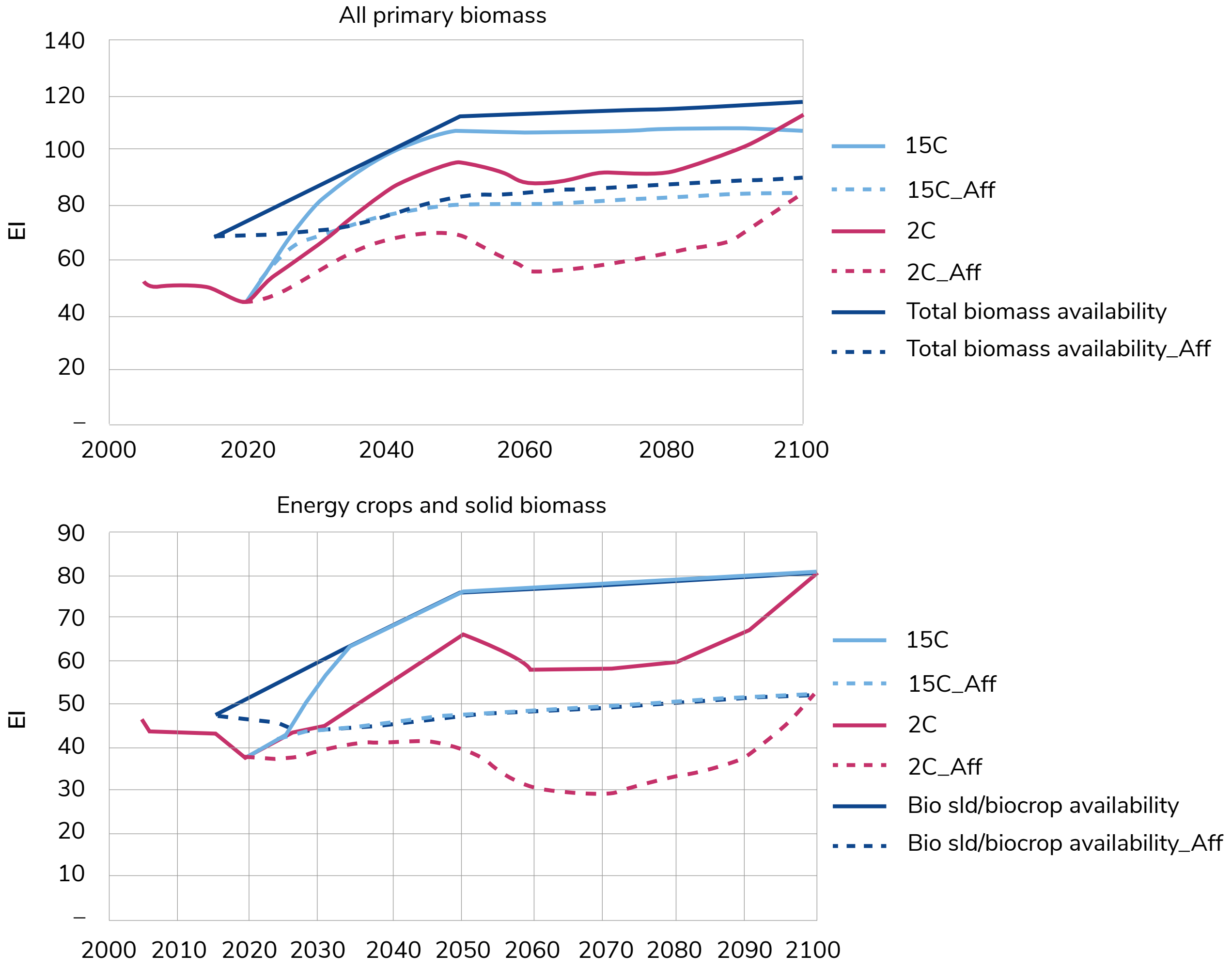


Consistent with this, the marginal cost of mitigation is lower when afforestation is deployed (Figure 3), particularly as it is introduced into the model as a low- to zero-cost option. In the 2°C case with afforestation, the marginal cost peaks in 2050 at 231 $/tCO_2$, as opposed to 435 $/tCO_2$ with energy crops (in the core case), before falling again (Figure 3). Note, the marginal cost cannot be considered in the 1.5C_Aff case as the backstop is deployed.

Under both climate targets, large-scale afforestation reduces the amount of CO_2 captured by BECCS (Figure 2). In the 2°C case (2C_Aff), the reliance on BECCS to capture CO_2 reduces strongly from a cumulative 200 to 83 Gt. In the 1.5°C case (1.5C_Aff), capture by BECCS is reduced less, from 271 to 169 Gt, as the biomass resource is reduced but more BECCS is required in order to remain within this more challenging temperature limit. With the 1.5°C target, all the potential biomass is used, while under the 2°C target, approximately the same proportion of the available woody biomass is used in the core and afforestation scenarios (under which the available biomass is lower) (Figure 4).

The large negative emissions from afforestation allows the model a little more flexibility in the rate of energy system decarbonisation under the 2°C target. In the 2°C case with afforestation, the rate at which fossil fuels are phased out of the power system is slightly reduced, most notably for gas. However, we note that changes are marginal, given the simple representation of afforestation in this modelling exercise and the large uncertainties over the timing and rate of carbon dioxide removal that could be achieved.

Figure 4: Primary biomass production for core and afforestation scenarios



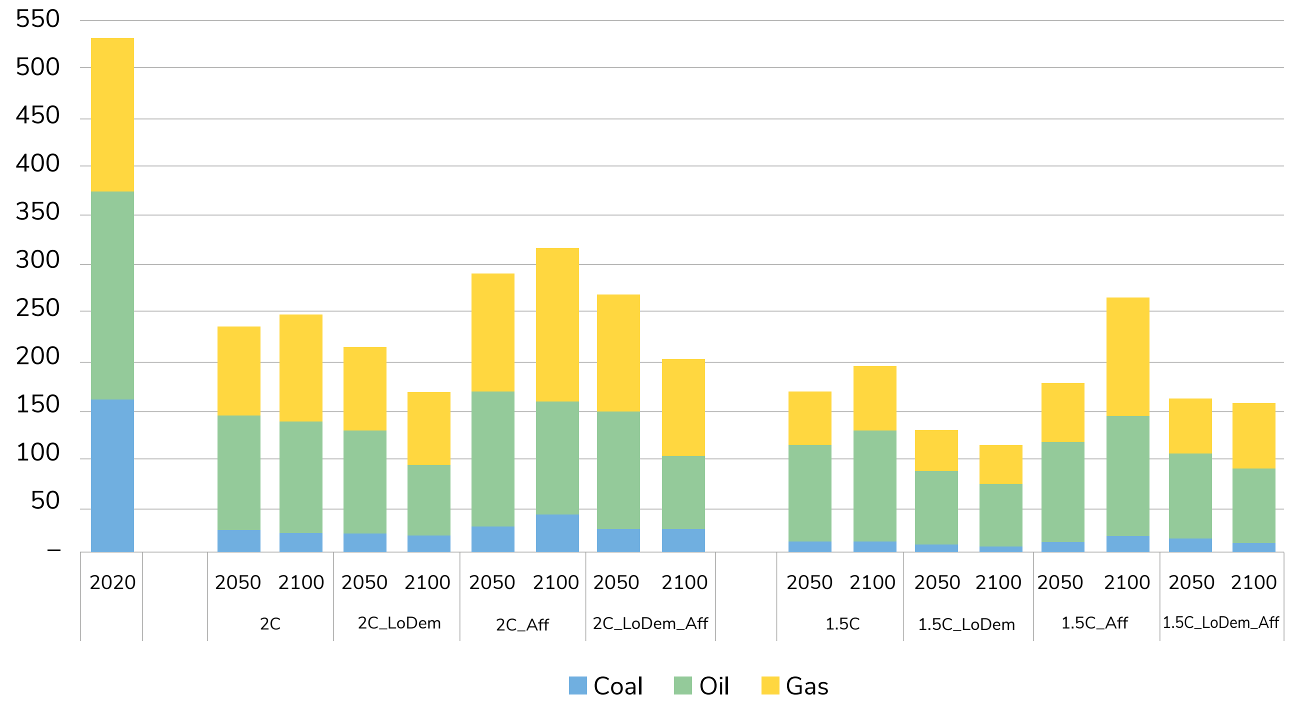
Test 2: Low demand

Lowering the service demand to be in line with an SSP1 scenario reduces the final energy consumption by approximately 11% in 2050 and by 30% in 2100 compared to the core scenarios. This reduces the required energy generation but under the 1.5°C ambition, it is not sufficient to avoid exceeding the emissions budget by 177 GtCO$_2$. This is about half of the exceedance observed under the equivalent core scenario but still equivalent to over a third of the remaining carbon budget. Despite the substantial reduction in demand, which is most significant in the second half of the century, it is still challenging to mitigate in the pre-2050 period when stronger mitigation is needed.

The effect of lower demand on the use of BECCS differs between the two climate target scenarios. Under the 2°C target, the requirement for BECCS is reduced from 200 Gt CO$_2$ to 147 Gt CO$_2$, while total bioenergy production falls from 114EJ/yr to 94EJ/yr in 2100. However, under the 1.5°C target, bioenergy is not reduced; it hits the maximum level of 115EJ in 2100, as per the core scenario. Under the more stringent 1.5°C target, lowering demand shifts the use of biomass resources between sectors; in the 1.5°C case with lower demands, it is cost-optimal to divert biomass away from transport fuels and direct use in industry, and instead use it for power generation. The CO$_2$ capture efficiency is higher at a BECCS power plant than when biomass is used for transport fuels (90% as opposed to 50%) so this shift increases the CO$_2$ captured by BECCS from 249 Gt to 275 Gt over the century.

For the rest of the global energy mix, reducing energy service demands has the effect of reducing the use of fossil fuels. In the 2°C case, oil, gas and coal production are all reduced by lower demand (Figure 5), with the strongest effect on gas. In the 1.5°C case, coal is already reduced to very low levels in the central demand case (below 26 EJ/yr by 2045) but lowering demands reduces oil and gas production substantially from 2020 onwards.

Figure 5: Annual fuel production [EJ]



Due to these changes, the marginal cost of mitigation is lower in the SSP1 case for both climate targets (Figure 3). Under the 2°C limit, the marginal cost of mitigation is reduced by approximately one third by 2100 compared with the core case. Note, the marginal cost is reduced more by the addition of afforestation than it is by lowering the demands alone. Again, for the 1.5°C case, the marginal cost cannot be considered due to the use of the backstop.

Test 3: Low demand and afforestation

Under the 1.5°C target, the combination of both large-scale afforestation and low energy service demand allows the model to solve without exceeding the carbon budget. With both these measures, the marginal cost of mitigation is comparable to the 2°C scenarios up to 2040 (373 $/tCO$_2$ in 2040), and much lower than any other 1.5°C scenario. After 2040, the rate of carbon removal rises steeply, indicating much of the energy emissions mitigation is undertaken in the second half of the century (Figure 3).

The combined effect of afforestation and demand reduction on the reliance on BECCS for CO$_2$ capture differs between the 2°C and 1.5°C tests (Figure 2). Under 2°C, reducing demand or adding afforestation reduces the reliance on CO$_2$ capture by BECCS compared to the core case. Applying both decreases the capture by BECCS by 82%. Under 1.5°C, it is so challenging to decarbonise the energy system sufficiently that all biomass is used even in the low demand scenario. Applying both afforestation and lower demand reduces the CO$_2$ capture by BECCS by only 31%.

In the 2°C case, biomass production is strongly reduced compared to the other scenarios; rather than doubling over the century as in the energy crops case, it remains close to current levels and is reduced to below 40EJ/yr in the second half of the century. Under 1.5°C case, biomass production is steady at 80EJ to the end of the century, as under the stringent 1.5°C target, almost all the available biomass is used, even with the low demands and afforestation.

Gas production differs most significantly between scenarios (Figure 5). Under both climate targets, adding afforestation allows the model to use more gas compared to the core scenario, while lowering the demands decreased the use of gas. Relative to the core case, the combined effect of afforestation and lowered demands is to increase the use of gas before approximately 2060, then decrease it in the later part of the century. In the 2°C scenario, these changes are up to +27%, then -22%. In the 1.5°C scenario they are up to +19% and -16%. For wind and solar capacity and fossil fuel production, the low demand afforestation scenarios are more similar to the low demand scenarios than the afforestation scenarios, which indicates that lowering the demand has a bigger impact on the energy mix than adding the afforestation. This is to be expected as the lower demands change the sectoral mix of service demands, whereas afforestation effectively relaxes the total carbon budget for the energy system. Despite this, the marginal costs of mitigation under the 2°C scenario indicate that afforestation has a bigger impact on the overall cost.

Power transmission tower and sugarcane field

Conclusions and further work

Based on the analysis undertaken, we summarise here the key findings:

- The model is able to meet the 2°C climate target but unable to meet the 1.5°C climate target in the core, low demand and afforestation scenarios. Budget exceedances of 79%, 42% and 9% are observed in the three 1.5°C cases respectively.
- Significantly reducing service demands is only sufficient to halve the carbon budget exceedance under the 1.5°C target. However, the combination of reduced demands and large-scale afforestation achieves the 1.5°C targets without using the backstop.
- Large-scale afforestation in place of dedicated bioenergy crops offers a higher level of CO_2 removal, at approximately 5 $GtCO_2$/yr per year, compared to a maximum 4 $GtCO_2$/yr via BECCS in the core scenarios that use energy crops. This suggests afforestation at scale should be considered more fully in such scenarios.
- Under the 2°C target, large-scale afforestation reduces the reliance on BECCS by 60% and allows lower mitigation rates in the energy system. Under the 1.5°C target, the system still uses all the biomass available as the target is so ambitious.
- Lowering service demands has a larger effect on the energy mix than the large-scale afforestation as demands are changed differently in each sector according to their projected economic drivers. However, the addition of afforestation has a bigger effect on the marginal cost of mitigation as it substantially decreases the level and rate of transformation required by the energy system, especially in the 2°C case.
- The use of biomass under the low demand scenarios differs between the climate cases. Under the 2°C target, less biomass is used in all sectors. Under the 1.5°C target, all the available wood and crop biomass is exploited in the low demand case but its use is shifted away from the production of biofuels for use in power generation.

Note, as mentioned above, the area of land assumed available for energy crops or afforestation in this study is equivalent to 24% the land area of Brazil, i.e. a huge level of afforestation is required to allow us to reduce the rate of oil and gas reduction.

Both lowering service demand and introducing large-scale afforestation present significant challenges and opportunities. Afforestation is a readily available CDR option, while BECCS is a less mature technology with substantial supply-chain risks. Each can have significant implications for biodiversity, and careful consideration of the emissions associated with land-use and land-use change is required, along with planning and regulation of forest management methods, to ensure the long-term regeneration of forests with high rates of carbon sequestration. Lowering service demands through energy efficiency and conservation measures offers potential co-benefits for energy security and access but challenges for effective behavioural interventions.

> “Large-scale afforestation offers an important CDR alternative to dedicated bioenergy crops.”

Based on the research for this briefing, the following areas for further research have been identified:

- In this case, negative emissions from afforestation are fixed in the afforestation scenarios. Furthermore, the costs and energy demands associated with land-use change are not included. Further research to include a deeper examination of land-use for different types of energy crop and afforestation would be beneficial, allowing TIAM-UCL to choose how best to balance energy crops with afforestation at the regional level.

- A review of how CDR rates depend on forest management practices would allow further sensitivity tests on the forest area and CDR rates in the context of the SSPs.
- Research into the social/technical/economic factors that affect the potential for converting abandoned agricultural land to energy crops or new forest. Implementation of these factors in the land-use scenarios in TIAM-UCL.
- More research is needed to understand the scope for social change that could lead to levels of energy demand such as the SSP1 pathway modelled in this briefing and lower. This is relevant to global modelling but also national net zero plans, including in the UK. An interdisciplinary research agenda is needed that brings together techno-economic modelling with research on social change with qualitative scenario development.

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