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A Deep Dive into the Modelling Assumptions for Biomass with Carbon Capture and Storage (BECCS): A transparency exercise.

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Abstract

Bioenergy with carbon capture and storage (BECCS) is envisaged as a critical element of most deep decarbonisation pathways compatible with the Paris Agreement. Such a transformational upscaling – to 3 - 7 Gt CO_2/yr by 2050 – requires an unprecedented technological, economic, socio-cultural and political effort, along with, crucially, transparent communication between all stakeholders. Integrated Assessment Models (IAMs) that underpin the 1.5°C scenarios assessed by IPCC have played a critical role in building and assessing deep decarbonisation narratives. However, their high-level aggregation and their complexity can cause them to be perceived as non-transparent by stakeholders outside of the IAM community. This paper bridges this gap by offering a comprehensive assessment of BECCS assumptions as used in IAMs so as to open them to a wider audience. We focus on key assumptions that underpin five aspects of BECCS: biomass availability, BECCS technologies, CO_2 transport and storage infrastructure, BECCS costs, and wider system conditions which favour the deployment of BECCS. Through a structured review, we find that all IAMs communicate wider system assumptions and major cost assumptions transparently. This quality however fades as we dig deeper into modelling details. This is particularly true for sets of technological elements such as CO_2 transport and storage infrastructure, for which we found the least transparent assumptions. We also found that IAMs are less transparent on the completeness of their treatment of the five BECCS aspects we investigated, and not transparent regarding the inclusion and treatment of socio-cultural and institutional-regulatory dimensions of feasibility which are key BECCS elements as suggested by the IPCC. We conclude with a practical discussion around ways of increasing IAM transparency as a bridge between this community and stakeholders from other disciplines, policy decision makers, financiers, and the public.

1. Introduction

Integrated Assessment Models (IAMs) are complex frameworks bringing together knowledge from several disciplines, e.g. energy systems modelling, land use, macroeconomics, and climate modelling (IPCC 2014). Their broad scope has made them very useful tools for designing and analysing scenarios of future global decarbonisation pathways, and IAMs have played a critical role in underpinning long-term climate change mitigation assessments (IPCC 2014) commissioned by the Intergovernmental Panel on Climate Change (IPCC). This has brought IAMs high scientific visibility (IPCC 2018), but also put them under intense scientific scrutiny, especially related to the transparency of their data and modelling assumptions (Weyant 2017, Pindyck 2017, Gambhir *et al* 2019). A focal point of this scrutiny has been on the models' reliance on biomass with carbon capture and storage (BECCS) to meet deep decarbonisation pathways especially in the latter half of the 21st century. Indeed, BECCS is the critical element of the majority of 2°C or 1.5°C compatible pathways (IPCC 2013, 2018). It is also simultaneously the most multi-disciplinary (Smith *et al* 2016) and most controversial technology (Fuss *et al* 2014). IAM results that include large scale deployment of BECCS have been scrutinised from an inter-generational equity perspective, i.e. near- vs. long-term climate mitigation (Anderson and Peters 2016, Obersteiner *et al* 2018), adverse impacts on other resources (Smith *et al* 2016), land use competition and social acceptability (Vaughan and Gough 2016), ethical issues and risk of use (Lawrence *et al* 2018), and the sheer scope of both innovation and upscaling required from an immature technology (Lenzi *et al* 2018, Nemet *et al* 2018). Notwithstanding, there was recognition that there is only a partial coordination between IAM modellers and other disciplinary experts who operate at a more detailed level of aggregation (Minx *et al* 2017).

To help bridge this gap between IAM modellers and broader disciplinary experts, our study examines the transparency of assumptions for the deployment of BECCS in IAMs. We conduct a structured review of six of the leading IAMs, one of which is our in-house IAM (TIAM-UCL), for which we have complete access to the underlying assumptions and documentation. To maintain an objective view on the transparency of assumptions in IAMs, including TIAM-UCL, we adopted a neutral position, in the sense that we reviewed assumptions that were publicly available, but we did not contact individual IAM modelling teams. This allowed us to test what non-modellers can actually see when they try to achieve a deeper understanding of IAM results and of the assumptions that underpin them. The aim of this transparency exercise is to offer guidance on model transparency to support the interpretation and comparison of future results. This should both enable an improved dialogue between the IAM community and different research communities (Geels *et al* 2016). It should also improve the integration of quantitative and qualitative insights (Pye *et al* 2018) for example along the (complex) supply chain of BECCS.

This paper is structured as follows: section 2 describes the methods we employed to undertake this review. Section 3 contextualises the most transparent key BECCS assumptions in TIAM-UCL as compared to other IAMs and sets the scene for the deeper transparency analysis that follows. Section 4 uses a traffic light categorisation to examine the transparency of underlying constraints and drivers of BECCS. Full explanatory details are found in the Appendix. Section 5 widens the discussion and highlights what is not included in the scope of the model (but instead is implicit) and (from an alternate disciplinary viewpoint) may be very important. Section 6 summarises findings of both transparency and the critical examination of key assumptions around BECCS, concluding with recommendations for increasing model transparency.

2. Methods for reviewing the transparency of BECCS assumptions in IAMs

Given their complexity, dissecting the highly detailed model structures and assumptions of IAMs is not straightforward. This is a well-known analytical problem, which requires up-to-date transparency (DeCarolis *et al* 2012) rather than a reliance on knowledge on past model versions and sources (Dodds *et al* 2015).

The complexity of BECCS adds a further challenge to investigating modelling assumption transparency. Firstly, BECCS is not an industrial technology with established efficiency. Instead, the term covers an entire supply chain, from cultivating and harvesting biomass to producing different biofuels. It also covers CO_2 capture, liquefaction, as well as its transport to, and injection into geological storage. Modelling assumptions need to be made at each stage of this supply chain, all of which are sector-, space- and time- specific.

Secondly, upscaling BECCS from its current level of 1 $MtCO_2/yr$ to those envisaged by IAM scenarios will require the fast ramping up of activities across the full supply chain. This assumes that all the markets involved whether for “biomass for energy”, biofuel commodities, or CO_2 function smoothly at both national and global levels (Lenzi *et al* 2018). Modelling assumptions on growth are usually sector, time-, and location-specific. Each of these will also be adjusted depending on views of future policy and socio-economic pathways.

Finally, in addition to providing low carbon fuels, BECCS is also assumed to provide "negative emissions". This means that the overall balance of GHG emissions over the full supply chain of BECCS is assumed to be negative. Understanding the transparency of this assumption relies on being able to assess the underlying assumptions that describe the full carbon balance of each individual step. This means reviewing the uptake of CO_2 by biomass growth; the GHG emissions from biomass cultivation, harvest, storage and processing; the efficiency of processing; the energy required for capturing, transporting and storing CO_2 as well as the carbon losses along the way.

We started the transparency review by comparing well-communicated BECCS assumptions in IAMs as reviewed by Fuss et al. (2018) vs. TIAM-UCL assumptions. These include BECCS costs, and the magnitude of global biomass production and CO_2 storage potentials. This comparison summarises the range of potentials and costs across the IAMs so as to guide further investigation of underlying constraints and assumptions. In a second step, we take advantage of our combined expertise in, and full knowledge of, TIAM-UCL to structure our review for specific parameters along the BECCS supply chain (Tables 5 to 9 in Section 4). As much as possible, these were selected to cover the complexity of BECCS, including carbon accounting over the full BECCS supply chains. The transparency of assumptions is characterised using a traffic light system. Green lights represent BECCS aspects that are well communicated by the modellers (including ourselves), amber ones denote partial communication or transparency, and red characterises those aspects that are or not transparent or not communicated. Transparent communication of parameter assumptions however implies that this respective parameter is included in the modelling framework that is under scrutiny. Accounting for the fact that some parameters are not included across all modelling frameworks, the traffic light system was adjusted so that: green lights represent BECCS assumptions which are included in the modelling framework and are well communicated by the IAM teams; amber ones denote that the parameter is included, but there is no clear communication of assumptions (partially specified assumption, or conflicting information coming from different sources, e.g. web documentation referring to several external documents); red means that the parameter is not specified at all and is potentially not included in the modelling framework. The basis for this quantification is what is written in the model documentation and key journal papers. It does not rely on any understanding of the full historical evolution of the structure of the models or of their application (Dodds *et al* 2015). A full and detailed discussion of the transparency assessment (green, amber, red) is given in the Appendix. To summarise the transparency findings, we assign each colour a score, i.e. green is assigned 1, amber 0.5 and red 0. A transparency score is then calculated for each IAM in each of the five BECCS aspects investigated here by dividing the sum of all its colour scores by the maximum score which could be obtained for that aspect, i.e. if all the parameters were communicated transparently.

We chose six leading IAMs: IMAGE, MESSAGE-GLOBIOM, GCAM, REMIND/MAgPIE, AIM, and TIAM-UCL. For each IAM, we have considered the model documentation and recent journal publications relevant to the deployment of BECCS under global deep decarbonisation scenarios (1.5 and 2 ºC), see

Table 1. We also considered model inter-comparison studies published by the IAM teams, the SSP database hosted by IIASA, and the recently released IPCC SR1.5C database. Our main criteria in examining each model's documentation and selected studies was that they should provide enough transparent information for a well-versed reader to scrutinise their BECCS assumptions. If a parameter or a parameter value is not easy to find, it means the information is not transparently communicated.

Table 1. List of IAMs considered in this work, covering main model characteristics and selected publications on BECCS

	IMAGE	**MESSAGE/ GLOBIOM**	**GCAM**	**REMIND/ MAgPIE**	**AIM**	**TIAM-UCL**
Hosting Institution	PBL, NL	IIASA, AU	PNNL, US	PIK, DE	NIES, JP	UK
Equilibrium concept	PE[i]	CGE[ii]	PE	CGE	AIM/PLUM and AIM/Enduse are PE, AIM/CGE: CGE	PE
Solution Algorithm	RD/S[iii]	MESSAGE is IO; GLOBIOM is RD; both are LP[iv]	NLP; RD/S	REMIND/ MAgPIE uses NLP; REMIND is IO, MAgPIE is RD/S	AIM/PLUM and AIM/Enduse are LP; AIM/CGE: MCP[v], both are RD/S	IO/LP
Land use (LU) representation	Endogenous LU dynamics; high resolution land surface representation from the LPJmL land surface model	MACCs for LU emissions LU dynamics from GLOBIOM Afforestation option	Endogenous LU dynamics Afforestation option	Endogenous LU dynamics from MAgPIE in some scenarios coupled to MACCs	Marginal Abatement Costs (MACs) for LU emissions	Exogenous assumption on LU, LUC emissions and afforestation
CCS representation	CO_2 capture, transport and storage modelled individually. Regional differentiation of CO_2 transport and storage costs.	No regional differentiation of CO_2 transport and storage costs. One global geological reservoir.	Regional differentiation of CO_2 transport and storage costs.	Fixed CO_2 transport cost. Region and storage specific CO_2 storage costs.	Fixed carbon capture costs. CO_2 transport and storage costs not specified.	Fixed CO_2 transport cost. Regional differentiation of storage capacity and costs.
Selected publications	(van Vuuren *et al* 2011, 2013, Popp *et al* 2014, Koelbl *et al* 2014, Daioglou *et al* 2015, 2016, Popp *et al* 2017, Bauer *et al* 2018, Doelman *et al* 2018,	(Riahi *et al* 2011, Kraxner *et al* 2013, Valin *et al* 2015, Lauri *et al* 2014, Krey V, Havlik P, Fricko O, Zilliacus J, Gidden M, Strubegger M, Kartasasmit	(Calvin *et al* 2014, Muratori *et al* 2016, 2017a, 2017b, Calvin *et al* 2019)	(Bauer 2005, Klein *et al* 2014, Kriegler *et al* 2013, Luderer *et al* 2015, 2018, Strefler *et al* 2018, Heck *et al* 2018)	(Fujimori *et al* 2014a, 2014b, 2012, 2015, 2018, 2017, Hasegawa *et al* 2017, Ito and Inatomi 2012, Liu *et al* 2018, Luckow *et al* 2010, Akashi and Hanaoka	(Anandarajah *et al* 2011, McGlade 2014, McCollum *et al* 2018, Dessens *et al* 2016, Edelenbosch *et al* 2017, Winning *et al* 2018, Rogelj *et al* 2018, Marangoni

	Vaughan *et al* 2018)	a G, Ermolieva T, Forsell N, Gusti M, Johnson N, Kindermann G, Kolp P, McCollum DL, Pachauri S, Rao S, Rogelj J, Valin H, Obersteiner M 2016, Bauer *et al* 2017, Fricko *et al* 2017, Huppmann *et al* 2019, 2018)			2012, Wu *et al* 2019)	*et al* 2017, Pye *et al* 2018, 2019)

[i]PE denotes Partial Equilibrium models; [ii]CGE: General Equilibrium models; [iii] Recursive-dynamic (simulation); [iv] IO/LP: Inter-temporal optimisation (linear programming); [v] Mixed Complementary Program.

We explicitly acknowledge that the number of studies we reviewed is limited due to practical reasons, but it is fit for purpose. It shows how easy, or complex, is to find key assumptions when you are a third-party, not directly involved in the development and running of IAMs, but wishing to contribute to the BECCS debate.

3. Key IAM assumptions on BECCS

Key BECCS assumptions which are usually well communicated in IAM studies include BECCS costs and the global magnitude of both biomass resource and CO_2 storage (Fuss *et al* 2018). Based on these, each IAM estimates the global BECCS potential under different futures (shared socioeconomic pathways (SSPs)) and different projections of global GHG emission concentrations (representative concentration pathways (RCPs)). This section compares these aggregated assumptions (see Table 2) to those made in the database and code of our in-house IAM (TIAM-UCL) to which we have full access. This then leads us to an in-depth examination of the underlying model constraints and drivers of these assumptions in the six selected IAMs (in Section 4), which is our main contribution.

Table 2. Aggregated key BECCS assumptions in IAMs

Assumptions	**Data assumption in IAMs, based on Fuss et al., 2018**	**Data assumption in TIAM-UCL**
Global biomass potential	60 to over 1548 EJ/y in 2050	90-230 EJ/y in 2050
CO_2 storage potential	320 – 50,000 Gt CO_2	2,100 Gt CO_2
BECCS costs	100 to 200 \$/t CO_2	50-280 \$/t CO_2
Global BECCS potential	0.5 to 5 Gt CO_2/y in 2050	0 to 6.5 Gt CO_2/y in 2050

Global biomass potential

The global biomass potential is reported as being a key limiting factor for the large scale deployment of BECCS (van Vuuren *et al* 2013, IPCC 2018, 2014). Fuss *et al* (2018) identifies a wide range of global biomass potentials in 2050, between 60 and 1548 EJ/y. Assumptions used in TIAM-UCL are between 90 and 230 EJ/y in 2050 and therefore sit at the bottom of this range. These values rely on a recent, less optimistic, biomass resource update based on the latest literature estimates (Pye *et al* 2019).

The global biomass resource base in IAMs is usually composed of several biomass fractions, e.g. dedicated energy crops, agricultural and forest residues, and waste fractions. There is high uncertainty surrounding the availability, economic feasibility and sustainability of all these fractions (Fuss *et al* 2018), but the largest and most debated fraction, are energy crops. These usually include herbaceous and woody crops cultivated purposely for energy use. The global potential for energy crops is driven by agricultural development (i.e. yield increase) and by the availability of land for bioenergy production. The latter is subject to constraints that relate to (i) competition for land with other human uses, e.g. food, timber, conservation purposes; (ii) ecological limits, such as water scarcity, soil degradation or biodiversity protection; and (iii) issues of biomass seasonality and storage. Modelling assumptions made around each of these constraints combine to produce a wide range of possible biomass potentials. We investigate the transparency of these underlying assumptions in Section 4.

Global CO_2 storage potential

Following the Global CCS Institute (2016), there is enough global storage available for CO_2 captured from biofuel and fossil sources, especially when including offshore potentials. However, as indicated in Table 3, there is a large uncertainty around where this storage will be made available and the potential mismatch between production of CO_2 and available storage sites (IPCC 2018). Based on the review of 24 studies from literature, Fuss *et al* (2018) report global storage capacities of between 320 and 50,000 Gt CO_2. The lower value considers that only 1% of sedimentary basins are suitable for storage. The larger one includes trapping mechanisms in aquifers. In contrast, TIAM-UCL assumptions are based on (Hendriks *et al* 2004) updated with findings from (Weyant *et al* 2013), leading to a global cumulative storage potential of 2,100 Gt CO_2. The main difference in geological storage assumptions relates to potentials available in aquifers for which TIAM-UCL does not include trapping mechanisms. Note that, independently of its potential, the actual use of CO_2 storage may also be subject to other factors such as: the development of a CO_2 transport infrastructure, the public acceptance of CCS, the total cost of preparing the storage site, or that of monitoring and verifying the permanence of the storage (Haszeldine *et al* 2018). These topics are further investigated in the next section.

Table 3. Global and regional CO_2 storage potential in IAMs as reviewed by Fuss et al. (2018) *and TIAM-UCL.*

	Model	**Global potential (Gt CO_2)**	**Regional potential (Gt CO_2)**
Depleted oil and gas fields	IAMs*	458-923	North America 40-136 ; Europe 20-60 ; Russia around 277 ; MEA 208-250
	TIAM-UCL	1160	North America 66 , EU 74 , Russia 308 , MEA 440
Coal beds	IAMs*	60-700	Lowest estimate includes only top 10 countries with more economic storage; North America 65-120
	TIAM-UCL	267	North America 40 ; China 158
Aquifers	IAMs*	200-50,000	Lowest estimates include only the reservoirs with structural trap, while the highest ones are theoretical and include trapping mechanisms. Highest storage capacity in North America, China and the OECD Europe
	TIAM-UCL	680	Highest Storage in north America, EU and Australia – New Zealand

* as reviewed by Fuss et al (2018).

Costs of BECCS

Based on a systematic review of the literature and on expert judgement, Fuss et al. (2018) estimates the cost of BECCS in 2050 to be in the range of 100 to 200 \$/t CO_2. These estimations account for how difficult it is to access biomass, for the cost of land and its conversion, for the type of bioenergy facility, and for the CCS infrastructure required, see Table 4. TIAM-UCL estimates for these costs all fall in the same range with the exception of using BECCS for the production of advanced (Fischer Tropsch) biofuels. These are 50% higher, mainly due to the cost of the biomass and to both technology type and efficiency.

Table 4. Ranges of BECCS cost in 2050 by technology in IAMs and TIAM-UCL.

BECCS technology	**Model**	Estimated costs (\$/tCO_2**)**	Description of assumptions
Ethanol fermentation with CCS	IAMs*	20-175 -	Low estimates assume easy access to biomass and short transport distance to storage sites. Costs increase to 180-200 \$/tCO_2 if CO_2 from cogeneration is also captured.
	TIAM-UCL		Technology not available
Combustion BECCS	IAMs*	88-288	Lowest estimates come from oxy-fuelling.
	TIAM-UCL	62-165	Biomass combustion with CCS available for biomass only and co-firing coal-biomass in low (20%) and high (50%) biomass to coal ratios. The cost increases with the cost of biomass.
Gasification BECCS	IAMs*	30-70	Worst estimates could reach 150-400 \$/tCO_2 if large land areas are used for growing biomass.
	TIAM-UCL	79-143	Biomass gasification with CCS is only allowed for energy crops, agricultural and forestall residues, but not waste fractions.
BECCS from black liquor (pulp& paper mills)	IAMs*	20-70 20-55	when using recovery boilers *vs* when using gasification technologies
	TIAM-UCL		Not available in TIAM-UCL.
BECCS for Bio-SNG (Synthetic Natural Gas)	IAMs*	86-167	
	TIAM-UCL		Not available in TIAM-UCL.
BECCS for advanced (Fischer Tropsch) diesel	IAMs*	20-40	
	TIAM-UCL	102-340	Fischer Tropsch liquids can be obtained only from energy crops, agricultural and forestall residues, not waste fractions. FT fuels include bio-diesel, bio-kerosene, and bio-jet kerosene.
BECCS for Hydrogen	IAMs*		
	TIAM-UCL	57-207	Small, medium and large bio-hydrogen plants with CCS.

* As reviewed by Fuss et al (2018).

These cost assumptions influence the affect the extent to which BECCS is used in decarbonisation scenarios, i.e. how many tonnes of CO_2 BECCS technologies remove per year in these alternate futures. The aggregated assumptions discussed above are usually published in papers and reports from the IAM community. Based on knowledge of TIAM-UCL, the next sections proceed to unravel the underlying constraints and drivers that underpin these assumptions but that are not usually disclosed or discussed.

4. Deeper assessment: Underlying constraints and drivers of BECCS

In this section, we focus on the transparency of underlying constraints and drivers that relate to assumptions under scrutiny. A traffic light system is used for visual clarity. Green denotes BECCS aspects which are well communicated by IAM teams, amber denotes partial communication, and red denotes that these are not communicated with model results. The data values and modelling assumptions presented in each table are described in the Appendix together with our comments on the transparency of communication. We follow the full supply chain of BECCS, starting with biomass potential (*Table 5*), bio-technologies with carbon capture (including biomass to energy transformation and capture of CO$_2$, *Table 6*), CO$_2$ transport and storage (*Table 7*), and costs across the BECCS supply chain (*Table 8*). We investigate the transparency of carbon accounting in IAM modelling by including the GHG emissions that correspond to successive steps in the BECCS supply chain in each of the tables. We also include a table compiling cross-cutting issues that influence the use of BECCS for climate mitigation (*Table 9*).

Biomass potential

Future global biomass potential is highly uncertain because it depends on techno-economic, environmental and social factors which are complex as well as region and time dependant. In this section we investigate assumptions around land competition, yields of energy crops, ecological constraints, and bio-trade which determine the magnitude of the biomass that is available for energy. We also dig into the details of carbon accounting. Shown in *Table 5*, our results reveal that all the IAMs we assess are transparent around land competition and energy crops productivity. Different to TIAM-UCL, which has a simplified exogenous model of land use, all the IAMs we review include a spatially explicit representation of the competition for land between food, energy and forestry. The modelling teams share the resulting land allocation for energy crops transparently both in model inter-comparison studies, e.g. Popp et al. (2017), and model specific publications, e.g. Doelman et al. (2018). It is interesting to note that under a SSP2-2.6 scenario (a “middle-of-the-road” future with a climate forcing of 2.6 W/m^2 in 2100), the land allocated to biomass for energy ranges from 225 Mha in IMAGE to 1,100 Mha in GCAMv4 (Table 5a in the Appendix). This is due to a combination of low (IMAGE) vs high (MESSAGE) sensitivity of food demand to food prices (Popp *et al* 2017), and to the inclusion of sustainability criteria in IMAGE which limit the expansion of energy crops to lands that are not used for food production. In terms of yield assumptions, all IAMs, except TIAM-UCL, estimate energy crop yields endogenously. TIAM-UCL starts with 2015 regional yields as reported in Ricardo-AEA (Ricardo-AEA 2017) and then assumes 1.3% yield increase per year. This leads to regional yield values of between 5 and 12 dry tonnes/ha by 2100 as compared to 11 dry tonnes/ha estimated by IMAGE and GCAM, 14 in MESSAGE-GLOBIOM, and 21 in both AIM-PLUM and REMIND-MAgPIE.

Table 5. Transparency of underlying assumptions for estimating biomass potential. Green denotes transparent assumptions of parameters included in the modelling framework, amber denotes partial transparency (the parameter is included in the modelling framework but it has conflicting or partial value specification), and red means no transparency (the parameter is not specified at all, or potentially it is not included in the modelling framework).

Key category	**Underlying constraint**	**IMAGE**	**MESSAGE-GLOBIOM**	**GCAM**	**REMIND-MAgPIE**	**AIM**	**TIAM-UCL**
Potential of large scale	Competition for land energy- food – forestry	🟩	🟩	🟩	🟩	🟩	🟩

biomass production	Productivity of biomass for energy (yield assumptions)	🟩	🟩	🟩	🟩	🟩	🟩
	Ecological constraints, i.e. water scarcity, biodiversity, soil degradation	🟩	🟩	🟨	🟩	🟩	🟧
International trade of bioenergy	Type of biomass allowed for trade	🟩	🟨	🟩	🟩	🟨	🟩
	Trade links	🟩	🟨	🟧	🟩	🟧	🟩
GHG emission accounting	GHG caused by biomass production	🟩	🟩	🟩	🟩	🟩	🟩
	GHG caused by biomass transport	🟧	🟨	🟧	🟩	🟨	🟧

Looking at ecological constraints, i.e. water scarcity, soil and biodiversity concerns, we found that four out of six IAMs explicitly account for them (green in Table 5), while the others, including TIAM-UCL are vaguer on this topic (yellow in Table 5, see Appendix for more details). While these ecological constraints could reduce both yields and land suitability for energy crop production, we found no explicit quantification nor any communication of how much they could affect regional and aggregate biomass potentials.

Collaboration and trade between the different regions is essential to BECCS deployment, especially under stringent climate scenarios. Looking at how transparently the trade assumptions are communicated by IAM teams, we found that the type of biomass and biofuels for trade is fairly visible in all IAMs. However, the assumptions on trade links between regions and how they evolve under alternate future scenarios are less visible or not communicated by several IAMs.

Assumptions around carbon accounting in the biomass production stage are one of the main determinants of the potential carbon sequestration by BECCS. Van Vuuren et al (2013) report that considering an emission factor of 15 kg CO_2/GJ produced biomass reduces BECCS effectiveness by a fifth. Our results in *Table 5* show that while land use and land use change emissions are well represented in all IAMs, biomass storage and transport emission assumptions are either not included or vague. For example, while domestic transport of biomass is spatially explicit in GLOBIOM (Valin *et al* 2015), the corresponding transport emissions are not specified.

Bioenergy with carbon capture technologies

All the IAMs we reviewed include BECCS for the production of power, bio-liquids and hydrogen. Independently of the type of BECCS available in each IAM, all models usually make assumptions regarding the earliest implementation of these technologies, their build rate (how fast new capacity can be added each year), their availability factor (fraction of time the plant is operating), efficiency of transformation and how this evolves over time, and CO_2 capture rates. These technical assumptions (Table 6) are not as visible as land assumptions (Table 5). For example, only IMAGE reports a 36-month construction time for bio- power generation with CCS (Black&Veatch 2012, LAZARD 2015b). All the global IAMs assume that the conversion efficiency of technologies increase over time, albeit with significant variations in the magnitude of the increase (Krey *et al* 2019). Note that these efficiencies are usually exogenous inputs to the models based on average values taken over different technologies in operation, i.e. not theoretical efficiencies (Krey *et al* 2019). REMIND-MAgPIE and GCAM are transparent on their assumptions regarding plant life, capacity factor, efficiency of transformation and

CO_2 capture rates. It is interesting to note that GCAM has been transparent regarding updates of BECCS technologies e.g. they reduced the efficiency of BECCS for power from 41.6% (Luckow *et al* 2010) to 18% for a biomass steam plant + CCS, and to 25% for a biomass IGCC + CCS (Muratori *et al* 2017a). Generally, the technological updates in GCAM have reduced the technological potential of BECCS (see *Table 6*, and in the Appendix), but these updated values are still slightly more optimistic than in REMIND-MAgPIE (Luderer *et al* 2015), and TIAM-UCL.

It is interesting to note that the all the IAMs we assessed assume that bioenergy is carbon neutral, i.e. that the CO_2 emissions linked to producing and using bioenergy in any form are equal to the CO_2 that is sequestered by growing the biomass. Whilst there seems to be general agreement that sustainable biomass growth does re-capture the CO_2 that results from the combustion of biomass, the sequestration and emission rates might be in temporal imbalance (Lamers and Juninger 2013, EASAC 2019, Torvanger 2019). For woody biomass, scientific evidence shows that the time lag between biomass harvest and biomass growth to pre-harvest as compared to not harvesting the biomass (usually termed "carbon parity time") could be anywhere between 0 and hundreds of years, depending on the biomass resource and on what the resulting bioenergy substitutes (Lamers and Juninger 2013).

Table 6. Transparency of underlying assumptions for bioenergy with carbon capture technologies. Green denotes transparent assumptions of parameters included in the modelling framework, amber denotes partial transparency (the parameter is included in the modelling framework but it has conflicting or partial value specification), and red means no transparency (the parameter is not specified at all, or potentially it is not included in the modelling framework).

Technology	Assumption	IMAGE	MESSAGE-GLOBIOM	GCAM	REMIND-MAgPIE	AIM	TIAM-UCL
Biomass to power with carbon capture	Plant capacity	🟨	🟩	🟨	🟥	🟥	🟥
	Start year and Build rate	🟥	🟥	🟩	🟥	🟩	🟥
	Construction time	🟩	🟥	🟥	🟥	🟥	🟥
	Plant life	🟩	🟩	🟩	🟩	🟥	🟥
	Capacity factor	🟨	🟥	🟩	🟩	🟥	🟥
	Efficiency of transformation	🟨	🟨	🟩	🟩	🟥	🟩
	CO_2 capture rate	🟨	🟩	🟩	🟩	🟩	🟩
	Bioenergy emissions	🟨	🟥	🟥	🟩	🟨	🟥
Biomass to transport fuels: FT fuels and hydrogen, with CCS	Availability factor	🟥	🟥	🟥	🟥	🟥	🟥
	Start year and Build rate	🟥	🟥	🟩	🟥	🟥	🟩
	Construction time	🟥	🟥	🟥	🟥	🟥	🟥
	Plant life	🟨	🟨	🟨	🟩	🟥	🟥
	Efficiency of transformation	🟥	🟥	🟩	🟩	🟥	🟥
	CO_2 capture rate	🟥	🟥	🟩	🟩	🟥	🟥

	Bioenergy end use emissions	🟨	🟩	🟩	🟩	🟩	🟩

CO_2 storage, including transport of CO_2 to storage

Usually IAMs report regional CO_2 storage capacity, sometimes per type of geological storage (*Table 7*, and in the Appendix). Note that the geological storage of CO_2 is shared between BECCS, fossil CCS, and other negative emission technologies if available, e.g. Direct Air Capture. The injection rates of CO_2 captured from BECCS are usually communicated, although mostly at global level, e.g. 0-10 $GtCO_2$/y in 2050 and 10-20 $GtCO_2$/y in 2100 (van Vuuren *et al* 2013). The wider policy audience would benefit from more transparent assumptions around the preparation and use of geological storage. We have not found any reporting of CO_2 leakage rates, nor monitoring, reporting and verification (MRV) mechanisms to ensure that the stored CO_2 is kept in the geological storage.

The biggest gap in reporting transparency of BECCS modelling assumptions concerns the CCS infrastructure, which connects the CO_2 capturing plants to the geological storage. Except for MESSAGE-GLOBIOM which reports the assumed length of CO_2 pipelines (Riahi *et al* 2007), we have not found any mention of assumed availability, efficiency, or build rate of CCS pipeline networks in different regions. It seems that most models (including TIAM-UCL) are modelling the CCS infrastructure based on costs estimated by Hendricks et al. (Hendriks *et al* 2004), subsequently updated with other reports, e.g. from EMF28 (Weyant *et al* 2013). These updates are however not usually made clear. Instead, all IAMs take a rather binary view of CCS availability, running sensitivity analyses assuming, for example, the absence of BECCS in the system because of challenges in developing the CCS infrastructure (e.g. (Bauer *et al* 2018)).

Table 7. Transparency of assumptions for CCS pipelines infrastructure and geological storage. Green denotes transparent assumptions of parameters included in the modelling framework, amber denotes partial transparency (the parameter is included in the modelling framework but it has conflicting or partial value specification), and red means no transparency (the parameter is not specified at all, or potentially it is not included in the modelling framework).

Key category	**Assumption**	**IMAGE**	**MESSAGE-GLOBIOM**	**GCAM**	**REMIND-MAgPIE**	**AIM**	**TIAM-UCL**
CCS pipelines	Efficiency	🟥	🟥	🟥	🟥	🟥	🟥
	Availability factor	🟥	🟥	🟥	🟥	🟥	🟥
	Build rate	🟥	🟥	🟥	🟥	🟥	🟥
	Pipeline network design	🟨	🟩	🟥	🟥	🟥	🟥
CO_2 storage	Global capacity per type of sink	🟨	🟩	🟥	🟩	🟨	🟥
	Regional distribution of storage	🟨	🟩	🟥	🟩	🟥	🟥
	Leakage rate	🟥	🟥	🟥	🟥	🟥	🟥
	MVR costs	🟥	🟥	🟥	🟥	🟥	🟥
	Max injection rate	🟨	🟥	🟨	🟩	🟨	🟥

BECCS costs

All IAMs investigated here have endogenous estimations of the costs of primary biomass for energy, e.g. considering yields, regional land prices and regional income (IMAGE, (van Vuuren *et al* 2009)), or as a function of capital, labour and intermediate costs (AIM (Hasegawa *et al* 2017)). In TIAM-UCL the cost of primary bioenergy is given using supply-cost curves derived from Ricardo-AEA (Ricardo-AEA 2017). When we dig into the detail of land rental rates per region and agricultural subsidies assumed for bioenergy production, the transparency of model assumptions decreases, with only some models detailing these costs, e.g. REMIND–MAgPIE applies a bioenergy tax, rising from 0% in 2030 to 100% in 2100, to reflect sustainability concern, while IMAGE adds explicit energy taxes and subsidies at both the primary and end-use level (PBL 2014). We also found (*Table 8*) that assumptions on the cost of storing and processing biomass prior to its transformation into energy are usually not available: GCAM is the only IAM to report average biomass processing costs of $1.87/GJ, or $36.5/tonne biomass (Luckow *et al* 2010), while none of the IAMs report biomass storage costs (including TIAM-UCL). International transport costs usually result from endogenous model calculations, but it is not clear whether they reflect only the cost of fuels used for transport or if they also account for temporary storage and handling in the ports. Domestic transportation is less accurately represented, except for MESSAGE-GLOBIOM, which calculates it endogenously based on distance and mode of transport (Valin *et al* 2015). IMAGE and GCAM consider fixed transport costs per GJ biomass, US$ 0.5/GJ (IMAGE (van Vuuren *et al* 2011)) vs $0.37/GJ, or $6/tonne biomass in GCAM (Luckow *et al* 2010).

Table 8. Transparency of cost assumptions along the full supply chain of BECCS. Green denotes transparent assumptions of parameters included in the modelling framework, amber denotes partial transparency (the parameter is included in the modelling framework but it has conflicting or partial value specification), and red means no transparency (the parameter is not specified at all, or potentially it is not included in the modelling framework).

Key category	**Assumption**	**IMAGE**	**MESSAGE-GLOBIOM**	**GCAM**	**REMIND-MAgPIE**	**AIM**	**TIAM-UCL**
Biomass feedstock	Import	🟩	🟩	🟥	🟨	🟥	🟥
	Production	🟩	🟩	🟩	🟩	🟩	🟩
	Land rental	🟩	🟥	🟩	🟨	🟩	🟥
	Agricultural taxation/subsidy	🟨	🟥	🟥	🟩	🟥	🟥
	Biomass storage	🟩	🟥	🟥	🟥	🟥	🟥
	Processing (drying, pelletizing, etc.)	🟩	🟨	🟩	🟥	🟥	🟥
	Domestic transportation	🟩	🟩	🟩	🟥	🟥	🟥
	International transportation	🟩	🟩	🟥	🟥	🟨	🟩
Biomass to power with CCS	CAPEX	🟨	🟩	🟩	🟩	🟥	🟩
	Fixed O&M	🟨	🟥	🟩	🟥	🟥	🟥
	Variable O&M	🟨	🟥	🟩	🟩	🟥	🟥
Biomass to transport fuels: FT fuels and hydrogen with CCS	CAPEX	🟥	🟩	🟥	🟩	🟥	🟥
	Fixed O&M	🟥	🟥	🟩	🟩	🟥	🟥
	Variable O&M	🟥	🟥	🟥	🟥	🟥	🟥
CO_2 capture	Cost	🟩	🟩	🟩	🟩	🟩	🟥
CO_2 transport costs	Cost	🟩	🟩	🟨	🟩	🟥	🟥
CO_2 storage	Costs	🟩	🟩	🟨	🟩	🟥	🟥

IAMs make more transparent assumptions about the capital, fixed and variable costs of operating bioenergy technologies with carbon capture. These assumptions are visible in individual IAM publications and are also specified in the inter-model comparison (Krey *et al* 2019). Similar to (Krey *et al* 2019) we found that the variation of capital costs is quite large between IAMs, and that the O&M costs are usually given as a percentage from the CAPEX, which is constant both across the regions and in time. In IMAGE, the web documentation points to several data sources which, in turn, lead to a range of different data assumptions. For example, the sources for the CAPEX of BECCS for power are: (LAZARD 2015a, Black&Veatch 2012) and (IRENA 2015). These sources then give different CAPEX specifications: 3,000-4,000 $_{2005}$\$/kW ((LAZARD 2015a)), 3,843 $_{2005}$\$/kW (Black&Veatch 2012), and 400-8,000 $_{2005}$\$/kW depending on the region, technology and feedstock (IRENA 2015). It is interesting to note that GCAM differentiates between the costs of capturing high vs. low purity CO_2: 72 $_{2010}$\$/tCO_2 for a biomass steam plant + CCS, 66 $_{2010}$\$/tCO_2 for biomass IGCC + CCS, 32-70 $_{2010}$\$/tCO_2 for cellulosic ethanol with CCS, and 32-46 $_{2010}$\$/tCO_2 for FT biofuels +CCS (Muratori *et al* 2017a). Also AIM-PLUM assume 100~150 \$/tCO_2 for the manufacturing sector and 50~120 \$/tCO_2 for the power sector (based on (IEA 2008)). Ultimately, the IMAGE web documentation suggests 35-45 $_{2005}$\$/tCO_2 captured. The other IAMs report CAPEX costs that include the capture of CO_2. This increases the cost of energy production by about 50% (Hendriks *et al* 2004).

While the technical assumptions on CO_2 transport and storage are less transparent (*Table 7*), the cost assumptions of these stages are both very visible (*Table 8*) and quite similar between models. For example IMAGE assumes region and storage specific CO_2 transport costs of between 1 and 30 $_{2005}$\$/tCO_2, with the majority remaining below 10 $_{2005}$\$/tCO_2 ((Hendriks *et al* 2004)). TIAM-UCL uses similar values, between 1 and 10 $_{2005}$\$/tCO_2. MESSAGE-GLOBIOM reports 7-9 $_{2005}$\$/tCO_2 for fossil CO_2 and double values for biogenic CO_2, as BECCS plants are smaller than their fossil counterpart, requiring more infrastructure to transport CO_2 to storage (Koelbl *et al* 2014). REMIND-MAgPIE suggests 3.1-4.2 million\$/km CO_2 pipeline (Bauer 2005), which translates to 8 - 15 \$/tCO_2 metric, considering an average pipeline length of 1000 km, 10 to 15 mtCO_2 transported per year (Bauer 2005) and pipeline operation lifetime of between 20 and 25 years.

Cross-cutting issues

Several cross-cutting assumptions in IAMs, such as the availability of other Carbon Dioxide Removal technologies or the date of peak emissions, will influence the use of BECCS for climate mitigation, see *Table 9*. We found that all IAMs do very well at communicating the stringency of climate targets, i.e. the date at which the system reaches net zero CO_2 emissions, which is usually after 2070. They also communicate transparently that corresponding trajectories of global CO_2 emissions would peak in 2020. All the IAMs recognise that climate mitigation is biased towards supply side measures, e.g. increased efficiency, fossil fuel substitution by renewable fuels, or the use of negative emission technologies (NETs). The NETs usually included in IAMs are afforestation/reforestation and BECCS. The carbon prices are usually uniform across all regions, but the application of regional GHG emission caps can also lead to regional carbon prices, e.g. in MESSAGE GLOBIOM (Fricko *et al* 2017). It is interesting to note that the general discount rate applied in IAMs is 5%, vs 3.5% usually considered in TIAM-UCL. Finally, IMAGE is the only IAM that mentions the inclusion of the disruptive impacts of climate change on the system through e.g. extreme weather events.

Table 9. Transparency of model assumptions influencing the uptake BECCS. Green denotes transparent assumptions of parameters included in the modelling framework, amber denotes partial transparency (the parameter is included in the modelling framework but it has conflicting or partial

value specification), and red means no transparency (the parameter is not specified at all, or potentially it is not included in the modelling framework).

Assumption	IMAGE	MESSAGE-GLOBIOM	GCAM	REMIND-MAgPIE	AIM	TIAM-UCL
Peaking of emissions under a SSP2 RCP2.6 scenario	🟩	🟩	🟩	🟩	🟩	🟩
Timing of achieving net-zero emissions	🟩	🟩	🟩	🟩	🟩	🟩
Options for emission mitigation	🟩	🟩	🟩	🟩	🟩	🟩
Carbon pricing regime	🟩	🟩	🟩	🟩	🟩	🟩
General discount rate	🟩	🟩	🟩	🟩	🟩	🟩
Availability of other Negative Emission Technologies	🟩	🟩	🟩	🟩	🟩	🟩
Climate change impacts on the system, e.g. extreme weather events	🟩	🟧	🟧	🟧	🟧	🟧

5. Broader Assessment: What is not included/ or missing from IAMs

Thinking about the feasibility of different mitigation options, the IPCC suggests a framework for their full assessment across six dimensions: (i) geophysical; (ii) environmental-ecological; (iii) technological; (iv) economic; (v) socio-cultural; and (vi) institutional (IPCC 2018).

On the feasibility of BECCS (Table 4.11, IPCC (2018)), the report notes that geophysical and technological dimensions have neither a negative nor a positive effect. Conversely, it highlights potential feasibility barriers in the remaining four of the six dimensions including: environmental (biomass availability), economic status, legal framework for operating BECCS, and social acceptance.

Following our results in *Table 5*, the IAM teams are largely transparent in communicating assumptions in the geophysical dimension. IMAGE probably has the most comprehensive coverage, including terrestrial and aquatic biodiversity, flood risks, land degradation, and ecosystem services (Doelman *et al* 2018). REMIND MAgPIE has pushed the boundaries of geophysical domain representation in IAMs by assessing the deployment of BECCS within the nine planetary boundaries (Heck *et al* 2018). In particular, they include biosphere integrity, biogeochemical flows, and fresh-water use required for large scale biomass plantations. MESSAGE-GLOBIOM also includes soil quality and water scarcity and their potential impact on biomass production. AIM explicitly includes biodiversity and soil protection when assessing the global bioenergy potential (Wu *et al* 2019). However, the geophysical dimension is less transparent in the other IAMs, but implicitly assumed favourable, e.g. GCAM assumes that under a SSP2-RCP2.6 future 1,100 Mha of land are suitable for biomass production, five times more than in IMAGE (Popp *et al* 2017).

Following our results in Table 6, IAMs are more opaque in their technological assumptions on bioenergy with carbon capture, while assumptions on the CO_2 transport and storage infrastructure development and roll out are rather absent from all the IAMs we reviewed here (*Table 7*). BECCS are still in their infancy and there are largely unknown risks associated with their large scale deployment (Obersteiner *et al* 2018). We have not found any IAM communication of technology readiness level and scalability of different types of BECCS in different regions, assumptions which seem critical for a large scale roll out of BECCS (IPCC 2018).

Biomass availability is determined by the competition for land between food, energy, and other human uses, including ecosystem restoration. Considering our results in *Table 5*, IAMs are transparent in communicating assumptions around the competition for land. Future developments of land use are heavily influenced by parameters such as crop yields and livestock intensification (Popp *et al* 2017).

Intensification of land use (or land sparing), as well as its opposite, agricultural expansion, are driven by complex factors such as institutional, government, regulatory and market based instruments, type of land, income of stakeholders, etc. (IPCC 2014). These factors cut across the six dimensions indicated by the IPCC and are region and context specific. They are not usually represented in IAM frameworks, but are implicitly assumed to be in place.

One of the most critical aspects of BECCS is their ability to deliver “negative emissions” on the timescales envisaged by the IAM scenarios, i.e. to 2100 and beyond. If managed sustainably, bioenergy could contribute to global decarbonisation in the long-term, i.e. after 2050 (IEA 2017). This assumes the CO_2 emissions caused by biomass harvest would be sequestered over the life-time growth of biomass. This could be the case when harvesting fast growing woody plantations on unused or degraded land, or harvesting processing residues and standing deadwood from insect infested sites. However, harvesting currently unmanaged forests or replacing forests by fast growing plantations could result in carbon debts which could not be “paid back” this century (Lamers and Juninger 2013). Furthermore, the efficiency of bioenergy for climate change mitigation is conditioned by what it substitutes at the point in time when it becomes “carbon neutral”. With the fast increase of cheaper renewable energy options, betting on bioenergy on the long term might result in more emission rather than sequestration. In any case, informed decision making should always consider regional forest carbon balances (Lamers and Juninger 2013) and wider system impacts and counterfactuals of the whole forest and its products (Röder *et al* 2019, EASAC 2019, Torvanger 2019).

The economics of BECCS are well communicated by the IAM teams, covering the full supply chain from biomass production to the geological storage of CO_2 (*Table 8*). Missing elements however include assumptions on regional availability of financing the for roll out both large scale biomass production (including large scale modern irrigation and fertilisation (Heck *et al* 2018)), CO_2 transport infrastructure, and assessment and deployment of geological storage.

Probably the most underrepresented and least communicated dimensions that affect the feasibility of BECCS are socio-cultural and institutional/legal. (Robledo-Abad *et al* 2017) and (Gough *et al* 2018) focus on the social licence to operate, labour and skills availability, and health concerns of workers along the supply chain of BECCS. These are usually not represented in IAMs, but are implicitly assumed to be available. Institutional conditions and the governance of change in different regions are also important for the scale up and deployment of BECCS. These could include questions of regulation of the amount and certification of the sustainability of biomass, regulation of geological storage, political instability, equity (Gough *et al* 2018), or the coordination of global and national scale mitigation strategies (Obersteiner *et al* 2018). IAMs usually do not communicate institutional assumptions, but implicitly assume that they are in place to enable the deployment of up to 5 $GtCO_2$/y of BECCS in 2050 (Fuss *et al* 2018). Socio-cultural assumptions also influence the need for negative emissions, e.g. the magnitude of final demand and levers which need acting upon to reduce it. Recent IAM efforts open up and discuss assumptions around final demand, e.g. (Grubler *et al* 2018) adapt MESSAGEix- GLOBIOM to consider demand side measures, including decentralisation of supply, or change led by demand. Similarly, (van Vuuren *et al* 2018) uses IMAGE to run different scenarios of demand side mitigation options, such as lifestyle changes, populations decrease, technological change in how food - in particular meat - is produced.

6. Discussion and Conclusions on improving model transparency

IAMs have done a tremendous job in offering integrated multi-disciplinary frameworks for discussing plausible climate change mitigation futures. They have been able to both provide and quantify credible narratives of the future. By doing so, they offered a common platform (IPCC 2014) for ongoing discussions on global energy and GHG emission reduction for achieving the Paris Agreement targets. These discussions are vital for policy and investment decisions at global and national scales.

The contribution of this paper is a structured assessment of the transparency of assumptions in IAMs – using the crucial mitigation option of BECCS as a focus. We looked at five particular aspects: biomass availability, bioenergy with carbon capture technologies, CO_2 transport and storage, BECCS costs, and wider modelling assumptions which favour the deployment of BECCS. This is a difficult and time-consuming task and we employed a traffic light system to communicate levels of transparency (with full methodological details in the Appendix). The assessment of transparency also considered parameter inclusion in the modelling framework, i.e. a “red light” shows that a parameter is not referenced explicitly in the IAM publications we reviewed, and that it is potentially not included in the modelling framework. We took advantage of having one IAM (TIAM-UCL) as our in-house model to allow us to structure the specific model assumptions to investigate. While we disclose all the BECCS relevant data available in TIAM-UCL at the time of writing this paper in the Appendix, the colouring of the TIAM-UCL columns of the tables follow the same rules as for the other IAMs and are therefore based only on publicly available journal papers and documentation for TIAM-UCL.

To summarise our findings, we built a transparency ranking system by assigning each colour code a number from 0 to 1, i.e. 0 to red, 0.5 to orange, and 1 to green. Then, for each of the five BECCS aspects investigated here, we calculated individual IAM transparency scores expressed as percentage transparency to full transparency. The results of this exercise are presented in Figure 1. Note that this ranking is a snapshot of the status of these models at the time we reviewed them.

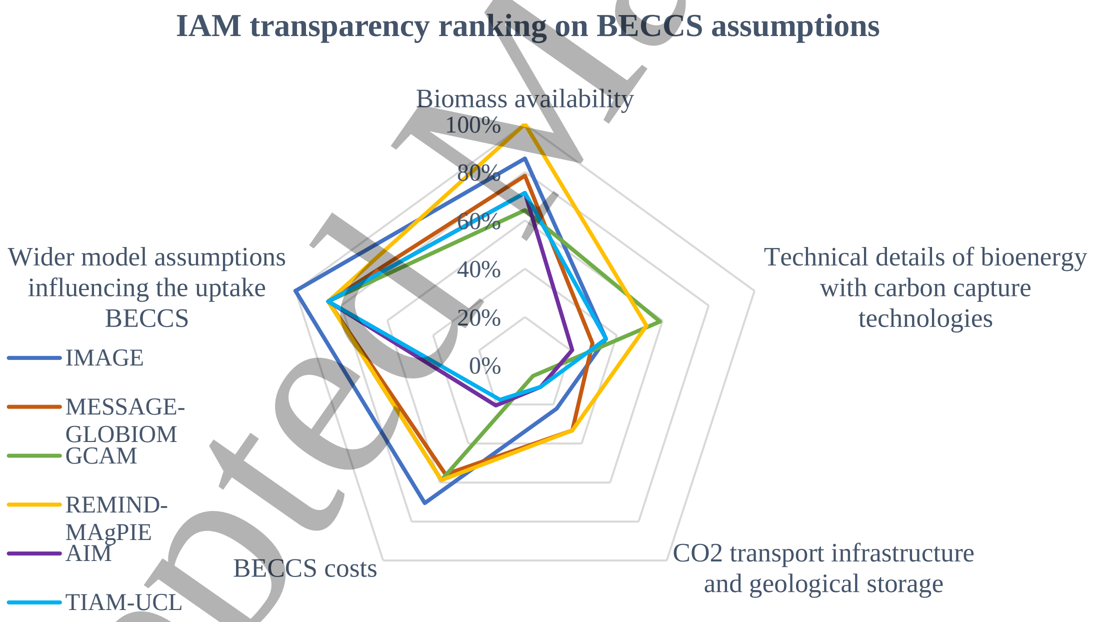

Figure 1. Summary of IAM transparency ranking on BECCS assumptions. The 5 axes represent the investigated BECCS aspects in this work. The percentages on each axis represent transparency of each IAM as percentage of full transparency of modelling assumptions, i.e. 100% means fully transparent assumptions on a given BECCS aspect vs. 0% which means no transparency (a parameter is not specified, and potentially it is not included in the modelling framework).

A notable finding is that IAMs are transparent in communicating wider system and biomass resource availability assumptions (Figure 1). This transparency decreases as we move into modelling details, the least transparent assumptions being around the CCS infrastructure. Indeed, all models score over 80%

transparency as compared to maximum transparency of the parameters we investigate here when we consider wider system settings such as general discount rate, carbon pricing regime, or availability of other NETs. IMAGE scores the highest, achieving 100% transparency on this aspect. Given the intense recent discussions around biomass availability for bioenergy and BECCS (e.g. Vaughan and Gough 2016, Robledo-Abad *et al* 2017), the IAMs also score over 60% transparency related to biomass resource assumptions, with REMIND-MAgPIE being the most transparent.

We also found that BECCS cost assumptions are more transparently communicated (between 60 and 80% transparency scores) than technological ones (between 10 and 60% transparency scores). These cost assumptions, combined with a perfect foresight (assuming correct prediction of the future) and a general discount rate usually around 5% (

Table 9), delay BECCS deployment after the second half of the century. This delay begs two topical questions around how the models account for intergenerational equity and global collaboration for aligning climate mitigation strategies (Lenzi *et al* 2018), assumptions which we found largely missing from IAMs communication. However, this has now begun to be addressed in recent analyses which vary discount rates (Emmerling *et al* 2019) or alternatively discuss the explicit intergenerational implications of mitigation pathways with regard to negative emissions technologies (Rogelj *et al* 2019).

IAMs score over 60% transparency in their assumptions on large scale biomass production. While our “green labelling” for transparency is assessed from the perspective of biomass availability for use within the global energy system, we recognise that national scale modellers, or readers from other disciplines might wish to see other aspects of land use competition which might not be included in the modelling framework or communicated transparently. The majority of the pathways that are compatible with a SSP2-RCP2.6 future deploy large scale BECCS in the second half of the century. This implicitly assumes that the land will be (i) available, at a time when the demand for land is likely to be high (Obersteiner *et al* 2018), and (ii) suitable for crop production, which is subject to climate change impacts on land, usually not included in the scenario runs (van Vuuren *et al* 2017). A further critical assumption is that biomass is supplied without carbon debts. For this assumption to hold, careful temporal carbon accounting with a focus on bioenergy would need to be conducted in each region (Lamers and Juninger 2013). This accounting is not visible in any of the investigated IAMs.

Modelling assumptions around the CCS infrastructure and geological storage were found to have limited transparency with all IAMs scoring below 40%. The IAM community is trying to address this problem either through detailed documentation (e.g. REMIND documentation (Luderer *et al* 2015)), topical model specific studies (e.g., (Muratori *et al* 2017b) for GCAM), or through model inter-comparisons (notably (Krey *et al* 2019), which makes technical assumptions visible (parameter values) and explains differences between IAMs). Comparison exercises could be repeated for other technologies, including BECCS for transport fuels and hydrogen. These studies should be complemented by analyses of the influence the technological assumption have on model results. Some IAM inter-comparison studies assess the sensitivity of model results to BECCS technology availability (Bauer *et al* 2018), and CCS assumptions (Koelbl *et al* 2014). However, for a better understanding of how assumptions influence the model results, cost and technological assumptions should be published with each individual IAM study (Koelbl *et al* 2014). This is in line with aspirations for the forthcoming IPCC’s 6th Assessment report (IPCC 2017).

While focusing on assessing BECCS assumptions, we found that it was difficult to separate transparency from completeness (i.e., what the IAMs do not include or is implicit). Our deep transparency analysis in Section 4 considered whether the IAM specifically includes the parameter of concern in its modelling framework. We acknowledge that our selection of parameters to investigate is not exhaustive, but is tailored to energy systems modelling needs. Scientists from other disciplines might wish to investigate other parameters which have not been considered here. This could be subject to further transparency analyses. In Section 5 we assessed the completeness by contrasting BECCS assumptions in IAMs against the six dimensions of feasibility suggested by the IPCC 1.5 ºC Special Report (IPCC 2018). We found that IAMs cover fairly well four out of six feasibility dimensions, namely, geophysical, economic, environmental, and technical. What is missing, but critical for establishing BECCS at large scale, are the socio-cultural and institutional-regulatory dimensions. This finding is in line with other studies, e.g. (IPCC 2018, Gough *et al* 2018).

We do not suggest that IAMs should be expanded to represent these socio-cultural and institutional-regulatory dimensions, but when assessing IAM scenario results it is important to acknowledge the missing elements so other disciplines can participate in the discussion. Some steps in this direction have already been made by IAM researchers recognising the need to complement global results with regional scale analyses to better consider regional specificities of competition for land and its effects on ecosystem services (IPCC 2018).

Overall, we can say that a higher transparency of assumptions in IAMs is possible. Figure 1 shows that for each category we investigated, different IAMs are “best in class” at communicating transparently in their assumptions. We cannot say that any single IAM is more transparent than the others, but we can say that if desired, higher transparency can be achieved in all the investigated categories. At present, finding modelling assumptions is not straightforward, and requires going from the model documentation to the referenced documents, or to prior model versions for which the documentation is inaccessible. Clear and easy to trace documentation for current and past model iterations would be ideal, so that past results can be understood and differentiated from more recent ones. Some modelling commentators (DeCarolis *et al* 2017), suggest that model assumptions should be documented with each publication, with links to a data repository. In the particular case of land competition assumptions in IAMs, given the incredible complexity of the topic, huge amounts of data and assumptions for long-term developments which are difficult to assess based on current drivers, increasing transparency through documentation in every publication might be overwhelming for both IAM teams and their readers. In this case, increased transparency could be achieved through multi-disciplinary workshops in which specific assumptions are discussed in specific contexts from a multitude of angles (Pye *et al* 2018).

One alternative to help increase transparency is the provision of open-source models, which GCAM and MESSAGEix-GLOBIOM teams already do. While they do provide training with their models, they remain complex, and running them with full understanding of underlying assumptions and drivers is a very time-consuming task. A more meaningful approach to increase transparency could consist in iterations with different audiences, gradually opening to scrutiny other assumptions in specific contexts (Strachan *et al* 2016).

A final key element is building explicit resources into projects for transparency work. In practice this is difficult to achieve, as the funding for model maintenance tasks is intermittent or inexistent, and the time and reward of researchers comes from high profile publications (Strachan *et al* 2016). But this brings us full circle to increase the transparency of assumptions in IAMs as a bridge to funders, policy makers and other disciplines (DeCarolis *et al* 2017). This would be a timely and critical exercise to increase the recognition of IAM results, and to enable different communities to work together for climate mitigation.

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Data availability statement

Any data that support the findings of this study are included within the article and the Appendix.

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