Assessing negative CO_2 emissions potential at national level, constrained by the Paris temperature goals: case study of Ireland

Barry MCMULLIN[1*#], Paul PRICE[1], Aideen O'DOCHARTAIGH[1], Mike JONES[2], Alwynne MCGEEVER[2], Paul RICE[2]

[1] *Dublin City University, Dublin, Ireland*

[2] *Trinity College Dublin, Dublin, Ireland*

**Corresponding Author, barry.mcmullin@dcu.ie, #Presenting Author*

Abstract

Informed by scientific assessment of severe risks to human welfare, the parties to the Paris Agreement have committed to goals of limiting warming to well below 2°C over pre-industrial and pursuing efforts to limit the increase to 1.5°C. For any given temperature goal, there is a corresponding limit on net cumulative CO_2 emissions, termed the Global Carbon Dioxide Budget (GCB). Ideally, net CO_2 emissions must cease ("global net-zero") before reaching the GCB limit for the temperature goal; however, if overshoot of this limit arises, then net negative CO_2 emissions (requiring gross Carbon Dioxide Removal or CDR) will be needed to return to the GCB level. Nonetheless, the prospect of deploying so-called negative emissions technologies (NETs) to achieve CDR carries a substantial moral hazard: such technologies vary greatly in maturity, and remain very uncertain in feasibility, scale and deployment timing. The Paris Agreement relies on *voluntary, bottom-up, actions* by the parties. An approach that could ensure the global GCB limit is respected would be for each Party to assess its claimed GCB "fair share" (National CO_2 *Quota* or NCQ), and formulate national net CO_2 mitigation pathways consistent with this assumed share, making explicit any putative role for CDR. The Irish Environmental Protection Agency (EPA) recently funded a research project, **IE-NETs**, to provide a preliminary research basis to inform such an assessment for the specific case of Ireland.

A prudent, minimally equitable, Paris-aligned CO_2 quota for Ireland was estimated as a maximum of 400 $MtCO_2$ from 2015. This relies on particular assumptions of prudence, equity and global mitigation of non-CO_2 greenhouse gases. Projections indicate that this national quota may be exceeded by 2024, and could exceed an accumulated overshoot of 600 $MtCO_2$ by 2050. Deployment of NETs might limit (and then reverse) such NCQ overshoot. Aggregate *technical* potential for accumulated CDR (up to 2100) was found to be approximately 600 $MtCO_2$. The corresponding *practical* potential is likely to be substantially less. It is recommended that a prudent policy for NETs potential in Ireland is to limit CDR

dependence to no more than 200 $MtCO_2$. In any case, we recommend formal adoption of a nationally determined net cumulative CO_2 quota (NCQ), with explicit limits on both the scale and duration of any NCQ overshoot. This could provide the basis for developing broad society-wide consensus on an equitable and prudential balance between *immediate* reductions in gross CO_2 emissions and *inter-generational commitment* to future, sustained and large scale, CDR.

1 Introduction

In this paper we summarise some key outcomes of a recent research project, IE-NETs, funded by the Irish Environmental Protection Agency (EPA) to provide a preliminary assessment of the potential for deployment of Negative Emissions Technologies (NETs)[1] in Ireland. This is derived from material presented in the IE-NETs final project report [1], and is a further development of methods and analysis previously presented in [2].

2 Overview of NETs Options for Ireland

Potential NETs approaches may be firstly classified according to the targeted carbon storage mechanism: either biogenic (soil organic carbon or standing plant biomass) or geological (typically by pumping captured CO_2, under pressure, into suitable porous rock formations). Concerns over saturation and permanence of biogenic storage mean that it is best viewed as only a transitional measure. Ultimately, only the return of carbon to secure geological storage can be relied on to adequately counteract the accumulated effects of transferring carbon from geological stocks of fossil fuels to the atmosphere. NETs can also be classified by the mechanism for initial removal of CO_2 from atmosphere. Again, there are two main possibilities: either biogenic (via photosynthesis) or technological (primarily "direct air capture" or DAC). Table 1 summarises the NETs technologies to be considered here for specific deployment in Ireland.

There is extensive prior experience in Ireland with afforestation, and more limited experience with bioenergy crop cultivation, and with enhancement of soil carbon sequestration via the use of biochar (BC) or otherwise. There is no existing experience with either DACCS or BECCS due primarily to the immaturity and cost (to date) of carbon capture and storage (CCS). BECCS, DACCS and EW would interact significantly with the overall energy system: BECCS could contribute net energy, whereas both DACCS and EW would require additional energy consumption. Note that while BECCS is most commonly conceived in terms of electricity generation, it may also include integration of bioenergy and CCS with conversion to other non-carbon energy carriers such as hydrogen (H_2) or ammonia (NH_3) and/or direct end use (e.g., for high temperature heat energy). With the exception of DACCS, all the NETs mentioned in Table 1 would interact very substantially with domestic land use and agricultural practices; in some cases competing with existing land use (bioenergy crops, afforestation) and in other cases

[1] For our purposes, we take NETs, "Negative CO_2 Emissions" and "Carbon Dioxide Removal" (CDR) to be essentially synonymous.

Table 1: High-level NETs classification

Negative Emission Technology	Removal	Storage
Enhanced Soil Carbon Sequestration (SCS)	Biogenic	Biogenic
Biochar (BC)	Biogenic	Biogenic
Afforestation (AF)	Biogenic	Biogenic
Enhanced weathering (EW)	Technological	Geological
Bioenergy with Carbon Capture and Storage (BECCS)	Biogenic	Geological
Direct Air Carbon Capture with Storage (DACCS)	Technological	Geological

potentially being complementary to, or co-existing with, existing use (enhanced soil carbon sequestration, enhanced weathering).

There are many challenges and limitations of deploying and scaling up various NETs options in Ireland. Barriers include technical readiness, cost, storage permanence, and knowledge gaps in Ireland-specific research.

As previously explained in [2] we adopt an assessment methodology originally developed by Smith et al. [3]. This presents a method to estimate the technical CO_2 removal capacity (annual flow, not cumulative/stock) of various NETs options under hypothetical land area availability scenarios for the UK. In [2] we developed this methodology to model the general potential for such NETs to contribute to effective (CO_2-quota based) climate change mitigation in Ireland. In the current paper we present further and updated analysis, focussed on the modelling of the potential time evolution of *cumulative* CO_2 removal. This provides an approximate estimate, or proxy, for the time evolution of the *climate forcing* reduction effect arising from such removal.

The analysis of Smith et al. [3] relies on a number of quantitative parameters for a variety of NETs (under UK conditions). Table 2 summarises these parameter ranges (with unit conversions for consistency with the conventions of the current paper). It is important to emphasise the caution by Smith et al. that this methodology omits important systemic and socio-political issues and interactions around NETs deployment, and that these "… would be expected to lower considerably" the estimates of technical potential [3] (p. 1401). Accordingly, we focus attention on the "low" estimates for the removal potential shown, noting that even these are likely considerably higher than could be realised under realistic economic, political and social constraints, especially under the expected additional stress of unfolding climate change impacts (nationally, regionally and globally).

With the exception of DACCS (which will be considered separately in the conclusion), the key limiting factor for indigenous use of all the NETs shown in Table 2 is the available land area for their deployment. In the current analysis we are focussed on the territorial potential for

Table 2: Estimated parameter ranges for specific negative emissions technologies (under UK/Irish conditions where relevant). Derived from [3].

Technology		**SCS**	**EW**	**AF**	**Biochar**	**BECCS**	**DACCS**
CO_2 removal rate (flow) per land area (tCO2/ha per year)	**Low**	0.1	3.0	12.5	4.2	11.0	
	High	3.7	40.0	12.5	27.5	44.0	
Water use (10^3 m^3/tCO_2)	**Low**	0.00	0.00	0.32	0.00	0.55	0.02
	High	0.00	0.00	0.64	0.00	0.68	0.03
Energy input (MWh/tCO_2)	**Low**	0.00	0.23	0.00	-3.79	-2.92	0.20
	High	0.00	3.50	0.00	-1.52	0.66	3.47
Nitrogen (kg N/tCO_2)	**Low**	21.82	0.00	0.55	8.18	3.00	0.00
	High	21.82	0.00	1.36	8.18	5.45	0.00
Phosphorus (kg P per tCO_2)	**Low**	5.45	0.00	1.09	2.73	0.22	0.00
	High	5.45	0.00	1.36	2.73	5.45	0.00
Potassium (kg K/tCO_2)	**Low**	4.09	0.00	0.11	19.09	1.55	0.00
	High	4.09	0.00	0.85	19.09	6.00	0.00
Albedo impact (dimensionless)	**Low**	0.00	0.00	0.00	0.08	0.00	0.00
	High	0.00	0.00	0.62	0.12	0.04	0.00
Cost (€/tCO_2)	**Low**	-41	23	16	-205	33	394
	High	10	1450	27	296	33	512

Ireland, so we must estimate the feasible land use change to facilitate this. COFORD (Council for Forest Research and Development, Ireland) classifies Irish land into four distinct levels [4]. The level most suitable for potential NETs deployment is level 4: 'Land most likely to have potential for forest expansion'. We assume that SCS could, in principle, be applied to all of this (3.75 Mha), without conflict with existing use. For BECCS, AF and BC, the assessment is informed by the potential land area available for bioenergy crops in Ireland [5], constraints on land use change (LUC) arising from the EU Common Agricultural Policy (CAP) [6] and the existing national afforestation target for 2050 [4]. On this basis, two illustrative land use change scenarios (for the aggregate of new AF, BC and/or BECCS) are considered: a "low" scenario of 0.55 Mha, and a "high" (very ambitious/disruptive) scenario of 1.0 Mha. We assume that EW at an application rate up to 10t rock/ha might be applied to all Level 4 land (3.75 Mha); though noting that the most comparable existing practice, liming, is generally applied at rates less than 0.4 t/ha, this would have to be considered as extremely ambitious in both total area and application rate. Based on these land use scenarios, we derived in [2] an assessment of the range of annual NETs potential, impacts and costs, specific to Ireland, and reproduced here as

Table 3. AF, Biochar and BECCS are regarded as competing for the same land use: so these potentials are mutually exclusive, and the separate potentials shown are *not* additive. This general caution on NETs interactions is also highlighted in the comprehensive assessment of [7].

Table 3: Summary of areas, CO_2 removal (negative emission) potential, impacts on water use, energy and nutrient (N, P and K) requirements, and bottom-up estimates of cost, for Ireland. Derived from [2].

Technology	**SCS**	**EW 10t/ha**	**AF**		**Biochar**		**BECCS**	
LUC scenario			**Low**	**High**	**Low**	**High**	**Low**	**High**
Area applied (Mha)	3.75	3.75	0.55	1.00	0.55	1.00	0.55	1.00
CO_2 removal rate (Mt CO_2 per year)	0.41	11	7	12	2	4	6	11
Water use (10^9 m^3 per year)	0.000	0.005	2.207	4.012	0.000	0.000	3.300	6.000
Energy input (TWh per year)	0.000	2.597	0.000	0.000	-8.785	-15.972	-17.692	-32.167
Nitrogen (kt N per year)	9.000	0.000	3.740	6.800	18.975	34.500	18.150	33.000
Phosphorus (kt P per year)	2.250	0.000	7.480	13.600	6.325	11.500	1.320	2.400
Potassium (kt K per year)	1.690	0.000	0.748	1.360	44.275	80.500	9.405	17.100
Cost, low estimate (M€ per year)	-17	259	110	200	-474	-862	197	358
Cost, high estimate (M€ per year)	4	16,572	182	332	686	1,247	197	358

While this provides a useful insight into the technical range of annual *flow* of NETs CO_2 removal potential for given land use, from the point of view of effective climate mitigation it is actually the cumulative *stock* of removed (and stored) CO_2 that is of critical interest. Several additional factors must be accounted for to assess this: the feasible deployment start year (varying according to the current maturity of different technologies), the deployment rate in time for any given land use change (ha per year) up to the specified target land use, and any carbon storage saturation effects.

For illustrative purposes, we assume SCS, BC and AF are already mature and could start deployment (as NETs: specifically no-harvest AF) from 2023. For BECCS we assume deployment starting from 2030, and EW (which requires access to commensurate, effectively zero-carbon, energy) from 2035.

In assessing feasible deployment rates, where this involves significant land use *change* (AF, BC, BECCS) we note that the existing target AF rate is estimated as 15 kha/year (from 2020), while recently achieved rates have been less than half this [4]. For the current illustrative purpose, we model a notional deployment rate for NETs specific (no-harvest) AF, BC and/or BECCS (each considered in isolation) of 30 kha/year, but acknowledging that this is likely at the extreme upper end of what might be achievable in practice. For EW (at 10 tonne rock/ha), which does not require full land use change, but would still involve very considerable changes in land use practice and deployment of large scale support infrastructure (in rock mining, processing, transport and application) we set a notional deployment rate of 60 kha/year. And for SCS which, in principle, requires the least changes in existing land use practice, we set a notional deployment rate of 200 kha/year.

Biogenic carbon storage saturation limits apply specifically to SCS, AF and BC. For illustrative purposes here, and consistent with the discussion of Smith et al [3], we model saturation after 20 years for SCS and AF, and after 40 years for BC. For AF we note that the most critical question is the harvest regime (if any) and the subsequent processing of harvested material. A specific scenario that would merit more detailed consideration could be intensive afforestation, without large scale harvest in the short to medium term (2-20 years), potentially allowing time for BECCS technology to mature and be deployed at scale. Then, as BECCS infrastructure becomes available, AF harvest (and replanting either in forest or short rotation dedicated bioenergy crops[2]) might be used to effectively convert the accumulated AF biogenic carbon store into more secure geological CO_2 storage, while continuing to maintain and expand the land area under AF and/or short rotation bioenergy crop cultivation. On the other hand, it must be noted that such a strategy *might* inhibit interim substitution of fossil energy use and/or fossil energy intensive building products (steel, concrete) by potentially lower impact forest harvest. There is an extensive existing literature on assessment of more conventional alternative pathways for carbon, energy and harvested wood products according to alternative forest use scenarios e.g., [8]–[10]. Nonetheless, detailed modelling of such integrated multi-NET pathways, potentially interacting with wider mitigation measures, is beyond the scope of the current analysis, so we simply show AF saturation at 20 years (effectively a conservative no-harvest assumption).

Of course, geological storage of CO_2 (BECCS and DACCS) is also subject to potential saturation limits on suitable available geology. The technical storage capacity in the close vicinity of Ireland has been estimated as approximately 1,600 $MtCO_2$ [11] , with the practical and economic capacity likely substantially smaller. Nonetheless, for the purposes of the current assessment, we assume that geological CO_2 storage capacity would *not* be a limiting factor on the deployment of BECCS (or DACCS) within the time frames and deployment scales being considered. In any case, in the event that domestic CO_2 geo-storage capacity was exhausted, there would also be potential for exporting of CO_2 for storage in other jurisdictions[3], albeit with significant added cost and potential added gross CO_2 emissions (to be offset against the assessed removals).

[2] Note that a change of land use from forestry to short rotation bioenergy crops would be classified as *deforestation* under current Irish legislation, and prohibited as such. New or amending legislation would therefore be required to enable any such policy intervention.

[3] See, for example, the **Longship CCS** project being developed by Norway: https://ccsnorway.com/

It should still be noted that the existence of limits on indigenous geological CO_2 storage capacity, even if currently uncertain, means that *all* CCS deployment, specifically including CCS on conventional fossil fuel use (FFCCS), should be critically assessed in the light of such limits. There may be a case for prioritising such CO_2 storage for BECCS/DACCS over FFCCS (i.e. favouring direct elimination of FF use rather than relatively temporary substitution of FFCCS), but detailed assessment of that issue is beyond the scope of the current paper. Separately, in the case of EW, where carbon is stored in stable mineral form, and ultimately transported to long term seabed storage, we assume no saturation or storage capacity limit would apply within relevant time frames and deployment scale.

3 Illustrative Pathways for NETs Deployment in Ireland

With these assumptions, it is then possible to model illustrative pathways for the deployment of the land-use constrained NETs in Ireland, and assess the CO_2 removal flow and corresponding cumulative CO_2 stock that might be removed from atmosphere. These pathways are summarised in Table 4 and shown graphically in Figure 1 and Figure 2 respectively.[4]

Table 4: Summary of illustrative NETs CO_2 removal pathways for Ireland.

Technology	Start year	Max area (Mha)	Max flow ($MtCO_2$/yr)	Max energy input (TWh/yr)		Stock ($MtCO_2$)			
				Low	High	2025	2050	2075	2100
SCS	2023	3.750	0.41			0	7	8	8
EW (@10t/ha)	2035	3.750	11.28	2.56	39.46	0	25	155	397
Biochar (low-LUC)	2023	0.550	2.32	-8.78	-3.51	1	45	91	93
Biochar (high-LUC)	2023	1.000	4.22	-15.97	-6.39	1	51	144	169
BECCS (low-LUC)	2030	0.550	6.05	-17.69	3.99	0	75	226	377
BECCS (high-LUC)	2030	1.000	11.00	-32.17	7.25	0	76	328	603
AF (low-LUC)	2023	0.550	6.86			2	119	137	137
AF (high-LUC)	2023	1.000	12.47			2	138	249	249

[4] The detailed spreadsheet modelling tool to produce these pathways has been separately released for re-use under open licencing. It is available at: https://tinyurl.com/IENETsPotentialV2

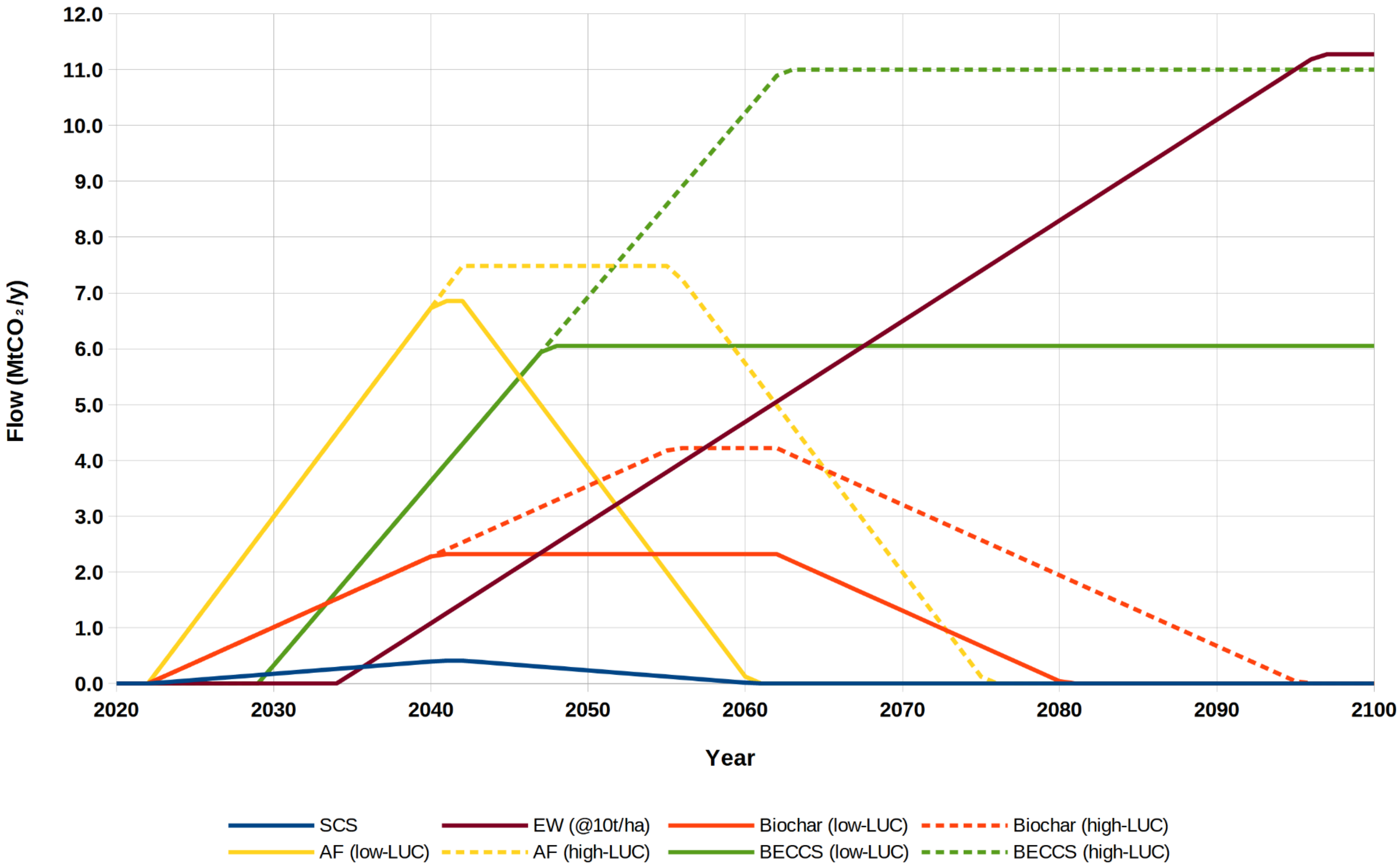

Figure 1:Illustrative NETs CO_2 removal flow pathways ($MtCO_2$/year) for Ireland, 2020-2100.

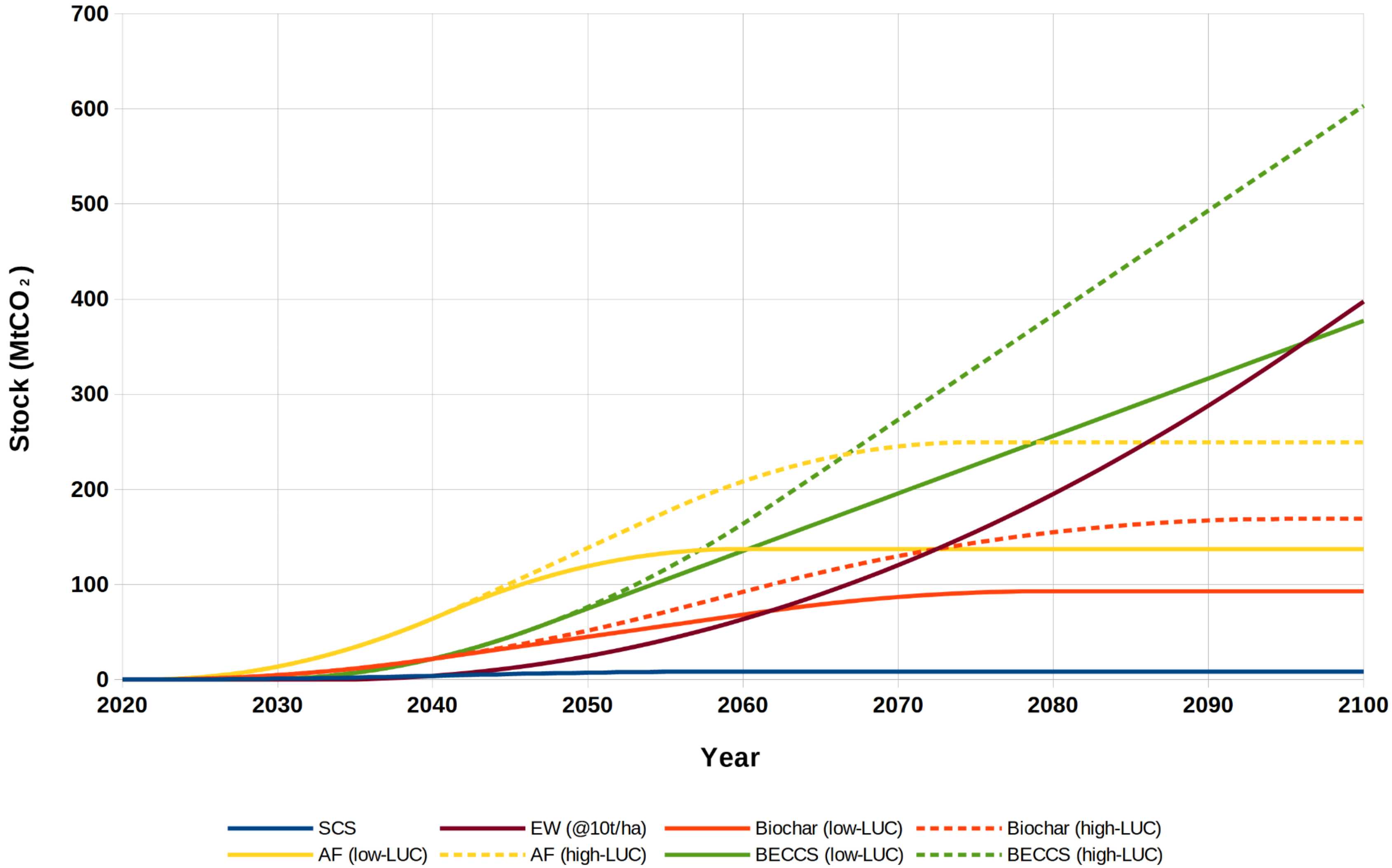

Figure 2: Illustrative NETs CO_2 removal stock pathways ($MtCO_2$) for Ireland, 2020-2100.

4 Discussion

We have presented an assessment and illustrative pathways for the deployment of NETs in Ireland. In the short to medium term (5-15 years), the most promising quantitative option appears to be afforestation (AF), due to its simplicity and technical maturity. However, effective CO_2 removal through AF depends critically on actually achieving a steadily increasing forest carbon stock, for example through a moratorium on harvest. As noted, such a moratorium may inhibit interim substitution of fossil energy use and/or fossil energy intensive building products (steel, concrete) by potentially lower impact forest harvest. Further, existing AF policy *assumes* economic support from harvest income, and would have to be fundamentally re-evaluated under any harvest moratorium. Even under this condition, depending on land use commitment, AF removal is estimated to saturate at the order of 140-250 $MtCO_2$ removed, with saturation reached between 2050 and 2065. While the assumed 20-year AF saturation time is likely an underestimate, the CO_2 removal flow rate of 12 tCO_2/ha per year is likely an overestimate cf., [12], [13]. The most critical constraints on AF removals are therefore the feasible deployment rate and maximum total land that can be afforested, within social, political and economic constraints as well as the resilience of the forest to possible negative impacts of climate change (particularly water stress during droughts), attacks of diseases, storm damage and forest fires. A prudent estimate of practically achievable total indigenous AF removal is therefore likely significantly less than 100 $MtCO_2$. Even this would be very vulnerable to re-release, either through harvest or natural loss (particularly under climatic stress). Accordingly, it appears that AF is best viewed as a short-term, CO_2 removal "triage" measure, with a clear strategic objective for the removed carbon to be transferred to secure, long term, geological storage as soon as possible: most likely through early deployment of BECCS.

In the longer term, BECCS (combined with indigenous bioenergy crop cultivation) currently appears to offer the prospect of large scale indigenous CO_2 removal with secure long-term storage. It has the additional possible co-benefit of providing net energy output, potentially in the form of dispatchable electricity and/or storable non-carbon chemical fuels (H_2, NH_3) which could substantially complement indigenous variable (non-dispatchable) renewable energy sources (primarily wind and solar). The illustrative pathway indicates a BECCS cumulative removal potential of 400-600 $MtCO_2$ by 2100. However, it should be emphasised that this is an estimated *technical* potential only. It is premised on extremely ambitious early, rapid and sustained deployment of BECCS infrastructure (including CO_2 geo-storage), rapid and sustained land use change to bioenergy cultivation, and ultimately large scale land use re-allocation. Further, the potential interactions of BECCS with other NETs and non-BECCS uses of bioenergy remain complex and difficult to anticipate [14]. Thus, at this point, while early BECCS deployment may usefully be made a significant policy priority, a prudent estimate of the cumulative removal potential, on relevant policy timescales, is likely significantly less than 200 $MtCO_2$. Note that this is not *in addition* to the AF potential: as AF and (other) bioenergy cultivation ultimately compete for the same land use, and AF carbon storage is impermanent, AF carbon stocks ultimately needs to be transferred to secure geo-storage (via BECCS or otherwise).

While, based on the methodology and specific parameter estimates of Smith et al [3], the potential contributions of SCS and BC (even with very ambitious deployment) appear less promising than AF and BECCS, nonetheless given the relative maturity of these techniques, their relatively low estimated costs (indeed, perhaps zero or negative – theoretically requiring no economic incentive) and the potential for other co-benefits (improved soil quality, reduced agricultural inputs) there is clear merit in also including these in the policy mix. A relevant consideration here is the recent advice from the Irish Climate Change Advisory Council (CCAC) that agroforestry deployment should be actively considered in Ireland [13], pp. 119-120. This potentially overcomes some disadvantages of conventional commercial (intensive monocrop) afforestation. While the expected CO_2 removal rate of agroforestry cited by the CCAC is significantly less than assumed above for conventional AF (c. 7 tCO_2/ha per year vs 12 tCO_2/ha per year), unlike AF it *can* be effectively combined with other complementary land use. A particular possibility may be with bioenergy crop cultivation, potentially contributing to both improved SCS and a BC pathway. This might conceivably allow early synergistic combination of agroforestry based AF, BC and SCS for short to medium term CO_2 removal and storage (pending the progressive – and uncertain – deployment of BECCS). This could also have some localised energy supply benefits (primarily heat energy in BC production). While such integrative possibilities should certainly be the subject of further research and pilot implementation, there is no current basis to suppose that such a combination would significantly increase the overall practical potential for cumulative CO_2 removal and storage as compared to conventional AF alone.

While the *technical* potential of EW is shown as being approximately comparable to BECCS, this again relies on extremely ambitious deployment rate and scale; and, more critically, would require very substantial net energy input – which would have to come from extremely low CO_2 sources, and would necessarily compete with other societal energy needs. While DACCS potential has not been quantitatively modelled here (as it is not constrained by indigenous land use as such) it would similarly require large scale, very low CO_2, energy inputs; and would additionally compete with BECCS (and FFCCS, if deployed) for CO_2 geo-storage capacity. Thus, while both EW and DACCS will bear continuing research and perhaps pilot scale deployments, it would not be prudent at this time to assume large scale contributions to cumulative CO_2 removal from either of these.

5 Conclusion

In conclusion, we find that a current *prudent* assessment of cumulative indigenous CO_2 removal potential for Ireland, across the full portfolio of NETs considered, would be significantly less than 200 $MtCO_2$; and even this would require urgent and disruptive new policy measures to bring it about on a timely basis. This assessment is preliminary and it is recommended that a programme of continuing research should be sustained to allow ongoing refinement and updating of estimates of CO_2 removal potential in the light of improvements in both underlying scientific understanding and deployment experience. Nonetheless, in the current state of knowledge, this assessment can be directly compared to the analysis presented in Chapter 2 of the full IE-NETs report [1], indicating a potential overshoot of Ireland's prudent, Paris-aligned, "fair share" CO_2 emission quota by as much as 600 $MtCO_2$ as early as 2050 (based on policy ambition as of the time of that report). The difference between these (400 $MtCO_2$+) is a quantitative indication of the gap, in mitigation scale and speed, between even an ambitious interpretation of national policy and the internationally agreed temperature goals of the Paris Agreement. This implies that, *even* assuming "anticipatory reliance" on NETs for future CO_2 removals, it is still the case that very deep, near term, reductions in gross CO_2 emissions are required. In particular, pending successful large scale deployment of NETs, it is recommended that a prudent ceiling on the accumulation of CO_2 quota *overshoot* would be c. 200 $MtCO_2$.

Climate policy in Ireland continues to evolve, with the recent adoption of new climate legislation [15], leading to a new framework of rolling, 5-year, multi-gas emissions "budgets", aggregating CO_2, N_2O and CH_4 (on a GWP_{100} basis) [16], [17]. However, as is well established, GWP_{100} aggregation is generally a poor indicator of warming effect for short-lived gases such as CH_4 [18]. Both CH_4 and N_2O play a very significant role in Ireland's overall GHG profile due to its relatively large ruminant agriculture sector. Accordingly, in separate work [19], we apply the complementary GWP* [20] aggregation method to assess the implications of setting a ceiling on cumulative emissions quota overshoot (implied CO_2 removal commitment) in such a multi-gas budgeting framework. We find that this is likely to require the achievement of Irish national net-zero territorial emissions specifically of CO_2 significantly earlier than the current aggregate "net-zero" target date of 2050 while *also* radically reducing the *rate* of annual CH_4 emissions (by 50% or more).

In conclusion, on the basis of the assessment presented here, it is proposed that a current, prudent, upper policy assumption for NETs potential in Ireland should be gross removals of no more than 200 $MtCO_2$. We recommend the formal adoption of a nationally determined net cumulative CO_2 quota (NCQ), with explicit limits on both the scale and duration of any CO_2 quota overshoot. This could provide the basis for developing broad society-wide consensus on an equitable and prudential balance between *immediate* reductions in gross CO_2 emissions and *inter-generational commitment* to future, sustained and large scale, gross removals of CO_2.

6 References

[1] B. McMullin, P. Price, M. B. Jones, A. McGeever, and P. Rice, 'IE-NETs: Investigating the Potential for Negative Emissions Technologies (NETs) in Ireland', Environmental Protection Agency (Ireland), Wexford, Ireland, Research Report 354, Nov. 2020. https://www.epa.ie/publications/research/climate-change/Research_Report_354.pdf

[2] A. H. McGeever, P. Price, B. McMullin, and M. B. Jones, 'Assessing the terrestrial capacity for Negative Emission Technologies in Ireland', *Carbon Management*, pp. 1–10, Jan. 2019. https://doi.org/10.1080/17583004.2018.1537516

[3] P. Smith, R. S. Haszeldine, and S. M. Smith, 'Preliminary assessment of the potential for, and limitations to, terrestrial negative emission technologies in the UK', *Environmental Science: Processes & Impacts*, vol. 18, no. 11, pp. 1400–1405, 2016. https://doi.org/10.1039/C6EM00386A

[4] COFORD, *Land availability for afforestation: exploring opportunities for expanding Ireland's forest resource*. Dublin, Ireland: COFORD, 2016. https://tinyurl.com/COford-LUF-2016

[5] SEAI, 'BioEnergy Supply Curves for Ireland: 2010 - 2030', Sustainable Energy Authority Ireland (SEAI), Dublin, Ireland, Oct. 2012. https://tinyurl.com/SEAI-BE-Supply-archived

[6] DAFM, 'A Guide to Greening: 2015', Department of Agriculture, Food and the Marine (Ireland), Dublin, Ireland, Feb. 2015. https://tinyurl.com/DAFM-Greening-2015

[7] S. Fuss *et al.*, 'Negative emissions — Part 2: Costs, potentials and side effects', *Environmental Research Letters*, vol. 13, no. 6, p. 063002, Jun. 2018. https://doi.org/10.1088/1748-9326/aabf9f

[8] A. Cowie, G. Berndes, and T. Smith, 'On the Timing of Greenhouse Gas Mitigation Benefits of Forest-Based Bioenergy', International Energy Agency, ExCo:2013:04, 2013. https://tinyurl.com/Cowie2013

[9] O. Cintas *et al.*, 'Carbon balances of bioenergy systems using biomass from forests managed with long rotations: bridging the gap between stand and landscape assessments', *Global Change Biology Bioenergy*, vol. 9, no. 7, pp. 1238–1251, 2017. https://doi.org/10.1111/gcbb.12425

[10] K. Koponen, S. Soimakallio, K. L. Kline, A. Cowie, and M. Brandão, 'Quantifying the climate effects of bioenergy – Choice of reference system', *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 2271–2280, Jan. 2018. https://doi.org/10.1016/j.rser.2017.05.292

[11] I. J. Farrelly, B. Loske, F. P. Neele, and M. P. Holdstock, *An Assessment of the Potential for Geological Storage of CO_2 in the vicinity of Moneypoint, Co. Clare*. Johnstown Castle, Co. Wexford: Environmental Protection Agency (Ireland), Geological Survey of Ireland, 2010. http://www.epa.ie/pubs/reports/research/climate/ccrpreport4.html

[12] I. J. Bateman and A. A. Lovett, 'Estimating and valuing the carbon sequestered in softwood and hardwood trees, timber products and forest soils in Wales', *Journal of Environmental Management*, vol. 60, no. 4, pp. 301–323, Dec. 2000. https://doi.org/10.1006/jema.2000.0388

[13] CCAC, 'Annual Review 2019', Climate Change Advisory Council [Ireland], Annual report, Jul. 2019. https://tinyurl.com/CCAC-IE-Review-2019

[14] I. Butnar, O. Broad, B. S. Rodriguez, and P. E. Dodds, 'The role of bioenergy for global deep decarbonization: CO_2 removal or low-carbon energy?', *Global Change Biology Bioenergy*, no. 12, pp. 198–212, Dec. 2019. https://doi.org/10.1111/gcbb.12666

[15] Oireachtas, 'Climate Action and Low Carbon Development (Amendment) Act 2021', Houses of the Oireachtas (Parliament of Ireland), text No. 32 of 2021, Jul. 2021. https://www.oireachtas.ie/en/bills/bill/2021/39

[16] S. Burns, 'Carbon budgets to help halve emissions passed in Dáil without a vote', *The Irish Times*, 07-Apr-2022. https://tinyurl.com/IE-Carbon-Budgets-Adopted

[17] CCAC, 'Technical report on carbon budgets', Climate Change Advisory Council (Ireland), Oct. 2021. https://tinyurl.com/CCAC-CB-TR

[18] M. R. Allen *et al.*, 'A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation', *npj Climate and Atmospheric Science*, vol. 1, no. 1, p. 16, Jun. 2018. https://doi.org/10.1038/s41612-018-0026-8

[19] Paul Price, Barry McMullin, and Aideen O'Dochartaigh, 'Methane mitigation, including agriculture, is crucial to limiting dependence on uncertain carbon dioxide removal in national carbon budgeting equitably meeting Paris goals', presented at the 2nd International Conference on Negative CO_2 Emissions, Göteborg, Sweden, 2022

[20] M. A. Smith, M. Cain, and M. R. Allen, 'Further improvement of warming-equivalent emissions calculation', *npj Climate and Atmospheric Science*, vol. 4, no. 1, pp. 1–3, Mar. 2021. https://doi.org/10.1038/s41612-021-00169-8

7 Funding

This work was supported by the Environmental Protection Agency (EPA, Ireland) Research Programme 2014-2020, project award 2016-CCRP-MS.36 (IE-NETs), and by a Research Fellowship award to Paul Price from the Irish Climate Change Advisory Council.