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Policy incentives for Greenhouse Gas Removal Techniques: the risks of premature inclusion in carbon markets and the need for a multi-pronged policy framework

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A B S T R A C T

Almost all modelled emissions scenarios consistent with the Paris Agreement's target of limiting global temperature increase to well below two degrees include the use of greenhouse gas removal (GGR) techniques. Despite the prevalence of GGR in Paris-consistent scenarios, and indeed the UK's own net-zero target, there is a paucity of regulatory support for emerging GGR techniques. However, the role of carbon pricing is one area that has experienced more attention than others, including discussion about the future inclusion of GGR in carbon markets.

Here we identify three risks associated with using carbon markets as the sole, or main, policy lever to encourage the deployment of GGR techniques. Our categorisation of risks stems from discussions with policymakers in the UK and a review of the broader literature on carbon markets and GGR. We present a three-pronged risk assessment framework to highlight the dangers in doing so. First, treating emissions removals and emissions reductions as entirely fungible allows for undesirable substitution. Second, carbon markets may provide insufficient demand pull to drive currently more-costly GGR techniques to deployment at commercial scales. Third, opening up a carbon market for potentially lower-cost GGR (such as nature-based solutions) too early could exert downward pressure on the overall market-based price of carbon, in the absence of adjustments to emissions caps or other safeguards. We discuss how these risks could hamper overall efforts to deploy GGR, and instead suggest a multi-pronged and intertemporal policy and governance framework for GGR. This includes considering separate accounting targets for GGR and conventional emissions abatement, removing perfect fungibility between GGR permits and carbon market permits and promoting a a wide range of innovation and technology-specific mechanisms to drive currently expensive, yet highly scalable technological GGR down the cost curve. Such a framework would ensure that policymakers can utilise carbon markets and other incentives appropriately to drive development and deployment of GGR techniques without compromising near-term mitigation, and that the representation of GGR in modelled low-carbon pathways is cognisant of its real-world scale-up potential in light of these incentives.

Key Policy Insights

Policymakers should consider a more complex set of mechanisms to deliver GGR innovation cost reductions including a range of innovation and technology-specific mechanisms

Environmental integrity issues that may arise such as permanence and additionality can be mitigated by removing perfect fungibility between GGR permits and carbon market permits

Should mature GGRs be incorporated into emissions trading schemes in the future, unrestricted linking should be avoided to avoid substitution and downward price pressure

Those modelling and simulating the take-up of GGR in low-carbon pathways should be mindful of the real-world incentives driving its realistic deployment.

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1. Introduction

Almost all modelled emissions scenarios consistent with the Paris Agreement's target of limiting global temperature increase to well below two degrees include the use of greenhouse gas removal (hereafter GGR) techniques. This is as much the case in the United Kingdom as anywhere else, even though the UK reduced domestic emissions further and faster than most developed economies.

This was made clear in the Committee on Climate Change's landmark review [18] published in May 2019, with its recommendation that emissions should fall to net-zero by 2050 rapidly being adopted by the UK Government in June 2019. In doing so, the UK became the first major economy to enshrine a genuinely Paris-compliant target in law. Encouragingly, a number of other countries have since legislated for net-zero targets, including New Zealand France and Sweden, or announced net-zero targets, including China and South Korea. It is important to note that not all nations need to achieve net-zero emissions at the same time, with several considerations including responsibility, capacity and level of economic development implying that some nations can and should achieve net-zero emissions earlier than others [98]. Furthermore, there will be an uneven geographical distribution of emissions removals potentials [98].

As implied in their name, the net-zero targets announced are based on ***net*** emissions levels, and it is important to distinguish between gross-zero and net-zero emissions. A gross-zero emissions target reduces all emissions, in all sectors, uniformly to zero. Net-zero allows for some residual emissions in hard to abate sectors – i.e. those where emissions abatement is too expensive or technological solutions do not exist – on the assumption they are offset by deeper emissions reductions or emissions removals elsewhere. The latter can be achieved using natural or engineered sinks. Net negative emissions are achieved when gross negative emissions match or exceed gross positive emissions.

Every effort needs to be made to reduce greenhouse gas emissions across all sectors of the economy. But it is also clear that a net-zero target will require some GGR techniques, also known as, 'negative emission techniques (NETs)' and henceforth used interchangeably with GGRs. For example, even under its 'Further Ambition' scenario, the CCC estimates that the UK demand for negative emissions will be 90MtCO_2e annually in 2050, with residual emissions from aviation and agriculture accounting for 35 per cent and 29 per cent of GGR demand respectively [18].

Despite the prevalence of negative emissions in Paris-consistent scenarios, and indeed the UK's own net-zero target, there is a paucity of research and development and regulatory support for emerging techniques [37]. This is especially acute for demand-side policies [75]. Understanding the viability and feasibility of demand-side policies and the role of public and private finance in the context of innovation pathways will be critical to the successful deployment of negative emissions. The role of carbon pricing, and specifically inclusion of GGRs in carbon markets, is one area that has experienced more attention than others. Research by Cox and Edwards [23] and [68] has previously examined the risks of carbon markets as the predominant policy lever for GGRs, concluding that inclusion of GGRs in carbon markets risks exacerbating moral hazard and a range of policies are needed to recognise and reward additional co-benefits that nature based GGRs offer. Our perspective piece builds on this research, highlighting two further risks beyond 'moral hazard` in a three-pronged risk assessment framework.

Our categorisation of GGR risks in carbon markets into essentially three classes stems from a review of the broader literature on carbon markets and GGR, as well as discussions with policy makers in the UK, who are now focused on the precise question of whether, and if so how, to incorporate GGR into carbon markets as a key mechanism to drive GGR development and deployment.

Hepburn [43] highlights a range of canonical problems in carbon markets, focusing on the EU Emissions Trading System, the Clean Development Mechanism and the Joint Implementation mechanisms, all established as part of the Kyoto Protocol mechanisms to cut emissions. Specific problems with the EU ETS include: the potential of free allowance allocation to drive firms to emit more in the present to secure more allowances in the future, potentially leading to over-allocation and low prices; the lack of long-term incentives for mitigation if the permit price is too low; and sudden release of permit supply-demand information which can drive price volatility, including price collapses. Specific issues of linking mechanisms such as the CDM include most importantly the risk that it has removed incentives for developing country governments to enact climate policies, since they can now fund such policies via CDM payments, thereby making CDM projects not genuinely additional to what would have occurred anyway. From this and other critiques of carbon markets we derive three salient risks – lack of fungibility, additionality and durability of linking new mechanisms and technologies into carbon markets, lack of adequate price signal for investment in more expensive technologies, and risk that over-allocation, or flooding of a carbon market, may lead to very low prices. To these technocratic risks, we add to the already large and still-expanding literature on "moral hazard" and mitigation deterrence [66] on GGR in particular, as part of a further manifestation of lack of fungibility – this time temporal rather than sectoral or spatial.

This reflects risks that are more political and cultural in nature. Indeed, there is a large literature on the political economy of carbon markets. Paterson [79] suggests that the adoption of carbon markets is in part, due to the power they cede to certain powerful actors, such as financiers, and the strong coalitions they build with environmentalists. Such coalitions have the potential to further entrench knowledge claims and discourses that construe offsetting as scientifically valid and legitimate, despite criticisms [103]. Although the risks here may be considered endemic to carbon markets, they are extended to examine specific characteristics of GGR.

These risk categories appear to chime amongst discussion with policy makers in the UK, with whom both authors of this paper have engaged in recent years, specifically on the subject of how, and if so whether, carbon markets can provide a strong policy driver for the development and deployment of GGR techniques. The framework and findings developed in this paper should not only therefore be of great use to these and other policymakers in helping them develop appropriate GGR incentives, but should also provide useful context for those modelling and simulating the take-up of GGR in low-carbon pathways which have proven so central to policy development. The rest of the paper is set out as follows: Section 2 acts as an overview of the reasons why GGRs prominently feature in IAMs and climate discourse more generally, as well as the rationale for including GGRs in carbon markets. Section 3 follows with a more detailed review of the risks associated with including GGRs in carbon markets. This is followed by Section 4 where we introduce our risk assessment framework and outline the policies needed to simultaneously mitigate these risks at the same time as incentivising GGR deployment. Section 5 concludes.

2. Why negative emissions and why carbon markets?

The international case for negative emissions has been strongly made by the IPCC where 87% of Integrated Assessment Model (IAMs) pathways that achieve 1.5 or 2 degrees rely on negative emissions [76]. Indeed, this increasing acceptance and reliance is reflected by the fact that only one of four illustrative scenarios, known as "P1", in IPCC SR1.5 [48] doesn't assume large deployment of technological GGR techniques.

The prominence given to these techniques - particularly in the latter part of the 21st century – is often driven by the commonly-implemented objective of achieving present-value cost minimisation over the long term within IAMs. This often results in a solution to the problem of meeting long-term climate goals at least cost which favours delaying some more costly near-term emissions reductions, in favour of longer-term emissions removals which, because of discounting assumptions in the models, are relatively cheaper in present value terms. Even in more myopic IAMs which do not consider century-long timescales as part of their least-cost optimisation, large-scale reliance on GGRs is still prevalent, purely as a result of the simple fact that the remaining 1.5°C-consistent carbon budget is now very small - just 500 $GtCO_2$ from the start of 2020, for a 50% likelihood [47] with current annual emissions above 35 $GtCO_2$ [29]. This implies large-scale CO_2 removal is likely to be a prerequisite of meeting a 1.5°C long-term temperature goal. In a number of IAMs, towards the second half of the 21st century, increasing levels of carbon pricing incentivise the large-scale deployment of what is currently the most commonly-implemented GGR in IAMs, bio-energy with carbon capture and storage (BECCS)[107]. This is because carbon prices reach values that make BECCS cost-competitive with other CO_2 reduction options. In this context, IAMs include an implicit (or explicit) assumption that carbon pricing can act as an economic enabler to create markets for new techniques, to drive their diffusion and commercialisation and, in the case of BECCS and other GGRs, generate revenues linked to techniques that remove and store greenhouse gases [85].

But the present-day discussion of GGRs (particularly those which are land-based) can also be seen as an extension to past discourse on the need for flexibility within climate policy, which parallels research and literature on carbon sequestration and carbon sinks [16]. The incorporation of flexibility mechanisms into climate mitigation frameworks dates back to the Kyoto Protocol and the Marrakesh Accords [8] as well as the more recent Paris Agreement. A key feature within these agreements is flexibility in terms of what, when and where emissions reductions occur, the importance of which Stern [94] also highlights. The inclusion of GGRs in policy instruments to achieve emissions reductions speaks well to these constituents of flexibility. For example, regarding "what" flexibility, GGRs can remove CO_2 (or potentially other gases) to atone for CO_2 and non-CO_2 GHGs that aren't easy to mitigate, like N_2O in agriculture, or CH_4 in waste; regarding "when" flexibility, GGRs can "pay back" any overshoot of the carbon budget, though with potential consequences in terms of impacts when the budget is exceeded; and regarding "where" flexibility, particularly through techniques like Direct Air Carbon Capture and Sequestration (DACCS) which could in theory be deployed in a variety of locations, GGRs might be deployed in entirely different locations to the sources of residual emissions that they are intended to offset. As such, the what, when, and where flexibility provided by GGRs suggests that - subject to resolving issues of permanence - they are suited to inclusion in carbon markets, as they in principle afford the allocative efficiency that would keep mitigation costs to a minimum.

The above discussion of flexibility and need for GGRs helps explain why demand-side policies to incentivise GGRs have thus far focused on carbon pricing, with the dominant policy discourses typically assuming that GGR deployment will be driven by carbon markets [99]. Yet, the eligibility of GGRs within existing carbon markets is currently uncertain (Table 1) as the characteristics that are required to guarantee and enable perfect fungibility between carbon market permits and GGR permits have yet to be defined. Consequently, cap and trade systems like the EU Emissions Trading System (ETS) are not yet permitted to accept potential GHG 'credits' created when emissions are captured and sequestered using GGR techniques.

However, although the EU ETS is not designed to support crediting of GGRs, it has been suggested that the Sustainable Development Mechanism under the Paris Agreement, a successor to the Clean Development Mechanism (CDM), might usefully be expanded to analogously include international trade in negative emission offsets [44].

Work undertaken by the Royal Academy of Engineering and the Royal Society espouse similar views, suggesting that carbon trading frameworks with or without some form of linkage with the EU ETS may encourage business to use a wide portfolio of GGR techniques. Overall, carbon pricing and carbon markets more specifically, can play an important role in financing and scaling GGR technology, but it may be that placing a penalty on positive emissions alone is not enough to fully incentivise a broad suite of GGR techniques [11].

Yet recent consultations suggest the UK Government is now considering how domestic carbon markets, and carbon pricing more generally, can be augmented to support the development of GGRs, reflecting the growing maturity of such techniques. Deploying GGRs at significant scales is already possible through afforestation, whilst the company Drax – owner of the UK's largest biomass power station - has developed the UK's first BECCS pilot facility. Subject to regulatory interventions and public acceptance, this is schedule to be scaled up to full commercial scale over the course of the 2020s. Meanwhile, there are now several pilots and scale-up plans for DACCS across the world [34].

Allowing GGR permits to be used by UK operators to meet their compliance may also be deemed desirable if a UK-only ETS remains unlinked to the EU ETS. This is because it may help to increase market liquidity for a standalone UK ETS, which would reduce the burden on the complementary decarbonisation policies that polluters in these sectors face [12]. Yet despite strong support by industry for a linking agreement [102], progress remains slow.

But this creates a link between positive and negative emissions markets. Two emissions trading schemes become linked if a participant in one of the schemes can use allowances or credits issued by the administrator of either scheme for compliance. In other words, the allowances and credits of the two schemes are entirely fungible and equivalent for compliance use [71]. Here we argue that either accidental or formal linkage creates policy risks.

3. Risks

Within the literature, there are a number of misgivings expressed about NETs. The uncertain nature of their scalability due to energy, land, water and biodiversity impacts [30, 42] contrasts with their prevalence in IAM-modelled emissions reduction pathways. Moreover, there remain large uncertainties over the integrity of sequestration, particularly from land use changes and CO_2 leakage [60]. Above all, it has been argued that the moral hazard of the existence or even possibility of GGRs delays or even removes the will to undertake rapid and potentially less politically appealing near-term mitigation, in favour of the more politically appealing promise of future technological deployment [1].

Here we demonstrate how each of these challenges can create risks to overall mitigation efforts, particularly if they are incorporated into carbon markets. We present a three-pronged risk assessment framework to highlight the dangers in doing so, and suggest alternative mechanisms to ensure that GGRs are both kept on the table and incentivised in such a way that they can make a more certain and more cost-effective contribution to mitigation efforts, without compromising near-term, non-GGR-based mitigation actions.

3.1. Risk 1 – lack of real fungibility between emissions reductions and removals

Lack of fungibility refers to different aspects with regards to NETs substituting for emissions reduction measures: first, the lack of real-world intertemporal substitutability, which has been highlighted in "moral hazard" arguments around why relying on NETs to remove emissions later in the century risks less stringent near-term mitigation (known as mitigation deterrence) and the possibility of temperature overshoots; secondly, lack of sectoral substitutability in any given time period, owing to a lack of environmental integrity around the permanence of removals. As discussed in Section 3.1.1, moral hazard and any mitigation deterrence that follows from it is a potentially serious risk, in a context where mitigation ambition is already lacking. For example, many G20 countries' net-zero targets, set around mid-century (2050) in most cases, are ambiguous on scope of the use of offsets, and more importantly, in five cases (representing 28% of global GHG emissions), the near-term NDCs of these countries imply 2030 emissions of 25-95%

above a linear path from now to the net-zero target [98]. This demonstrates that mitigation ambition is seriously lacking, and in such a context of already-delayed mitigation action, any additional deterrence to enhanced ambition stemming from the promise of future emissions removals could be risky if the world is to meet the Paris Agreement's long-term temperature goal of 1.5°C

Additional non-fungibility factors have been identified: lack of spatial fungibility, which impacts on the distributional burden of emissions reductions and removals, depending on where they are undertaken; lack of fungibility between "biotic" carbon (i.e. that which is part of the active carbon cycle, such as from land use) and "fossil" carbon (i.e. that which is locked away in fossil fuels), with consequent societal, temporal and distributional implications [17]. Indeed, Markusson et al. [63] see misplaced fungibility as a critical problem for NETs. Here we focus in the following sub-sections on the moral hazard / inter-temporal non-fungibility and the sectoral non-fungibility arguments. The latter in particular draws in aspects of the spatial and biotic / fossil non-fungibility issues.

3.1.1. Moral Hazard and Mitigation Deterrence

There is an increasing literature on the potential for negative emissions to create a moral hazard/weaken deep near-term mitigation. The term "mitigation deterrence", referring to this latter effect in particular, is now gaining widespread usage in the literature (e.g. [17, 39, 66]), reflecting a generalisation of the individual, insurance-based notion of moral hazard to a more social-systemic level [63, 67]. While a certified, permanent negative emission does not create moral hazard per se, reliance on future negative emissions does. Anderson and Peters [1] describe GGRs as "moral hazard par excellence" owing to the risk of being locked into a high-temperature pathway if we rely on GGRs which are not deployed, or which do not remove emissions, at the necessary scale. It has additionally been argued that substituting ambitious near-term mitigation with speculative future techniques is an unjustifiable transfer of risk from the present to the future, and that the impacts of any overshoot of weaker near-term mitigation cannot be reversed [91]. The ability to quantify such a risk is hampered by the lack of large-scale demonstration projects which makes it challenging to evaluate their performance from a full life cycle perspective [96].

In the longer term, even if GGR deployment enables the Paris Agreement target to be met, by continuing to offset emissions from fossil fuel infrastructure, this has the potential to legitimize the continued use of unabated fossil fuels in a carbon-constrained energy system. Higher future carbon prices can be used to prevent a resurgence of emissions. However, carbon pricing policy has often been accompanied by complementary policies such as technology phase-out mandates to make up for lack of confidence and certainty that future carbon prices will rise as expected [108]. Indeed, Tvinnereim and Mehling [97] highlight the prevalence of technology phase-out mandates – such as the UK's coal phaseout – as a reflection of the political economy constraints of carbon pricing, where prices are not sufficiently high to prevent new investment in carbon emitting techniques.

Some research has shown that the idea of GGRs as moral hazard has already been demonstrated amongst a representative sample of the UK public [22]. In addition, a survey of adults in the USA has found that learning about certain carbon dioxide removal strategies (particularly bioenergy with carbon capture and storage and direct air capture) indirectly reduces support for mitigation, because it reduces the perceived threat of climate change [15]. However, others have pushed back, asserting that criticism of GGRs as moral hazard risks closing off a potentially essential mitigation option [61]. In addition, Jebari et al. [52] assert that the moral hazard framing is incorrect, since, unlike in the case of insurance, policymakers can actually influence the level of risk of any lack of mitigation stemming from future assumed carbon removal, by implementing a whole suite of policies. Furthermore, these policies can be complementary to, rather than substitutes for, mitigation. Despite limited knowledge on the jeopardy of GGR inaction, it has been estimated that postponing GGR in the EU beyond 2050 has the potential to reduce the capacity of deployed GGR by 50% as well as costing 0.12−0.19 trillion EUR for every year of inaction [31]. Near term mitigation inaction and delaying GGR are both risky, yet there is considerably more literature about the former [51, 59, 89], suggesting further research is needed to determine the magnitude of mitigation deterrence, adding to initial efforts already made [39, 66]

In addition, a commonly-asserted criticism of GGRs such as BECCS, that they have yet to be demonstrated at scale, is just as easily made against other low-carbon energy system transformations which have no historical precedent, such as 20%+ per annum sustained growth in multiple energy techniques at the same time and over decadal timescales [72]. Indeed, alternative pathways to 1.5°C without reliance on technological GGRs have arguably more challenging implications in terms of sustained and widespread behaviour changes, including dietary shifts, changes to transport and home energy use behaviours, and changing patterns of consumerism [40, 100]

Researchers modelling NETs have asserted that mitigation should be pursued at the same time as R&D and demonstration of DACCS, because there are temperature overshoot consequences if DACCS is planned for, but ultimately fails [80], and as such, further discussion is required to understand the role of DACCS in a way that respects inter-generational equity and reduces moral hazard [34].

Given this context, and notwithstanding that the case for GGR as moral hazard has been contested, it is nevertheless right to question whether GGR credits should be treated as entirely fungible with conventional carbon permits. Moral hazard concerns relate to fungibility in carbon markets because under neo-liberalism, markets have become primary arbiters of whether and to what extent technologies are substitutable [63]. Technologies are often preferred solutions because they require less behaviour change and can be constructed as fungible. Such fungibility is easier to operationalise if technological functions are viewed are having standardized effects [58]. In the context of GGR, standardization between nature based and engineered GGR techniques could mask differences in environmental durability and additionality. Consequently, poor substitutability between GGR and convention mitigation could be obscured under a policy framework that promotes carbon markets, and thus increase the likelihood of mitigation deterrent.

This could further exacerbated if policymakers wish to incorporate intertemporal flexibility mechanisms - such as banking or borrowing - into a carbon market to reduce compliance costs. But too much borrowing - in combination with the inclusion of GGR-based carbon permits in a trading scheme - may lead some firms to over-emit in the current trading period, deterring mitigation and potentially locking themselves into carbon-intensive activities, with the hope that future abatement through GGRs would atone for this. If GGRs fail to scale up and this future abatement fails to materialise, this could be ruinously costly for those firms, or incentivise them to lobby for a relaxation in policy stringency – a risk that was identified early in the development of ETSs [77]. This would suggest that allowing GGR borrowing in an ETS should have a limited role. As discussed in Section 3.1.2, this also prevented an over-substitution of "easier" CDM emissions reductions whose additionality was questionable, compared to longer-term investments towards a low-carbon transition.

3.1.2. Durability and Additionality

Risks associated with the genuine permanence and environmental integrity of the offset credit present a further set of risks. At the heart of this is whether the codification of CO_2, or other greenhouse gases, as a tangible commodity provides GGRs with absolute fungibility with established emissions reductions measures. Implicit in this assumption is that a tonne of CO_2 sequestered by natural sinks is equivalent to either a tonne of CO_2 captured by engineered solutions such as BECCS or DACCS, or a tonne of CO_2 not emitted (abated).

Such an assumption must recognise the distinctive contexts in which these very different solutions operate and the risks embedded within them, especially as it can be difficult to scientifically define the equivalence between one negative emissions unit generated through a given GGR and one positive emissions unit abated. If these two units are to be considered entirely fungible, long-term durability and overall net additionality of emissions reductions needs to be ensured in both the capture and storage of greenhouse gases, to ensure genuine and permanent emissions reductions. For example, nature-based solutions are far more prone to reversal than engineered solutions, particularly in jurisdictions with a chequered history of land use governance [4], due to the imperative to protect stocks of vegetation over substantial periods of time [38]. Inclusion of GGR in carbon markets therefore raises important considerations for regulation and temporal governance in relation to monitoring, reporting and evaluation [24].

At the market level, to some extent we have already seen the pitfalls of such overly-easy substitution of mitigation options whose integrity is questionable, for genuinely desired options to drive forward the low-carbon transition; in the early phases of the EU ETS, the inclusion of hydrofluorocarbon (HFC) incineration activities outside of the European Union arguably incentivised chemical companies (particularly in China) to expand production of HFC-23 (a refrigerant gas) in order to benefit from relatively lucrative CDM credit sales to EU companies in the ETS [105]. In some cases these companies earned twice as much from the sales of CDM credits as they earned from the sale of the refrigerant gases themselves [101]. This allowed the EU-based companies (primarily power generation and industrial manufacturing firms) to benefit from emissions reductions whose additionality was at best questionable, rather than investing in long-term low-carbon solutions such as renewables – though it should be noted that there was not unlimited fungibility for such CDM credits, but rather a constrained quantity, so as to offset this risk to some extent. Although there were quantitative restrictions on the number of HFC's in the CDM, in risk 3 we discuss the implications of a more extreme case where unrestricted linking exerted significant downward pressure on carbon market prices within the New Zealand emissions trading scheme. The HFC debacle might be expanded to analogously apply to future use of nature based GGR which have low levels of permanence or additionality. It could also apply to engineered removal techniques should emissions leakage occur from geological stores although this is less likely.

Hence, whilst in principle GGR solutions meet the criteria of "what, when and where" flexibility very well, they bring with them distinct challenges that must be addressed before they can be confidently incorporated into emissions trading systems, in such a way that they do not undermine the integrity of such systems. Doing so could exacerbate the risk of too-easy substitution of cheaper GGR options in particular, in place of more costly, and more difficult, near-term mitigation efforts which could nevertheless help avoid a longer term lock-in to high-carbon infrastructures.

3.2. Risk 2 - GGR may not be incentivised by a carbon price alone in the near term

Whilst the above section focused heavily on the potential risks deriving from the fungibility of cheaper, but less environmentally robust, GGR options for emissions removals, in reality, many large-scale GGRs (particularly technological solutions such as BECCS and DACCS) remain relatively expensive compared to other near-term mitigation options. There are several reasons to be sceptical about the ability of an emissions trading system to on its own drive the requisite innovation and cost reductions in such techniques in the coming decades.

The most striking, and arguably most relevant, precedent is carbon capture and storage (CCS), which continues to languish in terms of its contribution to climate change mitigation, with just two power generation plants operating with CCS, at a combined power output of less than half a GW [36]. This technology was over a decade ago singled out as one of the most important solutions to climate change by the International Energy Agency (IEA), envisaging 38 CCS power plants with a combined 22GW of capacity by 2020 [46]. Whilst there are tens of operational CCS projects outside of the power generation sector (primarily for natural gas processing and chemicals production), in total all operational CCS projects contributed just under 40 $MtCO_2$/yr of carbon capture [35], about 0.1% of global emissions.

The reasons for CCS's underperformance are multiple: the challenges of demonstrating first-of-a-kind fully integrated plants, costing of the order of $1bn [90]; the simultaneous progress of more granular [104], less complex or more mass-customised techniques [62], such as solar PV and wind turbines, whose cost reductions continue to weaken the CCS investment case even though these techniques are by no means perfect substitutes; the rapidly diminishing carbon budget ([48], p. 5), which leaves decreasing atmospheric space for any CO_2 emissions from energy techniques like CCS that are not strictly zero-carbon [9]; and the net energy penalty of the technology (at least in power generation) [3], in the context of a need to maximise energy efficiency to achieve climate goals at least cost [20]. Martin-Roberts et al. [65] summarise CCS's lost decade from 2009 onwards as one in which most demonstration projects failed to transition to operational plants because of *"fluctuating markets, insufficient financial support and a shift to other fuels and technologies."*

Even though a strong future carbon price could provide a much-needed boost to the economic prospects of CCS, such a price has failed to materialise in most world regions to date. The EU ETS has been able to contribute to a switch from coal to gas power in some countries [64, 95], repeating experiences from earlier pollution (e.g. NO_x) trading systems which also saw an early preference for operational over investment solutions [13], as well as an overall increase in low-carbon innovation [14]. But only in recent months has its carbon price strengthened to a level which could drive meaningful deployment and cost reduction of more expensive technologies.

As already alluded to in the above section, not all GGRs are likely to be so expensive that they will require a significant carbon price and in this current carbon markets could be effective in incentivising low cost GGRs, most notably afforestation and reforestation, which come with multiple environmental and other co-benefits [92]. However fully integrating all viable GGRs into carbon markets would create an incentive to prioritise the use of these low-cost solutions at the expense of conventional emission reductions, at the same time as potentially impeding GGRs with higher investment costs and higher abatement potentials [84].

This is particularly important, as the potential for such lower-cost, nature-based solutions to contribute on the possible scale of removals required to meet stringent climate change mitigation goals is unlikely to be sufficient [92]. In addition, as discussed in Section 3.1.2, nature-based solutions could have potential risks regarding their long-term sequestration of carbon, as well as ensuring genuine additionality of removals.

As such, the large-scale technological solutions such as BECCS and DACCS loom large. In both cases, mitigation costs could well remain high for decades to come, requiring carbon prices of over £100/tCO_2 in addition to specific provisions for these GGR measures (Figure 1). Daggash and Mac [25] suggest that even a social cost of carbon that peaks at £349/tCO2 in 2075 from £6/tCO2 in 2015 is insufficient to kickstart deployment of BECCs and DACCS throughout this time period. This further illustrates that even very high carbon pricing levels may be unable to deliver CDR at scale.

Based on UK Climate Change Committee "Balanced net-zero pathway" analysis [18]. "Wood in construction" bar does not show as assumed to have a cost of £0/tCO_2e. "M&C" = manufacturing and construction.

A moderate and steadily rising carbon price - which might in principle be delivered by a carbon market - could help provide a useful backdrop to the development of these technological GGR techniques, such that they can compete cost-effectively with other mitigation solutions in the future. For this to happen, there would have to be investor confidence that the price would steadily rise, especially since volatile

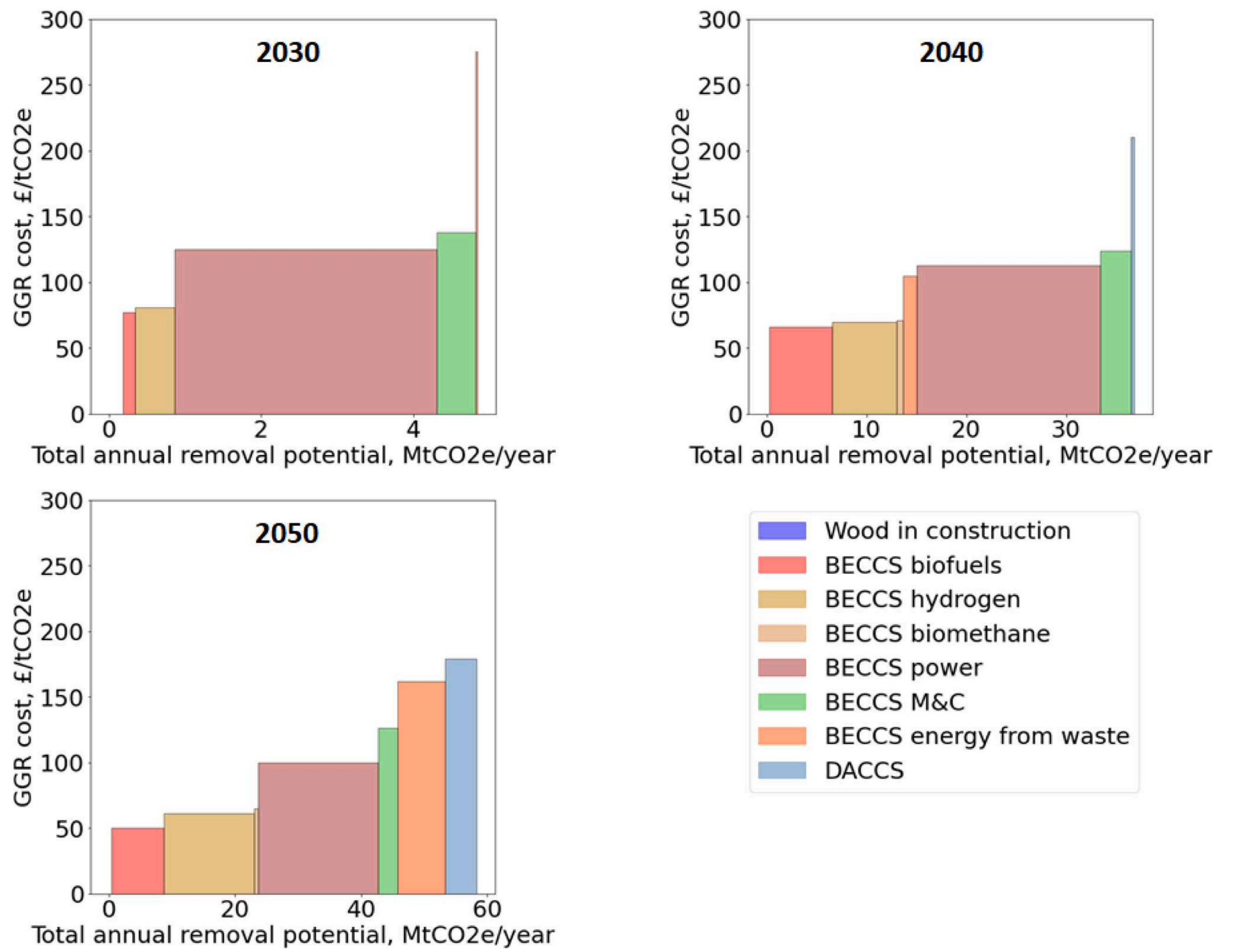

Fig. 1. Illustrative UK Marginal Abatement Cost Curves (MACCs) for selected CDR techniques

prices can have a detrimental effect on low-carbon, capital-intensive investments like CCS [74].

However, there is a long list of market barriers to GGR deployment that needs addressing (including failures in capital markets and externalities related to low-carbon innovation) [109]. Nemet et al.'s [[75]8] systematic review of innovation and upscaling for negative emissions technologies asserts that several processes will be necessary to drive this innovation and learning, including deployment incentives, niche markets and public acceptance, in addition to the demand created by carbon markets. Evidence from technological innovation systems (TIS) analysis around offshore wind, for example, points to a multi-faceted innovation system, consisting of government working closely with entrepreneurs to set the direction of research, support for pilots and demonstrations, as well as associated demand-pull policies such as Feed-in-Tariffs and Contracts-for-Difference to provide a stable, high revenue for initial projects [81]. Nor do carbon trading schemes feature heavily in the story of solar PVs remarkable innovation and cost reduction journey [33], which is far more a result of staged periods of research and development, demonstration and direct deployment support, the latter coming in many cases from targeted Feed-in-Tariffs which created a huge demand-pull for the technology at a time when carbon pricing was either absent, or an order of magnitude too low to level the playing field for it. This reflects the innovation-related market failures that exist in low-carbon technology development and deployment [50], and whilst the carbon price can correct for the climate externality, all of these other interventions are needed to correct for the innovation externality, at least in the near-term.

A policy suite which at least in the near-to-medium term sees targeted R&D, demonstration support and demand-pull for GGRs, within a well-functioning innovation system that coordinates government with GGR developers and financiers, is therefore likely to be a *sine qua non* if we are to capitalise on this technology at the scales required. The specific mix and staging of policies will require careful attention, however. Izikowitz [49] asserts that the cost reduction experience of solar and batteries should be central to DACCS developers' considerations, whilst McQueen et al. [70] calculate the cost reduction prospects of DACCS assuming "fast" (20%) and "slow" (10%) learning rates, drawing on lessons of how renewables, batteries and other low-carbon techniques have fallen down the cost curve in the past. It should be noted that these learning rates are not guaranteed and could be too optimistic. Whilst there is little empirical evidence on which to base CCS learning rates for example, owing to limited deployment, learning rates for CCS power plants have been estimated at values as low as 1-2% [86]. Policy-makers shouldclosely consider the unique aspects of the DACCS national and international innovation system. For example, this will include a consideration of the extent of required national government support for research, legitimation and market demand of the technology, given international efforts in this area. It will also include a consideration of different DACCS techniques and the extent to which they are less or more "complex", as well as the extent to which they are modular or customised [62, 104].

Such considerations are likely to reveal that many complementary mechanisms are needed in addition to a pure carbon price [32], and that inclusion in carbon markets alone would not drive the requisite innovation, learning and cost reduction in more expensive GGR techniques. It may well be that carbon markets and other forms of carbon pricing and taxation could be used to provide subsidies to such GGR solutions. But there remains a question of inter-temporality. For example, Bednar et al. [5] demonstrate that in a 2°C scenario, subsidies required for DAC come much later than, and far outweigh, those generated by carbon pricing in the next few decades. Nemet et al., [75] also highlight the potentially long lead-times for innovation and scale-up of negative emissions technologies. Both of these studies point to the essentiality of public, philanthropic and other finance in filling the near-term innovation funding gap. This could come through advanced market commitments by companies and governments to purchase carbon removal over a specified time period [2], carbon take-back obligations [53], or governments issuing "shares" of carbon in the atmosphere, whose value diminishes as a result of the estimated damage done by that carbon, thereby incentivising GGR to lower the carbon in - and reduce the damage done by – each share [57].

3.3. Risk 3- Linking a GGR market with traditional carbon markets may impose downward pressure on the positive emissions carbon price

Reducing positive emissions through domestic mitigation should remain a near-term priority even if emissions could eventually be offset more cheaply via international GGRs. Such a position can be predicated on the moral case for domestic ambition, rather than the economic one, given many developed countries' history and legacy of high emissions and the risks of low quality, non-permanent offsets that could be prone to reversal. But it can also be justified on the grounds that future lack of availability of large-scale GGR, even if this is quite unlikely, nevertheless justifies stronger near-term emissions reductions [39]. Nevertheless, there remain legitimate economic reasons for why policymakers may wish to build flexibility in to cap and trade systems. This is reflected by the choice of emissions trading design measures, including the existence of intemporal flexibility (banking and borrowing) and the ability to use offset credits for compliance, as already stated in Section 2.1. Using international offsets or GGRs in the longer term should bring down overall abatement costs, especially if the marginal cost of abating the last few per cent of emissions in hard to treat sectors is particularly high. It may, for example, be cheaper to procure international GGR permits from countries where concentrated solar-driven direct air capture may cost less than abating emissions from domestic agriculture.

Although the nascent nature of GGR techniques prevents any ex-post evaluation of linking these markets, the historical use of offsets in carbon markets provides useful context to highlight the risks of allowing cheap GGR permits in future carbon markets. This includes reversal, governance or price risk [10, 21, 45]. For the latter, this is best demonstrated by the New Zealand carbon market where the allowance of unlimited offsets can be considered analogous to the future inclusion of unlimited cheap GGR permits in carbon markets. The NZ ETS was initially introduced with unrestricted linking to the international CDM market [28] where Certified Emissions Reductions (CER) units could be used for compliance. When the financial crisis occurred, NZ experienced excess supply from both a decline in emitting activity and from an oversupply of international offset credits (CERs) in the trading market [73]. This led to a collapse in the New Zealand allowance price (NZU) from $20 in May 2011 to $2 in May 2013 [82].

Figure 2 illustrates that the price of NZUs from 2011 to 2013 were closely tied to and influenced by the price of CERs. Unlike the other ETSs such as China, South Korea and California, until 2015, the NZ ETS was not subject to a quantitative restriction on the number of international offset credits (Kyoto Units) that could be purchased and surrendered for compliance. It wasn't until 2013 when a de-linking announcement was made that the NZU price rose above the CER price. This was formalised during the NZ ETS's second compliance period (2015) when the government formally de-linked from the Kyoto market, thereby preventing further access to the international offset market [55].

It might be questioned why a low carbon price is such a bad thing, if ultimately emissions are kept to the desired level under the cap in an ETS. The obvious reason is that ETSs not only set a cap on emissions to limit them, but also set a price on carbon, signalling both the damage costs of carbon emissions and the long-term incentive to reduce them. A low price makes mitigation unattractive, and stifle low-carbon investment [88]. A number of studies conclude that unrestricted linking, with participants opting for low cost CER units, had a significant impact on the ability to deliver genuine additional abatement [54, 87] with the resulting low prices discouraging low carbon investment and higher-cost domestic mitigation [82, 83].

This suggests that non-additional CERs in the Kyoto Protocol and pre-Paris Agreement world were particularly problematic given that they exaggerate genuine emissions reductions and in the absence of demand side measures (such as adjustments to emissions caps) contributed to an oversupply of permits within emissions trading schemes.

The parallels with future use of GGR credits is clear. In such a

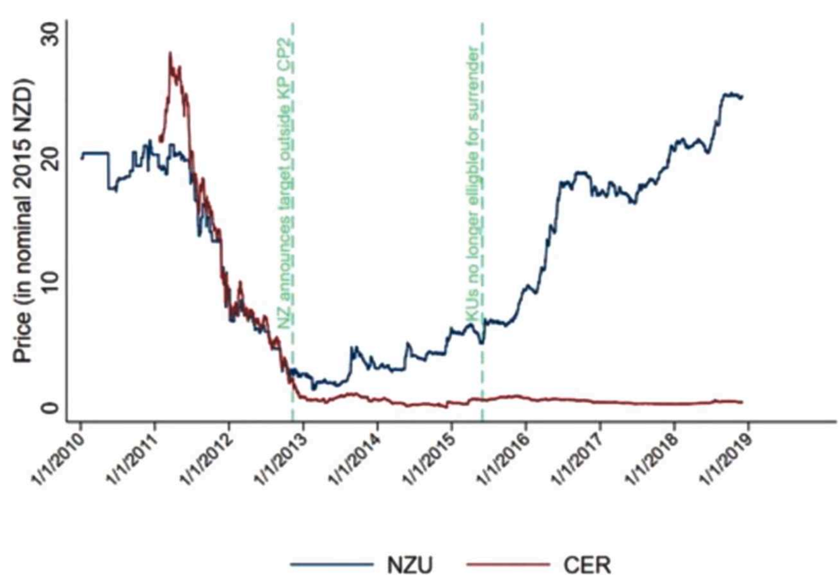

Fig. 2. NZU price history 2010-18 [56]

scenario, facilities undertaking GGR activities could generate GGR credits or allowances to be sold to market participants who need to meet their compliance obligations. But because early abatement in offset sectors can often be achieved at relatively low costs, as is the case with cheap nature based GGR credits [19], allowing unlimited use of such credits for compliance could result in a linked future GGR market overly influencing market outcomes in an ETS. When deciding whether it is appropriate to include GGRs in carbon markets, the distinction needs to be made between GGR techniques that will be likely to be additional - often more expensive engineered GGRs that won't depress the market price) and GGRs that may never be additional – often cheap with the potential depress the market price

Post-Paris there is a growing number of countries adopting or planning to implement net-zero emissions targets. This reflects that we are now living in a world characterized by increasing climate ambition. Thus the demand for GGRs will continue to grow, inherently attenuating the historic oversupply problem associated with having some non-additional projects in the market.

Although this may temper the price depressing impacts of including GGRs in carbon markets, there is still an important policy lesson here for the UK when deciding whether to allow the use of GGR credits in a future UK ETS. Although the NZ example is perhaps an extreme one, as most other ETSs have linking restrictions, of note is that in the NZ EU ETS, CERs only comprised approximately 10% of total units surrendered for compliance in 2012 [82]. Yet without adjustments to emissions caps, or tighter restrictions on eligible GGR, even this relatively small amount of cheap offsets created an oversupply of allowances in the market and put downward pressure on the carbon price. The amount of afforestation CDR credits that the UK could include is strikingly similar. In the UK, afforestation is estimated to provide approximately 18MtCO_2e of sequestration [18]. If the UK achieved all of this afforestation abatement and credits were eligible this would equate to 11.5% of the total UK emissions cap today.

4. Moving forward with GGR and carbon markets

The significant governance implications associated with Risk 1 require additional safeguards to manage mitigation deterrence risk [63]. One possible solution is put forward by McLaren et al. [69] who suggest that targets for accounting for negative emissions should be explicitly set and managed separately from existing and future targets for conventional emissions abatement. The authors argue that a policy of separation can prevent substitution and ensure that GGR techniques deliverer genuine additional carbon removal. Carton et al. [17] further extend the argument for separate targets, describing how such a policy can undo three other equivalences – carbon, geographical and temporal – all of which are crucial to prevent mitigation deterrence. Counter arguments are offered by Smith [93] who suggests that rather than enforcing separate targets, a "better approach is to accompany net targets with ambitious near-term action, disclose measures to achieve them and closely monitor and manage carbon sinks".

Environmental integrity issues that may arise such as permanence can be mitigated by removing perfect fungibility between GGR permits and carbon market permits. For example, a ratio that is higher than a one-to-one relationship between GGRs and generated credits can be implemented. Under such a scenario, system level risk could be hedged if, for example, for every GGR permit, two conventional permits are surrendered.

Ostensibly, this is a policy design issue which can in theory be managed by regulations, for example stating that carbon market participants can only generate offset credits for a real, certified GGR measure, not the speculative promise of a future removal. But in designing the appropriate framework, policymakers must also be cognisant of how powerful actors can shape the accounting frameworks that will govern them. This highlights the importance of recognising the tension between technocratic responses available to policymakers and the broader social and political issues that will influence Government decisions. Assuming the former is divorced from the latter fails to reflect the political and cultural foundations that underpin policymaking.

Regarding Risk 2, a more complex set of mechanisms are needed to deliver innovation cost reductions than purely an emissions trading system-determined carbon price, as demonstrated in the literature and by real world experience. Therefore, we suggest that well before any integration of GGRs in carbon markets, there should be a range of innovation and technology-specific mechanisms to drive currently expensive, yet highly scalable technological GGR down the cost curve. This involves a multi-pronged intertemporal policy framework. In the short term this means a near-term focus on ensuring the cost-effective, scalable and reliable development of these novel techniques through piloting and demonstration support. In the medium-term policymakers can draw on the successful experience of promoting renewable energy sources in the electricity sector, particularly the role of Contracts for Difference (CfDs) in deploying significant quantities of offshore wind offshore wind in the UK. A similar, but modified approach could be used to encourage nascent GGR techniques. For example, the government may choose to ringfence negative emissions techniques into different pots based on technological maturity with deployment support offered via a stable price for each tonne of carbon removed. It may be attractive to use a competitively awarded public procurement contract such as Carbon Contracts for Difference, with the contract benchmarked against a reference price (e.g. the prevailing carbon price) and the top-up payed by Government. This may be preferable to a general subsidy for negative emissions (such as Feed-in-Tariffs in the electricity sector where the Government rewards all producers with a fixed level of support) as an auction is more responsive to technological progress, which can reduce the overall cost of the policy and well as control the levels of deployment which tend not to be fixed under a Feed-in-Tariff policy. Although not a simple process, if in the longer-term, robust monitoring, reporting and verification (MRV) standards are established - and enforced through an independent MRV regulator as proposed by the UK Government ([6]) - a separate negative emissions carbon market could be established, for eventual linking to existing markets.

Finally, for Risk 3, by having a separate market for negative emissions it is possible to ensure that cheap GGRs don't put downward pressure on carbon market prices. In addition, should mature GGRs be incorporated into emissions trading schemes in the future, in order to avoid substitution and downward price pressure, unrestricted linking should be avoided, regardless of the efficiency gains that may result. An optimum outcome can be achieved if restricted linking or measures to support a carbon price collar - such as the proposed UK Supply Adjustment Measures (SAM) or the EU's Market Stability Reserve (MSR) - are put in place in emission trading schemes when supply and demand imbalances occur. To ensure low-cost domestic offsets do not disrupt efficient market functioning, policymakers could review the intake rate of allowances to the MSR or the UK SAM by reviewing the supply-regulating MSR/SAM as GGR permits enter the market. In its current form, the MSR absorbs 24 per cent of EUA oversupply annually until 2023, when this rate is then scheduled to halve [27]. But the effect on the allowance supply is delayed somewhat, with the absorption figure calculated each May based on the previous calendar, and with corresponding monthly sums to then be withdrawn from member state auctions over the 12 months starting in the following September.

However, it is worth noting that if policymakers had the capabilities to adjust emissions caps this may have additional challenges. For example, greater flexibility may allow potential for political interference, which could adversely affect the credibility of governments' commitment to reducing the emissions cap and introduce new uncertainties into the system. Taken further, frequent intervention in the market can create distortions greater than the gains from trade [41]. Moreover, qualitative and quantitative restrictions on the use of offsets can help ensure environmental integrity and manage the impact of offsets on markets as the EU ETS has done in its second trading period.

Figure 3 summarises the risks discussed in this paper, with guidance on how to mitigate each one and at the same time incentivise the development of GGRs towards eventual inclusion in carbon markets. GGRs may be included in carbon markets if they are able to provide proven, high-integrity removal and sequestration of CO_2 and / or other GHGs, as well as benefit from the carbon price in ETSs in a way that allows them to be deployed and reduce in cost, and if they can be incorporated without risking downward price pressure on the market. If not, then there are a range of measures that should be undertaken to maintain the integrity and strength of carbon markets, whilst on the other incentivise the development and cost reduction of GGRs. In all cases, a technology-specific approach must be taken, since different GGR solutions will entail different risks, depending on their stage of development, the durability of emissions removals and sequestration that they provide, and their cost.

In concluding this section on how to incentivise GGR and maintain the integrity of carbon markets, we note that our proposals are based primarily on a rationalist, economic assessment of effective and dynamically efficient mechanisms. There are several additional real-world considerations which must also be taken into account in specific political and cultural contexts: these include more general support for, or opposition to, carbon markets in different jurisdictions, as well as public opinion views on the merging of GGRs with emissions avoidance or reduction measures. For example there is already a heated debate on the over-reliance on GGR in mitigation pathways, as alluded to in Section 3.1.1, which could lead to political or societal resistance to GGR inclusion in carbon markets.

Political and societal resistance could be further exacerbated if the policy framework is perceived as distributionally unfair. This is reflected in public deliberation exercises where the topics of fairness and equity often arise, with people reacting negatively to proposals that are perceived to engender an unfair distribution of risks and benefits [7, 26]. Even though carbon markets, and by extension, the polluter pays' principle - which rests on a key principle of environmental law - is framed as an equitable policy choice, it is not inherently fair. Research show that even under a polluter pays approach to funding GGR, low-income households are still disproportionately affected [78].

5. Conclusions

Whilst GGRs meet the criteria of "what, when and where" flexibility very well, they bring with them distinct challenges that must be addressed before they can be confidently incorporated into emissions trading systems. The arguments presented here demonstrate how each of these challenges can create risks to overall mitigation efforts, particularly if they are incorporated into carbon markets.

First, there is a risk that moral hazard around GGRs could be operationalised in the design of carbon markets through future borrowing provisions. At the same time, there could be sufficient uncertainty about the ability of different GGR techniques to deliver genuine and permanent abatement at scale. It is therefore fair to raise doubts about whether early GGR permits should be granted perfect fungibility with conventional carbon permits. Perfect fungibility rests on the belief that a tonne of CO_2 sequestered by natural sinks is the same as a tonne of CO_2 captured by engineered solutions such as BECCS or DACs, and that it is the same as a tonne of CO_2 avoided through deploying low-carbon alternatives to high-carbon techniques. Butdifferences between sequestered, captured and avoided emissions exist due to the different timescales involved, particularly the temporal characteristics of fossil versus biotic carbon which pose a fundamental barrier to equivalence. Thus when comparing the viability of nature based and engineered solutions, both with emissions reductions and with each-other, policy-makers must recognise the distinctive contexts in which these very different solutions operate and the risks embedded within them.

Second, there are several reasons to be sceptical about the ability of the carbon price delivered by an emissions trading system – at least in the short term - to drive the requisite innovation and cost reductions in GGR techniques. Even though a strong future carbon price could provide a much-needed boost to the economic prospects of GGR techniques, such a price has failed to materialise in most jurisdictions to date, given the

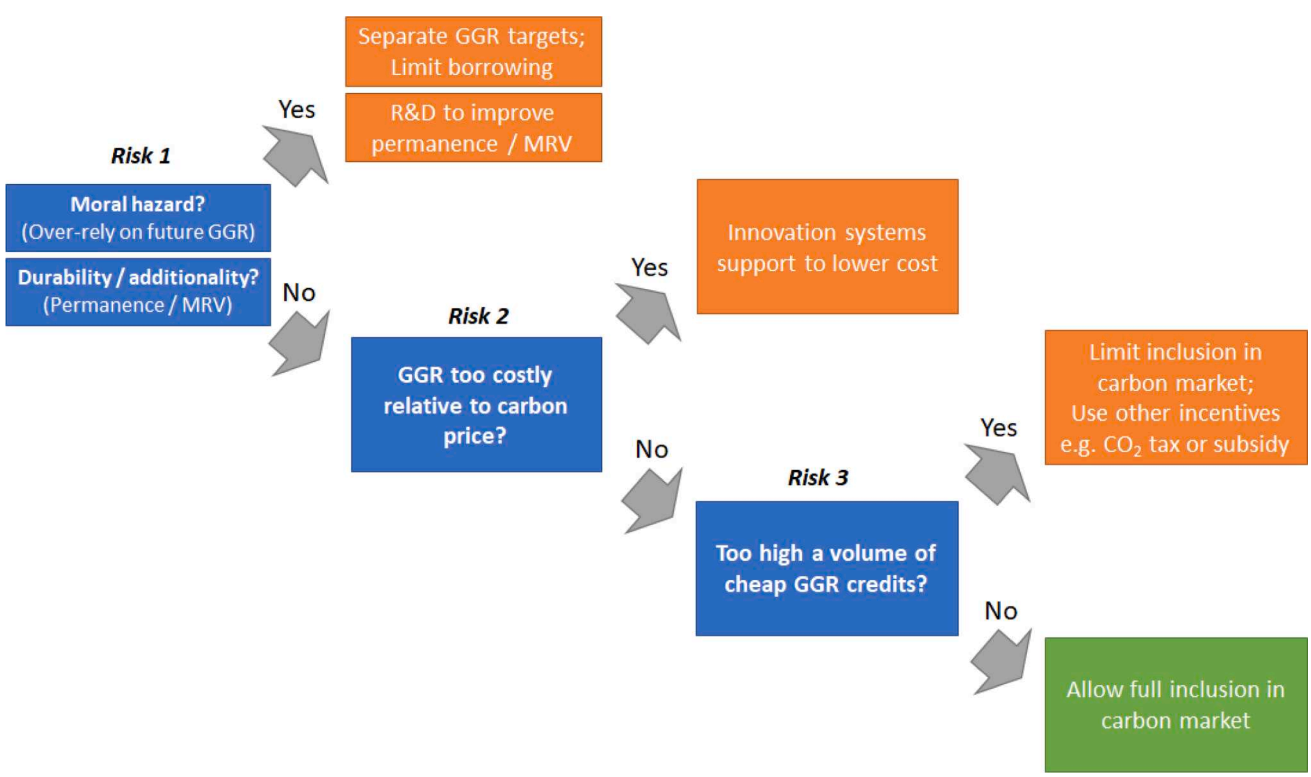

Fig. 3. Summary of carbon markets risk taxonomy GGR incentives framework

projected costs of engineered, technological GGRs.

Third and finally, unrestricted linking of a future GGR market – and indeed afforestation credits available today - with a traditional carbon market may impose downward pressure on the positive emissions carbon price. Whilst GGR credits may seem an attractive option to policymakers to maintain flexibility or reduce compliance costs, without adjustments to emissions caps even a relatively small number of GGR credits could disproportionately affect market outcomes within an ETS.

The future design and linking of a negative emissions market must consider these implications and have a clearly defined objective (e.g., driving GGR innovation, reducing market compliance costs). These objectives may well imply different policies: for example an unrestricted link to the positive emissions market may be effective at reducing compliance costs but use of GGR credits could mean domestic emissions still rise in the near-term (Risk 1), GGR innovation is insufficiently incentivised (Risk 2) and prices in carbon markets are depressed (Risk 3), compromising their ability to drive emissions reductions and innovation across a range of techniques and measures. As we have demonstrated, these risks can be mitigated through appropriate, multi-faceted and technology-specific policy design choices. Although our policy responses are largely technocratic, real-world political and cultural factors will also be critical in developing a fair and durable policy framework for GGRs that fosters high levels of public legitimacy.

Datasets related to Figure 1 can be found at [https://www.theccc.org.uk/publication/sixth-carbon-budget/], hosted at the Committee on Climate Change.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary materials

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