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Accounting for non-equivalence of carbon emissions and removals in meeting national net zero emissions targets in the United Kingdom

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Abstract

Carbon dioxide removal is expected to play a crucial role in counterbalancing residual emissions and limiting temperature rise in line with Paris Agreement targets. Durable temperature stabilisation requires fossil CO2 emissions to be balanced by geological timescale storage – a condition defined as *geological net zero* (GNZ). Replicable for other countries, our analysis uses the UK as a case study, assessing how different GNZ implementations reshapes energy system pathways and mitigation strategies under strict, progressive, and cumulative policy formulations. We find that GNZ could be reached as early as 2040, delivering lower emission pathways than current carbon budgets prescribe, with savings of 0.9-2.34 GtCO2e between 2030-2050. These outcomes are challenging, vulnerable to disruptions in technology and feedstock supply-chains, and subject to the pace of emissions' reductions and removals uptake. Yet they reflect earth system emissions accounting principles required to meet stated climate targets, and as such merit increased policy scrutiny.

Main text

To halt global warming and keep it well below 2°C,[1] anthropogenic CO_2 emissions need to reach net zero and non-CO_2 greenhouse gas (GHG) emissions need to be significantly reduced[2,3]. Consequently, many countries, including the UK, have committed to net zero GHG or CO_2 emission targets[3–5].

When accounting for emissions, emissions removed through CDR are assumed to balance out the warming effect of released emissions one-to-one[6]. Yet recent scientific findings have shown that complex earth system dynamics introduce inequivalences that undermine this assumption[6–8]. One key factor is the heterogeneity in durability of carbon storage associated with different CDR methods, with releases of stored carbon back to the atmosphere diminishing or negating its initial value for climate change mitigation. This has increasingly raised questions of fungibility between residual emissions and CDR in national climate mitigation action both in academic literature and policy[9–13].

Recent net zero clarifications in scientific literature have formalised the conditions required for durable temperature stabilisation[11,12] and introduced the concept of Geological Net Zero (GNZ)[14] .GNZ states that

anthropogenic fossil CO_2 emissions (i.e., fossil fuel extraction and combustion, and fossil carbonate processing) that cannot be phased out should be balanced with equivalent volumes of CO_2 sequestered in geological-timescale storage – recognising the "like-for-like" concept that untouched fossil carbon would have remained in similar stores[14]. GNZ is grounded in the recognition that relying on land-based sinks to store fossil-based CO_2 emissions entails significant risks, including the potential saturation terrestrial sinks under continued warming[15–17], the risk of reversal under increasingly frequent disturbances (e.g. wildfires, pest outbreaks)[18,19], as well as constraints on land availability and resources[20]. Further, accurate measurement of land sink capacity remains methodologically challenging[21], and robust, uniform frameworks for long-term monitoring and governance of land-based removals are not yet fully established[21–24]. While GNZ is scientifically grounded, no quantification of the feasibility of GNZ implementation, nor an assessment of GNZ's potential effect on national climate mitigation strategies, has been undertaken.

Reaching national net zero requires careful balancing of emissions reduction and CDR, which calls for a whole system perspective on energy and infrastructure transitions[25]. Introducing a GNZ-aligned policy approach could reshape the current pathways to net zero by influencing the scale, timing, and composition of both emission reductions and CDR, as well as the build-out of carbon transport and storage infrastructure, and the system use of scarce resources. Here, we translate the GNZ concept into energy system modelling scenarios using the UK TIMES whole energy system model. We explore variations in GNZ timing and scale-up and assess their implications on durable CDR deployment and wider energy system transformation, including the expansion of geological storage. Although applied to the UK, the methods are transferable to other national or regional contexts. The findings support international climate negotiations and national climate target setting by exploring challenges a delayed fossil phase-out could cause when partially accounting for the inequivalence of emissions and removals.

Modelling geological net zero policies for transition to net zero

Current net zero pathways typically overlook the fundamental inequivalence between fossil CO_2 emissions, which could have remained stored on geological timescales if untouched, and CO_2 removals, which could include low-durability options that risk re-emitting stored carbon later in the century (e.g. soil carbon sequestration). Considering GNZ as an approach for reducing the risk of imbalanced mitigation, we test its introduction alongside existing emissions targets in the national UK context. Our approach explicitly accounts for open GNZ design questions, focusing specifically on timing and levels of stringency.

The original definition of GNZ focuses on balancing fossil CO_2 emissions[14]. Here, we expand the concept, mirroring the UK's net zero emission target and including all fossil GHG emissions converted to CO_{2e} using AR6 GWP100 factors. This ensures total residual fossil emissions are balanced by equivalent injection into geological storage over the same set timeframe (see Methods). This creates internal consistency with current net zero definitions, ensuring a more complete "polluter pays" concept is included in GNZ. This also increases climate

change mitigation ambition as it implies not just warming stabilisation but a decline in temperatures if implemented at a global scale[26].

To explore how these choices shape mitigation outcomes, we evaluate three GNZ implementations, each tested under three sensitivity cases and compared with a baseline scenario (Table 1).

Table 1: Scenario framework description including main scenarios considered (Baseline, Strict-GNZ, Cumulative-GNZ and Progressive-GNZ) and selected sensitivities (biomass availability, Transport and Storage (TnS) scaling-up rate, and inclusion of Biomass with Carbon Capture and Storage (BECCS) as CDR in the GNZ). All scenarios include a net zero GHG emissions by 2050 constraint and are subject to all UK legislated carbon budgets. CCC stands for Climate Change Committee.

Scenarios	***Baseline***	***Strict-GNZ***	***Cumulative-GNZ***	***Progressive-GNZ***
Definition	Net zero UK pathway representing a CCC compatible trajectory	Annual GNZ constraint applied from 2030 onwards. All fossil GHG emissions within a given year must be balanced by geological storage in the same year.	Applied between 2030 and 2050. All fossil GHG emissions 2030 onwards must be balanced by geological storage before the 2050 net zero target year.	Applied between 2030 and 2050. An increasing share of fossil GHG emissions year after year must be balanced by geological storage in the same year.
Sensitivity	***S1 - Biomass availability*** Low/high biomass imports available to the UK			
	S2 - BECCS availability Inclusion/not of BECCS within the GNZ scenario			
	S3 - TnS scaling up rate Slow/fast scaling up of Transport and Storage infrastructure			

In the *Strict*-GNZ scenario, fossil GHG emissions must be fully balanced by geological removals on an annual basis, starting from 2030 onwards. While conceptually simple, this implementation poses considerable feasibility challenges: the stringency of annual balancing from an early start date has to reconcile the current scale of fossil GHG emissions in the UK with available CCS-based emission reductions, and with the rate at which CCS-enabled removals, such as bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS), are projected to scale (see Methods)[27]. Therefore, we also consider two more gradual GNZ implementations. In a *Cumulative-GNZ* scenario*,* strict annual fossil GHG emissions balancing is replaced with a period-based balance for 2030-2050 - where emissions from all years can be matched by appropriate sequestration later in the period. In a *Progressive-GNZ* scenario, the "strict" balance is applied annually to a progressively increasing share of fossil emissions. The speed of this increase is derived iteratively, assessing the levels of compliance the model can achieve before using a "fail-safe" CDR option – widely used in the *Strict* scenario (see Methods). *Cumulative-GNZ* offers timing flexibility but accounts for all emissions, whereas incremental steps in the *Progressive-GNZ* seek the fastest possible trajectory towards strict annual GNZ implementation, emulating how a gradual Carbon Takeback Obligation[28,29] might be translated into whole energy system modelling. These scenarios are compared against a *Baseline* without GNZ. All cases account for UK carbon budgets and 2050 net zero GHG target. "Fail-safe" removals are always available, providing expensive abatement where emissions constraints cannot be met. Finally, sensitivity analyses test changes to key model assumptions across the scenario design, including shifts in imported biomass availability (low to high), the option of using BECCS to comply with GNZ (included or excluded), and changes to scaling in transport and storage (TnS) of CO_2 (fast to slow). The BECCS sensitivity reflects continued concerns that life-cycle

accounting for supply chain carbon balances may limit the ability of BECCS to deliver net atmospheric carbon removals[30].

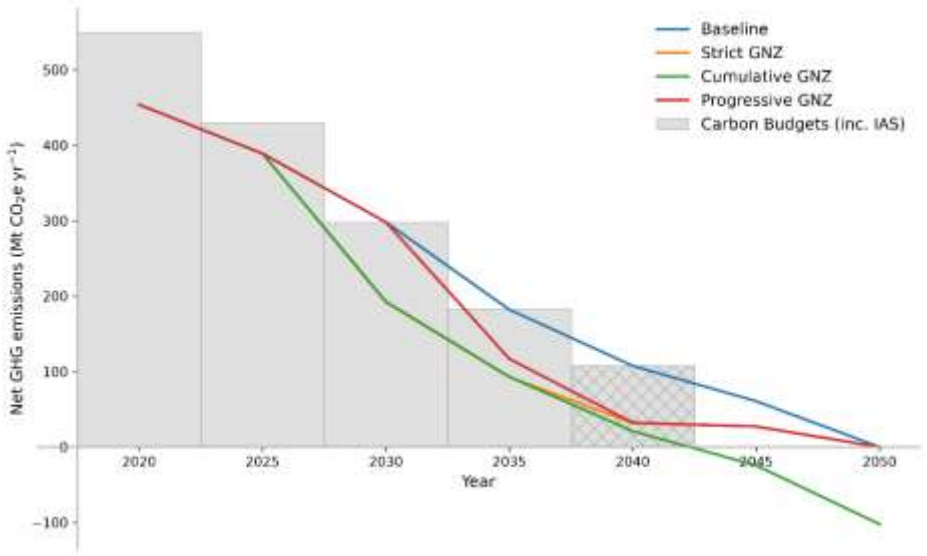
Implementation of GNZ leads to faster net GHG emission reductions

While all scenarios reach net zero by 2050, GNZ futures reduce net GHG emissions faster before 2035 compared to the *Baseline* (Figure 1a). In particular, the *Strict* and *Cumulative-GNZ* scenarios share the fastest short-term net emission reductions, diverging from 2035 onwards. *Cumulative-GNZ* reaches net zero by 2042, going net negative by 2043 to compensate for earlier fossil emissions "overshoot", while *Strict-GNZ* slows its rate of emissions reduction from 2040. The *Progressive-GNZ* comparatively increases its mitigation rate gradually, joining the *Strict-GNZ* trajectory from 2040 onwards.

Short- and medium-term dynamics reveal how different pathways converge to net zero. Bridging the large gap between available durable removals and residual fossil emissions in 2030–2035, the *Strict-GNZ* scenario relies heavily on expensive fail-safe removals providing on average 98 $MtCO_{2e}y^{-1}$ to converge. In practice, with existing technologies constrained in deployment and scale-up, the system cannot expand options for durable removal and fossil mitigation at the pace required within this short timeframe. Although the fail-safe is available to all scenarios, only *Strict-GNZ* activates it in the years after the GNZ target takes effect. Comparatively, the *Progressive* scenario is derived iteratively to determine the share of fossil emissions that could avoid the fail-safe whilst maximising GNZ implementation. It reaches compliance levels of 1% in 2030, 28% in 2035, and 100% from 2040 onwards, suggesting a 1:1 GNZ constraint could be achieved ahead of the current 2050 net zero target.

In the long term, the *Cumulative GNZ* scenario imposes a substantially higher mitigation burden than the *Baseline* and other GNZ scenarios, pushing the system into net-negative emissions by 2043 and delivering roughly -100 Mt $CO_2.y^{-1}$ by 2050. This reflects the scenarios' accountability for earlier fossil emissions and its requirement to compensate for them by 2050.

a



b

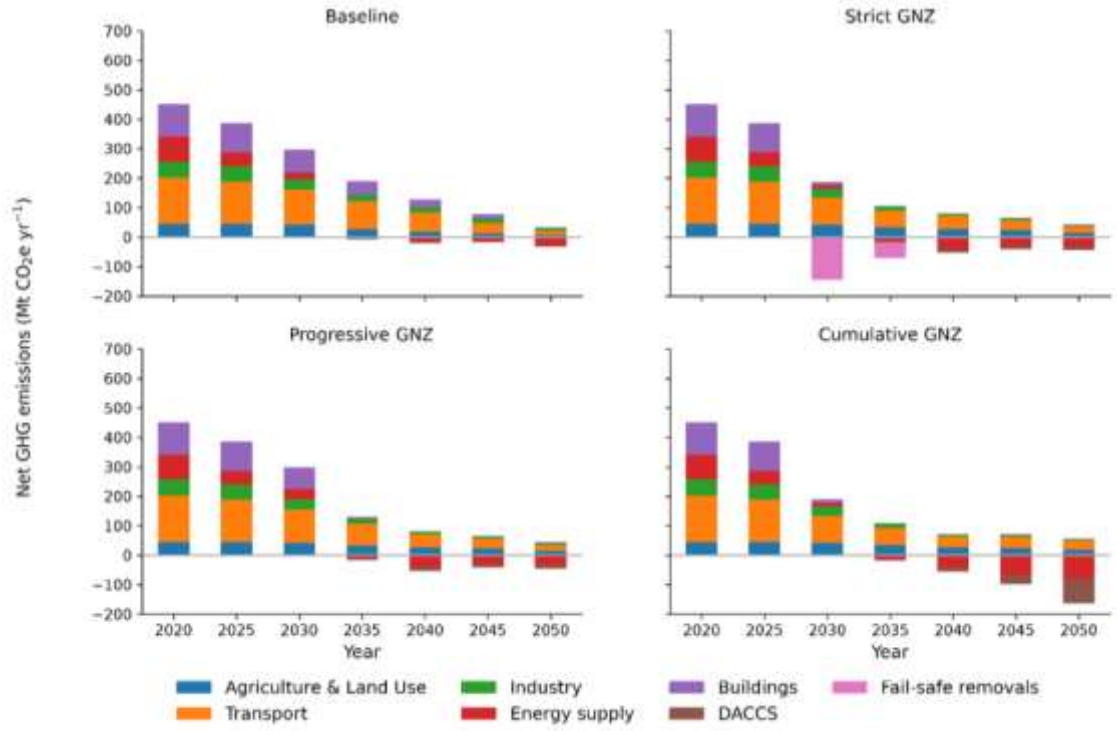


Figure 1a *Net GHG emissions across the four main scenarios investigated here: Baseline (dark blue, no GNZ policy), Strict-GNZ (orange, full GNZ implemented from 2030), Cumulative GNZ (green, GNZ policy implemented on cumulative GHG emissions from 2030 to 2050), and Progressive-GNZ (red, GNZ gradually implemented from 2030 to 2050). The legislated carbon budgets are represented in bars, including international aviation and shipping (IAS).* ***Figure 1b****. UK GHG emissions and removals aggregated by sector of activity. "Energy Supply" includes production of electricity, hydrogen, Fischer-Tropsch (FT) fuels as well as upstream and secondary energy processing. Negative vs. positive values in a given sector illustrate whether remaining emissions are smaller or larger than the removals in that sector.*

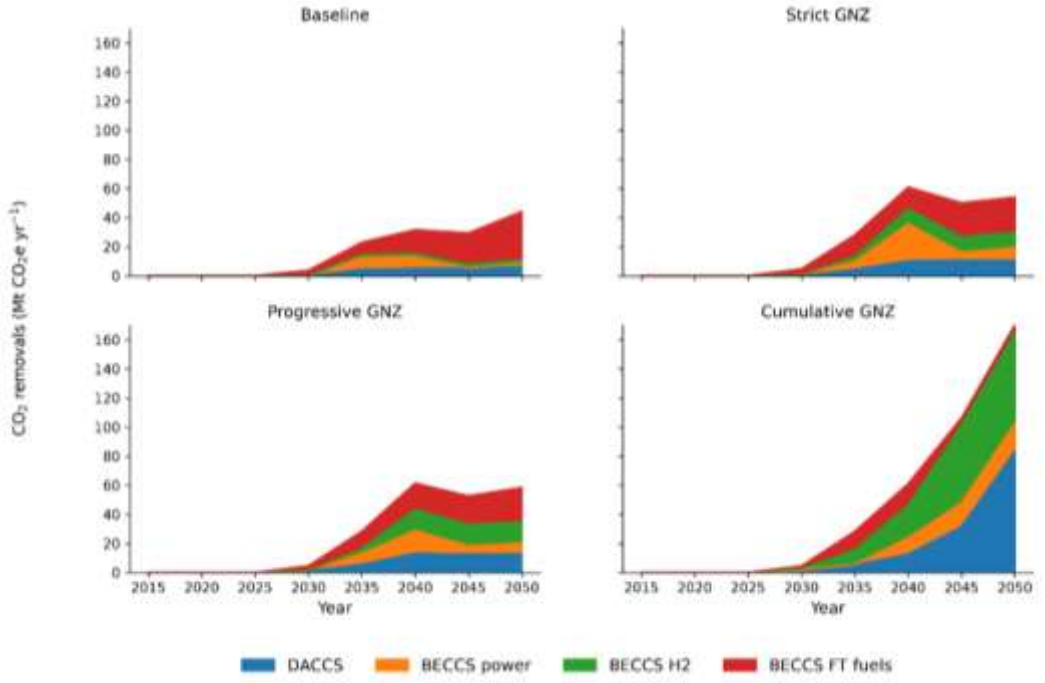
Each GNZ constraint implementation reshapes sectoral decarbonisation (Fig. 1b). In the *Baseline* scenario, sectors reduce emissions smoothly in line with legislated carbon budgets. Gas consumption in residential buildings drops progressively and is phased out by 2050, and road transport electrification progresses to represent 62% of energy use in the sector, alongside biofuels (21%) and residual fossil (17%). This combines with comparatively modest CDR of 44 $MtCO_2y^{-1}$ and fossil CCS of 47 $MtCO_2y^{-1}$ by 2050. Under GNZ scenarios, the system strengthens early emission reduction efforts in sectors where fuel substitution is possible. Road transport electrification exceeds 55% and gas use in residential buildings is phased out by 2035. These scenarios imply rapid near-term transitions compared to baseline with system changes in the 2030's likely to challenge infrastructure delivery at scale. A cumulative approach pushes fossil CCS as far as other GNZ, alongside sustained and deeper progress in net removals through DACCS and hydrogen-BECCS in the later part of the period. (See SI.2 for further detail)

GNZ significantly affects the scale and share of durable removals and fossil CCS

Durable removals rise most sharply in the *Cumulative GNZ* scenario, reaching roughly 170 Mt $CO_{2e.}yr^{-1}$ by 2050, exceeding both *Strict* and *Progressive-GNZ* pathways which remain below 60 Mt $CO_{2e.}yr^{-1}$, and the *Baseline,* which stabilises at around 55 Mt $CO_{2e.}yr^{-1}$ (Figure 2a.). These trajectory shifts are significant. From similar levels of 4 to 5 Mt $CO_{2e.}yr^{-1}$ in 2030, *Baseline* needs imply capacity additions of 2.8 Mt $CO_{2e.}yr^{-1}$ to 2040, where GNZ futures require 5.7 Mt $CO_{2e.}yr^{-1}$. After 2040, durable removal needs in *Strict-GNZ* and *Progressive-GNZ* scenarios stabilise to 2050, while *Cumulative-GNZ* CDR needs grow by a factor of 2.8 to 2050, reaching 170 $MtCO_{2e}y^{-1}$. This is split equally between DACCS (84 $MtCO_{2e}y^{-1}$) and BECCS (87 $MtCO_{2e}y^{-1}$), including power, hydrogen (H2) and FT fuel production, both individually exceeding durable removal needs in every other scenario.

Across all cases except *Cumulative-GNZ,* durable CDR deployment is dominated by BECCS. This reflects, in part, its ability to generate energy, supporting fuel-switching alongside removals where other CDRs consume energy, and in part, its earlier availability and lower marginal costs relative to DACCS. Sensitivities s1 and s2 affect this balance, increasing both the role of DACCS across GNZ scenarios, and the ratio of fossil emission reductions to removals in total geological storage.

a



b

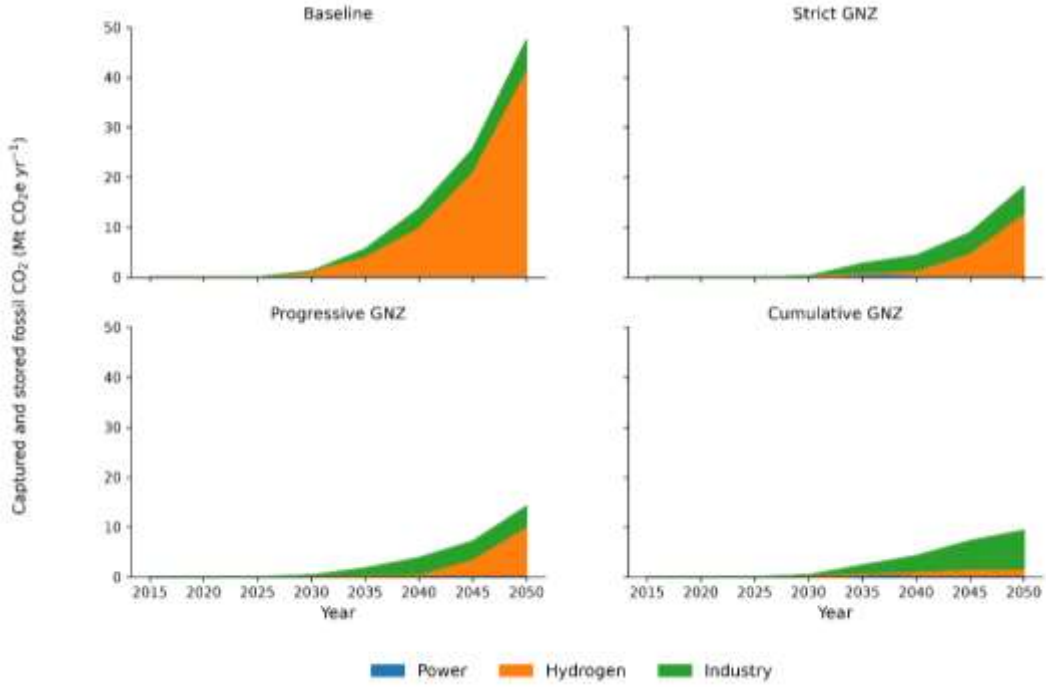


***Figure 2a**. Shows stacked areas representing durable removals to geological timescale storage through CDR. Results are shown per scenario, per aggregation of CDR distinguishing between DACCS and different forms of BECCS included in UK TIMES. **Figure 2b** uses a similar presentation to show levels of fossil CCS transferring emissions to geological timescale storage differentiating between sectors of the model in which they occur. Both figures ensure y-axis scales are comparable across scenarios.*

Fossil CCS shows a markedly different trajectory from durable CDR. The *Cumulative-GNZ* pathway deploys the lowest fossil CCS capacity —at 9.3 Mt CO_{2e}.yr^{-1} by 2050, half and 65% of levels reached in *Strict* and

Progressive-GNZ respectively, and 19% of *Baseline* needs. This reflects the difference between net removal or fuel switching options, which reduce atmospheric emissions concentrations or leave them unchanged; and fossil-CCS, where residual emissions continue to accrue. While the former support GNZ compliance, the latter do not. Because GNZ scenarios add early constraints on residual emissions that are absent in the *Baseline*, their fossil-based energy consumption drops more aggressively, leaving fewer residual fossil emissions by 2050. Therefore, the use of fossil-based systems – with and without CCS – is lower across GNZ scenarios, with pathways moving from blue to green hydrogen, or phasing out hybrid vehicles for full electrification.

Overall, total geological carbon storage requirements vary significantly across scenarios. The *Cumulative-GNZ* scenario exhibits the largest overall storage needs with 180 Mt $CO_{2e}.yr^{-1}$ in 2050. *Strict* and *Progressive-GNZ* scenarios rely on less than half at 72 Mt $CO_{2e}.yr^{-1}$ - noting that the first requires the fail-safe to converge and the second represents a much lower level of accountability for fossil emissions. The *Baseline* requires 98 Mt $CO_{2e}.yr^{-1}$ evenly split between emission reduction and removals, but allows fossil emissions to continue as long as carbon budgets are met. (See SI.3 for further detail)

GNZ requires wider and faster system decarbonisation

The stricter carbon constraints implied by GNZ scenarios involve faster and larger power-system expansion than in the *Baseline* (Figure 3a). This represents a considerable challenge. *Baseline* scenario results require power output to nearly double from 286 TWh in 2020 to 575 TWh in 2050 with 45% of this increase after 2035 – representing a trend reversal considering UK generation has decreased by 25% since 2000[31]. GNZ scenarios go further, requiring generation levels between 640-735 TWh in 2050, with 73-90% of that increase taking place by 2035. These shifts imply significant near-term infrastructure roll-out, and support for earlier and deeper end-use sector electrification. This includes phasing out gas use in buildings by 2035 in *Strict* and *Cumulative* cases, and deeper transport electrification in *Cumulative,* increasing electricity consumption by 25% and 45% by 2050 compared to other GNZ and *Baseline* cases, respectively.

Changes in *Progressive-GNZ* are more gradual as the GNZ constraint is phased in, suggesting a smoother delivery trajectory for end-use electrification.

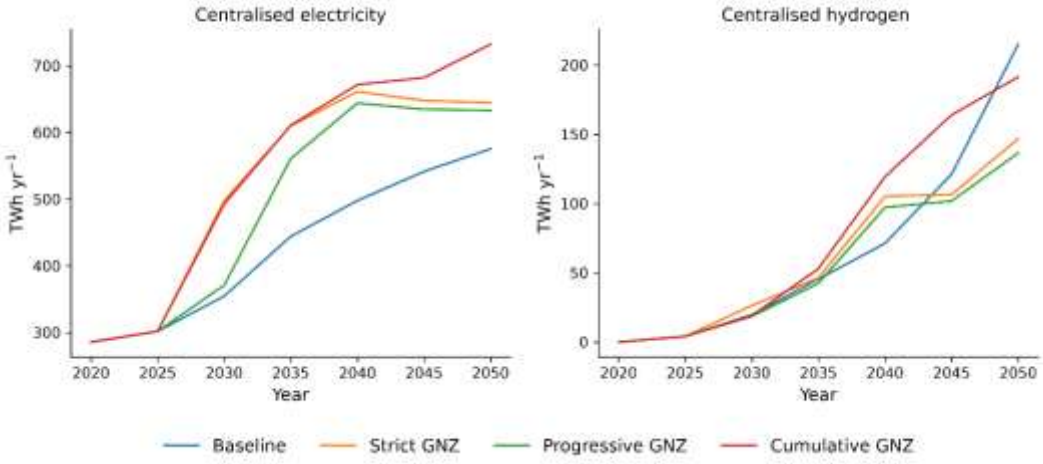


***Figure 3a**: Shows annual centralised electricity production consistent with each scenario in TWh. GNZ scenarios depart from Baseline trends early, reflecting the deeper end use sector electrification as well higher uses DACCS and electrolysis for hydrogen production. Progressive futures describe the more gradual shift supported by the an incremental GNZ introduction.* ***Figure 3b.** Describes the corresponding trends for the production of hydrogen. Orders of magnitude are slower together across scenarios, but higher levels of ambition imposed under GNZ approaches requires earlier infrastructure buildout and, in Cumulative futures larger total volumes of hydrogen production over the model period.*

When tested against sensitivity to biomass resource availability, TnS scale up rates and inclusion of BECCS in the GNZ constraints, the four scenarios show different stability. The *Baseline* uncertainty remains narrow (580–605 TWh), *Strict-GNZ* and *Progressive-GNZ* are also quite stable (647–674 TWh and 640–672 TWh, respectively). While this reflects limited structural change by 2050, sensitivity runs require the higher levels of electricity generation and lead to larger systems earlier in the modelling period. The *Cumulative-GNZ* scenario exhibits both the highest central estimate and the widest range of system size in 2050 (734–968 TWh), revealing that cumulative target pathways are strongly conditioned by assumptions regarding resource availability, renewable generation and TnS scale-up. Together, these results show that while GNZ pathways consistently drive higher electricity production, the scale of expansion remains highly sensitive to system-level uncertainties. Hydrogen (Figure 3b) has similar and connected dynamics. Larger volumes, earlier, highlight the need for early technology roll-out in GNZ cases. While *Strict* and *Progressive* cases stabilise at levels ~40% lower than the baseline in 2050, reflecting higher end-use electrification, recovering early fossil emissions under *Cumulative* runs implies maintaining 90% of baseline hydrogen use while increasing power sector size by 27%. (See SI.4 for further detail)

Discussion – 703

Durable temperature stabilisation implies balancing fossil CO_2 emissions with removals to geological timescale storage. While GNZ is established in the literature, and increasingly discussed in national and global policy, it is not currently considered in decarbonisation pathways. This work shows, for the first time, the impact of integrating GNZ constraints into national long-term energy modelling. Using a UK case study, it demonstrates that annual balancing of fossil GHG emissions with durable CDR could be achieved by the early 2040's, conditional on significant energy system shifts, with different GNZ implementations reducing net emissions between 0.9-2.34 $GtCO_{2e}$ between 2030-2050 compared to current climate legislation. Implementing GNZ relies on the accelerated phase-out of fossil fuel use across the economy, leading dependent sectors to fuel-switch aggressively towards hydrogen or deep electrification, alongside ambitious scale up of both capture (CCS) and removal (CDR) capacity, compensating residual emissions with durable CO_2 transfer to geological storage.

Early planning and scaling of consistent infrastructure to transition the energy is essential. Our analysis explores possible translations, implications, and vulnerabilities of GNZ. The speed of fossil use phase-out dictates the levels of residual emissions that must be balanced, and the availability and scale of mitigation and capture infrastructure over time conditions residual emissions' removal to durable storage. Strict compliance constraints without adequate infrastructure and policy support fail to deliver. A progressive approach could reach "like-for-like" fossil emission accountability by 2042, requiring offtake infrastructure to grow at 2.8 $MtCO_2y^{-1}$ to 2040. Cumulative approaches would account for early fossil emissions, foregone under progressive designs, but require stronger removal build-out reaching 180 $MtCO_2y^{-1}$ capacity by 2050.

Developing robust GNZ formulations means understanding energy system dependence on key feedstock and technology supply chains. The role of biomass is widely discussed as a pillar for both UK and global decarbonisation pathways. Under GNZ formulations, imported biomass feedstock and the use of BECCS are important parts of a feasible outcome. Sensitivities exploring lower future UK shares of international global biomass markets, or unreliable feedstock sustainability, delay Progressive-GNZ to 2045, and push Cumulative-GNZ ability to recover all period fossil emissions beyond 2050. Variations in technology supply chain readiness for TnS lead to similar outcomes, suggesting that while many UK storage formations are at high Storage Readiness Levels[32], coordinated scale-up of CO_2 capture, transport, and storage infrastructure and coordination across actors requires strong attention.

This analysis carries direct relevance for national policy processes. In the context of the UK, these include the integration of CDR within the UK Emissions Trading Scheme, the continued development of GHG Removal business models, and decisions regarding CCS and CDR infrastructure investment. Here, we present a quantitative basis for these processes, highlighting the need for greater coherence between national ambition and scientific definitions for emissions and removals equivalence. We find that a "Progressive" implementation represents the most practically achievable route to GNZ, mirroring the existing concept of "Take Back Obligations"[28], and combining high political ambition with challenging but achievable rates of system transformation.

Higher national decarbonisation ambitions as set by GNZ constraints will rely on national and international supply chains, putting constrained global resources to contribution and raising the question of increased reliance on international offsets. Most countries have yet to develop sufficient geological storage capacity – or secure long-term access to capacity abroad – implying that competition for biomass, storage sites, and supporting infrastructure – all highlighted as key in this study – are likely to intensify. These challenges may be particularly pronounced in nations with large heavy-industry sectors or high dependence on fossil fuel combustion. While countries may, under Articles 6 of the Paris Agreement, access internationally transferred mitigation outcomes to supplement domestic efforts, integrity risks including concerns around additionality, durability, and double-counting, remain significant; with governance frameworks to ensure robust verification yet to be developed..

As GNZ frameworks continue to gain traction across academic and policy communities, future work should examine how simultaneous adoption across jurisdictions might interact, including whether coordinated approaches could alleviate resource pressures or, conversely, exacerbate competition for scarce but essential resources on which durable stabilisation of global warming depends. Further analysis is also required to understand how such levels of ambition are compatible with a just and equitable transition, both nationally and in the context of global energy and carbon supply chains.

Methods (online)

A national whole systems modelling framework

UK TIMES is the whole systems model of the UK that is currently used by the UK government to assess different long-term national energy and emissions pathways. It was built in 2014 to replace the UK MARKAL model, and its current versions are co-developed between UCL Institute for Sustainable Resources and modelling teams at the UK Government Department for Energy Security and Net Zero (DESNZ)[33] .

The model uses the TIMES model generator, a widely used optimisation framework. It combines technology detail with economic rigour to support policymaking at national, regional and global scales. The TIMES code is maintained by the International Energy Agency, and supported by the global IEA-ETSAP modelling community, making the approach proposed in this study widely transferable to other international contexts.

In detailed terms, TIMES is a least-cost, bottom-up, technology rich, partial equilibrium modelling system that dynamically adjusts energy supply to changing energy demand. It uses explicit material and energy flow data to describe how different technology options operate and compete; it links technologies and energy carriers together to map possible energy supply chains; and it uses these chains to deliver expected societal needs in "energy service" terms. It combines this engineering perspective with technologies' expected capital and operational costs, accounts for the expected cost of importing or extracting resources, and derives exogenous fuel costs for internal energy commodities. Optimal future pathways are obtained based on investment and operation decisions that minimise the discounted net-present value of building and running the whole-energy system, subject to relevant exogenous constraints.

The UK TIMES model is a TIMES based representation of the UK whole energy system. The assumptions that underpin the model can be found described in annex A.2. of the Sixth Carbon Budget impact assessment[34]. UK TIMES uses sectoral demand modelling alongside national statistics to set exogenous growth trajectories for energy service demands in five end-use sectors: transport, industry, agriculture, services, and residential buildings. These societal needs for e.g. "space heat" or "passenger kilometres of car travel" are energy agnostic. As they change over time, they drive upstream investment in supply chain designs that can deliver them. Resulting technology and energy carrier portfolios complement the incumbent infrastructure and respond to system-wide constraints. In this way, the model represents and compares current and potential future energy supply chains for the UK, including primary energy (extraction, imports); upstream transformation, power and processing sectors that deliver secondary energy carriers (electricity, hydrogen, liquid fuels, etc.); and transmission & distribution to, and consumption in, aggregated end use sectors. For each future pathway, UK TIMES produces outputs that detail the cost, energy and emission flow implications of meeting expected energy service demands across the economy.

To ensure these outputs are relevant for the UK context, the database of techno-economic parameters describing future technology options is paired with national statistics and user constraints that calibrate its starting point and restrict its solution space. These constraints limit modelling options – including e.g. roll-out

speed or maximum technology shares – to represent technical, behavioural, economic or acceptance barriers to technology development. They also include national emissions targets, with explicit representation of the UK's national Carbon Budgets, NDC commitments, and 2050 Net Zero GHG target.

Overall, the UK TIMES model includes more than 2100 technologies linked together by up to 1000 commodities. These include emissions, intermediate and final energy vectors, and material commodities. It has underpinned the UK government's carbon budget analysis process since 2016[33–35] and is widely used in the academic literature[36–42]. It is currently co-developed between the UCL Institute for Sustainable Resources and the Department for Energy Security and Net Zero.

(See SI.1 Figure A for information CDR and CCS technologies included in UK TIMES)

Accounting for GHG Emissions

The UK TIMES model tracks emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs). This accounting takes place both at a whole energy system level, accounting for all aggregate emissions within the system boundary, and at a within each sector.

Whole system, or global, emissions tracking deals with energy-related emissions embedded in all energy commodities that cross the system boundary: in any modelling period, emissions are accrued as commodities are mined or imported, and deducted as they are exported or captured and sequestered in either land or geological sinks. This generates "total" emissions counters (CO_2TOT, CH_4TOT, N_2OTOT and HFCTOT) which are used to track the levels of atmospheric emissions that are consistent with a given future energy system pathway. The accounting approach applied here mirrors IPCC guidelines for territorial emissions accounting.

Sectoral emissions accounting deals with the same emissions as the whole system trackers but attributes them to the sectors in which the commodities are combusted, either to power other processing systems, or to generate intermediate energy vectors or final energy demands. For example, the processing of crude oil to refined products leads to Process sector (PRC) emissions, but the refined products (e.g. diesel) may lead to Transport sector (TRA) or Industrial sector (IND) emissions. To balance this accounting system, emissions are accrued to a sector (sec1) when an energy commodity is first combusted or transformed in there. Value added fuels created in sec1 are given a negative (sec1 sectoral) emission factor. Emissions are this deducted from sec1 counters when the commodity is transferred to other parts of the model. When carbon is captured and transferred to land or geological sinks, or when a commodity is exported, corresponding emissions are deducted both from the sectoral and whole systems accounting trackers. For example, emissions captured through DACC and stored in geological storage are deducted from process sector and global accounts.

Emission factors applied to all fuels in UK TIMES are taken from Scope 1 emissions listed in Greenhouse Gas Reporting Conversion Factors documentation provided by the government[43]. These apply global warming potential 100 (GWP100) equivalences to non-CO_2 emissions such that all emissions accounting in UK TIMES remains in CO_{2e} terms. Acknowledging the changes in this reporting framework over time, we apply corrections to base-model emission factors shifting them from AR4 to AR6 equivalence values using[44] based on table 7.15

in Chapter 7 of IPCC 6th Assessment Report Working Group 1 report[45]. Endogenously derived fuels (hydrogen, electricity, ammonia, etc.) are not given an emission factor. Instead, their carbon intensity is internally consistent with the pathway choices made by the model and derives from the production methods and input fuels used to generate them.

Implementing whole systems emissions constraints is supported by the introduction of a total Greenhouse Gas (GHGTOT) counter defined as the sum of other total counters in CO_{2e} terms. The UK's carbon budgets and net zero 2050 constraint are built by constraining amounts of GHGTOT allowable over 5-year periods and linearly decreasing from to zero in 2050 (see Figure 1).

Implementing GNZ

As described above, we take Geological Net Zero (GNZ) to describe the requirement that all fossil emissions added to the atmosphere over a chosen timeframe be compensated for within the same timeframe by removals to durable storage. This definition expands beyond the foundational concept presented in Allen et al. 2025[14], and includes all UK TIMES tracked GHG emissions related to fossil extraction accounted for in CO_{2e}. For clarity, we note that we understand durable storage to designate storage on geological timescales.

The scenario framework we present describes three different GNZ implementations each with different timeframes over which the constraint is applied, or different stringencies within a given timeframe. Strict, Progressive, and Cumulative implementations are described mathematically using equations (1), (2) and (3) below respectively.

Each equation is written using technology activities, to be most simply understood as a unitless equivalent to the amount of output of a technology; and emission factors, which represent the GHG emissions in $ktCO_{2e}$ expected per unit of output of the same technology. These equations are introduced to UK TIMES in parallel to the emission systems described above without affecting either of the sectoral or atmospheric (TOT) accounting.

A Strict implementation, (1), shows that for each model period between 2030 and 2050, the sum of all TOT emissions from fossil fuel extraction, fossil fuel imports, or from fossil process emissions, netted off for embodied emissions of exported fuels, must be smaller or equal to emissions committed to geological storage. Any shortfall is met using a fail-safe option.

$$\forall y \in \mathcal{P} \sum_{t \in \{\mathcal{J},\mathcal{M},\mathcal{Q}\}} A_t(y) * EF_t(y) - \sum_{t \in \{\mathcal{E}\}} A_t(y) * EF_t(y) \leq \sum_{t \in \{\mathcal{S}\}} A_t(y) + A_{BCK}(y) \quad (1)$$

A Progressive implementation, (2), amends the formulation in (1) to restrict the left-hand side (LHS) to include an “appropriate” share of netted off fossil emissions. Shortfalls remain met using a fail-safe option. The “appropriate” share increases from one period to the next. In our implementation it is chosen iteratively such that fail-safe use is eliminated.

$$\forall y \in \mathcal{P} \left(\sum_{t \in \{\mathcal{J},\mathcal{M},\mathcal{Q}\}} A_t(y) * EF_t(y) - \sum_{t \in \{\mathcal{E}\}} A_t(y) * EF_t(y) \right) * R(y) \leq \sum_{t \in \{\mathcal{S}\}} A_t(y) + A_{BCK}(y) \quad (2)$$

A Cumulative implementation, (3), adjusts the formulation in (1) to apply not to each model period, but to the sum across model periods from 2030 to 2050. Similarly, the right-hand side (RHS) is amended to represent the sum over all periods (2030-2050) of emissions committed to geological storage. Any shortfall is met using a fail-safe option.

$$\sum_{y \in \mathcal{P}} \left(\sum_{t \in \{\mathcal{J},\mathcal{M},\mathcal{Q}\}} A_t(y) * EF_t(y) - \sum_{t \in \{\mathcal{E}\}} A_t(y) * EF_t(y) \right) \leq \sum_{y \in \mathcal{P}} \left(\sum_{t \in \{\mathcal{S}\}} A_t(y) + A_{BCK}(y) \right) \quad (3)$$

Notations for equations include:

t	UK TIMES technology, with BCK denoting the fail-safe technology
y	model period
A_t	technology activity
EF_t	technology emission factor in CO_{2e} (including $CO_{2,}$, CH_4, N_2O and HFC as relevant for t)
$R(y)$	The ratio of fossil emissions included in the constraint in period y. Value between [0, 1].
$\mathcal{I}, \mathcal{E}$	Fossil fuel import and export technologies
$\mathcal{M}$	Domestic mining technologies
$\mathcal{Q}$	Processing and transformation technologies, including non-energy emissions
$\mathcal{S}$	Geological storage technologies
$\mathcal{P}$	Model periods between 2030 and 2050

Import, export, and domestic mining technologies ($\mathcal{I}, \mathcal{E}, \mathcal{M}$) include processes that delimit the boundary of the energy system. Their activity describes the amounts of fossil fuel entering and leaving the system. Processing and transformation technologies ($\mathcal{Q}$) include systems whose activity releases process related fossil emissions to the atmosphere, i.e., emissions unrelated to the imported or extracted energy commodities accounted for at the system border, but who remain fossil in nature. These cover industrial process emissions from the production of cement, and iron & steel, as well as HFC leaks from industrial and service sector refrigeration systems. Geological storage technologies ($\mathcal{S}$) here refer to transport technologies that transmit captured CO_2 to geological storage, and for which each unit of activity represents one unit of CO_2 removed to durable storage.

Note that equations (1)-(3) do not explicitly differentiate between mitigation (i.e. fossil technologies with carbon capture and storage (CCS)), and removals (i.e. Direct Air Capture (DAC)). Yet because the LHS accounts for all fossil energy and process emissions that remain in the system, any residual emissions from CCS in that total will imply higher removals required on the RHS (alongside the CCS captured quantities).

Note also that LULUCF accounts emissions are not included in equations (1)-(3). UK TIMES includes afforestation and energy crop options which increase soil carbon sequestration on the hectares of land that apply these practices, while also providing woody biomass to the wider energy system. Accounting for the significant risk of reversal for the land carbon sink, however, these sequestered emissions are not considered durable on geological timescales[6,14,18,19].

Finally, emissions from biomass and organic waste-based technologies are not included on the LHS of equations (1)-(3). Accounting rules effectively consider these activities to be carbon neutral. When equipped with CCS to deliver bioenergy with carbon capture and storage (BECCS), however, the emissions are captured and accounted for on the RHS of the equations.

Sensitivity analyses

The three implementations described above define three families of scenarios with different approaches to reaching GNZ as fast and / or as sustainably as possible. To test how resilient each implementation is to changes in underlying system-wide assumptions about future decarbonisation pathways, we implement three sensitivity variants to each implementation. Many alternative sensitivities could be envisaged here, and our approach aims to be illustrative rather than exhaustive in nature.

The role of sustainable biomass in the future UK energy system has been at the centre of a long-standing policy discussion. Biomass availability to, and its appropriate use in, the UK have been the focus of 3 national strategy policies since the Climate Change Act set national emissions targets into law in 2008[46–49]. The use of biomass for the provision of heat and power has received government's financial support under the Renewable Obligations Certification scheme [50] , and successive carbon budget analyses by the CCC and government have suggested a significant role for biomass use for these applications as well as for BECCS. Yet domestic production of energy crops in line with these ambitions has been stalling with planting rates systematically falling behind annual targets; and the most recent exemplar pathways to net zero put forward under Carbon Budget 7 have examined international biomass availability to the UK dropping to zero by 2050[51]. It is unclear whether this reflects concerns about energy security, or contentious debates that continue to highlight the complexity of defining and monitoring "sustainable" biomass, and demonstrating its ability to remove carbon through BECCS on a full life-cycle basis [30,52]. To recognise both, we implement sensitivity scenarios (s1) and (s2).

(s1) Considers the future availability of imported biomass to the UK. We use government analysis presented in the 2023 Biomass Strategy [48] which relies on the latest version of the "UK and Global Bioenergy Resource Model"[53] . Our default assumptions across all scenarios use the "Ambitious" scenario, which sees imported sustainable biomass availability to the UK increase to 622 PJ by 2050. Our sensitivity run for any scenario, when applied, uses instead the "Restricted" scenario, where imported sustainable biomass in 2050 is limited to 124 PJ. In both cases, feedstock in 2050 are dominated by energy crops and agricultural residue (See Biomass Strategy 2023[48] document for more details).

(s2) Considers the future sustainability of biomass, specifically seeking to understand its role in delivering negative emissions in the context of GNZ. To this end, our default GNZ assumptions include BECCS generated CO_2 streams in the GNZ constraint formulation. This is ensured by the default formulation of equations (1), (2) and (3) where the RHS is based on the activity of TnS infrastructure of all captured CO_2. BECCS options rely on this TnS offtake. Our sensitivity assumption amends these formulations to deduct all CO_2 emissions captured through BECCS from the RHS – whether for power, industry, our hydrogen. This does not affect the model's ability to use these technologies for meeting its carbon budget (CB) and net zero GHG by 2050 target.

Our final sensitivity scenarios concern the TnS system. Providing geological storage in the UK is currently understood to imply transporting captured CO_2 via pipeline to offshore injection into saline aquifers or depleted oil and gas fields. UK government plans describe the ambition to expand Carbon Capture Use and Storage (CCUS) to 20-30 $MtCO_2$ by 2030, including 5 $MtCO_2$ from removals, and 3-6 $MtCO_2$ from industrial CCUS [54]. More recently, confirmed funding announcements cover projects able to deliver the capture of 8.5 $MtCO_2y^{-1}$ [55] in industrial clusters most likely to rely on pipeline storage [55]. In UK TIMES, future growth of pipeline offtake is described using injection rate limits, total available capacity, and expected timelines to first site operation for the leading offshore geological UK storage sites as identified in [56]. These include 8 projects totalling 1.6 $GtCO_2$ storage capacity at max site injection rates of between 2 and 13 $MtCO_2y^{-1}$. Recognising the significance of the UK's technical offshore storage potential, suggested to be 78 Gt, identified development sites detailed are complemented by a generic option costed at the maximum detailed site CAPEX and OPEX. First offshore

storage availability is set to 2030, and growth over time follows site readiness order describing an average growth in sequestration capacity of 9 $Mtyr^{-1}$.

(s3) Recognises that delays in pipeline availability will have significant impacts both on wider system decarbonisation pathways, and on the ability of the model to meet emissions related constraints – including the GNZ we investigate here. While we maintain the offshore storage system formulation described above, s3 introduces a delay in first TnS availability, shifting the first year in which UK TIMES can build and operate this infrastructure from 2030 to 2035. This directly impacts the ability of the model to comply with formulations (1), (2), and (3) of the GNZ by affecting the RHS of the equations and the need to use fail-safe technologies, or carbon capture and use more widely.

Limitations

Carbon dioxide removal is a fast-growing area of research with novel CDR methods both increasing in number and maturity. While global novel CDR removals remain 1000 times smaller than conventional methods, they have shown an average annual growth of 36% between 2020-25, with leading options including biochar and enhanced weathering [57]. Although not yet widely used for carbon removal, these options are expected to deliver carbon storage on geological timescales without relying on pipelines and offshore infrastructure. Including these options in this version of the UK TIMES model was out of scope. Yet they would diversify routes GNZ delivery, increasing its resilience and strengthening policy relevance. Other methods like ocean alkalinisation remain nascent but are subject to the same comment.

While they show that CDR designs are vulnerable to changes in energy system conditions, our restricted sensitivity runs do not include alternatives that might strengthen the case for GNZ. For example, Barrett et al. (2022)[36] and Sharmina et al. (2025)[37] examined alternative energy demand futures. They show that reducing energy demand by 52% by 2050 without affecting quality of life is possible, and that policy-makers can envisage alternative and low demand scenarios. Lower energy demand would also support GNZ delivery, reinforcing the policy environment for transformational change. While this work demonstrates the first national analysis of GNZ, future work should consider these interactions more actively.

Finally, this work presents a first consideration of inequivalences between emissions and removals related to complex planetary system dynamics as described in Zickfeld et al. (2023)[6] in a national whole energy system model. We focus first on the like-for-like principle as the most discussed option for inclusion into energy policy[14]. Arguably, wider interactions between future technology options, emissions pathways, and the planetary systems we depend on need to make their way into both long-term energy planning and policymaking. Future work should thus both consider better representing impermanence, biogeophysical, and non-CO_2 GHG effects leading to non-equivalence of CDR with emissions in long-term national energy planning; while at the same time seeking to more actively integrate national energy planning with earth system modelling.

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