Expanding New Zealand’s emissions removals tool-kit: Policy development for carbon mineralisation

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1. Summary

To efficiently achieve our 2030 and 2050 Paris Agreement commitments, New Zealand will require a substantial supply of greenhouse gas (GHG) emission offsets to complement its reduction aims. Urgency for climate-change action has led to rapid development of carbon markets and global demand for high-quality offsets is expected to grow markedly over the next decade. In particular, as emissions budgets shrink towards net-zero, the need for carbon removal offsets will become acute. Meanwhile, our current model of offsetting by perpetual forestation is increasingly recognised as socially unpopular, unsustainable, and laden with long-term external risks. On the other hand, political, regulatory, and legislative barriers currently encumber the adoption of non-forestry carbon sequestration technologies in NZ.

The geology of Aotearoa provides a tremendous opportunity for the permanent removal and sequestration of hard-to-abate industrial emissions. By utilising NZ’s plentiful and accessible ultramafic rock deposits, captured CO_2 can be chemically trapped and transformed – quickly, safely, and permanently – into stable minerals completely eliminated from the atmosphere. From a tiny footprint, carbon mineralisation can be scaled without practical limit: The sequestration capacities of suitable geological formations are orders of magnitude larger than the total of all carbon emissions humans have ever produced.

NZ must act swiftly to enable domestic development of carbon mineralisation and other emerging removal technologies. Without a clear pathway to market – either through inclusion into the emissions trading scheme (ETS) or otherwise secure government recognition – methods like mineralisation will not receive the capital investment necessary for deployment. Expanding the suite of sanctioned carbon removal mechanisms will help allay NZ’s exposure to fiscal risk from international offset procurement and allow market discovery of efficient emission mitigation strategies.

Acronyms

BECCS	Bioenergy with carbon capture and storage
CCS	Carbon capture and storage
CDR	Carbon dioxide removal
CO_2-e	Carbon dioxide equivalent
DAC	Direct-air-capture (of CO_2)
DACCS	Direct-air-carbon capture and storage
ETS	Emissions Trading Scheme
EU	European Union
GHG	Greenhouse gas
GNS	Geological & Nuclear Sciences (Crown Research Institute)
Gt	Giga-tonne (1 billion tonnes)
HWP	Harvested wood products
IPCC	Intergovernmental Panel on Climate Change
MBIE	Ministry of Business, Innovation & Employment
NDC	Nationally Determined Contribution (Paris Agreement aim)
Mt	Mega-tonne (1 million tonnes)
NET	Negative emissions technology
NZAS	New Zealand Aluminium Smelter Ltd.
NZD	New Zealand Dollar
NZU	New Zealand Unit (an emissions credit within the ETS)
R&D	Research and development
t	tonne
TRL	Technology readiness level
USD	United States Dollar
yr	year

2. Carbon mineralisation: Permanent and scalable emissions sequestration

The Earth's crust contains an abundance of minerals that are chemically reactive with CO_2 (see Eq. 1). Each year ca. 150 Mt CO_2 is consumed in naturally occurring mineralisation reactions globally.[1] As such, fixation of anthropogenic-CO_2 within rock deposits has long been proposed as an ideal climate-change solution – on geological time-scales, the final fate of all atmospheric carbon is its chemical binding in geological minerals.[2] The technical challenge in the context of emissions mitigation is to bring large amounts of CO_2 into contact with suitable rocks (which are typically shielded from the atmosphere in subterranean or submarine formations) and enhance the process for application on human timeframes.

$$\mathrm{MgO} + \mathrm{CO_2} \longrightarrow \mathrm{MgCO_3} \qquad \Delta H^{\circ} = -118\ \mathrm{kJ\ mol^{-1}}$$

Equation 1. CO_2 naturally reacts with compounds like Magnesia (MgO), leading to its chemical combination to form a new carbonate mineral – in this case Magnesite ($MgCO_3$). The carbonation reaction is highly exothermic meaning heat is generated as it occurs, which both increases the rate of conversion and reduces overall process costs.

Despite its theoretical appeal, natural carbon mineralisation was conventionally thought to occur too slowly (or its acceleration too costly) to have practical value as a climate-change response. For this reason, most work on geologic storage of emissions has centred upon pumping compressed CO_2 into depleted oil and gas fields. However, this traditional approach to carbon capture and storage (CCS) – often associated with enhanced oil recovery – is inherently uncertain and temporary due to the intractable threat of CO_2 leakage (developed petroleum reservoirs are at constant risk of exposure and releasing their contents).[3] In contrast, mineralised CO_2 is chemically transformed and energetically stable, making its sequestration permanent.

Although previously considered impractical, the Carbfix project in Iceland has recently proven the commercial viability of carbon mineralisation by disposing more than 80,000 t CO_2 produced from the Hellisheidi geothermal power plant (Box 1). Through subterranean injection of CO_2 into basaltic rock formations under hydrothermal conditions, complete conversion into mineral carbonates was observed to occur in less than two years. Spurred by this discovery, multiple research programs and commercialisation efforts are now developing across Europe,[4] US,[5] Australia,[6] and the Middle East.[7]

Box 1: Carbfix

Since 2014, Carbfix Iceland ohf. have commercially deployed carbon mineralisation to permanently dispose ca. 20,000 t CO_2 per year captured from a geothermal power plant (images: top) at a cost of $25 USD per tonne.[8] Carbfix have also joined with DAC firm Climeworks AG to remove and sequester CO_2 directly from the ambient atmosphere (photo: lower-left).[9,10] Carbfix is currently up-scaling infrastructure to handle tanker-ship delivery of CO_2 captured from European industry (Coda Terminal, photo: lower-right).[11]

While the Carbfix process reacts captured CO_2 with underground minerals *in situ* via deep boreholes, other pilot projects show *ex situ* applications are also possible if a surface supply of suitable rock is available.[12] In *ex situ* schemes, quarried materials are transported to industrial sites for reaction with process emissions, directly fixing flue-gas CO_2 before it can reach the atmosphere. Although *in situ* mineralisation presents far greater sequestration potential for minimal environmental impact, *ex situ* techniques have the advantage of avoiding an expensive CO_2 capture stage. In addition, the resulting carbonate minerals and by-products from ex situ reactions can be valorised as construction aggregates or fillers, and in certain cases precious metal recovery is also possible.

Overall, not only is carbon mineralisation a near perfect CCS technology for existing industrial point source emitters, it can also seamlessly integrate with bioenergy and direct-air-capture (DAC) to become a negative emission technology (NET) or carbon dioxide removal (CDR) scheme. Scale is practically unlimited, with estimates suggesting that NZ's ultramafic rock deposits alone could likely sequester more carbon than the total fossil-fuels burnt since the industrial revolution.[13,14] Out of decades of research into emissions mitigation, carbon mineralisation has emerged as perhaps the most applicable and sustainable solution to climate-change (Table 1).

Method	TRL[*] (1 to 9)	Est. cost[†] (USD / t CO_2-e)	CO_2 storage durability[‡]	Practical scale[§] (Gt CO_2-e / yr)
Forestation (incl. HWP)	8-9	2-150	med	0.5-3.6
Soil carbon and terrestrial sinks	8-9	45-100	low	2-5
Carbon mineralisation (and enhanced weathering)	5-8	25-200	permanent	1-10
Traditional CCS	6-8	20-150	med-high	10-30
Biochar	6-7	30-345	med-high	0.3-2
BECCS	6	15-400	med-perm.[**]	0.5-5
DACCS	6	100-300	med-perm.[**]	5-40
Coastal blue carbon	2-3	10-300	low-med	0.4-1.2
Ocean alkalinity enhancement	1-2	40-260	med-high	1-100
Ocean fertilisation	1-2	50-500	low-high	1-3

* Technology readiness level, based on Horizon-2020 scale.[15]
† 2018 dollar values.
‡ Qualitative categorisation combining theoretic longevity with failure risks.
§ Estimated feasible global implementation by 2050.
** Durability depends upon CO_2 storage method used in combination with the capture process.

Table 1. Overview of leading CDR and sequestration technologies, adapted from IPCC and NewClimate research with additional data from McKinsey & Co. and the Global CCS Institute.[16–20] Shaded colours denote overall qualitative assessment of the feature (red: poor, yellow: good, green: best). Scientists estimate that 5-16 Gt CO_2-e of worldwide removals will be required annually by 2050 to achieve net-zero emissions.[21,22]

3. NZ's geological advantage

Straddling the Australian and Pacific tectonic plate boundary, Aotearoa is a unique landmass with a tumultuous geological past. This dynamic history has created an immense diversity of formations, including extensive mineralogy suited to carbon mineralisation (Box 2). Specifically, the Dun Mountain-Maitai Terrane stretches the length of the country as a geographic belt of ultramafic rocks (Fig. 1). Exposed directly at the surface in some regions and buried elsewhere, this belt lies near to major industry including chemical production, electricity generation, cement manufacture, and metal smelting. Such proximity provides NZ a unique advantage for carbon mineralisation deployment (e.g. Box 3); most ultramafic formations around the world lie under the ocean or are distant from major population centres.[23]

Box 2: Ultramafic rocks

Originating from deep in the Earth's mantle, ultramafic rocks are defined by their high magnesium and iron contents. Dominated by the mineral olivine – $(Mg^{2+}, Fe^{2+})_2SiO_4$, – ultramafic formations often produce distinct landscapes (e.g. Red Mountain, South Westland, photo: left) owing to chemical weathering reactions. Dunite (sample from Mt. Dun, Nelson, photo: right) is the olivine-rich (>90%) endmember of the peridotite ultramafics.

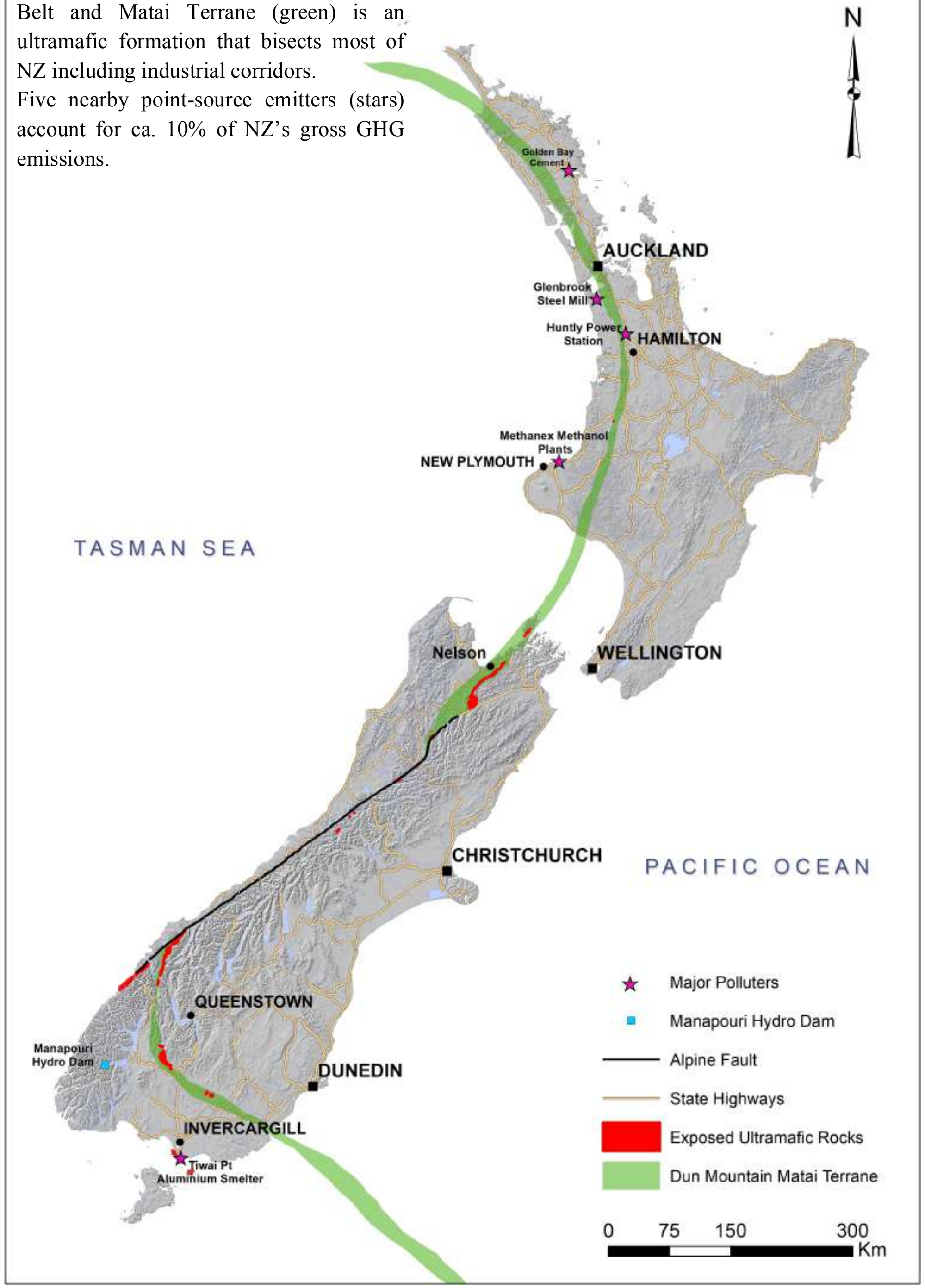
Ultramafic and Mafic rocks, which contain high concentrations of divalent cations, such as Ca^{2+}, Mg^{2+} and Fe^{2+}, are well suited for the rapid mineralisation of CO_2 to calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), or magnesite ($MgCO_3$).

In addition to being favourably located, the Dun Mountain-Maitai Terran's ultramafic composition frequently contains fertile outcroppings of dunite and other peridotite rock types. Lab testing has found the specific chemistry of these rocks to be more reactive than the serpentinite and basaltic formations frequently put forth as mineralisation candidates elsewhere.[24] As well as faster mineralisation rates, dunite deposits frequently reach 50% MgO by weight meaning that under optimal conditions less than 2 t of material are reacted for each t CO_2 mineralised.[2] This high conversion ratio substantially out performs the basalts targeted in Carbfix, where a theoretic minimum of 7 t is required and considerably more in practice.[25]

Beyond fortunate geology, NZ is already home to the technical knowledge required to successfully realise carbon mineralisation technology. Our universities and research institutes have experience in the seismology, geophysics, and petrology necessary for carefully mapping the ultramafic resource. The extensive geothermal, petroleum, drilling and mining industry is well accustomed to resource management, borewell implementation, gas and chemical handling, and equipment development. With many of these industries in gradual decline, carbon mineralisation offers an excellent opportunity for skills-transfer and can complement existing commercial activities.

Few other countries share this set geographic and societal circumstances to benefit from a burgeoning international carbon sequestration market: After handling domestic emissions, there is no reason why NZ should not follow the Icelandic path towards taking international tankers of CO_2 (for safe and secure disposal) captured from industrial sites throughout the southern hemisphere (Box 1).

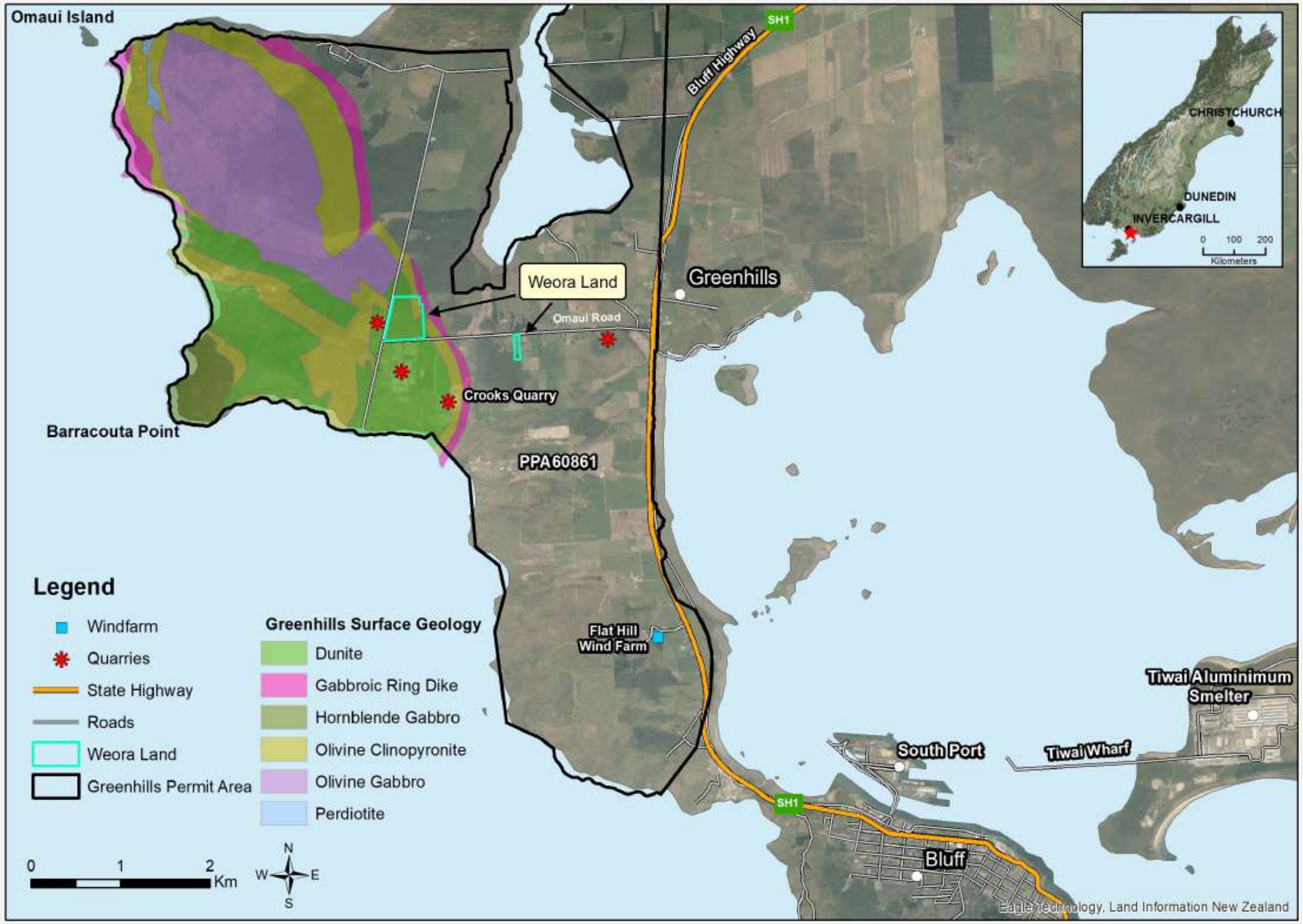
Figure 1. The Dun Mountain Ophiolite Belt and Matai Terrane (green) is an ultramafic formation that bisects most of NZ including industrial corridors.
Five nearby point-source emitters (stars) account for ca. 10% of NZ's gross GHG emissions.



Box 3: Weora

Part of the Hardie Pacific Group, Weora Ltd. is a privately funded NZ company that has been pursuing carbon mineralisation technology since 2017.

Increasing efforts in 2021, Weora currently has five Mineral Prospecting Permit applications (table below) totalling 1283 km^2 across NZ, covering key areas of the Dun Mountain-Maitai Terrane (Fig. 1) and the Greenhills Ultamafic Igneous Complex (map: right).



Permit number	Name / location	Area (km^2)
PPA60864	Waikato	286
PPA60875	King Country	401
PPA60863	Whakatu	321
PPA60862	West Dome	247
PPA60681	Greenhills	28

First focusing on Greenhills due to the proximity to South Port and significant CO$_2$ emitters including the Tiwai Point Aluminium Smelter (NZAS), Weora owns strategic free holdings and is engaging local stakeholders. Partnerships with iwi, commercial emitters, landowners, local and central government are being sought – responses to date have been entirely favourable.

Scientifically, Weora is planning geophysical and seismic surveys to map the lithologies of the Greenhills Complex and determine subsurface geometry. Ongoing academic collaborations include the Universities of Otago, Auckland, Canterbury, New South Wales, and GNS.

Greenhills has considerable amounts of the mineral Olivine (contained in Dunite and other ultramafic rocks) in surface and subterranean deposits, which is an excellent candidate for carbonation.

Weora's initial drilling programme commences in July 2022 with several pilot holes to ca. 800m depth to examine the extent and overall suitability of the geology for *in situ* carbon mineralisation. Drilling will showcase the potential of carbon mineralization to the public and generate further stakeholder and media engagement. After completing initial boreholes, Weora aims to conduct trial mineralisation operations within 12 months (pending consents).

Once tests have confirmed successful transformation and chemical binding of CO$_2$ in NZ conditions, Weora will deploy at commercial scale. Initial estimates suggest the Greenhills site could annually sequester up to 1 Mt CO$_2$ captured from local emitters, with even greater scale possible from tanker-ship delivery of CO$_2$ from other point sources in NZ.

Aside from disposing of CO$_2$ generated by industry, DACCS can be also easily implemented at Greenhills owing to local availability of renewable electricity.

4. The case for non-forestry carbon sequestration technologies in NZ

NZ faces a difficult 30-year challenge in reducing emissions without economic stagnation or decline. The proximate national emissions goal for 2030 (NDC) equates to a total net reduction of ca. 150 Mt CO_2-e this decade (ca. 20% lower than business-as-usual).[26] However, under the current Emissions Reduction Plan and ETS settings, around two-thirds of this reduction will be met through international offset purchases (despite the fact formal mechanisms for such offset trading are yet to be established).[27] This approach carries substantial fiscal risk – many governments and international organisations are similarly intending to procure offsets to oblige their respective emissions targets, with forecast global demand increasing more than 10-fold by 2030.[28] Wary of a repeat of the faulty emissions credits that undermined the Kyoto Protocol in the 2010s, high standards of environmental integrity and additionality for offsets are expected. Together these factors are likely to drive emission prices to \$80-150 USD per t CO_2-e by 2035 (2020 dollars).[28] In relying on international supply to meet emission targets, the Climate Change Commission estimates a deadweight economic loss to NZ of up to \$30.5 billion NZD from offshore offset purchases this decade alone.[29]

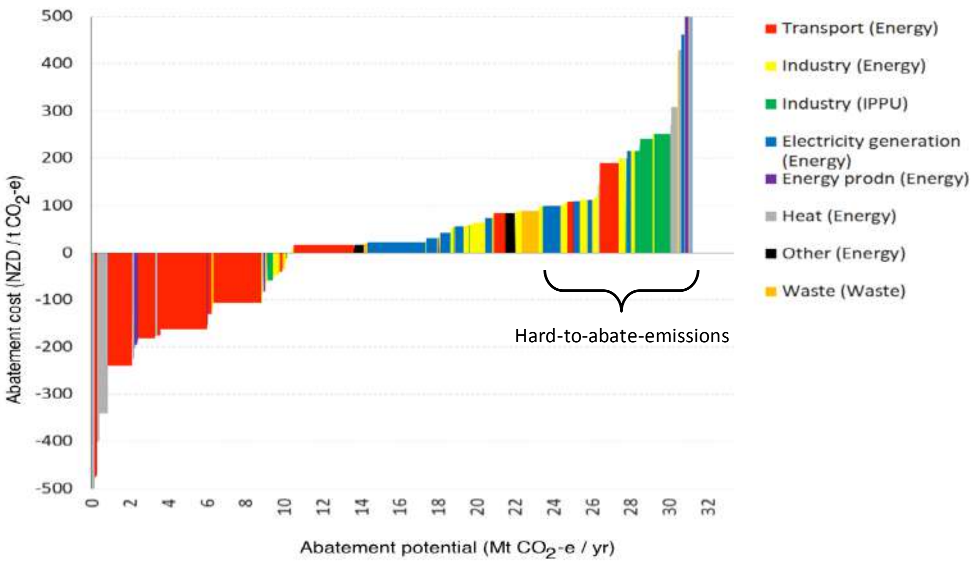


Figure 2. Marginal Abatement Cost Curve analysis for NZ energy and industry sectors in 2030.[30] Abatements of many industrial emissions are especially costly and will rely on methods like CCS and carbon mineralization.

Domestically, NZ is currently engaged in a policy of emissions reduction that focuses on decarbonisation of the economy.[31] While emission-less alternatives may be used in many sectors for minimal costs, decarbonisation in industrial processes like metal smelting and cement production is either not possible or prohibitively expensive (Fig. 2). However, hard-to-abate emissions are frequently those of high productive value – meaning that their curtailment would cause the greatest economic impact in the event of industry closure.[32] Until recently, fast-growth exotic forestry within the ETS provided the ability to counter such emissions for modest cost, but a growing understanding of risks accompanying exotic forestation have led to its probable future exclusion (Box 4).

Box 4: Drawbacks of forestry

To date, forestation has been the only CDR tool used significantly in NZ. Particularly, radiata pine forests were instrumental for NZ meeting previous emission obligations under the Kyoto Protocol.[33] While pursuing extensive fast-growth exotic forestry would also allow NZ to meet its 2030 and 2050 Paris Agreement targets, such an approach invites additional problems to the point that the current government is likely to preclude future exotic forests from the ETS.[34]

Aside from disease, fire and ecological hazards, carbon forests carry externalities in the form of social disruption to rural populations, the eventual permanent loss of potentially productive land, and (if the carbon sequestered is to remain secure) perpetual management burdens that extend long beyond private foresters' investment returns.[34]

Compounding these issues are open scientific questions over growing forests outside of their endemic areas as a means of climate-change mitigation:[35] Changes in albedo, evapotranspiration, and volatile organic compound release brought about by extensive exotic forestation all independently impact global climate, potentially undermining a forest's entire atmospheric carbon removal benefit.[36]

While rebalancing the supply of carbon forestry in the ETS may be prudent for avoiding long run ecological liabilities, its constraint will make it more difficult for NZ to abide future emissions budgets. In lieu of fortuitous emission-less technological breakthroughs, sustained emphasis on decarbonisation will eventually push the cessation of certain industry and agriculture when alternative mechanisms like CCS or CDR offsets could have instead obtained net-zero emission outcomes without the same economic fallout. Claims of moral hazard that the pursuit of removal technologies will weaken emission reduction efforts are misplaced: There is a parallel danger that blinkered decarbonisation will eventually make future emission reduction commitments politically untenable, with otherwise cost-effective CCS, CDRs, and NETs being unavailable due to their premature preclusion from the usable solution-set (Box 5). Ultimately the problem is excess GHGs in Earth's atmosphere and every tool that removes or otherwise prevents emissions (and fulfills requisite environmental standards) should be made available for market evaluation.

In opening the door to emerging technologies like carbon mineralisation, NZ will reduce the risk of becoming cornered between the juncture of international offset markets and unnecessarily painful domestic curtailments. And apart from the economic flexibility that non-forestry sequestration techniques will provide, the IPCC has recently assessed that large-scale CDRs and NETs will play a critical role in limiting global warming to acceptable levels,[16] These are also the only mechanisms that can successfully redress historical emissions or resolve climate overshoot scenarios.[37] With an extraordinary geologic resource, NZ can position itself near the forefront of these technological innovations in a rapidly growing global market. Not only could carbon mineralisation safeguard NZ's ability to achieve its emission targets, it also presents a lucrative economic possibility in the form of emission removal exports and servicing international demand for specialist carbon sequestration expertise.

Box 5: Institutional security of emission reductions and the ETS

Enforcing GHG emission reductions in NZ is only possible through widespread political buy-in and social license. Stable, transparent, and durable institutional support for emission abatement methods is similarly critical for instilling investment confidence in capital-intensive projects like carbon mineralisation. Conflicting government policies, direct interventions, ambiguous messaging, and political posturing undermine both these missions, and thereby reduce the likelihood of emissions reduction success in the long run.

NZ is fortunate to enjoy strong support for an emissions reduction programme, however considerable room remains for promoting commercial enterprise and major investment in emission mitigation. Within the first year of capped unit supply in the ETS, prices and demand have surpassed government containment mechanisms, with current and future emission prices tracking higher than Climate Commission modelling predicted as necessary for incentivising meaningful reductions.[29,38] While these price signals demonstrate business confidence in the ETS, they also suggest that real-world reductions and technological changes are more difficult than supposed in analytical models. In particular, steep price rises in the face of a large segment of negative and low abatement values in cost analyses (Fig. 2) imply the presence of other non-financial barriers to emissions reductions and should serve as an important warning to government. Furthermore, the very large stockpile of NZU emissions credits (mostly bought at prices much cheaper than current) means that the ETS impetus for emission reductions is misaligned with domestic budgets.[39]

Unless policy actions are taken to better enable commercial solutions to emissions abatement, including the ability to deploy removal technologies like carbon mineralisation, NZ risks simultaneously missing its near-term emissions budgets and increasing the political pressure to undermine the ETS (either through low-cost international linking, or simply reneging on emissions targets). In the extreme, market participants may view political lobbying as a more effective strategy for defraying their ETS costs than actual emissions abatement.

To head-off such a possibility, the NZ government must immediately and unambiguously cement long-term ground rules for the ETS (in terms of NZU supply matching domestic carbon budgets, stockpile reduction, international linking prospects, emissions backing, and removal technologies) as well as clarifying its intentions for purchasing offsets in meeting its Paris Agreement targets. This will significantly improve ETS credibility and let actors assess market realities for expensive emission reduction decisions.

5. Policy for non-forestry carbon sequestration

The NZ government must promptly signal its intention to recognise the value of non-forestry carbon sequestration options and take proactive steps towards their integration within the ETS. Just as many low-emissions technologies require long-term market security to secure large-scale investment, emission removal innovations will not receive private funding for commercialisation without a requisite pathway to market.

Unfortunately, the machinery of government often treats novel instances of technology as speculative or unproven. For the case of emissions sequestration where market value is entirely dependent upon government license, this stance produces a stifling chicken-and-egg situation whereby a technology must demonstrate market success to gain market access but cannot do so without having market access in the first place. Such a dilemma encapsulates the primary barrier to entry for large-scale carbon-neutral or carbon-negative climate-change solutions and is ostensibly the reason that non-forestry carbon removal ideas have largely languished in academic incubation.

Fortunately, voluntary carbon markets,[40] other governments,[41] and carbon accounting firms have already traversed much of the terrain for quantification and verification of sequestration methods,[42] thus partly simplifying the task for NZ policy makers. Current work by Ara Ake is exploring deployment paths for CDR and CCS in NZ.[43] For most CDR instances, ETS incorporation will result in an emissions unit award system comparable to that in operation for forestry. For CCS schemes that interrupt emissions from reaching the atmosphere in the first place, an alternative regulation is possible by exempting those ‘emissions’ from the ETS entirely (i.e. GHGs captured and stored are not subject to any NZU surrenders). While these two modes are largely equivalent in terms of monetisation, the latter would necessitate revision of carbon inventory rules but give the nominal benefit of being considered a gross emissions reduction rather than an offset.

Apart from ETS regulation, legislative changes may be necessary for specific sequestration methods. Carbon mineralization will likely require an amendment to the Crown Minerals Act and a specific CCS or CDR Act to govern *in situ* processes. Extensive previous research into traditional CCS by MBIE,[44] the Productivity Commission,[45] GNS,[46] and University of Waikato included a comprehensive review and framing for CCS legislation,[47] providing a primary foundation for advancement. The frameworks in Iceland,[48] Norway,[49] and the EU also serve as potential blueprints for legislative development.[50]

Beyond regulation and legislation, additional policy tools will be needed to shore up the market confidence and long-term price certainty that are required for justifying free-enterprise investments in sequestration schemes. Table 2 below gives a basic overview of general government policy options that may be used to bolster investment appeal.

Policy	**Description**
Proactive ETS inclusion, smoothing other barriers	Provides pathway-to-market for commercial investments in sequestration projects.
NZU free allocations conditional on R&D and removal investments	Incentivise investments through ETS free-allocations to trade exposed entities – allocations could be dependant on R&D and capital expenditure into climate-change solutions.
Carbon border tariffs	Indirectly increase the business advantage for domestic investments.
Emission removal purchase guarantees / option contracts	Government forward purchase contracts or put-options for domestic removals at set quantities and minimum prices. Future procurement of emission offsets should be first offered domestically (with prices suitably adjusted for multiplier effects).
Tax rebates	Increases profitability of successful carbon sequestration projects.
ETS removals quantified according to risk and longevity	CDR methods have different permanencies and associated risks (Table 1). The ETS may account for risk through differential quantification, e.g. forests receive fewer NZU per t CO_2-e compared to carbon mineralisation.[51]
Direct funding of carbon sequestration projects	Government co-investment or contribution with a negotiated supply of offsets offered to the Crown at favourable prices upon project success.

Table 2. General policy options to encourage non-forestry carbon sequestration in NZ.

References

1. Alt, J.C., Teagle, D.A.H. (1999) The uptake of carbon during alteration of ocean crust. *Geochimica et Cosmochimica Acta*, 63, 10.
2. Lackner *et al.* (1995) Carbon dioxide disposal in carbonate minerals. *Energy*, 20, 11.
3. Vinca *et al.* (2018) Bearing the Cost of Stored Carbon Leakage. *Front Energy Res*., 6, 40.
4. www.geco-h2020.eu
5. Blondes *et al.* (2019) *Carbon Dioxide Mineralization Feasibility in the United States*. U.S. Geological Survey.
6. www.mineralcarbonation.com
7. www.4401.earth
8. www.carbfix.com
9. www.climeworks.com
10. techcrunch.com/2021/12/03/co2-capture-iceland-climeworks-orca/
11. www.bloomberg.com/news/articles/2021-04-21/iceland-s-carbfix-wants-to-turn-co-shipped-from-europe-to-rock
12. Gadikota, G. (2016) Commentary: Ex Situ Aqueous Mineral Carbonation. *Front Energy Res*., 4, 21.
13. Scott *et al.* (2021) Transformation of abundant magnesium silicate minerals for enhanced CO_2 sequestration. *Commun Earth Environ*., 2, 25.
14. Scott, J.M. (2020) An updated catalogue of New Zealand's mantle peridotite and serpentinite. *New Zealand Journal of Geology and Geophysics*. 63, 4.
15. enspire.science/trl-scale-horizon-europe-erc-explained/
16. Babiker *et al.* (IPCC 2022) Cross-sectoral perspectives. In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
17. Jeffery *et al*. (2020) *Options for Supporting Carbon Dioxide Removal Discussion Paper*. NewClimate Institute.
18. Claes *et al.* (2022) *Blue Carbon: The Potential of Coastal and Oceanic Climate Action*. McKinsey & Company.
19. *The Global Status of CCS 2021* (2021) Global CCS Institute.
20. Ciais *et al.* (IPCC 2014) Carbon and Other Biogeochemical Cycles. In: *Climate Change 2013: The Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
21. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda* (2019) National Academies Press.
22. www.climateworks.org/blog/carbon-dioxide-removal-is-now-essential/
23. Snæbjörnsdóttir *et al.* (2020) Carbon dioxide storage through mineral carbonation. *Nat Rev Earth Environ*., 1, 2.
24. Kelemen *et al.* (2020) Engineered carbon mineralization in ultramafic rocks for CO_2 removal from air: Review and new insights. *Chemical Geology*, 550, 119628.
25. Marieni *et al.* (2018) Towards 'green' geothermal energy: Co-mineralization of carbon and sulfur in geothermal reservoirs. *International Journal of Greenhouse Gas Control*, 77.
26. www.newsroom.co.nz/govt-seeks-overseas-trees-to-meet-paris-climate-pledge
27. environment.govt.nz/publications/aotearoa-new-zealands-first-emissions-reduction-plan/
28. *Essential, Expensive and Evolving: The Outlook for Carbon Credits and Offsets* (2022) EY Net Zero Centre.
29. *Ināia tonu nei: a low emissions future for Aotearoa* (2021) Climate Change Commission (NZ).
30. *Marginal Abatement Cost Curves Analysis for New Zealand: Potential Greenhouse Gas Mitigation Options and Their Costs* (2020) Ministry for the Environment.
31. *Transitioning to a Low-Emissions Future - the Government Response to the Productivity Commission's Low Emissions Economy Report* (2019) New Zealand Government.
32. *Environmental-Economic Accounts: 2019 (Data to 2017)* (2019) Stats NZ.
33. environment.govt.nz/what-government-is-doing/areas-of-work/climate-change/emissions-reduction-targets/latest-update-on-new-zealands-2020-net-position/
34. *Managing Exotic Afforestation Incentives: A Discussion Document on Proposals to Change Forestry Settings in the New Zealand Emissions Trading Scheme*. (2022) Ministry for Primary Industries.
35. Popkin, G. (2019) How much can forests fight climate change? *Nature*, 565, 7739.
36. Unger, N. (2014) Human land-use-driven reduction of forest volatiles cools global climate. *Nature Clim Change*., 4, 10.
37. Sørensen *et al.* (2021) *Negative Emissions and Carbon Dioxide Removal (CDR)*. NTNU.
38. github.com/theecanmole/nzu
39. Leining, C. (2022) *A Guide to the New Zealand Emissions Trading Scheme: 2022 Update*. Motu Economic and Public Policy Research Trust.
40. www.puro.earth
41. www.cleanenergyregulator.gov.au/ERF/Choosing-a-project-type/Opportunities-for-industry/carbon-capture-and-storage-method
42. www.carbon-direct.com
43. *Carbon Dioxide Removal and Usage in Aotearoa New Zealand* (2022) Ara Ake.
44. *CCS in New Zealand* (2011) Transfield Worley Ltd..
45. *Low-Emissions Economy: Final Report* (2018) New Zealand Productivity Commission.
46. www.gns.cri.nz/Home/Our-Science/Energy-Futures/Carbon-Capture-and-Storage/Research
47. Barton *et al.* (2013) *Carbon capture and storage: Designing the legal and regulatory framework for New Zealand*. Centre For Environmental, Resources and Energy Law. The University of Waikato.
48. www.althingi.is/altext/stjt/2021.012.html
49. Weber, V. (2021) Regulation of CCS Storage Sites in Norway and Compliance With EEA Law. *SINTEF proceedings*, 7.
50. Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009.
51. Whitmore, A., Aragones, M.P. (2022) *Addressing Differences in Permanence of Carbon Dioxide Removal*. Bellona Foundation.