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Sequestration Cost Reduction Workshops Report

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The list of participants is below, note that some participants have preferred to remain anonymous and are not included.

Planted vegetation workshop participants:

Natasa Sikman ,Anthony Fitzgerald, Zoe Ryan,Tai, White-Toney, Shaun Levick, Stephen Roxburgh, Paul Ryan, Peter Ritson, Jenny Sinclair, Beren Spencer, Arjan Wilkie, Philipp Kilham, Annette Cowie, Simon Dawkins, Martin Moroni, Tim Moore, Rod Keenan, Liam Costello.

Blue carbon workshop participants:

Andy Steven, Ray Marcos Martinez, Cath Lovelock, Lauren Drake, Mat Vanderklift, Valerie Hagger, Nikki Fitzgerald, Veda Fitzsimmons.

Direct Air Capture workshop participants:

Paul Feron, Roger Aines, Timothy Fout, Paul Webley, Deanna Dalessandro, Julian Tureck, Ali Kiani, M Lucquiaud, Christopher Jones.

Biomass/biochar workshop participants:

Peter Burgess, Annette Cowie, Craig Bagnall, Fabiano Ximenes, Rajinder Singh, Ian O'Hara, Stephen Joseph, Gustavo Fimbres Weihs, Jenny Hayward, Nawshad Haque.

Carbon Capture and Storage workshop participants:

Peter Cook, Charles Jenkins, Darren Greer, Andrew Garnett, Phil Grainger, Geoff Obrien, Noel Simento, Matthew Sherwell.

Mineral carbonation workshop participants:

Renee Birchall, Andrew Lenton, John Beever, Sophia Hamblin-Wang, Philip Fawell, Mei Yuan, Stuart Watson, Ralf Haese

1 Key messages

This report details the methods, outputs and analysis from a series of workshops held to elicit expert advice on how technical innovation can lower the cost of carbon sequestration and correspondingly decrease an economic barrier to the uptake of different sequestration approaches. The expert advice is translated into estimates of sequestration cost reduction either by using simple cost flow models or by interpretation of workshop participant estimates. A ranked list of technical innovation options for each sequestration technology is developed using cost reduction estimates and other metrics.

The report findings do not constitute a formal review, an economic analysis, or the final word on any of the sequestration technologies reviewed, which in some cases, are changing rapidly.

The report does not provide estimates of additional economic potential sequestration that could be unlocked due to the cost reduction potential, and this is left for future studies to undertake.

All cost reduction figures should be taken as indicative, or "ballpark", and used more as a means of ranking or prioritising action to drive down the technology cost rather than for formal evaluation of costs of implementation.

Workshops were conducted for sequestration opportunities using planted vegetation, blue carbon, direct air capture, biomass/biochar, carbon capture and storage, and mineral carbonation sequestration approaches. In addition, a brief review of two technology options for savanna fire management was undertaken.

Key messages from the analysis of the workshops' outputs are:

- For each sequestration approach, the identified technical innovation opportunities have varying potentials to reduce the sequestration cost. In some cases, such as direct air capture, biomass/biochar and mineral carbonation sequestration approaches, these technical innovations have significant potential to lower costs and accelerate uptake.
- Each sequestration approach is at a different maturity stage (commercial readiness level or technical readiness level). The less mature approaches (generally the engineered sequestration approaches) have a better potential for lower costs because the current costs per tonne of sequestered carbon are typically higher. This is particularly the case with direct air capture, where current costs are high ($878 per tonne[1]), with reductions of about 25% on current costs suggested as possible for each of the technologies.
- The cost reductions determined for this report are not additive. There are dependencies and feedbacks between the different cost drivers for each of the technology options. As a result, summing the individual cost reductions to determine an overall possible end cost for a sequestration approach is strongly discouraged.
- Blue carbon technical innovations could reduce costs by up to 42% on current costs ($92 per tonne).
- Innovations in sequestration using planted vegetation could result in a more modest 9–30% cost reduction on a baseline of $19.50 per tonne.

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[1] All costs in this report are in Australian dollars except where otherwise specified.

- Although mineral carbonation is at a low maturity level, there are good opportunities to lower costs for ex-situ approaches, with workshops indicating a reduction range from 38% to 72% based on current costs of $222 per tonne. In-situ approaches have a lower baseline cost ($37 per tonne) and good potential to lower costs by 13–54% of the current cost.
- No cost reduction estimates for carbon capture and storage are reported due to differences with the workshop format and the general feeling that the technology is relatively mature with a reasonable commercial readiness level and that the challenges are elsewhere (financing, social license etc.)
- The provision of fire risk and remotely sensed fire severity information can potentially improve the setting of the early dry or late dry season cut-off dates for the savanna fire management sequestration approach.
- Developing a common language (terms and concepts) to discuss sequestration issues would be valuable, helping to avoid confusion and improving the efficiency of these discussions. Most workshops took time to reach a common understanding of the terms and concepts under discussion. This is not unexpected as different sectors (e.g. industry, government, academia) often have their preferred dialect.
- It should be noted that at time of writing the spot price for one tonne of carbon is $35.50.

1.1 Summary of cost reduction potential results

The economic viability of sequestration approaches can be improved by reducing costs or generating additional values from the sequestration activity that provide an economic return – for example, developing new long-lived products from biomass residue. . In such cases, creating a new product does not impact the sequestration cost but will improve the overall economic viability of the approach. In instances where such additional value creation is used in the analysis, the cost reduction is reported as zero.

Table 1.1 A summary of the individual technologies reviewed, and their cost reduction potential is provided in Table 1.1. For more detail and description of the technology innovation areas, see the relevant chapters of this report.

Table 1.1: Summary of the cost reduction potential of technology innovation areas for each sequestration approach reviewed.

Sequestration technology	Technical innovation area	Cost reduction from baseline ($ per tonne)	Net cost ($ per tonne)
Vegetation	Baseline cost	0	19.5
	Low-cost imagery	–2.8	16.7
	Zero or low emission fuels	–3.4	16.1
	Small-scale equipment for agroforestry	–4.7	14.8
	Control of pests, diseases and browsing animals	–6.1	13.4
	Decision support for informing optimal species selection	–3.9	15.6
	Lower-cost fencing	–2.9	16.6

	Genetic improvements	–1.8	17.7
	New products for biomass residue	0	19.5
	Driverless or automated vehicles	–3.0	16.5
Blue carbon	Baseline cost	0	92
	Methods and indices for measuring other benefits	0	92
	National model for tidal introduction and feasibility assessment	–39	53
	Earth observation technologies for restoration site identification and assessment	–17	75
Direct air capture	Baseline cost	0	878
	Materials	–218	660
	Energy supply	–232	646
	Process and equipment	–197	681
Combined biomass/biochar	Baseline cost	0	60
	Technology at scale	–10.2	49
	Large-scale modular plants	–14.7	45
	Utilisation cases	0	60
	Biochar conversion	–11	48
	Guidelines	0	60
Mineral carbonation ex-situ	Baseline cost	0	222
	Characterisation of feedstock	–86	136
	Feedstock/mineral pre-treatment	–128	94
	Catalyst/additive development for enhancing mineral carbonation kinetics	–89	133
	Creating high-value end products	–159	63
Mineral carbonation in-situ	Baseline cost	0	37
	In-situ mineral carbonation mapping	–20	17
	Innovations that enable use of seawater	–14	23
	Understanding the kinetics to improve the efficiency	–5	32
	Optimisation of injection strategy and patterns	–17	20

Readers should use the following definitions to provide a consistent interpretation of the opportunity created by the technical innovations investigated:

- Cost factor is defined as a sequestration cost reduction factor relative to current sequestration costs achieved through routine use of the technical innovation opportunity.
- Maturity is defined as the year at which the technical innovation would be suitable for routine use (subject to appropriate investment).
- Scaling factor is defined as the multiplier increases in sequestration uptake if the technical innovation was routinely used.

Maturity, cost reduction and scaling factors are presented on bubble diagrams. A cost reduction/maturity space is created on the x–y plane, with the x-axis being the year of maturity and the y-axis being the cost reduction in dollars. The lower left-hand quadrant describes a space of high-cost reduction and early maturity, with the lower right-hand quadrant maturing later. The scaling factor is represented as the size of the bubble. The technology options with the greatest scale, highest cost-reduction potential and earliest maturity dates will generate the largest additional sequestration – that is, the largest bubbles in the lower left-hand quadrant.

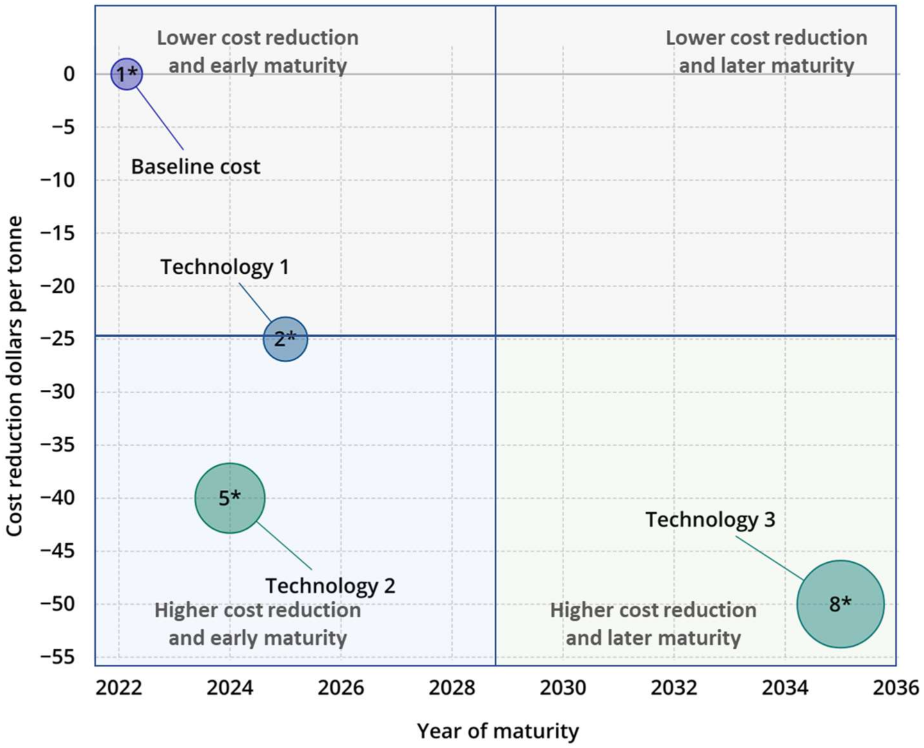

Figure 1-1: Visualisation of cost reduction, scaling factor and maturity. * Indicates the scaling factor.

To answer the question, is it better to have a greater scaling factor or earlier maturity time for a technical innovation, an S-curve model typically found in the uptake of innovations is used to compare scaling factors and maturity time frames. Six scenarios were modelled with three different scaling factors(baseline - one, two and three) and three different maturity dates (2025, 2030 and 2035). The output of the scenario modelling is Mt per year of sequestration, and more details of this approach are in Chapter 4.

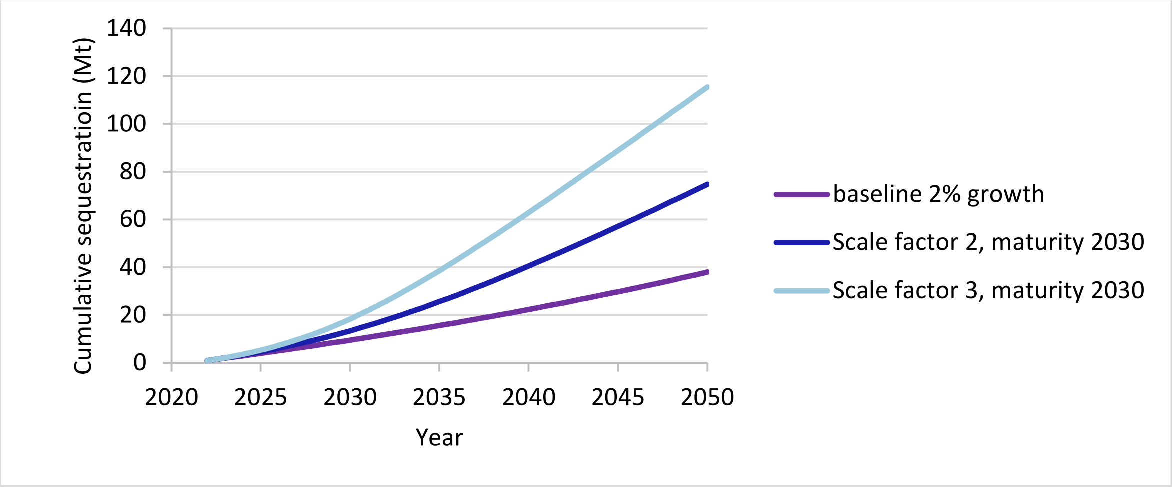

Figure 1-2:Hypothetical cumulative sequestration for the uptake of technical innovation for scaling factors of 2 and 3, for maturity timeframes of 2030.

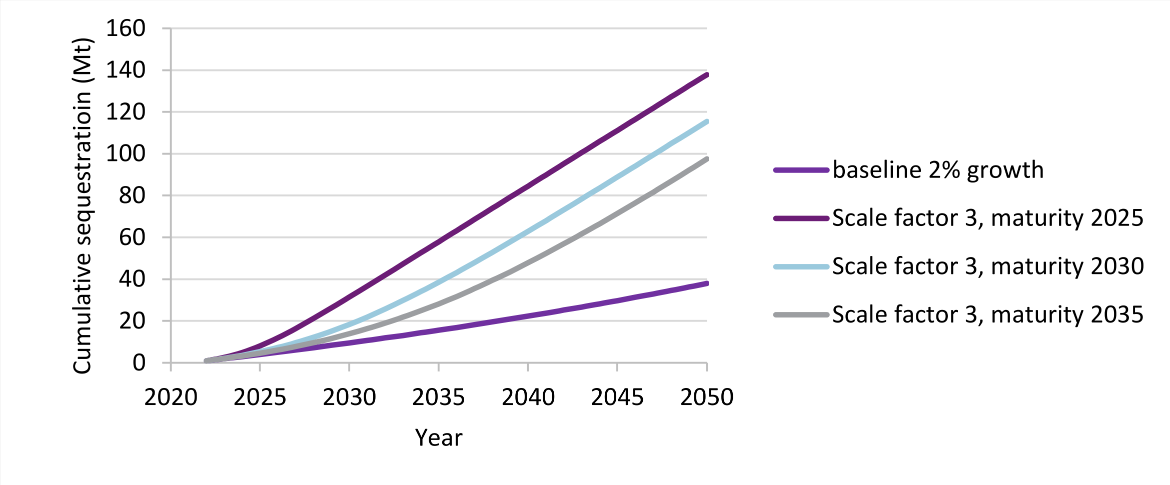

Figure 1-3: Hypothetical cumulative sequestration for the uptake of technical innovation for maturity timeframes of 2025, 2030 and 2035, for a scaling factor of 3.

The modelling shows that the scaling factor has a larger impact on cumulative sequestration than maturity time for this analysis (Figure 1-2 and Figure 1-3). A technical innovation with a maturity year of 2030 and a scaling factor of three would deliver an additional 40Mt of sequestration by 2050, compared to a scaling factor of 2 (Figure 1-2). The earlier the maturity date, the more sequestration will be potentially delivered (Figure 1-3). Overall, technical innovations with an earlier maturity date and a larger scaling factor have the greatest sequestration benefit. By 2050, all scenarios with larger scaling factors generate more sequestration than the lower scaling factor cases.

1.2 Planted vegetation

- The best technology innovations to lower cost are those that mature early as they provide greater cumulative sequestration, have large cost reduction potential and have a large scaling factor. The control of pests, diseases and browsing animals and species decision support are the two technical innovation areas that have good cost reduction potential and early maturity and scaling factors. Small-scale agroforestry equipment has good cost reduction potential though a later maturity time and smaller scaling factor.
- All technical innovations reviewed have potential to lower costs, with cost reductions of up to 30% (range 9–30% on a baseline of $19.50 per tonne, see Table 1.2).
- The baseline cost ($19.50 per tonne) determined in this analysis compares well to the figures reported in chapters of Fitch et al. (2022) of $20–$30 per tonne for permanent plantings and $10–$30 per tonne for plantation and farm forestry.
- The rankings of the technology options (see Table 1.3), and the broader analysis results, are sensitive to the modelling assumptions, particularly biomass revenue and biomass yield. Further detailed analysis of the high-priority options identified in the workshop would provide greater insight and greater confidence for potential future investment.

Table 1.2: Cost reductions for planted vegetation technical innovation areas.

Technical innovation area	Cost reduction from baseline ($ per tonne)	Net cost ($ per tonne)
Baseline cost	0	19.5
Control of pests, diseases and browsing animals	–6.1	13.4
Small-scale equipment for agroforestry	–4.7	14.8

Decision support for informing optimal species selection	–3.9	15.6
Zero or low emission fuels	–3.4	16.1
Lower-cost fencing	–2.9	16.6
Low-cost imagery	–2.8	16.7
Genetic improvements	–1.8	17.7
New products for biomass residue	0	19.5

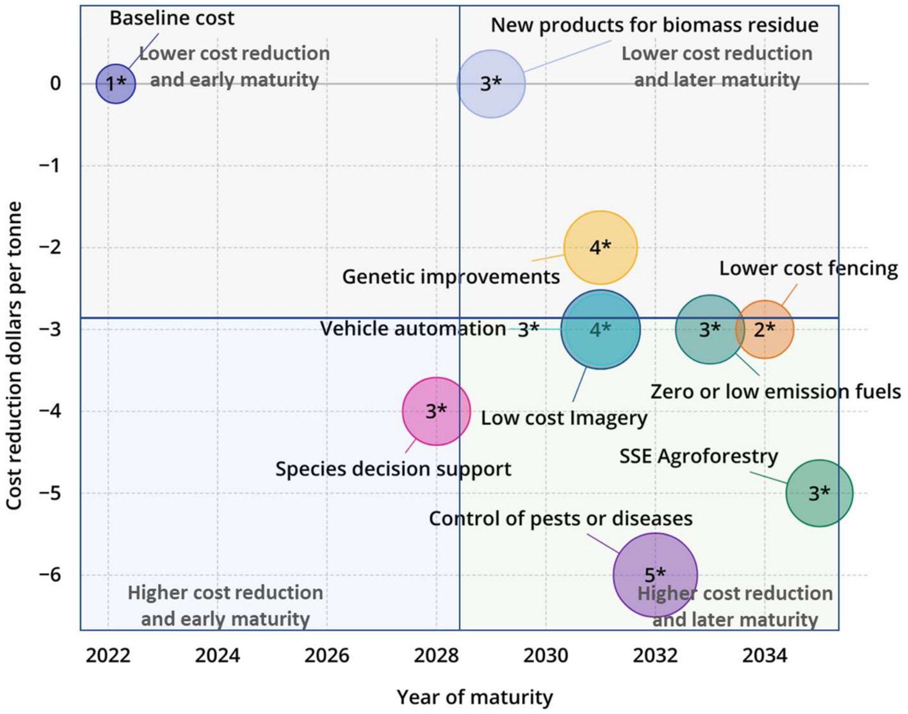

Figure 1-4: Comparison of cost reduction, year of maturity and scaling factor for planted vegetation technical innovation areas. * Indicates the scaling factor.

Technical innovation area	Cost reduction ($ per tonne)	Scaling and maturity relative benefit	Implementation complexity	Priority group
Low-cost imagery	–2.8	0.9	Low–medium	1
Decision support for informing optimal species selection	–3.9	0.7	Medium	1
Small-scale equipment for agroforestry	–4.7	0.4	Medium	1
Lower-cost fencing	–2.9	0.3	Low	1
Control of pests, diseases and browsing animals	–6.1	1.0	Low–high	2
Genetic improvements	–1.8	0.8	High	2
New products for biomass residue	0	0.7	Medium	2
Zero or low emission fuels	–3.4	0.5	High	3
Driverless or automated vehicles	–3	0.7	High	3

Table 1.3: Ranking of technical innovation areas for planted vegetation carbon sequestration.

1.3 Blue carbon

- This report reviewed technical innovation opportunities of blue carbon (mangrove and saltbush) restoration projects for their potential to lower costs and improve project economic viability. The analysis indicated cost reductions ranging from 20–42% were possible on a baseline of $92 per tonne.
- The baseline cost ($92 per tonne) determined in this analysis is significantly higher than the $18–$30 per tonne reported in the chapters of Fitch et al. (2022). This high baseline uses updated estimates of costs (Hagger et al., 2022) and reflects the low maturity and scale of blue carbon projects.
- The economic viability of blue carbon projects is challenging, and technical innovations that lower the establishment or start-up costs have significant potential to reduce costs, improve the economic viability and unlock additional sequestration. A national tidal hydrodynamic model that could produce the necessary outputs to quickly confirm the suitability and eligibility of blue carbon projects has good cost reduction potential.
- Any technologies that can increase the revenue stream for blue carbon projects will improve economic viability. Methods and indices that quantify environmental service provision of projects and enable a premium carbon price for a differentiated product or support other environmental crediting schemes (e.g. reef credits) would be beneficial.
- This analysis and ranking (see Table 1.5) is sensitive to the underlying assumptions in the modelling.

Table 1.4: Cost reductions for blue carbon technical innovation areas.

Technical innovation area	Cost reduction from baseline ($ per tonne)	Net cost ($ per tonne)
Baseline cost	0	92
Methods and indices for measuring other benefits	0	92
National model for tidal introduction and feasibility assessment	–39	53
Earth observation technologies for restoration site identification and assessment	–18	74

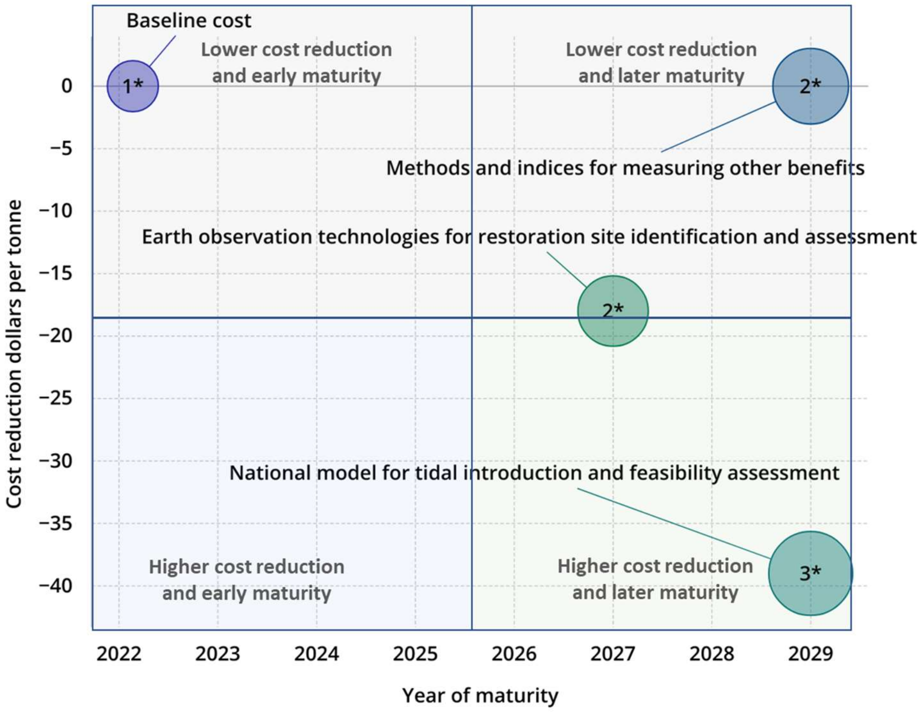

Figure 1-5: Comparison of cost reduction, year of maturity and scaling factor for blue carbon technical innovation areas. * Indicates the scaling factor.

Table 1.5: Ranking of technical innovation areas for blue carbon sequestration.

Technical innovation area	Cost reduction ($ per tonne)	Scaling and maturity relative benefit	Implementation complexity	Priority
Methods and indices for measuring other benefits	0	0.7	Medium–high	1
National model for tidal introduction and feasibility assessment	–39	1	Medium	2
Earth observation technologies for restoration site identification and assessment	–17	0.6	Medium	3

1.4 Direct air capture

- Direct air capture technologies are improving rapidly.
- Analysis of workshop-participants' inputs indicated that an average overall cost reductions of 69% could be anticipated through technology innovation and scale-up. There was, however, considerable variation in the individual responses.
- Two of the innovation areas identified (materials, and process and equipment) were considered most effective in reducing the direct air capture cost and should be pursued for the achievement of optimum performance.

- The baseline cost ($900 per tonne) used in this analysis is higher than the $300–$600 per tonne reported in chapters of Fitch et al. (2022) and is sourced from the latest literature (IEAGHG, 2021).
- Achievement of these cost reductions is anticipated in the early 2030s.

Table 1.6: Cost reductions for direct air capture technical innovation areas.

Technical innovation area	Cost reduction from baseline ($ per tonne)	Cost ($ per tonne)
Baseline cost	0	900
Materials	–243	657
Energy supply	–72	828
Process and equipment	–306	694

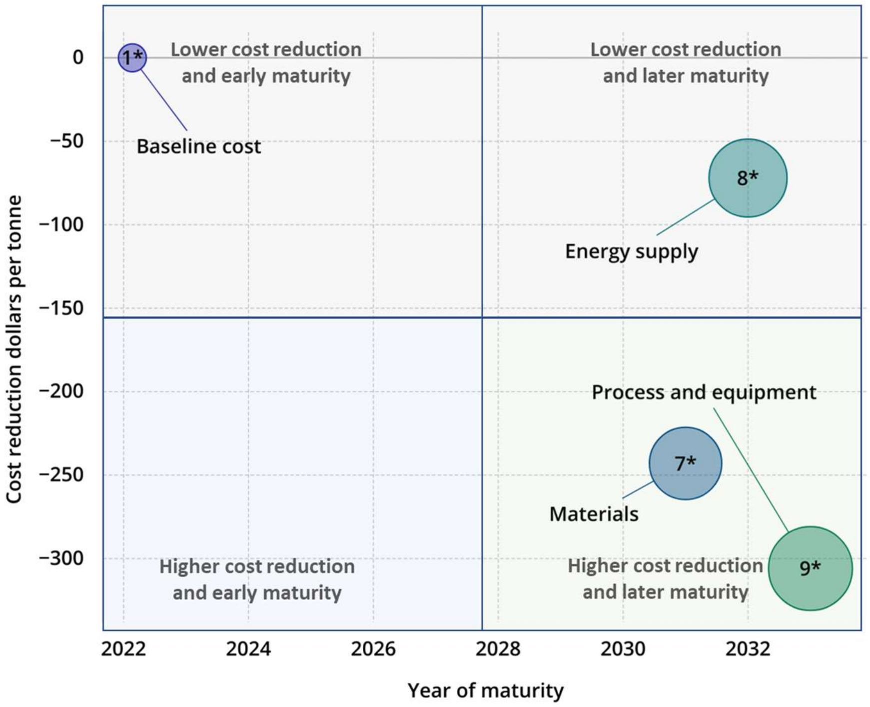

Figure 1-6: Comparison of cost reduction, year of maturity and scaling factor for direct air capture technical innovation areas. * Indicates the scaling factor.

1.5 Savanna fire management

- There is high agreement among those consulted, and evidence from the literature, that the 1 August cut-off date for early/late dry season fires could be improved, or replaced, with a more appropriate measure.
- A transition to a system based on vegetation curing could be established and supplemented with weather conditions to forecast fire severity.
- Emerging technology may provide a means for better mapping fire severity and extent and could form the basis of evidence- or outcome-based assessment of burning, rather than relying on hard dates.

- Fire severity prediction has recently been shifted to the Australian Fire Danger Rating System. It is likely that the system will undergo extensive refinement and updating to improve its applicability across the continent.

1.6 Carbon capture and storage

- Carbon capture and storage is an industry made-up of mature components. Cost reductions in carbon capture and storage will likely come about through numerous small improvements throughout the processing chain. It is the execution of large projects that will require ‘learning by doing’ that will lead to subsequent cost reduction.
- Carbon capture and storage hubs are clear examples of system-level improvement involving developments and enhancements across the entire carbon capture and storage chain.
- There are opportunities for focused research and development into capture technology in hard-to-abate areas such as steel and cement manufacturing.
- A horizon-scanning exercise undertaken as an IEAGHG study (Orchard et al. 2021) projected operational cost reductions by 2040 in the 20–30% range. These are likely to result from a combination of factors, including smarter materials, additive manufacturing, and more effective operations and maintenance due to the use of the Internet of Things, virtual reality and artificial intelligence.

1.7 Biomass/biochar

- All technical innovation options looked to have the potential to lower costs either through reducing costs or improving the overall economic viability of char production (Table 1.7, Table 1.8). The cost reductions ranged from $11 to $14.70 per tonne, with large-scale modular plants having the largest cost reduction potential.
- The baseline cost ($60 per tonne) used in this analysis is lower than the $80–$120 per tonne reported in the chapters of Fitch et al. (2022). The lower cost reflects the larger scale plant used for this analysis (13,000 tonnes per year).
- There was a sentiment during the workshop that most of the technical challenges of this sequestration method have been solved (i.e. the industry knows how to produce char) and that the obstacles to scaling the output relate to increasing the commercial readiness level and confidence in economic viability.
- There are opportunities to grow the demand for biochar by better identifying utilisation cases and articulating the co-benefits of use.
- There are specific technical areas identified during the workshop that could aid in lower sequestration costs. These are:
    - cost-effective methods to convert syngas to a more readily transportable form
    - decision support for process optimisation
    - decision support for plant location, including as part of a regional hub.

Table 1.7: Cost reductions for biomass/biochar technical innovation areas.

Technical innovation area	Cost reduction from baseline ($ per tonne)	Net cost ($ per tonne)
Baseline cost	0	60
Technology at scale	–10.2	49
Large-scale modular plants	–14.7	45
Utilisation cases	0	60
Biochar conversion	–11	48
Guidelines	0	60

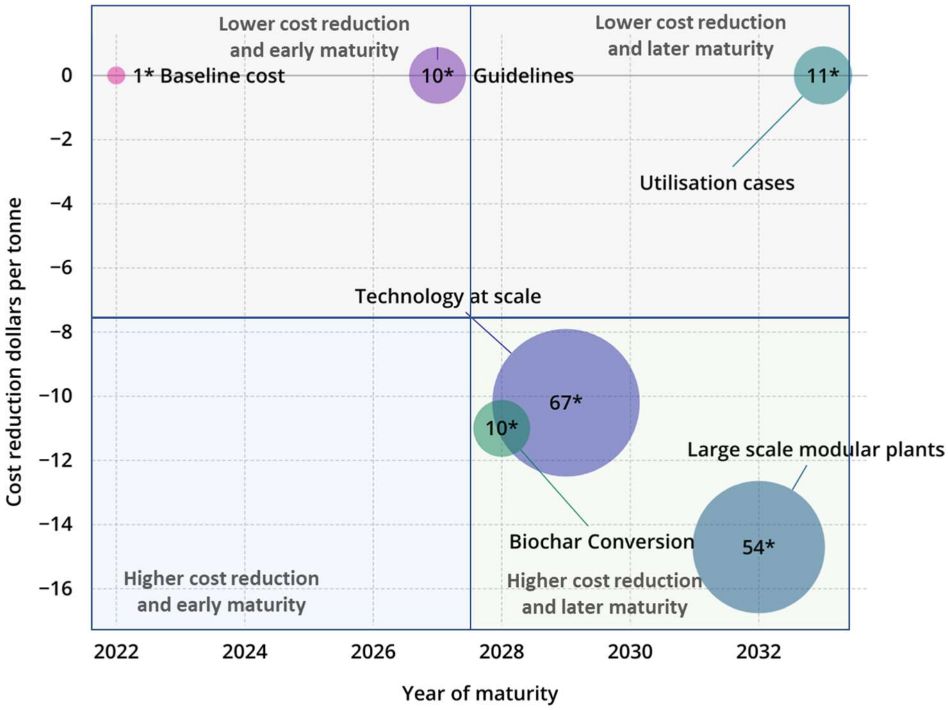

Figure 1-7: Comparison of cost reduction, year of maturity and scaling factor for biomass/biochar technical innovation areas. * Indicates the scaling factor.

Table 1.8: Ranking of technical innovation areas for biomass/biochar carbon sequestration.

Technical innovation area	Cost reduction ($ per tonne)	Scaling and maturity relative benefit (2050)	Implementation complexity	Ranking
Large-scale modular plants	–14.7	0.7	Moderate	1
Technology at scale	–10.2	1.0	Moderate	2
Biochar conversion	–11	0.1	Not discussed	3
Guidelines	0	0.2	Not discussed	4
Utilisation cases	0	0.1	Low	5

1.8 Mineral carbonation

- There is no globally agreed list of definitions for each area of mineral carbonation. An opportunity and need exist to develop formal guidelines here that will aid knowledge exchange.
- When ex-situ carbonation involves dissolution or partial dissolution to solubilise magnesium, there is generally little detail on what is left behind in any residue or what becomes of the process liquor after reaction of magnesium to form a product. Consideration needs to be given to whether the carbonation process is creating a new problem for which a response then introduces additional costs. This will be dependent on the minerals/tailings being considered.
- There is often an assumption that critical metals within tailings or mine waste can be recovered. The reality is that they need to be present at levels that make the additional processing a viable option, with recovery processes being complex and expensive.
- The methodology associated with measurement, reporting and verification of carbon dioxide removal and storage methods are critical. They may have a huge impact on the cost reduction potential and uptake scaling potential for technology innovation areas. The measurement, reporting and verification process needs to be as cost-effective as possible in meeting the requirements of a given carbon crediting scheme.
- The cost reduction potential may increase significantly by expanding existing feedstock options to include novel feedstocks from industrial waste streams in Australia. These industrial waste streams might include steel slags or incinerator bottom ash.
- Product market scaling potential is much larger than existing markets. The exact intent of these product markets needs additional work.

Table 1.9: Cost reductions for mineral carbonation technical innovation areas.

Mineral carbonation type	Technical innovation area	Cost reduction from baseline ($ per tonne)	Net cost ($ per tonne)
Ex-situ	Baseline cost(ex-situ)	0	222
	Characterisation of feedstock	–86	136
	Feedstock/mineral pre-treatment	–128	94
	Catalyst/additive development for enhancing mineral carbonation kinetics	–89	133
	Creating high-value end products	–159	63
In-situ	Baseline cost (in-situ)	0	37
	In-situ mineral carbonation mapping	–20	17
	Innovations that enable use of seawater	–14	23
	Understanding the kinetics to improve efficiency	–5	32
	Optimisation of injection strategy and patterns	–17	20

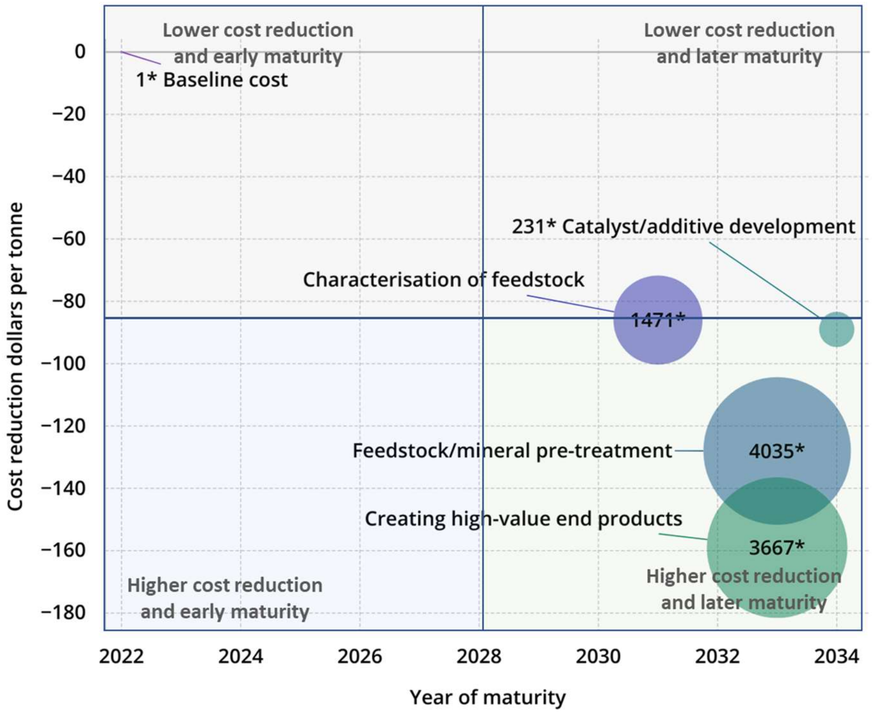

Figure 1-8: Comparison of cost reduction, year of maturity and scaling factor for ex-situ mineral carbonation technical innovation areas. * Indicates the scaling factor.

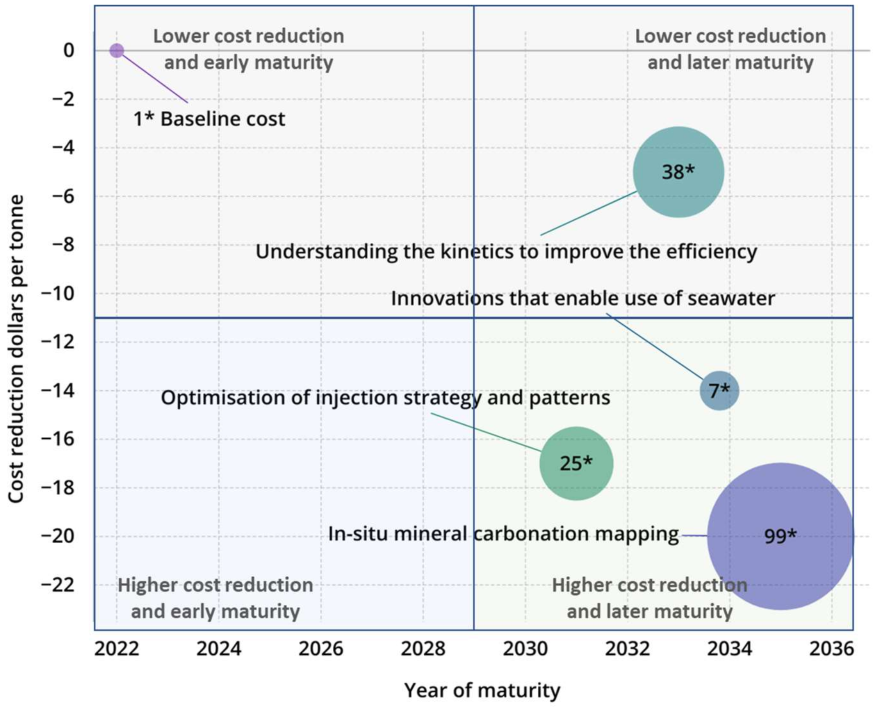

Figure 1-9: Comparison of cost reduction, year of maturity and scaling factor for in-situ mineral carbonation technical innovation areas. * Indicates the scaling factor.

1.9 Using these estimates for integrated assessment modelling

As described in this report, the cost reduction estimates and the time it is likely to take for these reductions to be realised will be an important input into modelling technology uptake and assessing the contributions these technologies can make to Australia's emission reduction pathway. They provide guidance on where investment can unlock the most change in costs. Integrated assessment modelling will help us understand plausible pathways of emissions reduction when combined with the other key considerations of resource supply, trade-offs and social barriers to scaling.

Uncertainty about the reduction in costs over time and the best investment pathway to achieve these reductions is high. Notably, one of the critical outcomes of comparing the results across different workshops is the varying agreement on the critical issues for cost reduction of each technology. Not unexpectedly, there is a broader and better-developed understanding of the cost reduction trajectories of more mature technologies (higher technical readiness level) and a poorer understanding of those of the less mature technologies. This makes a quantitative and robust comparison between two or more technologies challenging. Carrying this forward into marginal abatement cost curves that project technology changes over time for integrated assessment modelling will be tricky and may introduce high levels of uncertainty into pathways.

Nonetheless, the workshops for each technology have provided powerful insights from a cross-section of key stakeholders around cost barriers to scale, deployment and innovation, as well as critical insights around perceived innovation timelines, resource requirements, challenges such as permanence and the importance of other market drivers of environmental co-benefits.

Given that technologies underpinning the net-zero transition through sequestration are rapidly being refined, developed and scaled, particularly with recent significant investments around the world, estimates of time to delivery and even breakthrough pathways may need to be revisited regularly.

1.10References

Fitch P, Battaglia M, Lenton A, Feron P, Gao L, Mei Y, Hortle A, Macdonald L, Pearce M, Occhipinti S, Roxburgh S, Steven A (2022) *Australia's carbon sequestration potential: a stocktake and analysis of sequestration technologies*, CSIRO, Canberra.

Hagger V, Stewart-Sinclair P, Rossini R, Waltham NJ, Ronan M, Adame MF, Lavery P, Glamore W, Lovelock CE (2022) *Coastal wetland restoration for blue carbon in Australia. Values-based approach for selecting restoration sites*. Report to the National Environmental Science Program, The University of Queensland.

IEAGHG (2021) *Global assessment of direct air capture costs: technical report 2021-05, December 2021*, IEA Greenhouse Gas R&D Programme, Cheltenham, UK.

Orchard K, Simon R, Durusut E, Neades S, Kemper J (2021) 'Value of emerging and enabling technologies in reducing costs, risks and timescales for CCS,' 15th International Conference on Greenhouse Gas Control Technologies, GHGT-15 proceedings.

2 Introduction

This report details the methods, outputs and analysis from a series of workshops that aimed to explore how technical innovation might lower the cost of carbon sequestration and increase the uptake of different sequestration approaches. The workshops were run as part of phase 2 of the Climate Change Authority Carbon Sequestration Project. They built on work from phase 1, which resulted in a report titled *Australia's carbon sequestration potential* (Fitch et al. 2022). The report provided defensible estimates of economic sequestration quantity and cost.

The phase 2 workshops were designed to identify technical innovations that could be applied to sequestration approaches reviewed in phase 1 and to estimate their potential to reduce costs and increase uptake. The sequestration approaches workshopped were:

- planted vegetation
- blue carbon
- direct air capture
- combined biomass/biochar
- carbon capture and storage
- mineral carbonation.

The workshops aimed to elicit qualitative information that the project team could use to develop cost reduction estimates and rank the technical innovation opportunities based on their cost reduction and scaling potential.

The workshop methodology is detailed in Chapter 3, and the results are presented in Chapter 4, with workshop outputs presented in Appendix A .

3 Workshop method

3.1 Method

The technology workshops utilised a modified Delphi method to elicit participant (expert opinion) responses (Helmer 1967). In the Delphi method, participants are asked questions and must state their level of agreement with a proposition. The Delphi process is widely used to develop expert consensus. Expert opinions were captured using three continuums (cost reduction, maturity and scaling factor). A fourth continuum (investment) was added for the later workshops (blue carbon; carbon capture and storage; biomass/biochar; and mineral carbonation).

The consensus building method is illustrated in Figure 3-1. The participants place a marker on a continuum, representing their opinion in response to a question. The group then reviews the continuum and, based on the evidence provided, the responses on the continuum are updated until no further change occurs (i.e. when the emergence of distribution becomes apparent).

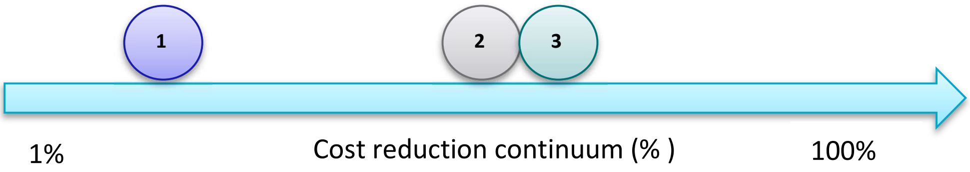

Figure 3-1: Delphi continuum for expert opinion elicitation. The circles labelled 1–3 represent the opinions of three participants.

3.2 Miro board

The workshops made use of an online collaboration tool called Miro©[2]. Miro enables online visual collaboration and can be used by multiple geographically distributed participants concurrently. It allows users to place content in the form of notes on virtual whiteboards. The workshop utilised Miro to provide a virtual whiteboard for framing and capturing responses. Ahead of the workshop, the facilitator established the required Miro boards, one for each continuum and one for each implementation step capture. A brief Miro training session for participants was held prior to the workshop to facilitate ease of use. Despite the sessions to familiarise participants with Miro, several users experienced problems that impacted the schedule of the workshop. At all workshops, additional facilitators engaged with participants who were experiencing challenges with the technology, and in most cases, they were able to include their responses manually.

3.3 Determining the technical innovation areas

Each workshop was primed with a set of questions designed to identify technical innovation areas that could drive down the cost and increase the uptake of carbon sequestration technologies. A goal of priming the workshop was to help participants get to a common point where the workshop could proceed efficiently. This proved to be more difficult than expected, and each workshop took time to create/reach common ground.

3.4 Process

The workshop process consisted of five steps.

1. A pre-workshop online questionnaire and relevant chapters from the Climate Change Authority phase 1 report, *Australia's carbon sequestration potential* (Fitch et al. 2022), were emailed to all participants.
2. The pre-workshop questionnaire responses were collated by the workshop technical lead to prepare the key focus areas for the workshop.
3. Participants attended a facilitated online workshop, with input capture via a Miro board (as described in section 3.2). There was a 5-day period after the workshop to capture additional input from attendees or those unable to attend.
4. Workshop outputs were analysed, forming this report.

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[2] https://miro.com

3.5 Outputs

The primary output of the workshops is estimates of cost reduction enabled by specific technology innovations. A second output is a prioritised list of technology innovation areas for each sequestration approach.

3.6 Definitions

The following continuum definitions were used during the workshop and in this report:

- Cost factor is defined as a sequestration cost reduction factor relative to current sequestration costs achieved through routine use of the technical innovation opportunity.
- Maturity is defined as the year when the technical innovation would be suitable for routine use (subject to appropriate investment).
- Scaling factor is defined as the multiplier increases in sequestration uptake if the technical innovation was routinely used.
- Investment is defined as the quantity of funds required to take the technical innovation to routine use.

3.7 Out of scope

At the client's request, these workshops were limited in scope to technology innovation areas where investment could lower costs and increase uptake. Consequently, policy and institutional barriers were out of scope.

3.8 Participants

The participants for the workshops were from academia, government and Industry.

3.9 Schedule

The workshop schedule is listed in Table 3.1.

Table 3.1: Workshop schedule.

Technology	Technology lead	Workshop date	Notes
Planted vegetation	Stephen Roxburgh	28/10/2022	This was the first workshop completed, and it was used to test the Delphi methodology.
Blue carbon	Andy Steven	8/12/2022	Cost reduction did not resonate with the participants; improvements to financial viability used instead of cost reduction factor.
Direct air capture	Paul Feron	14/12/2022	
Savanna fire management	Michael Battaglia	N/A	A review was agreed to instead of a workshop; the early/late season cut-off date and approaches to predicting fire severity were reviewed.
Biomass/biochar	Nawshad Haque	2/3/2023	The broad scope made the workshop difficult, despite the commonality with the biomass feedstock.

Carbon capture and storage	Charles Jenkins	9/3/2023	A broad workshop with diverse views and difficulty in reaching consensus. The workshop was hampered in some regards due to the limited breadth of experts able to be convened.
Mineral carbonation	Renee Birchall	4/4/2023	Final workshop. The workshop discussed the two types of carbonation (ex-situ and in-situ) separately.

3.10 Participant Review

To ensure an opportunity for workshop participants to provide feedback on the workshop report, a web-based review form was developed. The review consisted of 5 questions and was emailed to each participant along with a copy of the draft chapter and report summary to solicit feedback. :

1. Does the report broadly capture the discussion of the workshop?
2. Do you feel a qualifying statement is required to ensure your perspective is represented? If so, what is it?
3. Are you broadly comfortable with the methodology used to translate workshop outputs to estimates of cost reduction?
4. Are you broadly comfortable with the summary of findings?
5. Is there anything else that you think is important for readers to be aware of in reading this workshop report?

Qualifying statements gathered as part of this review by workshop participants are detailed in Appendix D

3.11References

Fitch P, Battaglia M, Lenton A, Feron P, Gao L, Mei Y, Hortle A, Macdonald L, Pearce M, Occhipinti S, Roxburgh S, Steven A (2022) *Australia's carbon sequestration potential: a stocktake and analysis of sequestration technologies*, CSIRO, Canberra.

Helmer O (1967) Analysis of the future: the Delphi method, http://www.rand.org/content/dam/rand/pubs/papers/2008/P3558.pdf.

4 Scaling and maturity analysis

This chapter details the trajectory modelling approach used for this project and will assist in interpreting the relative sequestration benefit tables presented in the subsequent chapters. The analysis allows for answers to two key questions:

- Is it better to have a larger scaling factor or an earlier technology maturity date?
- With technologies that have different maturity dates and scaling factors, which one will yield the greatest additional sequestration by 2050? This question is answered using a relative sequestration benefit metric.

Integrated assessment modelling, where a broad range of techno-economic considerations are included in the analysis, is the routine approach to providing defensible estimates. This form of modelling is out of scope for this project, and a simpler approach is used.

Logistic models are widely used to produce an S-curve typically found in the uptake of innovations. They are a useful tool for modelling the diffusion of innovations, offering a simple, flexible and predictive approach for understanding the adoption of new products and technologies (Shimogawa et al. 2012).

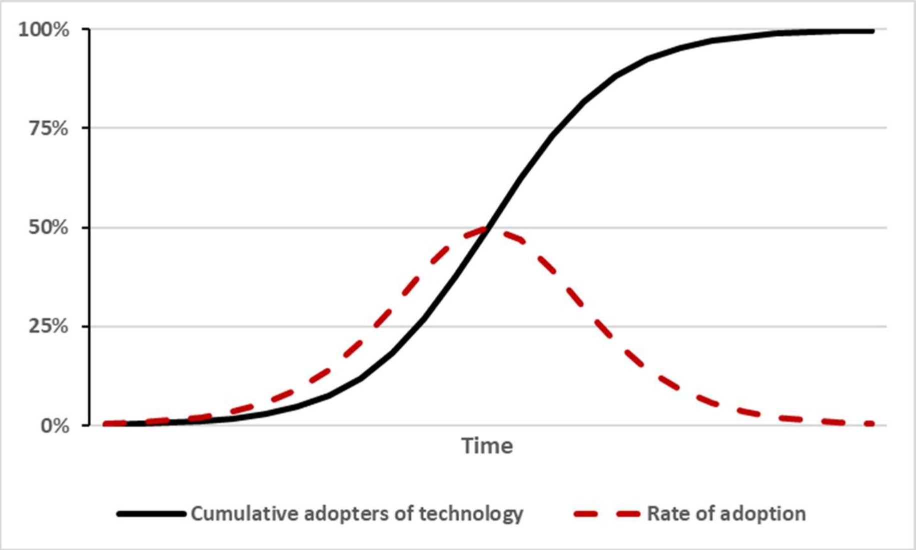

Figure 4-1: Example of an S-curve, representing adoption of a new technology/innovation.

Figure 4-1 presents a typical S-curve, representing the slow early diffusion of an innovation, where an initial uptake is a small number of all the potential adopters. The adoption rate (dashed line in the figure) increases over time, leading to an inflection point where it starts to decrease as the number of adopters reaches saturation. This gradual uptake, followed by saturation, contributed to the wide use of the model.

Here a basic logistic function (Equation 2) that simulates an S-curve is used to compare scaling factors to maturity time frames. The logistic model nicely simulates the initial slow rate of change (adoption), and this accelerates as technological learning rates increase and widespread adoption occurs (Figure 4-1). It is also important to recognise that for this modelling, the saturation point (maximum vertical asymptote) will be the scaling factor multiplied by the base rate.

A baseline is created with a nominal annual growth to make comparative assessments, as shown in Equation 1:

$$baseline(t) = 1 * (1 + growth\ rate)^t \text{ where } growth\ rate = 0.02 \quad \text{(Eqn 1)}$$

The growth rate is arbitrarily selected.

The logistic model used is presented in Equation 2, with c and b being fitted parameters.

$$sequestration(t) = \frac{baseline(2050) * scalefactor}{\left(1 + e^{(-c*(t-d))}\right) + b} \quad \text{(Eqn 2)}$$

4.1 Possible uptake trajectories

To understand how different maturity timeframes and different scaling factors can influence the uptake of a technology, two scaling factor scenarios and three maturity scenarios were defined. For these scenarios, the maturity timeframes used were 2025, 2030 and 2035, with the scaling factors being two times and three times the baseline values. The maturity timeframes were selected to cover most of the timeframes identified as part of the workshops. Similarly, the scaling factors considered are representative of the outputs from the initial planted vegetation workshop. In subsequent workshops, larger scaling factors were identified (6–10).

For each scenario, the logistic model (S-curve) was fitted to three data points: the initial value, in this case 1; a mid-point, being the maturity year with a sequestration estimate of the baseline sequestration multiplied by the scaling factor; and the end-point, being the baseline sequestration multiplied by the scaling factor. The mid-point was selected based on the rationale that on maturity the technology is routinely used and therefore delivers the scaling factor multiplied by the baseline increase of sequestration.

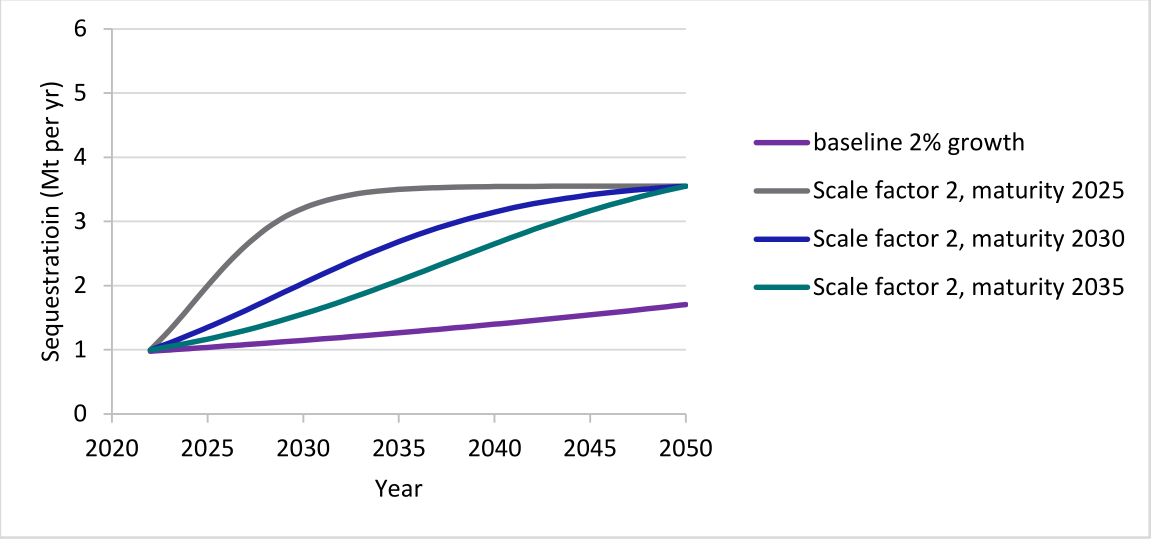

Figure 4-2: Hypothetical increase of sequestration modelled by S-curve, based on uptake of technology innovation with a scaling factor of 2, with maturity timeframes of 2025, 2030, and 2035.

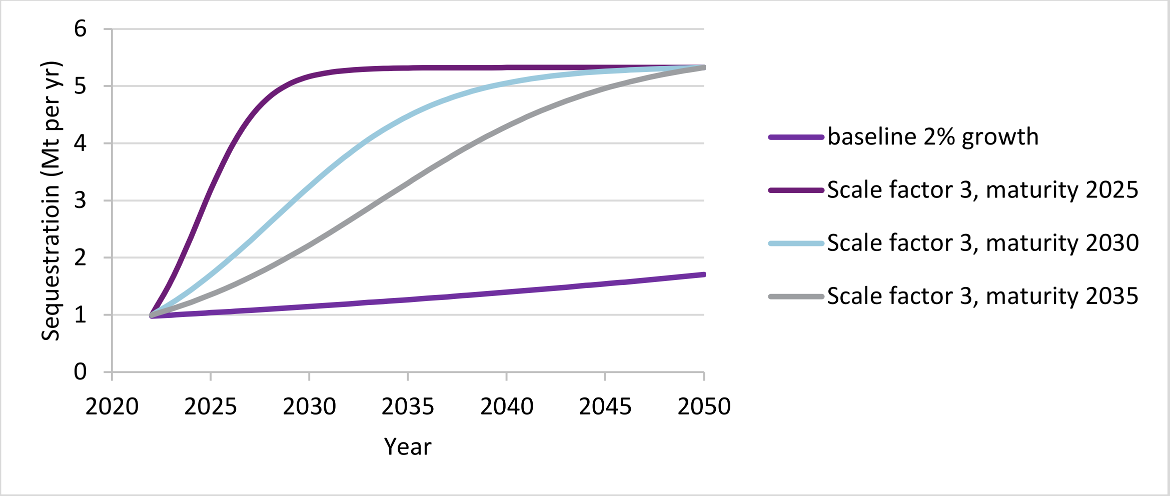

Figure 4-3: Hypothetical increase of sequestration modelled by S-curve, based on uptake of technology innovation with a scaling factor of 3, with maturity timeframes of 2025, 2030, and 2035.

Figure 4-2 and Figure 4-3 present the results of the modelled sequestration generated by the uptake of technical innovation. Both sets of results commence with an initial sequestration of 1 Mt per year and yield a sequestration value in 2050 of baseline sequestration amount at 2050 multiplied by the scaling factor.

The results illustrate that investment in technology that matures earlier, over a timeframe to 2050, has a greater benefit (greater sequestration generated) than technology that matures later. This intuitive finding confirms that higher scaling with the earliest maturity has the highest benefit.

Note that for maturities in 2035, the modelled curve has not reached equilibrium by 2050, so running the model to a later end date would possibly generate additional benefits.

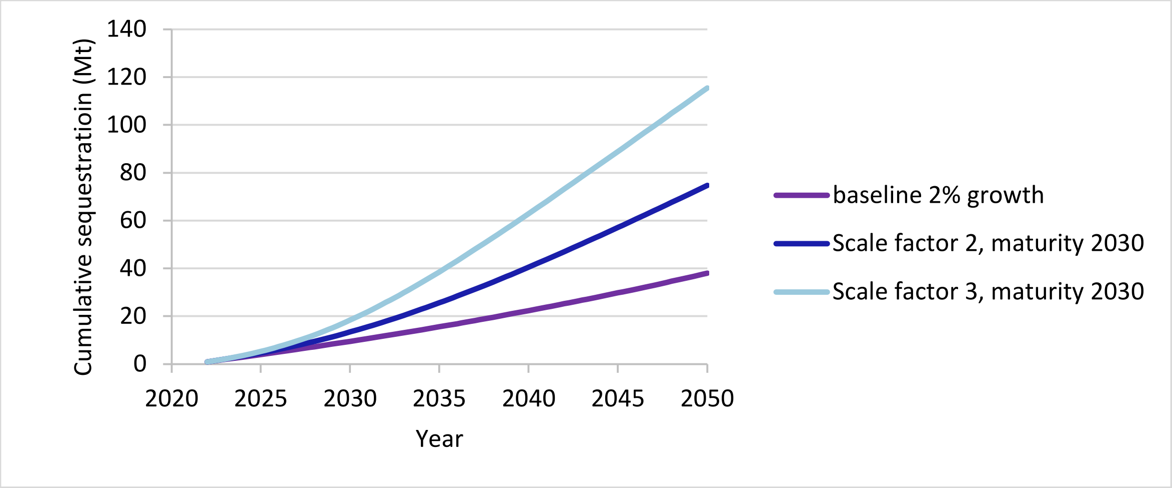

Figure 4-4:Hypothetical cumulative sequestration for the uptake of technical innovation for scaling factors of 2 and 3, for maturity timeframes of 2030.

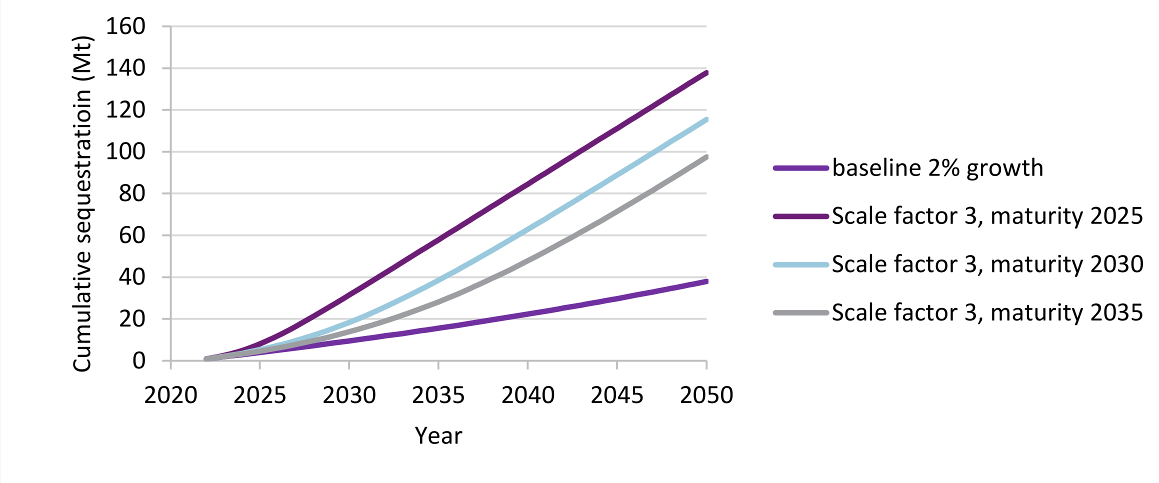

Figure 4-5: Hypothetical cumulative sequestration for the uptake of technical innovation for maturity timeframes of 2025, 2030 and 2035, for a scaling factor of 3.

The cumulative sequestration modelling shows that the scaling factor has a larger impact on cumulative sequestration than maturity time for this analysis (Figure 4-4 and Figure 4-5). A technical innovation with a maturity year of 2030 and a scaling factor of three would deliver an additional 40Mt of sequestration by 2050, compared to a scaling factor of 2 (Figure 4-4Figure 1-2). The earlier the maturity date, the more sequestration will be potentially delivered (Figure 4-5).

A clear benefit can be seen with a technical innovation that matures in 2025, with the scaling factor of 3 yielding an additional 100 Mt of sequestration over 28 years relative to the baseline (Figure 4-5).

It is important to note that this analysis is purely illustrative, aiming to explore the interplay between investing in technology options with different scaling factors and maturity time frames. A technology that matures during 2025–2030 with a scaling factor of two has roughly the same benefit as a technology innovation that has a scaling factor of three but matures in 2040. The actual uptake depends on a wide range of factors, including suitable economics, resolution of resource competition, suitable policy and institutional settings, and social license.

4.2 Relative sequestration benefit metric

For the relative sequestration benefit analysis, the workshop outputs were used to calibrate a logistic model, producing sequestration estimates for 2030, 2035, 2040 and 2050.

The baseline was created by taking an arbitrary starting point (in this case, 1 Mt of sequestration per year) and applying a growth rate of 2% per year.

The values were normalised to the maximum sequestration obtained for year T. The equation for calculating the relative sequestration benefit is shown in Equation 3, where T is the end year for cumulative sequestration (2025, 2030, 2035, 2050), and S is sequestration calculated from the logistic model at time t, where t is the year between 2022 and T.

$$Relative\ sequestration\ benefit = \frac{1}{\max\left(S(T)\right)} \sum_{t}^{T} S(t) \quad \text{(Eqn 3)}$$

For each year of interest, the relative sequestration benefit for each technology will be between 0 and 1. A technology with a value of 1 will potentially deliver the greatest additional sequestration by year T, and a technology with a value closest to 0, the lowest additional sequestration.

4.3 References

Shimogawa, S., Shinno, M., & Saito, H. (2012). Structure of S-shaped growth in innovation diffusion. *Physical Review E*, *85*(5), 056121.

Workshop outputs

5 Planted vegetation sequestration

The planted vegetation workshop was held on 28 October 2022 with 20 participants. Appendix C, section C.1.1, includes a full list of workshop participants.

5.1 Workshop results

5.1.1 Technology list

The first workshop output is a list of technology innovations that can lower the cost and increase the uptake rate of sequestering carbon with vegetation. The technology list was assembled from the responses given to the pre-workshop questionnaire and reviewed by the workshop technical lead.

Table 5.1 presents and defines the technical innovation opportunities. Note that the specifics of the technical innovation area were not discussed or agreed to at the workshop and so the definitions are indicative.

Table 5.1: Technical innovation opportunities for carbon sequestration through planted vegetation.

Technical innovation area	Description	Cost reduction area
Low-cost imagery	Remotely sensed imagery is used to locate suitable project locations and ensure that the carbon project eligibility requirements are met. In addition, imagery can be used as part of the verification and auditing of a vegetation project. Currently, costs for acquiring high-resolution imagery can be high and impact the transaction costs of the carbon project.	Potential to reduce establishment and carbon project costs.
Zero or low emission fuels	Fuels contribute to project costs in two ways. Firstly, the emissions from the fuels used to generate sequestration are deducted from the sequestration generated, making the project less economically viable. Secondly, fuel adds costs to operations that require machinery, including harvest and transport to the mill. An ideal fuel is low or zero emission and low cost.	Potential to reduce establishment and operational costs.
Small-scale equipment for agroforestry applications	Reduced-cost small-scale equipment is becoming available more widely. The equipment includes small-scale all-terrain vehicles for operations, cranes and log forwarders. It has the additional benefit of reducing environmental impacts during operations. Using lower-cost equipment has the potential to lower the operational costs for vegetation or forestry projects.	Potential to reduce establishment and operational costs.
Control of pests, diseases and browsing animals	Pests, diseases and browsing animals all have the potential to reduce vegetation growth and potentially increase mortality, especially when trees are young. Invasive weed and pest	Potential to reduce establishment and operational costs with

	management is also a requirement under state and federal legislation. Control typically involves mechanical and/or chemical application techniques. Improved and/or lower-cost methods for pest and disease control have the potential to both reduce establishment costs and improve overall biomass yield.	potential to also improve biomass yield.
Decision support for informing optimal species selection	Selecting the most appropriate species for a given location is a key decision, especially given the potential for the impacts of climate change to alter future growth conditions. The desired outcome of the planting is a key consideration influencing species selection. It might range from long-term restoration of a multi-species mixture of native or endemic species to the establishment of monocultures for timber and other plant products. Improved decision support for species selection has the potential to reduce operational costs and increase biomass yields.	Potential to reduce operational costs and increase biomass yield.
Lower-cost fencing	Fencing can be a significant cost to planted vegetation carbon sequestration projects that require the exclusion of non-domestic browsers and/or domestic livestock, or for defining and separating carbon farming activity from traditional production areas. Because fencing is an initial cost outlay, it can play a significant role in determining overall total costs when considered over the full lifetime of a project. Lower-cost fencing could include the development of new materials or methods for fence construction, which could also include virtual fencing. Reducing the costs of fencing contributes to reduced establishment costs.	Potential reduction of establishment costs.
Genetic improvement	Tree breeding for genetic improvement in commercial plantation species has a long and continuing history in Australia, starting in the 1950s with radiata pine and then extending to include eucalypt tree improvement. Tree breeding is typically guided by economic considerations, focusing on traits such as improved disease resistance, wood density, seedling survivorship, and increased yields. Although the development of new genetic strains can incur additional costs through increased costs for seeds or seedlings, these additional costs are assumed to be overcome by improvements in performance and yield.	Potential to increase establishment costs due to added cost of genetically improved seedlings, with potential improvements in biomass yield.
New products for biomass residues	There is increasing interest in using forest biomass residues to develop new products, such as engineered wood products, biomaterials and biochemicals, which could displace plastics and other fossil fuel–based chemicals. The potential benefits include increased revenue through the development of these new products, product diversification and the displacement of non-renewable fossil fuel–based products with products based on renewable biomass.	Potential to improve prices paid for biomass.
Driverless or automated vehicles	Robotic and autonomous machinery has the potential to play an important role in forest operations into the future, with potential technologies ranging from remote ‘telecontrol’ of machinery for tree harvesting, transport and processing (for example, in remote or hazardous terrain) to autonomous vehicles for forestry operations and the use of drones/autonomous aircraft for broadscale seeding operations.	Potential to lower costs of establishment and operations.

5.1.2 Workshop outputs

The most significant innovations were determined by voting to be:

- access to low-cost imagery for remote mapping and monitoring (9 votes)
- zero or low emission fuels (6 votes)

- control of pests, diseases and browsing animals (5 votes)
- small-scale equipment for agroforestry (5 votes).

The other technologies either received 3 or 4 votes.

The workshop continuum results are summarised in Table 5.2. To help interpret the results, please see the definitions in section 3.6.

Table 5.2: Summary of outputs from the planted vegetation workshop.

Technical innovation area	Cost reduction (%)			Maturity (Year)			Scaling factor		
	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
Low-cost imagery (n=11)	20	15	28	2031	2025	2034	4.1	2.7	5.8
Zero or low emission fuels (n=6)	29	19	42	2033	2030	2035	3.1	2	4
Small-scale equipment for agroforestry (n=6)	21	12	29	2035	2032	2037	2.9	2	4.7
Control of pests, diseases and browsing animals (n=7)	20	12	33	2032	2029	2036	4.6	2.7	6.5
Decision support for informing optimal species selection (n=7)	23	14	29	2028	2026	2031	3.0	2.3	3.9
Lower-cost fencing (n=3)	10	4	13	2034	2034	2034	2.2	2.2	2.2
Genetic improvements (n=4)	27	10	50	2031	2027	2038	3.5	2.4	5.8
New products for biomass residue (n=3)	17	6	39	2029	2027	2032	3	3	3
Driverless or automated vehicles (n=6)	20	15	28	2031	2027	2035	3.3	1.9	4.2

All the average cost factors are in the order of 10–30% with significant variation, despite the process of consensus building. For example, the cost reduction estimates for low-cost imagery vary from 5 to 31% compared to current costs. Similarly, the estimates vary with maturity timeframes but are generally more consistent than the cost reduction factors. Most of the maturity estimates are in the order of 10 years, possibly reflecting an overly optimistic outlook by the participants.

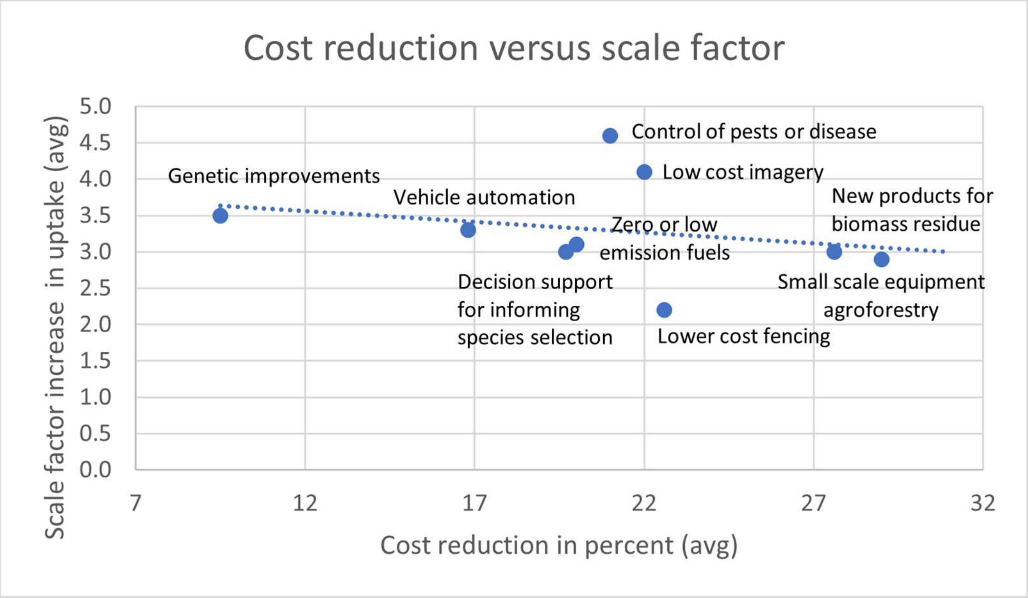

Figure 5-1: Plot of cost reduction percentages versus scaling factor for planted vegetation technical innovation areas.

In Figure 5-1, the cost reduction was plotted against the scaling factor. If the technology has a significant cost reduction factor, it would be reasonable to expect that the scaling factor would similarly be high. Conversely, if the cost reduction factor was relatively low, it would be reasonable to expect a low scaling factor. As shown in Figure 5-1, the cost factors do follow this trend, with a few outliers (control of pests, diseases and browsing animals, low-cost imagery and lower-cost fencing).

5.1.3 Cost reduction analysis

Planted vegetation sequestration cost areas or cost drivers

The following cost and revenue categories were defined in preparation for the cost reduction modelling:

- **Establishment**: costs of establishing the technology at a location, excluding cost of land.
- **Operations:** ongoing maintenance costs, e.g. weeding, fertiliser application and operations including thinning, pruning and harvest.
- **Carbon project costs:** carbon offset project establishment, auditing and crediting costs.
- **Yield:** revenue obtained from biomass yield.
- **Revenue:** revenue obtained from biomass products.

The workshop cost factors were assigned to the cost areas defined above and presented in Table 5.3.

Table 5.3: Cost reduction factors for planted vegetation technical innovation areas. All factors are percentage reductions (costs) or increases (revenues) relative to current costs. Blank cells indicate no change to cost drivers.

Technical innovation area	Costs			Revenues	
	Establishment (%)	Operational (%)	Project (%)	Yield (%)	Price (%)
Low-cost imagery	22	–	22	–	–
Zero or low emission fuels	20	20	–	–	–
Small-scale equipment for agroforestry	29	29	–	–	–
Control of pests, diseases and browsing animals	21	21	–	10	–
Decision support for informing optimal species selection	–	20	–	10	–
Lower-cost fencing	23	–	–	–	–
Genetic improvements	–10	–	–	10	–
New products for biomass residue	–	–	–	–	27
Driverless or automated vehicles	17	17	–	–	–

Where the cost reduction factor can reduce several areas, it is applied to all applicable areas. For example, small-scale agroforestry equipment has the potential to lower both the establishment and operational costs of projects. Also note that for genetic improvements, the cost factor has been represented as a cost increase as well as a yield increase, anticipating that plantation stock costs could increase.

Cost model

The outputs from the vegetation workshop are translated into comparable results using a simplified cash flow model to determine changes to the net present value (NPV) and the cost per tonne of sequestration for an indicative commercial plantation or farm forestry (with product harvest) project. The model allows partitioning of costs, allowing cost reductions to be applied selectively to the relevant cost area and for the lifetime cost reductions (in this case, over 100 years) to be converted to NPVs. The cash flow model used for this analysis is based on Roxburgh et al. (2020), and more detail can be found there.

The default parameters used for this analysis are shown in Table 5.4, following Roxburgh et al. (2020). Note that water offset costs were not included in the analysis.

Table 5.4: Cost factors for planted vegetation projects.

Cost area	Cost item	Value
Establishment	Planting	$1800 per ha
	Fertiliser	$400 per ha
	Weeding	$400 per ha
	Windrow burn	$400 per ha

	Chopper roller	\$400 per ha
	Land	Area specific \$4000–\$7000 per ha
Operation	Distance to processing plant	50 km
	Haulage cost per km for 1 cubic metre wood	\$15.60
	Thinning	\$400 per ha
	Pruning	\$400 per ha
	Harvesting	\$400 per ha

The transaction costs associated with administering the carbon project were calculated as a fraction of the carbon project revenue. The annualised carbon project revenue was calculated from the FullCAM modelled abatement (tonnes CO_2-e per ha) and multiplied by the project area. The carbon project costs are modelled to be a factor widely used of 25% of the carbon sequestration revenue. Therefore, the cost reduction of carbon project costs is modelled as an increase in revenue rather than directly as a cost.

Project costs are defined using Equation 4:

$$Cost = NPV\left(\sum_{i.t} cost_{i.t}\right) \quad \text{(Eqn 4)}$$

where *i* is the cost area and *t* the project year. Future costs were calculated over a 100-year timeframe. Cost per tonne of sequestration was calculated by calculating the total NPV cost of sequestration and dividing it by the total sequestration generated over the life of the project as per Equation 5:

$$Cost\ per\ tonne = \frac{Cost}{\sum_t Sequestration_{\ t}} \quad \text{(Eqn 5)}$$

Project NPV was calculated by determining the net cash flow (revenue – costs) and subtracting the carbon project costs, as shown in Equation 6:

$$Project\ NPV = NPV(revenue) - NPV(Costs) - NPV(Carbon\ Project\ Costs) \quad \text{(Eqn 6)}$$

For the analysis, a discount rate of 7% was used, with a nominal carbon price of \$20 per tonne, a project size of 100 ha and a project duration of 100 years. Note that at the time of writing, the spot carbon price is \$35.5 per tonne. The sequestration yield data is from Roxburgh et al. (2020) and was generated using FullCAM for each National Plantation Inventory (NPI) plantation region, species type and management scenario. The model was initially run with no changes to costs to develop a baseline. This baseline was then used for the cost reduction analysis.

Note, the cost reductions and changes to NPV are averages for all NPI regions, species and scenarios.

Cost analysis

The results of the modelling are listed in Table 5.5. The cost reductions are the difference in cost in \$ per tonne compared to the baseline.

Table 5.5: Cost reductions for planted vegetation technical innovation areas.

Technical innovation area	Cost reduction from baseline (\$ per tonne)	Net cost (\$ per tonne)
Baseline cost	0	19.5
Low-cost imagery	–2.8	16.7
Zero or low emission fuels	–3.4	16.1

Small-scale equipment for agroforestry	−4.7	14.8
Control of pests, diseases and browsing animals	−6.1	13.4
Decision support for informing optimal species selection	−3.9	15.6
Lower-cost fencing	−2.9	16.6
Genetic improvements	−1.8	17.7
New products for biomass residue	0	19.5

The innovation area with the greatest potential to lower the cost of sequestration over the life of a project is better control of pests, diseases and browsing animals, which is discussed further in the following paragraph. Note that the cost reduction for new products for biomass is listed in Table 5.5 as 0. This is due to the benefit being realised as increased revenue rather than a cost reduction, resulting in no change in costs.

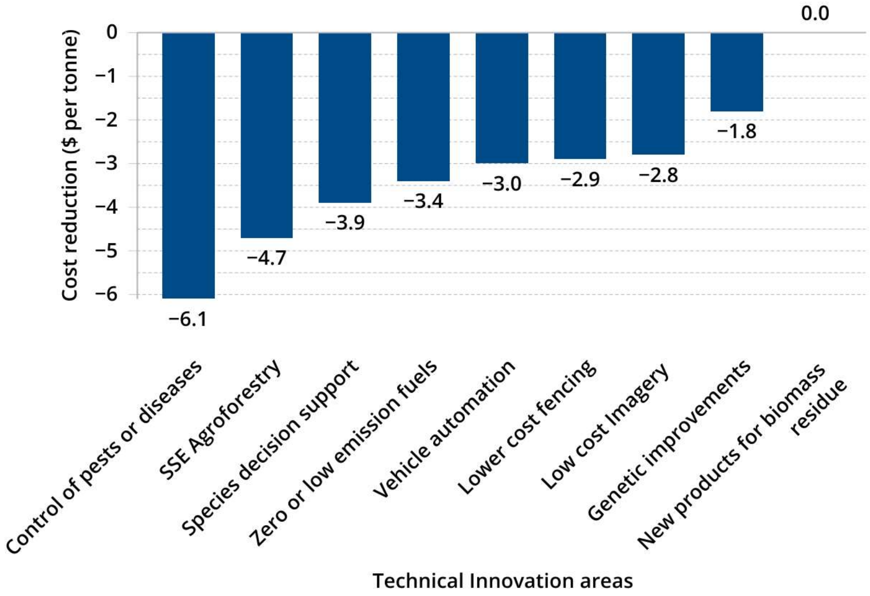

Figure 5-2: Bar graph of cost reductions for planted vegetation technical innovation areas.

The cost reductions are presented as a bar graph in Figure 5-2. The largest cost reduction is control of pest and diseases at around $6 per tonne less than the baseline of $19.50 per tonne. This is due not only to a reduction of operational costs but also to the corresponding additional benefit in biomass yield. The model is sensitive to changes in biomass yield, as discussed in section 5.1.5, and the result here is likely to reflect that. The next most beneficial technology is small-scale equipment for agroforestry, with a cost reduction of almost $5 per tonne, followed by decision support for informing optimal species selection. In the case of decision support, this reduction is due to the assumed yield benefit corresponding to better species selection. Small-scale equipment for agroforestry provides benefits to both operational and establishment cost areas. The least cost-effective technical innovation area is genetic improvements (apart from new products from biomass, which provides additional revenue rather than reducing costs). Genetic improvements were simply modelled, and the benefits of improved genetics can apply to several cost areas. A cost penalty was applied as part of the genetic improvement to represent the additional cost of improved tree stock.

5.1.4 Cost reduction, maturity and scale

Figure 5-3 summarises the outputs of the workshop on one chart. The x-axis represents the year of maturity, the y-axis the cost reduction per tonne of CO_2 sequestration, and the size of the bubble represents the scaling factor.

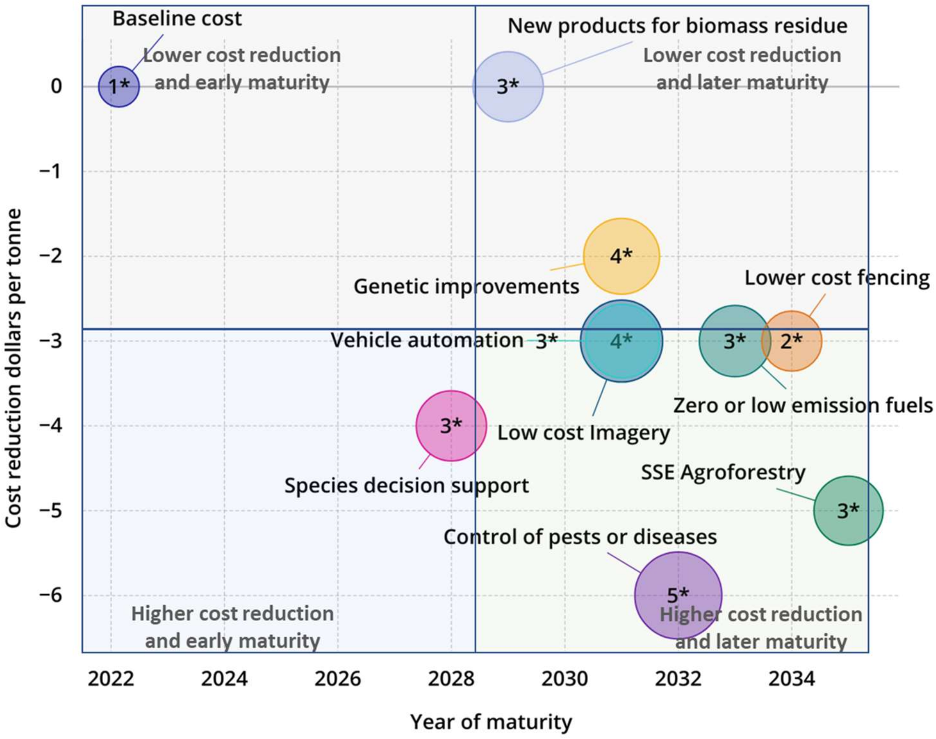

Figure 5-3: Comparison of technology cost reduction, year of maturity and scaling factor for planted vegetation technical innovation areas. * Indicates the scaling factor.

The best technologies are those that mature early, as they provide greater cumulative sequestration, have large cost reduction potential and have a large scaling factor. The control of pests, diseases and browsing animals and species decision support are the two technical innovation areas that have good cost reduction potential, early maturity and high scaling factors. Small-scale equipment for agroforestry has good cost reduction potential though a later maturity time and smaller scaling factor than control of pests, diseases and browsing animals and species decision support.

5.1.5 Sensitivity analysis of the cash flow model

A sensitivity analysis can readily be done to explore which cost areas are more likely to change either the NPV or the cost of sequestration. NPV is important as it reflects changes to the economic viability of the sequestration approach, and in many cases, improvements in economic viability can unlock additional sequestration.

In the analysis presented in Figure 5-4, different cost parameters in the model were varied in four steps relative to the baseline: –10%, –5%, +5% and +10%. The changes to NPV as a percentage of the baseline are presented as a colour-coded heatmap. The purpose of this analysis is to identify those cost or revenue areas that, if changed, can significantly lower the cost of sequestration or change the economic viability of a project.

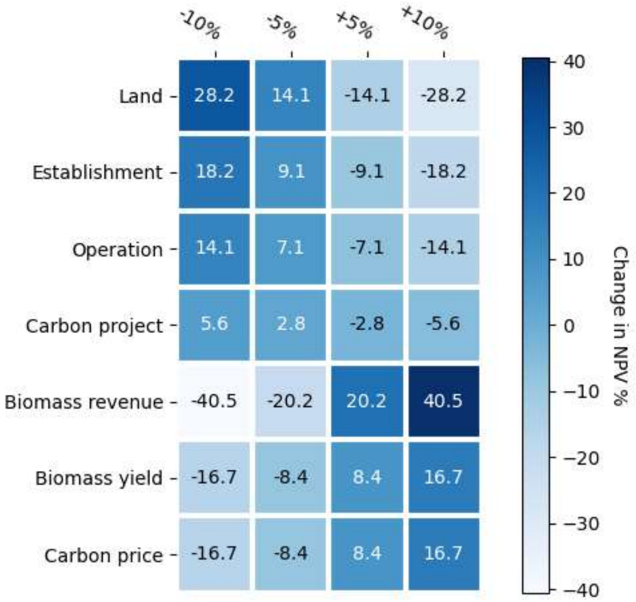

Figure 5-4: Sensitivity analysis of the cash flow model for planted vegetation carbon sequestration projects.

Figure 5-4 presents the results of this analysis, in which changes to NPV are presented as a percentage change from the no-change baseline. The model is most sensitive to biomass revenue (price for products), followed by biomass yield. Land cost and project establishment are the next highest factors, followed by the carbon price. Any changes to these costs or revenues will significantly affect the economic viability of planted vegetation carbon sequestration projects. The carbon price has a smaller but still significant impact on economic viability. Reducing the project establishment cost is a significant opportunity, as the cost is accrued at the start of a project, which has greater impact on the overall economic viability, than costs incurred later in a project.

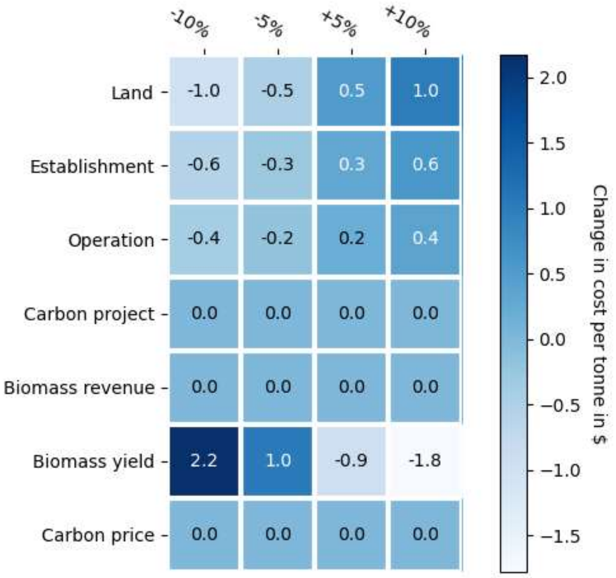

Figure 5-5: Sensitivity analysis of sequestration costs for planted vegetation carbon sequestration projects.

Figure 5-5 presents a sensitivity analysis of cost areas. As with the NPV sensitivity analysis, biomass yield changes sequestration cost the most; therefore, any technologies that can increase biomass yield will have the greatest impact on cost reduction. This is followed by land cost, then by establishment costs. Reducing operational costs has the lowest impact on cost reduction. Zeros indicate that the factor has no impact on cost reduction.

5.1.6 Scaling and maturity analysis

The results in Table 5.6 allow for the ranking of the technology innovation areas and present a relative measure of additional sequestration generated compared to the baseline. The results have been obtained per the relative sequestration benefit analysis described in section 4.2.

The baseline is created by taking an arbitrary starting point (in this case, 1 Mt per year of sequestration) and applying a growth rate of 2% per year.

Table 5.6: Relative sequestration benefit of each planted vegetation technical innovation area.

Technical innovation area	2030	2035	2040	2050
Low-cost imagery	0.8	0.9	0.9	0.9
Zero or low emission fuels	0.4	0.5	0.5	0.5
Small-scale equipment for agroforestry	0.3	0.3	0.4	0.4
Control of pests, diseases and browsing animals	0.9			
Decision support for informing optimal species selection	1	0.9	0.8	0.7
Lower-cost fencing	0.2	0.3	0.3	0.3
Genetic improvements	0.8	0.8	0.8	0.8
New products for biomass residue	0.9	0.9	0.8	0.7
Driverless or automated vehicles	0.8	0.8	0.8	0.7

Control of pests, diseases and browsing animals has the highest relative sequestration benefit for 2040 and 2050, with decision support for informing optimal species selection having the highest benefit in 2030. The early maturing of control of pests, diseases and browsing animals (2029), with its high scaling factor (4.1), has the potential to provide additional sequestration by 2050, as does decision support for species selection (maturing in 2028). This is contrasted with lower-cost fencing, with a longer maturity timeframe (2034) and lower scaling factor (2), which delivers a lower relative benefit by 2050.

The results are to be expected as technical innovations that mature earlier and have larger scaling factors will deliver the largest additional sequestration relative to the baseline case.

5.1.7 Assumptions and limitations of the analysis

The limitations and assumptions used in this analysis are described below.

- This analysis only used plantation forestry data for economic modelling. The costings will be different for different planted vegetation and farm forestry projects.
- The assessment used a single discount rate and project size. Discount rate variability and project size variability were not considered, but we note that the cost model is sensitive to both factors.
- The trajectory modelling is illustrative only and excludes a range of factors, including the actual current trajectory, resource competition and any social license constraints on the uptake.

5.2 Analysis of implementation steps

The implementation steps in this section were obtained during the workshop by asking workshop participants to attempt to define the steps required to implement the technical innovation areas.

A brief qualitative analysis of the workshop implementation steps is done below (the complete implementation step list is in Appendix A.1) to obtain an overall implementation complexity score used in the final ranking of technology areas in section 5.3.

5.2.1 Low-cost imagery

The use of remotely sensed imagery for vegetation sequestration projects falls into three areas: project site selection, site eligibility and monitoring/auditing of sequestration generation. For plantation forestry projects, site selection may not be a major issue with NPI regions and established plantation estates already defined. Extending the current plantation footprint and for farm forestry and permanent plantings, site eligibility could be more of an opportunity. Perhaps the greatest benefit of low-cost imagery would be in monitoring/auditing the generation of sequestration. What is unclear are the specific barriers to uptake, if the major barrier is cost, or if there are limitations with the resolution that higher resolution imagery (such as LIDAR) would overcome.

The implementation steps captured in the workshop can be organised into five groups:

- improved calibration and validation
- better (higher resolution) imagery
- lower-cost imagery
- improved models (including AI) to convert imagery to indicators or parameters of interest
- tools to access and use imagery resources.

The implementation complexity depends on what the solution is. Suppose the scope is reduced to utilising existing remote sensing data products (of which there are many with high resolution available). In that case, the implementation complexity is assessed as being low to medium.

5.2.2 Zero or low emission fuels

Identifying zero or low emission fuels as an opportunity to lower costs and baseline emissions is no different from other sectors, such as mining. ARENA (2019) estimates the cost of developing the required infrastructure to produce biofuels in Australia to be $25 to $30 billion dollars. McKinsey and Company (2022) estimate the cost of building an electric vehicle network to support the expected growth in these vehicles to be $18 billion for the infrastructure alone. Clearly, these costs are significant and are part of a broader economic transition to net zero. The benefit of low emission fuels is a reduction in emissions generated to produce sequestration, which in turn increases the sequestration generated.

The implementation complexity is assessed as being high.

5.2.3 Small-scale equipment for agroforestry

There is growing interest in small-scale forestry because of perceived environmental and economic benefits. Small-scale projects could be part of a broader portfolio of vegetation sequestration projects that contribute to the national pool of sequestration. Manufacturers such as SAMPO Rosenlew, Vimek and others are now manufacturing a range of small-scale equipment that can reduce the cost of planting, thinning and harvest processes for smaller-scale operations, improving economic viability. The barriers to this technology are tractable, as the equipment itself is readily available globally. The limitations to uptake relate to the cost-effectiveness of small-scale projects.

As the technology for small-scale agroforestry equipment exists, although the required capital investment is high, the implementation complexity is assessed as medium.

5.2.4 Control of pests, diseases and browsing animals

Better control of pests, diseases and browsing animals is one of the technology areas with the best potential to lower sequestration costs. The implementation steps are relatively easy and low-cost for fencing or stock exclusions, and technology for the implementation steps is readily available. Genetic improvements to plant stock (also covered in section 5.2.7) are categorised as moderately difficult to implement.

Overall, the implementation complexity is assessed as being low to high.

5.2.5 Decision support for informing optimal species selection

Most of the implementation steps identified during the workshop for better decision support for informing optimal species selection are categorised as easy or very easy. This implies that the knowledge required for better decision support for species is readily available. Implementation complexity is assessed as medium.

5.2.6 Low-cost fencing

For low cost fencing, only one implementation step was captured during the workshop. It appears that with this technology, the major challenge is developing pest-specific solutions that seem easy to implement. Thus, the implementation complexity is rated as low.

5.2.7 Genetic improvements

Selective breeding and genetically improving tree stock is a well-established though time-consuming process. Recent advances in genetic engineering and genomics have made it easier to manipulate genes that produce desirable traits such as increased growth rate, drought tolerance or disease resistance. However, due to the complex nature of tree genetics and the timeframes required to produce generations of trees, it can take decades to produce new varieties. The implementation complexity is therefore rated as high.

5.2.8 New products for biomass residue

A recent study has identified many new innovative products that can be produced from biomass residue and more generally, (Hassegawa et al. 2022). These include wood foam, glycols, bioplastics, lignin-based adhesives and composite wood products. The implementation steps vary in difficulty from very easy to somewhat hard. Several steps relate to the challenges of scaling, though it is unclear what technical innovation is required to lower costs. Overall, the implementation complexity of this technology area is rated as medium.

5.2.9 Driverless and automated machinery

Driverless vehicles are already available in some industries, including agriculture, with driverless trucks being tested on the road. Despite the rapid progress towards autonomous operation, there are still challenges in achieving full autonomy. The availability and uptake of driverless machinery will ultimately depend on regulatory approval, resolution of technical challenges (e.g. working on forest terrain) and public acceptance. The implementation steps collected during the workshop relate to cost, public acceptance and technical capabilities. As there are still outstanding technical challenges and challenges to bring the cost of this technology down, the implementation complexity is rated as high.

5.3 Ranking

The workshop results and modelled outputs are ranked in Table 5.7. The ranking was achieved by normalising the outputs (cost reduction, scaling and maturity relative benefit, and implementation complexity) into a figure between zero and one, summing and then ranking the technologies based on the total sum. Implementation complexity was translated into a numerical value, with low being assigned 1 and high 0.2. Where a range of complexities was given, the highest complexity was taken (e.g. low to medium was taken as medium with a numerical value of 0.6). The rankings are grouped into three priority groups to indicate the most prospective group of technologies. Note that in the final rankings, control of pest and diseases was relegated from priority 1 to priority 2, as although the benefit was high, specifics on how this was to be achieved were not well identified during the workshop.

Table 5.7: Ranking of technical innovation areas for planted vegetation carbon sequestration.

Technical innovation area	Cost reduction ($ per tonne)	Scaling and maturity relative benefit	Implementation complexity	Priority group
Low-cost imagery	–2.8	0.9	Low–medium	1
Decision support for informing optimal species selection	–3.9	0.7	Medium	1
Small-scale equipment for agroforestry	–4.7	0.4	Medium	1
Lower-cost fencing	–2.9	0.3	Low	1
Control of pests, diseases and browsing animals	–6.1	1.0	Low–high	2
Genetic improvements	–1.8	0.8	High	2
New products for biomass residue	0	0.7	Medium	2
Zero or low emission fuels	–3.4	0.5	High	3
Driverless or automated vehicles	–3	0.7	High	3

5.4 Discussion

For reference, the baseline cost ($19.50 per tonne) determined in this analysis compares well to the figures reported in Fitch et al. (2022) of $20–$30 per tonne for permanent plantings and $10–$30 per tonne for plantation and farm forestry.

All technologies looked at have benefits in reducing the cost of sequestration and increasing uptake, with cost reductions ranging from $4.7 to $2.8 per tonne. As noted above, improved control of pest and disease (without identifying how this was to be done), investment in small-scale equipment for agroforestry and decision support for optimal species selection potentially have the most significant cost reductions. When we include the scaling and maturity analysis, the picture is a little different; however, investment in better control of pests, diseases and browsing animals was still the most beneficial opportunity. From a scaling perspective, low-cost imagery (due to its early maturity date) and genetic improvement rate highly.

This is at odds with the economic analysis, in which low-cost imagery and genetic improvement do not yield as much cost reduction, at $2.8 and $1.8 per tonne, respectively. This difference is likely due to the optimistic outlook by the participants on the relative benefits of the technologies and their potential scaling factors, which are not borne out in the economic analysis.

Zero or low emission fuels and driverless or autonomous vehicles are options that have a moderate ability to lower costs, but the maturity times are likely optimistic. This is particularly true for driverless or autonomous vehicles, with significant technical and legislative challenges.

The workshop participants assembled the implementation list, and although the list was reviewed, it did not have sufficient review or harmonisation for a consensus to be formed. The implementation steps captured provide a first cut on what could be involved in implementing the technology areas. A more comprehensive review of the technology area status, including barriers, options and costs, is required to turn these into an action plan.

In some technologies, the implementation steps are straightforward and require no additional investment (e.g. control of pests and disease with the use of fencing), whereas others, such as those for genetic improvement and autonomous vehicles, are far more complex.

Overall, the technologies that have the highest likelihood of reducing cost and increasing carbon sequestration through planted vegetation are:

- low-cost imagery
- decision support for informing optimal species selection
- small-scale equipment for agroforestry
- lower-cost fencing.

5.5 References

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Hassegawa M, Karlberg A, Hertzberg M, Verkerk PJ (2022) Innovative forest products in the circular bioeconomy [version 2; peer review: 2 approved]. *Open Research Europe*, 2:19. doi:10.12688/openreseurope.14413.2.

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6 Blue carbon

This chapter details the results and analysis of the blue carbon workshop. The workshop aimed to explore how technical innovation can lower the cost of blue (coastal) carbon sequestration and correspondingly increase the uptake of this sequestration approach in Australia. Specifically, the workshop considers the sequestration that could be achieved in coastal areas (mangroves and saltmarsh) by reintroducing tidal flows to previously drained or ponded coastal areas. This is the only approved eligible activity under the methodology determination of the Australian carbon credit unit (ACCU) scheme.

The workshop was held on 8 December 2022 with eight participants, using the workshop methodology detailed in Chapter 3. Appendix C, section C.1.2, includes a list of workshop participants. The cost reduction results are presented with a brief commentary on the implementation steps developed, with details of those steps listed in Appendix A.1.

6.1 Workshop results

6.1.1 Technology list

Table 6.1 presents the technical innovation opportunities collated for the workshop and a brief definition of the opportunity for cost reduction. Note that the specifics of the technical innovation areas were not discussed or agreed to at the workshop and so are indicative of the technology innovation discussed.

Table 6.1: Technical innovation opportunities for carbon sequestration through blue carbon.

Technical innovation area	Description	Cost reduction area
Earth observation technologies for national assessment	Remotely sensed imagery is used to locate suitable project locations and ensure that the carbon project eligibility requirements are met. In addition, imagery can be used as part of the verification and auditing of a blue carbon project. Currently, costs for acquiring high-resolution imagery can be high and impact the establishment and transaction costs of the carbon project.	Potential to reduce establishment and carbon project costs.
National models for tidal introduction and feasibility assessment	A nationally consistent model to estimate the likely extent and frequency of inundation of coastal areas under highest astronomical tide conditions and to account for projected sea-level rise. The model would identify coastal areas	Potential to identify coastal areas suitable for inundation and thus reduce project establishment costs under the ACCU scheme tidal method.

	suitable for tidal reintroduction and available to project proponents. Current hydrological assessments are inconsistent and cost prohibitive.	
Standardised hydrological modelling tool that project proponents can implement to identify risks and future abatement	Similar in purpose to a national hydrological model but focused on making publicly available a toolkit for undertaking a standardised project-level hydrological assessment as a requirement of ACCU scheme accreditation.	Potential to identify coastal areas that could be suitable for inundation and reduce project establishment costs under the ACCU scheme tidal method.
Earth observation technologies for restoration site identification and assessment	Remotely sensed imagery is used to locate suitable project locations and ensure the carbon project eligibility requirements are met. Currently, costs for acquiring high-resolution imagery can be high and impact the transaction costs of the carbon project.	Potential to reduce establishment and carbon project costs.
Methods and indices for measuring other benefits	The development of appropriate methods for quantifying other ecosystem benefits derived from blue carbon habitat, including coastal protection, water quality improvement, fisheries enhancement and biodiversity benefits. There is great interest in developing high-value environmental credits that recognise the broader suite of services provided by blue carbon habitats (besides carbon) and account for these services in national ecosystem accounting processes.	Potential to support participation in national and international crediting systems. These methods would assist in achieving a higher carbon price by valuing other non-market ecosystem services for inclusion in Environmental and Economic Accounts (EEA) processes and reporting obligations.
AI and improved data management of monitoring, reporting and verification	Access to publicly accessible, relevant and timely inventory and project blue carbon data would streamline reporting, assessment approvals and verification processes.	Potential to reduce establishment and carbon project costs.
National model of sea level rise impacts on coasts	Access to publicly accessible, relevant and timely inventory and project blue carbon data would streamline reporting, assessment approvals and verification processes.	Potential to reduce establishment and carbon project costs.
Methane satellites for knowledge of potential avoided emissions from land-uses	Methane measurement is a gap, but using satellites is out of scope.	Not described.

6.1.2 Workshop outputs

The most significant innovations were determined by voting to be:

- methods and indices for measuring other benefits (11 votes)
- national model for tidal introduction and feasibility assessment (9 votes, 2 more for a standardised hydrological model)
- earth observation technologies for restoration site identification and assessment (3 votes + 1 for earth observation for national assessments).

The other technologies received 3 votes.

As in the other workshops, each technical innovation area was investigated by workshop participants for its cost reduction and scaling potential. These results are summarised in Table 6.2, with copies of the Miro board outputs in Appendix A, section A.1.2. To help interpret the results, please see the definitions in section 3.4.

Table 6.2: Summary of outputs from the blue carbon workshop.

Technical innovation area	Economic viability improvement (%)			Maturity (Year)			Scaling factor		
	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
Methods and indices for measuring other benefits (n=6)	58	25	90	2029	2027	2031	2.21	1.7	3
National model for tidal introduction and feasibility assessment (n=7)	46	19	77	2029	2027	2030	2.76	2.5	3.1
Earth observation technologies for restoration site identification and assessment (n=4)	19	10	30	2027	2025	2029	1.9	1.7	2.2

There was a wide range of opinions regarding improvements to economic viability for both methods and indices for measuring other benefits and the development of a national model for tidal introduction and feasibility assessment. Overall, developing methods and indices for measuring other benefits was seen to have the greatest potential economic viability improvement, followed by the national model for tidal introduction and feasibility assessments. New methods and indices for measuring other benefits would include a broader set of values (economic and environmental) alongside the carbon sequestration benefit, thereby increasing demand for blue carbon, with additional revenue reflecting payment for those environmental services.

The workshop participants agreed that focusing on cost reduction was inappropriate for blue carbon sequestration, and improved economic viability was the critical issue. In response, the workshop convenors reframed the cost reduction question around economic viability. Changes to economic viability gathered in the workshop were converted to a proportional cost reduction using the method described in the next section.

Conversion of improved economic viability to cost reductions

The approach to converting improvement in economic viability to percentage cost reduction is as follows:

- Economic viability is defined as NPV; therefore, an improvement in economic viability of *x*, translates to an improvement in NPV of *NPV(1 + x)*.
- The corresponding cost reduction *y* was determined numerically by adjusting the NPV and determining the corresponding cost reduction that generated that change.

Conversion of improved economic viability to revenue increase

As with the conversion of improved economic viability to cost reductions, a conversion was required to convert changes in economic viability into an increase or decrease in revenues. The technical innovation area generating additional revenue in this way was methods and indices for measuring other benefits.

A similar approach to converting economic viability to cost reduction was used to convert economic viability to increases in project revenue.

The calculated cost reductions for improvements in economic viability are listed in Table 6.3.

Exploratory data analysis

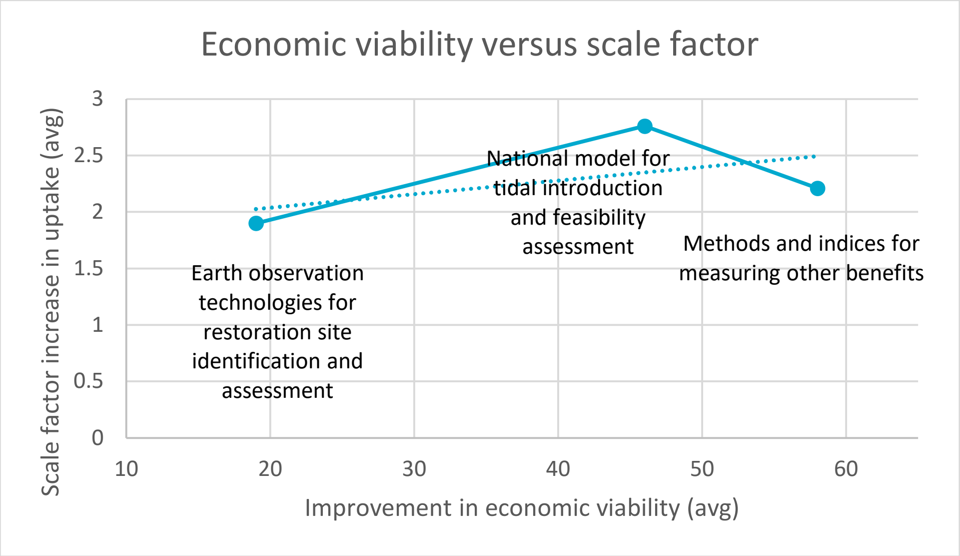

Figure 6-1: Plot of average cost reduction percentages versus scaling factor for blue carbon technical innovation areas.

Cost reduction estimates were plotted against the scaling factors to explore the consistency of the workshop outputs. If the technology has a significant cost reduction factor, it would be reasonable to expect that the scaling factor would similarly be high. Conversely, expecting a low scaling factor would be reasonable if the cost reduction factor was relatively low.

The lack of a relationship between the scaling factor and cost reduction is likely an artefact of the workshop and is a signal to interpret the results with care. This result could be due to insufficient time to reach a consensus or the lack of a consensus process to compare scaling factors to cost reduction. The weak trend line is plotted in Figure 6-1, reflecting relatively poor consistency between improvements in economic viability and scaling potential.

6.1.3 Cost reduction analysis

Blue carbon sequestration cost areas or cost drivers

The following cost and revenue categories were defined in preparation for the cost modelling:

- **Establishment**: project start-up costs include planning feasibility, engineering assessment and hydrological modelling, site and regulatory approvals, application to the clean energy regulator, project management for the first 2 years, and environmental impact consultation; project maintenance costs include pest and animal control and other on-ground engineering maintenance as required.
- **Operations:** ongoing maintenance costs for years 1 to 5 inclusive.

Yield: revenue obtained from sequestration generated.

The workshop cost factors were then assigned to the cost areas defined above and presented in Table 6.3.

Table 6.3: Cost reduction factors for blue carbon technical innovation areas. All factors are percentage reductions (costs) or increases (revenues) relative to current costs.

Technical innovation area	Change in NPV	Cost reduction (%)	Costs		Revenue
			Establishment (%)	Operational (%)	
Methods and indices for measuring other benefits	0.58	–	–	–	5.6 multiplier of revenue
National model for tidal introduction and feasibility assessment	0.46	41	29	12	–
Earth observation technologies for restoration site identification and assessment	0.18	17	12	5	–

Cost model

A simplified cash flow model translates the outputs from the blue carbon workshop into changes to NPV (economic viability) and reductions to the cost per tonne of sequestration for a project. The model allows partitioning of costs, allowing cost reductions to be applied selectively to the relevant cost areas and for lifetime cost reductions (in this case, over 25 years) to be converted to changes in NPVs.

The following default parameters were used for this analysis, following Hagger et al. (2022) , for a 25-year project lifetime.

Table 6.4: Cost factors for blue carbon projects.

Cost area	Cost item	Value
Establishment	This includes project start-up costs including ACCU scheme recognition, state and local government site approvals (e.g. for removal and placement of hydrological structures) and feasibility assessment (e.g. hydrological modelling). Removal of hydrological structure could sit in either establishment cost area or operational costs or be rolled in together.	$8159 per ha.

Maintenance	The cost incurred for the first 5 years after establishment.	\$750 per ha per annum for the first 5 years after establishment (Waltham et al. 2021).

In Table 6.4, project establishment or start-up costs are defined and listed in cost areas, with the transaction costs associated with administering the carbon project are included in establishment costs.

The annualised carbon project revenue was calculated from the BlueCAM modelled abatement (tonnes CO_2e per ha) and multiplied by the project area.

The cost per tonne of sequestration was determined by calculating the total NPV cost of sequestration and dividing it by the total sequestration generated over the life of the project as per Equation 7.

$$Cost\ per\ tonne = \frac{Cost}{\sum_t Sequestration_t} \quad \text{(Eqn 7)}$$

Project NPV was calculated by determining the net cash flow (revenue – costs) and subtracting the carbon project costs, as shown in Equation 8:

$$Project\ NPV = NPV(revenue) - NPV(Costs) - NPV(Carbon\ Project\ Costs) \quad \text{(Eqn 8)}$$

For the analysis, a discount rate of 7% was used, with a nominal carbon price of \$20 per tonne of carbon and a project size of 200 ha with a project duration of 25 years. Note that at the time of writing, the spot carbon price is \$35.5 per tonne.

Modelled sequestration

The generation of cost per tonne estimates requires estimates of sequestration quantities for typical blue carbon projects.

The Blue Carbon Accounting Model (Clean Energy Regulator, 2022) has been developed to support the blue carbon method (Clean Energy Regulator, 2022). BlueCAM is used to calculate the net carbon abatement from the soil and vegetation sequestration and emissions avoidance components of a project.

For blue carbon projects, the project activity will be to introduce tidal flow, resulting in the rewetting of previously completely or partially drained coastal wetland ecosystems. This could involve removing or modifying part or all of a sea wall, bund, drain or other type of tidal flow restriction device, such as a tidal gate.

For this analysis, four representative scenarios were used, one for each of the four expected blue carbon project climate zones. The scenarios are described in Table **6.5**. In the scenarios, earthworks were estimated as 10% of the project area.

Table 6.5: **BlueCAM scenario modelling results.**

Scenario	Project size (ha)	Initial land use	Final land use	Net sequestration (tonnes)	Annual sequestration (tonnes per ha per year)
Tropical monsoon	200	Grazing	Mangrove	15366.6	3.1
Temperate	200	Cropping	Mangrove	27991.5	5.6
Tropical humid	200	Sugarcane	Mangrove	39034.3	7.8
Subtropical	200	Cropping	Mangrove	24041.0	4.8

The sequestration yield estimates from the scenarios were averaged, and an amount of 5.3 tonnes per ha per year was used to calculate cost reductions from the changes in economic viability. For more detail on the scenarios used, see assumptions and limitations in section 6.1.7 .

The model was initially run with no changes to costs to develop a baseline. This baseline was then used for the cost reduction analysis.

Cost analysis

The results of the modelling are listed in Table 6.6. The model determined the baseline cost as $92 per tonne with a carbon price of $20 per tonne and a discount rate of 7%. The cost reductions are the difference in cost in $ per tonne compared to the baseline.

Table 6.6: Cost reductions for blue carbon technical innovation areas.

Technical innovation area	Cost reduction from baseline ($ per tonne)	Net cost ($ per tonne)
Baseline cost	0	92
Methods and indices for measuring other benefits	0	92
National model for tidal introduction and feasibility assessment	–39	53
Earth observation technologies for restoration site identification and assessment	–18	74

In Table 6.6 and Figure 6-2, developing a national model for tidal introduction and feasibility assessment is shown to have the most significant potential to lower the cost of sequestration (–$39 per tonne) for the technical innovation areas assessed, followed by earth observation technologies (–$18 per tonne). Methods and indices for measuring other benefits does not impact the cost of sequestration.

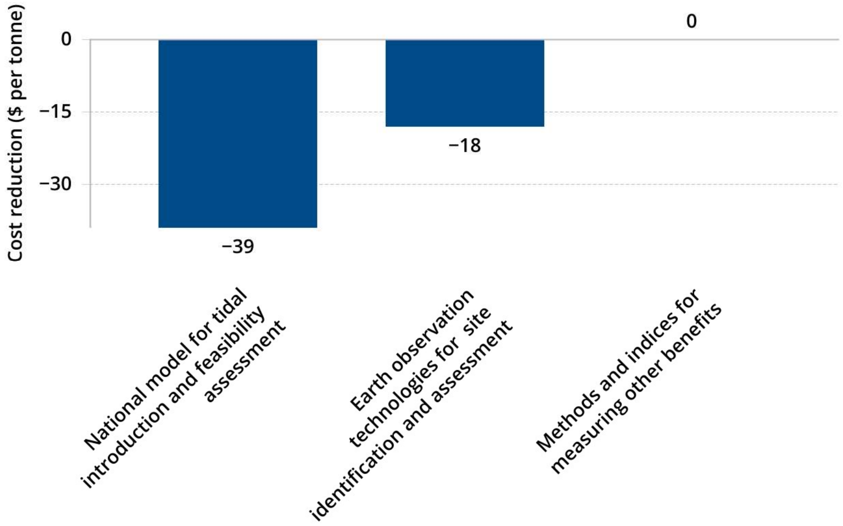

Figure 6-2: Bar graph of cost reductions for blue carbon technical innovation areas.

6.1.4 Cost reduction, maturity and scale

Figure 6-3 summarises the outputs of the workshop on one chart. The x-axis represents the year of maturity, the y-axis the cost reduction per tonne of CO_2 sequestration, and the bubble size represents the scaling factor. The larger the circle, the lower on the chart and closest to the left-hand axis, the greater the potential for cost reduction and scaling.

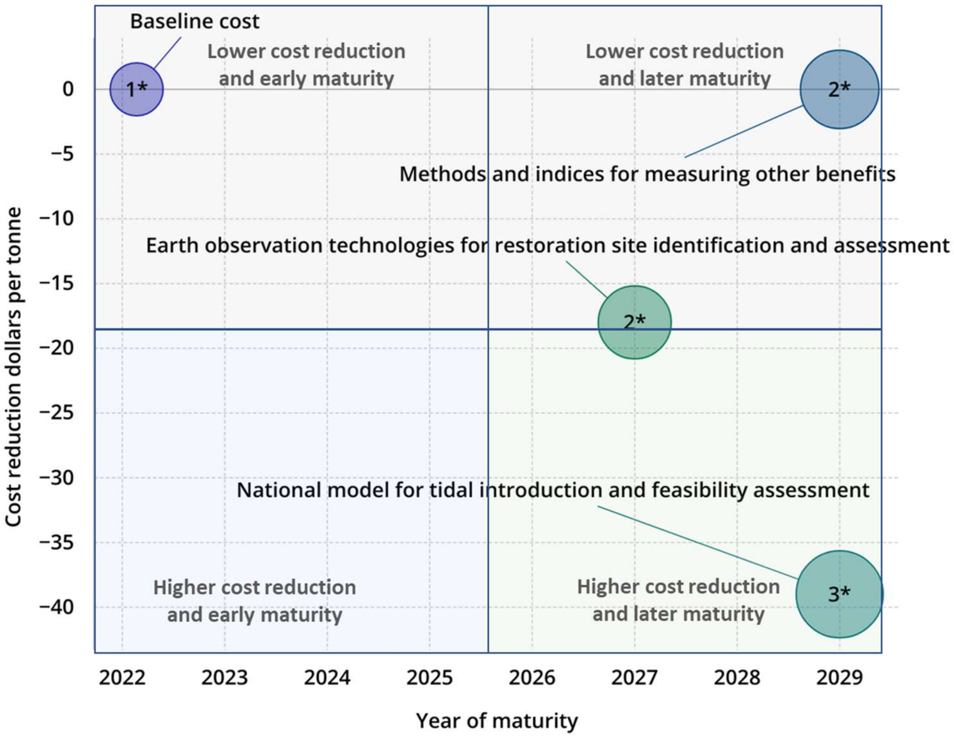

Figure 6-3: Comparison of technology cost reduction, year of maturity and scaling factor for blue carbon technical innovation areas. * Indicates the scaling factor.

6.1.5 Sensitivity analysis of cashflow model

With a cashflow model, a sensitivity analysis can readily be performed to explore which cost areas more likely to change the NPV (economic viability) or the cost of sequestration. The economic viability of blue carbon projects is currently challenging, and technical innovations that lower the establishment or start-up costs have significant potential to reduce costs, improving the project's economic viability, thus unlocking additional sequestration. The sensitivity analysis presented in Figure 6-4 identifies those cost areas with the greatest potential to improve the economic viability of blue carbon projects.

In the analysis presented in Figure 6-4, different model cost parameters were varied in four steps relative to the baseline: –10%, –5%, +5% and +10%. The changes to NPV as a percentage of the baseline are presented as a colour-coded heatmap.

Figure 6-4: Sensitivity analysis of the cash flow model for blue carbon sequestration projects.

As shown in Figure 6-4, establishment costs have the most significant impact on economic viability. The magnitude of the investment required is one reason for that impact, and the other reason is the timing of those costs being right at the beginning of a project.

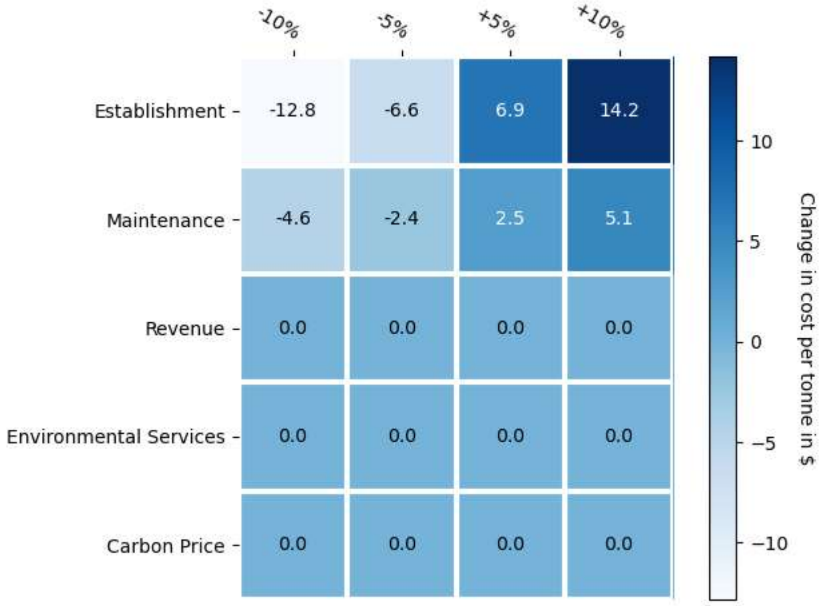

Figure 6-5: Sensitivity analysis of sequestration costs for blue carbon sequestration projects.

Additional revenue from environmental services or enhanced carbon pricing has no impact on the cost of sequestration. The insight here is that any technology innovation that can lower establishment costs will have the most significant potential to reduce the cost of blue carbon sequestration.

6.1.6 Scaling and maturity analysis

The results in Table 6.7 allow for the ranking of the technology innovation areas and present a relative measure of additional sequestration generated compared to the baseline. The results were obtained using a calibrated logistic model (as described in Chapter 4) using the scaling factors and maturity dates developed as part of the workshop (listed in 6.1.2) and are colour coded to form a heatmap, with lower values lighter and higher values dark blue (higher is a larger benefit).

The baseline was created by taking an arbitrary starting point (in this case, 1 Mt of sequestration per year) and applying a growth rate of 2% per year.

In 2050, the greatest potential sequestration generated is for the national model for tidal introduction and feasibility assessment (value of 1 is the highest and the best), and the other technology options are scaled relative to that. Earth observation technologies for restoration site identification and assessment would generate 0.6 times as much additional sequestration by 2050 compared to the national hydrodynamic model.

Table 6.7: Relative sequestration benefit of each blue carbon technical innovation area.

Technical innovation area	2030	2035	2040	2050
Methods and indices for measuring other benefits	0.6	0.6	0.6	0.7
National model for tidal introduction and feasibility assessment	1	1	1	1
Earth observation technologies for restoration site identification and assessment	0.7	0.7	0.6	0.6

6.1.7 Assumptions and limitations of the analysis

In undertaking these assessments, the following limitations and assumptions were made:

- **Blue carbon habitats**: only mangroves were considered; other blue and teal carbon habitats were not included.
- **Sequestration methods:** only the ‘tidal reintroduction’ method was considered here; the tidal reintroduction method relies on the removal of barriers that have restricted natural tidal ingress to naturally re-establish blue carbon habitats, mainly mangrove and saltmarsh.
- **BlueCAM model**: as part of the tidal restoration method (Clean Energy Regulator, 2022), an Excel-based model, BlueCAM, has been developed to assist proponents with calculating potential sequestration.[3]

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[3] BlueCAM can be found at: https://www.cleanenergyregulator.gov.au/DocumentAssets/Pages/The-blue-carbon-accounting-model-BlueCAM.aspx.

Project costs

Establishment costs ($ per ha). In this analysis, establishment costs of $8589 were assumed, based on recent analyses by Hagger et al. (2022b). This analysis considered an earlier study (Bayraktarov et al. 2016) of restoration costs, adapting the lower range of costs derived for saltmarsh on the assumption that hydrological restoration involves mainly earthworks for modification of drains/bunds and not costly active (i.e. replanting) restoration methods. Establishment costs available from two current tidal restoration projects (Blue Heart, Queensland and Dry River, South Australia) confirmed these costs.

The costs considered under establishment costs include project approval and site remediation costs.

An economy of scale factor to account for project size of 20 ha was assumed. It was based on a study of terrestrial restoration projects that demonstrated a non-linear cost reduction in restoration, particularly for projects over 50 ha in size (Strassburg et al. 2019.)

Maintenance costs ($ per ha). Given that natural recovery requires minimal maintenance, maintenance costs of $750 per ha per year were applied for the first five years of the project (Waltham et al. 2021).

Discount rate. Typically discount rates between 5–10% are used; in this case a 7% discount rate was applied.

Technology costs reductions

Cost of high-resolution imagery. The average cost of acquiring high-resolution (<5 m) commercially available satellite data (e.g. Geo-eye, Planet, World View, Ikonos, Pleiades) was US$22 (AU$33) per km^2 or $0.33 per ha. Most of the satellite data have minimum order quantities (typically 25 to 50 km^2) and the cost varies with the spatial resolution of the satellite image.

Cost of hydrological modelling. It is a requirement under the ACCU scheme to undertake a hydrological/hydrodynamic assessment of project sites. Commercial companies undertake these assessments, which cost between $15,000 and $35,000 depending on the size of the project. This is a considerable up-front cost and a significant proportion of establishment costs. For this analysis, a cost of $15,000 for a 100-ha project site was assumed and scaled at $2,000 per 100 ha. Thus, providing a public-use national modelling capability was assumed to significantly reduce these up-front costs. Implementing the model is likely to cost $3–5 million over 3 years, with an ongoing operational sustainment requirement.

Viability of co-benefits. Beyond carbon sequestration potential, there are a number of recognised co-benefits that blue carbon habitats provide, including biodiversity, fisheries, water quality improvement, coastal protection and myriad cultural and material benefits to customary landowners. The quantification and potential commodification of co-benefits, such as bundling them with carbon abatement, has been recently evaluated and could add a premium of 30% compared to projects with lower co-benefits (Lou et al. 2022). The caveat with the analysis is that the volume of credits produced must also be considered. While a project cost is associated with quantifying and verifying these co-benefits, the principal effect on project viability is the greater price yield.

Scenarios summary. Baseline scenarios were estimated using the BlueCAM model for an assumed 20-ha project size in each of the main bioregions, assuming the initial land uses, vegetation type and tidal conditions shown in Table 6.8. While projects nearly always comprise multiple CEAs, for this analysis, only a single CEA was used with the dominant land use.

Table 6.8: Summary of BlueCAM modelled scenarios

Scenario	Project size (ha)	Initial land use	Final land use	Tidal range (HAT, mAHD)	Net abatement (tonnes)	Annual sequestration (tonnes per ha per year)
Tropical monsoon	200	Grazing	Mangrove	8 (4, 0.05)	15366.6	3.1
Tropical humid	200	Sugarcane	Mangrove	3 (1.5, 0.1)	39034.3	7.8
Temperate	200	Cropping	Mangrove	2.4 (1.4, 0.1)	27991.5	5.6
Subtropical	200	Cropping	Mangrove	0.7 (0.4, 0)	24041.0	4.8

HAT, highest astronomical tide; mAHD, metres above Australian Height Datum,

6.2 Analysis of implementation steps

6.2.1 Methods and indices for measuring other benefits

The implementation steps collated during the workshop for methods and indices for measuring other benefits, such as environmental services, are brief. Determining and valuing non-carbon benefits is viewed as a market-based approach to achieving additional revenue; however, methods and indices are only one part of establishing a market for these benefits. There are difficulties in valuing these benefits (such as biodiversity) and establishing a market. There are many options to value different parts of the environmental services that these blue carbon projects can provide, each requiring reasonable investment. Implementation complexity is rated as medium to high.

6.2.2 National model for tidal introduction and feasibility assessment

A significant part of the blue carbon project costs relates to the need to undertake a hydrodynamic modelling analysis to confirm water movements within the carbon project area.

A national model for tidal introduction and feasibility assessment for blue carbon projects has good potential to lower the sequestration cost. During the workshop, it was estimated that a high-resolution hydrodynamic model that works from a single platform would require an investment of $200 million and more than 10 years to build. Unfortunately, due to the lack of time during the workshop, it was impossible to explore or reach a consensus on the timing of implementation steps and the scale of investment required. In subsequent discussions, the authors felt the estimate was overstated, and such a capability could be established with less investment and be ready at an earlier date. For this reason, the implementation complexity is rated as medium.

6.2.3 Earth observation technologies for restoration site identification and assessment

Earth observation technologies for site identification and monitoring, reporting and verification have good potential to lower the costs of sequestration. The implementation steps identified during the workshop include improving the availability of key remote-sensed datasets, developing new indices or indicators that could aid in estimating the non-carbon benefits, as well as developing improved data and methods to estimate the above and below-ground carbon sequestration. Most of the implementation steps required moderate investment, less than $5 million, with a relatively early maturity timeframe of 2025 to 2030. For these reasons, the implementation complexity of earth observation technologies is rated as medium.

6.3 Ranking

The workshop results and modelled outputs are ranked in Table 6.9. The ranking was achieved by normalising the outputs (cost reduction, scaling and maturity relative benefit, and implementation complexity) into a figure between zero and one, summing and then ranking the technologies based on the total sum. Implementation complexity was translated into a numerical value, with low being assigned 1 and high 0.2.

Table 6.9: Ranking of technical innovation areas for blue carbon sequestration.

Technical innovation area	Cost reduction ($ per tonne)	Scaling and maturity relative benefit	Implementation complexity	Priority
Methods and indices for measuring other benefits	0	0.7	Medium–high	1
National model for tidal introduction and feasibility assessment	–39	1	Medium	2
Earth observation technologies for restoration site identification and assessment	–17	0.6	Medium	3

6.4 Discussion

For reference, the baseline cost ($92 per tonne) determined in this analysis is significantly higher than the estimate reported in Fitch et al, (2022) of $18-$30 per tonne. The difference is likely due to the low maturity of this technology and it is likely that the costs will reduce as uptake increases. The analysis indicated that a range of cost reductions from 20 to 42% was possible on the baseline cost.

The economic viability of blue carbon projects is challenging, and technical innovations that lower the establishment or start-up costs have significant potential to reduce costs, improve the economic viability and unlock additional sequestration. A national modal for tidal introduction and feasibility assessment that can rapidly produce the necessary outputs to confirm the suitability and eligibility of blue carbon projects has good cost reduction potential.

Any technologies that can increase revenue streams for blue carbon projects will help improve the economic viability of projects. Methods and indices that quantify the environmental service provision of projects and enable a premium carbon price for a differentiated product or support other environmental crediting schemes (e.g. reef credits) would be beneficial.
The analysis in this report is sensitive to the underlying assumptions in the modelling as described in section 6.1.7.

The performance of blue and teal carbon projects around Australia may vary depending on regional ecosystem type, condition and performance, and the prevailing policy setting. At a project level, proponents’ technical understanding of basic ecological and physiological requirements (e.g. low tide exposure) and their adoption of emerging technologies will affect the project's success. Costs of entry, long (decadal) timeframes for a return on investment, and ongoing monitoring, reporting and verification (MRV) requirements are further factors that will influence the success of projects.

Better data for predicting the feasibility of blue carbon projects include better resolution of tidal planes, mapping of hydrological modification and structures, more accurate income data from different land-uses and the costing of restoration activities. Increasing the range of case study regions would further help understanding of the extent of tidal restoration opportunities and limitations across Australia.

The studies of Hagger et al. (2022a, b) conclude that carbon prices in Australia are too low for many projects to be feasible and that bundling or stacking co-benefits is the most viable medium-term solution to increasing adoption (Hagger et al. 2022a, b).

Up-front project establishment costs can be high and include regulatory approvals that can require hydrological/hydrodynamic modelling to be undertaken, and capital outlays to remove or emplace structures and to undertake any earthworks and fencing. Ongoing maintenance costs and meeting MRV requirements must also be factored into assessments of the financial viability of any proposed projects. Studies from forest carbon projects have shown that the costs of monitoring and verification can exceed the revenue from carbon credits and that the cost is a critical component in developing forest carbon methods that provide incentives (Köhl et al. 2020). A key motivation for developing modelling tools like BlueCAM is that they do not require costly field measurements of sequestration and so reduce the costs borne by project proponents.

Blue carbon ecosystems provide multiple co-benefits, including biodiversity, fisheries enhancement, pollutant removal, coastal protection and reduced pest incursions. They are culturally significant to Indigenous people who rely on them for materials and resources.

Co-benefit hotspots can be identified where multiple benefits are bundled to attain higher carbon prices for restoration projects or to undertake projects for emerging markets, such as biodiversity credits. As these ecosystem services vary regionally and locally, relevant systematic data collection and the development of modelling tools are required.

National hydrological models that can assess the extent and frequency of inundation of coastal areas and habitats with improved delineation of the areal extent over which management interventions may feasibly operate are required. The CSIRO and BHP are undertaking a national blue carbon project to develop some of this national hydrological capability, and it should be available later in 2023.

A key motivation for the development of modelling tools like BlueCAM is that they do not require costly field measurements, ensuring consistency and reducing the costs borne by project proponents. However, for assessing the potential of tidal introduction methods, national hydrological models that can assess the extent and frequency of inundation of coastal areas and habitats are also required, along with improved delineation of the areal extent over which management interventions may feasibly operate.

6.5 Blue carbon case study: the benefits of a national hydrological modelling capability for blue carbon tidal inundation modelling

A requirement of the Tidal Restoration of Blue Carbon Ecosystems (the blue carbon method, Clean Energy Regulator, 2022) is a hydrological study to assist the planning of engineering works and to establish the extent of tidal inundation that would be likely to be achieved in the project area with the removal of identified tidal barriers. This typically requires engaging a commercial engineering consultant to develop a hydrodynamic model for the project area. Depending on the project size, this might cost between $15,000 and $45,000 – a considerable outlay and up-front cost for any project proponent.

In this study, we considered providing a public-use national modelling capability to reduce these up-front costs and stimulate project uptake. Such a national hydrological modelling capability would assist proponents in assessing the extent and frequency of inundation in their project areas, lower start-up costs, shorten delays in acquiring the data and engaging consultants, and contribute to more robust cost feasibility assessments.

Fortunately, there are several initiatives already underway that could be harnessed to reduce costs and accelerate implementation. A national blue carbon project undertaken by the CSIRO and BHP provides a nationally consistent determination of the highest astronomical tides around Australia, which will be available for projects to use. Under the Australian Climate Services (https://www.acs.gov.au), national inundation modelling is being developed, primarily for more effective planning and response to extreme weather resulting in fluvial or storm surges. While the spatial resolution of this model is probably too coarse for the scale of many blue carbon projects, it provides an important framework and the necessary forcing data to nest more refined models. Such models will need better data, including fine-scale harmonised bathymetry and digital elevation information, particularly in the upper reaches of estuaries and floodplains. Sediment accretion models that underpin the BlueCAM models could also feasibly be used as part of this modelling approach and would further increase the rigour of project-scale and national assessments. In Queensland, a project along catchments adjacent to the Great Barrier Reef is being developed for assisting projects. The approach will be to trial the models in several pilot sites where data or models are already available. The trials will document sediment accretion on bare and vegetated coastal areas or finely resolved hydrological models for comparison.

Given the above investments, we believe a modest investment of approximately $4–6 million could deliver the additional capability required to undertake blue carbon assessments.

Figure 6-6: Reintroduction of tidal flow site, Maroochy flood plain, Queensland. Photo credit Blue Heart.

One of the first projects to apply for accreditation under the blue carbon method is the approximately 5000-ha Blue Heart project located on the Maroochy flood plain, Queensland. This project proposes the reintroduction of tidal flow to an area of approximately 480 ha through the removal of 17 tidal barriers. A feasibility study estimated that the proposed blue carbon area could generate 93,394 tCO_2e over a 25-year period (Whitehead and Lipsett-Moore 2022). Assuming a carbon price of \$35 per tCO_2e, a return of \$3.269 million could be expected. The costs associated with the project were estimated to be about \$2.8 million, with more than 90% (up to \$2.25 million) being associated with the on-ground engineering works for tide gate removal. Start-up costs, including hydrological assessments and various approvals, of \$240,000 were a relatively minor overhead. Importantly, this study also identified that the economic value of co-benefits could generate about \$25,000 ha per year and contribute significantly to the project's profitability.

6.6 References

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7 Direct air capture

The direct air capture workshop was held 14 December 2022 with 11 participants. Appendix C, section C.1.3, includes a list of workshop participants.

One pre-workshop question was sent to participants: 'Please list up to five technological innovations or barrier removals that will drive cost reduction of carbon abatement using this sequestration approach.' The three technological innovations that have the most significant impact on cost reduction were reviewed in detail.

For this workshop, a fourth continuum was added to the Miro boards. The continuums discussed were:

- **Cost reduction potential:** What is the cost reduction of each technological innovation in $ per tonne?
- **Maturity timeframe:** What year in the future could we reasonably expect this innovation to be routinely used and the cost reduction to occur?
- **Uptake scaling potential:** If this price reduction for delivered abatement could be achieved, what is the potential supply of abatement compared with current levels of delivered abatement? (Unit is a multiplier of current uptake rate – if 0 is current, assume 1 tonne.)
- **Investment required:** How much is it going to cost to realise the potential of this technological innovation? (Unit is millions of dollars.)

In the third round of the workshop, the implementation steps required to realise the potential of each technological innovation were explored. The participants were asked to indicate how much investment would be necessary to develop that innovation to maturity.

7.1 Workshop results

7.1.1 Technology list

Table **7.1** presents the technical innovation opportunities collated during the workshop, together with a brief definition of the opportunity. Note that the specifics of each technical innovation area were not discussed or agreed to at the workshop and so are indicative. Apart from the technical innovations in direct air capture (DAC) technologies, the considerations around energy supply to operate the DAC process were also considered as important.

The technology innovation areas are closely linked to each other. The performance of materials in DAC will be influenced by the process and equipment design and the method of energy supply.

Table 7.1: Technical innovation opportunities for carbon sequestration through direct air capture.

Technology innovation area	Description	Cost reduction area
Materials	Robust, low-cost, fast-reacting CO_2 capture agents.	Stability of capture agents in service over time. Capture equipment size and costs. Scale of manufacturing of affordable capture agents including supply chains.

		Energy requirement for regeneration of capture agents.
Energy supply	Integration of DAC system with zero-emission, most likely variable, energy supply.	Storage of heat, electricity or CO_2. Electricity-driven DAC systems. Physical integration option of DAC system with zero-emission energy supply.
Process and equipment	Scalable low-cost process and equipment designs that minimise process energy requirements.	Low pressure drop air contactors. High specific surface area air contactors. Design and construction of large-scale plants. Manufacturing and equipment supply chain.

7.1.2 Workshop outputs

All detailed outputs are presented in Appendix A. The methodology used to develop the outputs is detailed in Chapter 3. Table 7.2 presents an overview of workshop outputs, indicating the cost reduction potential, anticipated year of maturity, scaling factor and required investment (average, minimum and maximum). The experts expressed a wide range of cost reduction potentials for each technical innovation area. At the maximum, the cost reduction potential was approximately double the average for all technical innovation areas. At the minimum, the cost reduction potential could be zero (energy supply) or half the average cost reduction potential (process and equipment). We used the average data in our subsequent analysis. Significant variation was also encountered in the required investment discussions.

Table 7.2: Summary of outputs from the direct air capture workshop.

Technical innovation area	Cost reduction potential (%)			Maturity (Year)			Scaling factor			Investment required ($)		
	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
Materials	27	6	50	2031	2027	2035	6.7	1	10.5	530	45	1500
Energy supply	8	0	17	2032	2028	2037	7.8	0	10	500	225	7500
Process and equipment	34	17	67	2033	2030	2038	9	3	10	1065	3200	15000

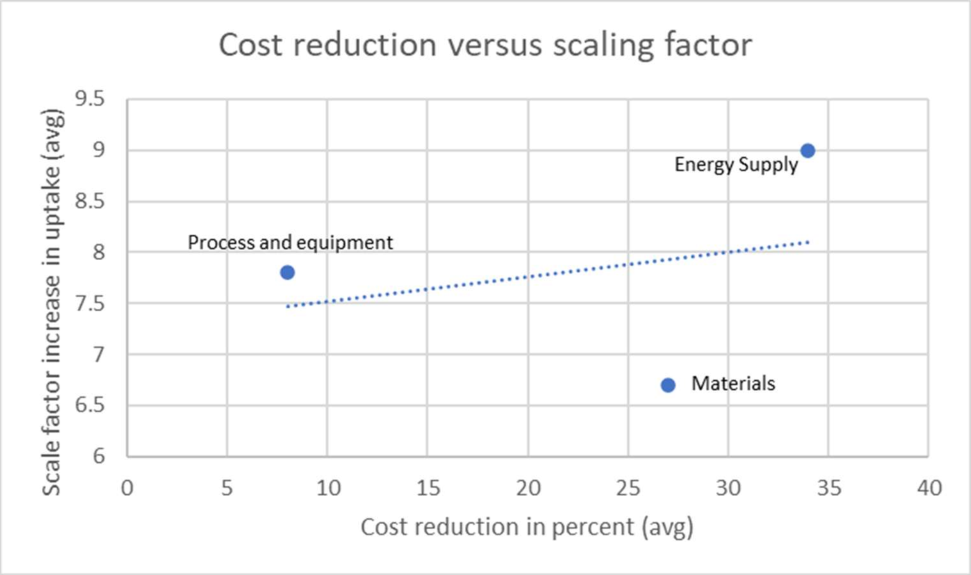

Figure 7-1: Plot of average cost reduction percentages versus scaling factor for direct air capture technical innovation areas.

In Figure 7-1, cost reduction estimates are plotted against the scaling factors. The lack of a relationship between the scaling factor and cost reduction is likely an artefact of the workshop and is a signal to interpret the results with care. This could be due to insufficient time to work through to a consensus or due to lack of a consensus process to compare scaling factors to cost reduction.

7.1.3 Cost analysis

Workshop participants used a baseline figure of $900 per tonne (equivalent to US$600 per tonne) to estimate cost reduction. This analysis is different to other chapters as no modelling was done; instead, the cost reduction estimates were applied directly to the baseline cost to yield the figures below. The original percentage reductions can be seen in Table 7.2. The future average cost reductions for each technical innovation area are shown in Table 7.3.

Table 7.3: Cost reductions for direct air capture technical innovation areas.

Technical innovation area	Cost reduction from baseline ($ per tonne)	Cost ($ per tonne)
Baseline cost	0	900
Materials	–243	657
Energy supply	–72	828
Process and equipment	–306	694

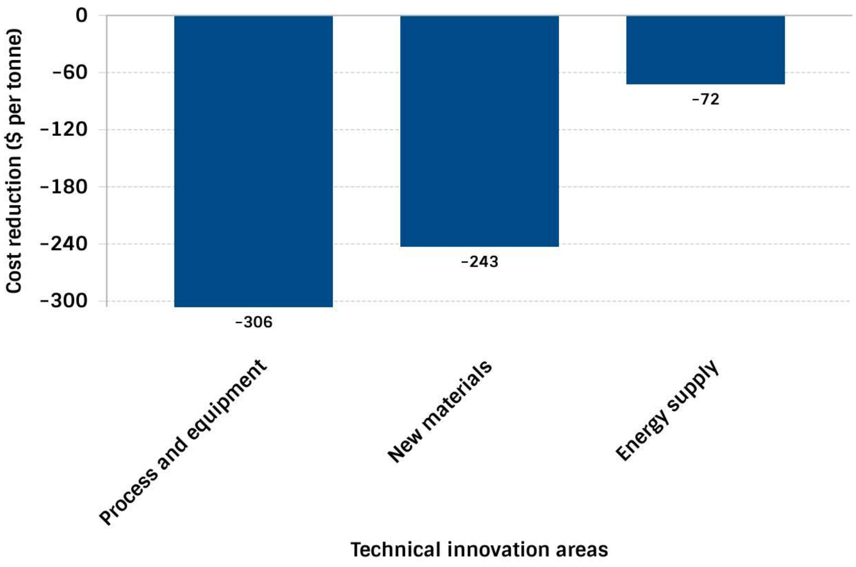

Figure 7-2: Bar graph of cost reductions for direct air capture technical innovation areas.

From Figure 7.2 and Table 7.3 above, innovations in process and equipment were estimated to have the most significant effect (cost reduction of $306 per t CO_2), followed by innovations in materials (cost reduction of $243 per t CO_2). Innovations with energy supply had the least impact on cost (cost reduction of $72 per t CO_2). In total, an average cost reduction of $621 per t CO_2 was deemed cumulatively feasible through the three innovation areas, equivalent to a 69% reduction. Note that the cost reductions described above are not necessarily additive, as there will be dependencies and feedback with the implementations.

7.1.4 Cost reduction, maturity and scale

Figure 7-3 summarises the outputs of the workshop on one chart. The x-axis represents the year of maturity, the y-axis the cost reduction per tonne of CO_2 sequestration, and the size of the bubble represents the scaling factor.

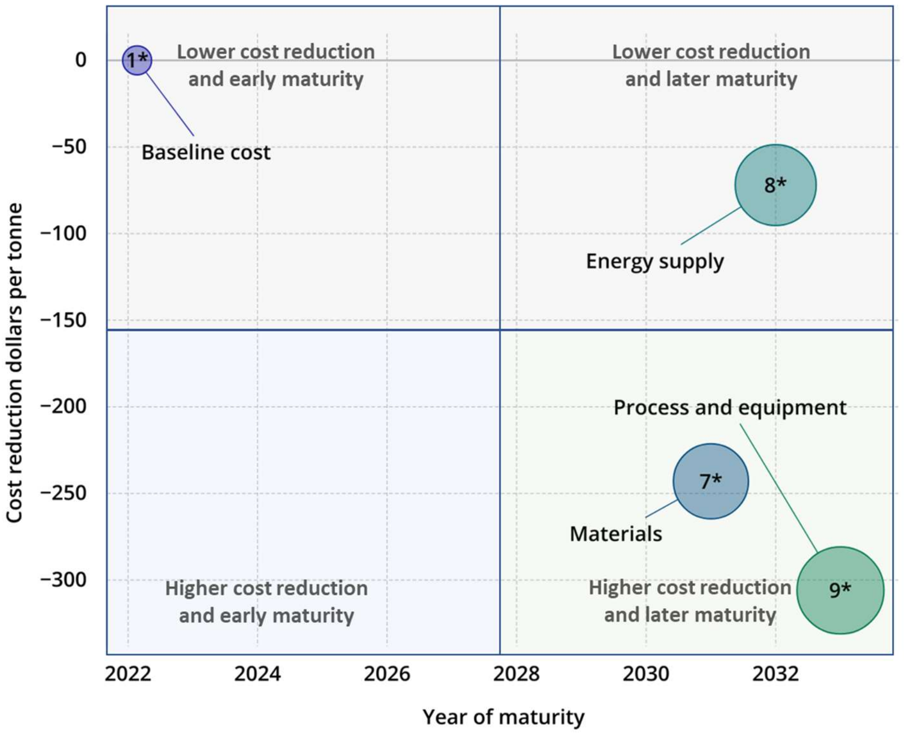

Figure 7-3: Comparison of technology cost reduction, year of maturity and scaling factor for direct air capture technical innovation areas.

7.1.5 Sensitivity analysis of cash flow model

The assessment of global direct air capture potential provides a sensitivity analysis for a model used for estimating costs for different configurations of direct air capture facilities (IEAGHG 2021). Figure 7-4 is adapted from figure 12 on page 18 of the IEAGHG (2021) report and is a sensitivity analysis for the major cost drivers for a direct Nth-of-a-kind hybrid solid sorbent system with a 1 Mt per year capacity.

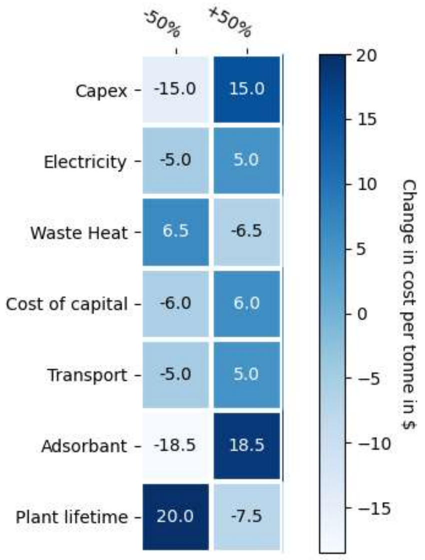

Figure 7-4: Sensitivity of sequestration costs to relative changes in different cost drivers, adapted from global assessment of direct air capture costs based on sensitivity of 1 Mt CO_2 per year capacity Nth-of-a-

kind hybrid solid sorbent system costs ($ per t CO_2 net). Capex = capital expenditure. Adapted from IEAGHG (2021).

The sensitivities reported in Figure 7-4 are expected to differ slightly for other configurations of DAC technologies and in locations where the cost drivers are different. However, these figures are indicative and can be used to derive general conclusions. Extending the lifetime of a plant has the greatest potential to reduce project lifetime costs, followed by lowering the cost of the materials (adsorbent) and then the cost of the initial establishment (capital expenditure).

7.1.6 Assumption and limitations of the analysis

The modelling for cost reduction was based on the averages determined from the experts' input, which showed a wide range of opinions on the achievable cost reductions for each technology innovation area. The average cost reduction was deemed representative, but this can only be considered indicative and does not represent a consensus opinion.

7.2 Analysis of implementation steps

The results in this section were obtained by asking workshop participants to attempt to define the steps required for the implementation of the technical innovations. The participants were asked to provide cost estimates, but due to time limitations, these were not captured. The cost of the steps warrants further investigation, though some of the steps are a wish list and not grounded. The outputs have been reviewed and grouped, with some analysis of the feasibility of the steps.

7.2.1 Materials

The innovations in materials for CO_2 capture are broad, ranging from materials that are more robust in the DAC operation, materials that release CO_2 at relatively low temperatures, which enables the use of waste heat, and materials that require a lower heat input for the release of the CO_2. The capture materials also need to be low cost and their supply chains secure.

7.2.2 Energy supply

Innovation in the energy supply would enable the use of low-carbon energy sources to operate the DAC process. Variable renewable energy requires storage to increase capacity factors where integrating a DAC unit with the energy supply could benefit as CO_2 could be stored with the capture agent and regenerated at a time when energy was available at lowest cost. Other benefits might be derived from integration with other sequestration options.

7.2.3 Process and equipment

Innovations in process and equipment would result in DAC unit designs and components that are easy to mass produce, transport and install on location. The process and equipment design needs to enable low-energy operation. Apart from the unit design, the overall spatial design of a large-scale DAC plant needs to be optimised for the best system performance.

7.3 Discussion

The key messages from the direct air capture workshop are summarised below:

- Analysis of workshop participants' inputs indicated that average overall cost reductions of 69% are anticipated through technology innovation and scale-up. There was considerable variation in the individual responses.
- Two of the innovation areas identified (materials and process and equipment) were considered most effective in reducing the DAC cost and should be pursued to achieve optimum performance.
- Achievement of these cost reductions is anticipated in the early 2030s.

7.4 References

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8 Savanna fire management

8.1 Background and methodology

The Climate Change Authority requested a 2–4-page synthesis derived from consultation with subject matter experts on two topics. The two topics identified for the review were:

- the opportunity for remotely sensed fire severity to remove the need for an early dry season/late dry season cut-off date
- improved provision of fire risk information to inform prescribed burn planning.

Consulted for this synthesis were the following scientists recommended by the Climate Change Authority :

- Dr Shaun Levick, CSIRO, https://people.csiro.au/L/S/Shaun-Levick
- Dr Anna Richards, CSIRO, https://people.csiro.au/R/A/Anna-Richards
- Dr Garry Cook, CSIRO, https://people.csiro.au/C/G/Garry-Cook
- Dr Andrew Sullivan, CSIRO, https://people.csiro.au/S/A/Andrew-Sullivan
- Dr Adam Liedloff, CSIRO, https://people.csiro.au/L/A/Adam-Liedloff

The consultation consisted of an extended question and answer session, commentary on notes and recommended literature to consider for the topics of concern. Parties were invited to review the content.

8.2 Remotely sensed fire severity to remove the need for an early dry season/late dry season cut-off date

The 'Savanna fire management – emissions avoidance method' (DCCEEW 2022) defines the late dry season start date as 1 August and the end date as 31 December. The 1 August cut-off date is used for the division of areas burnt into early and late dry season fires, which are then included in SavBAT[4] to compare the area burnt in each period to a baseline period and thereafter estimate emissions avoidance.

There is high agreement among those consulted and also from the literature that this cut-off date could be improved or replaced with a more appropriate measure.

Fire severity in the tropical savanna is strongly driven by rainfall in the preceding months and fuel availability and temperature at the time of the fire (strong agreement, strong evidence) (Beringer et al. 2015; Williams et al. 1998, 2009).

There is high agreement that fire severity increases in the late season, and that early-season fires may be patchier than late-season fires (Price et al. 2003; Williams et al. 2003; Murphy and Russell-Smith 2010).

Northern Territory government climate analysis shows that northern Australia is already experiencing the impact of climate change, showing warmer temperatures, a wetter December to

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[4] SavBAT Savanna Burning Abatement Tool (environment.gov.au)

February period and drier June to August period, and an increased number of days with high fire danger (NESP Earth Systems and Climate Change Hub 2020). The latter implies that we may see an earlier cut-off to the fire season, in July rather than 1 August, as outlined in the Savanna fire management methodology. However, climate change effects on the timing and amount of rainfall in the longer term are uncertain (Whetton et al, 2016).

In addition to climate-induced increases in fire severity, the spread of invasive grasses such as gamba grass (*Andropogon gayanus*) and Mission grass (*Cenchrus* spp.) will increase fine fuel loads (up to four-fold) and hence fire intensity where it has invaded (Rossiter-Rachor et al. 2008). The phenology of gamba grass means that it stays greener longer into the dry season and cures later than native grasses (Rossiter-Rachor et al. 2009; Setterfield et al. 2013).

The impacts of a changing climate described above and the effect of vegetation composition on curing (noting that these weeds described make areas where they occur ineligible for carbon projects under the ACCU scheme) suggest that a cut-off based on vegetation curing rather than a hard date is desirable. Ideally, the severity of a burn (and thus its greenhouse gas consequences) would not be linked to whether it occurred before or after 1 August but to the local site fuel and weather conditions (at the time of fire and in preceding weeks/months), the change that is imparted on the vegetation, and the gasses released.

Fire behaviour can also be manipulated using different ignition patterns to reduce overall intensity and emissions (Queensland Government 2013). Use of judiciously spaced point ignitions on a grid (such as incendiaries from a helicopter) can consume fuel without creating high-intensity flames – basically, each fire completes its build-up phase from ignition just as it runs into its neighbour and then goes out. This way, you avoid having a large propagating fire that can become high intensity. This would be useful for late-season ignitions required for gamba grass, for example, which does not cure until late in the season.

Fire extent and severity mapping in northern Australia could be greatly improved through a more robust analysis of Sentinel-2 and Sentinel-1 time series data (Grivei et al. 2020; Gaveau et al. 2021), using machine learning approaches (Belenguer-Plomerm et al. 2019; Zhang et al. 2021) to examine trends in spectral indices rather than thresholds. The use of C- and L-band synthetic aperture radar, which is not impeded in its capability by cloud, can help overcome limitations from optical sensors due to cloud (Phillip and Levick 2020). Fire patchiness can be determined by combining different remote sensing products (e.g. Sentinel, Landsat and MODIS/VIIRS) and mapped pyrodiversity (Williamson et al. 2022). This was not possible when the savanna burning methodology was first developed, but we now have the satellite and datacube infrastructure to accomplish these tasks. Synthetic aperture radar and passive microwave observation can estimate water content within vegetation, matched with hyperspectral sensing, and may be able to form the basis of remote sensing of vegetation curing (how green the fuel is, Owe et al. 2001; Liu et al. 2011). Additional investment would be required to set up an operational system to utilise these approaches.

The best prospect for assessing the burnt area, patchiness of burns and potential curing status of vegetation is to combine complementary datasets of various spatial, temporal and radiometric differences (Levick et al. 2018; Abdi et al. 2022). Further research is required over a range of spatial scales and across a broader spectrum of fire regime conditions before automated products can be developed.

8.3 Improved provision of fire risk information to inform prescribed burn planning

The agreed unifying framework for patterns of fire regime in Australia is the Bradstock ‘four switches’ model (Bradstock 2010). In this model, variations in area burned and fire frequency result from differences in the rates of ‘switching’ of biomass growth, availability to burn, fire weather and ignition. To a large extent, fire risk intensity in tropical savannas is seasonal, with early dry season fires being of low intensity (<1000 kW per m) and late dry season fires being up to a magnitude higher in intensity (Beringer et al. 2015). The principal difference is rate of fuel consumption and fire continuity. Late-season fires are characterised by higher fuel levels and higher temperatures.

The current practice is to use the Australian Fire Danger Rating System, which identifies eight fuel types across the country. The relevant model for tropical savanna is the Australian Fire Danger Rating System Grassy Woodland Model, which is based on the CSIRO Grassland Fire Spread Model (Bureau of Meteorology 2022). In this model, strong drivers of fire risk (severity and rate of spread) are fuel load, wind speed, degree of grass curing and dead fuel moisture content, which is determined by air temperature and humidity. The model applies to three pasture states: natural, grazed and eaten out. The grassland layer strongly influences fire behaviour based on observations that grass structure, height and continuity strongly influence grassfire propagation.

The veracity and fidelity of this new system in predicting fire danger for northern Australia is unknown and will take time to determine, particularly for early and late season conditions and for regions affected by exotic grass species such as gamba and Buffel. The Australian Fire Danger Rating System will likely undergo extensive refinement and updating to improve its applicability across the continent, but much of the initial focus of this work is likely to be in the populated south rather than the north.

There are no data available on the accuracy of this system, but a recent analysis of the M~~a~~cArthur Fire Danger rating system shows no relationship between elevated fire danger classes and burned area (Shah et al. 2023). This result is not to say that the models do not predict fire intensity and rate of spread well, rather that fire weather does not correlate well with burned area (Preisler et al. 2008).

8.4 Conclusion

There is high agreement the 1 August cut-off date for early/late dry season could be replaced with a more appropriate measure by combining different remote sensing products and using machine learning.

What is needed is:

- further research over a range of spatial scales and across a broad spectrum of fire conditions
- investment to set up an operational system
- combination of complementary datasets of various spatial, temporal and radiometric differences for assessing the burnt area, patchiness of burns and potential curing status of vegetation.

Fire risk information has undergone a recent transformation with the implementation of the Australian Fire Danger Rating System.

- The veracity and fidelity of this new system in predicting fire danger for northern Australia is unknown and will take time to determine, particularly for early and late season conditions and regions affected by exotic grass species such as gamba and Buffel.
- Good data for the north needs to be acquired for this task.

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9 Combined biomass/biochar

The combined biomass/biochar workshop was held on 2 March 2023 with 10 participants. The workshop focused on a process flow requiring biomass as an input, and generating electricity, syngas and char/biochar by a pyrolysis process as outputs. A key challenge for this workshop was the breadth of activities covering both biomass for bioenergy and biomass for production of char/biochar. The multiple process flows encompassed in this breadth meant that the initial part of the workshop was dedicated to ensuring participants had a common understanding of the concepts, terms and the scope of the system under consideration. Appendix C.1.4 includes a complete list of participants. Participants explored five technical innovations during the workshop. The current quantity of carbon sequestration from pyrolysis biochar is approximately 0.01 Mt per year at $80–$120 per tonne (Fitch et al. 2022, p. 160).

9.1 Workshop results

9.1.1 Technology list

Table **9.1** presents the technical innovation opportunities identified, and a brief definition of the opportunities explored for cost reduction. Note that the specifics of the technical innovation areas were not discussed or agreed to during the workshop and are the authors' definitions.

Table 9.1**: Technical innovation opportunities for carbon sequestration through biomass/biochar.**

Technical innovation area	Description	Cost reduction area
Technology at scale	Innovations that enable technology implementation at scale, generally requiring larger plant. A larger plant means more than 1000 tonnes per year biochar plant.	Decreases the cost of char by improving the efficiency of production.
Biochar conversion	Lower-cost methods of biochar conversion result in lower costs per tonne to land users.	Lower costs of operating the plant.
Transportation	Lower cost transportation for both transport of feedstocks and products such as syngas.	Lower costs of feedstock by reducing transport costs.
Pre-processing of feed for pyrolysis	Different feedstocks have different requirements for pre-processing (e.g. drying or pelletising). Innovation that reduces costs of pre-processing.	Lower overall cost of feedstock.
Emission calculation and standards	Net Green House and other emissions associated with the process, calculation and reporting protocols, standards etc.	Emission and calculation standards.
Syngas to liquid form	Converting syngas to a readily transportable form (liquid).	Allows for plant location in regional areas, close to biomass sources, potentially lowering biomass cost and increasing revenue from by-product production.
Large-scale modular plants	Hub of plants for biomass processing and pyrolysis for biochar at significant volume.	Lowers costs of producing char, as well as making regional production hub costs economically viable.

Inventory of high-quality biomass	Production of maps and types of high-quality biomass availability. Answers the question of what biomass is available where.	Supports the pre-evaluation and financing of char production plants, perhaps lowering the cost of establishing a char production plant.
Utilisation cases	Identification of biochar utilisation cases where carbon will be locked up and generate demand and provide value.	Increases demand for biochar.
Guidelines	Guidelines on choosing and making the 'right' biochar.	Increases efficiency of production and increase demand.
Quantifying additional value or avoided emissions in Australian landscapes of biochar application	The panel felt that there was value in better quantifying the avoided emissions and other agricultural benefits of the application of biochar to the land.	Increases demand for biochar.

Participants chose to add technology themes during the first round of the workshop. The themes added were:

- syngas to liquid form
- guidelines on choosing/making the right biochar
- additional value generated by application to soil to enhance productivity.
- Industry roadmap

9.1.2 Workshop outputs

The most significant innovations were determined by voting to be:

- technology at scale (7 votes)
- utilisation cases (5 votes)
- guidelines (4 votes)
- large-scale modular plants (3 votes)
- emission calculation and standards (2 votes)
- transportation, syngas to liquid form and roadmap (all 1 vote).
- biochar conversion (0 votes)

The workshop continuum results are summarised in Table 9.2 below. To help interpret the results, please see the definitions in section 3.6.

Table 9.2: Summary of outputs from the biomass/biochar workshop.

Technical innovation area	Cost reduction (%)			Maturity (Year)			Scaling factor			Investment required ($ billion)		
	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
Technology at scale	38.8	20	65	2029	2026	2032	67	6	110	1	1	1
Large-scale modular plants	48.2	29	62	2032	2030	2037	54	4.4	100	1.05	0.8	1.2

Utilisation cases	49	69	100	2033	2030	2035	10.5	7.4	12	0.66	0.1	1.14
Biochar conversion	54.5	50	65	2028	2027	2030	10	10	10	0.9	0.5	1.1
Guidelines	31.7	17	50	2027	2027	2029	10	10	10	0.03	0.01	0.06

The average cost factors vary from 31 to 54%, with significant variation. For example, technology at scale cost reduction estimates range from 20 to 65%, with an average of 39% compared to current costs. Similarly, the estimates vary with maturity timeframes but are generally more consistent than the cost reduction factors. Most of the maturity estimates are less than 10 years.

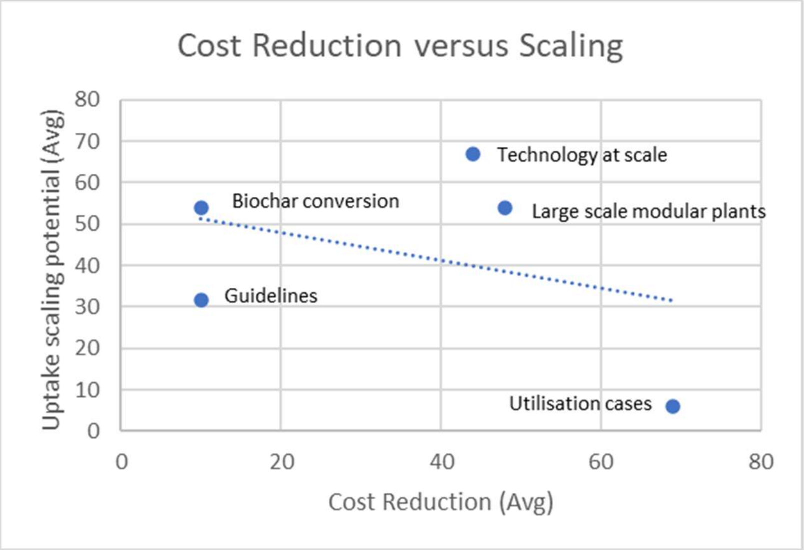

Figure 9-1: Plot of average cost reduction percentages versus scaling factor for biomass/biochar technical innovation areas.

There is no clear trend between the scaling factor and cost reduction (Figure 9-1). This may an artefact of how the workshop was run, possibly relating to insufficient time for participants to reach consensus.

9.1.3 Cost reduction analysis

Combined biomass/biochar sequestration cost areas or drivers

The following cost and revenue categories were defined in preparation for the cost modelling:

- **Establishment**: costs of establishing the technology at a location, plant equipment and construction.
- **Operations:** ongoing maintenance costs, maintenance and labour.
- **Transport:** costs of transporting feedstock to pyrolysis plant.
- **Feedstocks:** costs of feedstock.
- **Yield:** the conversion efficiency of converting feedstock to char (tonnes of feedstock per tonne of char).
- **Revenue:** revenue obtained from selling the char produced, electricity and gas co-produced, and carbon credits.

The workshop cost factors were then assigned to the cost areas defined above and presented in Table 9.3. Where the technical innovation areas do not change any of the cost of revenue areas, the cell in the table is left blank.

Table 9.3: Cost reduction factors for biomass/biochar technical innovation areas. All factors are percentage reductions (costs) or increases (revenues) relative to current costs.

Technical innovation area	Costs			Revenues
	Establishment (%)	Operations (%)	Transport (%)	Biochar price (%)
Technology at scale	–39	39	–	–
Large-scale modular plants	–48	–	–48	–
Utilisation cases	–	–	–	49
Biochar conversion	–	–55%	–	–
Guidelines	–	–	–	32

Where a cost reduction factor can reduce several cost reduction areas, it is applied to all applicable areas. For example, technology at scale has the potential to lower both the establishment and operational costs of projects.

Cost model

The outputs from the biomass/biochar workshop are translated into comparable results using a simplified cash flow model to determine changes to NPV and the cost per tonne of sequestration for an indicative project. The model allows the partitioning of costs to cost areas (as defined above), allowing cost reductions to be applied selectively to the relevant cost area and for the lifetime cost reductions (in this case, over 25 years) to be converted to NPVs.

There are many possible feedstock and process flows that can lead to production of char/biochar and bioenergy. For the purpose of this report, a medium-sized biochar production system located in NSW with a feedstock of sawmill residue was modelled. It is not possible to model all possibilities and having an indicative scenario allows the cost reductions and cost sensitivities to be determined.

The hypothetical biochar production system is a medium sized (1 MWh) slow-pyrolysis system with fixed bed twin-fire pyrolyser. We assume this type of system because:(1) its medium size means that there is likely sufficient feedstock to run the system in several Australian regions; and (2) Homagain et al. (2016) used this type of system for their economic assessment of biochar production in Canada, providing some cost data for this analysis. We assume that the biochar produced is applied into agricultural fields.

Rajabi Hamedani et al. (2019) provide the following inventory for 1 tonne of biochar obtained via willow pyrolysis and applied into fields. Note, in our analysis we assume that woodchips from sawmill residue log rather than willow woodchips are used as a feedstock and assume that the pyrolysis requirements are the the same.

- Inputs: willow woodchips 3.73 t; heat (pyrolysis) 1.92 GJ
- Outputs: biochar 1 t; syngas (SO_2 0.015 kg; NO_x 0.2 kg)
- Avoided products: natural gas 0.37 t; electricity 1.01 GJ; N fertiliser 0.66 kg; K fertiliser 0.13 kg; P fertiliser 0.1 kg
- Avoided emissions from the application of 1 t of biochar into fields: 2.2 t CO_2 and 2.6 kg N_20, which combine for total avoided emissions of 2.975 t CO2-e

We assume that the production plant will be operational for 25 years (Homagain et al. 2016) and will have 7000 working hours per year (Rajabi Hamedani et al. 2019). As such, the plant produces

13,125 tonnes of biochar per year, which requires 48,956 tonnes of sawmill residue log per year as feedstock. Based on NSW sawmill residues data,[5] there are several regions in NSW that have over 50,000 tonnes of sawmill residue log within a few hundred kilometres of a hypothetical production plant.

We assume that the production system starts with the purchase and transportation of the feedstock to the plant and ends with the production of biochar, which is then stored on site. That is, we exclude the sale and transportation of biochar and its co-products (fertilisers, SO_2, NO_x) from the model, as the feasibility and costs of selling these products in different regions are unknown.

Full details of the model used are described in Appendix D.

Cost analysis

The results of the modelling are listed in Table 9.4. The cost reductions are the difference in cost in $ per tonne compared to the baseline.

Table 9.4: Cost reductions for biomass/biochar technical innovation areas.

Technical innovation area	Cost reduction from baseline ($ per tonne)	Net cost ($ per tonne)
Baseline cost	0	60
Technology at scale	–10.2	49
Large-scale modular plants	–14.7	45
Utilisation cases	0	60
Biochar conversion	–11	48
Guidelines	0	60

From the modelling, the baseline cost was determined to be $60 per tonne. This compares well to the estimate provided in the phase 1 report of $80 to $120 per tonne (Fitch et al. 2022, p. 160), noting that the modelled scenario is for a plant producing approximately 13,000 tonnes of biochar per year, which is similar in magnitude to the current national production.

The innovation area with the greatest potential to lower the cost of carbon sequestration over the life of a project is large-scale modular plants, with a cost reduction of $14.70 per tonne compared to the baseline, followed by biochar conversion methods, with a cost reduction of $11 per tonne (Figure 9-2). Utilisation cases and guidelines were modelled as having benefits to the demand for char/biochar, so there was no effect on cost reduction.

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[5] https://spatial.industry.nsw.gov.au/arcgis/rest/services/Bioenergy_Assessment/Forestry_SawmillResidues/MapServer

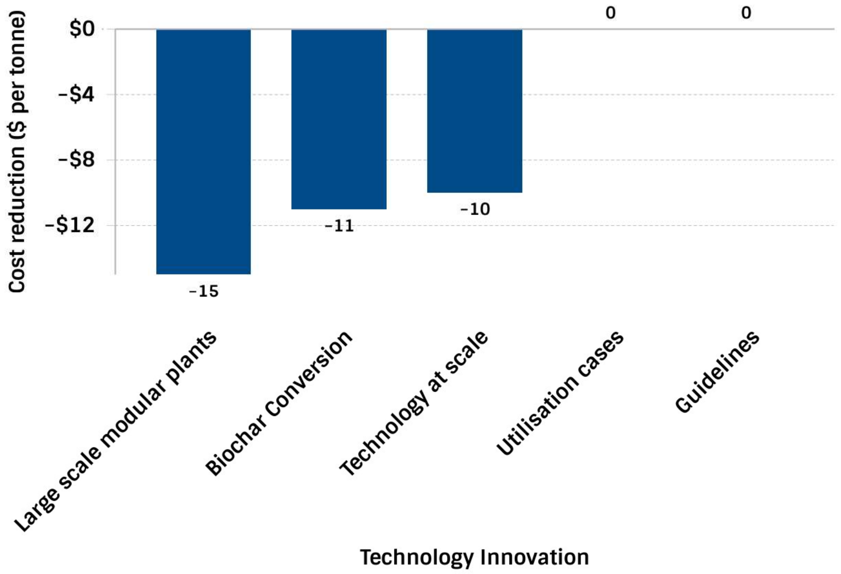

Figure 9-2: Bar graph of cost reductions for biomass/biochar technical innovation areas.

9.1.4 Cost reduction, maturity and scale

Figure 9-3 summarises the outputs of the workshop on one chart. The x-axis represents the year of maturity, the y-axis the cost reduction per tonne of CO_2 sequestration, and the size of the bubble represents the scaling factor. As described in 1.1 the most beneficial innovation are those that mature early with higher scaling factor. Innovation that enable Technology at scale and Large scale modular plants both have good cost reduction potential.

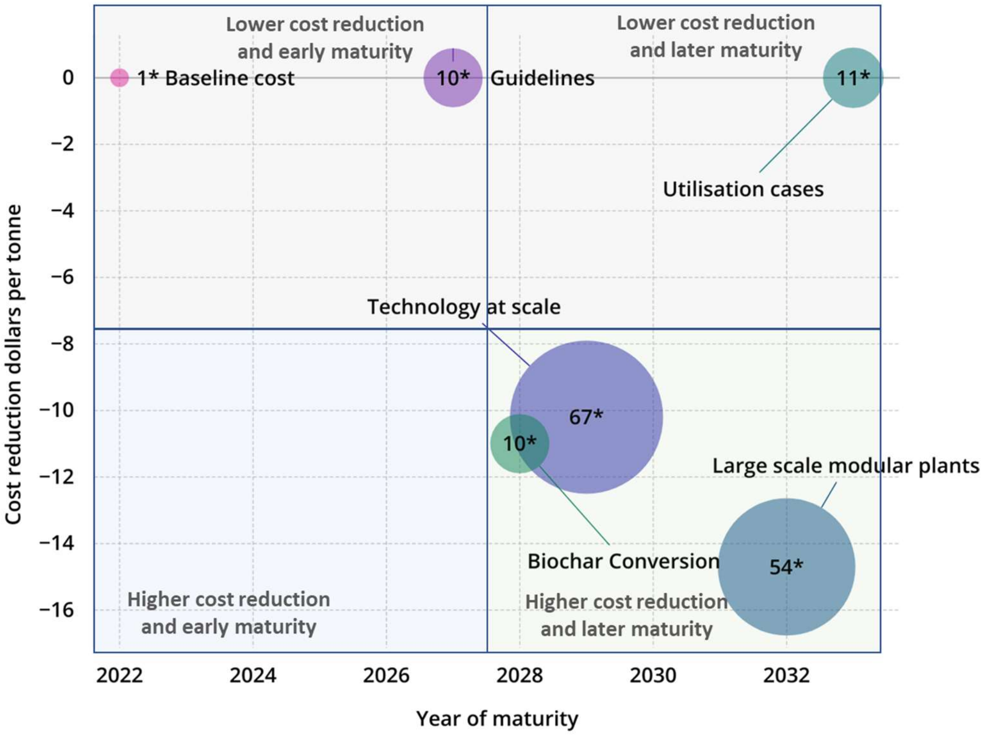

Figure 9-3: Comparison of technology cost reduction, year of maturity and scaling factor for biomass/biochar technical innovation areas.

9.1.5 Sensitivity analysis of cash flow model

The sensitivity analysis presented below identifies those cost areas with the greatest potential to improve economic viability. The results represent pyrolysis/char production systems and are useful in understanding the key opportunities to improve profitability and cost reductions.

In the analysis presented in Figure 9-4, different model cost parameters were varied in four steps relative to the baseline: –10%, –5%, +5% and +10%. The changes to NPV as a percentage of the baseline are presented as a colour-coded heatmap. In addition to the cost areas defined in section 9.1.3, other costs and revenues included in the modelling are:

- electricity: cost of electricity required for pyrolysis
- natural gas: revenue for syngas produced.

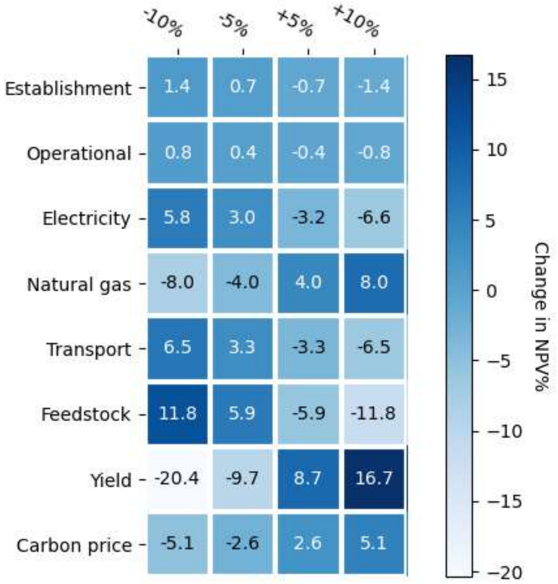

Figure 9-4: Sensitivity analysis of the cash flow model for biomass/biochar sequestration projects.

An interesting outcome of this modelling analysis is that the establishment costs have a relatively small impact on NPV, which is different to planted vegetation where these costs are a significant driver. NPV is most sensitive to changes in yield, that is, feedstock conversion efficiency to char. Feedstock costs, natural gas prices and electricity costs are also significant drivers.

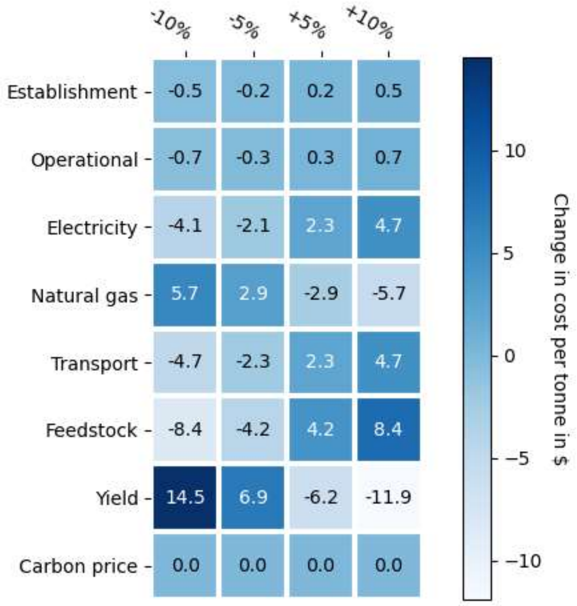

Figure 9-5: Sensitivity analysis of sequestration costs for biomass/biochar sequestration projects.

Regarding cost reduction drivers, conversion yield has the most significant opportunity to reduce costs, followed by feedstock costs. Transport costs are also a driver, with the implication that it is important to select the plant's location such that a suitable supply of low-cost feedstock is proximally available in order to keep transport costs low.

9.1.6 Scaling and maturity analysis

The relative sequestration benefit compares the different technology options to identify the option that generates the greatest additional sequestration at different end years. The method to derive this metric is detailed in 4.2. The relative sequestration benefit is calculated using scaling factors and maturity time frames determined during the workshop.

Table 9.5: Relative sequestration benefit for each biomass/biochar technical innovation area.

Technical innovation area	2030	2035	2040	2050
Technology at scale	1.0	1.0	1.0	1.0
Large-scale modular plants	0.0	0.4	0.6	0.7
Utilisation cases	0.1	0.0	0.1	0.1
Biochar conversion	0.2	0.2	0.2	0.1
Guidelines	0.4	0.2	0.2	0.2

The technology option with the potential to deliver the greatest additional sequestration benefit in all possible end years is technology at scale, followed by large-scale modular plants. The scaling factor (64) and early maturity date (2029) are the drivers.

9.1.7 Assumptions and limitations of the analysis

The modelling used in this section assumes that the production system starts with the purchase and transportation of the feedstock to the plant and ends with the production of biochar, which is then stored on site. That is, we exclude the sale and transportation of biochar and its co-products (fertilisers, SO_2, NO_x) from the model as the feasibility and costs of selling these products in different regions are unknown. NSW is used as an exemplar study region, with results indicative for the national context. The feedstock used is sawmill residue, and a full list of costs and parameters can be seen in Appendix E.3. Like all modelling, it is sensitive to the selection of parameters.

9.2 Analysis of implementation steps

As with previous chapters, this section reviews the implementation steps captured during the workshop.

9.2.1 Technology at scale

The first implementation steps for technology at scale are exemplars or pilots. These steps are relatively straightforward to implement and were rated very easy to easy. The investment required is $10–25 million. Two scaling hurdles were identified: the need to convert syngas into a liquid form to reduce transport costs and improve the economic viability of the plant, and the scale-up opportunity to convert syngas to hydrogen. These steps are rated as moderate to hard in complexity. Overall, the implementation is rated as moderate.

9.2.2 Large-scale modular plant

Large-scale modular plants require both technological and commercial/financial implementation steps. The implementation steps identified for large-scale modular plants most relate to improving the commercial readiness level through economic studies and commercial-scale demonstrations. Strictly speaking, these implementation steps are outside the scope of the workshop. There are a couple of technical challenges though they were not articulated. These are:

- cost-effective design of a modular plant
- development of cost-effective conversion approaches for syngas to hydrogen and a liquid form suitable for transportation.

9.2.3 Utilisation cases

The utilisation cases aim to grow the market for char and biochar by identifying biochar utilisation cases where carbon will be locked up but provided demand and value. The implementation steps listed varied in difficulty, investment and timeframe. Most implementation steps focused on the idea of building exemplars from field trials to commercial-scale demonstrators. No specific technology steps were identified other than cost-effective design, rated as easy with an investment required of $200,000 to $450 million. Implementation complexity is rated as low.

9.2.4 Biochar conversion

Implementation steps for biochar conversion approaches were not discussed during the workshop.

9.2.5 Guidelines

This area relates to utilisation cases in which guidelines are needed for each utilisation case. Guidelines are required to choose and make the ‘right’ biochar. The implementation steps listed are all rated as easy and range from identifying knowledge gaps to researching to fill those gaps. The need for standards was also raised to ensure that the properties of the product (and therefore the benefits) can be guaranteed. Implementation complexity is rated as low.

9.3 Ranking

Table 9.6: Ranking of technical innovation areas for biomass/biochar carbon sequestration.

Technical innovation area	Cost reduction ($ per tonne)	Scaling and maturity relative benefit (2050)	Implementation complexity	Ranking
Large-scale modular plants	–14.7	0.7	Moderate	1
Technology at scale	–10.2	1.0	Moderate	2
Biochar conversion	–11	0.1	Not discussed	3
Guidelines	0	0.2	Not discussed	4
Utilisation cases	0	0.1	Low	5

The final ranking for technology options is listed above. Although large-scale modular plants have the most significant potential to reduce carbon sequestration costs, technology at scale can potentially deliver the greatest additional sequestration due to the more significant scaling factor.

9.4 Discussion

The four options reviewed during the workshop combine technical and non-technical (mainly financial or economic) aspects. It is not surprising that much of the discussion during the workshop centred on the need for medium- to large-scale demonstrators to facilitate building scale and lowering the costs of production rather than any specific technology needs. Increased scaling can be driven by both reducing costs, and increasing demand for char and biochar. The development of utilisation (use) cases will support market expansion for char products by clarifying the economic viability and co-benefits of early stage investments.

Technical innovation needs or barriers were identified during the workshop but were not explicitly discussed. The need to develop cost-effective approaches to convert syngas to a more readily transportable form, as well as technical innovation to support hydrogen generation, were both identified as needs by the participants. Other needs regarding scaling are related to engineering existing approaches and making the plants more cost-effective. Other technical areas for progress that were identified but not explicitly discussed were determining the optimal location of plants in relation to biomass for feedstock, transport and electrical networks to support distribution and input needs, and decision support for feedstock selection and for optimising the pyrolysis process to produce outputs with the required properties.

Key messages

- All options looked to have the potential to lower costs either through reducing costs or improving the overall economic viability of char production. The cost reductions ranged from $11 to $14.70 per tonne, with large-scale modular plants having the largest cost reduction potential.

- The baseline cost ($60 per tonne) used in this analysis is lower than the $80 to $120 per tonne reported in chapters of Fitch et al. (2022). The lower cost reflects the larger-scale plant used for this analysis (13,000 tonnes per year).
- There was a sentiment during the workshop that most of the technical challenges have been solved (i.e. the industry knows how to produce char) and that the obstacles to scaling the output relate to increasing the commercial readiness level and confidence in economic viability.
- There are opportunities to grow the demand for biochar by better identifying utilisation cases and articulating the co-benefits of use.
- There are specific technical areas identified during the workshop that could aid in lower sequestration costs. These are:
    - cost-effective methods to convert syngas to a more readily transportable product
    - decision support for process optimisation
    - decision support for plant location, including as part of a regional hub.

9.5 References

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Homagain K, Shahi C, Luckai N, Sharma M (2016) Life cycle cost and economic assessment of biochar-based bioenergy production and biochar land application in Northwestern Ontario, Canada. *Forest Ecosystems*, 3:21.

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10 Carbon capture and storage

This chapter reports on the carbon capture and storage (CCS) workshop held on 8 March 2023 with 11 participants from industry, academia and government. Appendix C, section C1., includes a list of workshop participants. This section of the report is different to the other chapters due to some differences with how the workshop proceeded. As for the combined biomass/biochar workshop, considerable time was taken up developing a common language and understanding of the concepts and scope for discussion.

10.1 Workshop differences

The Delphi process is predicated on the assumption that a clear set of propositions can be identified early on, followed by a cycle of voting–discussion–voting. In discussion with the panel of CCS experts, this proved challenging with good cause.

In initial polling, the panel identified three topics as important. These were cheaper CO_2 capture, optimised storage, and hubs (a CCS hub is a central collection or distribution point for CO_2, Global CCS Institute, 2016) . In a later discussion, a panel member argued that the transport of CO_2 should also have been discussed. Accepting this point, the panel identified that improvements were desirable in the main components of the CCS chain – capture, transport, storage and system integration. The subsequent discussion failed to reach a consensus on key topics within these general areas. This was not a failure – rather, it revealed complex interactions that will guide the process going forward. Whenever discussion began to isolate a topic, a typical response from a panel member was to point out, in effect, that ‘context is everything’ and that it made little sense to treat one technology as important in isolation from others.

This reflects the fact that CCS is an industry made of mature components. Most have been used in oil and gas or chemical engineering for a long time. Integrating these components, at a large scale, for the entire CCS chain is a less mature process but far from novel or unproven. Cost reductions in CCS will likely come about by numerous small improvements throughout the processing chain: *it is the execution of large projects that is the key to ‘learning by doing’ and consequent cost reduction.* While breakthrough technologies cannot be ruled out, it is significant, for example, that one promising new component of the CCS chain is nothing more than the development of economically viable transport of CO_2 by ship – scarcely a new technology.

It follows that improvements in CCS may be expected to be incremental (which is not the same as unimportant), to occur throughout the processing chain and to produce relatively modest cost reductions. None of this will occur without executing large projects.

Although large-scale projects will be needed to achieve technological maturity, there are nonetheless narrower technical areas that may be important. The panel debated these at some length, noting forcefully the importance of project context.

The emphasis on learning by doing, context and incremental improvement in costs is reflected in a horizon-scanning exercise undertaken as an IEAGHG study (Orchard et al. 2021). This study projected operational cost reductions by 2040 in the 20–30% range, resulting from a combination of factors, including smarter materials, additive manufacturing, and more effective operations and maintenance, resulting from the use of the Internet of Things, virtual reality and artificial intelligence. However, no breakthrough technologies were identified.

10.2Workshop findings

10.2.1 CO_2 capture

In the Australian context, much CCS will be part of natural gas processing, and the capture technologies are mature. ‘Hard to abate’ emitters, especially steel and cement processing, are a research opportunity. Direct air capture is emerging as an unavoidable technology. Research into capture technologies is an extensive area worldwide. Research and development within Australia, with more modest resources, would need to be focused on solving distinctively Australian problems. An example of a specific problem is the high SO_2 level in Australian coal-fired power flue gas, a consequence more of regulations than chemistry.

10.2.2 Optimised storage

Optimised storage is a good example of context being everything. Optimised with respect to what? Any actual project will have many constraints and multiple objectives. There are opportunities for the much narrower objectives of improving injectivity and sweep (and hence attainable storage capacity). However, ‘capacity’ itself is a context-dependent concept: a project may only need to store what can feasibly be captured. If current storage methods can achieve that, no improvements are required. Likewise, monitoring and verification of storage could conceivably be improved, but the objectives are diverse – lower cost, more social acceptance or greater sensitivity are potential objectives among many.

10.2.3 CO_2 hubs

By connecting multiple sources with multiple sinks, hubs reduce operational risks by adding redundancy and giving economies of scale for infrastructure. The development of hubs is at an early stage, but international examples are already progressing. Hubs are clear examples of system-level improvement involving developments and enhancements across the entire CCS chain. They are public-good infrastructures that must be initiated, designed and built with strong leadership from governments at all levels.

Finally, while ‘institutional factors’ were out of scope for this workshop, they are inseparable from the consideration of large CCS projects and especially hubs. Accepting that the primary need is for ‘learning by doing’ means that large projects need to be facilitated by governments both financially and institutionally. This would include matters such as sustained and consistent policy objectives, stable carbon pricing and trading, and a well understood and predictable regulatory framework for CCS. These are not more important than technology, but they are as essential.

10.2.4 Indicative costs

Several think tanks (e.g. the International Energy Agency and the Clean Air Task Force, among others) have provided estimates of the costs per tonne of CO_2 at which various types of CCS could break even financially. These are costs for Nth-of-a-kind projects and presume incremental improvement. This is the expectation for a mature technology (see Orchard et al. 2021). These estimates focus on capture, which (apart from the nature of the source) is less affected by contingent factors. Transport and storage will depend more strongly on local conditions, mainly the distance to a suitable storage site. The key message is that capture costs can vary widely, depending on the source. Within the USA, many types of projects will become viable now that the US$85/tonne tax credit is in force. The longevity of this crediting arrangement is important as it extends to projects commenced by 2033. This certainty is extremely important for project developers, especially as permitting delays are feared to be considerable. In Europe, CO_2 prices have risen to 100 Euro/tonne but are very volatile; hence, there is a risk premium that increases the carbon price at which project developers will embark on CCS.

10.3 References

Global CCS Institute 2016, The Global Status of CCS. Special Report: Understanding Industrial CCS Hubs and Clusters, Melbourne, Australia.

Orchard K, Simon R, Durusut E, Neades S, Kemper J (2021) 'Value of emerging and enabling technologies in reducing costs, risks and timescales for CCS,' 15th International Conference on Greenhouse Gas Control Technologies, GHGT-15 proceedings.

11 Mineral carbonation

This chapter outlines the activities and outcomes of the mineral carbonation workshop, which was held on 5 April 2023 with 14 participants. Appendix C, C.1.6, includes a full list of workshop participants. Section 3 presents the detailed workshop methodology.

Mineral carbonation is a term used to describe the formation of stable carbonate minerals by the reaction of CO_2 with divalent alkaline earth metal cations. Mineral carbonation reactions occur very slowly in nature as a part of the rock weathering cycle. These reactions can be 'engineered' or accelerated by injecting CO_2 into mafic or ultramafic rock formations, combining concentrated CO_2 with crushed silicate materials or ultramafic tailings, or by applying crushed silicate rock on soil to passively interact with atmospheric CO_2. Considering Australia's unique geology, engineered mineral carbonation is an emerging CO_2 sequestration method with great potential, which requires further research and technology innovation to be fully realised.

The aim of the mineral carbonation workshop was to understand how technological innovation in pre-determined areas of mineral carbonation can lead to a reduction in the cost per tonne of abatement delivered and provide an indication of the timeframe in which these cost reductions will occur. A diverse selection of global and national stakeholders in both ex-situ and in-situ mineral carbonation from across industry, government and academia were invited to participate in the workshop.

The workshop was split into two themes: ex-situ mineral carbonation and in-situ mineral carbonation. In this context, ex-situ mineral carbonation refers to engineered reactions that take place above ground or outside naturally occurring geological formations (e.g. crushed rock). In-situ mineral carbonation refers to engineered reactions that take place underground or within geological formations in their original location (e.g. bedrock).

The participants were asked to answer two pre-workshop questions in the context of either ex-situ or in-situ mineral carbonation:

1. Please list up to five technological innovation areas that you think will drive cost reduction and increase scalability of carbon abatement using this sequestration approach?
2. In your opinion, what are the key barriers to successful implementation and uptake of this sequestration approach?

Eighty percent of participants responded to the pre-workshop survey. Their responses were summarised into five key technology innovation areas, which are presented in the following section.

11.1Workshop results

11.1.1 Technology list

Table 11.1 and Table 11.2 present the technical innovation opportunities collated during the workshop, together with a brief definition of the opportunity. Note that the specifics of the technical innovation areas were not discussed or agreed to during the workshop and are the authors' definitions.

Table 11.1: Technical innovation opportunities for carbon sequestration through ex-situ mineral carbonation.

Technical innovation area	Description	Cost reduction area
Characterisation of feedstock	A consistent supply of material/feedstock with high mineral carbonation potential will increase return-on-investment due to overall efficiency from high rates of carbonation; this needs to be balanced against the volumes available, and the opportunity for continuous flowsheet operation can also contribute towards reducing overall operating costs.	Comminution/particle size reduction: by avoiding or reducing processing of unwanted material. Energy consumption: reactive materials can be treated under less intense conditions. Capital/operating: as a default by achieving the above points.
Feedstock/mineral pre-treatment	Pre-treatment refers to novel mining, crushing or milling, metal recovery, and heat activation. Particle size plays a crucial role in determining the rate and extent of carbonation, but milling minerals is highly energy intensive. Some hydrometallurgical flowsheets employ ultra-fine grinding in seeking higher value metal extraction, but it is also well known that different grinding techniques can be more energy efficient or produce narrower size distributions. Exploring and possibly even developing novel low-energy technologies, and further novel mining technologies, for mineral pre-treatment (including heat treatment for engineered mineral carbonation) and grinding may have scope to increase the efficiency of the mineral carbonation process.	Comminution/particle size reduction: by avoiding the need for any grinding (or overgrinding) with tailings solids. Reductions in heat treatment costs.
Catalyst/additive development for enhancing mineral carbonation kinetics	Aside from the particle size effect, the rate of reaction between CO_2 and minerals in surficial carbonation (i.e. silicate rock or tailings applied to land) is impacted by the surface chemistry, which can be influenced to advantage by pre-treatment with catalysts or other additives. Innovations in this area can also improve the reaction rate for more engineered approaches to the leaching of magnesium, moderating required temperatures and pressures to make the process more economical. Innovations in lixiviants (chemicals used to extract or dissolve elements from an ore or concentrate) may also be significant. The potential for some to be recycled gives scope for cost reduction through reduced waste treatment.	Energy: reactive phases can be treated under less aggressive conditions. Throughput: more carbon captured, and higher quality CO_2. Reagent consumption and waste treatment: if lixiviants recycled or green.
Creating high-value end products	Developing innovative materials from carbonates. Some research has been done on using carbonates or silica generated from mineral carbonation to create building materials. However, further innovation is needed in this area to improve the economic viability of mineral carbonation as a Carbon Capture Utilisation and Storage (CCUS) process and promote circular economy principles.	Offsetting of process costs. Reduction of long-term storage/rehabilitation costs/levies.

Table 11.2: Technical innovation opportunities for carbon sequestration through in-situ mineral carbonation.

Technical innovation area	Description	Cost reduction area

In-situ mineral carbonation mapping	Offshore storage can unlock the large-scale potential of this technology. These sites have the potential to offer greater storage capacity and reduced risks associated with storage leakage.	Facilitate industrial scale deployments that could decrease the overall cost per tonne of injected CO_2. Cost of injection if the storage site has a good injectivity rating. Cost of CO_2 fluid transport if the storage site is near emission sources. Cost of carbon capture if CO_2 sources are near the injection site.
Innovations that enable use of seawater	Large volumes of water are required for this technology. Given that seawater is more abundant and readily available than freshwater, developing effective techniques for using seawater rather than freshwater or low salinity waters from aquifers would save operational costs while greatly expanding the large-scale potential of this technology.	Costs of water supply and transport.
Understanding the kinetics to improve the efficiency	Identification of the kinetics, optimum conditions and mineralogy composition for mineral carbonation can save operational costs and increase the scale.	Could increase the scale which could reduce the net cost per tonne of CO_2 injected.
Optimisation of injection strategy and patterns	To save operational costs and improve the scale, injection fluid and strategy can be optimised. Furthermore, well placement and patterns are important for injectivity and not over-pressurising the reservoir.	Injection cost reduction.
Fractures characterisation	Fractures are the conduits for fluid to flow and for mineral carbonation to occur. They provide the surface area for the minerals to react with the injected fluid. If the fractures are not well connected and dense enough, operational costs and large-scale applications of this technology will be severely impacted. As such, characterising the fractures and their connectivity for any potential storage site is essential. Even within a reservoir with the right mineralogy composition, pressure and temperature conditions, a well-connected and dense fracture network is necessary for the reservoir to function as an optimal site for operation.	Injection cost and monitoring cost reductions.

The voting results for the technology themes are outlined in Table 11.3. For ex-situ mineral carbonation, three technical innovation areas were prioritised. For in-situ mineral carbonation, two technical innovation areas were prioritised. Five key technical innovation areas across both themes were assessed as priorities using the Delphi continuum method.

Table 11.3: Voting results for the mineral carbonation technical innovation areas. The technical innovation areas with the highest votes for each theme are shown in bold font. These areas were assessed as a priority in the workshop.

Theme	Technical innovation area	Votes
Ex-Situ	**Characterisation of feedstock**	**5**
	Feedstock/mineral pre-treatment	3
	Catalyst/additive development for enhancing mineral carbonation kinetics	**5**
	Creating high-value end products	**6**
In-Situ	In-situ mineral carbonation mapping	3
	Innovations that enable use of seawater	3
	Understanding the kinetics to improve the efficiency	**6**

	Optimisation of injection strategy and patterns	**5**
	Fractures characterisation	3

11.1.2 Workshop outputs

The workshop results for the technology innovation areas are summarised in Table 11.4. To help interpret the results, please see the definition of terms in section 3.6.

Table 11.4: Summary of outputs from the mineral carbonation workshop. The prioritised in-situ and ex-situ technical innovation areas are shown in bold. Note: fractures characterisation was not included in the workshop.

Technical innovation area	Cost reduction (%)			Maturity (Year)			Scaling factor (%)			Investment required ($ million)		
	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max
Characterisation of feedstock (ex-situ)	39	16	100	2031	2027	2035	1471	15	10000	398	200	590
Feedstock/mineral pre-treatment (ex-situ)	58	30	100	2033	2029	2035	4035	40	15000	350	150	550
Catalyst/additive development for enhancing mineral carbonation kinetics (ex-situ)	40	10	50	2034	2030	2036	231	15	520	633	400	1000
Creating high-value end products (ex-situ)	72	15	100	2033	2028	2038	3667	50	10000	650	400	900
In-situ mineral carbonation mapping (in-situ)	53	50	60	2035	2034	2035	99	95	100	250	200	300
Innovations that enable use of seawater (in-situ)	38.6	20	50	2033.8	2030	2035	7.2	5	10	165	50	250
Understanding the kinetics to improve the efficiency (in-situ)	14	10	20	2033	2031	2035	38	1	65	52	30	75
Optimisation of injection strategy and patterns (in-situ)	46	25	75	2031	2028	2033	25	10	50	128	45	240

The average cost reduction potential was plotted against the average uptake scaling potential (Figure 11-1). If the technology has a significant cost reduction factor, it would be reasonable to expect that the scaling factor would similarly be high. Conversely, if the cost reduction factor was relatively low, expecting a low scaling factor would be reasonable.

For ex-situ mineral carbonation (Figure 11-1A), the technical innovation areas are moderately correlated ($R^2 = 0.72$). However, the correlation is weak for in-situ technical innovation areas ($R^2 = 0.16$; Figure 11-1B). This is likely an artefact of the workshop; therefore, the results should be interpreted with care. This could be due to insufficient time to work through to a consensus or lack of a consensus process to compare scaling factors to cost reduction.

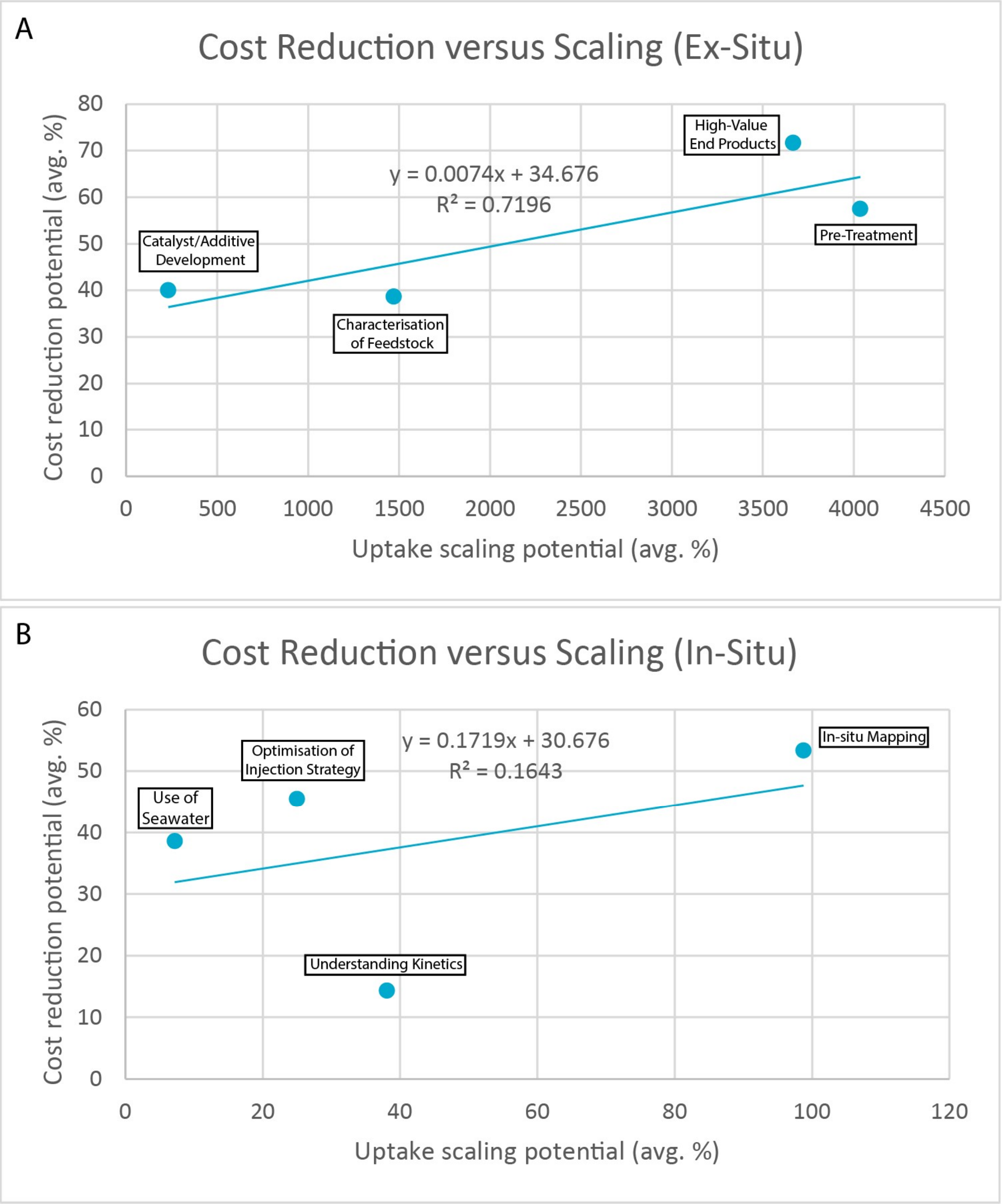

Figure 11-1: Plot of average cost reduction percentages versus scaling factor for (A) ex-situ and (B) in-situ mineral carbonation technical innovation areas. Both datasets have a positive association ($R^2 > 0$). Ex-situ data are moderately correlated ($R^2 = 0.72$); in-situ data are weakly correlated ($R^2 = 0.16$).

11.1.3 Cost analysis

The input baseline costs for the cost model and analysis were estimated from cost reports in the available literature. For ex-situ mineral carbonation, cost data were limited. The baseline cost estimate of US$150 per tonne was taken from IEAGHG (2022). For in-situ mineral carbonation, the baseline cost estimate of US$25 (AUD$37)[6] per tonne was averaged from cost estimates provided by Kelemen et al. (2019). These baseline cost estimates were presented to and agreed on by the workshop participants at the beginning of the workshop.

Therefore, for the cost model and analysis, we will apply the cost reductions directly from the baseline of:

- US$150 (AUD$222) per tonne, for ex-situ mineral carbonation
- US$25 (AUD$37) per tonne, for in-situ mineral carbonation.

The results of the modelling are listed in Table 11.5. The cost reductions are the difference in cost per tonne (in AUD) compared to the baseline.

Table 11.5: Cost reductions for mineral carbonation technical innovation areas.

Technical innovation area	Cost reduction from baseline ($ per tonne)	Net cost ($ per tonne)
Baseline cost(Ex-situ)	0	222
Characterisation of feedstock	–86	136
Feedstock/mineral pre-treatment	–128	94
Catalyst/additive development for enhancing mineral carbonation kinetics	–89	133
Creating high-value end products	–159	63
Baseline cost(In-situ)	0	37
In-situ mineral carbonation mapping	–20	17
Innovations that enable use of seawater	–14	23
Understanding the kinetics to improve the efficiency	–5	32
Optimisation of injection strategy and patterns	–17	20

The innovation areas with the greatest potential to lower the cost of sequestration over the life of a project are:

- Ex-situ: creating high value end products, with a reduction of $159 from the baseline of $222 per tonne (72%), for a net cost of $63 per tonne.
- In-situ: mineral carbonation mapping, with a reduction of $20 from the baseline of $37 per tonne (53%), for a net cost of $17 per tonne.

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[6] Exchange rate of $.67 USD to AUD.

All cost reductions are presented below as bar charts (Figure 11-2 and Figure 11-3). For ex-situ mineral carbonation, the cost reduction potential ranges between 38 and 72%, with an average of 52% per tonne. For in-situ mineral carbonation, the cost reduction potential ranges between 13 and 54%, with an average of 38% per tonne.

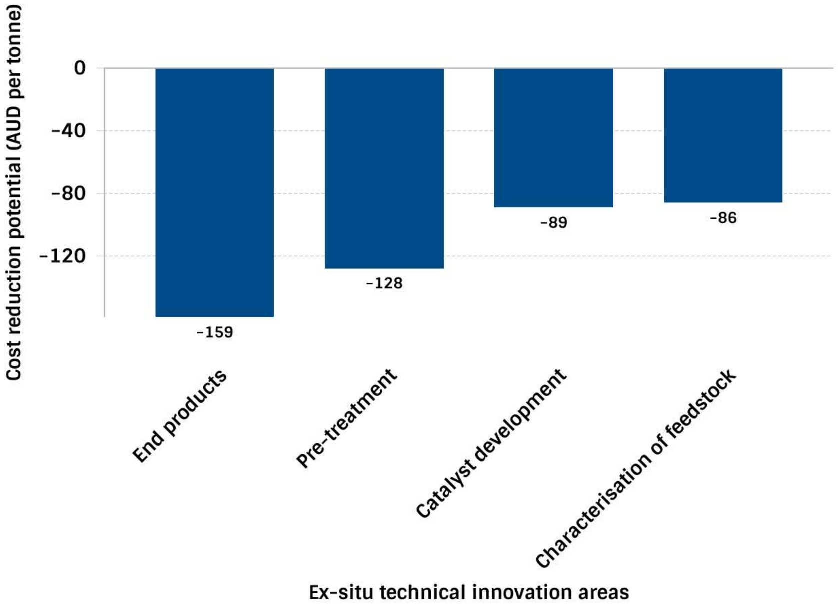


Figure 11-2: Bar graph of cost reductions for ex-situ mineral carbonation technology innovation areas. The cost reductions are from a baseline of $222 per tonne.

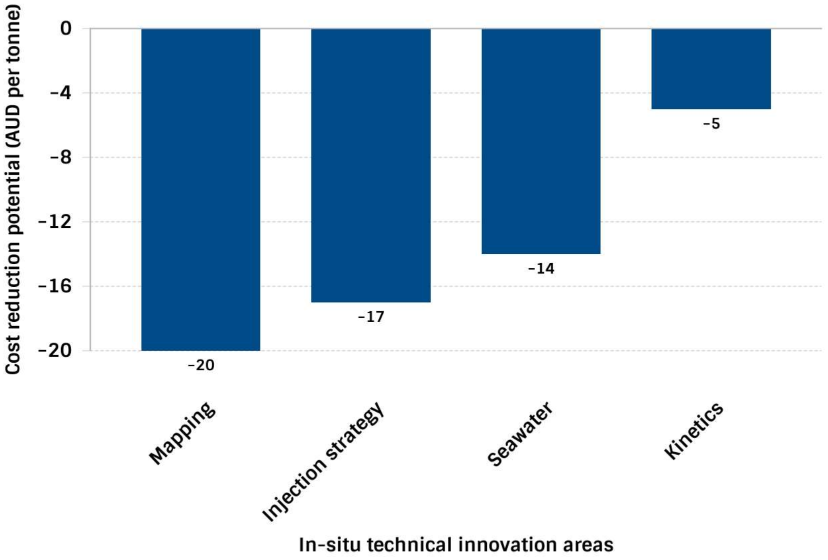


Figure 11-3: Bar graph of cost reductions for in-situ mineral carbonation technology innovation areas. The cost reductions are from a baseline of $37 per tonne.

11.1.4 Cost reduction, maturity and scale

To allow a comparison between technology innovation areas by ex-situ and in-situ technologies, Figure 11-4 and Figure 11-5 summarise the outputs from the workshop. The x-axis represents the year of maturity, the y-axis the cost reduction per tonne of carbon sequestration, and the bubble size represents the scaling factor. The most viable technologies are those that reach maturity early (see section 4.1) and have a large scaling factor (bubble size).

For ex-situ mineral carbonation, advances in feedstock and creating high-value end products will have the greatest impact in terms of cost reduction per tonne and overall scalability in the next decade. For in-situ mineral carbonation, the greatest impact is likely to come from accurate mapping of in-situ carbonation sites, despite the timeline for reaching full maturity.

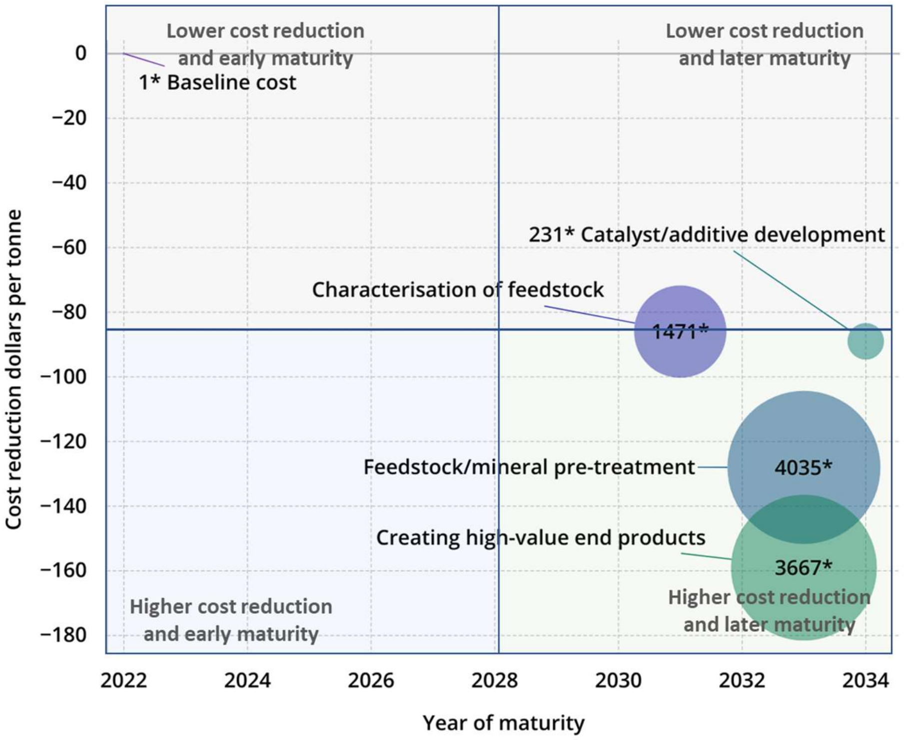


Figure 11-4: Comparison of technology cost reduction, year of maturity and scaling factor for ex-situ mineral carbonation.

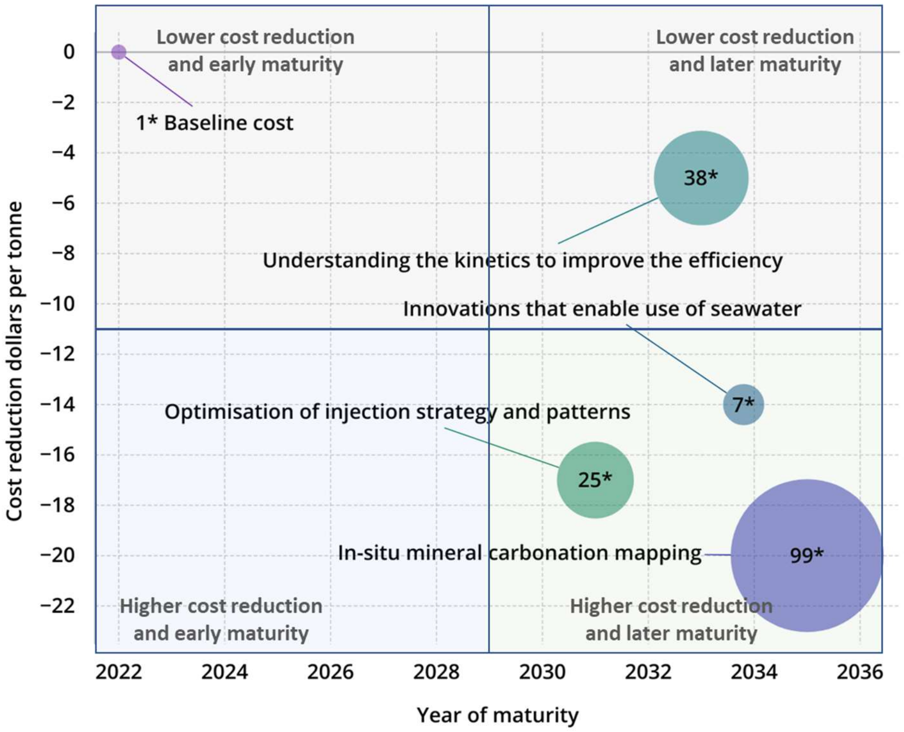


Figure 11-5: Comparison of technology cost reduction, year of maturity and scaling factor for in-situ mineral carbonation.

11.1.5 Scaling and maturity analysis

The relative sequestration benefit compares the different technology options to identify the option that generates the greatest additional sequestration at different end years. The relative sequestration benefit is calculated using scaling factors and maturity time frames determined during the workshop. Section 4.2 has more detail on this approach.

The greatest sequestration generated by 2050 is for feedstock/mineral pre-treatment (value of 1), and the other technology options are scaled relative to that. Characterisation of feedstocks would generate nearly half (0.4) as much additional sequestration by 2050 compared to feedstock pre-treatment.

Table 11.6: Relative sequestration benefit of each ex-situ mineral carbonation technical innovation area.

Technical innovation area	2030	2035	2040	2050
Characterisation of feedstocks	1.0	0.7	0.5	0.4
Feedstock/mineral pre-treatment	0.7	1.0	1.0	1.0
Catalyst additive development	0.1	0.1	0.1	0.1
Creating high-value end products	0.7	1.0	0.9	0.9

Table 11.7: Relative sequestration benefit of each in-situ mineral carbonation technical innovation area.

Technical innovation area	2030	2035	2040	2050
In-situ mineral carbonation mapping	0.9	1.0	1.0	1.0
Innovations that enable use of seawater	0.2	0.1	0.1	0.1
Understanding the kinetics to improve the efficiency	0.8	0.7	0.5	0.4
Optimisation of injection strategy and patterns	1.0	0.7	0.4	0.3

11.1.6 Assumptions and limitations of the analysis

This study included the assumption that the baseline cost of ex-situ mineral carbonation is consistent across all areas (i.e. ex-situ carbonation of mine tailings, ex-situ application of silicate rock to land, or ex-situ carbonation of industrial waste streams). Therefore, variations on the baseline costs are highly likely.

11.2 Discussion

While innovation within all identified technical innovation areas will reduce the cost per tonne of CO_2 sequestered, at the current rate of investment in mineral carbonation research and development, the most impactful outcomes will not reach maturity for at least a decade. The delay in realising the more significant cost reduction outcomes puts industry adoption and investment into Australian-owned mineral carbonation technologies and methodologies at risk. International carbon crediting methodologies for the voluntary market are currently available (e.g. enhanced rock weathering methodologies), and are likely to form part of Australia's emerging enhanced rock weathering industry.

International investment in such initiatives and the small number of initiatives existing nationally (i.e. BHP Nickel West, MCi Carbon, and Boral Limited) indicate the potential of mineral carbonation as a (Carbon Dioxide Removal (CDR) technique (Fitch et al. 2022). Further, an opportunity exists for the development of technology and Monitoring, Reporting and verification (MRV) methodologies. International Organization for Standardization–certified methodologies for mineral carbonation CDR techniques are currently limited. The design of future methodologies around MRV for CDR (and storage) are critical. They may have an impact on the cost reduction and uptake scaling potential for mineral carbonation techniques if they are highly complex and time intensive. Accessible and cost-effective methodologies will promote uptake of mineral carbonation techniques and proponents of future emissions reduction funds or other carbon crediting schemes. Additionally, consideration of scope 4 emissions (avoided emissions) is also important; validation of emissions that reduce CO_2 intensity in supply chains (beyond CO_2 storage) currently does not exist. Further, recognising industrial integration and novel business models that champion Environmental, Social and Governance (ESG) criteria in this area is important.

Environmental and health and safety considerations (and mitigation) will play an important role in mineral carbonation methodology development and pilot deployments. An example of risk mitigation within ex-situ carbonation relates to tailings. During mineral/tailings dissolution (or partial dissolution) to solubilise magnesium, there is little understanding about what occurs in the process liquor after the reaction of magnesium to form a product or about what residues remain. In some cases, it is possible that the mass of the starting minerals/tailings is significantly reduced but changes in particle size or residue phase may lead to a net increase in the residue volume.

Leaching of magnesium can also liberate other metals that may be toxic or have other downstream implications. Consideration, therefore, needs to be given as to whether the mineral carbonation process may create a new problem, which may in turn introduce additional costs.

Conversely, with improved feedstock characterisation, some of these risks will be mitigated or removed entirely. Exploring new feedstock options from industrial waste streams may expand the capability of engineered ex-situ mineral carbonation methods. Expanding existing feedstock options to include novel feedstocks from industrial waste streams in Australia may significantly increase the cost reduction potential for this mineral carbonation technique. Industrial waste streams might include steel slags or incinerator bottom ash. The addition of new feedstocks and waste streams may see the scale of the product market become much larger than existing markets; the exact intent of these product markets needs additional work.

Mapping mafic and ultramafic units for in-situ mineral carbonation will require detailed characterisation of the host rocks with careful and ongoing monitoring to manage and mitigate risks (Fitch et al. 2022). Monitoring and risk mitigation requirements of offshore in-situ carbonation remain poorly elucidated.

Finally, the lack of a globally agreed list of definitions for each area of mineral carbonation remains an ongoing challenge; an opportunity exists to develop these guidelines. While it is easier for people working in mineral carbonation to understand what commonly used terms mean in each context, this is not always the case for non-subject matter experts.

11.3 References

Fitch P, Battaglia M, Lenton A, Feron P, Gao L, Mei Y, Hortle A, Macdonald L, Pearce M, Occhipinti S, Roxburgh S, Steven A (2022) *Australia's carbon sequestration potential: a stocktake and analysis of sequestration technologies*, CSIRO, Canberra.

IEAGHG (2022) *Mineral carbonation using mine tailings – a strategic overview of potential and opportunities.* IEAGHG Technical Report 2022-10, July 2022, IEA Greenhouse Gas R&D Programme, Cheltenham, UK

Kelemen P, Benson SM, Pilorgé H, Psarras P, Wilcox J (2019) An overview of the status and challenges of CO_2 storage in minerals and geological formations. *Frontiers in Climate*, 1:9.

Appendix

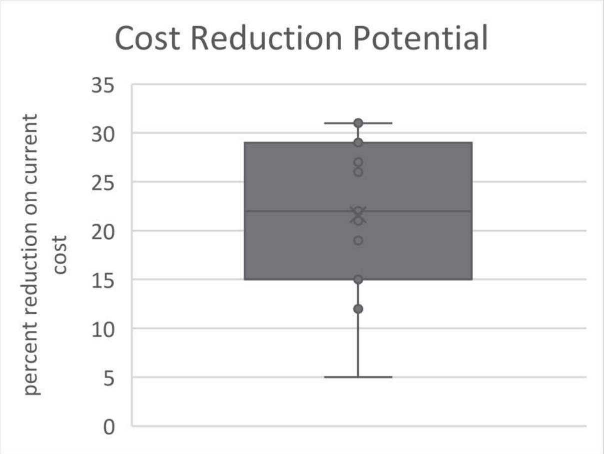
Appendix A Workshop outputs

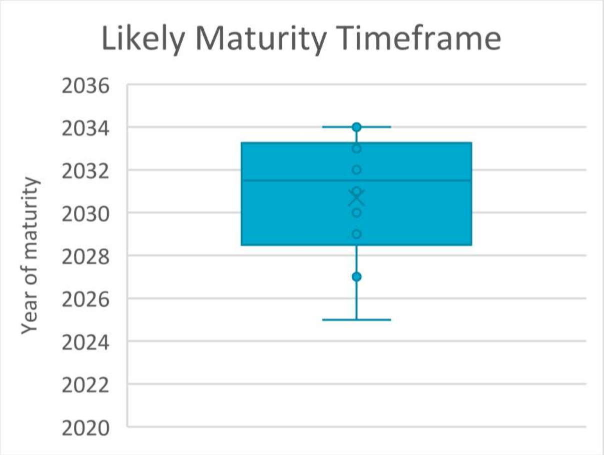
This section contains digitised outputs from the workshops. No analysis has been done; it is simply a translation from the Miro board to box and whisker plots for the numerical results and tables for the implementation steps.

A.1 Workshop results

A.1.1 Planted vegetation workshop

Low-cost imagery





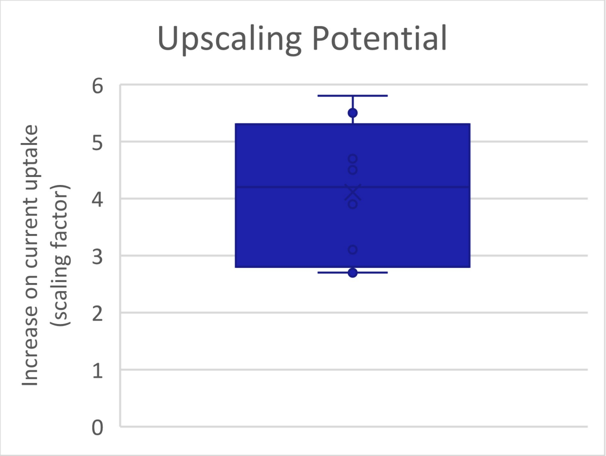


Figure A1.1: Translated Miro results for low-cost imagery.

Table A1.1: Implementation steps for low-cost imagery.

Technology implementation steps		
Timeframe	**Difficulty**	**Implementation step**
2025–2030	Very easy	Field calibration/validation for remote sensed data
2025–2030	Easy	High resolution optical CubeSats
2025–2030	Easy	High altitude autonomous drones with updated MSS packages or LEO satellites
2030–2035	Easy	Multispectral sensors to species ID calibration AI/ML
2030–2035	Easy	Easy-to-understand tools related to spatial monitoring
2025–2030	Moderate	Price accessibility to existing technologies
2025–2030	Moderate	LiDAR everything, everywhere, all the time
2025–2030	Moderate	Models correlating indicator/data collected to question
2030–2035	Moderate	Improved vegetation recognition for Australian species
2030–2035	Moderate	Improved resolution (spatial and spectral) wall-to-wall high frequency imagery = Planet labs, but at 50 cm
2035–2040	Moderate	LiDAR-done fleet/network for calibration/validation
2025–2030	Somewhat hard	NASA NISAR mission (L-band SAR at 10 m)
2030–2035	Somewhat hard	High altitude drone/dirigible-based LiDAR with 1 m resolution
2025–2030	Hard	Australia-wide publicly available LiDAR mission
2030–2035	Hard	GEDI follow-on mission (wall-to-wall spaceborne LiDAR at 25 m)
2040–2045	Hard	Space based LiDAR with 1 m resolution

Zero or low emission fuels

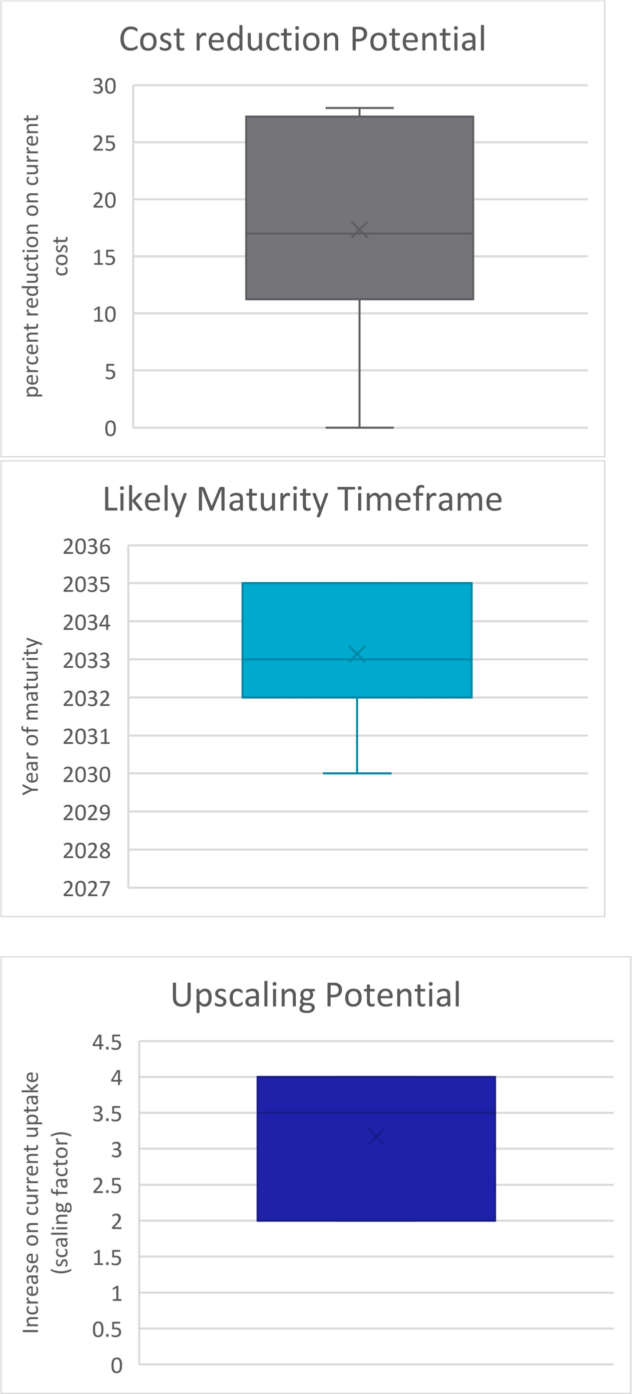


Figure A1.2: Translated Miro results for zero or low emission fuels.

Table A1.2: Implementation steps for low emission fuels.

Technology implementation steps		
Timeframe	**Difficulty**	**Implementation step**
2025–2030	Very easy	Industry buy-in
2025–2030	Easy	Low or zero emissions biofuels can be available from regional agroforestry
2025–2030	Moderate	Regional co-op investment in low emission fleets (vehicles, drones, other agricultural equipment)
2035–2040	Moderate	Fossil fuel equipment lifecycle/replacement cycle/sunk cost

2040–2045	Somewhat hard	More efficient and safer batteries
2025–2030	Hard	Better policy

Small-scale equipment for agroforestry

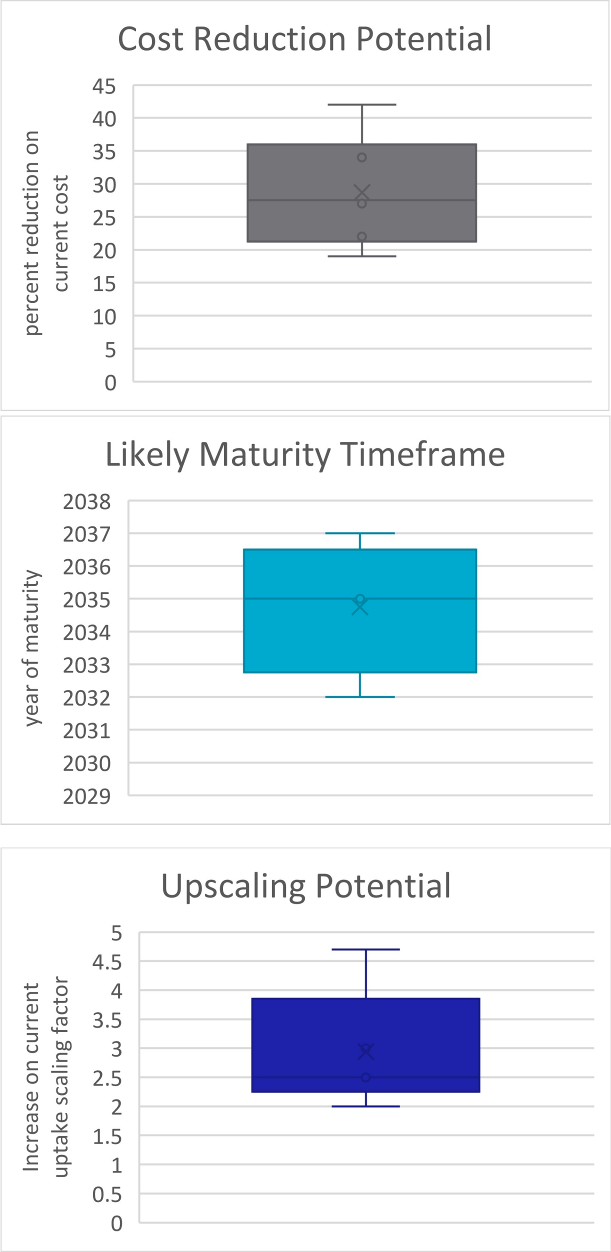


Figure A1.3: Translated Miro results for small-scale equipment for agroforestry.

Table A1.3: Implementation steps for small-scale equipment for agroforestry.

Technology implementation steps		
Timeframe	**Difficulty**	**Implementation step**
2025–2030	Moderate	Incentives for operators to deploy a crew with potential to harvest small-scale plantings

2025–2030	Somewhat hard	Case studies including costs and benefits, so that people feel comfortable to invest
2030–2035	Easy	Aggregation of biomass can be facilitated by farm-based harvesting
2030–2035	Moderate	Open-source hardware/equipment sharing/lease models

Pests and diseases

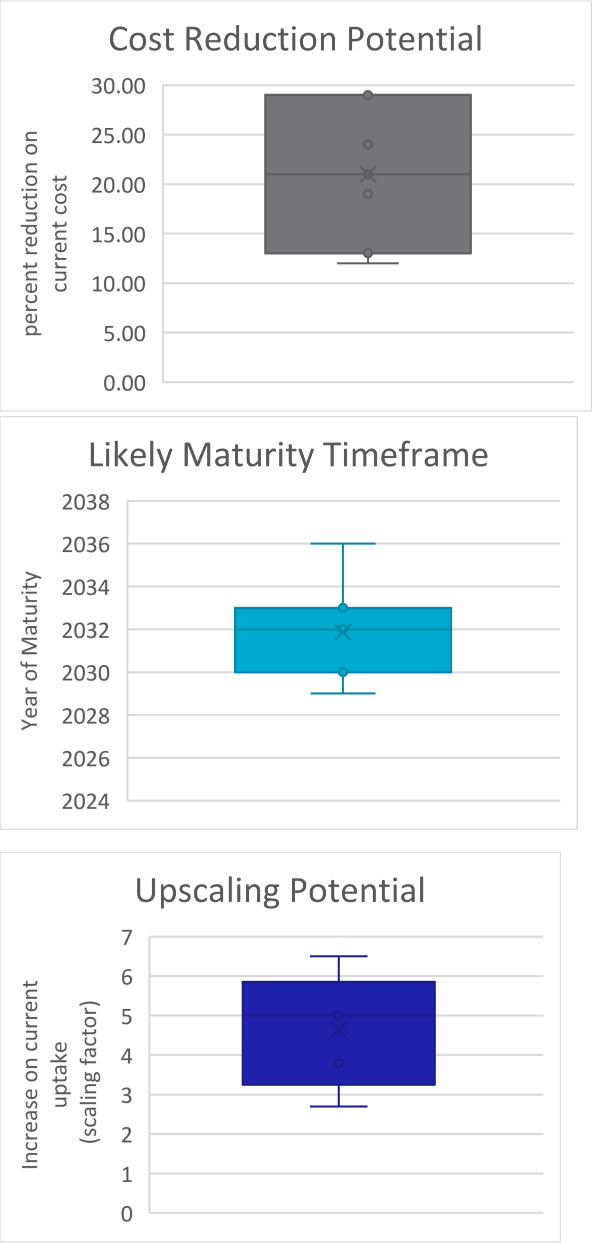


Figure A1.4: Translated Miro results for pests and diseases.

Table A1.4: Implementation steps for pests and diseases.

Technology implementation steps		
Timeframe	**Difficulty**	**Implementation steps**
2025–2030	Very easy	Single line electric wire with solar

2025–2030	Very easy	In the Western Australian wheatbelt it is rare to fence out sheep or pests, but in the south some sheep fencing is required
2025–2030	Moderate	Plant breeding for browsing resistance
2030–2035	Moderate	Plant breeding for pest resistance

Decision support for informing optimal species selection

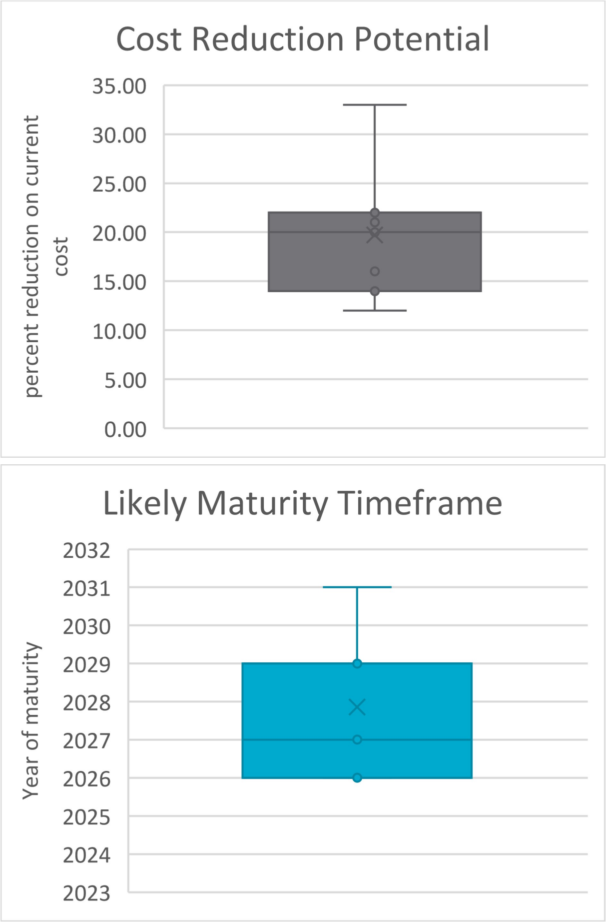


Figure A1.5: Translated Miro results for decision support for informing optimal species selection.

Table A1.5: Implementation steps for decision support for informing optimal species selection.

Technology implementation steps		
Timeframe	**Difficulty**	**Implementation steps**
2025–2030	Very easy	Detailed case studies, including outcomes and impacts
2030–2035	Very easy	Cal/Val carbon growth forecast tools
2025–2030	Easy	Local species allometric database
2025–2030	Easy	Improved understanding of water trade-offs to placate water authorities planning processes
2025–2030	Easy	Sharing of allometric datasets
2025–2030	Easy	Soil carbon/biomass metrics

2025–2030	Moderate	Comprehensive spreadsheets providing key information on economics and risks
2030–2035	Moderate	Detailed local species databases with allometry for each species

Lower-cost fencing

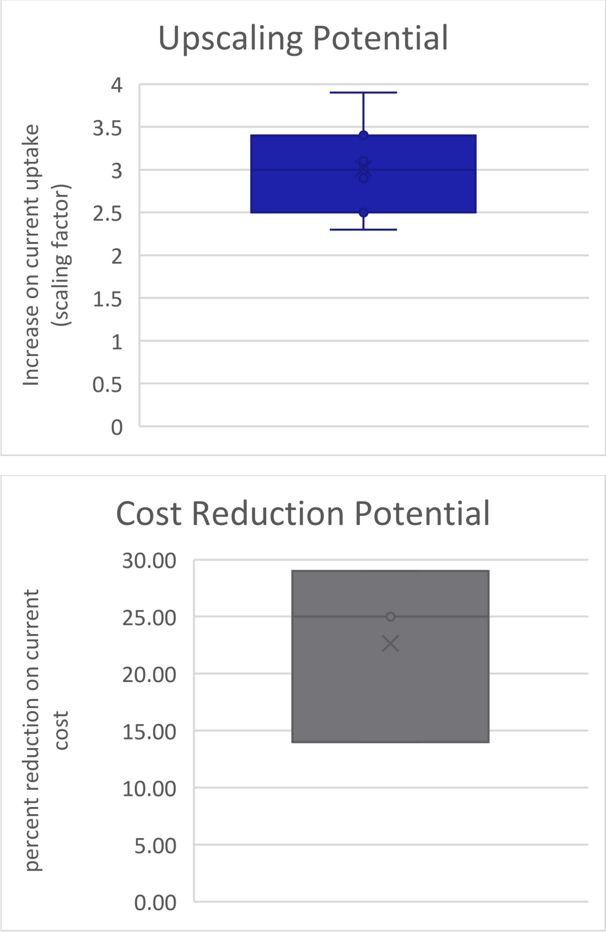


Figure A1.6: Translated Miro results for low-cost fencing.

Table A1.6: Implementation steps for low-cost fencing.

Technology implementation steps		
Timeframe	**Difficulty**	**Implementation steps**
2030–2035	Very easy	Species-specific animal control technology

Genetic improvement

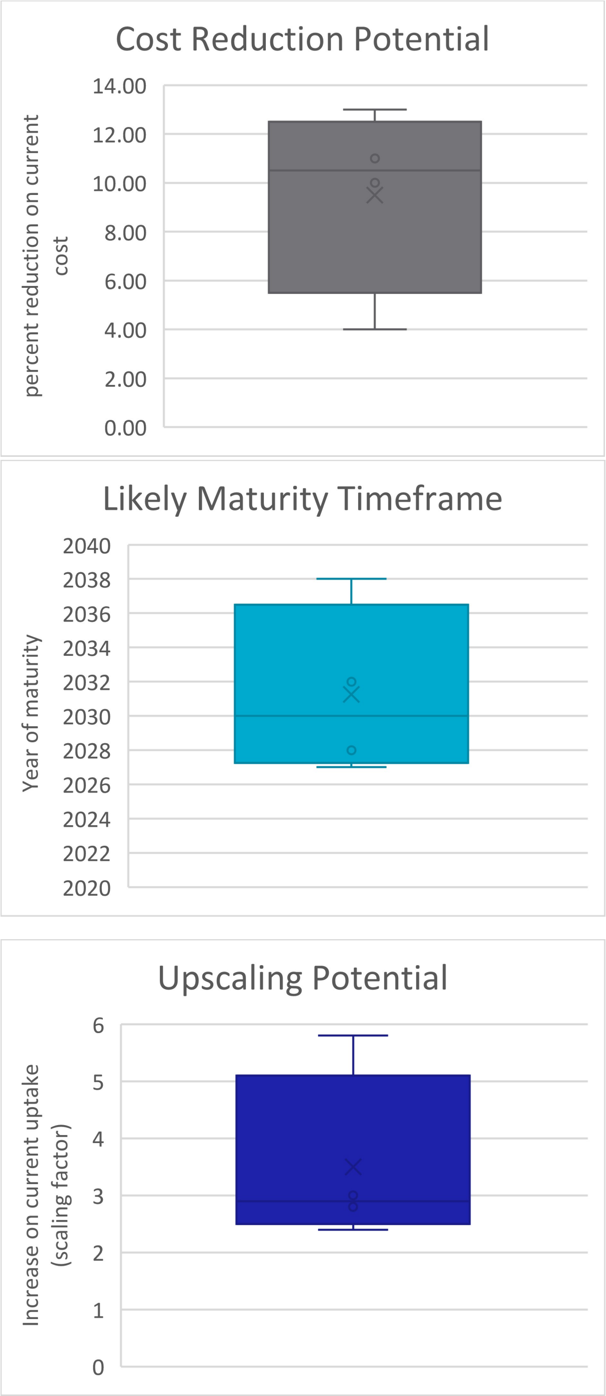


Figure A1.7: Translated Miro results for genetic improvements.

Table A1.7: Implementation steps for genetic improvements.

Technology implementation steps		
Timeframe	**Difficulty**	**Implementation steps**
2030–2035	Very easy	For some leaf area limit (environmental limit) can breed for taller trees and thicker stems, i.e. more biomass (carbon sequestration) and more timber
2030–2035	Somewhat hard	Improved breeding (access to seed) of alternative hard wood species for agroforestry

New products for biomass residues

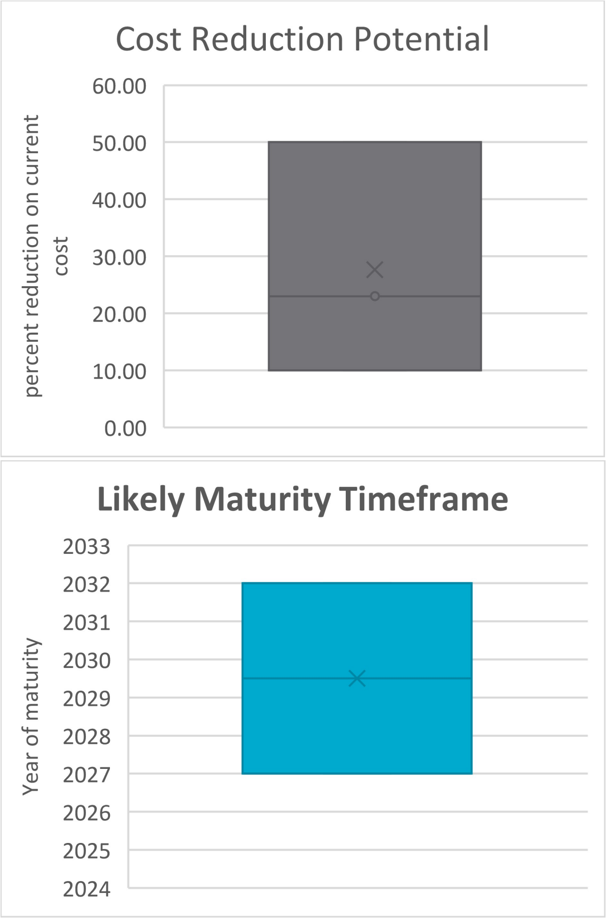


Figure A1.8: Translated Miro results for new products for biomass residues.

Table A1.8: Implementation steps for new products for biomass residues.

Technology implementation steps		
Timeframe	**Difficulty**	**Implementation step**
2025–2030	Very easy	Biofuel development business being promoted with drop in fuels. Likely this will add to the economics and lower net costs
2025–2030	Easy	Low-cost veneer biomass energy technologies that already exist need investment linked to supply capacity
2030–2035	Moderate	Important to develop bioenergy and biofuel products. Benefits include improved profitability of timber production and opportunities to displace fossil fuels
2035–2040	Somewhat hard	Lignocellulosic ethanol

Driverless and automated vehicles and machinery

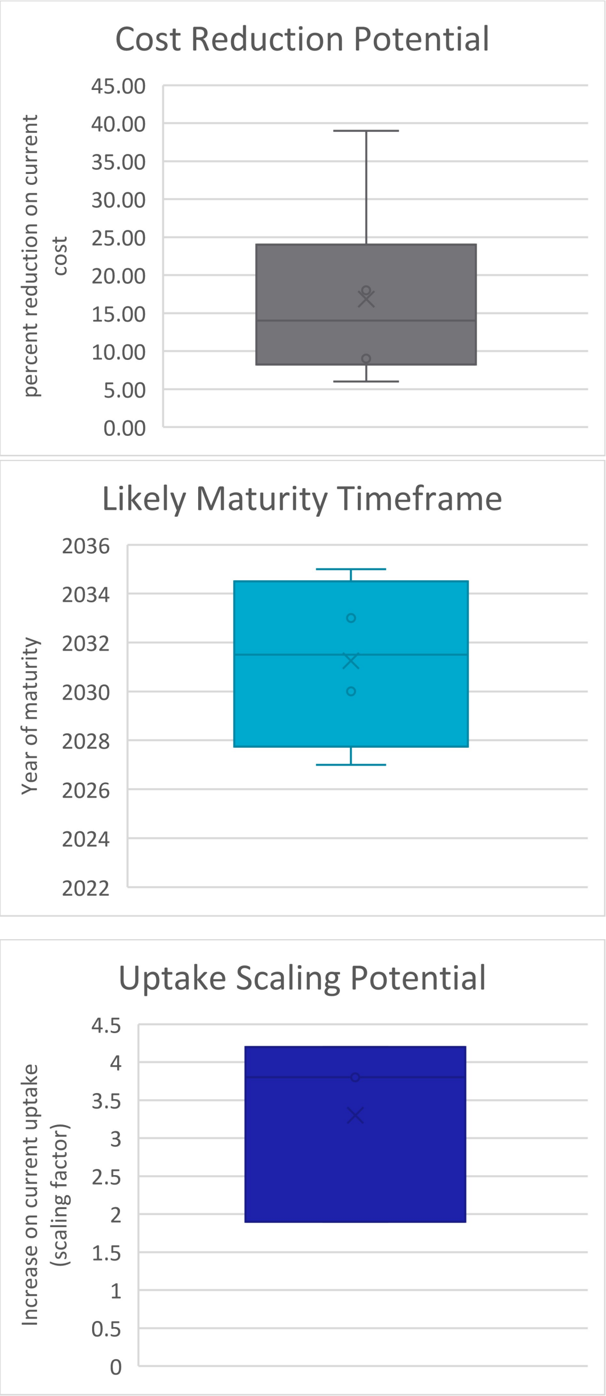


Figure A1.9: Translated Miro results for driverless and automated vehicles.

Table A1.9: Implementation steps for driverless and automated vehicles.

Technology implementation steps		
Timeframe	**Difficulty**	**Implementation step**
2025–2030	Easy	Grants/low interest finance/concessions etc. to increase affordability and facilitate transition
2025–2030	Somewhat hard	Case studies including costs and benefits, so people feel comfortable to invest

2030–2035	Moderate	Scope for autonomous operations, e.g. intelligent spraying operations, site preparation and planting, harvesting and transport
2030–2035	Hard	Lack of trainer operators = replace low-cost labourers with specialists
2035–2040	Hard	More efficient and safer batteries

A.1.2 Blue carbon workshop

Earth observation technologies for restoration site identification and assessment

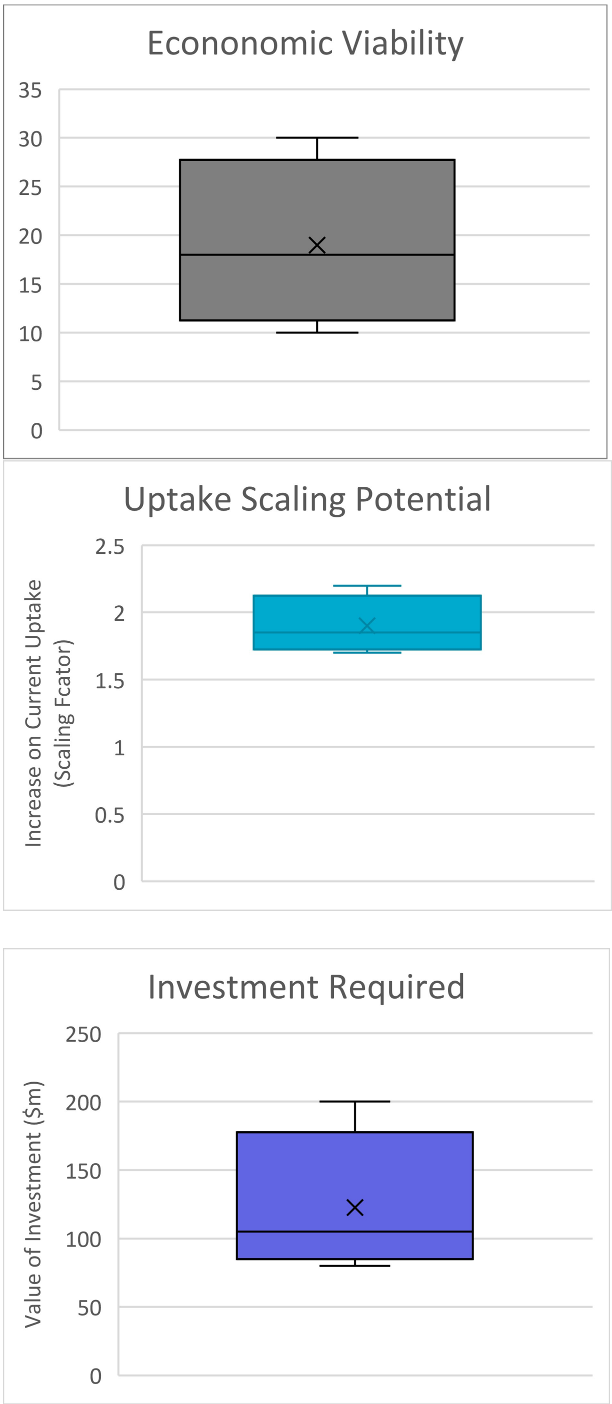


Figure A1.10: Translated Miro results for earth observation for restoration site identification and assessment.

Table A1.10: Implementation steps for earth observation for restoration site identification and assessment.

Technology implementation steps			
Timeframe	**Difficulty**	**Implementation step**	**Investment**
Now–2025	Very easy	Collate drained landscape data (collate, digitise, harmonise)	\$2 m
Now–2025	Very easy	Consult with project proponents to determine what information they would need to resolve the barriers to identifying sites	Low
Now–2025	Easy	Purchase of high-resolution imagery and maybe fill in gaps on LiDAR	\$4 m
Now–2025	Easy	Develop vegetation condition cover that updates weekly that is open to all	\$4 m
Now–2025	Moderate	Testing and calibration of developed tools	\$0.5 m
Now–2025	Moderate	Developing data, models and software structures to analyse and visualise data	\$3 m
Now–2025	Moderate	Designing strategies to cover data gaps and prioritise data collection efforts	\$250 k
Now–2025	Hard	Developing a catalogue of available datasets	\$100 k
Now–2025	Very hard	Identifying data needs for site identification and assessment	\$250 k
2025–2030	Very easy	Instrumented pilot sites for technology development	\$100 m
2025–2030	Easy	Consider social safeguards (FPIC, privacy, safety risks related data) and inclusive and accessible design (involve communities and consider First Nations voices and design)	?
2025–2030	Moderate	Seagrass change detection	\$1 m
2025–2030	Moderate	Algorithm development and testing	\$2 m
2025–2030	Moderate	Build a data cube and API interface	
2025–2030	Moderate	AUV to database technologies for automated MRV	\$3 m
2025–2030	Moderate	Automated biodiversity monitoring (e.g. acoustic)	\$3 m
2025–2030	Hard	Develop a sensor for salinised land	\$20 m
2030–2035	Hard	Automated methane/GHG sensors	\$2 m
2030–2035	Very hard	Building carbon monitoring with EO	\$50 m
2035–2040	Hard	Model for identifying vegetation species (including saltmarshes) from satellite date	\$50 m
2035–2040	Hard	CO_2 flux model at high resolution	\$100 m

National model for tidal introduction and feasibility assessment

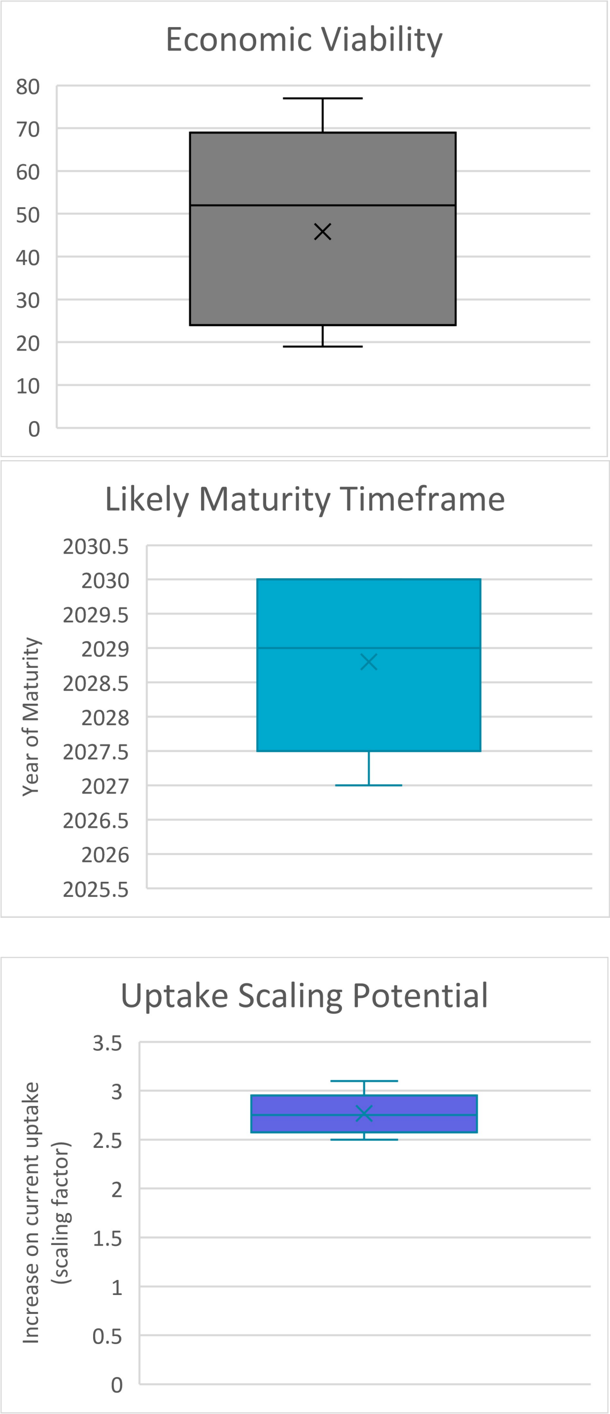


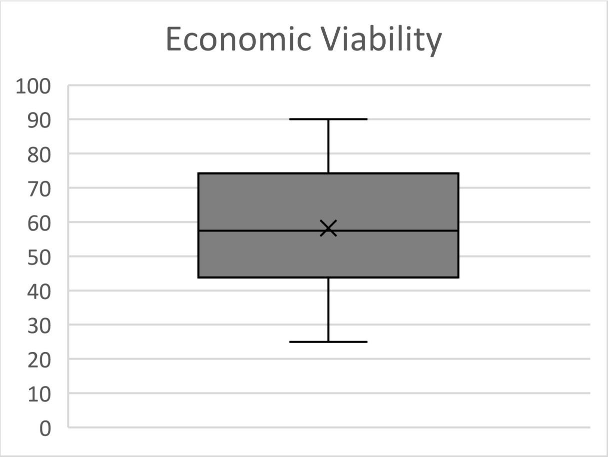
Figure A1.11: Translated Miro results for a national model for tidal introduction and feasibility assessment.

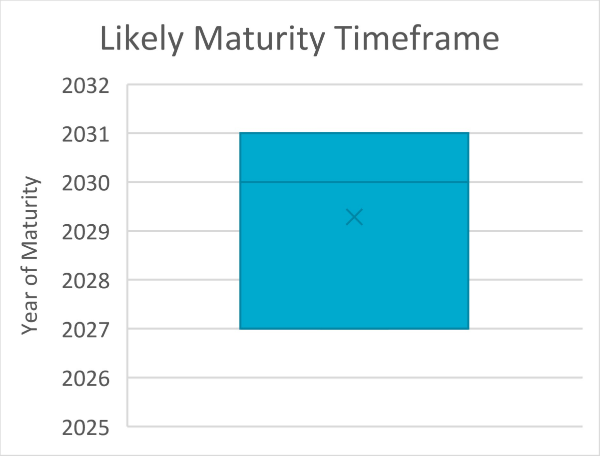
Table A1.11: Implementation steps for a national model for tidal introduction and feasibility assessment.

Technology implementation steps			
Timeframe	**Difficulty**	**Implementation step**	**Investment**
Now–2025	Easy	Determine scope of feasibility assessment de novo, add on, e.g. LUTO	$500 k

Now–2025	Hard	Accounting for uncertainties impacting project feasibility, e.g. potential impacts of climate change on survival rates	$200 k
Now–2025	Very hard	Developing a modular model to account for biophysical and economic factors impacting project feasibility	$600 k
2025–2030	Easy	Improve the coastal elevation model (high resolution), improve under vegetation	$100 m
2025–2030	Moderate	Biodiversity – what gains can we make and what is at risk	$50 m
2030–2035	Hard	Field to model workflows, AUV flight to model with plug and play	$100 m
2030–2035	Very hard	Deployment of water level data in high resolution grid	$100 m
2035–2040	Easy	Ideally ensure final outputs can be used by less sophisticated market users (local councils, NRM groups etc.)	??
2035–2040	Moderate	Nested and downscaled models that reliably predict hydrodynamics from automated DEM/bathymetry	$200 m
2035–2040	Very hard	Hydrodynamic high-resolution model that works off a single platform	$200 m

Methods and indices for measuring other benefits





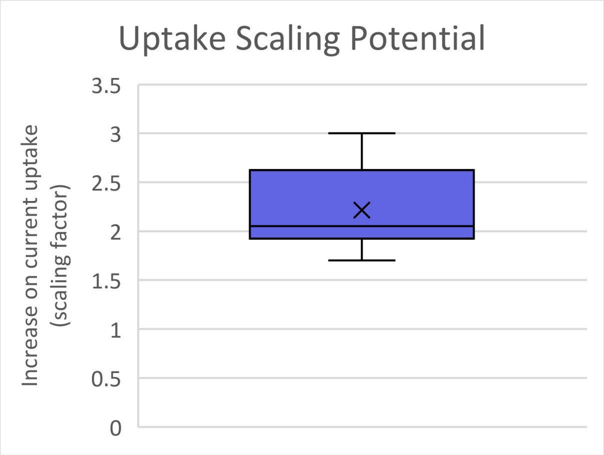


Figure A1.12: Translated Miro results for indices for measuring other benefits.

Table A1.12: Implementation steps for indices for measuring other benefits.

Technology implementation Steps			
Timeframe	**Difficulty**	**Implementation step**	**Investment**
Now–2025	Easy	Determination of what metrics to use now	$1 m
Now–2025	Easy	If non-carbon benefits are being viewed as a market-based approach to achieve additional revenue, then demand for these benefits needs to be assessed (or policies put in place to create demand) before they are relied upon too heavily as a solution	?
Now–2025	Hard	Engagement with First Nations communities to build First Nations perspectives and knowledge into approach	?
2025–2030	Moderate	Develop guidance for what claims can be made by buyers or producers of non-carbon benefits	?
2025–2030	Moderate	For water quality, need to know nitrogen (and other nutrients) in tidal water and residence time (links to hydro models)	$50 m
2025–2030	Hard	Pilot sites for sensor development and proof of concept to market	$300 m
2025–2030	Hard	Model of connectivity for species that transition through landscapes	$50 m
2030–2035	Very hard	Nested and downscaled models to predict coastal resilience (could be linked to hydrodynamic models)	?
2035–2040	Very hard	Automated biodiversity monitoring, e.g. acoustics for birds, insects, bats etc.	$100 m
2035–2040	Very hard	Detect species diversity of vegetation from satellites	$100 m
2035–2040	Very hard	Capacity to analyse eDNA for a range of species rapidly and cheaply – national platform. Can detect invasives and disease	$200 m
2040–2045	Hard	Government floor prices for voluntary biodiversity credits	?
2045–2050	Very hard	Valuing biodiversity	$50 m
2025–2030	Moderate	Incentives for operators to deploy a crew with potential to harvest small-scale plantings	
2025–2030	Somewhat hard	Case studies including costs and benefits, so that people feel comfortable to invest	

2030–2035	Easy	Aggregation of biomass can be facilitated by farm-based harvesting
2030–2035	Moderate	Open-source hardware/equipment sharing/lease models

A.1.3 Direct air capture workshop

Materials

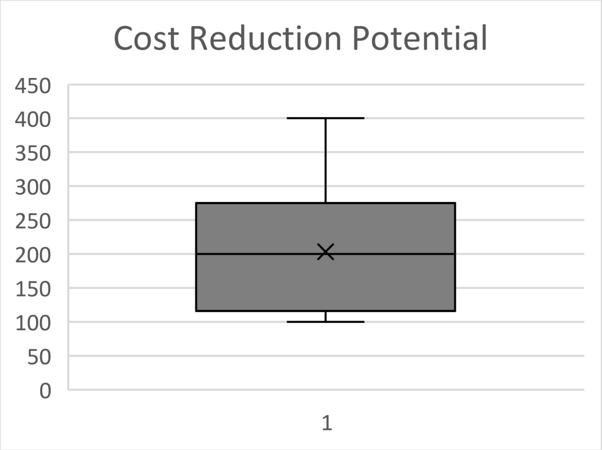
Figure A1.13: Translated Miro results for new materials for direct air capture.

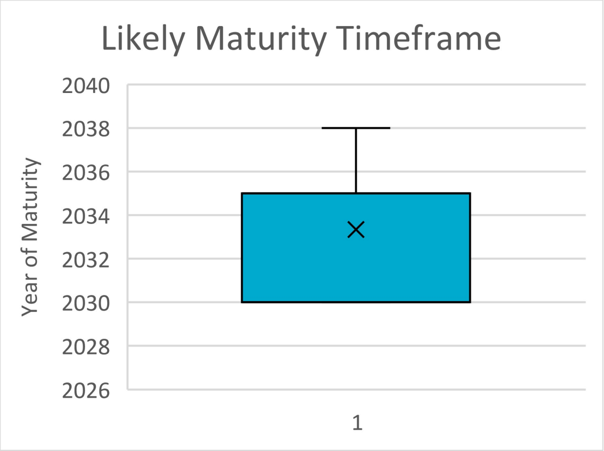
Table A1.13: Implementation steps for new materials for direct air capture.

Technology implementation steps			
Timeframe	**Difficulty**	**Implementation step**	**Investment**
2025–2030	Very easy	Evaluation of existing materials in lab and demo-plants	$100 m
2025–2030	Very easy	Establishment of several supply chains for different materials	$100 m
2025–2030	Easy	Solids and liquids – increase life – high reactive and low-cost sorbents	$50 m
2025–2030	Moderate	Improve material stability/lifetime	$100 m
2025–2030	Hard	Develop best materials (life, loading, reaction rate) at lab scale	$100 m
2025–2030	Very hard	Reduce material degradation	$500 m

2030–2035	Easy	Scale up manufacture and shaping	$100 m
2035–2040	Moderate	Scale up of best materials to operational scales	$100 m
2035–2040	Moderate	Recycle-regenerate spent materials	$100 m
2035–2040	Hard	Improved lifetime sorbents with strong supply chain	$1 b+
2035–2040	Very hard	Continued material improvements	$50 m
2040–2045	Moderate	Reduce supply chain costs of large amounts of material to millions of tonnes	$100 m
2040–2045	Very hard	Large-scale manufacturing of advanced materials	$1 b

Process and equipment





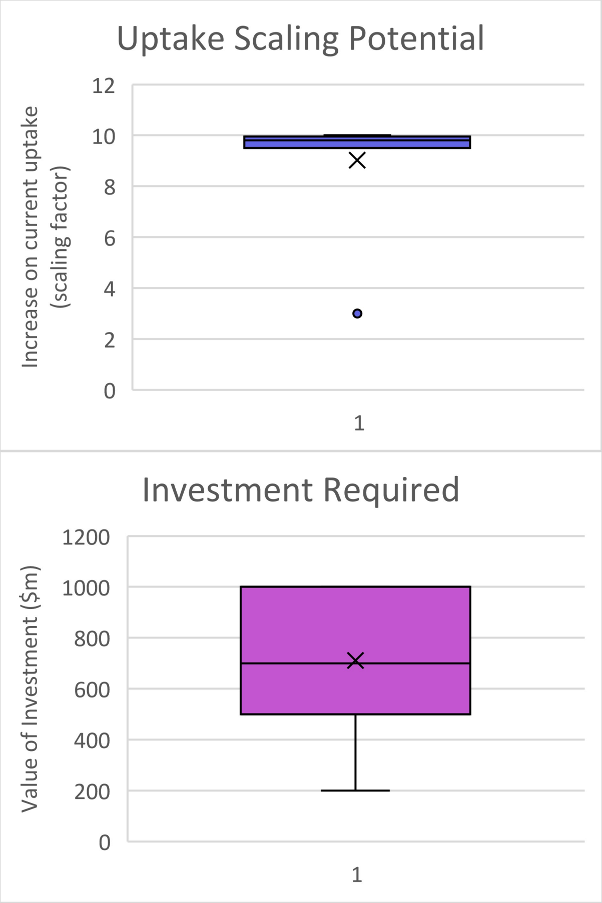
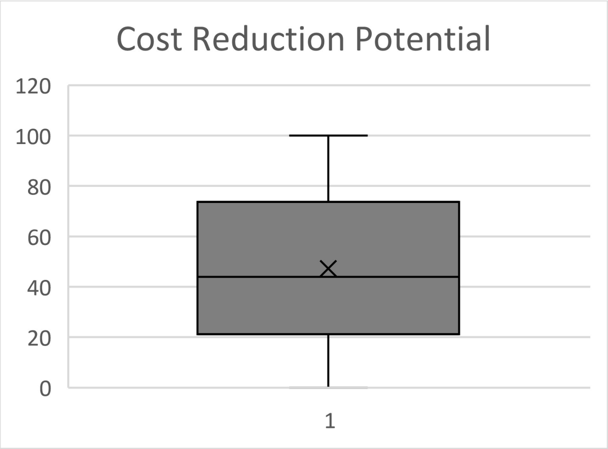


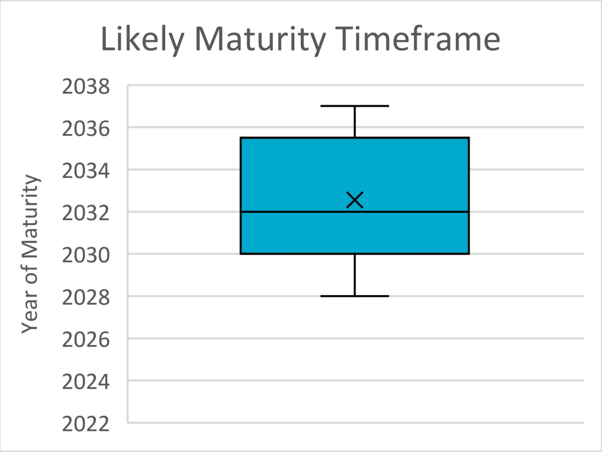
Figure A1.14:Translated Miro results for process and equipment.

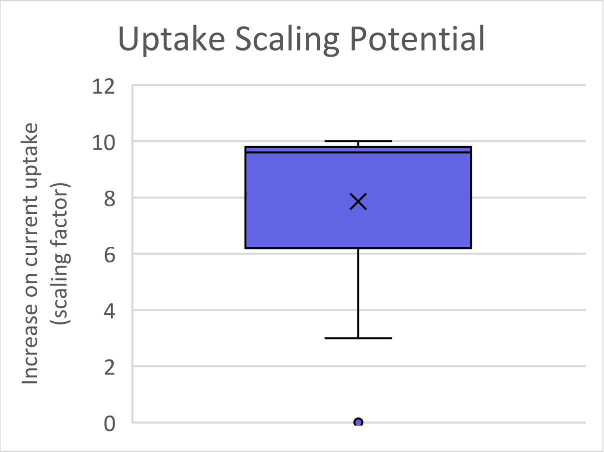
Table A1.14: Implementation steps for process and equipment.

Technology implementation steps			
Timeframe	**Difficulty**	**Implementation step**	**Investment**
2025–2030	Very easy	Concept evaluation in demo-plants	$50 m each tech
2025–2030	Moderate	Increase surface area and air flow over solids	$50 m
2025–2030	Hard	Large, low-pressure drop contractors	$30 m
2030–2035	Moderate	Efficient high-volume manufacturing, low-pressure drop contractor, maximum cost reduction through scale-up	$100 m
2030–2035	Moderate	Systems engineering and control	$100 m+
2030–2035	Moderate	Large-scale air movement with low energy	$100 m+
2030–2035	Very hard	Full use of heat pumps for heat supply	$300 m
2035–2040	Very easy	Demonstration of advanced systems	$100 m
2035–2040	Easy	Large-scale plant design and construction	Many billions
2035–2040	Moderate	Develop advanced materials into processes/equipment	$50 m
2040–2045	Very hard	Complete dynamic system at scale. Low pressure drop. Heat integration. Instrumented for complex process control to account for changes in weather and season	$1 b+

Energy supply







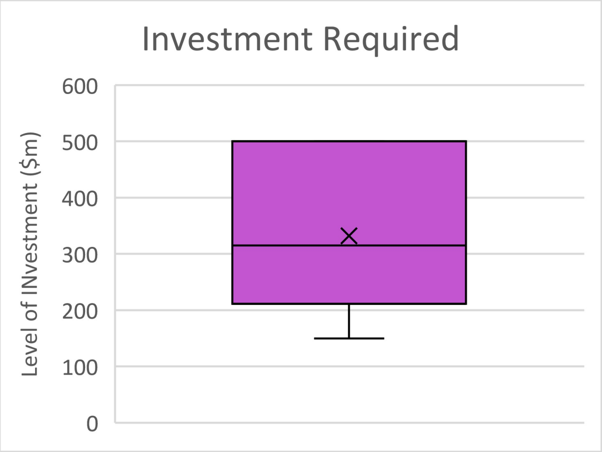


Figure A1.15: Translated Miro results for energy supply.

Table A1.15: Implementation steps for energy supply.

Technology implementation steps			
Timeframe	**Difficulty**	**Implementation step**	**Investment**
2025–2030	Easy	Assess different integration options for DAC plants with renewable energy (Solar Thermal, PV, Geothermal) or nuclear energy	In conjunction with demo-plants
2025–2030	Moderate	Store heat instead of electricity	$100 m
2030–2035	Easy	Examine large-scale use of gas on location (gas supply and storage without transport). Needs societal examination	$50 m
2030–2035	Moderate	Reduce energy consumption (MWh/t) of DAC equipment	$100 m
2030–2035	Moderate	Large scale 24/7 supply of renewable electricity	
2030–2035	Moderate	Assessment of flexible operation and its effect on cost (trade-off between emission reduction cost), reducing the energy requirement of the process, using energy integration between various processes and DAC	
2030–2035	Hard	Energy supply could be integrated and not require any integration with existing grids (e.g. autonomous DA systems). Australia would be ideally placed here given large areas of non-arable lands for use of solar	$100 m
2030–2035	Very hard	Dynamic system analysis	$100 m
2035–2040	Very hard	Low-cost integration of intermittent renewables with DAC	$100 m+
2040–2045	Moderate	Development of ~100% electrically driven DAC to leverage increased low-cost renewable energy	$1 b+

A.1.4 Biomass/biochar workshop

Technology at scale

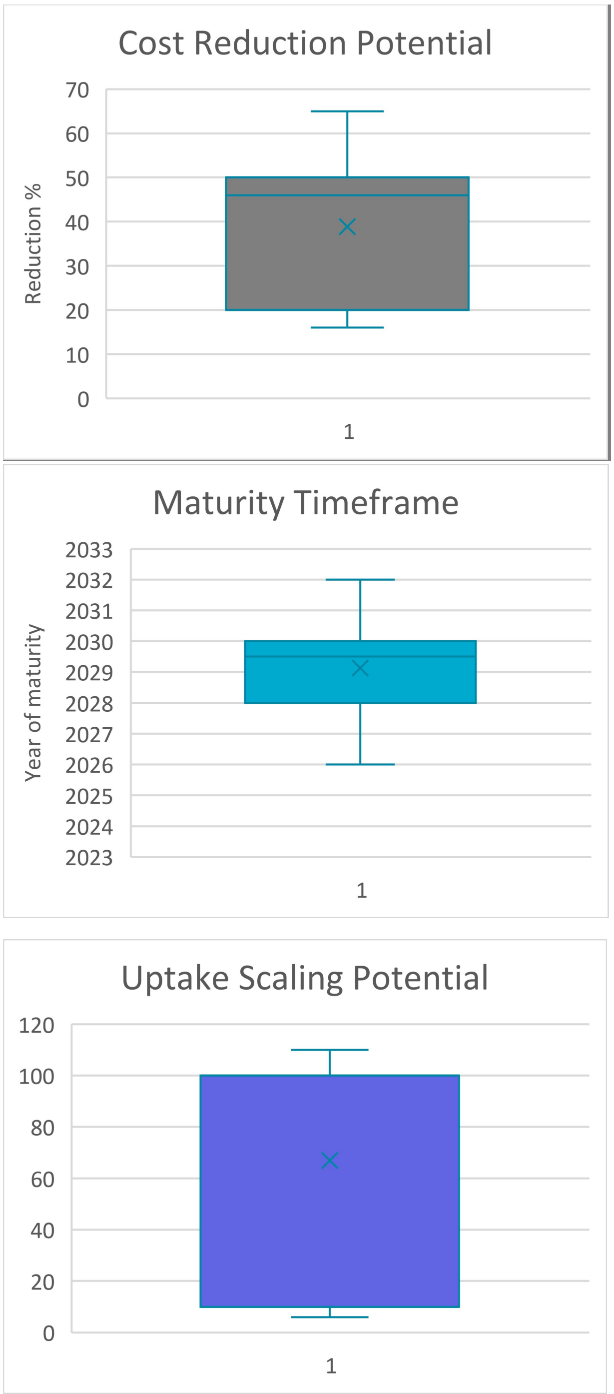


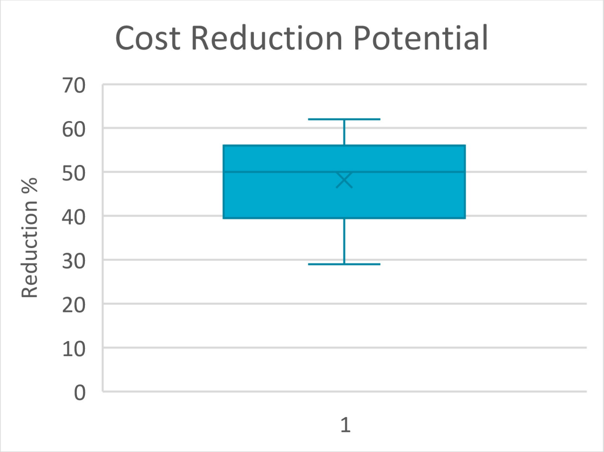
Figure A1.16:Translated Miro results for technology at scale.

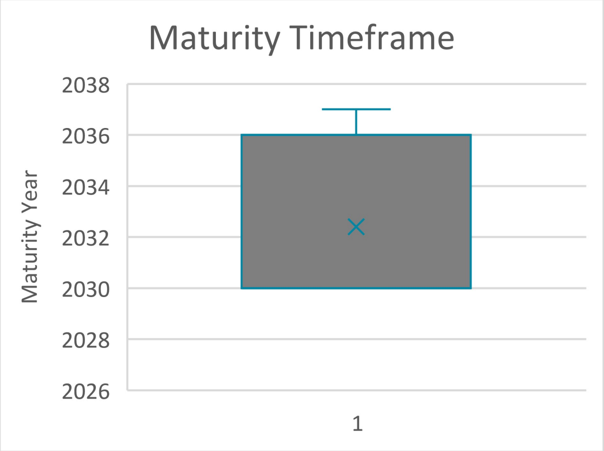
Table A1.16: Implementation steps technology at scale.

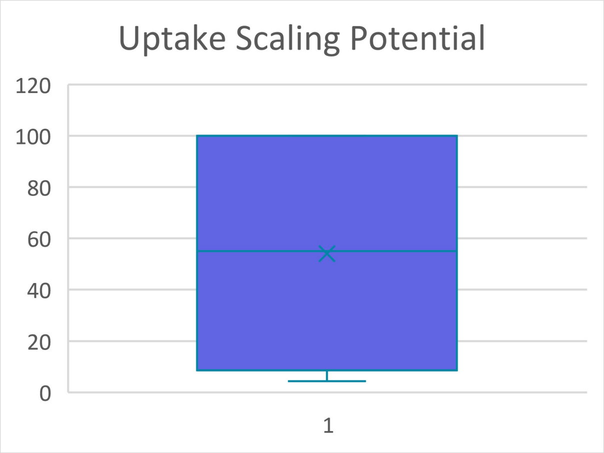
Timeframe	Difficulty	Implementation step	Investment
Now–2025	Very easy	PyCCS targeted community marketing and education	$5 m over 5 years
2025–2030	Very easy	Demo plants for different feedstocks and co-product applications (syngas)	$10 m

2025–2030	Easy	Exemplars in special activation precincts in industrial symbiosis ecosystem	
2025–2030	Moderate	Syngas to liquids at 1 MW scale enables use of remote biomass	
2025–2030	Moderate	Increase CRL of technologies required through pilot and demonstration projects. Also need to include wider value chains	$50 m
2025–2030	Hard	Demonstration of commercial scale hydrogen production	
2030–2035	Easy	Explore markets for use of products and set up offtake agreements	
2030–2035	Moderate	Community and stakeholder engagement, work on sourcing biomass for implementation	$20 m
2030–2035	Moderate	Build commercial-scale plant at location near sources of biomass and utilisation – a hub? Based on lessons learnt from pilot/demo scale	$200 m
2030–2035	Very hard	Pilot and demo scale plants, some commercial should be built, tested with lots of data to generate confidence about the technology	Billions

Large-scale modular plants







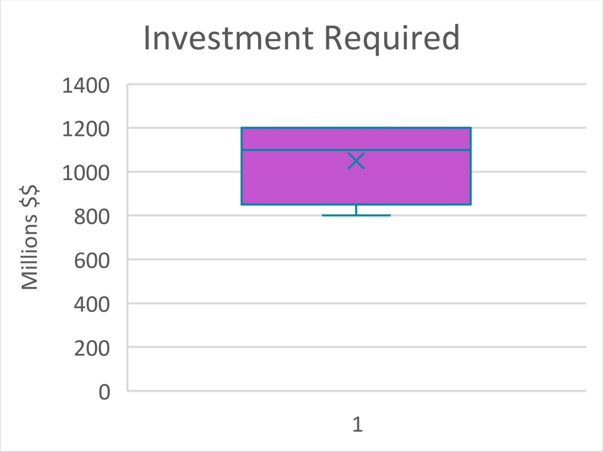


Figure A1.17:Translated Miro results for development of large-scale modular plants.

Table A1.17: Implementation steps for development of large-scale modular plants.

Timeframe	Difficulty	Implementation step	Investment
2025–2030	Moderate	Assessment of sustainable biomass in Australia for use in modular plants to allow for locations of plants to be determined	$10 m
2030–2035	Easy	Bankable feasibility studies with offtakes and feed security for regional hubs	
2035–2040	Hard	Detailed cost calculations with demonstrations to the investors	$1 b

Utilisation cases

Table A1.18: Implementation steps for utilisation cases.

Technology implementation steps			
Timeframe	**Difficulty**	**Implementation step**	**Investment**
Now–2025	Very easy	Commercial scale (broadacre) demonstrations for multiple soil applications and commercial scale demonstrations for non-soil (industrial) uses of biochar (e.g. concrete, roads, bioplastics, batteries etc.)	

Now–2025	Easy	Regional training facilities for highly skilled plant operators and managers	$10–$100 m
2025–2030	Easy	Standalone commercial PyCCS plants online – self funded with support from CORCs (10–15 plants circa 200,000 t/year biochar, 100 MW)	$250 m
2025–2030	Hard	Large-scale field trials of use of biochar in different conditions and soil types around Australia	$30 m
2030–2035	Moderate	Extensive community and potential market engagement on the use of biochar in agriculture and other use cases such as industry	$20 m
2030–2035	Hard	Industry has scaled up to allow widespread use of biochar in hubs including industry and agriculture	
2035–2040	Easy	Various products need to have specifications as per standard and have to be acceptable to the users in the final utilisation cases	$500 m

Guidelines

Table A1.19: Implementation steps for the development of guidelines and best practices.

Technology implementation steps			
Timeframe	**Difficulty**	**Implementation step**	**Investment**
2025–2030	Very easy	Identify knowledge gaps (soils, ag systems, formulations)	$200 k
2025–2030	Easy	Develop standards, get ratified and then develop guidelines and implement knowledge centres	$50 m
2025–2030	Easy	Regulatory sandboxes for environmental approvals	$5–$20 m
2025–2030	Easy	Research targeted to fill knowledge gaps (soil types/ag systems/biochar formulations/climatic regions). How much biomass can be removed whilst maintaining soil health	$20 m

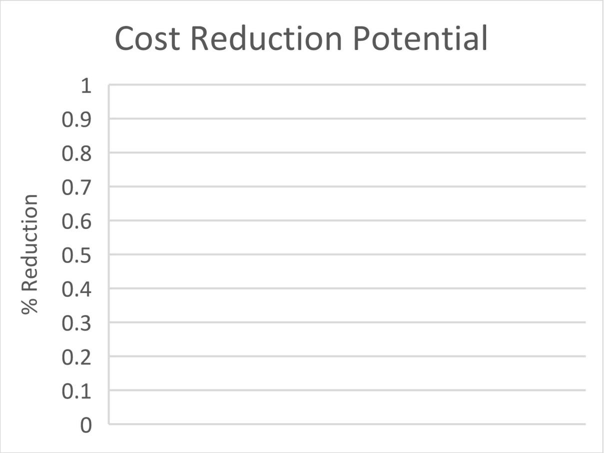
Pre-processing of feedstocks for pyrolysis

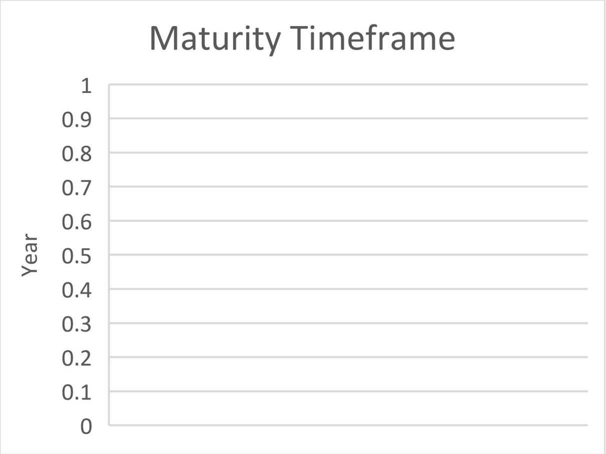
Table A1.20: Implementation steps for the pre-processing of feedstocks for pyrolysis.

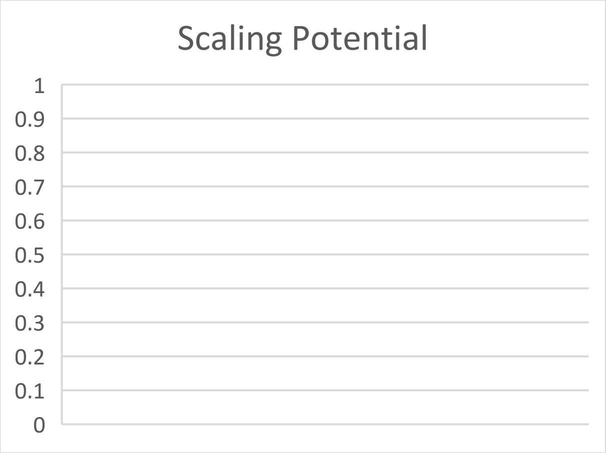
Technology implementation steps			
Timeframe	**Difficulty**	**Implementation step**	**Investment**
2025–2030	Very easy	Develop collection and continuous large tonnage throughput dryer and feed preparation technology for downstream conversion	$100 m

A.1.5 Carbon capture and storage workshop

Improved capture technologies



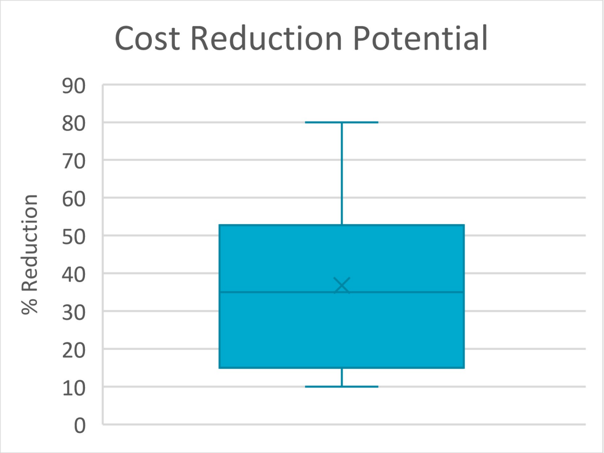


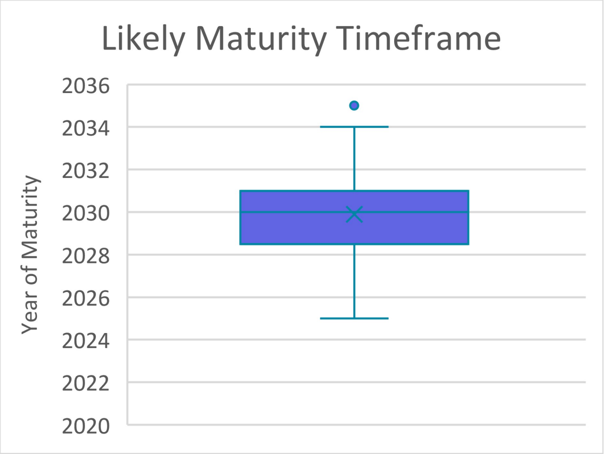


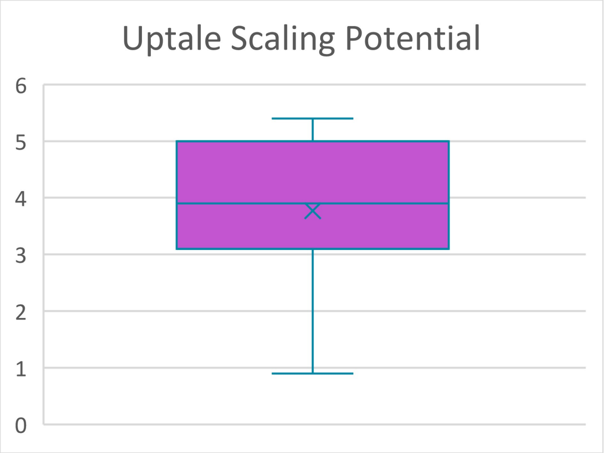
Technology implementation steps			
Timeline	**Difficulty**	**Implementation step**	**Investment required**
Now–2025	Very easy	Tax credits, funding and government financing for capturing R&D, pilots and early roll out	$200 m
2025–2030	Very easy	Collaboration internationally at scale rather than solo/Australian development for EITE Industries	$1 b
2025–2030	Very easy	Availability of early-stage funding	$100 m
2025–2030	Easy	Initial R&D	$100 m
2025–2030	Moderate	Development of high efficiency/low energy absorption solvents	$100 m
2025–2030	Moderate	International collaboration watching brief	$50 m
2025–2030	Hard	Incentivisation of carbon capture trials (without storage) in hard to abate industries	$100 m
2030–2035	Moderate	Pilot/trial capture plants	$500 m
2030–2035	Moderate	Pilot facilities	$500 m
2030–2035	Moderate	Pilot plants	$150 m
2030–2035	Moderate	Identify the key targets within the capture technologies (industries select the technology) and their locations (cannot work on everything – target the key needs)	$100–$500 m
2030–2035	Moderate	Full scale test	$300 m

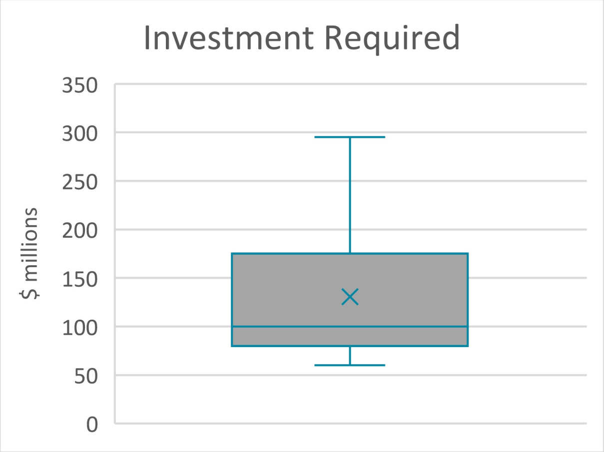
2030–2035	Hard	Ability to stack incentives	
2030–2035	Very hard	CCS (Full Chain) on cement – possibly via a pilot plant. Timing dependent on cement business case, technology development and set up of full chain	$100 m

Storage optimisation and efficiency





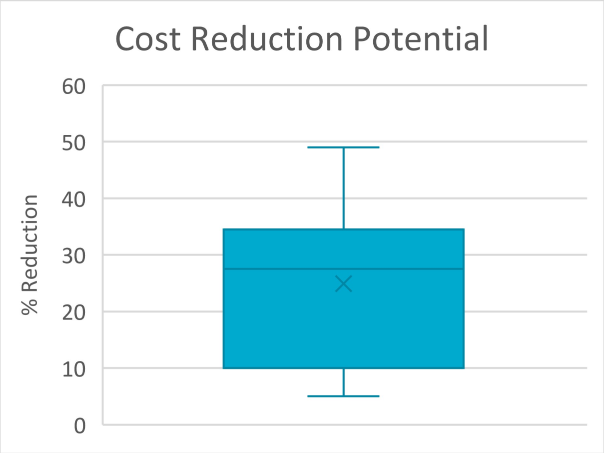




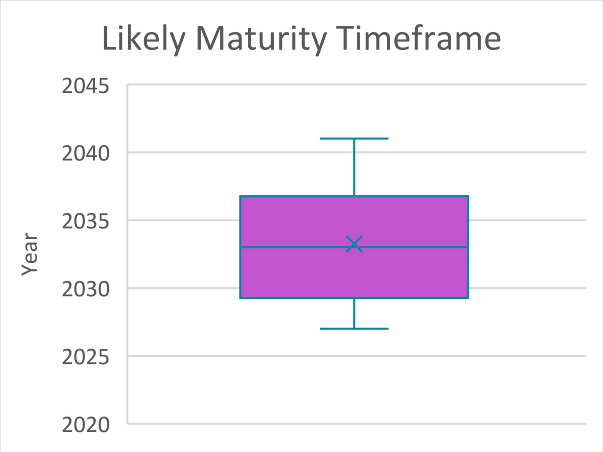
Technology implementation steps			
Timeline	**Difficulty**	**Implementation step**	**Investment required**
Now–2025	Hard	Complete site appraisal early and then develop potential secondary and tertiary technologies which may then be suitable for site optimisation	
2025–2030	Very easy	Evaluate existing systems and new injection technologies (MB, micropulsing, surfactants etc.) via demonstration projects to establish applicability into high quality (mostly offshore) and low quality (often onshore) storage systems. New modelling approaches in heterogeneous systems integrated with new MMV approaches, to confirm improvements in efficiency. Confirm early on how big the wins might be, therefore how applicable are the technologies – do they make a difference? What are the regulators after now and into the future?	$50–$200 m
2025–2030	Easy	Initial R&D	$10 m
2025–2030	Easy	Microbubble injection technology	
2025–2030	Easy	Site storage in the best location and highest confidence locations with optionality. Understand reservoir and seal variation and impact on storage factors – highly site specific	$1 b
2025–2030	Moderate	Incentives to pilot test new ideas in the most prospective and advanced development reservoirs	$50 m
2030–2035	Easy	Field testing	$5 m

2030–2035	Moderate	Innovative injection and plume management	$200 m
2035–2040	Very easy	Trial horizontal vs vertical injection wells in a storage reservoir to investigate improved storage efficiency	$50 m
2035–2040	Hard	Fund any technology that could increase efficiency of individual injector wells – assume global R&D across academia and industry	$1 b

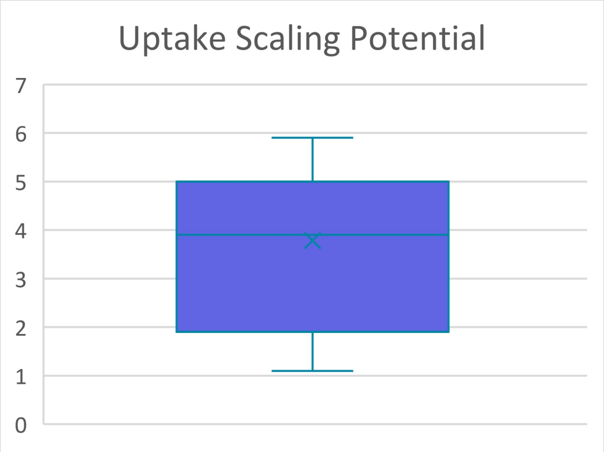
Implementation of hubs

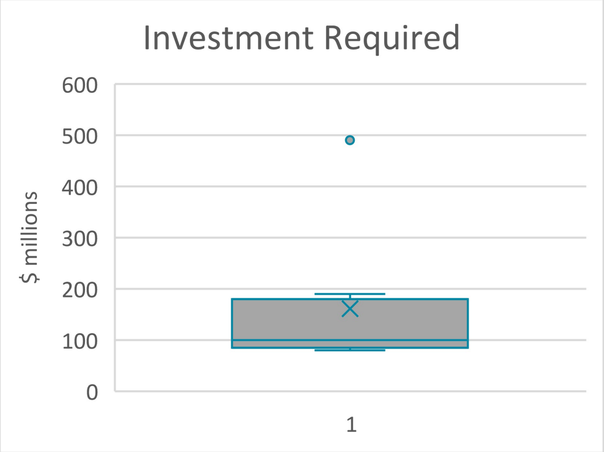


Cost Reduction Potential



Likely Maturity Timeframe





Technology implementation steps			
Timeline	**Difficulty**	**Implementation step**	**Investment required**
Now–2025	Very hard	Find the anchor sink(s) and increase confidence, then optimise hub (scale, sequence, routes etc.) to 'match' sink is the unit cost driver. Timing depends on getting the primary appraisal done	
2025–2030	Very easy	Information and community consultation	$50 m
2025–2030	Very easy	Investigate/model shared compression and pipeline facility costs to allow the aggregation and transportation of CO_2 captured from smaller industrial emitters	$3–5 m
2025–2030	Easy	Development of optimum gathering CO_2 quality standards	$10 m
2025–2030	Easy	Develop standards for blow-down/venting of CO_2	$10 m
2025–2030	Easy	Use NT LE Hub as example – but not really a CCS investment – it assumes we have located it in the right place	
2025–2030	Moderate	Establish required permitting	$100 m
2025–2030	Hard	Financial engineering	
2030–2035	Very easy	Potential government investment in common user infrastructure, i.e. Alberta trunk line	
2030–2035	Easy	Reduction of government red tape to facilitate growth of number of emitters in hubs (sea dumping)	

2030–2035	Moderate	Facilitation by government	$500 m
2030–2035	Moderate	Establish risk sharing contractual experience across common stakeholders	$500 m
2030–2035	Hard	Driven by industry; perhaps the role for government and others is in framing what is possible (middle arm etc.). Learn from other players overseas	$20–$100 m

Reservoir exploration and identification

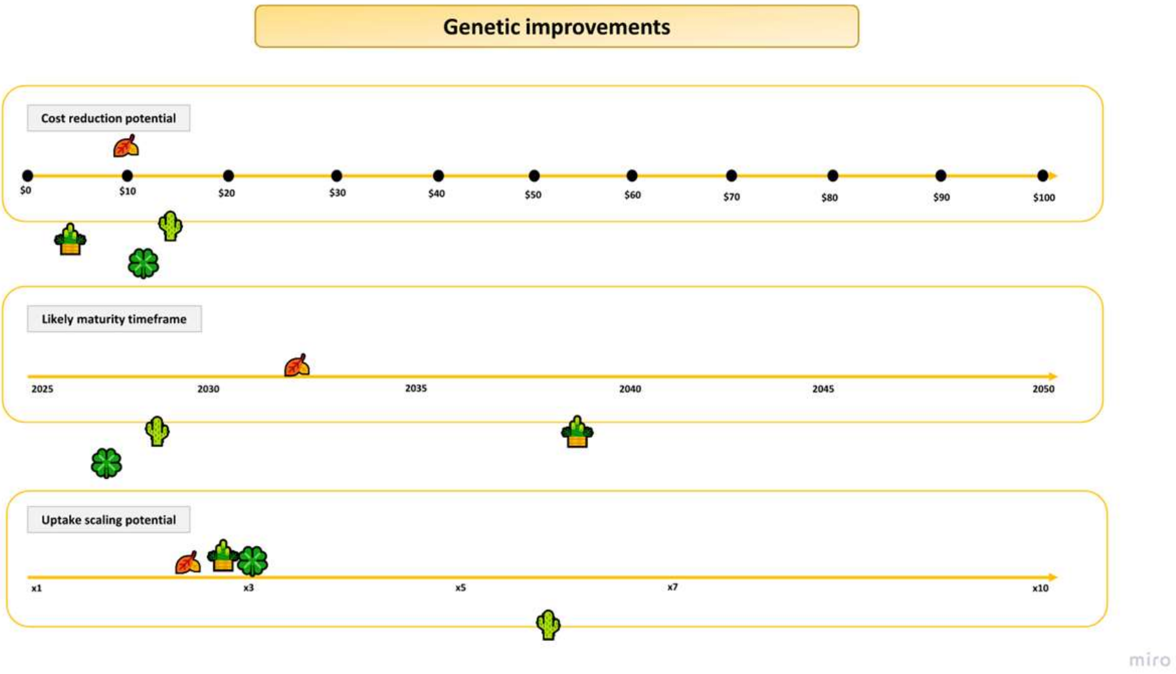
Technology implementation steps			
Timeline	**Difficulty**	**Implementation step**	**Investment required**
2025–2030	Very easy	Exploration for saline aquifer storage around Australia	$20–$25 m per annum
2025–2030	Moderate	Better assess the injection characteristics and storage potential of heterogeneous and lower permeability reservoirs in onshore settings (essential for hard to abate and DAC-S) – what storage is available where and can it be used, especially with new injection paradigms? Align the sources and sinks onshore	$5 m per annum

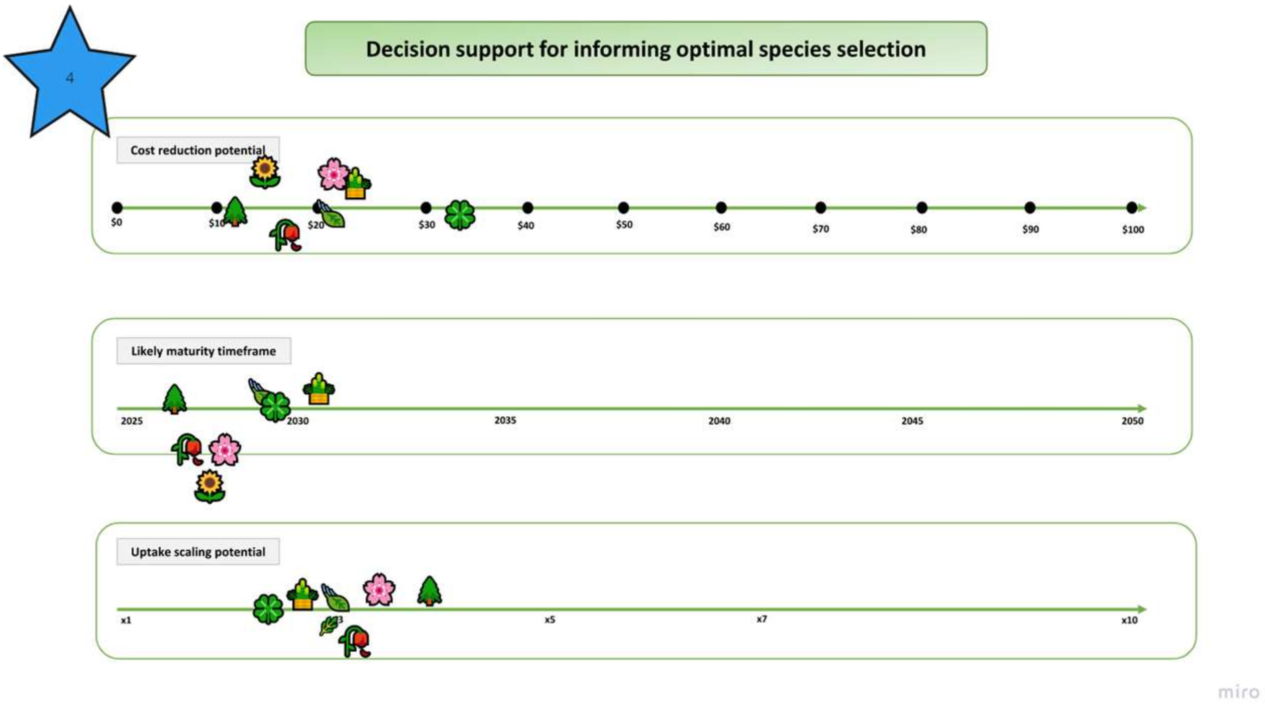
A.1.6 Mineral carbonation workshop

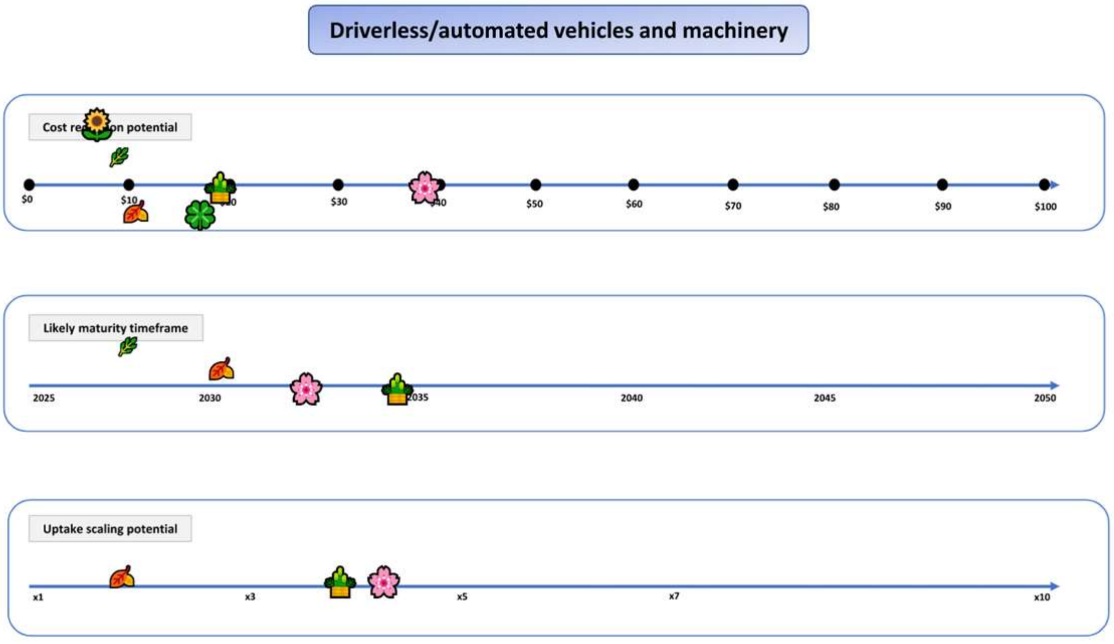
Still to come.

Appendix B Miro Screens

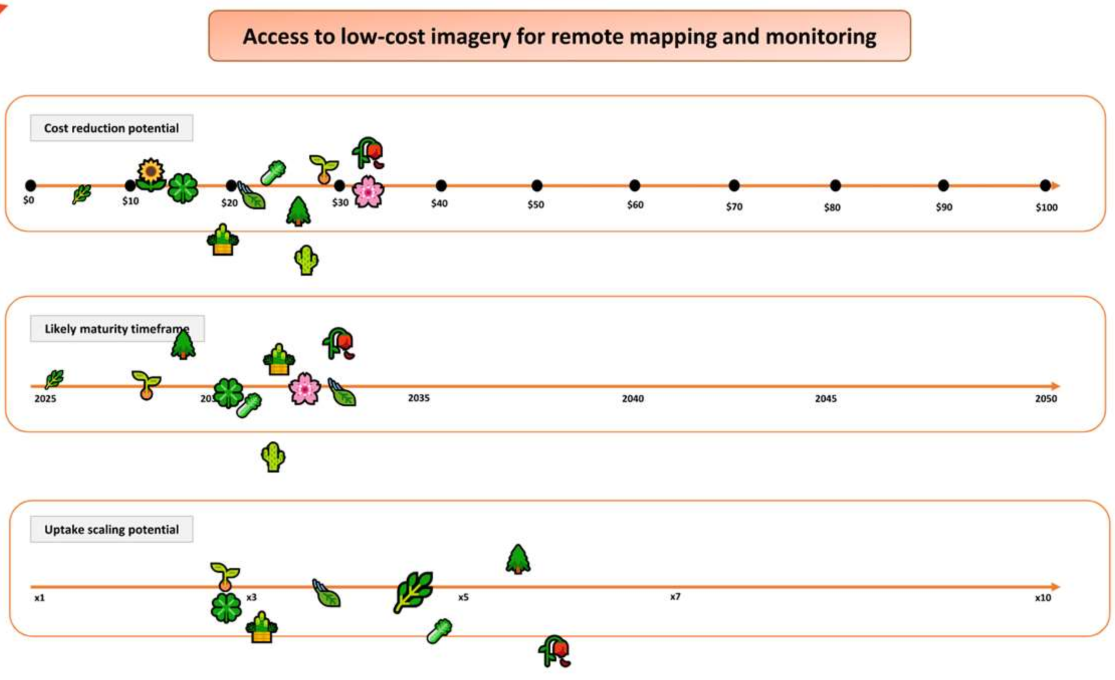
B.1.1 Planted vegetation workshop

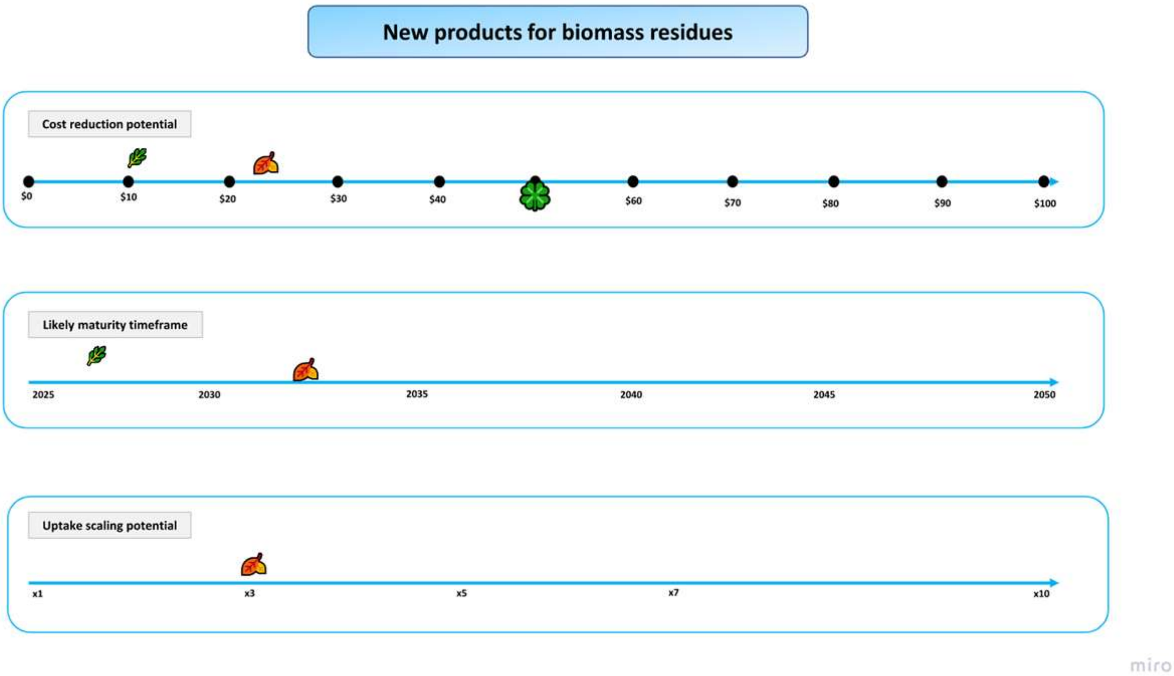


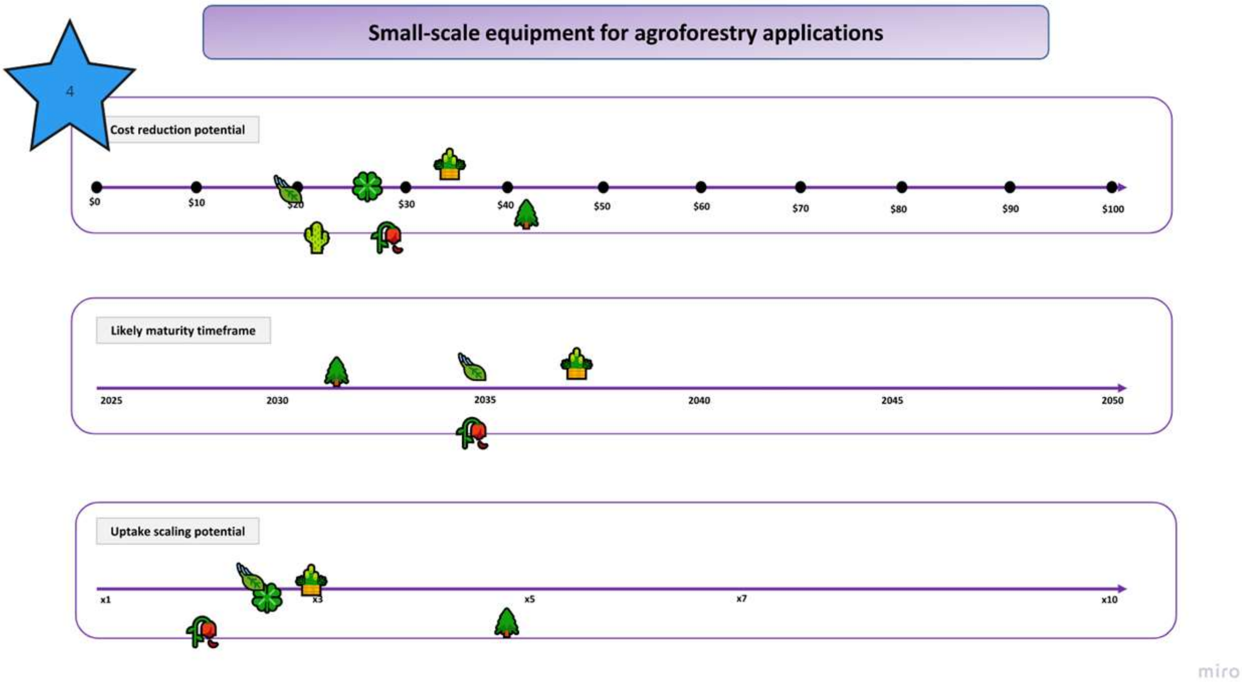



Driverless/automated vehicles and machinery
Cost reduction potential
$0
$10
$30
$50
$60
$70
$80
$90
$100
Likely maturity timeframe
2025
2030
2035
2040
2045
2050
Uptake scaling potential
x1
x3
x5
x7
x10
miro

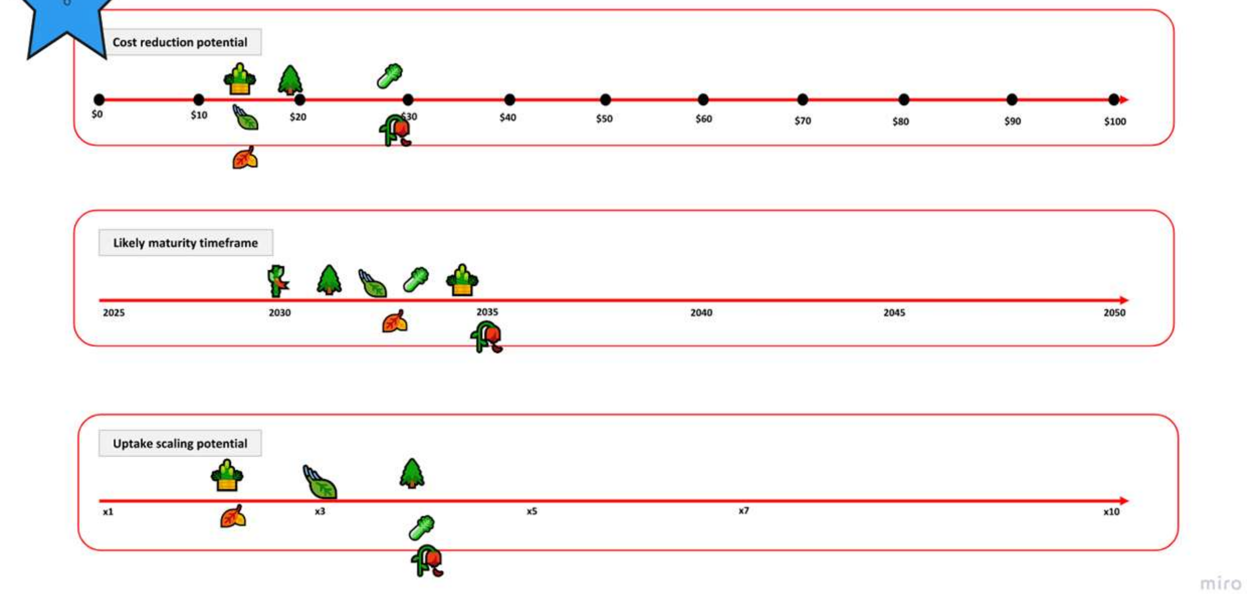
8


Access to low-cost imagery for remote mapping and monitoring
Cost reduction potential
$0
$10
$20
$30
$40
$50
$60
$70
$80
$90
$100
Likely maturity timeframe
2025
2035
2040
2045
2050
Uptake scaling potential
x1
x3
x5
x7
x10
miro

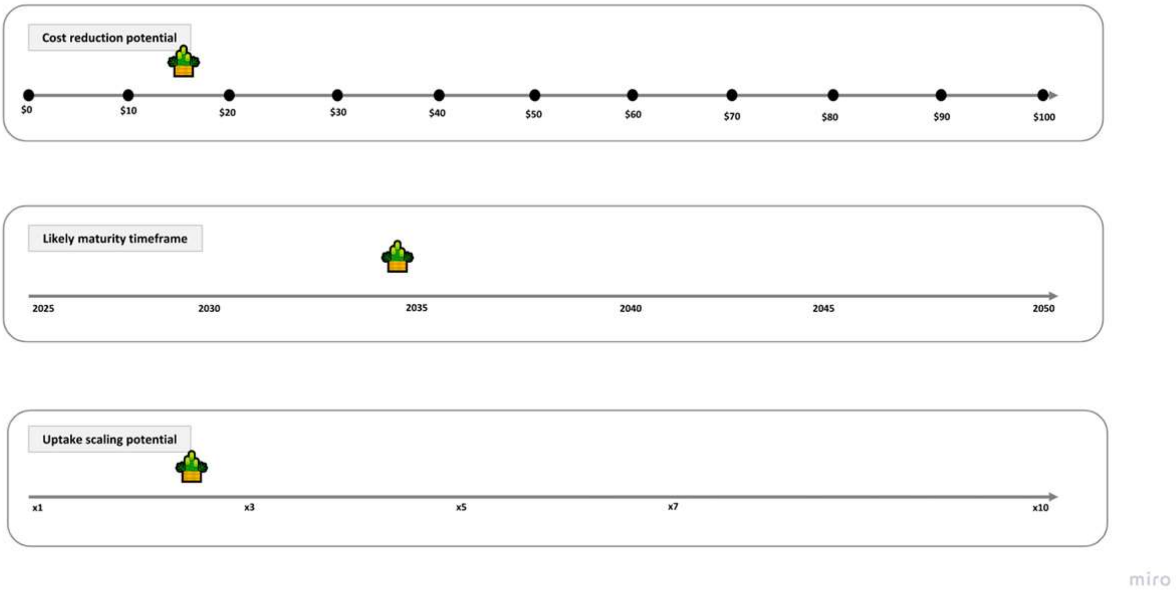

New products for biomass residues
Cost reduction potential
$0
$10
$20
$30
$40
$60
$70
$80
$90
$100
Likely maturity timeframe
2025
2030
2035
2040
2045
2050
Uptake scaling potential
x1
x3
x5
x7
x10
miro

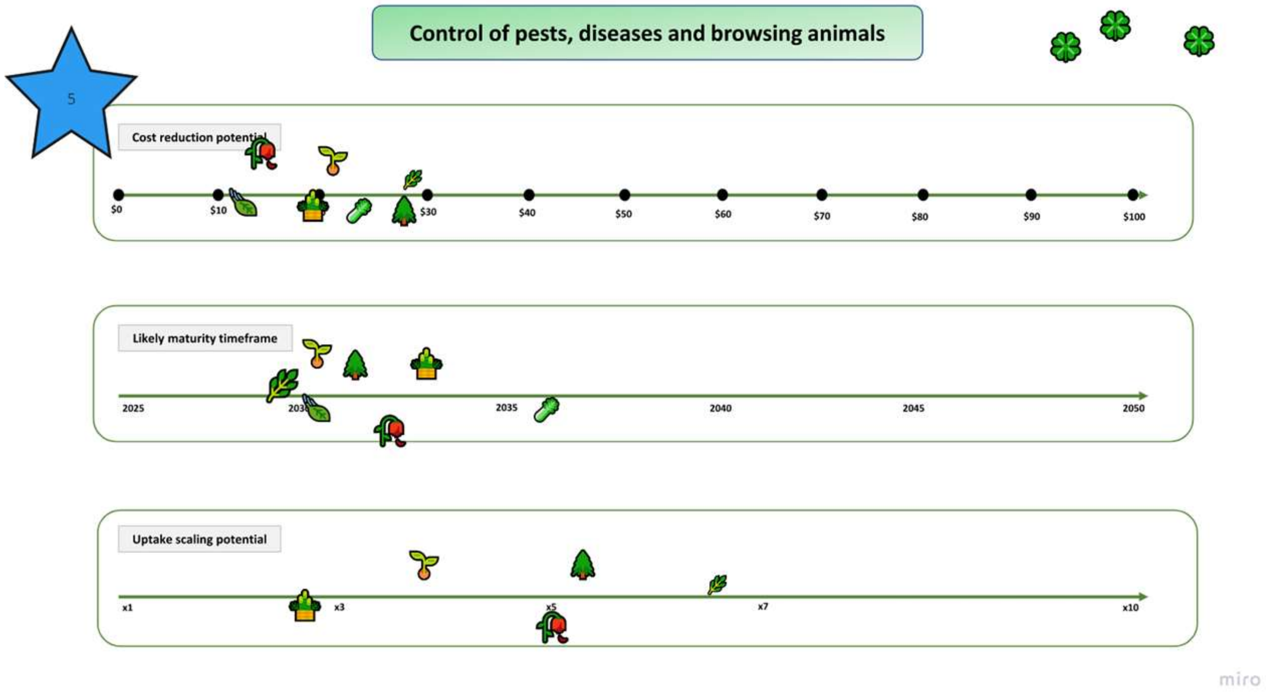

Small-scale equipment for agroforestry applications
4
Cost reduction potential
$0
$10
$20
$30
$40
$50
$60
$70
$80
$90
$100
Likely maturity timeframe
2025
2030
2035
2040
2045
2050
Uptake scaling potential
x1
x3
x5
x7
x10
miro

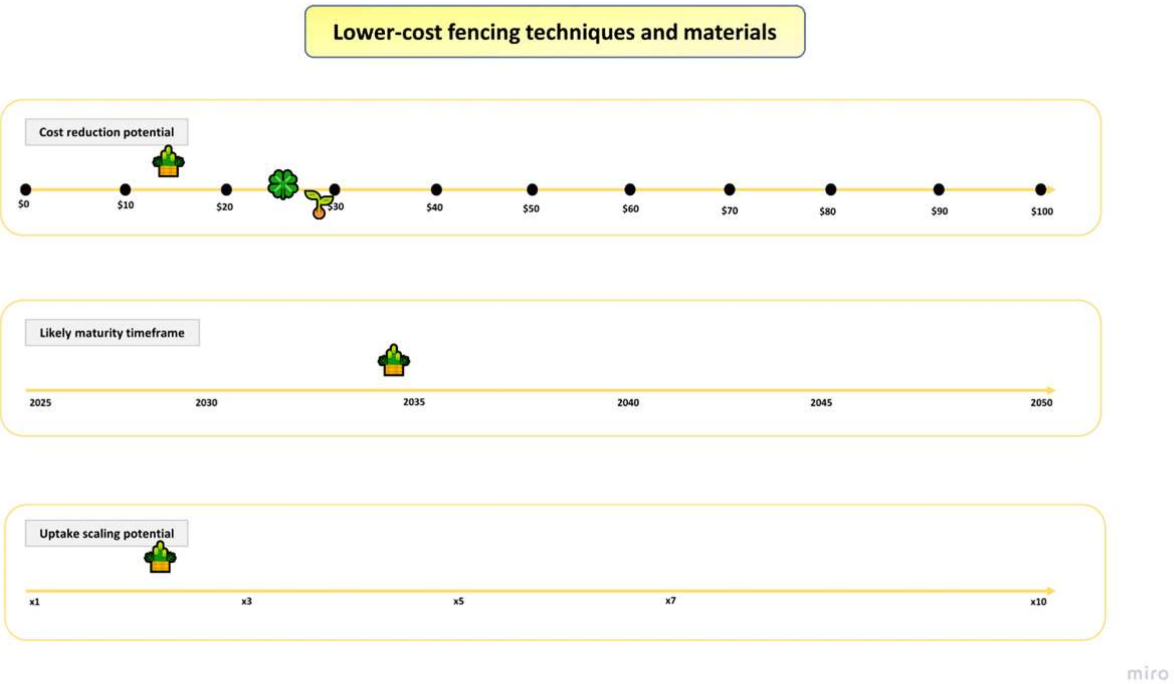
Zero or low emission fuels to replace fossil fuels in forestry applications



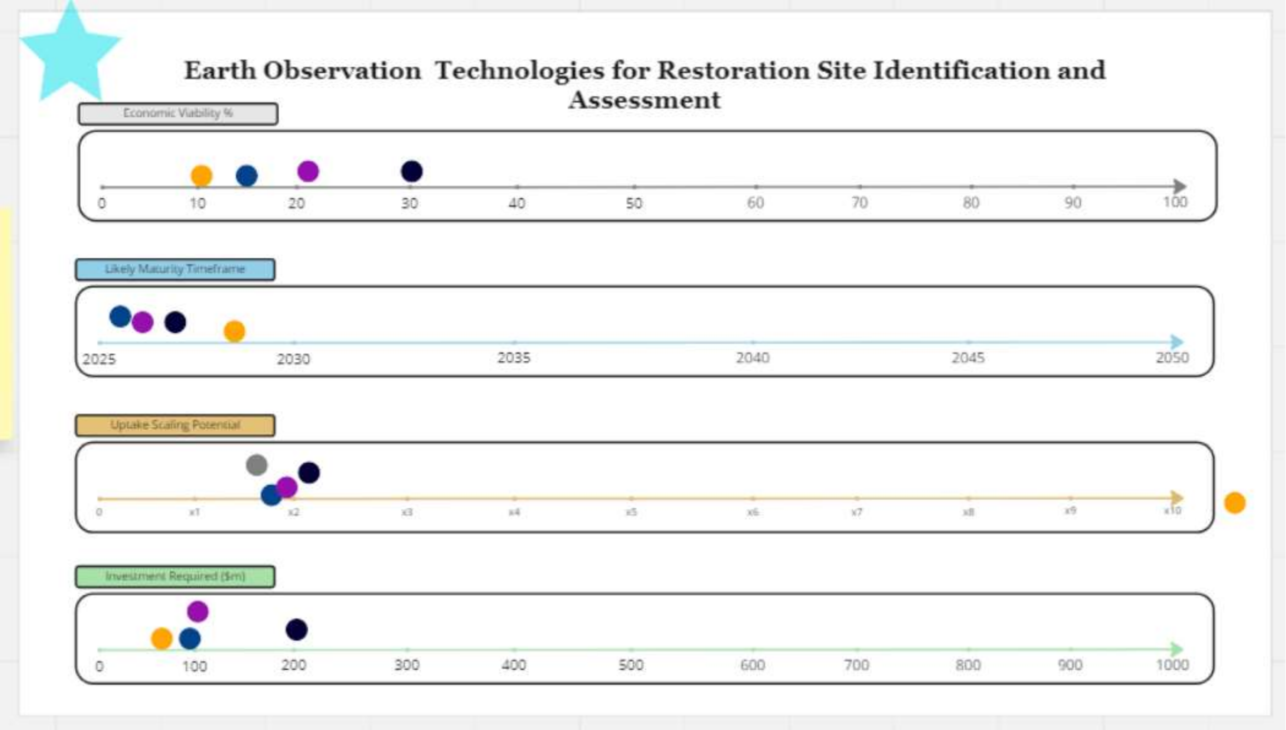
Enhanced weed control

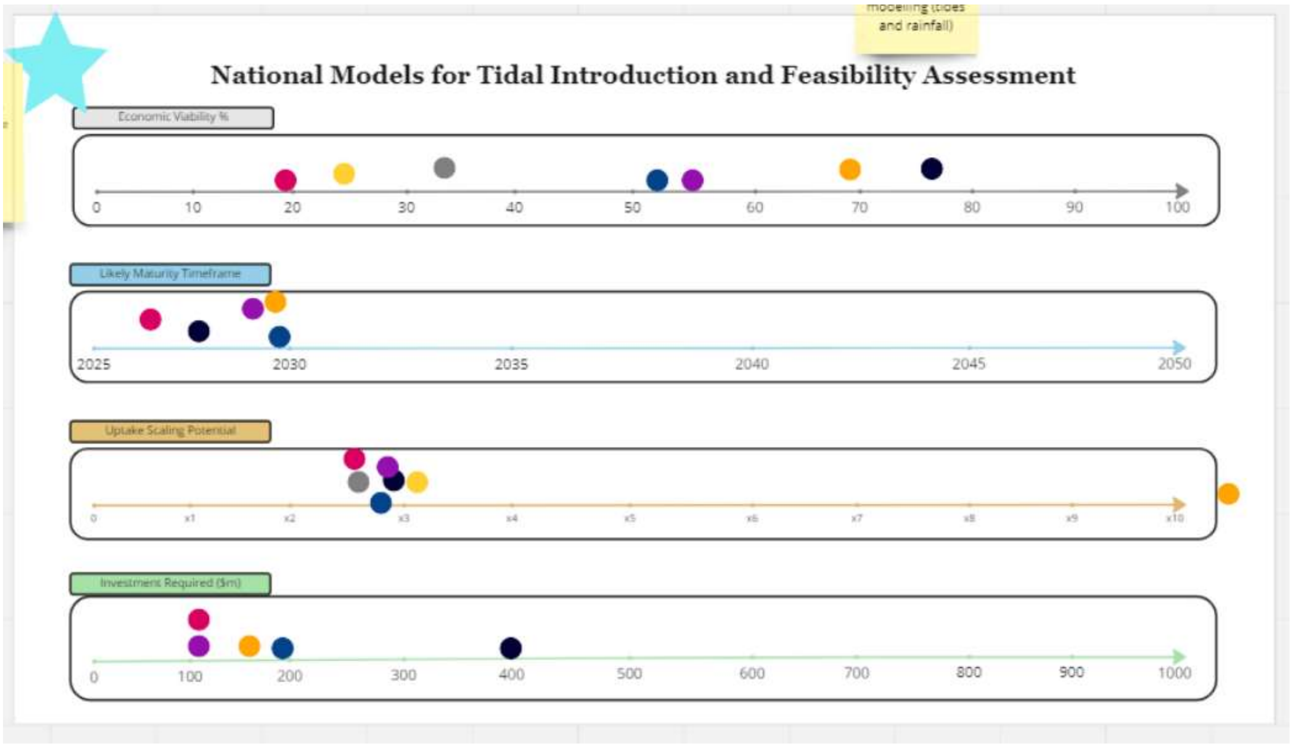


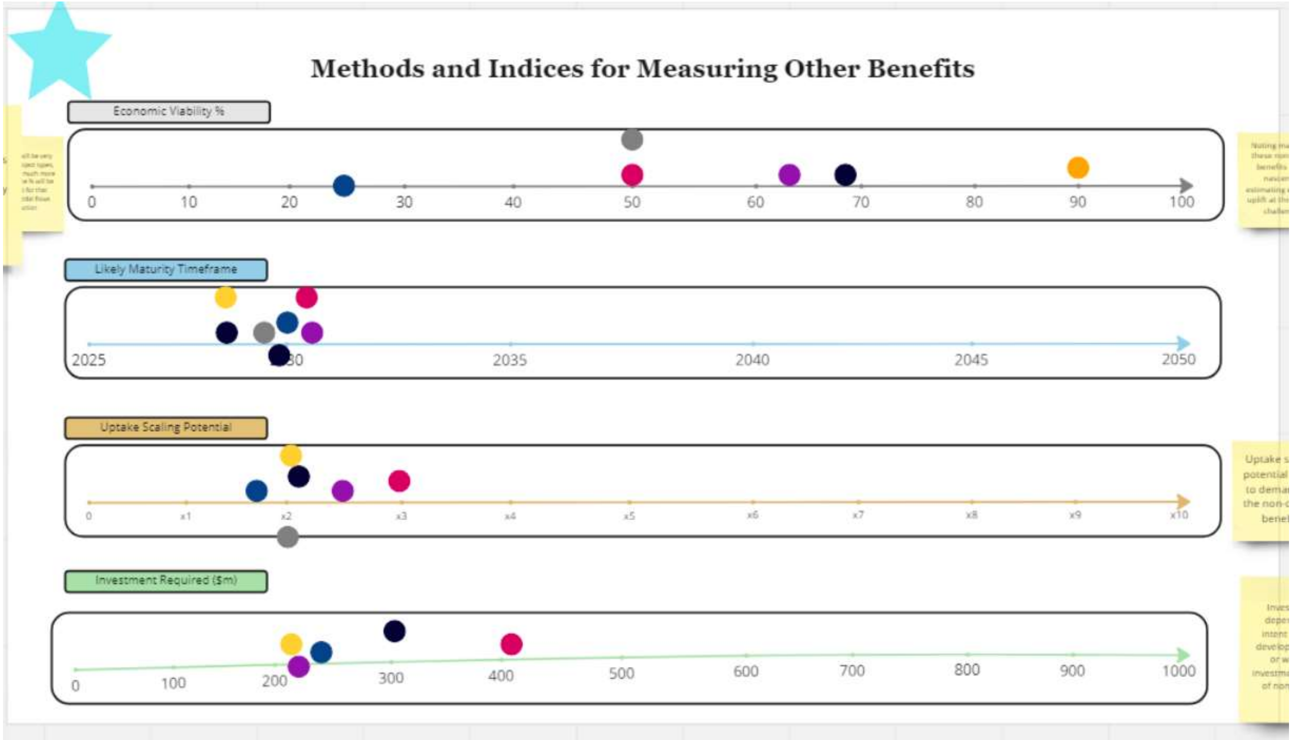

Control of pests, diseases and browsing animals
5
Cost reduction potential
$0
$10
$30
$40
$50
$60
$70
$80
$90
$100
Likely maturity timeframe
2025
2030
2035
2040
2045
2050
Uptake scaling potential
x1
x3
x5
x7
x10
miro


Lower-cost fencing techniques and materials
Cost reduction potential
$0
$10
$20
$30
$40
$50
$60
$70
$80
$90
$100
Likely maturity timeframe
2025
2030
2035
2040
2045
2050
Uptake scaling potential
x1
x3
x5
x7
x10
miro

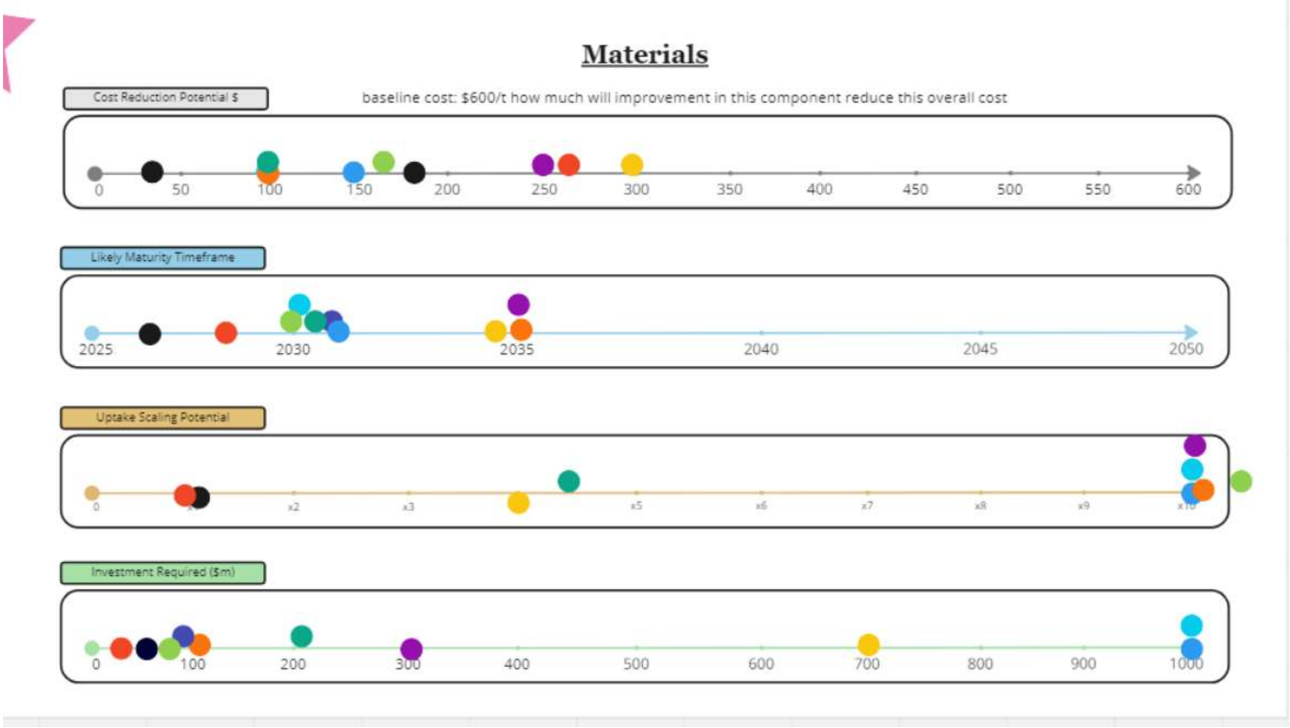
B.1.2 Blue carbon workshop

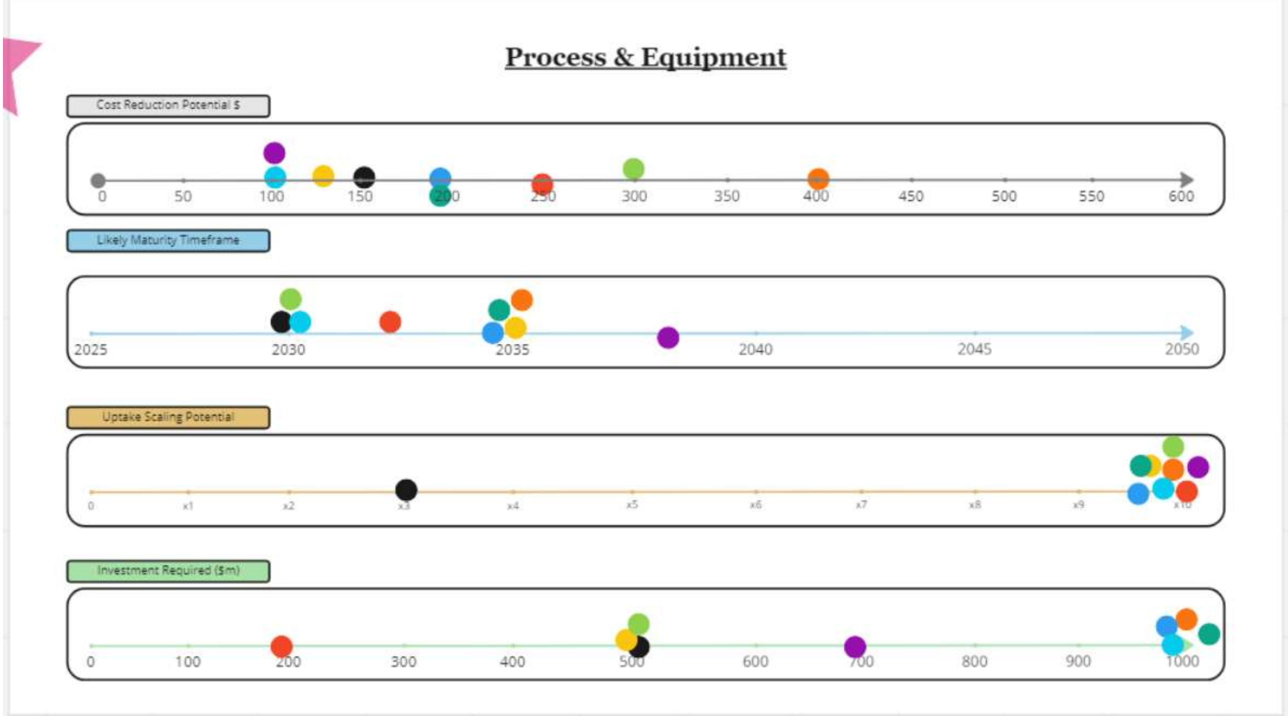


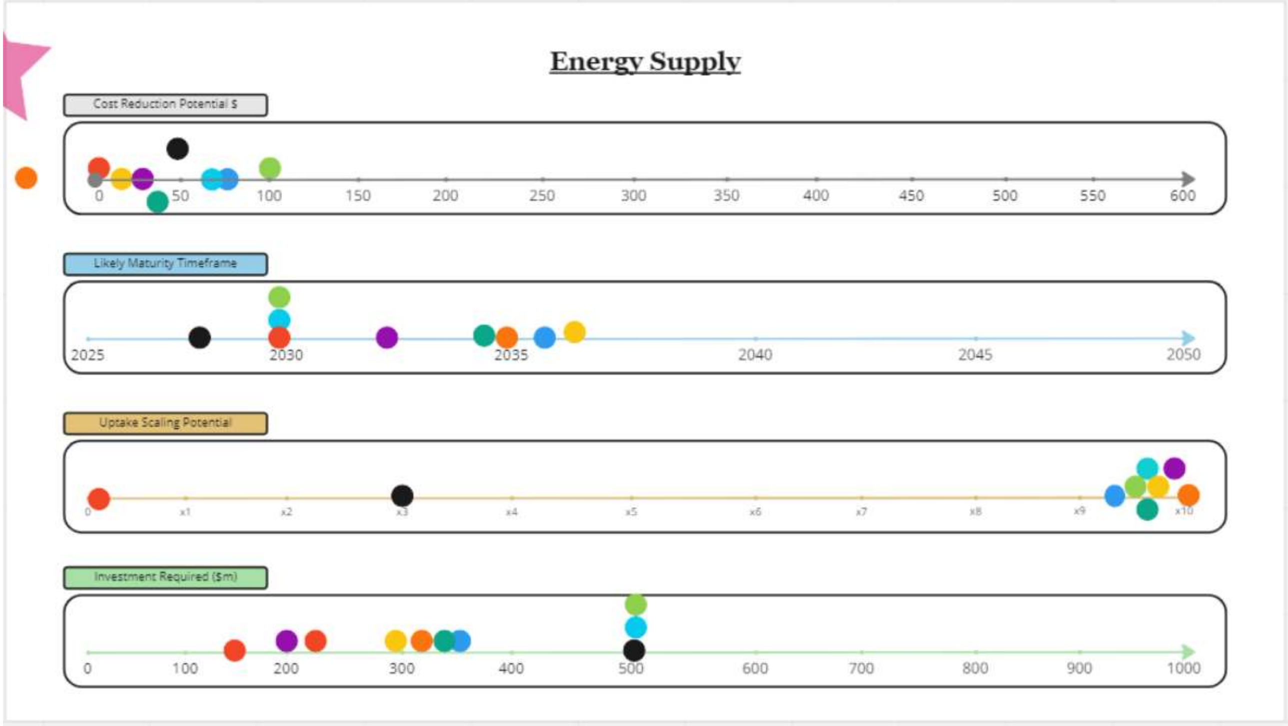




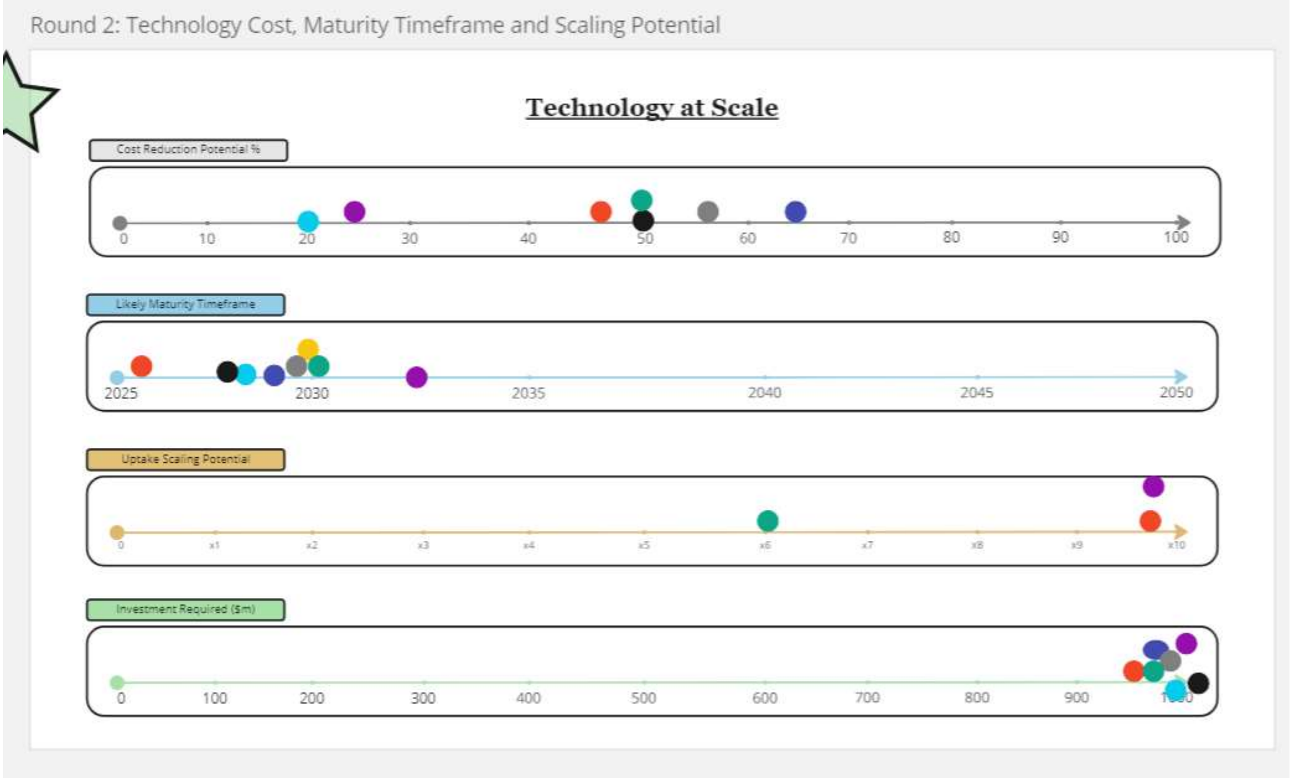
B.1.3 Direct air capture workshop




Process & Equipment
Cost Reduction Potential $
0 50 100 150 200 250 300 350 400 450 500 550 600
Likely Maturity Timeframe
2025 2030 2035 2040 2045 2050
Uptake Scaling Potential
0 x1 x2 x3 x4 x5 x6 x7 x8 x9 x10
Investment Required ($m)
0 100 200 300 400 500 600 700 800 900 1000

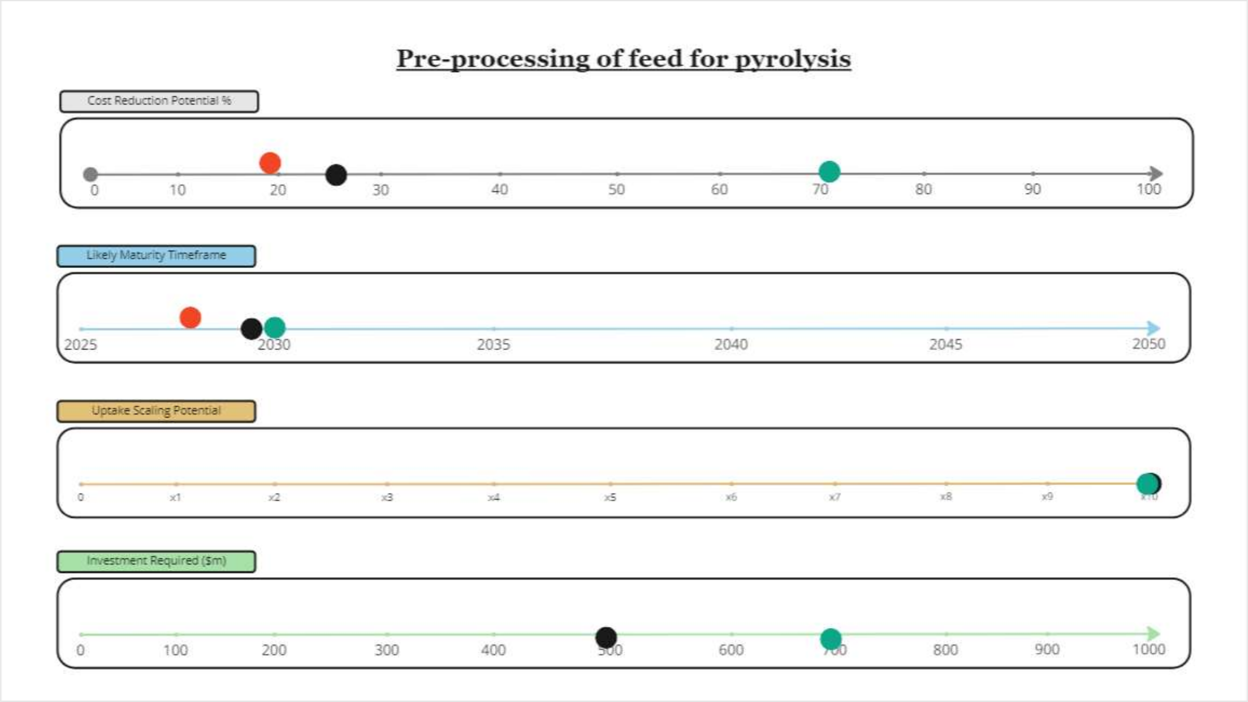

Energy Supply
Cost Reduction Potential $
0 50 100 150 200 250 300 350 400 450 500 550 600
Likely Maturity Timeframe
2025 2030 2035 2040 2045 2050
Uptake Scaling Potential
0 x1 x2 x3 x4 x5 x6 x7 x8 x9 x10
Investment Required ($m)
0 100 200 300 400 500 600 700 800 900 1000

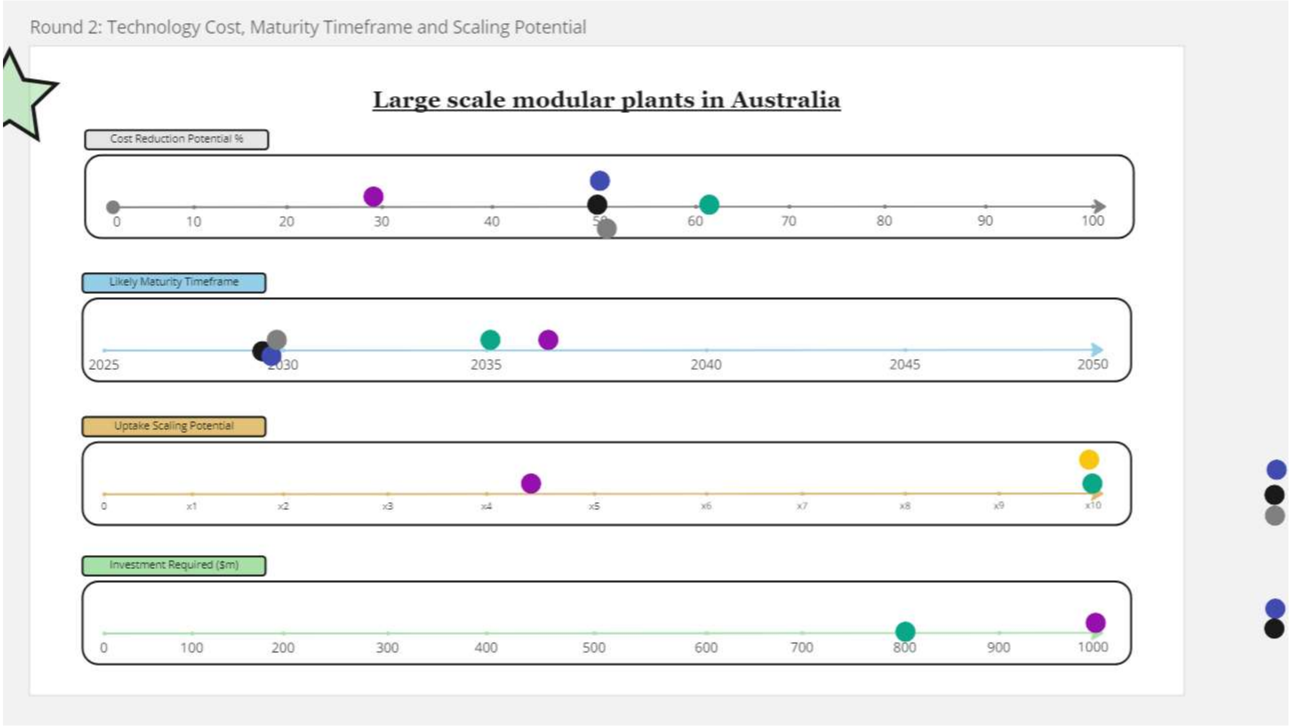
B.1.4 Biomass/biochar workshop

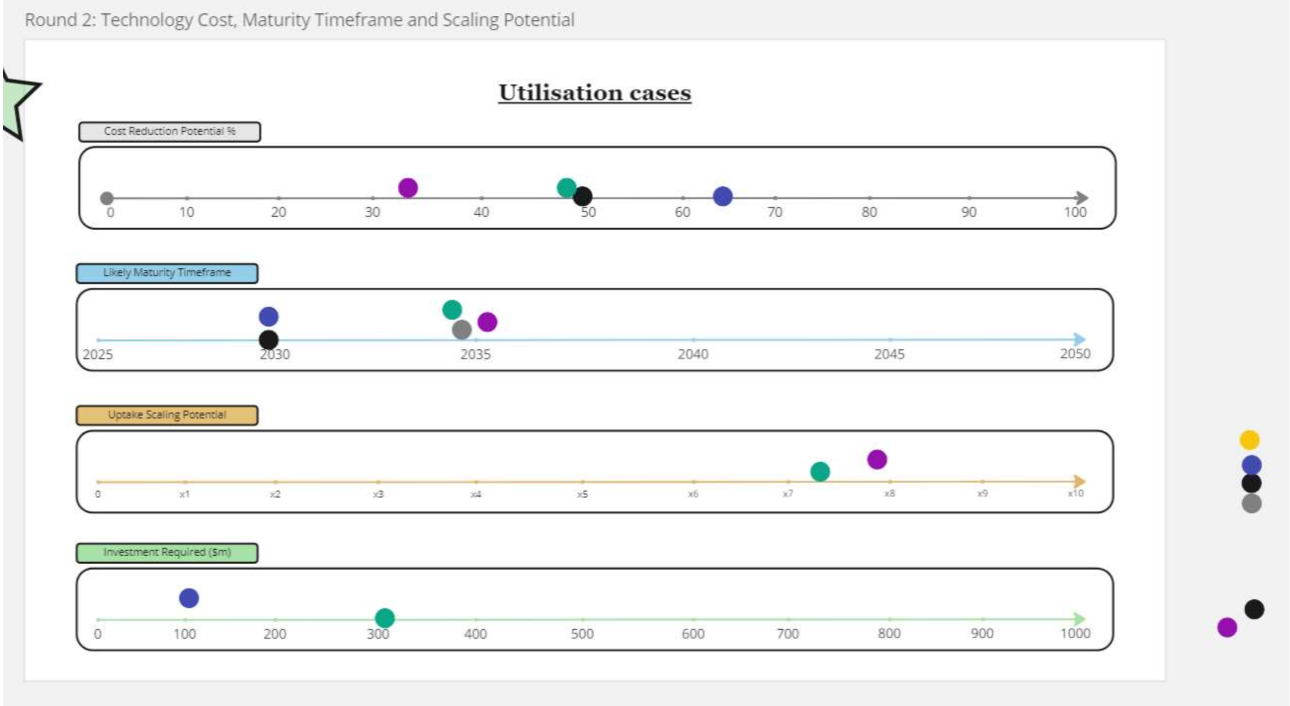


Round 2: Technology Cost, Maturity Timeframe and Scaling Potential

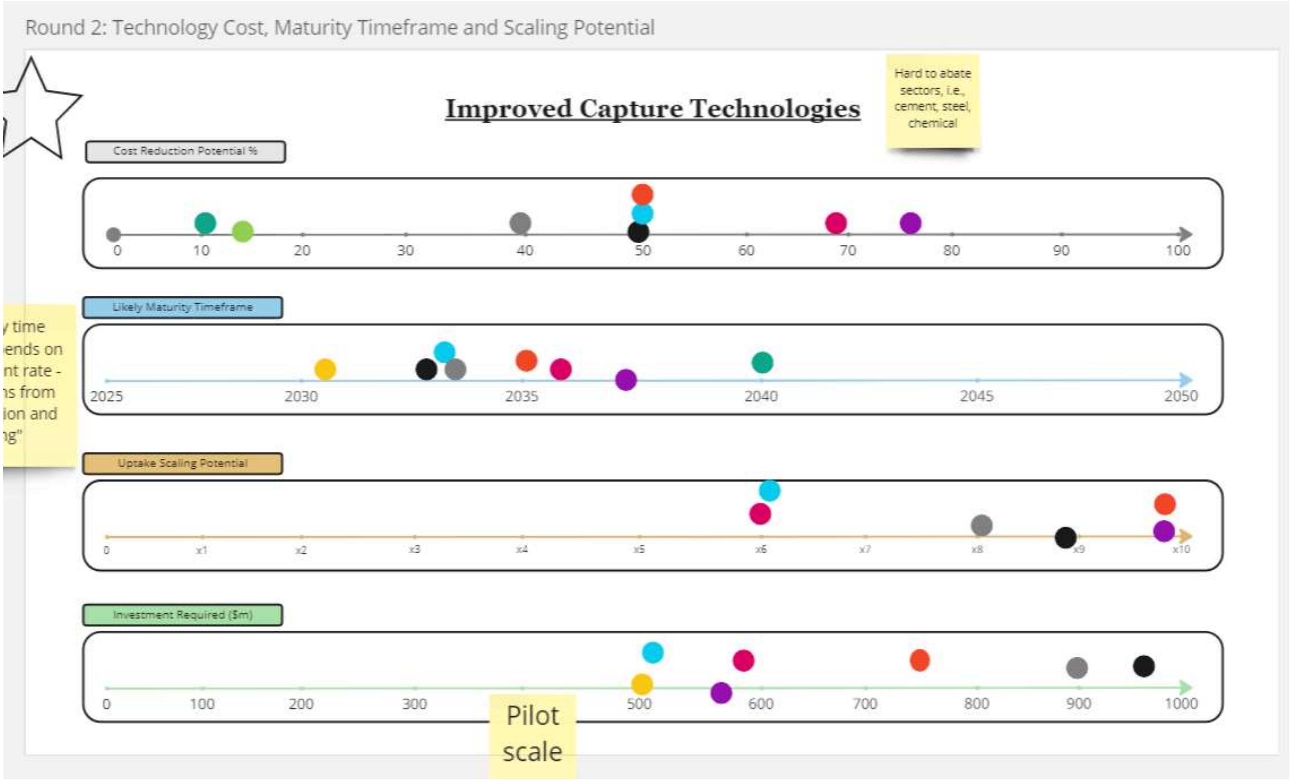
Round 2: Technology Cost, Maturity Timeframe and Scaling Potential

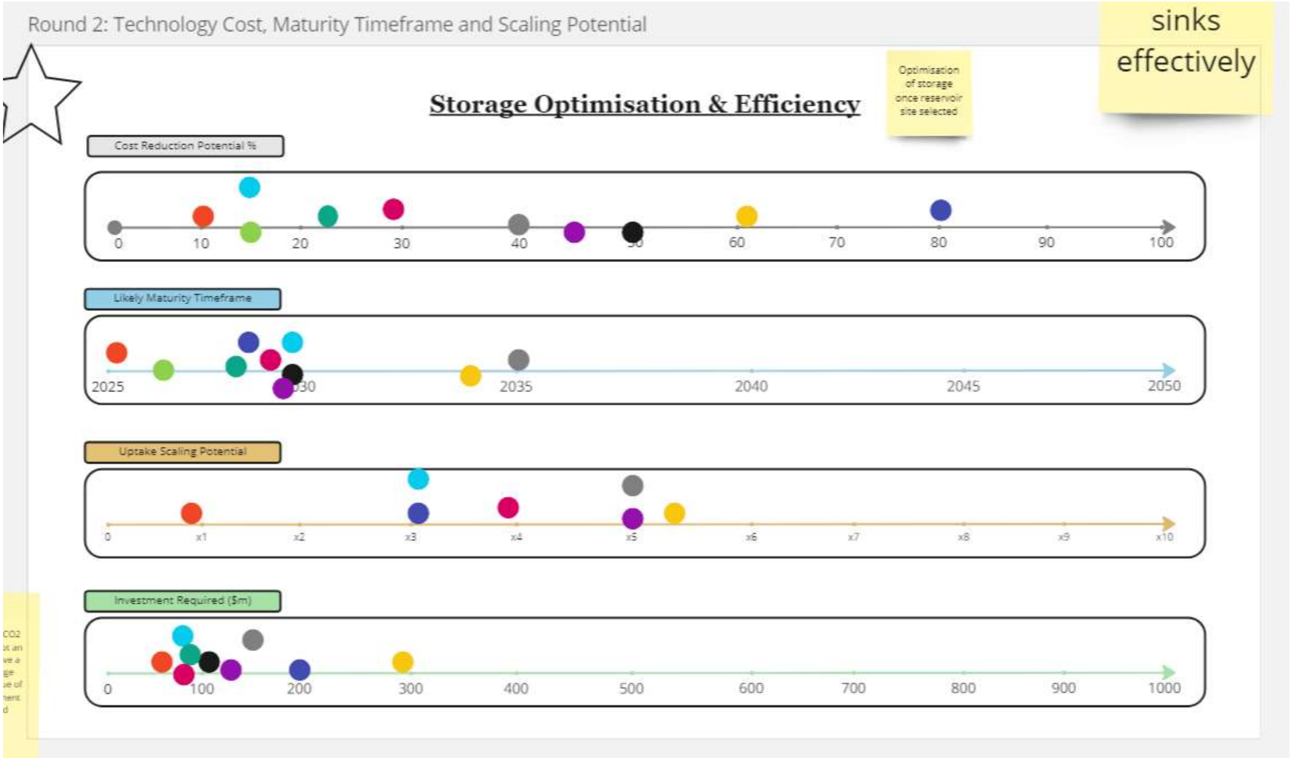



Round 2: Technology Cost, Maturity Timeframe and Scaling Potential
Large scale modular plants in Australia
Cost Reduction Potential %
0
10
20
30
40
50
60
70
80
90
100
Likely Maturity Timeframe
2025
2030
2035
2040
2045
2050
Uptake Scaling Potential
0
x1
x2
x3
x4
x5
x6
x7
x8
x9
x10
Investment Required ($m)
0
100
200
300
400
500
600
700
800
900
1000


Round 2: Technology Cost, Maturity Timeframe and Scaling Potential
Utilisation cases
Cost Reduction Potential %
0
10
20
30
40
50
60
70
80
90
100
Likely Maturity Timeframe
2025
2030
2035
2040
2045
2050
Uptake Scaling Potential
0
x1
x2
x3
x4
x5
x6
x7
x8
x9
x10
Investment Required ($m)
0
100
200
300
400
500
600
700
800
900
1000

B.1.5 Carbon capture and storage



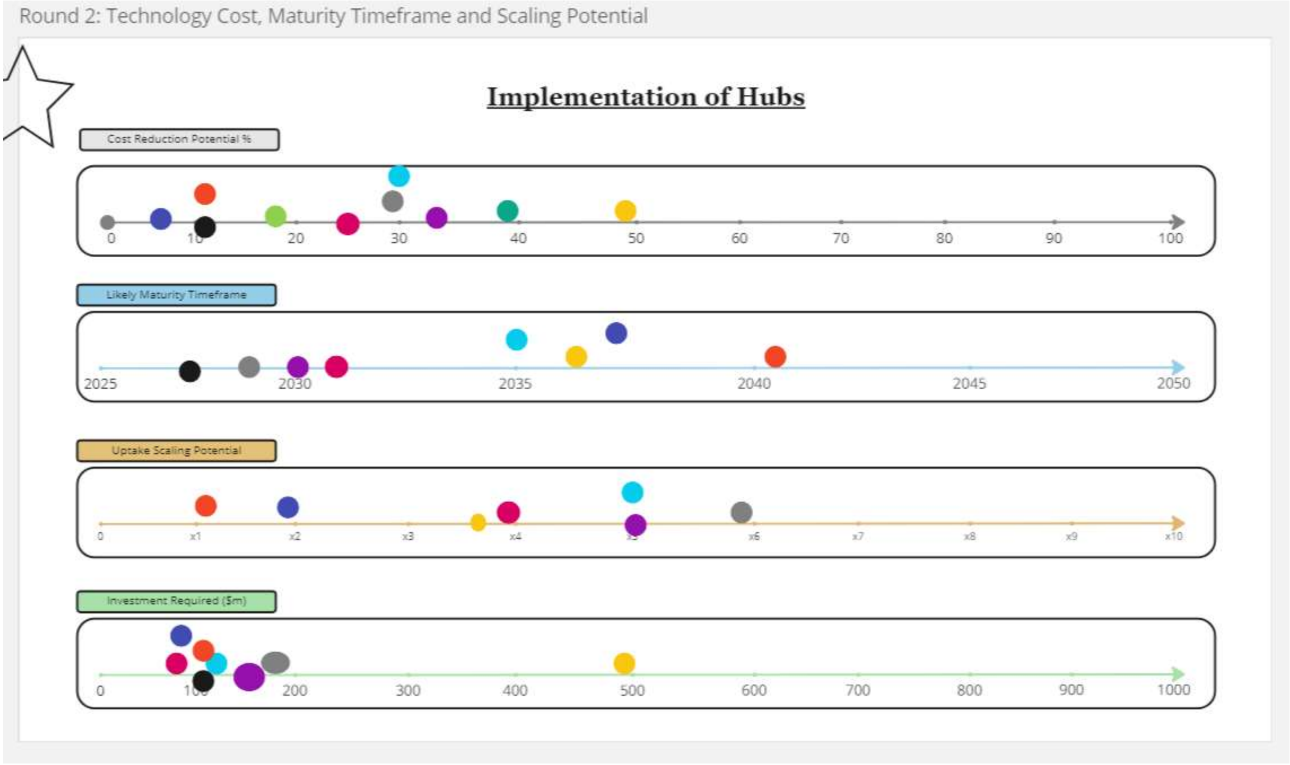


Round 2: Technology Cost, Maturity Timeframe and Scaling Potential

Storage Optimisation & Efficiency

Optimisation of storage once reservoir site selected

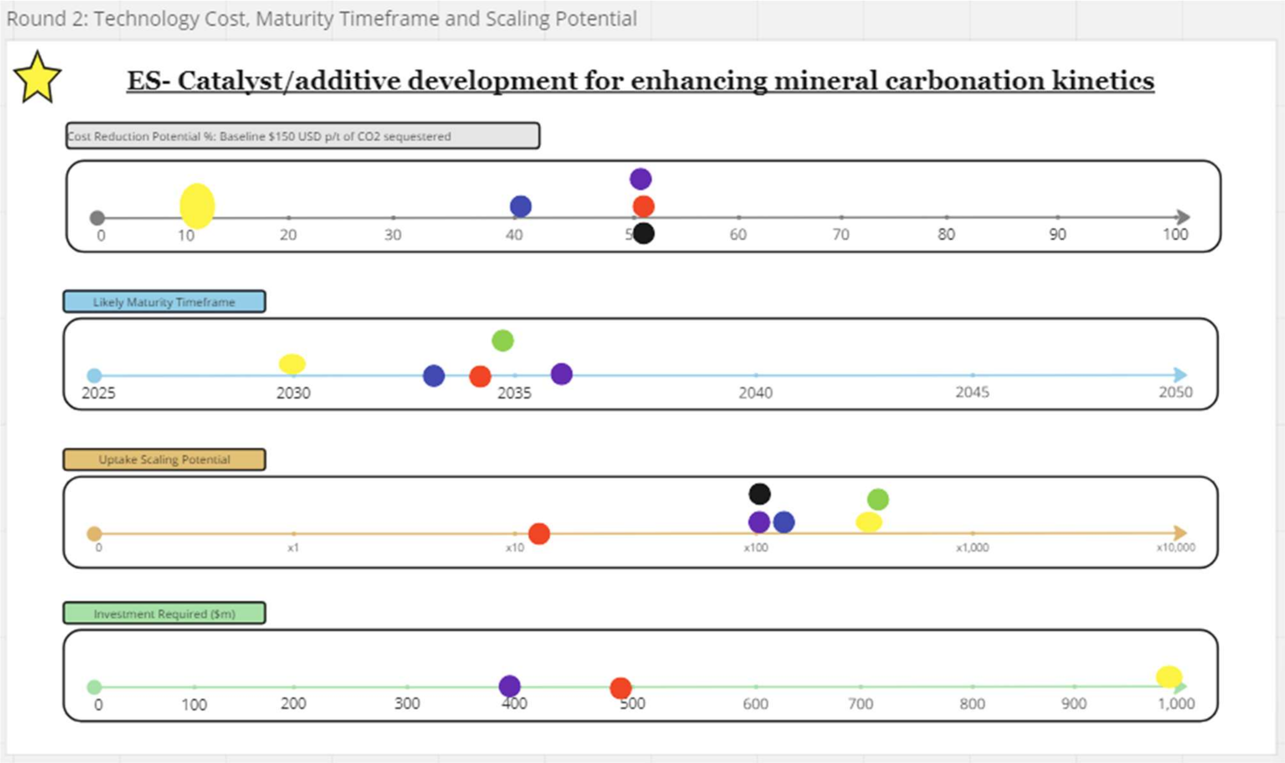
sinks effectively

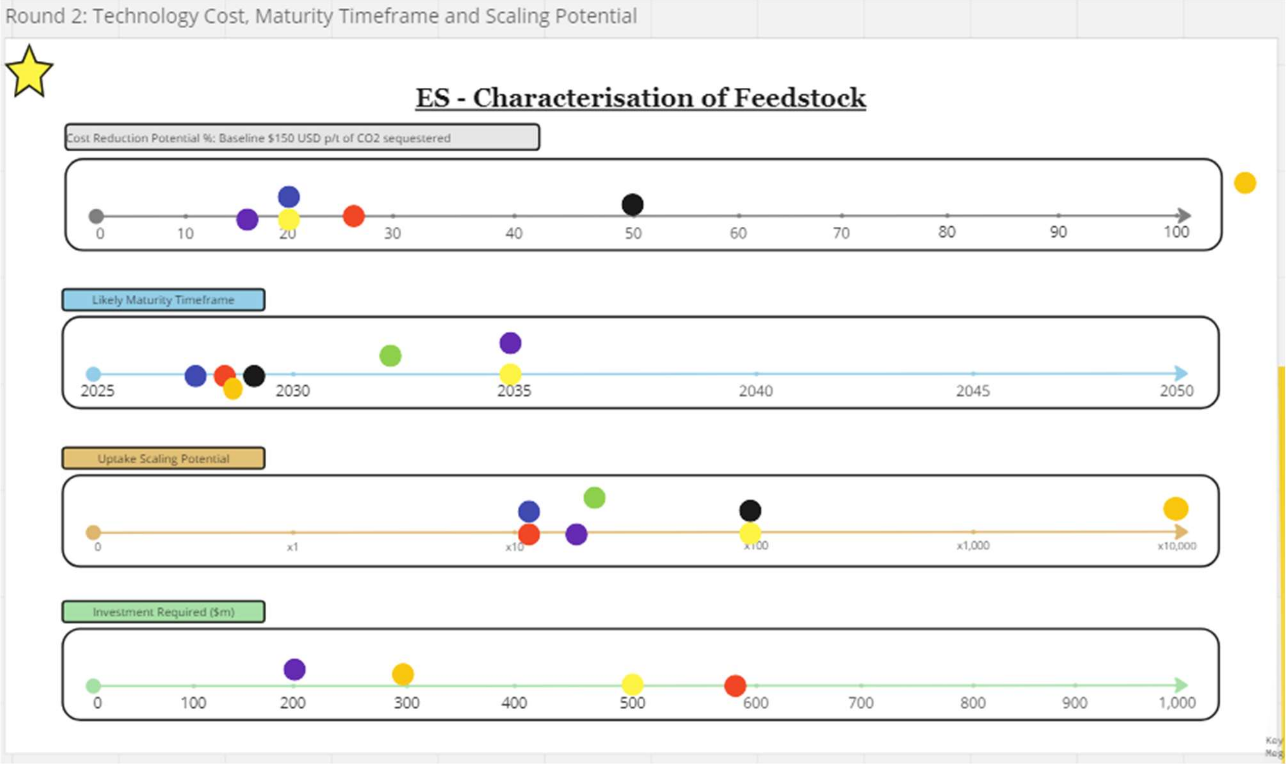


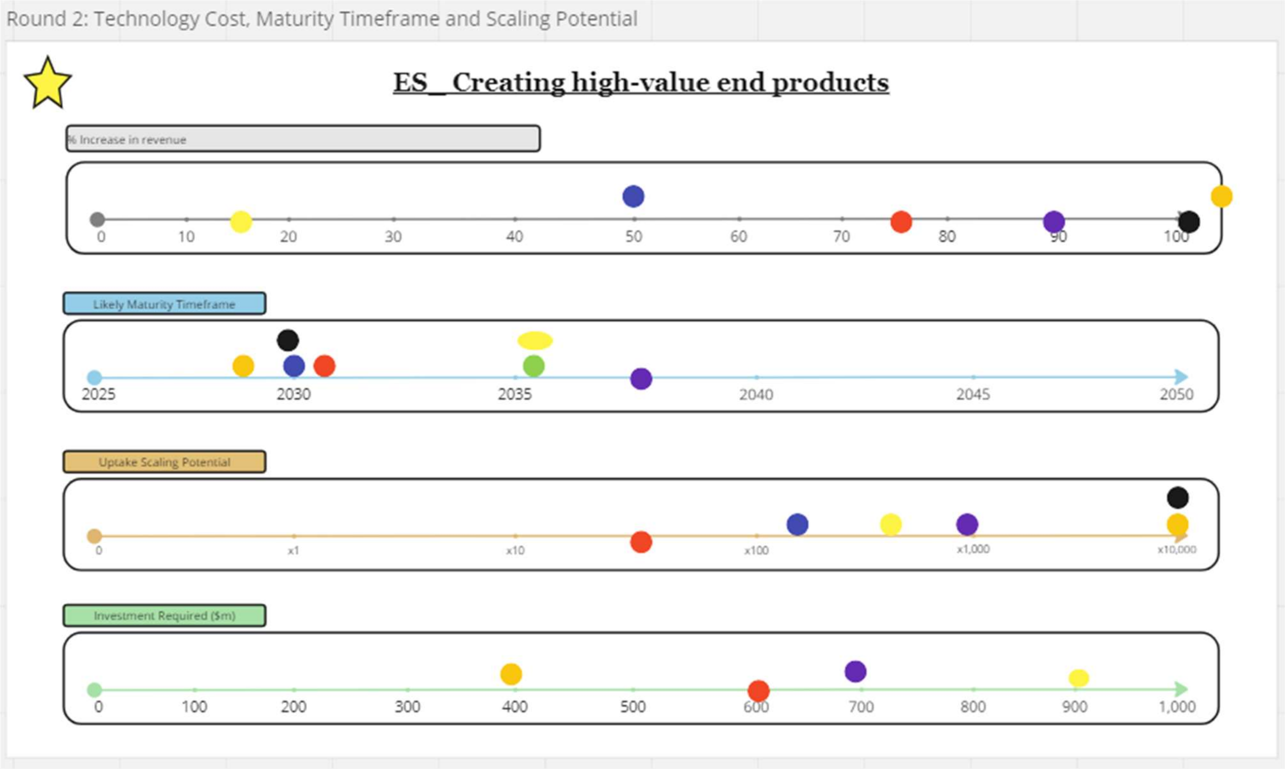
Round 2: Technology Cost, Maturity Timeframe and Scaling Potential

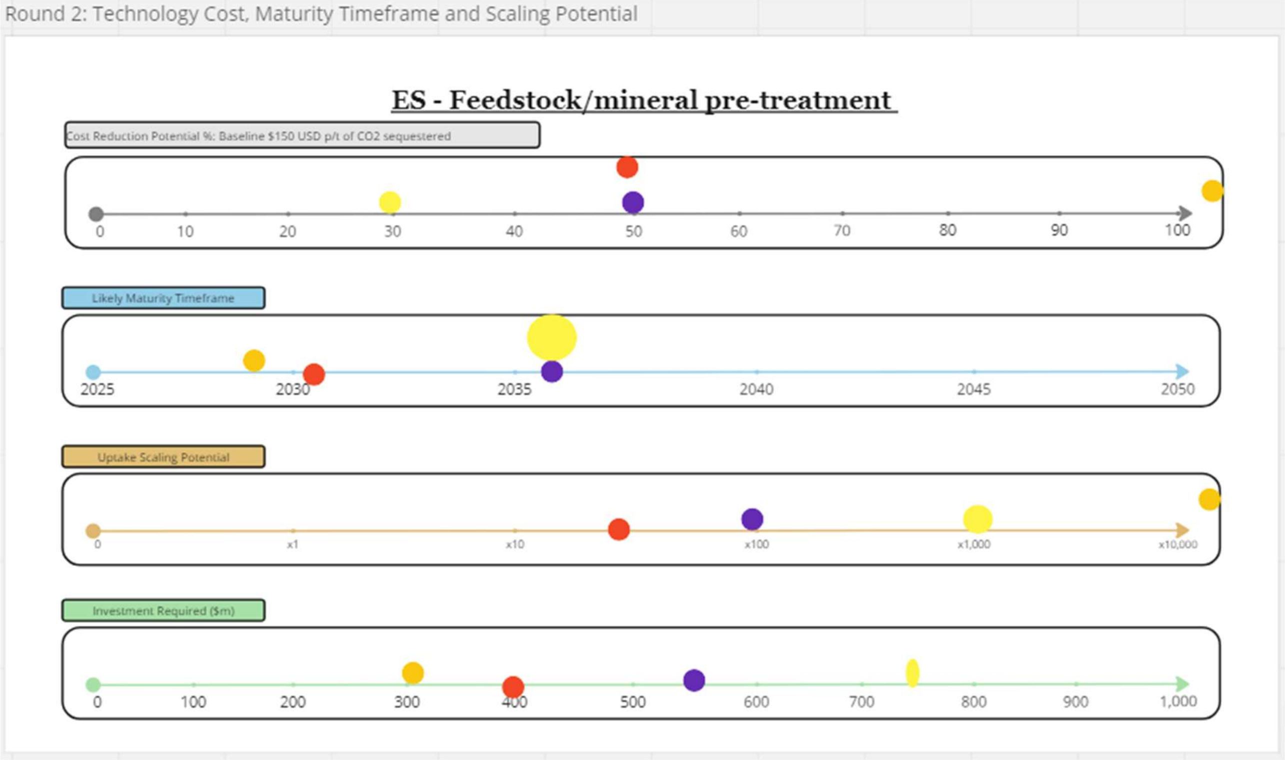
Implementation of Hubs

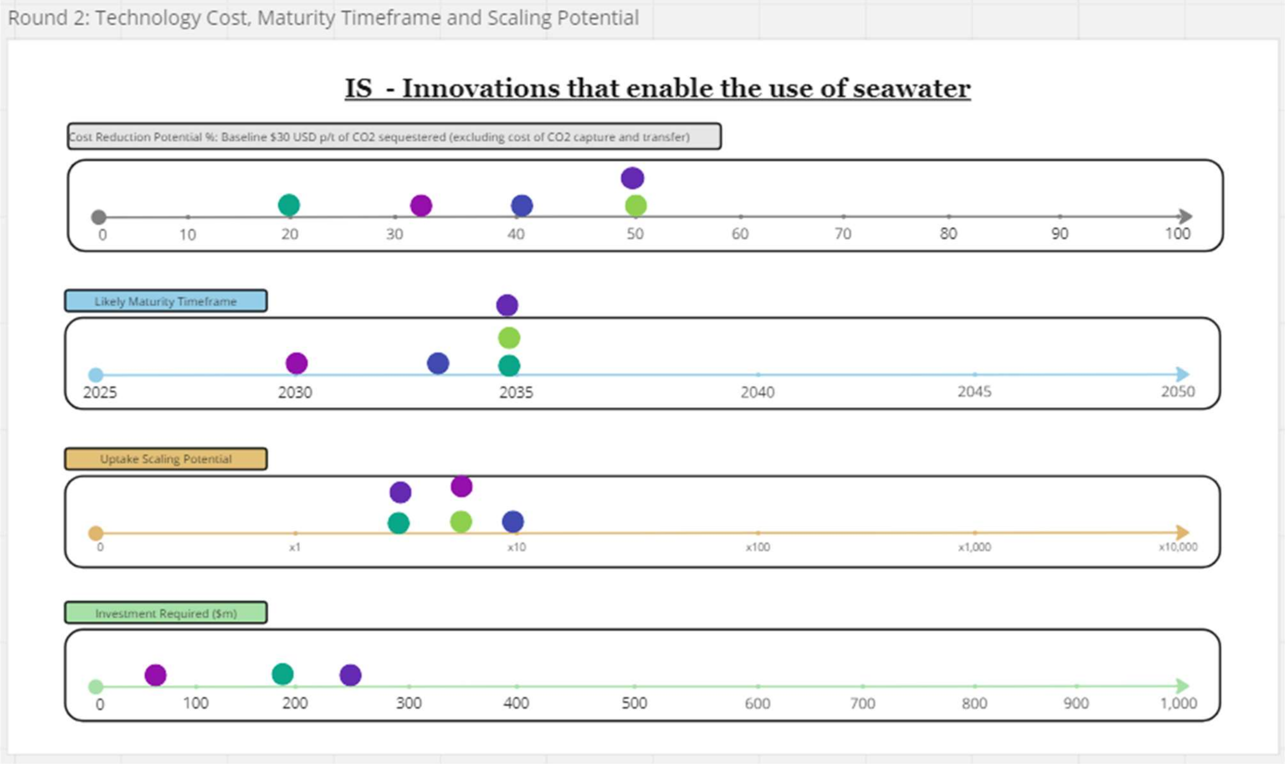
B.1.6 Mineral Carbonation

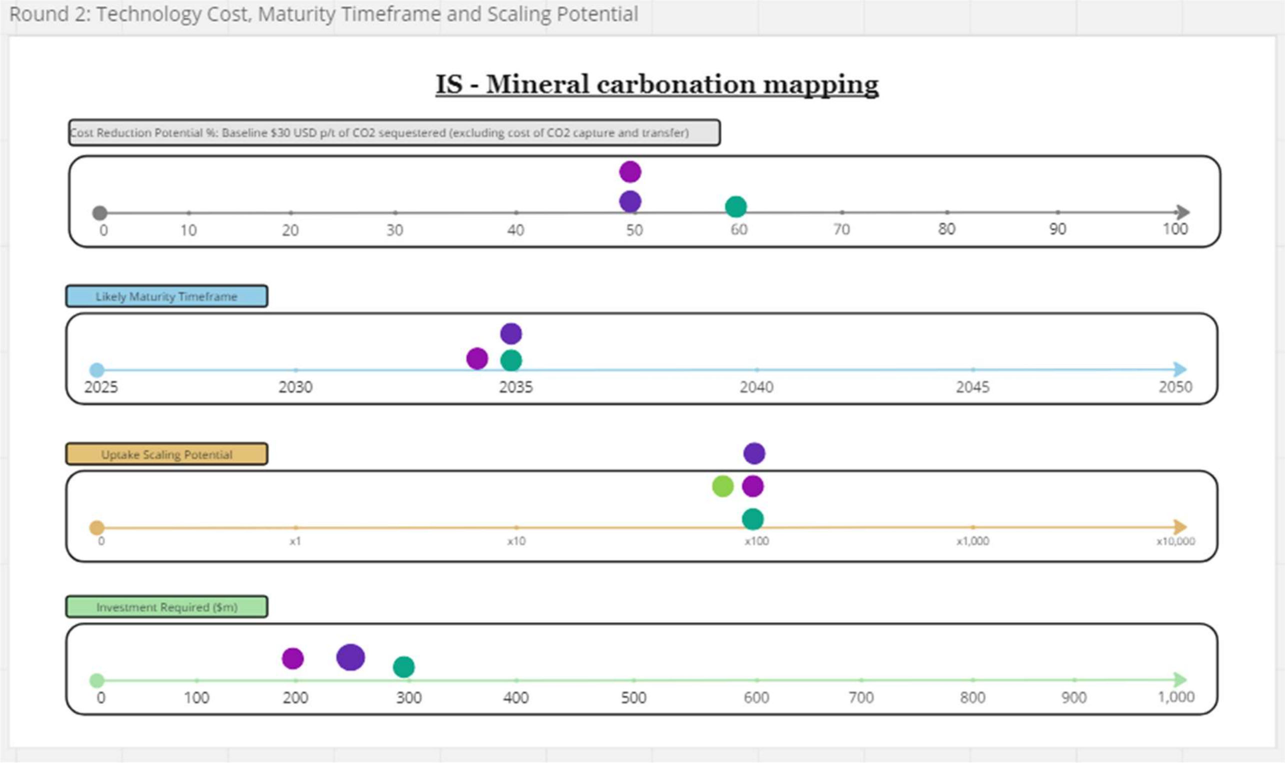


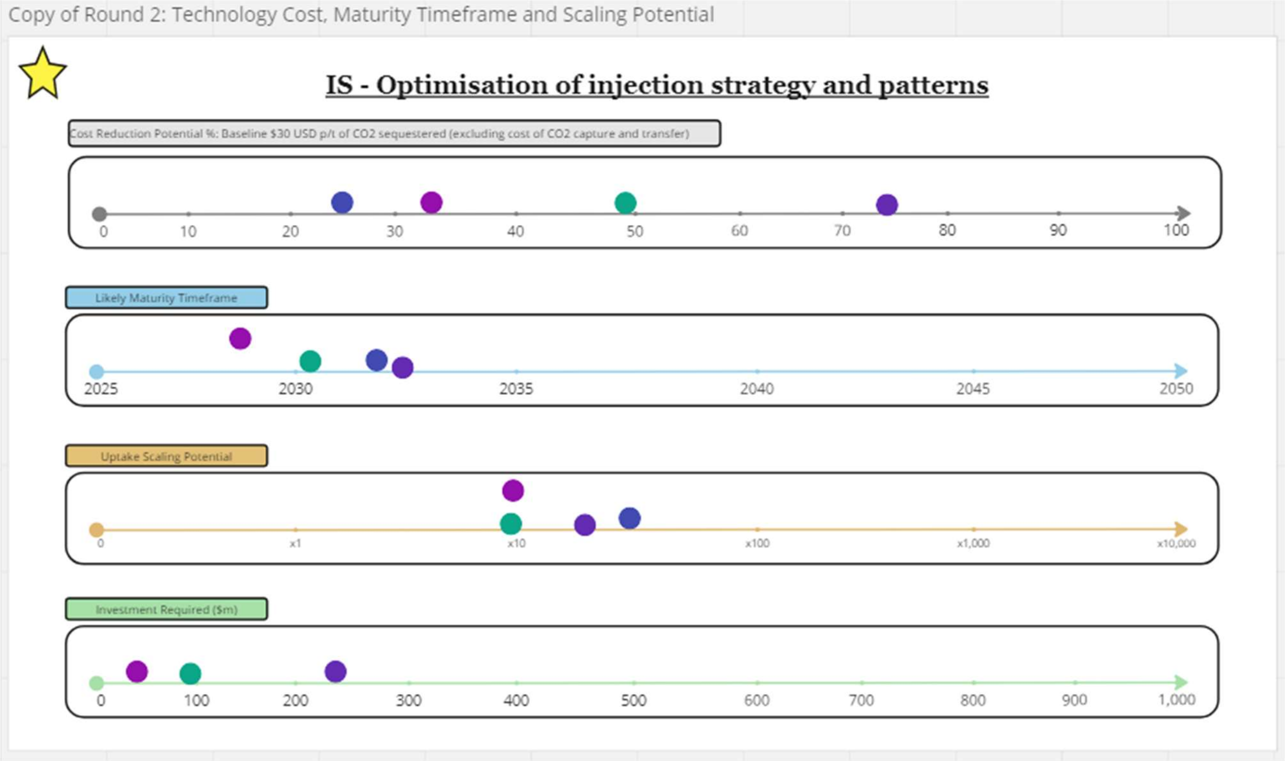



Round 2: Technology Cost, Maturity Timeframe and Scaling Potential
ES _ Creating high-value end products
% Increase in revenue
0
10
20
30
40
50
60
70
80
90
100
Likely Maturity Timeframe
2025
2030
2035
2040
2045
2050
Uptake Scaling Potential
0
x1
x10
x100
x1,000
x10,000
Investment Required ($m)
0
100
200
300
400
500
600
700
800
900
1,000


Round 2: Technology Cost, Maturity Timeframe and Scaling Potential
ES - Feedstock/mineral pre-treatment
Cost Reduction Potential %: Baseline $150 USD p/t of CO2 sequestered
0
10
20
30
40
50
60
70
80
90
100
Likely Maturity Timeframe
2025
2030
2035
2040
2045
2050
Uptake Scaling Potential
0
x1
x10
x100
x1,000
x10,000
Investment Required ($m)
0
100
200
300
400
500
600
700
800
900
1,000

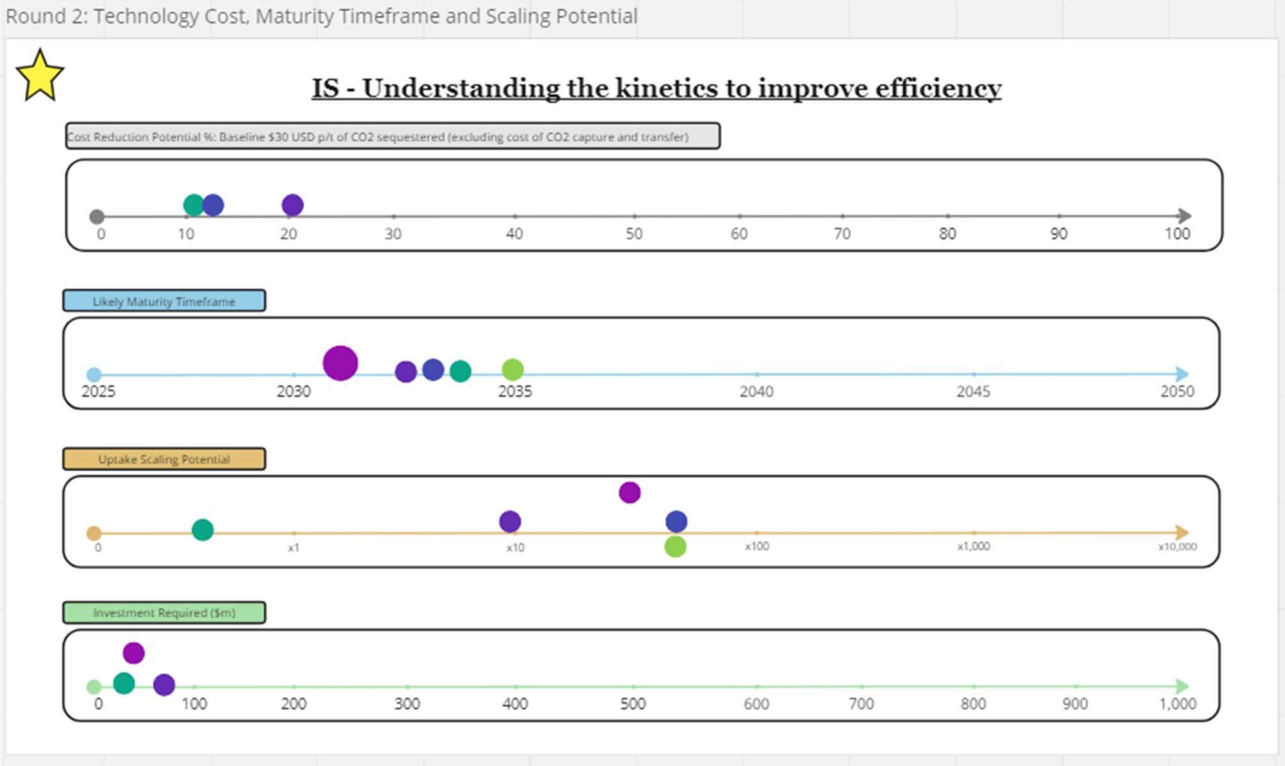

Round 2: Technology Cost, Maturity Timeframe and Scaling Potential
IS - Innovations that enable the use of seawater
Cost Reduction Potential %: Baseline $30 USD p/t of CO2 sequestered (excluding cost of CO2 capture and transfer)
0 10 20 30 40 50 60 70 80 90 100
Likely Maturity Timeframe
2025 2030 2035 2040 2045 2050
Uptake Scaling Potential
0 x1 x10 x100 x1,000 x10,000
Investment Required ($m)
0 100 200 300 400 500 600 700 800 900 1,000


Round 2: Technology Cost, Maturity Timeframe and Scaling Potential
IS - Mineral carbonation mapping
Cost Reduction Potential %: Baseline $30 USD p/t of CO2 sequestered (excluding cost of CO2 capture and transfer)
0 10 20 30 40 50 60 70 80 90 100
Likely Maturity Timeframe
2025 2030 2035 2040 2045 2050
Uptake Scaling Potential
0 x1 x10 x100 x1,000 x10,000
Investment Required ($m)
0 100 200 300 400 500 600 700 800 900 1,000



Copy of Round 2: Technology Cost, Maturity Timeframe and Scaling Potential

IS - Optimisation of injection strategy and patterns



Round 2: Technology Cost, Maturity Timeframe and Scaling Potential

IS - Understanding the kinetics to improve efficiency

Appendix C Workshop participants

C.1.1 Planted vegetation

Participant	Company
Natasa Sikman	AFPA/Forest Product Association
Anthony Fitzgerald	Carbon Conscious
Zoe Ryan	Climate Friendly
Tai White-Toney	CO2 Australia
Shaun Levick	CSIRO
Stephen Roxburgh	CSIRO
Paul Ryan	DCCEEW
Peter Ritson	FarmWoods
Jenny Sinclair	GreenCollar
Beren Spencer	INPEX
Arjan Wilkie	Landari
Philipp Kilham	Mullion Group
Annette Cowie	NSW DPI
Simon Dawkins	Oil Mallee Association
Martin Moroni	Private Forests Tasmania
Tim Moore	RegenCo
Rod Keenan	University of Melbourne
Liam Costello	Vic Department of Jobs, Precincts and Regions

C.1.2 Blue carbon

Participant	Company
Andy Steven	CSIRO
Ray Marcos Martinez	CSIRO
Cath Lovelock	University of Queensland
Lauren Drake	Pollination
Mat Vanderklift	CSIRO
Valerie Hagger	University of Queensland
Nikki Fitzgerald	DCCEW
Veda Fitzsimmons	Pollination

C.1.3 Direct air capture

Participant	Company
Paul Feron	CSIRO
Roger Aines	Lawrence Livermore national Laboratory
Timothy Fout	US Department of Energy
Paul Webley	Monash University
Deanna Dalessandro	University of Sydney

Julian Tureck	Aspiridac
Ali Kiani	CSIRO
M Lucquiaud	Sheffield University
Christopher Jones	Georgia Tech

C.1.4 Biomass/biochar

Participant	Company
Peter Burgess	Rainbow Bee Eater
Annette Cowie	NSW DPI
Craig Bagnall	Catalyst Environmental Management
Fabiano Ximenes	NSW DPI
Rajinder Singh	Daintree Bio
Ian O'Hara	QUT
Stephen Joseph	UNSW
Gustavo Fimbres Weihs	University of Sydney
Jenny Hayward	CSIRO
Nawshad Haque	CSIRO

C.1.5 Carbon capture and storage

Participant	Company
Peter Cook	Melbourne University
Charles Jenkins	CSIRO
Darren Greer	Glencore
Andrew Garnett	University of Queensland
Phil Grainger	Inpex
Geoff Obrien	Co2rc
Noel Simento	Anlecrd
Matthew Sherwell	Santos

C.1.6 Mineral Carbonation

Participant	Company
Renee Birchall	CSIRO
Andrew Lenton	CSIRO
John Beever	Green Mag Group
Sophia Hamblin-Wang	Mineral Carbonation
Mojtaba Seyyedi	Global CCS Institute
Philip Fawell	CSIRO
Mei Yuan	CSIRO
Stuart Watson	Rio Tinto
Ralf Haese	Melbourne University

Appendix D Review Comments

Workshop	Participant Comment
Planted vegetation	I just reviewed the docs provided and the one important observation from the workshop that is not covered in the report (that I can see) is that the technologies and hence savings depend on the specific methodology being used. The HIR, reforestation and plantations methods have different cost bases and different requirements, hence the spread in assessment of the cost/benefit for each technology, "despite the consensus building exercise". Is there a need to clarify what is covered by zero or low emission fuels, in relation to inclusion of electrification as part of this technology, i.e. is it correct to describe electrification as zero or low emissions fuels, or should the category description to changed to include electrification?
Blue Carbon	I understand the focus of this workshop was about exploring technology options for cost reduction in tidal restoration projects. Another option for cost reduction is aggregation of restoration sites to form a restoration program like is being done with environmental plantings under the ERF. Although we didn't identify a technology that could assist this. I notice that the co-benefits receive no cost reduction, but we should frame this as how it can build the regional economy (i.e. through enhancing natural resources), which could build the capacity/willingness of the community to undertake restoration projects.
CCS	CCS is a chain of technologies from capture, transport, compression, well design and storage - each has its own challenges and enablers. It is too diverse a topic to be easily captured in one 3 hour online workshop where not all elements of the chain were represented. Thus the workshop findings are a guide to some aspects of CCS but not comprehensive enough to be useful.
Mineral Carbonation	I think the quoted cost (from Carbfix) of $25/tonne as the base cost for in-situ carbonation is deeply misleading. First of all the Carbfix cost is only part of the system e.g. it doesn't include the wells for water supply, and the delineation of the boundaries around costing is crucial for any comparisons. The Carbfix cost also doesn't include the capture process, and that to me is not a fair comparison to other technologies. Lastly and most crucially, the Carbfix case is an extremely favourable case for in-situ carbonation because the effective permeability is so high (around a Darcy for Carbfix2). The costs in lower permeability could be 10 or 100 times greater. So the whole presentation of how particular advances in situ carbonation might reduce costs (which in themselves are incredibly speculative) are subject to enormous error based on a scale of orders of magnitude. I don't think that's a good basis for deciding which directions to follow.

Appendix E Cash flow model for a biochar production plant

E.1 Production system

The hypothetical biochar production system is a medium sized (1 MWh) slow-pyrolysis system with fixed bed twin-fire pyrolyser. We assume this type of system because:(1) its medium size means that there is likely sufficient feedstock to run the system in several Australian regions; and (2) Homagain et al. (2016) used this type of system for their economic assessment of biochar production in Canada, providing some cost data for this analysis. We assume that the biochar produced is applied into agricultural fields.

Rajabi Hamedani et al. (2019) provide the following inventory for 1 tonne of biochar obtained via willow pyrolysis and applied into fields. Note, in our analysis we assume that woodchips from sawmill residue rather than willow woodchips are used as a feedstock.

- Inputs: willow woodchips 3.73 t; heat (pyrolysis) 1.92 GJ
- Outputs: biochar 1 t; syngas (SO_2 0.015 kg; NO_x 0.2 kg)
- Avoided products: natural gas 0.37 t; electricity 1.01 GJ; N fertiliser 0.66 kg; K fertiliser 0.13 kg; P fertiliser 0.1 kg
- Avoided emissions from the application of 1 t of biochar into fields: 2.2 t CO_2 and 2.6 kg N_20, which combine for total avoided emissions of 2.975 t CO2-e

We assume that the production plant will be operational for 25 years (Homagain et al. 2016) and will have 7000 working hours per year (Rajabi Hamedani et al. 2019). As such, the plant produces 13,125 tonnes of biochar per year, which requires 48,956 tonnes of sawmill residue per year as feedstock. Based on NSW sawmill residues data,[7] there are several regions in NSW that have over 50,000 tonnes of sawmill residue within a few hundred kilometres of a hypothetical production plant.

We assume that the production system starts with the purchase and transportation of the feedstock to the plant and ends with the production of biochar, which is then stored on site. That is, we exclude the sale and transportation of biochar and its co-products (fertilisers, SO_2, NO_x) from the model, as the feasibility and costs of selling these products in different regions are unknown.

E.2 Revenues

In the above inventory for 1 tonne of biochar production, the quantities of carbon, electricity and natural gas produced are constants multiplied by the quantity of biochar produced B_t. Therefore, total revenue from the hypothetical plant's biochar production in each year $t = 1, 2, \dots, 25$ can be expressed as:

$$R_t = B_t(2.975P_{carbon} + 0.281P_{elec} + 0.37P_{gas})$$

where:

---

[7] https://spatial.industry.nsw.gov.au/arcgis/rest/services/Bioenergy_Assessment/Forestry_SawmillResidues/MapServer

- B_t is the amount (tonnes) of biochar produced
- P_{carbon} is the price per t CO_2-e avoided
- P_{elec} is the price per MWh of electricity
- P_{gas} is the price per tonne of natural gas.

The plant's pyrolysis process generates excess energy as a co-product in the form of bio-oil and syngas, avoiding some consumption and production of electricity and natural gas (Rajabi Hamedani et al. 2019). We assume that syngas is burnt to provide the internal energy requirements for heat and electricity of the pyrolysis process (i.e. it is a cost offset rather than a revenue stream). We also assume that excess energy from burning syngas on top of internal energy requirements is offset to the market as a substitute for natural gas and electricity.

E.3 Costs

The initial capital cost of the plant is:

$$C_0 = C_{equip} + C_{build} + C_{othe}$$

where C_{equip} is the cost of plant equipment, C_{build} is the construction cost of the plant, and C_{other} is the cost of related activities (feasibility study etc.).

Total production cost in each year $t = 1, 2, \ldots, 25$ is:

$$C_t = B_t[3.73(P_{wood} + 6.2 + 0.16D) + 0.533P_{elec}] + M_t + S_t + L_t$$

where:

- P_{wood} is the price of sawmill residue log (the feedstock)
- D is the average haulage distance of feedstock to the production plant for processing
- $6.2 + 0.16D$ is the cost of hauling 1 tonne of feedstock to the plant (Roxburgh et al. 2020)
- M_t is the annual plant maintenance cost
- S_t is the annual cost of storing the feedstock and the outputs
- L_t is the annual labour cost of running the plant.

E.4 Economic viability

Investing in the production plant is economically viable if the NPV of the above cash flows exceeds zero. The NPV of investing in the plant is:

$$NPV = \sum_{t=0}^{25} \frac{(R_t - C_t)}{(1 + i)^t}$$

where i is the discount rate.

E.5 Baseline parameter values

The table below provides the baseline parameter values used in the model.

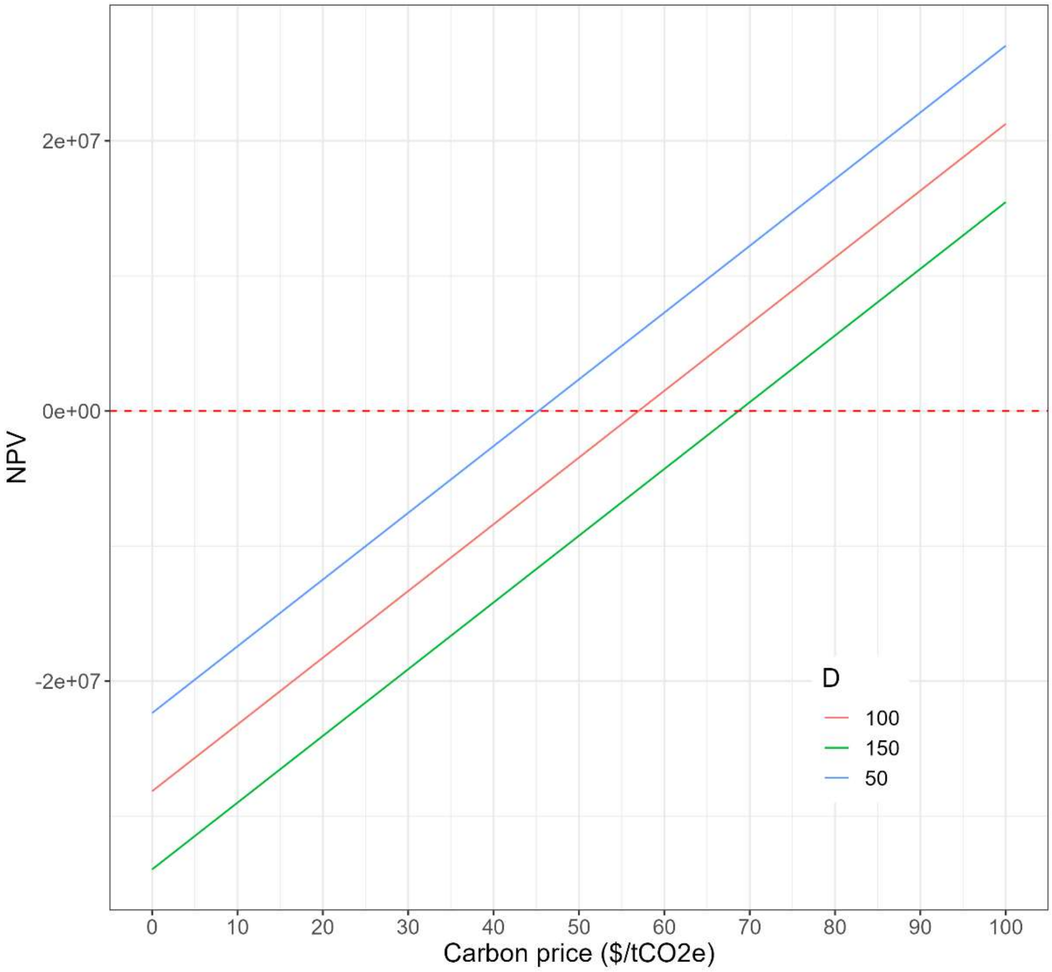
Parameter	Description	Value	Notes
B_t	Annual amount (t) of biochar produced	13,125 t	
P_{carbon}	Price per t CO_2e emissions reduction	\$20	

P_{elec}	Price for 1 MWh electricity	\$100	Based on recent wholesale electricity prices in Australia: https://www.aer.gov.au/wholesale-markets/wholesale-statistics.
P_{gas}	Price for 1 t of natural gas	\$273	Based on the longer-term average natural gas price of \$7 per GJ in Australia (with 39 GJ per tonne of natural gas): https://www.aer.gov.au/wholesale-markets/wholesale-statistics/gas-market-prices.
P_{wood}	Price for 1 t of wood residue	\$40	We assume a price of \$30 per tonne for residue log as per Roxburgh et al. (2020) and add a cost of \$10 per tonne to convert the log into pellets as feedstock.
C_{equip}	Cost of plant equipment	\$1.6 m	Source: Homagain et al. (2016), adjusted for inflation and exchange rates.
C_{build}	Cost of plant construction and installation	\$1 m	Source: Homagain et al. (2016), adjusted for inflation and exchange rates.
C_{other}	Other initial costs related to the installation of the plant	\$0.2 m	Source: Homagain et al. (2016), adjusted for inflation and exchange rates.
D	Average haulage distance (feedstock to plant and biochar to field)	100 km	Average haulage distance will depend on the region. Average haulage distance of feedstock to plant is likely to be less than 100 km for several regions in NSW based on this map: https://spatial.industry.nsw.gov.au/arcgis/rest/services/Bioenergy_Assessment/Forestry_SawmillResidues/MapServer
M_t	Annual plant maintenance cost	\$5000	Source: Homagain et al. (2016), adjusted for inflation and exchange rates.
S_t	Storage cost for feedstock and biochar	\$10,000	Source: Homagain et al. (2016), adjusted for inflation and exchange rates.
L_t	Labour cost to run the pyrolysis process	\$100,000	Source: Homagain et al. (2016), adjusted for inflation and exchange rates. To account for inflation, we assume labour cost increases by 3% per year from a value of \$100,000 in year 1.
r	Discount rate	7%	
i	Inflation rate	3%	

[1] https://www.soilwealth.com.au/resources/articles-and-publications/nitrogen-fertiliser-price-and-supply-a-good-reason-to-look-at-legume-cover-crops/#:~:text=As%20a%20result%2C%20the%20cost,tonne%20or%20%243.04%2Fkg%20N

[2] https://www.indexmundi.com/commodities/?commodity=potassium-chloride&months=60&currency=aud

[3] https://www.farmonline.com.au/story/7512258/phosphorus-fertiliser-could-hit-1500t-port-next-year/



E.6 Scenario analysis

We compute the cost per tonne of carbon sequestration (including electricity and gas cost offsets) and the plant's NPV under the scenarios below. The cost per tonne of carbon sequestration is:

$$C_{seq} = \sum_{t=0}^{25} \frac{C_t - B_t(0.281P_{elec} - 0.37P_{gas})}{B_t}$$

where $B_t(0.281P_{elec} - 0.37P_{gas})$ is the electricity and gas cost offset.

The scenarios we test are:

- **Baseline scenario.** All parameters are set at their baseline values from section 5.
- **Scenario 1: technology at scale.** This scenario involves a 39% reduction in establishment costs (C_0) and operational costs (maintenance costs M_t, labour costs L_t, and electricity input costs $0.533B_tP_{elec}$).
- **Scenario 2: large-scale modular plants.** This scenario involves a 48% reduction in establishment costs (C_0) and a 48% reduction in the cost of transporting the feedstock to the plant (which is $6.2 + 0.16D$ per tonne).
- **Scenario 3: biochar conversion.** This scenario involves a 55% decrease in operational costs (maintenance costs M_t, labour costs L_t, and electricity input costs $0.533B_tP_{elec}$).

E.7 Sensitivity analysis

We compute $C_{seq} = \sum_{t=0}^{25} C_t / B_t$ and the plant's NPV by varying the following variables: ±5% and ±10% from their baseline values:

- establishment costs C_0
- operational costs: maintenance costs M_t and labour costs L_t
- the electricity input cost $0.533 B_t P_{elec}$
- the natural gas price: increases in this price increase the value of the plant's cost offset from the production of natural gas
- the cost of transporting feedstock to the plant, which in the baseline scenario is $6.2 + 0.16D$ per tonne, where $D = 100\ \mathrm{km}$ is the assumed haulage distance
- feedstock costs p_{wood}
- yield (tonnes of biochar per tonne of feedstock). In the baseline scenario the yield is $\frac{1}{3.73}$ tonnes of biochar per tonne of wood chips. Note that increases in yield reduce the amount of feedstock required and therefore also reduce the cost of transporting the feedstock to the plant
- the carbon price P_{carb} .

E.8 References

Homagain K, Shahi C, Luckai N, Sharma M (2016) Life cycle cost and economic assessment of biochar-based bioenergy production and biochar land application in Northwestern Ontario, Canada. *Forest Ecosystems*, 3:21.

Rajabi Hamedani S, Kuppens T, Malina R, Bocci E, Colantoni A, Villarini M (2019) Life cycle assessment and environmental valuation of biochar production: two case studies in Belgium, *Energies*, 12(11):2166.

Roxburgh S, England J, Evans D, Nolan M, Opie K, Paul K, Reeson A, Cook G, Thomas D (2020) *Potential future supply of carbon offsets in the land sector in Australia*, CSIRO, Canberra.

Young P, Lawrence J, Batista R, Jensen-Fellows A, Richard B, Sheridan T (2019) *Biochar market profile report*.

Shortened forms

ACCU	Australian Carbon Credit Unit
AI/ML	Artificial Intelligence and Machine Learning
AUV	Autonomous Underwater Vehicle
Cal/Val	Calibration and Validation
CCUS	Carbon Capture Utilisation (Use) and Storage
CDR –	Carbon Dioxide Removal
CER –	Clean Energy Regulator
CRL	Commercial Readiness Level
DAC	Direct Air Capture
DEM	Digital Elevation Model
eDNA	Environmental DNA
ESG	Environmental, Social and Governance
EO	Earth Observation
FPIC	Free and Prior Informed Consent
FullCAM –	Full Carbon Accounting model
GEDI	Global Ecosystem Dynamic Investigation
GHG	Greenhouse Ga
ID	Identification
LE	Low Emission
LEO	Low Earth Orbit
LUTO	Land Use Trade-Off model
MSS	Management Support Systems
Mta	Million tonnes annually
NPV	Net Present Value
NRM	Natural Resource Management
PBS	Pyroloysis Biochar Systems
PV	Photo Voltaic – Solar Panels
PyCSS	Pyrolytic Carbon capture and Storage
SAR	Synthetic Aperture Radar

As Australia’s national science agency and innovation catalyst, CSIRO is solving the greatest challenges through innovative science and technology.

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