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Can digital monitoring, reporting, and verification (dMRV) unlock industrial CO_2 capture and removal in carbon markets?

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1. Introduction

Projects that capture and store carbon dioxide (CO_2) from point sources or directly from the atmosphere through technical means (Carbon Capture and Storage (CCS) and/or engineered Carbon Dioxide Removal (CDR), respectively) are complex, capital and resource-intensive, and involve many actors along the value chain of capture, transport, and storage. They typically require long-lived assets and large upfront capital [1, 2]. Given that such projects do not generate any goods and services that could be sold, and that public funding is often scarce, revenues from the sale of carbon credits on the voluntary carbon market (VCM) are important to mobilise investments [3, 4]. Carbon credits need to be real, additional, permanent, and avoid double counting [5, 6]. This can only be achieved through a robust monitoring, reporting, and verification (MRV) approach. For engineered CDR and other projects based on CCS, monitoring methodologies have been developed by programmes under the VCM (e.g. Gold Standard, Verra, Puro.earth, Isometric), compliance markets (e.g. the EU Emissions Trading System (ETS)), and by project developers (e.g. Climeworks & Carbfix, Drax & Stockholm Exergi) [7]. In any credible carbon market, periodical monitoring reports must be verified by an independent validation and verification body (VVB) before credits can be issued and sold. This perspective explores the financial implications of conventional versus digital MRV (dMRV) for CCS and engineered CDR project investments.

2. Digital MRV: a game changer?

In the past, conventional MRV systems have repeatedly raised questions about transparency and reliability [8]. As conventional MRV processes require substantial manual work, they are often costly and time-intensive [9]. For instance, a recent paper shows that CDR project proponents consider high MRV costs as one of the key barriers (i.e. 15% of total costs for bioenergy with CCS (BECCS) and 13% of total costs for direct air capture with CCS (DACCS) [10]).

To reduce the financial burden, the idea of dMRV has been introduced to automate data collection, streamline reporting processes, and enable transparent real-time verification, thereby reducing time needs [11, 12]. dMRV is emerging as a tool to improve transparency and to streamline credit issuance in carbon markets. For instance, remote sensing continuously feeds data into integrated platforms, thereby eliminating manual steps and shortening delays caused by periodic site visits and paper-based submissions (e.g. Verra's VM0048 methodology and Gold Standard's Methodology for the Sustainable Management of Mangroves).

Further, dMRV can efficiently link the project developer, the VVB, and the carbon crediting programme by automating and organizing data using an immutable ledger/blockchain. This accelerates verification by providing time-stamped records accessible to VVBs and registries simultaneously [13]. Isometric is the first VCM programme that has developed its own dMRV platform [14], allowing for monthly issuance of carbon credits.

The effectiveness of dMRV depends on standardisation. The multistakeholder CCS+ initiative [15], founded in 2021, aims to develop a suite of monitoring methodology modules for the entire value chain of CCS/engineered CDR projects, with the intent to make the framework available as a public good for Article 6.4 and domestic carbon markets. Even with continuous monitoring, conservative measures for

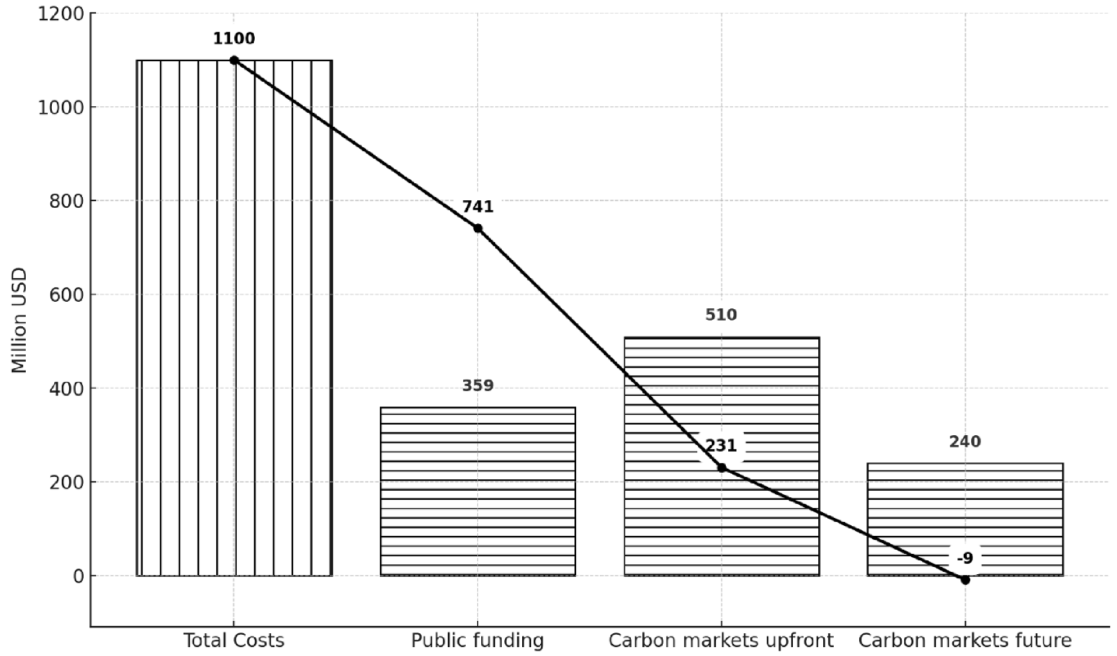

Figure 1. Total project costs vs revenue streams and cost gap reduction.

certain parameters remain essential to uphold confidence in carbon markets.

Beyond transparency, dMRV has direct financial implications. The cost implications of dMRV vary by value chain characteristics and project scale. While initial setup costs for digital infrastructure may be substantial, operational costs decrease over time due to automation, reduced labour, and fewer on-site audits [16]. However, a detailed discussion of these financial dMRV implications is beyond the scope of this article.

More frequent or even continuous carbon credit issuance has a direct effect on project investment decisions, inducing earlier breakeven and healthier cash flows. We illustrate this through a fictitious case. The assumptions and numbers presented for this case are based on data from a representative real-world BECCS project [17, 18]. Consider a bioenergy source facility retrofitted with a carbon capture plant, with transport and storage as a service (BECCS project) with a 20 year lifetime, a nominal capture capacity of 0.5 $MtCO_2$ yr^{-1}, and total costs for the CCS project activity (capital + operational) of 1.1 billion USD (indexed to 2026, USD_{2026}). The project receives 359 million USD in public funding, consisting of 100 million USD towards capital expenditures (CAPEX) and 15 million USD, inflation-adjusted[5], over 15 years for operational expenses (OPEX). Figure 1 shows the stepwise closing of the cost gap, starting with full cost in column 'Total costs'. Column 'Public funding' applies the state support, resulting in a remaining cost gap of 741 million USD (1.1 billion USD-359 million USD = 741 million USD), based on which a final investment decision (FID) cannot be taken. The implementation of the BECCS project must be covered by further revenue sources, e.g. through the sale of carbon credits. The revenue from the sale of carbon credits is thus critical.

At a nominal capture capacity of 500 $ktCO_2$ yr^{-1}, assuming a capture efficiency of 95%, a total of 475 $ktCO_2$ yr^{-1} is captured. The project activity emits 25 $ktCO_2$ yr^{-1} mainly attributed to energy use for the CCS operations, and including leakage and fugitive emissions. The project can thus generate carbon credits equivalent to 450 $ktCO_2$ yr^{-1} of permanently stored CO_2 per year, and can generate a total of 9 million credits over its lifetime (see appendix for calculations). We now assume that two buyers on the VCM procure 3 million tCO_2 over a period of 10 years at 170 USD_{2026}/tCO_2, a price representative for today's market [19]. This yields a revenue of 510 million USD (figure 1, column 'carbon markets upfront') and reduces the cost gap to 231 million USD_{2026}. Given that 6 million credits remain available for sale, the project developer is willing to take the FID for the project, as he would make a profit even at 40 USD_{2026}/tCO_2 (see figure 1, column 'carbon markets future'), which is much lower than the EU ETS allowance price in 2025.

The verification of monitoring reports is time consuming and depending on the complexity of the project activity. The verification process involves desk review of the project activity, monitoring report and its data, site visit(s), and interviews with stakeholders

[5] Note that without inflation adjustment the total amount is lower than the 359 m USD_{2026} presented here, namely 325 m USD. We use USD_{2026} for our calculations, i.e. 359 m USD_{2026}.

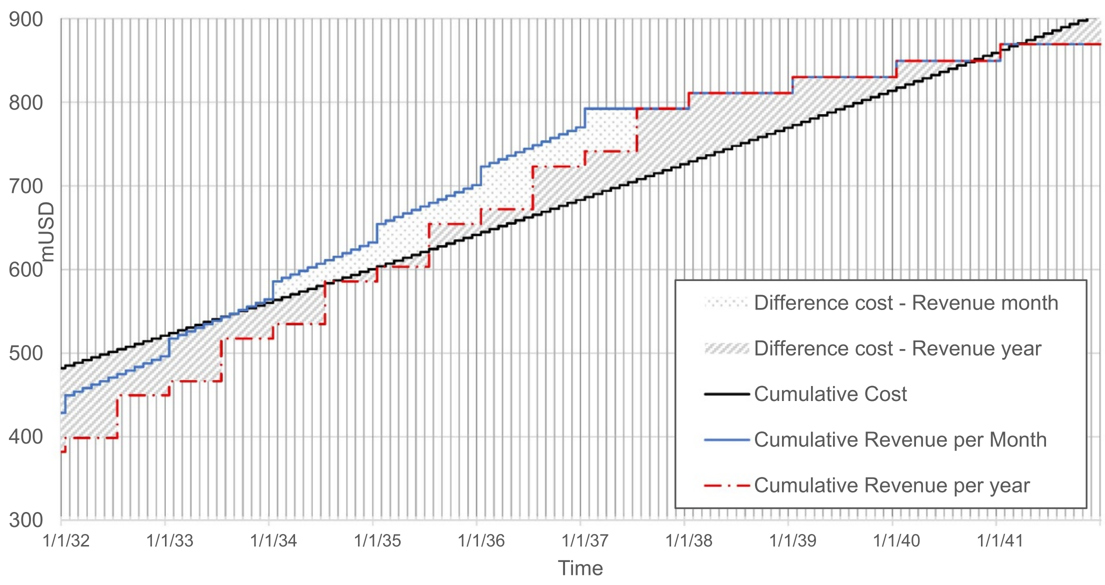

Figure 2. Cumulative cost of the BECCS project versus cumulative revenue of carbon credit sales, comparing yearly against monthly issuance.
Notes: The dotted area is the area between the monthly revenue (blue) and the cost (black), while the area with diagonal lines is the difference between the yearly revenue (red) and the cost. We assume the project starts in January 2026. We focus on the period between January 2032 and January 2042, as prior to 2032 the cumulative cost is higher than the cumulative income, and after 2037 no credits are assumed sold.

[20]. This time demand not only postpones revenue flows but also introduces risks for project developers seeking early financing. For the remainder of this article, we assume a delay of 18 months between project start and receiving the first VCM revenues.

Carrying the CAPEX and OPEX (minus public funding) for the first 18 months before receiving the first year's carbon credit revenues significantly constrains the company's cash flow. In addition, factoring in the time value of money, this results in a loss of over 2.1 million USD over the lifetime of the project, of which 0.21 million USD occur in the first 18 months (calculation given in the appendix). dMRV shortens this cycle, allowing issuances to start earlier, e.g. after 6 months, and continue on a monthly basis. As shown in figure 2, in our BECCS case, the introduction of dMRV and monthly issuance shifts the break-even point from July 2035 to September 2033—a crucial difference for investment decisions.

3. Conclusions and recommendations—why dMRV needs to be quickly introduced in carbon credit markets

Digital MRV allows continuous issuance of carbon credits, which enables earlier sale of credits than under conventional MRV and thus reaches earlier break-even, enabling investment into projects that otherwise would be unattractive. This is particularly relevant for capital-intensive CCS/engineered CDR projects [21], but also for all other types of carbon market projects. Therefore, all relevant programs in the VCM should introduce dMRV as quickly as possible. Why then, despite these financial benefits, is this not common practice in the VCM?

Carbon credits are the most verified and scrutinised 'commodity' in financial markets, given that they are generated in a space with a low level of regulation, and thus the credit demand depends on credibility of credit generation. In the last years, voluntary carbon crediting programmes have been criticised for over-crediting, fraud, or gaps in verification, leading to a loss of buyer confidence and a crash in credit prices. The MRV requirements and protocols therefore need to be robust and replicable. In the last few years, many MRV methodologies have been developed in the CCS/engineered CDR space [21]. As the mass of CO_2 can be measured at all inlets and outlets of the capture, transport and storage boundaries, this activity type is a good candidate for dMRV. Therefore, CCS/engineered CDR should become a frontrunner in dMRV in carbon markets. VCM programmes are in the process of introducing dMRV [22], including the use of ex-ante versus ex-post input data and parameters [23] for issuance. An important precondition for implementation of dMRV is the training of VVBs in verification of digital set-ups, amongst others.

Data availability statement

The data cannot be made publicly available upon publication because they contain commercially sensitive information. The data that support the findings of this study are available upon reasonable request from the authors.

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Appendix

Calculation of carbon market revenues:

- Number of carbon credits generated:
  $C = \left((\mathrm{CAP} * r_{\mathrm{cap}}) - \mathrm{emis}\right) * l$
  where:
  C = credits generated during lifetime;
  CAP = nominal annual capture capacity = 0.5 $MtCO_2\ yr^{-1}$
  emis = project, leakage and fugitive emissions = 25 $ktCO_2$;
  l = assumed lifetime = 20 yr.
  In our example this yields:

$$C = \left(\left(0.5\frac{\mathrm{MtCO_2}}{\mathrm{yr}} * 0.95\right) - 0.025\ \mathrm{MtCO_2}\right) * 20\ \mathrm{yr} = 9\ \mathrm{MtCO_2}.$$

- Carbon market revenues: $\mathrm{rev_{market}} = \sum_i C_i * p_i$
  where:
  $\mathrm{rev_{market}}$ = carbon market revenues during lifetime;
  i = price index;
  C = individual carbon credit;
  p = individual credit price.
  In our example, we calculate the revenues for 3 000 000 credits contracted at a price of p = 170 USD/credit to 2 individual buyers prior to the FID, thus:

$$\mathrm{rev_{market}} = 3\,000\,000 * 170\ \mathrm{USD} = 510\,000\,000\ \mathrm{USD}.$$

For the remaining 6 000 000 credits we assume a price of p = 40 USD/credit, thus:

$$\mathrm{rev_{market}} = 6\,000\,000 * 40\ \mathrm{USD} = 240\,000\,000\ \mathrm{USD}.$$

This adds up to 510 million USD + 240 m USD = 750 million USD

Calculation of cost gap

$$\mathrm{Gap} = \mathrm{Costs} - \left(\sum_j \mathrm{Rev}_j\right)$$

where:
Gap = cost gap
Costs = costs to implement the project
j = index for separate revenue streams
Rev = revenues
In our example the costs are 1.1 billion USD, and we consider three revenue streams: the public fund (359 million USD), upfront carbon market revenues (510 m USD), and future carbon market revenues (assumed 240 m USD). Without carbon market revenues the cost gap is:

$$\mathrm{Gap} = 1100\,\mathrm{m\ USD} - 359\ \mathrm{m\ USD} = 741\ \mathrm{m\ USD}.$$

Including upfront carbon market revenues yields:

$$\mathrm{Gap} = 1100\ \mathrm{m\ USD} - (359\ \mathrm{m\ USD} + 510\ \mathrm{m\ USD}) = 231\ \mathrm{m\ USD}.$$

Including future carbon market revenue yields:

$$\mathrm{Gap} = 1100\ \mathrm{m\ USD} - (359\ \mathrm{m\ USD} + 510\ \mathrm{m\ USD} + 240\ \mathrm{m\ USD}) = -9\ \mathrm{m\ USD}.$$

Based on these basic assumptions, the project is expected to make a surplus of 9 million USD, and an FID is taken.

Future value of money: $\mathrm{FV} = \mathrm{PV} \times (1+r)^{n \times t}$
where:
FV = Future value
PV = Present value
r = Interest rate per period
n = Number of periods
t = Time in years.

The present value of money PV ($MUSD_{2026}$) is equal to the sale of 3 million carbon credits at a price of 170 USD_{2026}/tCO_2 over 10 years, which equals to 4.25 million USD_{2026} per month.

Table A1. The future value of money for the fictitious BECCS project with assumptions as presented in the text. A monitoring period of 1 year following verification of 6 months for conventional MRV verification gives a 'loss' of 210 thousand USD for the first issuance compared to monthly issuance (starting 6 months after project operation).

Month	t	r	n	PV (MUSD)	FV (MUSD)	FV-PV (MUSD)
1	1.42				4.28	0.03
2	1.33				4.27	0.02
3	1.25				4.27	0.02
4	1.17				4.27	0.02
5	1.08				4.27	0.02
6	1.00				4.27	0.02
7	0.92	0.00425	12	4.25	4.27	0.02
8	0.83				4.27	0.02
9	0.75				4.26	0.01
10	0.67				4.26	0.01
11	0.58				4.26	0.01
12	0.50				4.26	0.01
					Total	**0.21**

Table A2. The future value of money for the second and subsequent annual issuance by conventional MRV verification compared to monthly issuance. A 12 month delay in issuance leads to a loss of 100 thousand USD per year.

Month	t	r	n	PV (MUSD)	FV (MUSD)	FV-PV (MUSD)
1	0.92				4.27	0.02
2	0.83				4.27	0.02
3	0.75				4.26	0.01
4	0.67				4.26	0.01
5	0.58				4.26	0.01
6	0.50				4.26	0.01
7	0.42	0.00425	12	4.25	4.26	0.01
8	0.33				4.26	0.01
9	0.25				4.25	0.00
10	0.17				4.25	0.00
11	0.08				4.25	0.00
12	0.00				4.25	0.00
					Total	**0.10**

The interest rate r per period (year) is set at 5.1%, which is the approximate weighted average cost of capital (WACC) paid by private companies in the Nordic countries in 2024[6].

The number of periods n is 12, for the 12 months in a year.

The time t is given in years. If we assume monthly issuance, the time needs to be converted from months to years through (months of considered period — number of past months)/12 months. For the first month of the first year this is (18–1)/12, equal to 1.42 years. The 18 months represent the typical time lag between generation and issuance of a carbon credit under conventional MRV in the first year. t decreases with time, as each month a higher number is deducted from the 18 months (table A1). Subsequent years have a delay of 1 year and the equation is adjusted to (12-n)/12 (table A2).

[6] Pre-tax WACC average for Nordic countries (Denmark, Finland, Norway and Sweden) as per table A2 of a 'Study on cost of capital' by Performance Review Body of the Single European Sky, 2024, Available at: https://eu-single-sky.transport.ec.europa.eu/document/download/31d201d9-e48b-4ad0-aec3-f66c7fe61d31_en?filename=240625_Cost%20of%20Capital%20Guidelines_published.pdf (Accessed 23 September 2025).

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