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Ensuring High Integrity Carbon Credits from Plugging Orphan Oil and Natural Gas Wells:

An Issue Primer

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**Environmental
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Executive Summary	4
II. Introduction	5
III. The Core Carbon Principles of high-integrity carbon credits	7
a. Overview	7
b. Principles 1-4: Governance and Implementation:.....	7
c. Principle 5: Additionality	7
d. Principle 6: Permanence	8
e. Principle 7: Robust quantification of emission reductions:	9
i. What do we want to quantify and what are the known challenges with current quantification approaches?	10
ii. What are our priorities for quantification?	11
iii. What are the decisions that will need to be made to quantify net avoided emissions in terms of CO2 equivalence?... 12	
a. Crediting period selection.....	12
b. GWP.....	12
c. Considerations for net avoided emissions.....	12
f. Principle 8: No double counting	13
g. Principle 9: Sustainable development benefits and safeguards	14
h. Principle 10: Contributions to the net zero transition	14
IV. Other challenges with early plugging of marginal wells	14
V. Co-benefits of plugging of marginal wells.....	15
VI. Frameworks for orphan well carbon credits.....	16
References	17

Executive Summary

Over 165 years of oil and natural gas development in the United States, millions of wells have been drilled to produce hydrocarbons from underground formations. Eventually, as production rates decline, individual wells become uneconomical and are permanently decommissioned. These are known as “abandoned” wells.

Modern regulations require abandoned oil and gas wells to be correctly remediated, or “plugged,” by their owners. However, some wells are left unplugged for a variety of reasons, such as pre-dating plugging requirements or because of compliance failures with modern regulations. When an unplugged abandoned well has no known responsible party, it is called an “orphan” well.

Estimates have placed the number of U.S. orphan wells in the hundreds of thousands — and potentially more than a million. These wells pose a danger to public health and the environment through groundwater contamination, surface spills and air pollution. Researchers have estimated that 14 million Americans live within one mile of a documented orphan well.¹

Some orphan wells also release methane, a powerful greenhouse gas (GHG) that accelerates global warming. However, there is both significant uncertainty and variability surrounding the scale of these emissions. Data from available sources suggest a tentative range of between 13,000 metric tons of annual methane emissions for documented orphan wells and 130,000 metric tons of methane emissions when estimates for undocumented orphan wells are included, though there is significant uncertainty in these estimates and recent research suggests emissions may be even higher.^{2,3}

Using a 20-year Global Warming Potential (GWP) for methane, the high end of this range amounts to 11 million metric tons of carbon dioxide equivalent (CO₂e). For purposes of comparison, this roughly equals the annual carbon emissions of:^{4,5}

- 2.6 million gasoline-powered passenger vehicles
- 2.9 coal-fired power plants
- The State of Delaware

Using a 100-year GWP for methane, the high end of this range amounts to 3.6 million metric tons of CO₂e. For purposes of comparison, this roughly equals the annual carbon emissions of:^{4,5}

- 849,000 gasoline-powered passenger vehicles
- One coal-fired power plant
- The District of Columbia

While U.S. orphan wells are the focus of this issue primer, similar challenges exist in other countries. For example, the global estimate for abandoned wells is 10 times higher than the U.S. estimate for abandoned wells, but it remains unclear how many of these abandoned wells in other countries are orphan wells.⁷

There has been recent interest in mitigating* the risks that orphan wells pose to human health and environment through remediation. The menu of existing and proposed solutions for the U.S. orphan well challenge include:

* Documented orphan wells were assumed to be responsible for 4% of emissions from all abandoned wells, leading to an estimate of 13kt CH₄, or approximately 0.13 tons CH₄/documented orphan well. If the orphan well number is closer to 1 million due to undocumented wells, this emission factor can be used to estimate both documented and undocumented orphan well emissions as 130kt CH₄.

- Enhanced enforcement of existing plugging and abandonment regulations
- Orphan well closure funds
- New laws and regulations governing financial assurance, idle well management and well transfers
- Litigation against scofflaw operators of abandoned wells

In addition to these solutions, the voluntary carbon market has emerged as another source of finance for plugging orphan wells, specifically the issuance of carbon credits for avoided methane emissions. However, there are differences in the protocols used to calculate carbon credits from plugging orphan wells, and a divergence in standards.

This means the number and value of carbon credits from plugging an orphan well can vary significantly depending on which methodology is used. The resulting uncertainty has undermined confidence in the environmental integrity of carbon credits from plugging orphan wells, with one major registry suspending the use of its methodology last year.

A useful benchmark for resolving this uncertainty has been developed by the Integrity Council for the Voluntary Carbon Market (ICVCM) — the Core Carbon Principles (CCP). This paper will discuss how the 10 core principles developed by the ICVCM apply to carbon credits for plugging orphan wells and identify issues that must be further addressed to develop high integrity carbon credits.

Following publication of both this orphan well primer and the parallel marginal well primer, **targeted technical guidance** on key unresolved questions identified in the work will be developed. **To be clear: the identification of issues in this primer does not imply that no solutions exist. Instead, this primer will structure future discussions to identify solutions — some which may already exist — to ensure adherence to the CCPs.**

II. Introduction

Abandoned oil and gas wells, or wells that are no longer in production, can pose a significant risk to ecosystems and human health if they are not correctly remediated, or “plugged.” Abandoned wells that are improperly plugged or left unplugged can be a source of groundwater contamination, toxic air pollutants, ecosystem degradation and GHGs, most notably methane.²

Orphan wells are a subset of abandoned wells that have no known responsible party. Wells can become orphaned for a variety of reasons, such as if the state cannot identify the responsible party of an abandoned well or if the company that was previously responsible for the well went bankrupt. The U.S. EPA estimates there are about 2.3 million unplugged and abandoned oil and gas wells.³ It is estimated that of these documented unplugged and abandoned oil and gas wells, on the order of 100,000, or approximately 4%, are orphan wells.² However, the total number of orphan wells is unknown because of the large number of undocumented orphan wells. Some estimates suggest there could be upwards of 1 million undocumented orphaned wells in the U.S.⁶

These nuances make it difficult to estimate the full scope of the potential methane emissions of plugging orphaned wells. To give a sense of the approximate scale, the U.S. EPA estimated that 4% of all methane emissions from oil and gas operations in 2022 came from unplugged abandoned wells, or 303kt of CH₄, which is equivalent to approximately 25 MMT CO₂e over a 20-year period.³ There is significant uncertainty in these numbers, which the EPA estimates to be –83%, +197%, driven mainly by uncertainty in well count and limited sample sizes in measurement campaigns. Globally, the International Energy Agency estimates that abandoned oil and gas wells are responsible for 10x the U.S.

estimate, or 3 MMT of CH₄.⁷

If we assume that orphan and abandoned wells exhibit roughly the same emission behavior, we can approximate that documented orphan wells account for approximately 13kt of CH₄, or about 1.1 MMT CO₂e using a 20-year global warming potential, in the U.S. We can also approximate both undocumented and documented orphan well emissions as 130 kt CH₄ or 11 MMT CO₂e in the U.S. if we assume documented and undocumented orphan wells have similar emissions.* These estimates are still highly uncertain, but there is ongoing research to improve the documentation and measurement of orphan wells. These estimates are meant to provide context for the relative size of potential emissions reductions. For comparison, 130kt CH₄ or 11 MMT CO₂e is roughly equivalent to the annual carbon emissions of:^{4,5}

2.6 million gasoline-powered passenger vehicles

2.9 coal-fired power plants

The State of Delaware

Using a 100-year GWP for methane, 130kt CH₄ is approximately 3.6 MMT CO₂e, or roughly equivalent to the annual carbon emissions of:^{4,5}

849,000 gasoline-powered passenger vehicles

One coal-fired power plant

The District of Columbia

Some orphan wells were abandoned before regulations of oil and gas were introduced, explaining the existence of historical orphan wells. But despite the introduction of regulations to prevent orphan wells the number of documented orphan wells continues to grow.⁸ Researchers estimate that 14 million Americans live within a mile of a documented orphan well and over 35% of documented orphan wells are within a half of a mile of a groundwater supply.¹ These values may underestimate the environmental hazard exposure of orphan wells, as they only consider documented wells, which may only represent about 10% of all orphan wells.⁶

Finding and plugging orphan wells is a resource-intensive task that currently falls on state and federal governments. Voluntary carbon markets (VCM), or private buying and selling of carbon credits based on removals or reductions in GHG emissions, are seen as a possible solution, or part of a possible solution, for financing orphan well plugging efforts based on avoided methane emissions. There are other possible solutions to accelerate orphan well plugging, such as enhanced enforcement of existing plugging and abandonment regulations; orphan well closure funds; new laws and regulations governing financial assurance and idle well management or well transfers; and litigation against scofflaw owners of orphan wells. However, there is growing interest in VCMs specifically as a mechanism to reduce emissions from orphan wells. This issue primer will focus on establishing the foundation on which VCMs could play an effective role in reducing orphan well emissions.

Trust in VCMs is critical to their effectiveness. Buyers, sellers and external parties must feel confident that the carbon credit value accurately reflects the magnitude of avoided carbon emissions. The ICVCM identifies 10 core principles for high integrity carbon credits, called the CCPs.⁹ The CCPs serve as a global framework to ensure appropriate rigor in VCMs and to ensure awarded carbon credits translate into defensible emission reductions. Through the lens of the CCPs, this paper will identify the main challenges associated with developing high integrity carbon credits for orphan well plugging. By identifying the key questions that need to be answered in developing high integrity carbon credits, this work will serve as a foundation for future discussions and decision points in issuing carbon credits for

orphan well plugging based on avoided GHG emissions. The identification of these issues is not meant to imply that no solutions exist; rather, this primer is meant to serve as a way to structure future discussions to ensure adherence to the CCPs. This primer will discuss in detail the issues as they relate to the United States, but these concepts can be applied globally.

III. The Core Carbon Principles of high-integrity carbon credits

a. Overview

The ICVCM is an independent non-profit organization that works to establish and ensure integrity in global carbon markets. The ICVCM has established 10 CCPs based on science and fundamentals to ensure that awarded carbon credits have a verifiable climate impact. The ICVCM is widely seen as a leader in the VCM space, and the CCPs are a solid foundation to begin discussion for identifying possible challenges with producing high integrity carbon credits for orphan well plugging. The CCPs have already been used to assess several frameworks spanning a variety of carbon credit categories, including reforestation, carbon dioxide removals and landfill gas capture. There are no current frameworks for orphan well plugging activities that have been submitted to the ICVCM for CCP approval.¹⁰

b. Principles 1-4: Governance and Implementation:

The first four principles of the CCPs are related to governance and implementation of carbon-crediting programs. These are effective governance; tracking; transparency; and robust independent third party validation and verification. These are important elements of a carbon credit program, but they do not present challenges that are unique to developing high-integrity carbon credits for orphan well plugging. Existing structures and market mechanisms have been developed for other forms of carbon credits and can be utilized for carbon credits from orphan well plugging projects. A decision about third party verification, who is qualified to be a third party verifier, and clarification on the objective of third party assessments (i.e. measurements, additionality/eligibility, process audit, checking plugging integrity/permanence, etc.) should be made. However, the bigger challenge is providing scientific and technical clarity to the methodologies used to determine which projects should receive carbon credits and how many they should receive. Principles 5-10 speak more directly to those challenges and are the larger focus of this paper.

Key questions:

- What is the primary objective of third-party validation and verification for orphan wells?
- What are the qualification requirements for a third-party verifier?

c. Principle 5: Additionality

Additionality requires that carbon reduction that is awarded carbon credits must be additional, or, in other words, would not have occurred without a VCM. The question of whether orphan well plugging satisfies the additionality requirement is not trivial. The Department of Interior has federal funds available for states and tribal lands to plug orphan wells. Per the 2025 Orphan Wells Project Progress report, state programs have over \$4 billion in funding, tribal lands have over \$140 million in funding and there is an additional \$93 million for federal well plugging activity.¹¹ Since the project was introduced in the Infrastructure Investment and Jobs Act (IIJA) (Public Law 117-58) in November 2021, over 10,000 wells have been plugged through June 2025.¹¹ The Interstate Oil and Gas Compact Commission (IOGCC) also collects state-level data on well plugging activity. The IOGCC reports a total of 14,592 orphan wells were plugged in the

three-year period from 2021-2023 in the United States, representing an increased rate of plugging due to the availability of federal funding from the IIJA based on 29 reporting states.¹²

Publicly funded well plugging activities represent a small fraction of total orphan wells, of which the total count is still relatively unknown. For example, if public efforts continue to plug wells at a rate of ~4,900 wells per year based on the IOGCC data for the U.S., it could take over 200 years to plug the estimated 1 million orphan wells in the United States, not accounting for additional wells that could become orphaned within that time frame. A VCM could accelerate the rate of plugging that would occur solely through public funding. However, not all orphan wells emit the same amount of methane, and the rate of plugging on a well basis will likely differ significantly from the rate of plugging on an emissions basis. In other words, if the top 0.5% emitting wells are plugged every year, this could represent a significant reduction in emissions despite plugging only a small fraction of total wells depending on the underlying emission rate distribution or potential for emissions. Also, the gap between wells that need to be plugged and available funds will vary by state. Most states also have an approach to prioritize plugging wells that pose the most environmental and human health risk.

There is an argument to be made that public funds alone cannot plug all orphan wells in the country. However, it is important to note that there continues to be public efforts to plug orphan wells and such activity would occur in the absence of carbon credit incentives, albeit likely at a slower rate than would be possible with private funding. A high integrity carbon crediting framework for orphan wells will need to distinguish which avoided emissions meet the additionality requirement.

Key questions:

- How does public funding affect additionality? Given current fund levels and prioritization, which wells are unlikely to be publicly plugged and therefore plausibly additional?
- What eligibility standards must be in place for a project to demonstrably satisfy the additionality requirement?
- Is mixing federal funds and carbon credits allowable?
- What are the key differences between the states that would need to be addressed?

d. Principle 6: Permanence

Permanence requires that avoided GHG emissions that are awarded carbon credits remain out of the atmosphere permanently. The question of permanence in the context of orphan wells can be boiled down into four questions: 1) How frequently does plugging failure occur and what parameters affect the probability of failure? 2) What does well failure look like? 3) How long should properly plugged wells last? and 4) What mechanisms need to be in place to ensure permanence?

Well plugging is intended to be permanent but plug failures do occur, which is defined in this paper as premature failure of plugging. There is limited data on the frequency of such events, though anecdotal accounts and a limited number of scientific studies show that emissions after plugging can occur and should be considered in a high-integrity carbon credit framework. A review of Ontario's orphan wells identified several factors that impact the probability of failure of plugged wells. The review found that technology used to drill the original well, well condition, the material used to plug the well (and the year the well

was plugged), and the presence of hydrogen sulfide were all found to influence the probability of well plugging failure.¹³ Some of these variables can be controlled through plugging technology requirements. For example, cement is now used to plug wells as opposed to sediment, rubber, wood or clay that were used prior to the 1960s.¹³

However, there are some drivers of failure that may not be preventable, even with modern equipment and materials. Older wells may have been drilled with non-standardized equipment. They may also have been shot (a method for removing obstructions by initiating explosions in the subsurface) or treated with acid to increase rock permeability.¹³ These activities can lead to well holes with non-uniform diameters or pockets of rock that are difficult to properly plug. The presence of hydrogen sulfide can also corrode equipment and cement, as well as posing serious safety concerns that should be addressed prior to plugging.¹³ Subsurface conditions can also lead to plugging failures, especially if there is connectivity between plugged wells and producing wells. Plugging failure can occur if there is fluids pressure buildup, injection from nearby wells or stress changes in the reservoir.^{14,15} A recent report by the National Academy of Sciences was unable to conduct a root-cause analysis of well plugging failures, calling for improved essential data collection to be able to better understand the causes of well plugging failures.¹⁶

The environmental impacts of plugged well failures can vary significantly. In extreme cases in the Permian Basin, geysers of toxic wastewater have been observed coming out of plugged wells.¹⁷ Other studies have found leaks from plugged wells in several other U.S. basins, though there is variability in the magnitude difference between methane emissions from plugged and unplugged wells in different studies.^{18,19,20} Plugged wells in coal areas can have similar emission rates to unplugged wells, while plugged wells in non-coal areas may leak at a significantly lower rate.^{18,19,20}

The literature suggests that proper plugging techniques can reduce the risk of plugging failure but cannot eliminate it entirely. Alternatively, even properly plugged wells may fail after a long time. A high-integrity carbon credit framework must recognize the risk of failure, identify actions to mitigate the risk of failure, and develop an action plan to quantify and, if appropriate, retroactively adjust carbon credit issuance if well plugging failure occurs and the permanence requirement is not met. The framework will also need to decide how to assess permanence, such as periodic checking of emissions, and specify how long a properly plugged well should last.

Key questions:

- How should permanence be assessed over the crediting period? What procedures, if any, need to be in place for reasonable assurance?
- Are there issues related to long-term site access that would impact the ability to assess permanence? Will this impact the integrity of the VCM?

e. Principle 7: Robust quantification of emission reductions:

Before developing a VCM framework that supports robust quantification of emission reductions, we must first achieve alignment on three key questions:

- What do we want to quantify and what are the known challenges with current quantification approaches?
- What are our priorities for quantification?

- What are the decisions that will need to be made in regard to quantifying net avoided emissions in terms of CO₂e?

These questions do not address the technical challenges associated with quantification of emissions but are an important first step that will inform the approach of subsequent technical decisions.

i. [What do we want to quantify and what are the known challenges with current quantification approaches?](#)

The decision on what to quantify hinges on the underlying philosophy of the avoided emissions. The first basis for quantification is the expected emissions basis (referred to as the EE basis), which quantifies all GHGs that could have been emitted at some point in the future from the well had it not been plugged. This basis predicts all current and future leaks that would be expected from an orphan well. The EE basis can also refer to two distinct philosophies from a regulatory standpoint. The EE basis could be interpreted as the maximum theoretical capacity that a well could emit, often referred to as the potential-to-emit in a regulatory context. This would result in a calculation of subsurface hydrocarbons, which in a theoretical yet unrealistic scenario would all migrate to the surface. Another interpretation of expected emissions would be to estimate what fraction of these hydrocarbons would reasonably migrate to the surface over a specified period of time such as by incorporating a probabilistic or time-weighted forecast. This is in contrast to the second quantification basis, which estimates avoided emissions based only on current emission rates (referred to as the CE basis). The CE basis requires the well to be actively leaking, and measures only the hydrocarbons that have been avoided if the well head continues to leak, unaltered. A high-integrity carbon crediting framework will need to clearly define the quantification objective and assess how that selected objective impacts the other CCPs.

The CE and EE bases can yield materially different estimates for avoided emissions and require different quantification protocols to establish baseline emissions. The different approaches also impact the additionality requirement, as states may prioritize plugging wells that are currently emitting (CE basis). In the CE case, on-site measurements or detection should be required to demonstrate that the well is actively leaking in its unaltered state. The challenge with converting these on-site rate measurements to an avoided volume of methane is estimating the duration and projected leak function had the leak continued unabated. Recent studies have found significant temporal variability in measured emission rates over the course of hours, suggesting that emission rates may vary based on barometric pressure, temperature, and other atmospheric and/or subsurface conditions.^{21,22}

The EE approach may also incorporate measurements, but with the intention of understanding the quantity of hydrocarbons in the subsurface that could migrate to the surface at some point in the future, as opposed to measuring methane leakage from an unaltered orphan well. EE-based approach may allow for the well to be “opened up” before emissions are measured, which can lead to a large increase in the short-term emission rate due to pressure buildup. Measurement-based EE approaches typically require that the emission rate stabilizes before extrapolating this to an avoided volume and may use decline-curve modeling to model the emission rate as a function of time, analogous to decline curve modeling for production forecasting from producing wells.^{23,24,25} EE-based avoided emissions have also been estimated using production models or reservoir models. One approach is estimating the volume only using decline curve modeling, which is commonly used for energy forecasting for producing wells, but the applicability of production curve modeling to non-producing wells to estimate

remaining hydrocarbons and their potential to emit is not well understood.^{23,24,25} This also requires an assumption about the fraction of hydrocarbons left in the subsurface that will ultimately migrate to the surface. Reservoir modeling is a more complex approach to modeling subsurface behavior and can take into account parameters like porosity and permeability, but requires more computational resources and information on the reservoir, which may not always be available but may be more accurate. Recent studies have also suggested that methane emitting from abandoned oil and gas wells may not originate from that gas formation, meaning that production-based estimates may not be entirely accurate.²⁶

Estimating emissions from orphan wells is a complex and evolving field. The quantification approaches for both bases (CE and EE) pose their own significant technical challenges. Measurement-based approaches are sensitive to environmental factors, data analysis assumptions and measurement selection, and can be difficult to replicate. Modeling-based approaches also rely on some degree of assumption, and more robust modeling requires more data. The first decision for a high-integrity VCM framework is first specifying the main quantification objective, whether it be current emissions, a theoretical maximum of expected emissions or a probabilistic estimate of expected or future emissions. Further technical investigation can occur after alignment is reached.

The VCM must also specify which emissions are in-scope, and whether they must be coming directly from wellhead equipment or whether nearby emissions from soil can be included as well. The U.S. DOI also allows for the inclusion of emissions from soil when quantifying the emissions from an unplugged well, though Lyman et al., found relatively minor methane flux rates from oil up to 5m away from the wellhead.^{27,28} The VCM will need to specify if a surrounding area can be included in a quantification and the appropriate radius.

The VCM should also specify the scale at which carbon credits will be awarded, which has direct implications for the market mechanism of carbon credit issuance. For example, a mechanism that awards carbon credits by project may require quantification at each well level. The existing frameworks take this approach. However, other approaches, such as a jurisdictional approach, would award carbon credits based on avoided emissions across an entire region. The market approach may dictate the quantification scale.

ii. What are our priorities for quantification?

Different priorities for the quantification objective will also influence protocol recommendations. Some possible objectives are listed as follows:

- Scientific accuracy of quantified avoided emissions
- Broad applicability of quantification approaches
- Transparency and consistency in methods
- Flexibility in methods

Some of these objectives are in tension with one another. For example, a prescriptive measurement protocol that specifies measurement technologies, measurement count, etc. may be limited in its applicability if the measurement techniques are prohibitively expensive, requires specialized training or the well is located in a difficult or dangerous to access location. The VCM could offer alternative quantification approaches in these cases, such as allowing modeling approaches or national averages instead of measurement, but flexibility in allowable methods could potentially compromise the consistency or accuracy of quantified carbon credits. For example, in one existing methodology, which quantifies emissions using the CE basis, emissions can either be estimated using on-site

measurements or an emission factor based on the national average. This decision to accommodate both measurement and emission factor-based estimates has implications for scientific accuracy of awarded credits on a per-well basis but allows for quantification where measurement is challenging due to safety or logistical concerns. There may also be a tradeoff in scientific accuracy, consistency and broad applicability. Tolerance for compromise in each of these objectives should be discussed ahead of building out a high-integrity VCM framework.

iii. What are the decisions that will need to be made to quantify net avoided emissions in terms of CO₂ equivalence?

a. Crediting period selection

The crediting period refers to the duration over which carbon credits will be calculated and, in the case of orphan wells, is used to convert annual leak rate estimates to a total credit volume. The crediting period is difficult to determine. As mentioned in an earlier section, there is a lack of long-term measurement data associated with emissions from orphan wells. Three out of four carbon crediting frameworks for orphan wells that are summarized in section VI use a 20-year crediting period, while one framework uses a 50-year crediting period. One framework justifies the 20-year crediting period based on Enverus data that the average last production date for documented orphan wells was 17 years prior. A high-integrity carbon crediting framework will need to determine an appropriate crediting period. One option is to predict the timescale during which the plugging effectively stops emissions. Another option is to credit the timeframe during which the VCM enabled early plugging of orphan wells, as opposed to delayed plugging via public funds. Quantified carbon credits and avoided methane is highly sensitive to the selected crediting period.

b. GWP

The volume of avoided methane is typically then converted into CO₂e, which is used as a common basis for awarding carbon credits based on the avoidance of different GHGs. The philosophy behind GWP is that different GHGs have different radiative efficiencies and lifetimes, which leads to different warming potentials. In basic terms, GWP is a way to compare how the warming impact of 1kg of a non-CO₂ GHG would compare to the warming potential of 1kg of CO₂. However, the GWP value can change depending on which time horizon is used. Methane has a GWP₂₀ of 81 based on the IPCC's 6th assessment report (AR6), meaning that over a 20-year horizon, the global warming potential of 1kg of methane is 81x higher than 1kg of CO₂.²⁹ The GWP₁₀₀ of methane is 27.9.^{29,30} The selected GWP (i.e. either GWP₂₀ or GWP₁₀₀) significantly impacts the resulting CO₂e value. The U.S. Environmental Protection Agency (EPA) and the Intergovernmental Panel on Climate Change (IPCC) use GWP₁₀₀ as their baseline.^{30,31} GWP has received criticism due to its dependence on timeframe selection, and some research recommends using different climate metrics or combinations of climate metrics to more accurately reflect climate impact.^{32,33} A carbon crediting framework will need to decide on the climate impact metric that will be used for awarding carbon credits, whether it be GWP on a specific time horizon or an alternative.

c. Considerations for net avoided emissions

There is a distinction between quantifying the avoided emissions from plugging a particular well and quantifying the net avoided emissions when a larger system is

considered. Physical leakage, which refers to increased emissions or production at a nearby well due to the plugging of another well through subsurface connectivity, has implications for the net avoided emissions of orphan well plugging. The magnitude of physical leakage is not well understood and will likely vary case by case depending on reservoir characteristics. The U.S. DOI guidelines on orphan well measurement recommend measuring nearby wells that are expected to have subsurface connectivity to get a better understanding of net avoided emissions.²⁷

Deciding whether to deduct project emissions from the avoided emissions is another critical choice. Project emissions can include the GHG emissions associated with on-site fossil fuel use or the concrete used for plugging. Existing frameworks for orphan well credits vary: some explicitly subtract project emissions, while others omit them entirely (Table 1).

Key questions:

- What is the underlying problem that we are trying to quantify? Are we estimating a theoretical maximum of future emissions, a realistic estimate of future emissions (expected emissions/EE) or are we estimating avoided emissions based on current and observed states (current emissions/CE)?
- What are the priorities for a quantification protocol? Are there tradeoffs between methods that are the most scientifically accurate, the most broadly applicable and the most consistent? Which methods are allowable? How rigid should the quantification protocol be?
- Do we have enough information to make decisions on key issues:
 - What crediting period is appropriate? Should the crediting period reflect the integrity of the plugging or the time until the well would have been plugged via public funds?
 - What GWP is appropriate or is another climate impact metric better?
 - How will physical leakage be accounted for?
 - What is the boundary for quantifying avoided emissions (i.e. methane from on-site equipment, methane from nearby soil, methane with specific origins from geochemical analysis)?
 - What scale of quantification does the market mechanism demand?
 - Should project emissions be deducted?

f. Principle 8: No double counting

High-integrity carbon credits also require that GHG removals or reductions only be credited once. In the context of orphan wells, this means that carbon credits can only be issued once per plugged well. The no double counting requirement can be achieved so long as there is transparency and tracking in well plugging activity. One consideration is whether credit stacking is allowable, or if mixing of funding sources is allowable, and if so, under which circumstances. Credit stacking can refer to either combining multiple carbon reduction and removal projects, or receiving other types of credits, such as water credits, for co-benefits associated with the activity.

Key questions:

- If there are multiple VCM registries, are there procedures in place to ensure no double counting across different platforms?
- Are there situations where funding mixing or credit stacking is allowable? If so, under what circumstances?

g. Principle 9: Sustainable development benefits and safeguards

High-integrity carbon credits must also have clear procedures to ensure that mitigation activities meet current industry standards. Well plugging efforts have occurred for a long time, and best practices and standards for orphan well plugging are well documented.^{34,35,36} A new report by the National Academies was published on technologies and practices for orphan well plugging and remediation.¹⁶ Proper well plugging is critical to developing high-integrity carbon credits, as improper well plugging can affect the permanence of the avoided emissions, and lead to other harmful outcomes such as the continued leaking of methane and contamination of underground sources of drinking water (USDWs). A high-integrity carbon crediting framework will need to identify acceptable methods and safety precautions for well plugging and site remediation and develop a process that ensures awarded carbon credits were achieved in a way that aligns with best practices.

Key questions:

- How will compliance with these safeguards be assessed?

h. Principle 10: Contributions to the net zero transition

Under this principle, action taken to mitigate GHG emissions must not lock in carbon intensive practices or contribute to a goal that is contradictory to the net zero transition. Plugging orphan wells does not conflict with net zero transitions, as the mitigation action occurs at wells that are no longer active and no longer associated with current and producing energy systems. The source of future energy, whether it be fossil fuels or an alternative source, is not impacted by orphan well plugging activity. In fact, plugging orphan wells can provide opportunities for underground carbon storage, facilitating the net zero transition.¹

IV. Other challenges with early plugging of marginal wells

Plugging orphan wells can present many challenges that do not impact the integrity of any awarded carbon credits but are still important to consider when developing a carbon crediting framework. The first challenge that is unique to orphan well plugging is locating emitting orphan wells. The majority of orphan wells are undocumented.⁶ The first step in plugging orphan wells is actually locating them and confirming that they are both orphan and emitting. Locating orphan wells is not a trivial task and can involve analyzing large amounts of remote sensing data, reviewing old records or going out in the field to locate orphan wells on the ground. This task can be highly resource intensive. Techniques are being developed to help improve this process, but it still requires considerable effort.^{37,38} Orphan wells are also often located on private property. Plugging operations must respect local jurisdictions and obtain permissions from landowners before accessing the site and reach an agreement on long-term site access for permanence assessments.

Related to the challenge of locating orphan wells is locating wells that are emitting a sufficient amount of

methane to warrant plugging for carbon credits. Studies show that there is significant variability in the emissions coming from individual orphan wells, with some emitting as high as 9.8×10^5 mg/h whereas some have near-zero emissions.³⁹ The distribution of emission rates from unplugged wells has been found to be highly skewed, with the top 12.1% of wellhead emitters accounting for 98% of total wellhead emissions.³⁹ This variability in methane emissions from orphan wells exacerbates the challenge of locating orphan wells, as they must be known emitters in order for carbon credits to be awarded.

Another challenge with plugging orphan wells is the associated cost. The cost of plugging a well includes not just the plugging operation itself, but the costs associated with finding eligible wells, site restoration and surface reclamation, and potential costs from third party verifiers. Plugging operations can encounter challenges that increase the cost, such as wells located in remote and difficult to access areas, difficult subsurface conditions, or the presence of dangerous substances such as hydrogen sulfide. Data from state regulators in Kansas, Pennsylvania, Montana and Texas suggest that the median cost of well plugging and surface reclamation for a single well is \$76,000, with some wells exceeding \$1,000,000.⁴⁰

Key questions:

- Do the significant challenges associated with orphan well plugging (i.e. locating orphaned wells that have a high potential to emit, high costs of plugging) need to be considered in the VCM carbon credit framework?

V. Co-benefits of plugging of marginal wells

In most carbon crediting frameworks, avoided methane emissions are the sole basis for awarding carbon credits. However, reducing methane emissions is not the sole environmental benefit to properly plugging orphan wells. Other air pollutants that can be co-emitted with methane in oil and gas production regions can be hazardous to human health, such as benzene (a known carcinogen), hydrogen sulfide, toluene, ethylbenzene, xylenes and other volatile organic compounds (VOCs).¹ Additional measurements are needed to understand the full extent of co-emitters. There have been several hundred studies focused on the environmental impacts of oil and gas development, identifying both chronic and acute effects on human health. These studies have not focused on orphan or abandoned wells, so it is difficult to conclude the health risk of unplugged orphan wells.¹ However, the proximity of orphan wells to residential communities, sometimes beneath residential structures or other community buildings, could pose significant risk if hazardous co-emitters are present.¹

There are also concerns that orphan wells can impact water quality, leading to both groundwater and surface water contamination. Orphan wells can function as a pathway for migration of brine, hydrocarbons and other contaminants into water resources. A study on groundwater contamination incidents in Ohio and Texas found that 22% and 14.2% of incidents in Ohio and Texas, respectively, were attributed to orphan wells.⁴¹ Water contamination from orphan wells remains a significant concern, as studies estimate that 35% of documented orphan wells are within a half mile radius of a groundwater well, and over 64,000 documented orphan wells intersect with a major aquifer system.^{1,42} Proper well plugging can greatly minimize the risk of water contamination.

It is important to consider that the benefits of plugging orphan wells may not be fully reflected in methane-based carbon credits. Co-benefits, such as protection against water contamination or mitigating carcinogenic emissions, can be hugely important to the health and protection of nearby communities.

Key questions:

- Should the VCM explicitly account for co-benefits when quantifying carbon credits?

VI. Frameworks for orphan well carbon credits

Table 1: Comparison of four existing frameworks for carbon credits of orphan well plugging

Methodology	Well Type	Countries	Max Crediting Pd. (yrs.)	Crediting Principle	Requires Production Data?	Volume Determination - Initial - Over Crediting Period	Project Stage at Which Issue Credits		GWP Factor for CO ₂ e ²	Buffer (Purpose of Buffer)	Deduct Project Emissions?	Requires Site Remediation?
American Carbon Registry ⁴³	Orphan	U.S. & Canada	20	Expected Emissions	N	-Measurement (2x before P&A) -Flat with Measured Rate	100% upon P&A		100 yrs.	5% (Uncertainty)	Y	N
BCarbon ⁴⁴	Orphan & Abandoned	U.S. & Canada	20	Expected Emissions	Y (42 months)	-Decline Curve Analysis -Declines from Initial Rate -Discounted by Leak Probability -Capped at 300K credits	80% upon P&A; 20% >1 year		20 yrs. with option to use 100 yrs	5% (Plug Failure)	Y	Y
CarbonPath ⁴⁵	Orphan & Abandoned	U.S.	50	Extrapolation of Leak	N	-Measurement (1x before P&A) or Default -Flat with Measured Rate	100% upon P&A		100 yrs.	None	N	Y
Open Carbon Protocol ⁴⁶	Orphan	U.S.	20	Expected Emissions	N	-Measurement (2x before P&A) -Declines from Initial Rate	70% less holdback upon P&A; balance >12-18 mos.		100 yrs.	5% (Leakage, if required)	Y	N

There is significant variability in the existing frameworks for carbon credits from orphan and abandoned wells. The same project could receive a substantially different volume of carbon credits based on which protocol or framework it follows. A high-integrity VCM should be defensible and transparent and such variability in the awarded credit amount could expose the VCM to criticism. There are several key differences among the four existing frameworks, not all of which are active, that are a result of different technical and policy decisions. The first major difference, as outlined in Table 1, relates to the robust quantification of emissions (Principle 7). The volume calculation method varies between all four frameworks as they seek to account for long-term and short-term variability in different ways. Some frameworks require measurements, while others allow for production-based decline modeling. Some frameworks assume a constant emission rate when extrapolating leak measurements, and others assume a decreasing emission rate over the years.

They also vary in crediting period, ranging from 20 years to 50 years, which has a significant impact on the quantified volume, as different frameworks will either assume that 20 or 50 years of emissions have been avoided. The GWP value is also different across frameworks, with three out of four initiatives using the GWP100 value (approximately 30 for methane) and one framework using the GWP20 value (81 for methane). This slight difference could lead to a CO₂e value that is 2.7x higher than frameworks that use the GWP100 value *for the same volume of avoided methane*. One of the other major differences is whether or not to account for project emissions when calculating avoided emissions. Three out of four frameworks require deduction of project emissions, which also impacts the carbon credit value even if the volume of avoided methane from the plugging calculation is identical. All of these key decisions that impact awarded carbon credits have been identified in Principle 7.

There are several other nuanced differences between the frameworks, including differences in how to demonstrate and prove additionality, permanence, and sustainable development benefits and safeguards.

Each framework addresses the major issues discussed in this issues primer, but different decisions for how to handle these grey areas leads to significant impacts on the awarded carbon credits.

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