REPORT EXECUTIVE SUMMARY

Navigating the Hydrogen Production Pathway

A Hydrogen Production GHG Control Technology Review for the Center for Applied Environmental Law and Policy (CAELP)

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About us

Worley Consulting is Worley's global group of consultants, scientists, engineers, and digital experts dedicated to solving the world's critical infrastructure, environmental, energy, and resource challenges.

We partner with our customers to find solutions that create value over the life of their assets. We implement new technologies to run assets more efficiently, secure and safeguard social license, support local communities, and accelerate the energy transition.

We evaluate options and identify opportunities and risks to support our customers' decision making. We assist with asset strategy and selection, business case preparation, concept and feasibility studies, technology evaluation, energy strategies and asset operational excellence.

Introduction

Hydrogen is a versatile element that can form compounds with a wide range of other elements, opening a large possibility of interesting opportunities in the pursuit of climate neutrality.

Worley Consulting was tasked by CAELP to conduct a study analyzing hydrogen production technologies and the Greenhouse Gas (GHG) emissions reduction potential of each, the objectives of which were:

Legislation and Regulation Overview

Summarize and evaluate applicable U.S. legislation and identify the consequences with consideration of key strategic objectives, opportunities (e.g., tax credits) and applicable limitations.

GHG Emissions Reduction Pathways and Economic Analysis

Identify ways to transform new and existing production pathways into producers of low GHG hydrogen. Evaluate resultant emissions reductions and costs for implementation of enabling technology.

Technology Overview and Economic Analysis

Summarize existing and emerging hydrogen production pathways with consideration of the potential scale, technology readiness level (TRL), commercial readiness index (CRI), Carbon intensity (CI) and associated costs.

Sensitivity Analysis

Create a discussion basis to inform the legislative and financial environment required to enable these paths (required policy incentives).

At a high level, the methodology followed for the study is shown in the following figure.

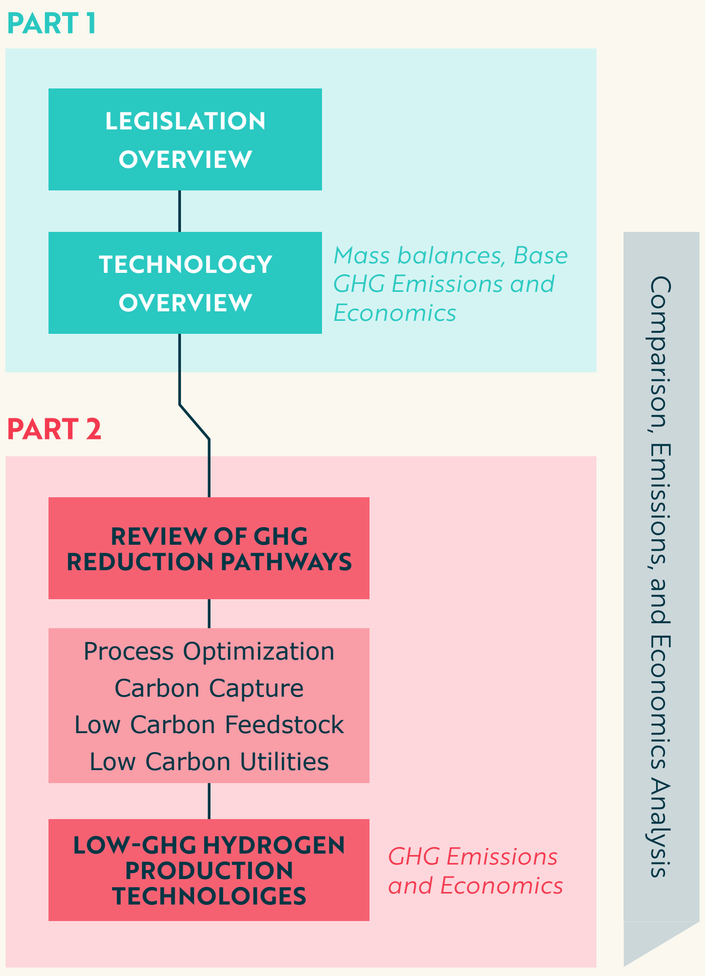
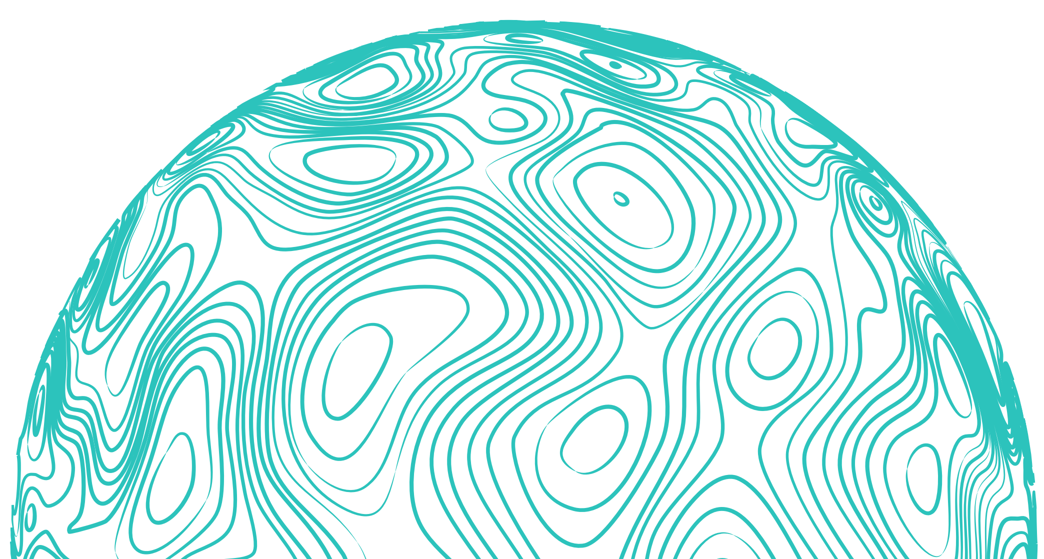


Fig. 0 1 High level study methodology

Legislation and Regulation Overview

A review of the relevant legislation and regulation was conducted and is summarized in Figure 0-2 as it relates to the production of hydrogen.



In the U.S., various incentives and standards for low-GHG hydrogen have been established as outcomes of relevant legislation and regulation.

The consequences of legislation on individual hydrogen production technologies are discussed in the report with specific focus on 45V, Q and Y, which are tax credit incentives associated with clean H2 production, CO2 sequestration and clean electricity production respectively. Figure 0-3 provides an overview of the tax credits, applicability, and the qualifying criteria of each.

Figure 0-2 Legislation Overview Summary

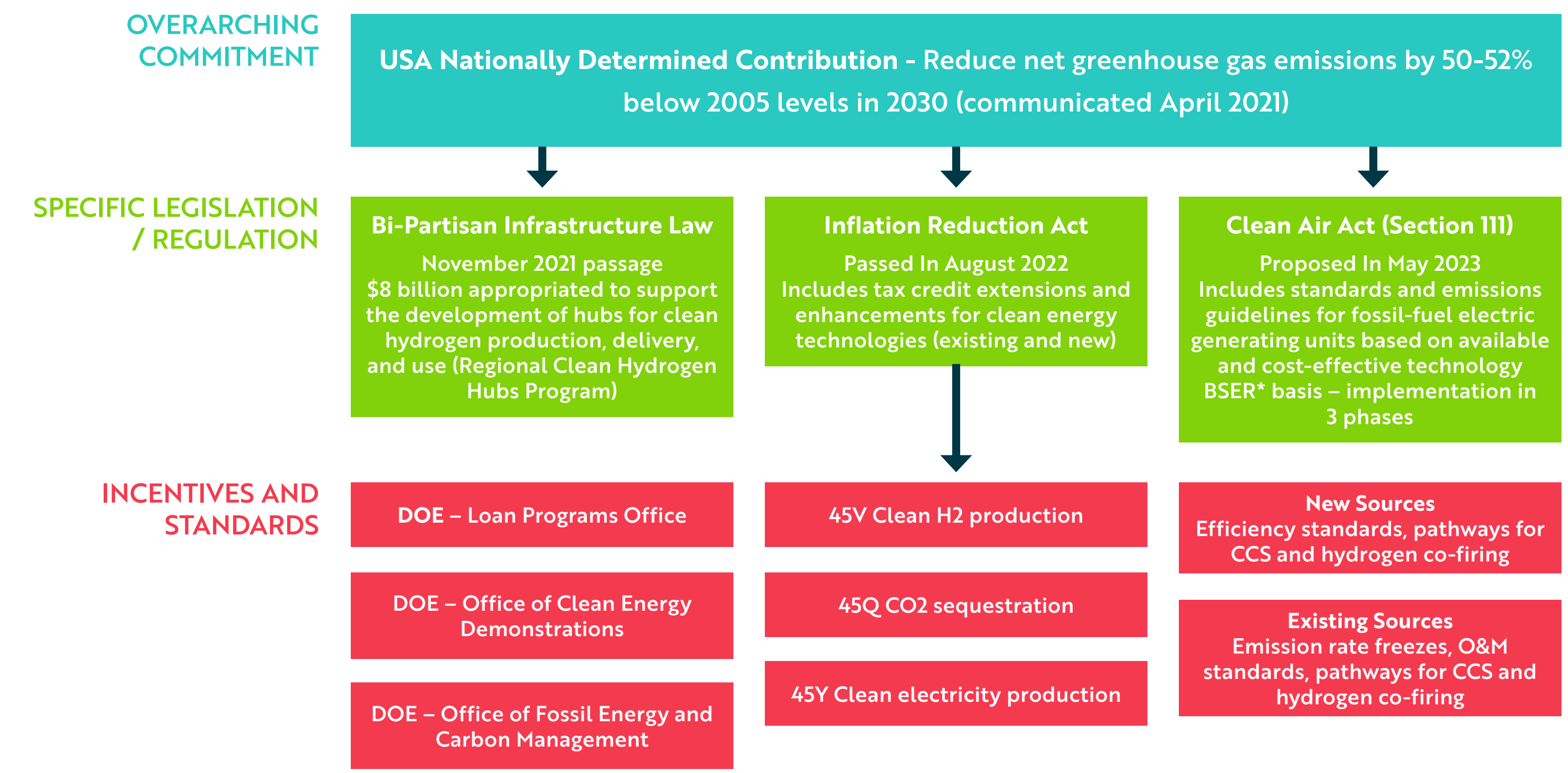
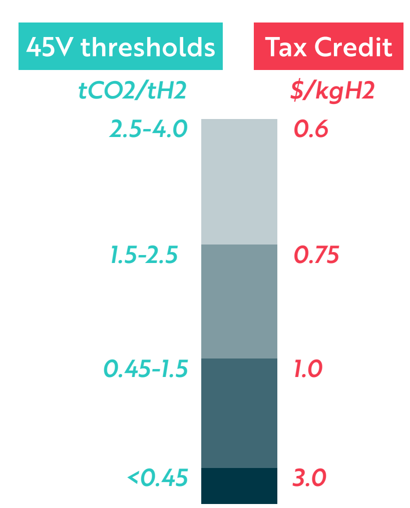


Figure 0-3 Overview of 45V/Q/Y Tax credits

45V

Needs to be traded off as only one can be claimed per taxable year

45V is applicable to clean H2 production facilities. Qualifying credit is on the basis of tons CO2 emitted per ton of H2 produced.



45Q

45Q is applicable for carbon dioxide sequestration. Qualifying credit is on the basis of min. capture. Capture and Secure Geological Storage is at a base credit of 17$/tCO2; and multiplied by 5 to 85$/tCO2 if prescribed operational requirements are met.

METHOD OF CARBON CAPTURE, USE & STORAGE	TAX CREDIT AMOUNT UNDER THE BIPARTISAN INFRASTRUCTURE LAW	TAX CREDIT AMOUNT UNDER THE INFLATION REDUCTION ACT
Capture and Secure Geological Storage	31.77$/tCO2 in 2020. Increasing to 50$/tCO2 by 2026, then CPI adjusted	Base: 17.00$/tCO2; or Bonus: 85.00$/tCO2
Capture and Use (including EOR)	20.22$/tCO2 in 2020. Increasing to 50$/tCO2 by 2026, then CPI adjusted	Base: 12.00$/tCO2; or Bonus: 60.00$/tCO2
DAC & Other capture facilities	(Dependent on Use/Storage Method, refer to above)	Base: 26.00 – 36.00$/tCO2; or Bonus: 130.00 – 180.00$/tCO2

45Y

45Y is applicable to electricity production from certain renewable resources. Qualifying Tax credit is on a base credit of 0.3 c/kWh, and multiplied by 5 to 1.5 c/kWh if prescribed operational requirements are met.

This credit may be stacked with the 45V credit when the qualifying clean electricity is used to power electrolyzers producing qualified clean hydrogen.

Technology Overview

The hydrogen production technologies analyzed in this study range from traditional to emerging.

These technologies have been classified into 4 distinct groups based on technology maturity and commercial readiness using the indicative metrics of technology readiness level (TRL) and commercial readiness index (CRI) as shown in Figure 0-4.

GROUP 1

Large scale: High TRL & CRI

STEAM METHANE REFORMING (SMR)

AUTOTHERMAL REFORMING (ATR)

Group 1 technologies are technically mature and rank high on the CRI as they have been proven at large scales and are either already widely available or in advanced stages of commercial application. Hydrogen produced from these technologies are commonly used in industrial processes such as refining, chemicals, including ammonia and steel (as direct reduced iron).

GROUP 2

Lower TRL & CRI

METHANE PYROLYSIS

Group 2 technologies are not as technically mature or commercially viable but have the potential to be scaled up.

GROUP 3

Smaller scale

GASIFICATION

Group 3 technologies are technically and commercially viable and implemented at large scale for syngas production, while at relatively smaller scale for on-purpose hydrogen production. Gasification from different feedstocks (including coal, petcoke, biomass, and residue) are evaluated in this analysis. However, for the case study comparison, biomass gasification is evaluated in more detail.

GROUP 4

Comparison

ELECTROLYSIS

Electrolysis, classed in Group 4, is evaluated as a clean emerging technology for comparison purposes; it is considered to have the lowest overall carbon intensity when powered with low-carbon renewable electricity and is used to benchmark other technologies.

**Note that the technologies included in Groups 1-3 are categorized to produce unabated hydrogen (commonly referred to as grey, black/brown, or turquoise hydrogen).*

Figure 0-4 Hydrogen Production Technology Categories

The above does not represent a comprehensive outline of all possible hydrogen production technologies but rather an assessment of those that are most advanced in terms of TRL and CRI. There are other emerging technologies with lower TRL's and CRI's which have not been evaluated in detail.

Hydrogen production technologies differ greatly, thus, archetype facilities were selected to enable baseline emissions and reductions calculations in evaluating GHG emissions reduction options for each. The archetype facilities are conceptualized based on capacity, configuration, current technological readiness, and commercial viability.

The archetype facilities are representative of typical facilities in the U.S. and globally; aspects of which can apply to multiple real-life operating facilities.

GHG emissions reduction options applied to these archetype facilities provide a wide range of solutions, which can be customized for individual application. The selected technology configurations and capacities for each hydrogen production technology archetype are provided in Table 0-1.

Table 0-1 Selected Technology Configuration and Capacity

	ATR	SMR	METHANE PYROLYSIS	GASIFICATION	ELECTROLYSIS
H2 capacity (tpd)	358	358	110	164	43
Key configuration specifications	Natural Gas/ O2 fed integrated heat reformer design	Fuel fired reformer furnace	Plasma arc pyrolysis	Biomass (woodchips) Feed	100 MW Electrolyzer

Emissions and Abatement

We used a well-to-gate approach to define the boundary limits for the emissions calculations as represented in Figure 0-5.

For the purposes of this study, boundary limit properties do not include additional compression or purification of hydrogen beyond standard levels for a given production technology. This is true for when the hydrogen is to be used for applications such as combustion but may not be true for applications such as chemical or industrial processes.

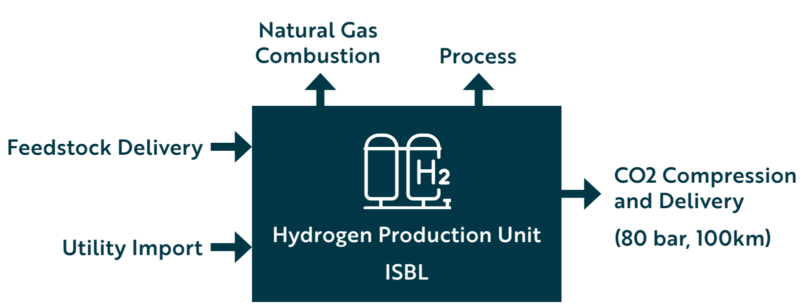


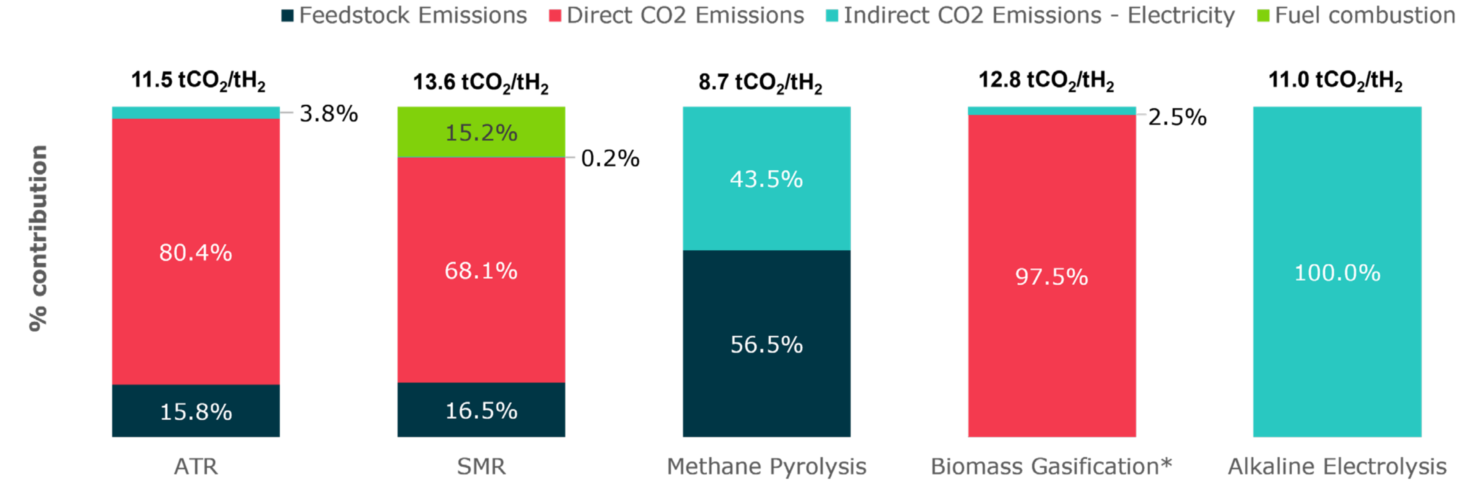
Figure 0-5 Points of Emission

It is important for putting the context of the results in perspective to understand and to be clear on the assumptions for any study of this kind. Sensitivity analyses have been conducted to highlight those variables with the greatest uncertainty and impact on the outcomes. When comparing different studies, it is critical to understand the assumption set used in any modelling of carbon intensity or levelized cost of hydrogen (LCOH) production.

Emissions related to the feedstock and electricity supply (driven by upstream processes) are included in the emissions calculation, although they are assumed to be outside the scope of influence for these facilities (i.e., the carbon intensity of the electricity or natural gas imported may not be fully dictated by the hydrogen producers). The emissions contributors, and therefore opportunities for possible GHG emissions reduction in the production process, for each technology are presented in Figure 0-6.

Implementation of GHG emissions reduction levers on the base cases of each technology results in low GHG hydrogen production as represented by Figure 0-7. Under the specified set of GHG reduction assumptions for this study, all the low carbon hydrogen production technologies considered in this study qualify for varying degrees of 45V tax credits and the three technologies that specifically use carbon capture to abate emissions are eligible for 45Q tax credits.

Figure 0-6 Unabated emissions contributors and GHG reduction levers



	ATR	SMR	Methane Pyrolysis	Biomass Gasification*	Alkaline Electrolysis
Process optimization	-	●	-	-	-
Low carbon feedstock	-	-	-	●	-
Low Carbon utility supply	●	●	●	●	●
Carbon capture	●	●	-	●	-

**Note: Figure is based on grid supplied electricity and not renewables; for gasification, base case feed is assumed to be non-biogenic*

Figure 0-7 Hydrogen production technologies abatement summary

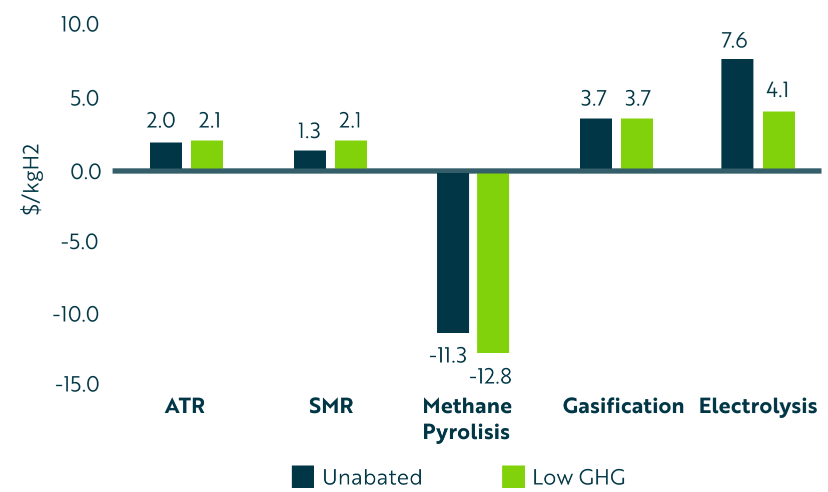
Technology	Unabated	Implementation of GHG emissions reduction technologies (Scope 1&2)	Low GHG H2
SMR	13.6 tCO2 / tH2	▶ Energy efficiency improvement / optimization ▶ Selected carbon capture ▶ Replace electricity supply with renewable source ▶ Replace with low carbon feedstock ▶ Decarbonize natural gas supply	3.6 tCO2/tH2
ATR	11.5 tCO2 / tH2		1.2 tCO2/tH2
METHANE PYROLYSIS	8.7 tCO2 / tH2		2.6 tCO2/tH2
GASIFICATION	12.8 tCO2 / tH2		0.8 tCO2/tH2
ELECTROLYSIS	11.0 tCO2 / tH2		0.3 tCO2/tH2

Note: Decarbonization of emissions associated with natural gas exploration/production/distribution imported may not be fully dictated by the hydrogen producers. These emissions are assumed to reduce by 50% by 2050. Renewable electricity supply assumed in all low GHG H2 cases.

Sensitivity Analysis

In terms of LCOH for the base case unabated modelling, methane pyrolysis is the lowest (and negative) since the H2 produced is a by-product and the primary product is carbon black which has a high value. This is followed by SMR and then ATR. Electrolysis has the highest LCOH, followed by gasification.

Figure 0-8 Levelized Cost of Hydrogen – Unabated and Low GHG H2



The LCOH is impacted by the assumptions around electricity costs and the value of additional products. In particular, the prices of natural gas, carbon black, biomass and renewable electricity are variables that have varying and at times significant impacts across the technologies.

For the LCOH of low GHG hydrogen, ATR and SMR are at comparable levels and likewise for gasification and electrolysis. Low GHG electrolysis is significantly lower than that of unabated due to a lower assumed renewable electricity price compared to the grid price. Unabated and low GHG gasification have the same LCOH as the value from lower renewable electricity prices is offset by additional carbon capture costs.

The key sensitivities to LCOH for unabated emissions for each technology are summarized in Figure 0-9.

The key sensitivities to LCOH for low GHG emissions for each technology are summarized in Figure 0-10.

Figure 0-9 Key sensitivities for unabated emissions

TECHNOLOGY	SENSITIVITY	RANGE	$/kgH2
SMR	Natural gas price (2025)	4.2–6.8 $/ MMBTU	1.2 / 1.8
ATR	Natural gas price (2025)1	4.2–6.8 $/ MMBTU	1.8 / 2.4
METHANE PYROLYSIS	Natural gas price (2025) 1	4.2–6.8 $/ MMBTU	-11.7 / -10.7
	Carbon Black price	0–1880$/t	7.6 / -11.3
GASIFICATION	Biomass feed price	35–75$/t	3.7 / 4.3
ELECTROLYSIS	Oxygen Product Price	0-580$/t	8.1 / 7.6

Low Sensitivity / High Sensitivity

Figure 0-10 Key sensitivities for low GHG emissions

TECHNOLOGY	SENSITIVITY	RANGE	$/kgH2
SMR	CO2 Transport and Storage Cost	10–40$/t	2.1 / 2.5
ATR	CO2 Transport and Storage Cost	10–40$/t	2.1 / 2.5
METHANE PYROLYSIS	Renewable Electricity price	17–35$/MWh	-12.8 / -12.4
GASIFICATION	CO2 Transport and Storage Cost	10–40$/t	3.7 / 4.8
ELECTROLYSIS	RE price	17–35$/MWh	3.3 / 4.5

Low Sensitivity / High Sensitivity

Conclusions & Comparative Analysis

A comparative analysis of the carbon emissions intensity is shown in Figure 0-11.

The relative carbon intensity of each technology is largely consistent with evaluated literature sources in terms of highest and lowest intensities.

Methane pyrolysis has the lowest carbon intensity while SMR and gasification have the highest in the unabated base case modelling.

For electrolysis, the carbon intensity is completely dependent on the carbon intensity of the grid or other electricity source.

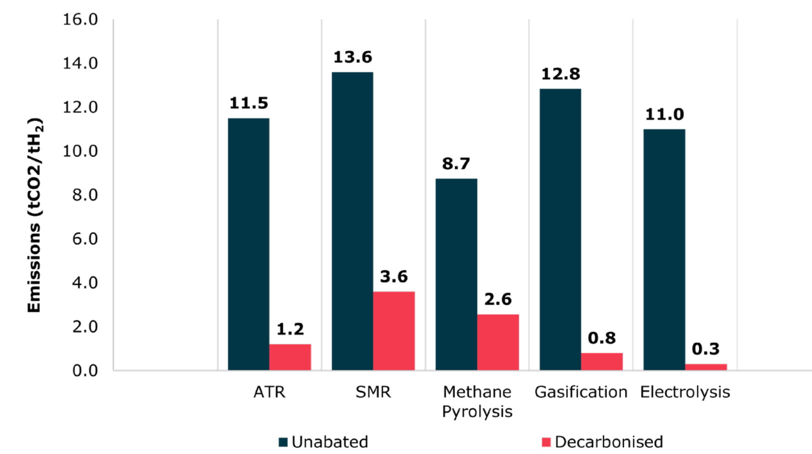
For the unabated model it is assumed that grid sourced electricity is used.

Application of GHG reduction technologies to the unabated cases could achieve the following order from lowest to highest carbon intensity: electrolysis, gasification, ATR, methane pyrolysis and finally SMR.

Methane pyrolysis has the lowest potential for GHG reduction while gasification has the highest.

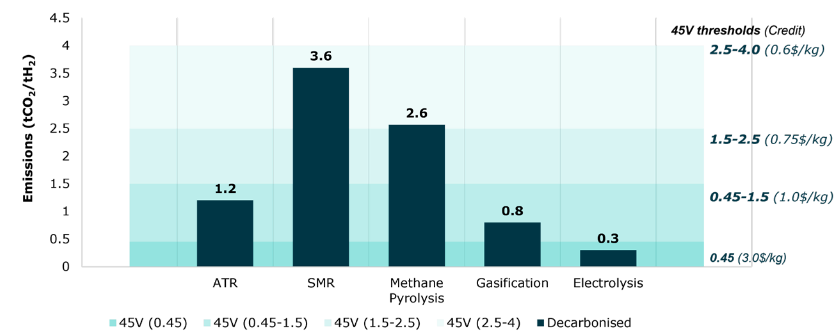
Under the specified set of GHG reduction assumptions in this study, all the low carbon hydrogen production technologies, once abated, qualify for varying degrees of tax credits under the 45V thresholds as summarized in Figure 0 12.

Fig. 0-11 Technology comparison: unabated & decarbonized emissions



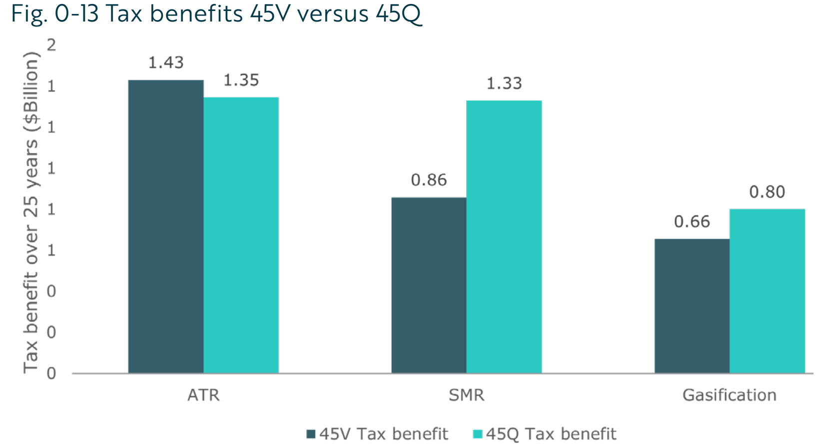
Note: Renewable Grid CI 0.005 tCO_2/MWh aligned with Evolved Energy ADP 2022; 50% feed emissions decarbonization (ex. Gate)

Fig. 0-12 Technology comparison for low GHG H2 production with 45V



**Renewable Grid CI 0.005 tCO2/MWh aligned with Evolve Energy ADP 2022*

Fig. 0-13 Tax benefits 45V versus 45Q



Additionally, under the specified set of GHG reduction assumptions in this study, all three technologies that use carbon capture to decarbonize are eligible for 45Q credits at a base credit of 17$/tCO2 and bonus credit up to 85$/tCO2. However, the Internal Revenue Code (IRC) specifically disallows the combination of the new 45V hydrogen production tax credit with the carbon dioxide sequestration tax credit provided under section 45Q for the taxable year or any prior taxable year. The practical application of 45V and Q can be described as follows:

- For tax liable companies, either incentive can be claimed as a direct payment for first 5 years, and thereafter to off-set tax for the next 5-7 years.
- The period for which the incentives can be claimed is for 10 years under 45V and 12 years under 45Q

An analysis to determine which of 45V or Q has a higher impact on the LCOH for the applicable technologies was conducted and is summarized in Figure 0 13.

In comparing the application of 45V and Q for the eligible technologies, 45Q represents better savings over 45V for the SMR and gasification, while for ATR, the reverse is true driven by SMR qualifying for a lower 45V tax credit than ATR (0.6 $/kg vs 1.0 $/kg respectively) and a higher hydrogen to CO2 ratio for reforming technologies in comparison to gasification technology.

The highest impact of the 45V tax benefit is for electrolysis as the associated carbon intensity of H2 produced through this pathway qualifies for the maximum 45V credit if low carbon renewable electricity is used. The analysis suggests that the reforming technologies (SMR and ATR) remain competitive against electrolysis even though they qualify for a lower tier value credit in comparison.

It is important to note that this analysis is based on several assumptions, the sensitivities for which are shown above in Figure 0 9 and Figure 0 10. For electrolysis, the renewable electricity price is particularly sensitive and this needs to be considered when comparing against other hydrogen production technologies.

The tax impacts (from year 6 onwards) need to be understood to further evaluate the impact of total credit savings on the LCOH. Since the levelized cost has not considered the financing parameters of the project, tax credit breaks cannot be directly deducted from the LCOH.

worley consulting

For more information, email

erica.bhasin@worley.com

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