RystadEnergy

Methane Tracking Technologies Study

Final Report

Environmental Defense Fund

Public version
October 18, 2023

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Project scope - Assessment of methane abatement potential for Australia’s energy sector

Overall project scope

1 Introduction to methane emissions

a. Overview of the current state of methane emissions from the coal mining and oil and gas sectors

b. Overview of the official emissions figures

2 Emissions MRV[1] and reduction

a. Overview of the main technologies used for MRV[1] and abatement in the coal mining and oil and gas sectors, based on what various energy and technology companies communicate publicly.

b. Insights from interviews with energy companies and technology providers covering questions such as:

   a. *Short- and medium-term plans*

   b. *Key drivers and realistic emission reduction potential*

   c. *Remaining technological or practical challenges*

   d. *Abatement cost and volume potential*

3 MACC[2] assessment

a. Overview of the abatement potential and associated costs

b. Assessment of the officially reported emission volumes, and the estimated share of various sources and the corresponding technology cost to address them to determine the cost of abatement for each source

c. Assessment of the value of gas recovered and the emissions cost avoided to understand the net impact of abatement

Note: (1) MRV refers to measurement, reporting and verification of emissions – I.e. direct measurement across all sources wherever feasible and reconciliation between sources and site-level measurements
(2) Marginal Abatement Cost Curve

Source: Rystad Energy

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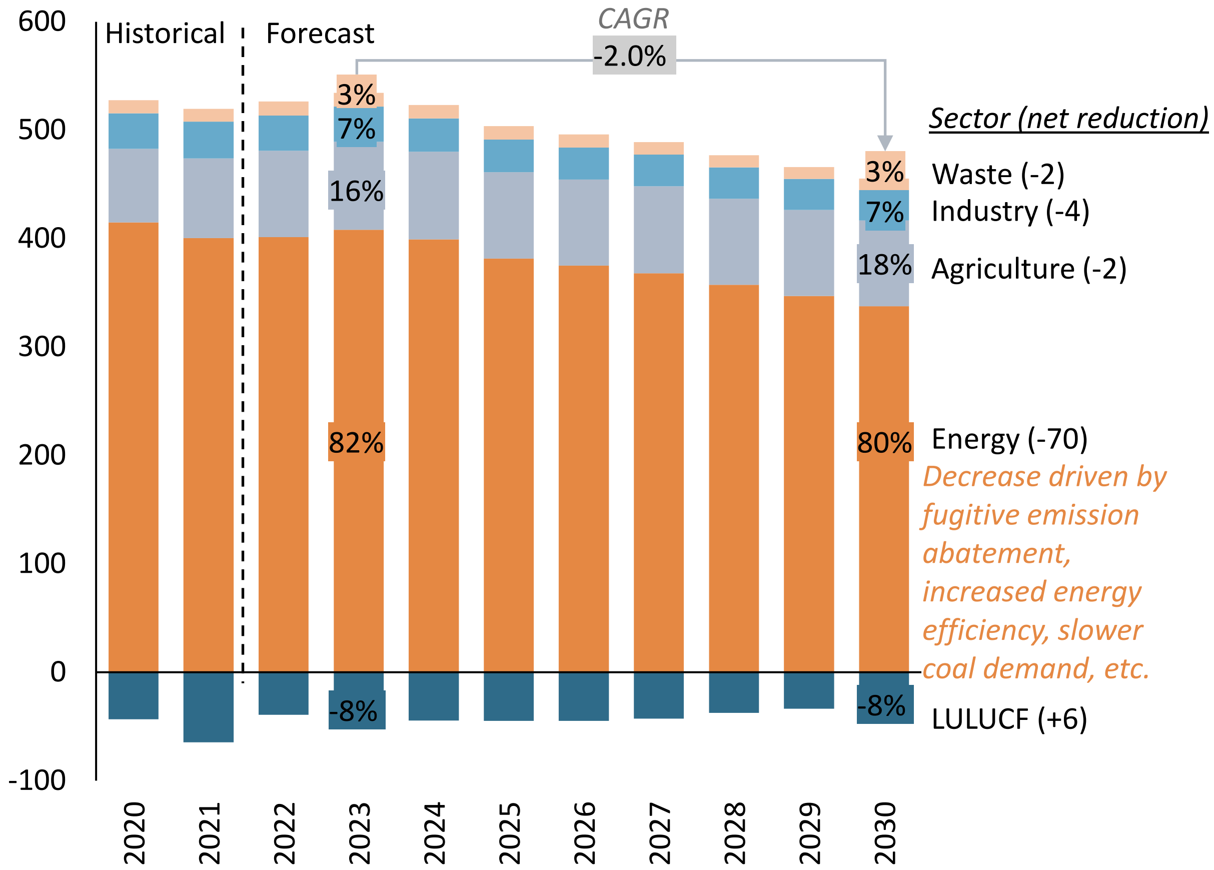
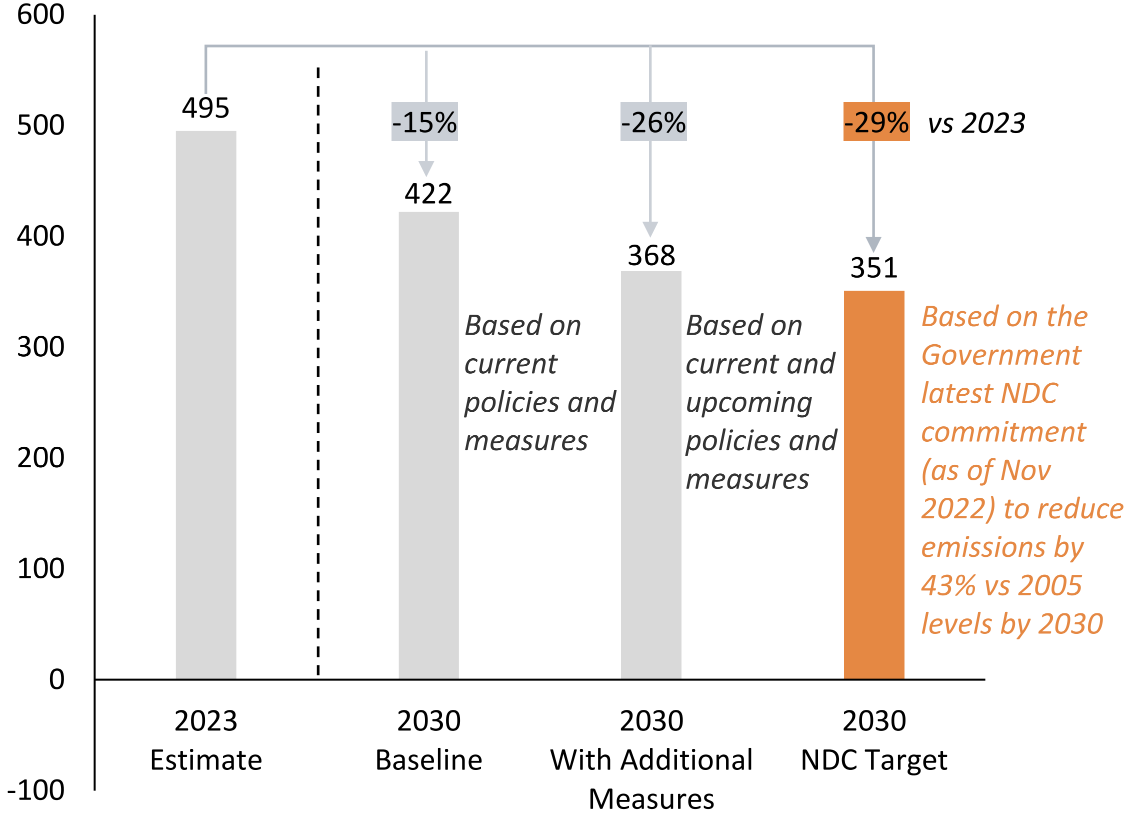
The energy sector is likely to drive overall baseline emissions reduction, although faster action is needed to meet the 2030 NDC target

Australia greenhouse gas emissions baseline projection by sector
Mt, CO2eq.



Decrease driven by fugitive emission abatement, increased energy efficiency, slower coal demand, etc.

Australia greenhouse gas emissions projections vs targets
Mt, CO2eq.



Based on current policies and measures

Based on current and upcoming policies and measures

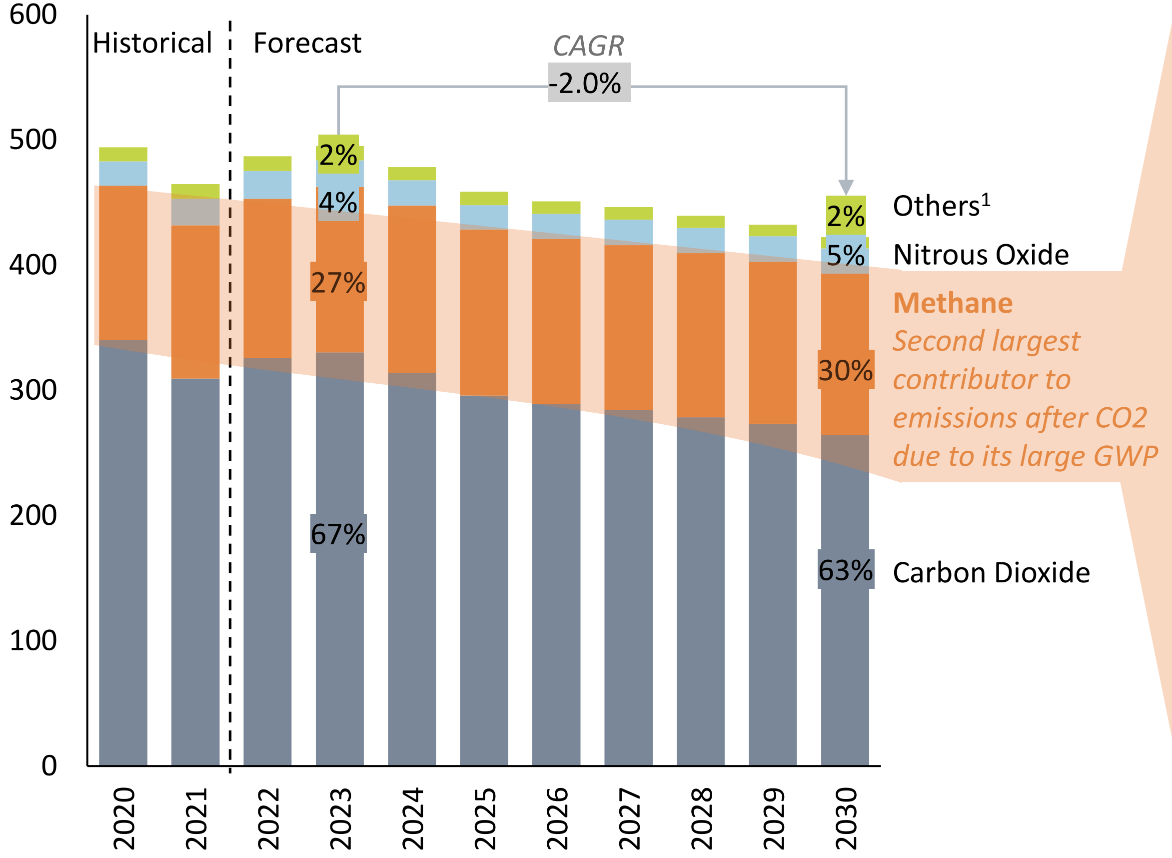
Based on the Government latest NDC commitment (as of Nov 2022) to reduce emissions by 43% vs 2005 levels by 2030

Note: (1) 100-year GWP factor of 28 used as per Australia National Greenhouse Accounts; (2) LULUCF = Land-use, land use change and forestry; (3) Totals might not add up due to National Greenhouse Accounts accounting and categorization methods;

Source: Rystad Energy research and analysis; Australian Government Department of Climate Change, Energy, the Environment and Water – National Greenhouse Accounts

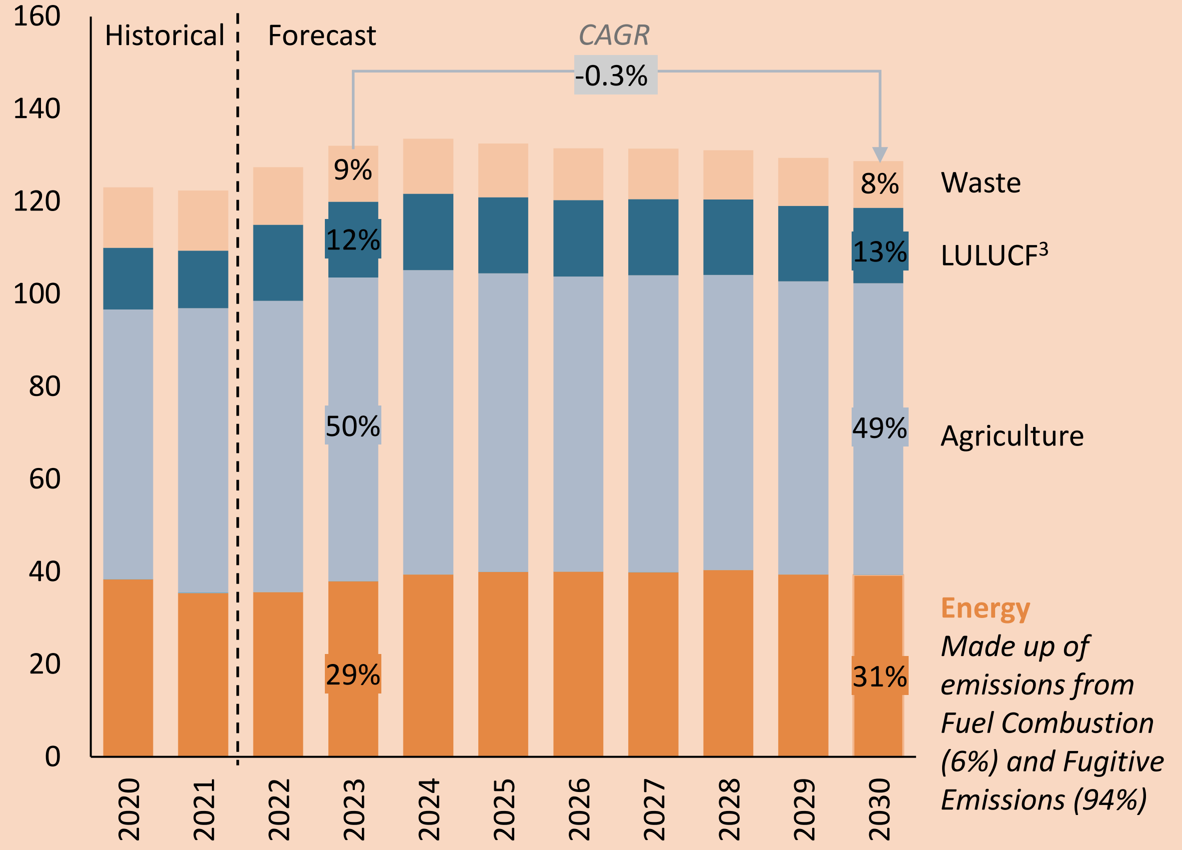
The share of methane emissions from the Australian energy sector is projected to steadily increase without stringent regulation

Greenhouse gas emissions in Australia by type
Mt, CO2eq.



Methane
Second largest contributor to emissions after CO2 due to its large GWP

Methane emissions in Australia by sector
Mt, CO2eq.[2]



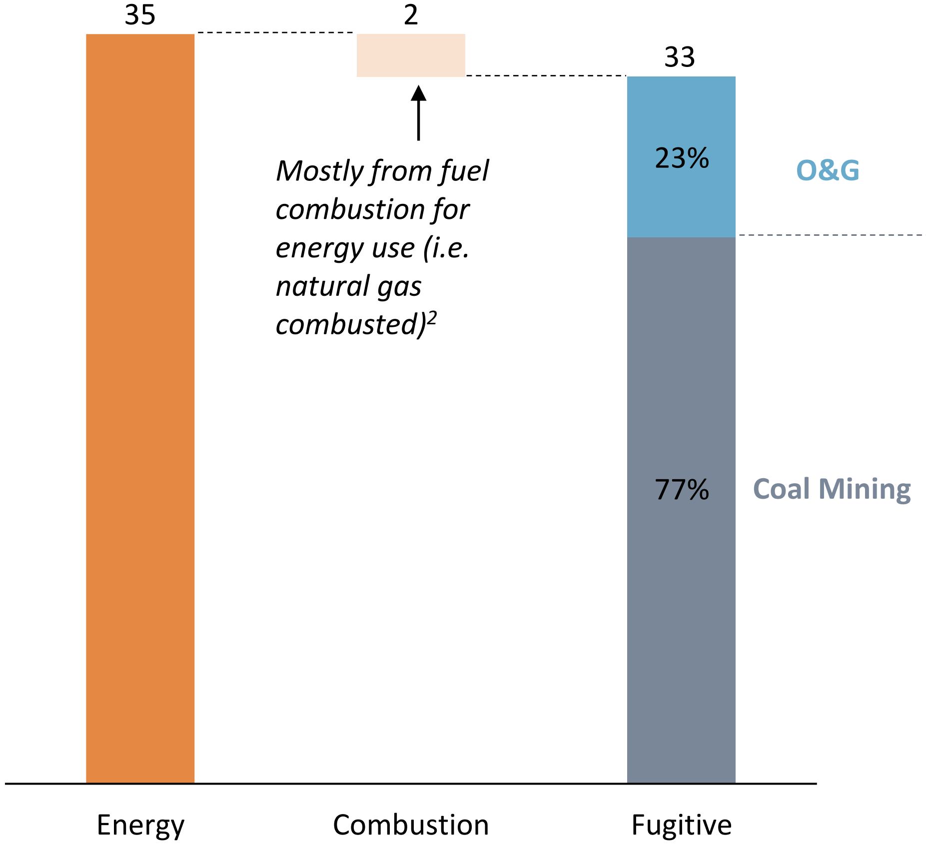
Energy
Made up of emissions from Fuel Combustion (6%) and Fugitive Emissions (94%)

Note: (1) Others includes Hydrofluorocarbons, Perfluorocarbons, Sulphur Hexafluoride; (2) 100-year GWP factor of 28 used as per Australia National Greenhouse Accounts; (3) LULUCF = Land-use, land use change and forestry
Source: Rystad Energy research and analysis; Australian Government Department of Climate Change, Energy, the Environment and Water – National Greenhouse Accounts

The majority of methane emissions in the energy sector come from fugitive emissions in coal mining

2021 breakdown of Australian methane emissions in the energy sector

Mt, CO2eq.[1]



Mostly from fuel combustion for energy use (i.e. natural gas combusted)[2]

- Methane is a key product of O&G so its recovery can be directly monetized - O&G players are active in methane recovery
- Majority of the emissions are from Western Australia and Queensland

- Majority of these are unaddressed though the coal industry is expected to ramp up its efforts since the Safeguard Mechanism was revised in Jul 2023
- It is understood that surface mine methane emissions may be under-reported due to the lack of active on-site measurements
- Methane emissions are often a by-product of coal production and vented
- Emissions are mostly from Queensland and New South Wales

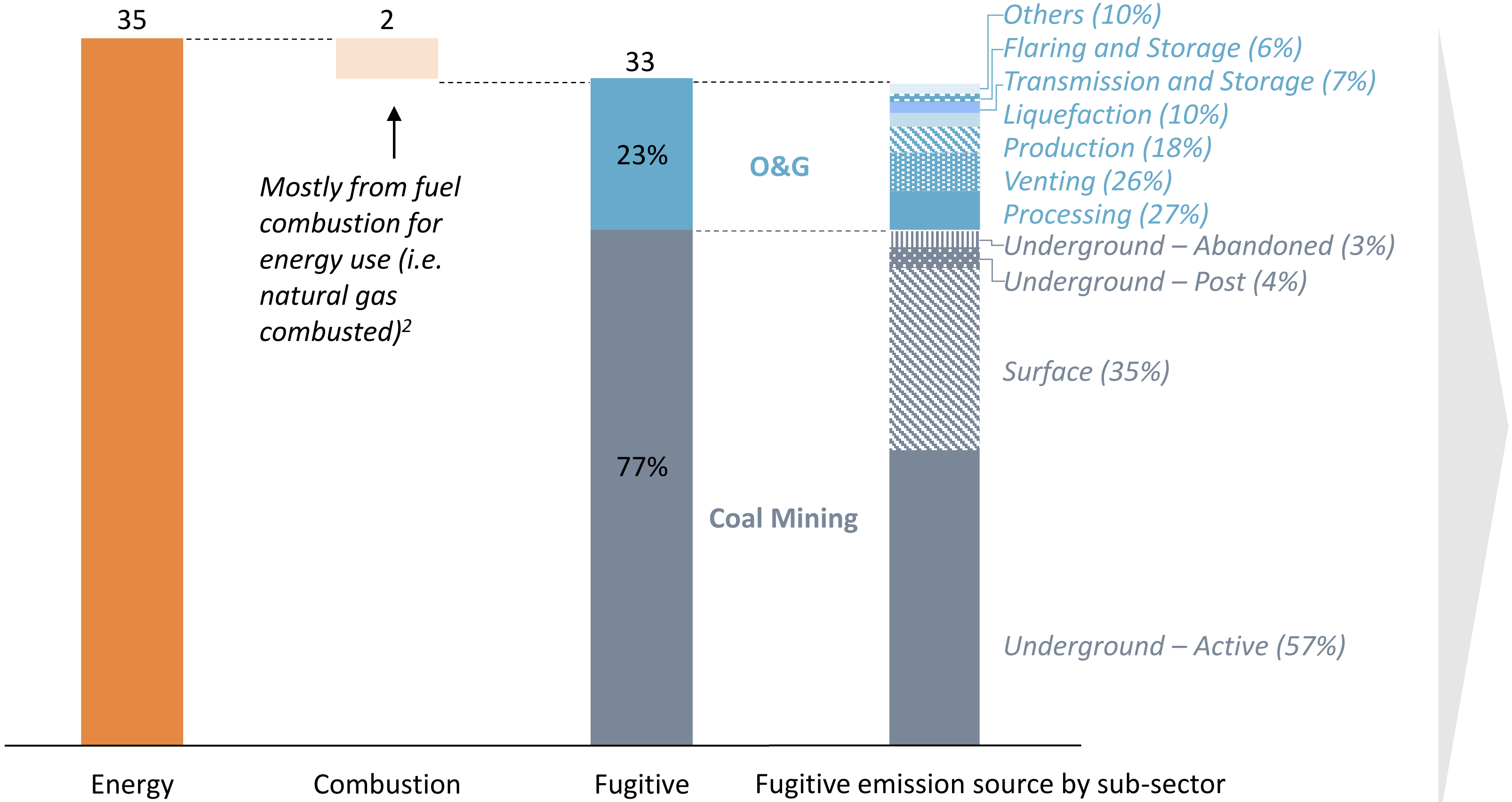
Note: (1) 100-year GWP factor of 28 used as per Australia National Greenhouse Accounts. If 20-year AR6 GWP factor of 82.5 is used, methane emissions from the energy sector will be 104 Mt CO2eq. with 6 Mt CO2eq. emissions from combustion, 76 Mt CO2eq. from coal mining sector and 22 Mt CO2eq. from O&G sector respectively.
(2) Most of which are used from public electricity and heat production and fuels use (in manufacturing industries and construction, transportation, commercial, residential, agriculture, forestry and fishing); methane emissions from combustion in the energy sector are from oil and gas extraction processes are considered separately from fugitive emission sources (such as venting, flaring)

Source: Rystad Energy research and analysis; Australian Government Department of Climate Change, Energy, the Environment and Water – National Greenhouse Accounts

A range of technological solutions are needed to drive deep methane abatement in the energy sector

2021 breakdown of Australia methane emissions in the energy sector

Mt, CO2eq.[1]



~65% of methane emissions from the energy sector can be abated using currently available technologies

Note: (1) 100-year GWP factor of 28 used as per Australia National Greenhouse Accounts. If 20-year AR6 GWP factor of 82.5 is used, methane emissions from the energy sector will be 104 Mt CO2eq. with 6 Mt CO2eq. emissions from combustion, 76 Mt CO2eq. from coal mining sector and 22 Mt CO2eq. from O&G sector respectively

(2) Most of which are used from public electricity and heat production and fuels use (in manufacturing industries and construction, transportation, commercial, residential, agriculture, forestry and fishing); methane emissions from combustion in the energy sector are from oil and gas extraction processes are considered separately from fugitive emission sources (such as venting, flaring)

Source: Rystad Energy research and analysis; Australian Government Department of Climate Change, Energy, the Environment and Water – National Greenhouse Accounts

US has seen regulatory change which could further accelerate technology and operational deployment in the short term

Overview of methane-related regulations introduced between 2021-2023 in United States

Key Stakeholders

Program	Overview	Key Details
Section 111 Methane Rule	New Source Performance Standards	• EPA to set new standards of performances for new/modified sources and enforce state plans to establish standards for existing sources in the power sector; to be reviewed every eight years • New sources to comply with standards by 2024 while state plans for existing sources to be by 2025
GHG Reporting Program	Revised Reporting Standards	• Reforms to address under reported methane emissions, with a two- year deadline for updating reporting protocols (revisions to be effective in 2025 onwards) • Reported emissions need to be evidence-based, accurate and verifiable/transparent • This will impact approx. 8,000 facilities (required to report emissions annually)
Methane Emissions Reduction Program	Introduction of Methane Charge	• **900 USD/ton in 2024, 1,200 USD/ton in 2025 and 1,500 USD/ton in 2026 and thereafter** • Applies to facilities emitting more than 25 ktCO2e per year • Charge does not apply to permanent plugged wells in previous year or transmission pipeline projects impacted by unreasonable permitting delays
	Provision of Financial and Technical Assistance	**Total of 1,550 MUSD** to provide technical and financial assistance where: • 850 MUSD allocated to supporting methane mitigation and monitoring • 700 MUSD targeted at methane mitigation for conventional wells
	Additional Funding Availability	**Up to 350 MUSD** allocated to support: • Formula grant funding to reduce methane emissions from low-producing conventional wells on non-federal land • Environmental restoration of well pads • Monitoring of methane emissions

Target

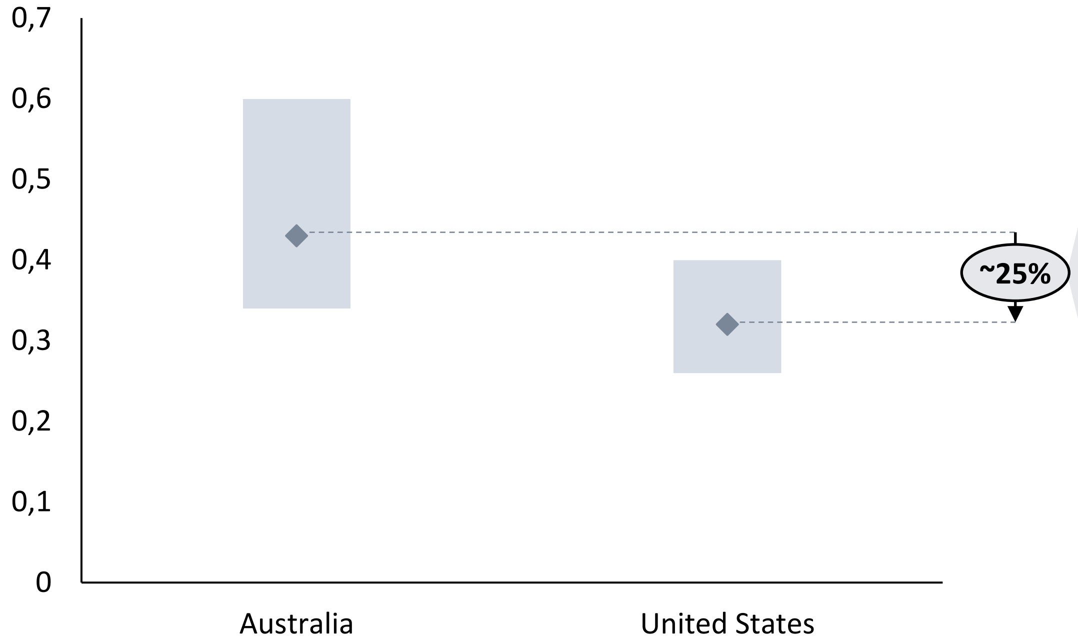
87% reduction versus 2005 levels by 2030

Regulatory push, technical and financial support have underpinned growth of methane technology industry in USA. Similar intervention could potentially drive supplier interest in Australia and lead to development of a robust MRV and abatement technology market.

Source: US EPA; Rystad Energy research and analysis

Increased regulations in Australia could drive substantial uptake in methane measurement and abatement, likely lowering deployment costs

2018-2022 Deployment CAPEX range estimates for oil and gas equipment installation
USD/boe, Real 2023



United States tends to see lower overall deployment cost versus Australia due to:

1. **Larger demand base** for methane measurement and abatement equipment thus providing economies of scale ✓
2. **Higher concentration of US oil and gas sites and existing infrastructure** enabling higher operational synergies and ease of deployment
3. **A more mature supplier market** which supports lower supply chain logistic costs to deliver equipment and services ✓

Various types of methane measurement and abatement equipment are present within Electrical and instrumentation, Major equipment and Material.

Regulation can boost measurement and abatement requirements, thereby driving demand, scale and encouraging suppliers to make a broader set of technologies available.

Notes: Electrical and instrumentation refers to cabling, electrical equipment such as transformers, rectifiers, converters, control, automation and measurement, telecommunication and software
Major equipment refer to compressors, motors, turbines, power generator and control systems
Material refer to piping, valves and actuators
Excludes shale/tight oil sector cost and production
Source: Rystad Energy research and analysis

✓ Areas where regulation could play a key role in driving higher demand/market change

Contents

Development of methane MRV and abatement technologies could drive down costs

Key takeaways

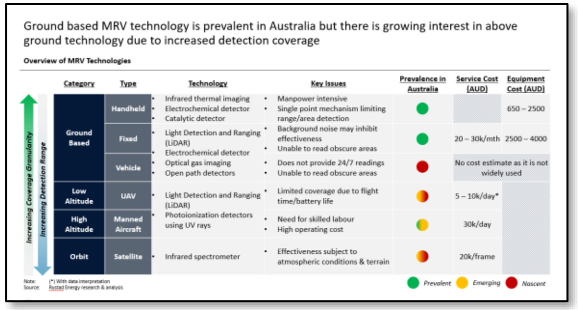
	MRV	Abatement
Supplier landscape	• Mature landscape comprising mostly ground-based MRV technologies • Aerial detection and measurement solutions may see increased offerings but still in the early stages.	• Abatement offerings are far more mature for the oil and gas industry than the coal mining sector given the industry's nature and focus • This has helped to sustain lower deployment cost for oil and gas versus coal
Deployment cost	• Pragmatic **ground-based MRV solutions** have **moderate deployment costs** • **Aerial/orbital solutions still see high deployment cost barriers** due to lack of scale	• Many options can be deployed at low or negative costs but abatement is limited by lack of detection (including MRV) • Deployment costs can be driven down by further market development
Prevalence	• **Overall sector uptake remains low** • The uptake is **more prevalent in oil and gas sector** due to safety concerns. The coal mining sector is yet to see the same uptake.	• **Overall sector uptake remains low** • Methane abatement is **more prevalent in the oil and gas sector** relative to coal

Source: Rystad Energy research and analysis

Rystad Energy assessed MRV and abatement technology types and the supplier landscape in Australia for this section

MRV and abatement technology analysis methodology

1 Overview of MRV and abatement technology types



Ground based MRV technology is prevalent in Australia but there is growing interest in above ground technology due to increased detection coverage

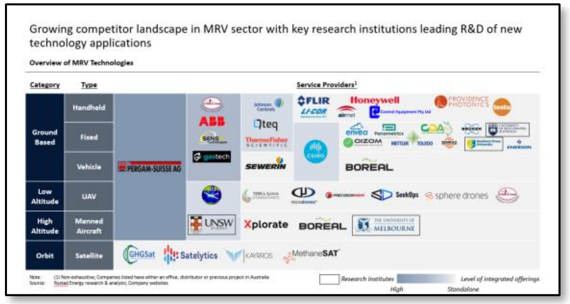
Overview of MRV Technologies

Category	Type	Technology	Key Issues	Prevalence in Australia	Service Cost (AUD)	Equipment Cost (AUD)
Ground Based	Handheld	Infrared thermal imaging Electrochemical detector Catalytic detector	Manpower intensive Single point mechanism limiting range/area detection	🟢		650 – 2500
	Fixed	Light Detection and Ranging (LiDAR) Electrochemical detector	Background noise may inhibit effectiveness Unable to read obscure areas	🟢	20 – 30k/mth	2500 – 4000
	Vehicle	Optical gas imaging Open path detectors	Does not provide 24/7 readings Unable to read obscure areas	🔴	No cost estimate as it is not widely used	
Low Altitude	UAV	Light Detection and Ranging (LiDAR)	Limited coverage due to flight time/battery life	🟡🔴	5 – 10k/day*	
High Altitude	Manned Aircraft	Photoionization detectors using UV rays	Need for skilled labour High operating cost	🟢🟡	30k/day	
Orbit	Satellite	Infrared spectrometer	Effectiveness subject to atmospheric conditions & terrain	🟡🔴	20k/frame	

🟢 Prevalent 🟡 Emerging 🔴 Nascent

Note: (*) With data interpretation
Source: Rystad Energy research & analysis

2 Assessment of technology provider landscape in Australia



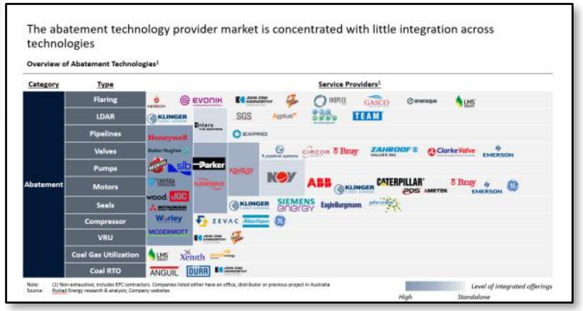
Growing competitor landscape in MRV sector with key research institutions leading R&D of new technology applications

Overview of MRV Technologies

Category / Type / Service Providers[1]

- Ground Based: Handheld, Fixed, Vehicle
- Low Altitude: UAV
- High Altitude: Manned Aircraft
- Orbit: Satellite

Note: (1) Non-exhaustive; Companies listed have either an office, distributor or previous project in Australia
Source: Rystad Energy research & analysis; Company websites



The abatement technology provider market is concentrated with little integration across technologies

Overview of Abatement Technologies[1]

Category / Type / Service Providers[1]

- Abatement: Flaring, LDAR, Pipelines, Valves, Pumps, Motors, Seals, Compressor, VRU, Coal Gas Utilization, Coal RTO

Note: (1) Non-exhaustive; includes EPC contractors. Companies listed either have an office, distributor or previous project in Australia
Source: Rystad Energy research & analysis; Company websites

We identified commercially-ready technologies for MRV and abatement of methane from the energy (coal, oil and gas) sector.

- MRV: assess technologies on coverage granularity, detection range, issues[1], prevalence in Australia and implementation cost.
- Abatement: assess technologies on issues, prevalence in Australia and potential cost per ton of methane abated.

We compiled a list of MRV and abatement technology providers in Australia based on:

- Presence of company office or distributor in Australia
- Press releases or communication indicating local presence or expansion to Australia
- Involvement in any projects in the Australian energy sector

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Note: (1) Issues covered include residual carbon emissions, logistical challenges, increased power consumption, containment of hazardous materials, impact to operations etc.
Source: Rystad Energy research and analysis

① MRV technologies are dominated by ground-based technologies, but with growing share of other ariel/orbit solutions

Overview of MRV technology types

↑ *Increasing coverage granularity*

↓ *Increasing detection range*

Category	Type	Technology	Key issues	Prevalence in Australia	Service cost (AUD)	Equipment cost (AUD)
Ground based	**Handheld**	• Infrared thermal imaging • Electrochemical detector • Catalytic detector	• Manpower intensive • Range/detection area limited by device's single point mechanism	🟢	*Not available*	>10k[1]
	Fixed	• Light Detection and Ranging (LiDAR) • Electrochemical detector • Optical gas imaging • Open path detectors	• Background noise may inhibit effectiveness • Coverage limited by range	🟢	20 – 30k/mth	2 – 4k[2]
	Vehicle		• Does not provide 24/7 readings • Emissions tracking limited to infrastructure with vehicular access	🔴	*No cost estimate as it is not widely used*	
Low altitude	**UAV**	• Light Detection and Ranging (LiDAR) • Photoionization detectors using UV rays • Tunable diode laser absorption spectrometer • Laser based spectrometer	• Operational range is impacted by battery life, flight time • Data granularity contingent on type of sensor used	🟡🔴	5 – 10k/day[3,4]	*Not available*
High Altitude	**Manned aircraft**		• Rely on skilled labor to maneuver aircraft • Emissions tracking limited to navigable inspection areas of large sources • Higher operating cost than other platforms	🟢🟡	30-60k/day[4]	
Orbit	**Satellite**	• Infrared spectrometer	• Unable to gather data from offshore, snow-covered assets • Effectiveness is subject to atmospheric conditions	🟡🔴	20k/frame	

Key Findings

- There is a wide range of MRV technologies with varying granularity, coverage and costs. Currently ground based solutions are generally cheaper and more granular but with limited range versus orbit and aerial which offer limited coverage, higher costs but with higher detection range.
- Reconciliation of data obtained through ground-based and aerial measurements, and its integration into operations through digitalization, remains a key task.

Note: (1) Range based on equipment cost of OGI cameras; (2) Range based on equipment cost of fixed-point electrochemical gas monitors; (3) With data interpretation; (4) Service cost for aerial technologies does not include mobilization cost

Source: Rystad Energy research and analysis; Company websites; Interviews; Secondary research articles

🟢 *Prevalent* 🟡 *Emerging* 🔴 *Nascent*

2 The competitor landscape in MRV offerings is growing, with key research institutions leading R&D of frontier technologies

Overview of MRV technology providers' landscape[1]

Category	Type	Service providers[1]
Ground Based	Handheld	PERGAM-SUISSE AG Heath Pipeline Services Pty Ltd ABB SENSIT Technologies gastech Johnson Controls Qteq ThermoFisher Scientific FLIR LI-COR Impacting Lives Since 1971 Honeywell airmet Control Equipment Pty Ltd Providence Photonics testo
	Fixed	CSIRO envea Panametrics GDA Gas Detection for Australia Bruker University of Wollongong Australia OIZOM Redefining Resources Mettler Toledo SEMRAD Southern Cross University Emerson
	Vehicle	SEWERIN BOREAL
Low altitude	UAV	ARA Terra Sana Consultants microdrones PrecisionHawk SeekOps sphere drones Heath Pipeline Services Pty Ltd
High altitude	Manned aircraft	UNSW Sydney Xplorate BOREAL The University of Melbourne
Orbit	Satellite	GHGSat Global Emissions Monitoring Satelytics Kayrros MethaneSAT Carbon Mapper

☐ Research Institutions

Degree of solution integration: High — Standalone

Note: (1) Non-exhaustive; Companies listed have either an office, distributor or previous project in Australia

Source: Rystad Energy research and analysis; Company websites

1

O&G abatement market is more developed and can be conducted at a lower implementation cost

Overview of abatement technologies

Category	Type	Technology	Key Issues	Prevalence in Australia	Implementation cost (AUD/t CH4)
Abatement	**Flaring**	• Enclosed flaring	• CO_2 is a major by-product	🟢🟡	600 – 785
	LDAR	• Utilization of MRV technologies	• Specific to site and equipment type	🟡🔴	50 – 245
	Pipelines	• Replacing leaking pipelines	• Replacement of key pipes would affect operations of plant	🟡🔴	10
	Pumps and instrumentation	• Convert from pneumatic to electric pump	• Increased power consumption	🟢	250
	Motors	• Convert from fuel to electric drive motors	• Increased power consumption	🟢🟡	740
	Seals	• Convert wet seals to dry seals	• Unable to effectively contain hazardous materials	🟢	60
	Glycol Pump	• Reroute gas from reboiler to pump	• Requires gas powered flash tank	🟢🟡	70
	VRU	• Utilization of excess vapors produced	• High OPEX	🟡🔴	180
	CMM gas utilization	• Utilization of coal seam gas	• Purity depends on groundwater quality	🟡🔴	360 – 880
	RTO	• VAM abatement through oxidation	• CO_2 is a major by-product	🟡🔴	760

Key Findings

- Abatement technologies are available commercially and at low costs – deployment efforts currently lacking due to inertia and lack of attention
- Relative to the coal mining segment, O&G abatement options are varied and can be conducted at a lower implementation cost

Note: Implementation cost excludes any revenue upside. Gas utilization cost different for application at surface and underground mines. LDAR cost different for application at O&G production, processing and transmission facilities. Flaring cost different for application at O&G facility and coal mines.

Source: Rystad Energy research and analysis; Company websites; Interviews; Secondary research articles

🟢 *Prevalent* 🟡 *Emerging* 🔴 *Nascent*

■ *Both* ■ *Oil and Gas* ■ *Coal*

2 The abatement technology landscape is currently fragmented with few companies offering integrated solutions. A limited number of providers are currently targeting the coal mining sector

Overview of abatement technology providers' landscape[1]

Category	Type	Service Providers[1]
Abatement	Flaring	AEREON, EVONIK Leading Beyond Chemistry, JOHN ZINK HAMWORTHY COMBUSTION, ZEECO, INOPLEX, GASCO MARINE, eneraque, LMS ENERGY
	LDAR	KLINGER trusted. worldwide., Entero THE SNIFFERS, SGS, Applus, air labs environmental, TEAM
	Pipelines	Honeywell, Baker Hughes, BECHTEL, slb, CHIYODA CORPORATION, wood., JGC, MITSUBISHI HEAVY INDUSTRIES, Worley, KBR, MCDERMOTT, EXPRO
	Pumps and instrumentation	Parker, FLOWSERVE, EMERSON, KIMRAY, GE, NOV, Bray, john crane, ZEVAC, ft pipeline systems, CIRCOR ENERGY, Atlas Copco, NPE, ZAHROOF VALVES INC, ClarkeValve
	Motors	KLINGER trusted. worldwide., ABB, CATERPILLAR, PDS, AMETEK
	Seals	SIEMENS energy, EagleBurgmann.
	Glycol Pump	KIMRAY, Rotor-Tech, Inc., Kelair Pumps, LEWA Creating Fluid Solutions
	VRU	JOHN ZINK HAMWORTHY COMBUSTION, ZEECO
	CMM gas utilization	LMS ENERGY, Xenith, arrow energy go further
	RTO	ANGUIL, DÜRR, JOHN ZINK HAMWORTHY COMBUSTION, CSIRO

Key Findings

- The supplier landscape for abatement technologies is fragmented with few offering integrated solutions, and limited providers are currently targeting the coal mining sector
- There is room for additional international suppliers to enter the Australian market, which can be sparked by additional demand for abatement solutions

Note: (1) Non-exhaustive; includes EPC contractors. Companies either have office, distributor or previous project in Australia
Source: Rystad Energy research and analysis; Company websites

■ *Both* ■ *Oil and Gas* ■ *Coal* ▨ *Degree of solution integration*
☐ *Research Institutes* *High* *Standalone*

Contents

Approx. 65% of energy sector methane emissions can be addressed with current technologies

Key takeaways

1 **A significant share of methane emissions from Australia's energy sector can be addressed with current technology at reasonable or no net cost**

- Approx. 65% of all methane emissions in energy sector can be abated based on present, available technologies
  - ✓ **Coal mining:** Up to 60% of methane emissions are abatable
  - ✓ **Oil and Gas:** Up to 90% of methane emissions are abatable

2 **Sizable pool of "negative-cost" abatement solutions available for energy sector to deploy**

- **Coal mining**: Up to 20% of emissions - Sector can leverage existing gas drainage system to deploy quick solutions to monetize methane via power or gas sales; gas utilization, oxidation and flaring are the viable pathways for emissions abatement
- **Oil and Gas**: Up to 50% of emissions - Sector sees a higher occurrence of "negative-cost" opportunities given available, proven technologies and accessible market; Replacement of methane emitting equipment, regular LDAR are some commercially ready options available for deployment

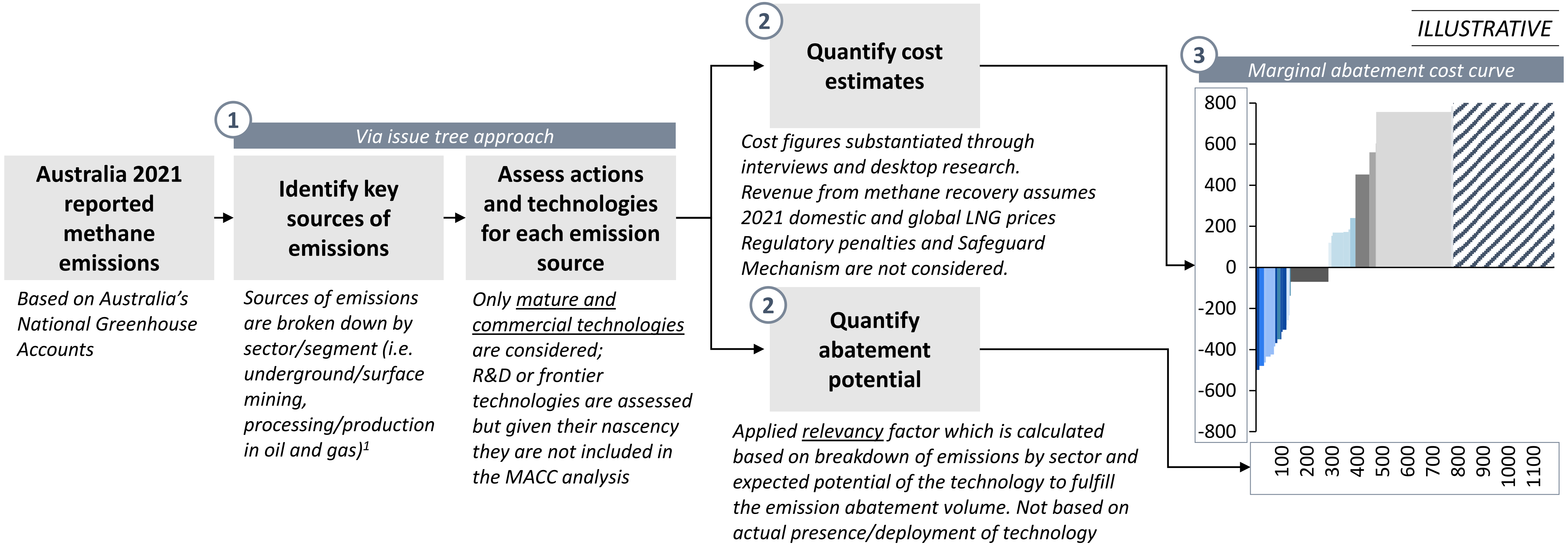
3 **More investment in technology development required to enhance deeper abatement efforts**

- **Coal mining:** A sizable portion of emissions remain challenging to abate due to perceived economic and technical concerns of new technologies such as VAM enrichment, catalytic oxidation, etc. which require further commercial/technical validation
- **Oil and Gas:** Smaller extent of emissions are challenging to abate; potential technologies solutions in areas of capture or oxidation have not been explored by companies

Source: Rystad Energy research and analysis

Our MACC assessment adopts a top-down sector approach to identifying viable technologies and deployment cost for the coal mining and O&G sectors

Overview of methodology adopted for assessing the abatement cost and abatement potential



Australia 2021 reported methane emissions

Based on Australia's National Greenhouse Accounts

1 *Via issue tree approach*

Identify key sources of emissions

Sources of emissions are broken down by sector/segment (i.e. underground/surface mining, processing/production in oil and gas)¹

Assess actions and technologies for each emission source

Only mature and commercial technologies are considered; R&D or frontier technologies are assessed but given their nascency they are not included in the MACC analysis

2 **Quantify cost estimates**

Cost figures substantiated through interviews and desktop research. Revenue from methane recovery assumes 2021 domestic and global LNG prices Regulatory penalties and Safeguard Mechanism are not considered.

2 **Quantify abatement potential**

Applied relevancy factor which is calculated based on breakdown of emissions by sector and expected potential of the technology to fulfill the emission abatement volume. Not based on actual presence/deployment of technology

ILLUSTRATIVE

3 *Marginal abatement cost curve*

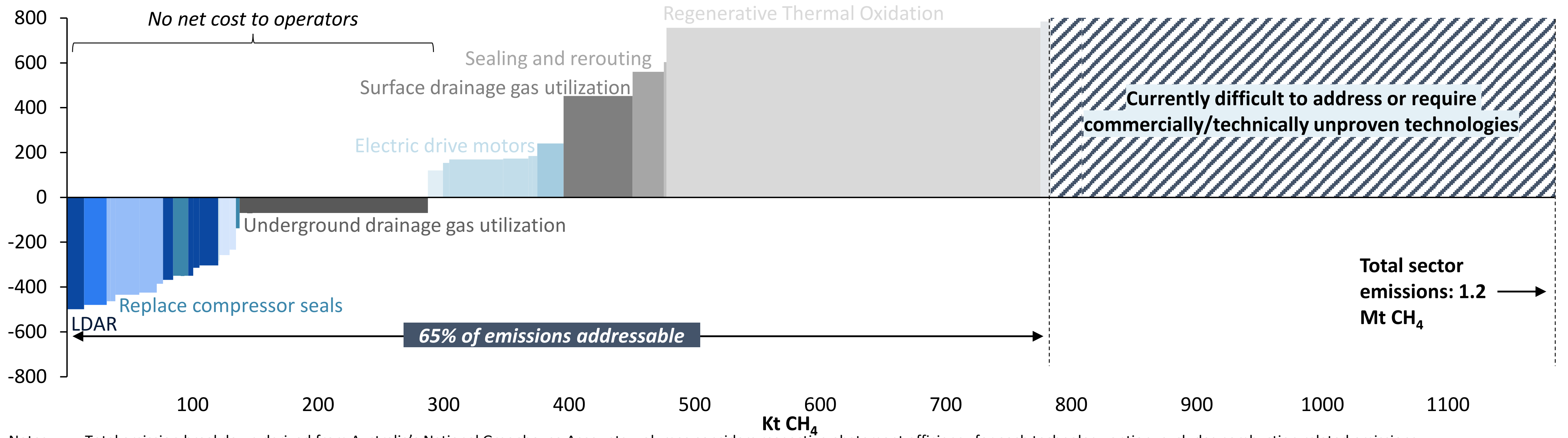
Analysis approach does not consider extent and potential of site/asset level abatement opportunities given the cost and potential can vary significantly depending on technical and commercial factors

Note: (1) Considers fugitive emissions (from coal mining and oil and gas sectors, including sources from flaring, venting, etc.) and combustion emissions (from oil and gas extraction processes only)
Source: Rystad Energy research and analysis

A sizable proportion of Australia’s energy sector methane emissions can be abated at a reasonable or negative net cost

2021 Methane marginal abatement cost curve (MACC) for energy sector

AUD / tCH_4, Real 2023



Notes: Total emission breakdown derived from Australia’s National Greenhouse Accounts; volumes considers respective abatement efficiency for each technology option; excludes combustion related emissions
MACC curve costs are illustrative and based on high level analysis of different abatement opportunities.
Project costs and technical viability of abatement technology deployment vary heavily site-to-site.
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Waste gas assumed to be sold at 50% discount to 2021 average West Australia domestic gas price; Flaring assumed to be enclosed.
Effects of Safeguard Mechanism (ACCU/SMC generation) not considered.

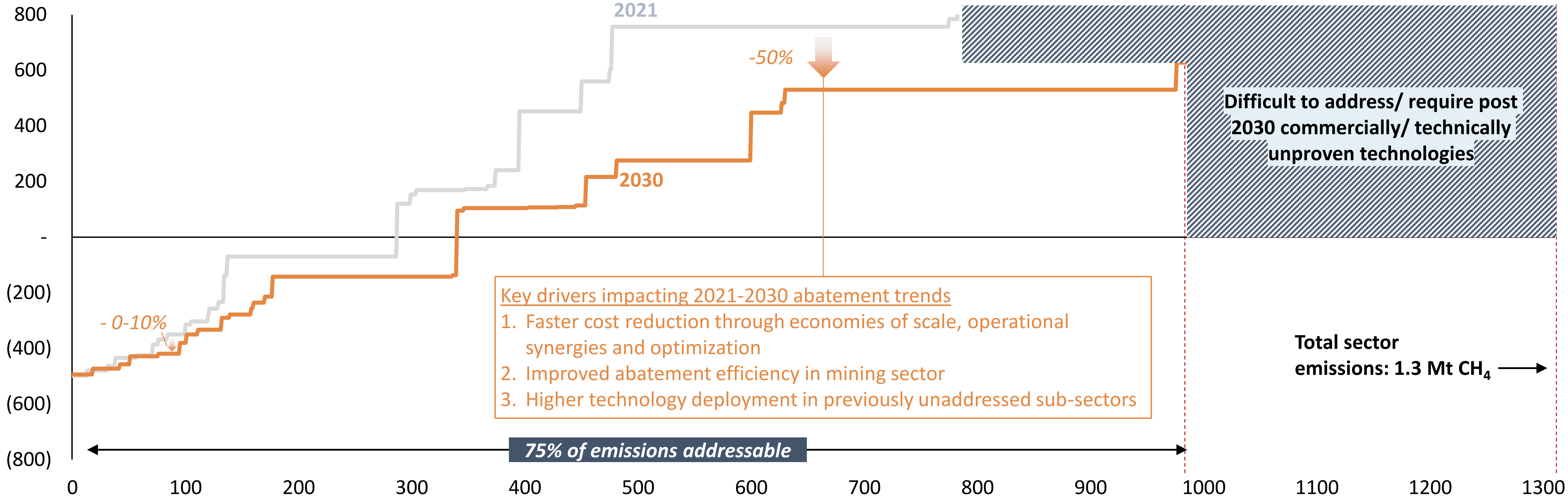
Source: Rystad Energy research and analysis; Australia Department of Climate Change, Energy, the Environment and Water; industry interviews; EPA; CCAC OGMP Technical Guidance Documentation

Oil and Gas sector
Coal mining sector

Addressability expected to improve by 25% and costs to decrease by up to 50% in 2030, driven by economies of scale, improved efficiency and increased technology adoption

2030 Methane marginal abatement cost curve (MACC) for energy sector

AUD / tCH_4, Real 2023



Key drivers impacting 2021-2030 abatement trends

1. Faster cost reduction through economies of scale, operational synergies and optimization
2. Improved abatement efficiency in mining sector
3. Higher technology deployment in previously unaddressed sub-sectors

Between 2021-2030, overall addressability could increase from 65% to 75% whilst abatement costs could decrease by up to 50%

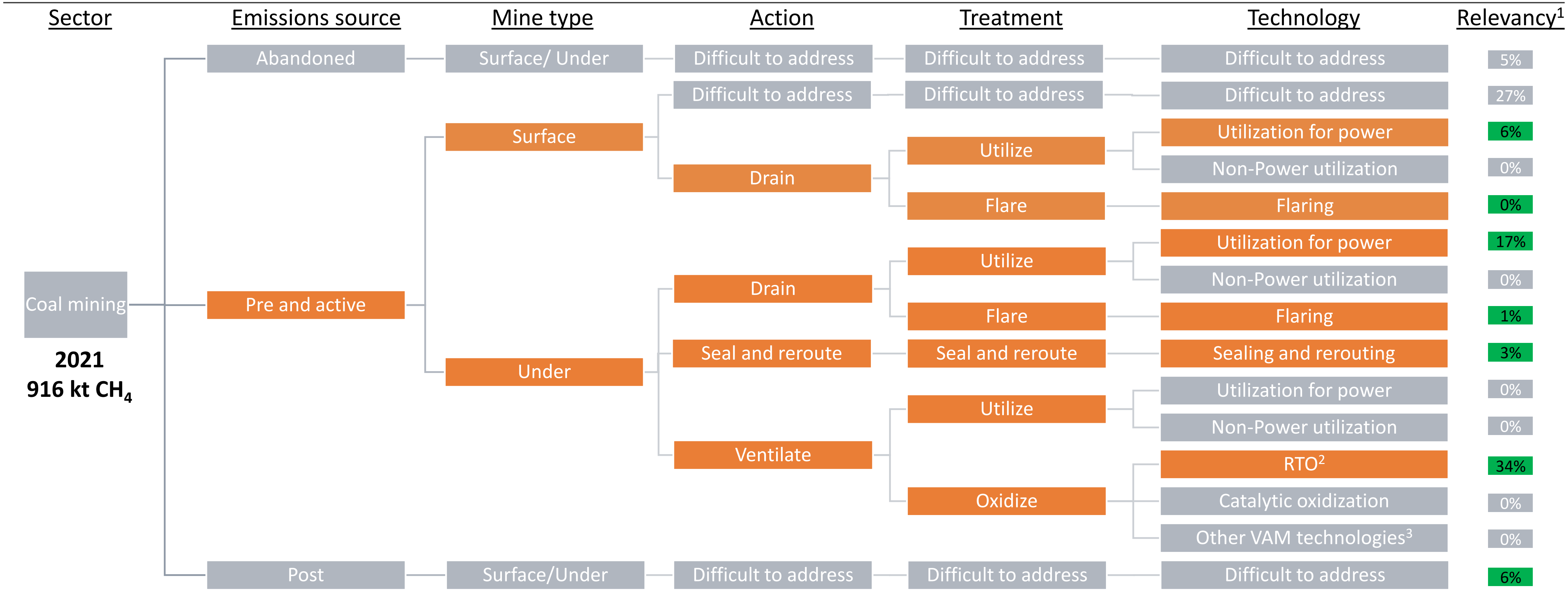
Notes: Total emission breakdown and projection derived from Australia's National Greenhouse Accounts; volumes considers respective abatement efficiency for each technology option; assumes 2021 proportion of emissions from each sub sector for 2030; cost reduction assumptions were based on assessment of the potential for cost reduction via economies of scale, operational synergies, efficiency and deployment level for the various technologies Assumptions are similar to the 2021 MACC curve analysis (refer to relevant section)

Source: Rystad Energy research and analysis; Australia Department of Climate Change, Energy, the Environment and Water; industry interviews; EPA; CCAC OGMP Technical Guidance Documentation

Coal mine methane marginal abatement cost curve

① About 60% of coal mining emissions in Australia are addressable by existing abatement technologies

Breakdown of coal mine methane emission abatement technology



Sector	Emissions source	Mine type	Action	Treatment	Technology	Relevancy[1]
Coal mining **2021** **916 kt CH_4**	Abandoned	Surface/ Under	Difficult to address	Difficult to address	Difficult to address	5%
	Pre and active	Surface	Difficult to address	Difficult to address	Difficult to address	27%
			Drain	Utilize	Utilization for power	6%
					Non-Power utilization	0%
				Flare	Flaring	0%
		Under	Drain	Utilize	Utilization for power	17%
					Non-Power utilization	0%
				Flare	Flaring	1%
			Seal and reroute	Seal and reroute	Sealing and rerouting	3%
			Ventilate	Utilize	Utilization for power	0%
					Non-Power utilization	0%
				Oxidize	RTO[2]	34%
					Catalytic oxidization	0%
					Other VAM technologies[3]	0%
	Post	Surface/Under	Difficult to address	Difficult to address	Difficult to address	6%

Notes: 1) Relevancy = Proportions of Emissions type * mine type * action * treatment * technology
2) RTO = Regenerative thermal oxidation; 3) Other nascent / R&D VAM technologies include lean-fuel gas turbines, supplemental fuel, stone dust looping, capture and enrichment

Source: Rystad Energy research and analysis

🟧 Focus areas ⬜ Challenging viability or pathway to address

② Many mature abatement options are currently available for coal mine methane emissions

Overview of commercial and mature abatement technologies for coal mine methane emissions

Technology	Est. abatement cost (AUD / tCH4)	Technology level	Deployment	Technology providers	Relevancy	Effectiveness	Abatement potential (kt CH4)
Drainage gas utilization	450/-70 (Surface/underground)	Mature	Low	Xenith	24%	95%	206
Sealing and rerouting	560	Mature	High	N/A	3%		24
Regenerative Thermal Oxidation (RTO)	760	Commercial	Low	Dürr Anguil Environment Systems Biothermica Conifer systems	34%		298
Flaring	600/790 (Surface/underground)	Mature	Low	Hofstetter Eneraque	1%		11

Note: Utilization costs modelled for large underground met coal mine, gas assumed to be sold at 30% discount to 2017-2023 YTD wholesale gas prices
Seal and reroute costs based on interview findings for 10-year sealing and pressure balancing operation for large underground met coal mine
Regenerative Thermal Oxidation (RTO) costs outlined based on commercial technology prices for 10-year RTO system for ventilated air methane emissions
Flaring assumed to be enclosed
Effects of Safeguard Mechanism (ACCU/SMC generation) not taken into account
Effectiveness factor for available abatement technologies found to be in 90%-100% range – 95% assumed across all technologies

Source: Rystad Energy research and analysis

② Focus on new technology could drive down cost of abatement for coal mining emissions

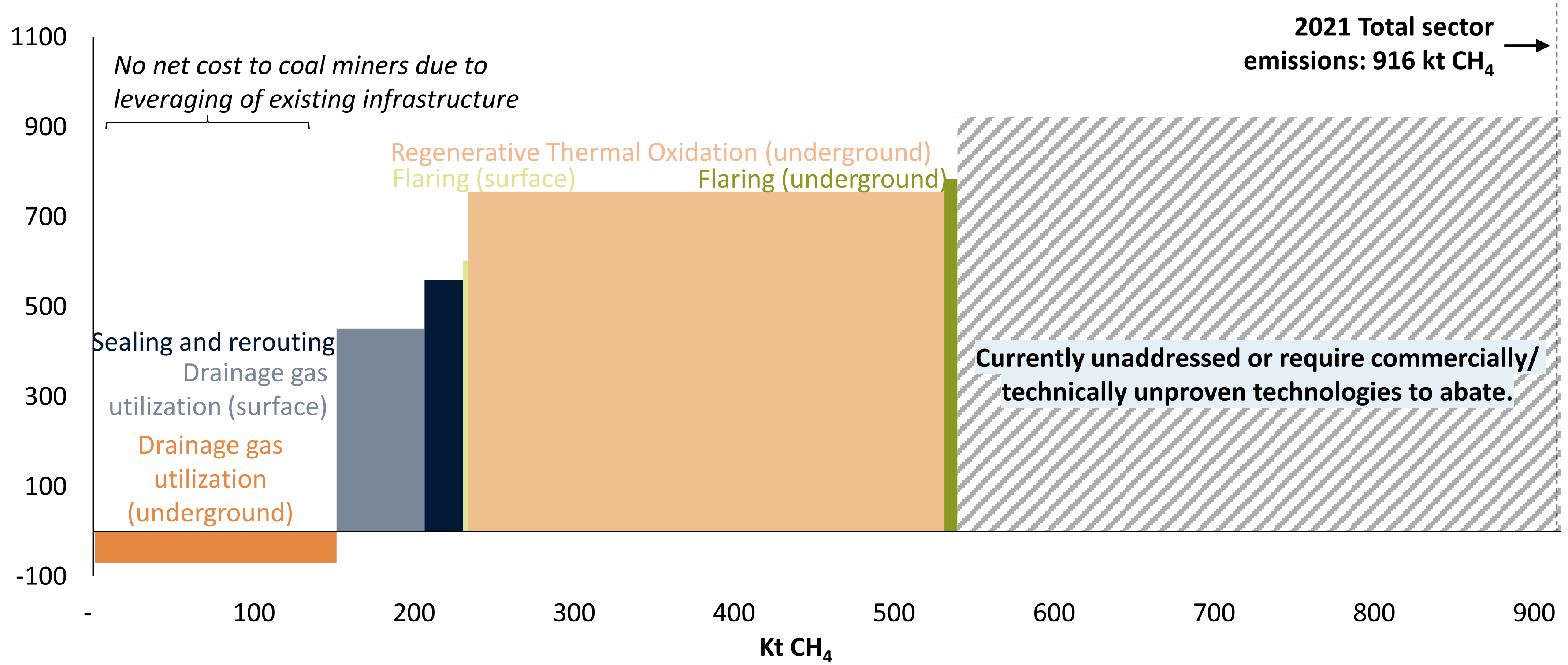
Overview of nascent, R&D abatement technologies for coal mine methane emissions

Technology	Technology level	Description	Key challenges	Technology providers
Catalytic Oxidation (RCO)	Nascent	Similar process as RTO but operable at lower tempertature due to use of catalysts	• Safety risk • High power consumption • Significant space requirement for oxidation unit	Johnson Matthey CSIRO
Lean-fuel gas turbines	Nascent	Utilization of VAM as primary fuel to operate gas turbines for power generation	• Requires VAM enrichment with pipe line gas/waste coal mine gas • Inefficiency increases at lower CH_4 concentration	CSIRO Ener-Core
VAM as supplemental fuel	Nascent	Utilization of VAM as combustion air to operate turbines, engines, rotary kilns or industrial boilers.	• Application limited to nearby facilities, if available	CSIRO
Stone dust looping	R&D	Catalytic oxidation of VAM and capture CO_2 released using limestone	• Pilot-scale demonstration needed to assess abatement effectiveness	University of Newcastle
VAM capture and enrichment	R&D	VAM capture and enrichment using carbon-based nanocomposite for potential subsequent utilization	• In pre-demonstration stage • Further testing needed to determine technology viability	CSIRO

Source: Rystad Energy research and analysis

③ More than 500kt of coal mine methane emissions could be abated for less than 800 AUD/t CH_4

Methane marginal abatement cost curve (MACC) for coal mining sector
(AUD / tCH_4)



- Utilization of drained gas and RTO at underground mines has potential to abate approximately 50% current addressable methane emissions.
- Drained gas utilization and flaring are main abatement pathways for surface mine methane emissions.
- Focus on new technology could drive down cost of abatement for coal mining emissions, increase proportion of addressable emissions

Notes: MACC assessment based on high level analysis of different abatement opportunities. Project costs and technical viability of abatement technology deployment vary heavily site-to-site; volumes considers respective abatement efficiency for each technology option; excludes combustion related emissions
Utilization costs modelled for large underground met coal mine, gas assumed to be sold at 30% discount to 2018-2023 YTD wholesale gas prices, with additional pre-drainage costs for surface mines
Seal and reroute costs based on interview findings for sealing and pressure balancing operation for large underground met coal mine, no gas sale assumption
Regenerative Thermal Oxidation (RTO) costs outlined based on commercial technology prices for 10-year RTO system for ventilated air methane emissions alongside industry interview figures
Flaring assumed to be enclosed
Effects of Safeguard Mechanism (ACCU/SMC generation) not considered

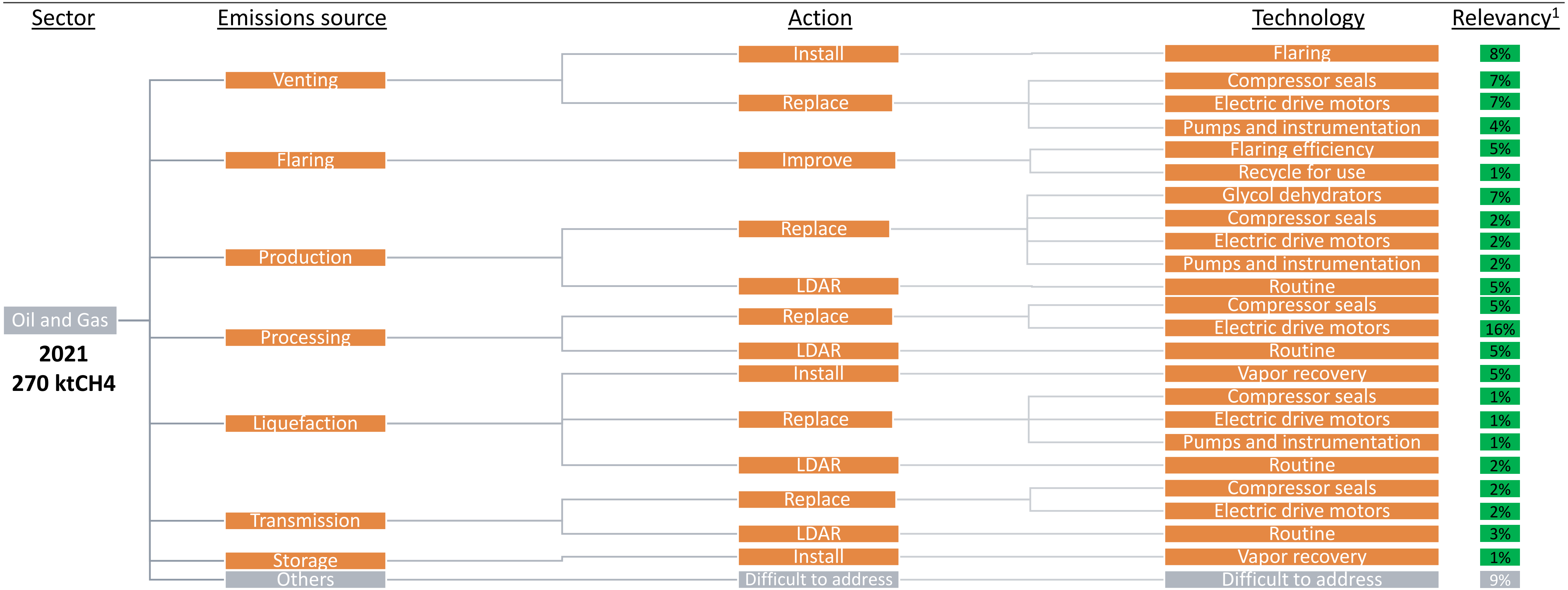
Source: Rystad Energy research and analysis; industry interviews

Oil and Gas methane marginal abatement cost curve

①

About 90% of methane emissions from the oil and gas industry in Australia are addressable by existing abatement technologies

Breakdown of oil and gas sector methane emission abatement technology



Sector	Emissions source	Action	Technology	Relevancy[1]
Oil and Gas **2021** **270 ktCH4**	Venting	Install	Flaring	8%
		Replace	Compressor seals	7%
			Electric drive motors	7%
			Pumps and instrumentation	4%
	Flaring	Improve	Flaring efficiency	5%
			Recycle for use	1%
	Production	Replace	Glycol dehydrators	7%
			Compressor seals	2%
			Electric drive motors	2%
			Pumps and instrumentation	2%
		LDAR	Routine	5%
	Processing	Replace	Compressor seals	5%
			Electric drive motors	16%
		LDAR	Routine	5%
	Liquefaction	Install	Vapor recovery	5%
		Replace	Compressor seals	1%
			Electric drive motors	1%
			Pumps and instrumentation	1%
		LDAR	Routine	2%
	Transmission	Replace	Compressor seals	2%
			Electric drive motors	2%
		LDAR	Routine	3%
	Storage	Install	Vapor recovery	1%
	Others	Difficult to address	Difficult to address	9%

Notes: 1) Relevancy = Proportions of Emissions type * mine type * action * treatment * technology
Source: Rystad Energy research and analysis

🟧 Focus areas ⬜ Challenging viability or pathway to address

② Mature technologies exist to replace methane emitting equipment across the O&G value chain

Overview of commercial and mature abatement technologies for oil and gas sector methane emissions

Technology	Est. abatement cost (AUD / tCH4)	Technology level	Deployment	Technology providers	Relevancy	Effectiveness	Abatement potential (kt CH4)
LDAR	-500 to -300	Mature	Medium	KLINGER Intero	15%	75%	41
Change glycol dehyrator pump	-480	Mature	Medium	Kimray Slb	7%	100%	18
Replace with dry compressor seals	-460 to -390	Mature	Medium	John Crane Siemens Energy	17%	97%	45
Vapor recovery unit	-350	Mature	Medium	Slb Baker Hughes Zeeco	6%	95%	16

Notes: MACC curve costs are illustrative and based on high level analysis of different abatement opportunities. Project costs and technical viability of abatement technology deployment vary heavily site-to-site.
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Waste gas assumed to be sold at 50% discount to 2021 average West Australia domestic gas price; Flaring assumed to be enclosed; Effects of Safeguard Mechanism (ACCU/SMC generation) not considered

Source: Rystad Energy research and analysis; industry interviews; EPA; CCAC OGMP Technical Guidance Documentation

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Overview of commercial and mature abatement technologies for oil and gas sector methane emissions

Technology	Est. abatement cost (AUD / tCH4)	Technology level	Deployment	Technology providers	Relevancy	Effectiveness	Abatement potential (kt CH4)
Pumps & instrumentation	-280 to -230	Mature	Medium	Hitachi Global Air Power Atlas Copco	6%	80%	14
Waste gas recycling	-140	Mature	Medium	Fesco TPE	1%	95%	3
Improve flaring efficiency	120	Mature	Medium	Zeeco Eneraque Aereon	5%	95%	12
Replace with electric motors	150 to 190	Mature	Medium	Baker Hughes Siemens Energy	28%	100%	75
Flaring	240	Mature	Medium	Zeeco Eneraque Aereon	8%	95%	20

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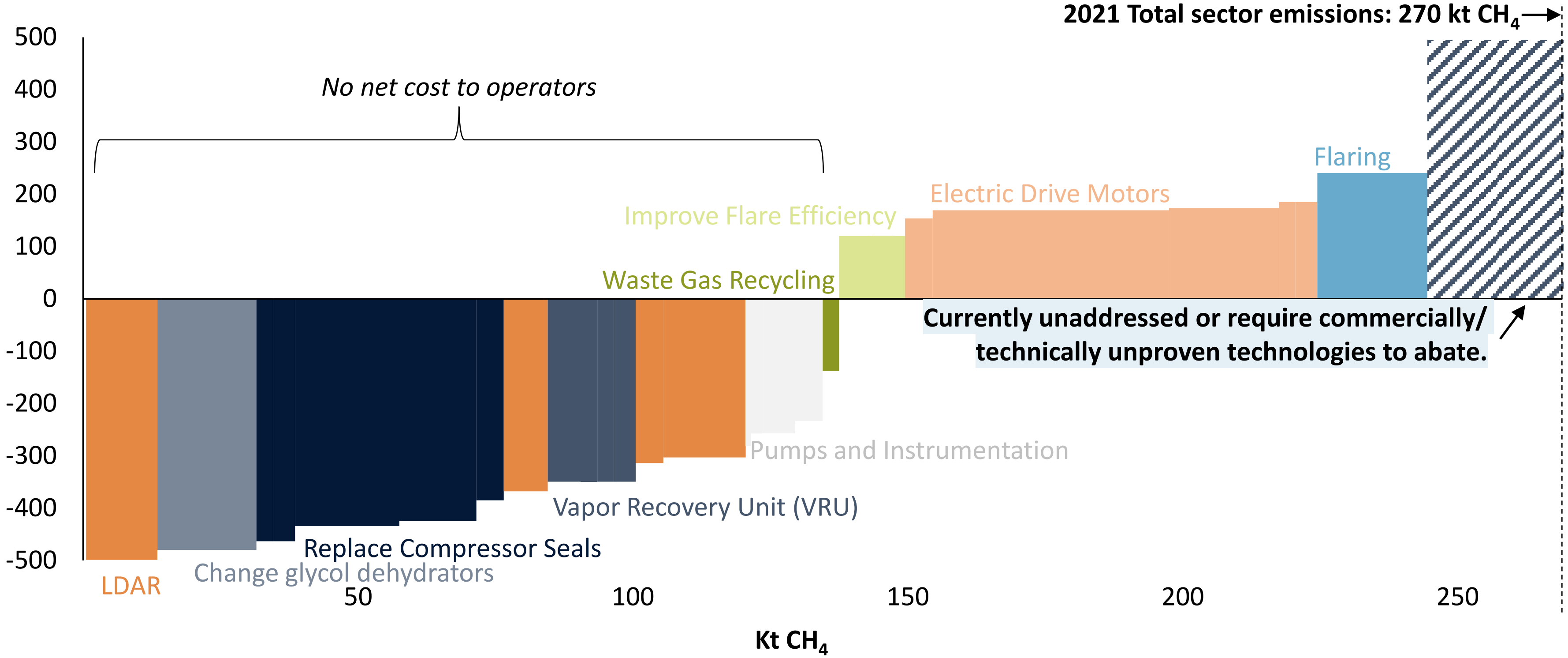
Source: Rystad Energy research and analysis; industry interviews; EPA; CCAC OGMP Technical Guidance Documentation

③ Over 240kt of O&G methane emissions could be abated for less than 250 AUD/tCH$_4$

Methane marginal abatement cost curve (MACC) for oil and gas sector
(AUD / tCH$_4$)



- ~51% of methane emissions reported from oil and gas sector can be potentially abated at no net cost to operators.
- Implementation of LDAR, replacing wet seals with dry seals in compressors and installing electric motors could abate significant share of addressable methane emissions.
- An estimated 9% of current emissions considered not addressable using available technology.

Notes: MACC assessment based on high level analysis of different abatement opportunities. Project costs and technical viability of abatement technology deployment vary heavily site-to-site; volumes considers respective abatement efficiency for each technology option; excludes combustion related emissions
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Source: Rystad Energy research and analysis; industry interviews; EPA; CCAC OGMP Technical Guidance Documentation

Contents

Glossary (1/2)

Key abbreviations

Term	Definition
ACCU	Australian Carbon Credit Units
ARENA	Australian Renewable Energy Agency
AUD	Australian Dollars
BAUD	Billion Australian Dollars
BMA	BHP Billion Mitsubishi Alliance
Boe	Barrel of Oil Equivalent
CAGR	Compounded Annual Growth Rate
CCAC	Climate and Clean Air Coalition
CEFC	Clean Energy Finance Corporation
CEO	Chief Executive Office
CH_4	Methane
CO_2	Carbon Dioxide
CO_2 eq	Carbon Dioxide Equivalent
CSRIO	Commonwealth Scientific and Industrial Research Organisation
E&P	Exploration and Production
EPA	Environmental Protection Agency

Term	Definition
EPC	Engineering, Procurement and Construction
ESG	Environmental, Social and Governance
EU	European Union
FOB	Free on Board
GHG	Greenhouse Gas
GMP	Global Methane Pledge
GWP	Global Warming Potential
IEEFA	Institute for Energy Economics and Financial Analysis
IPCC	Intergovernmental Panel on Climate Change
Kt	Kilo Tonne
LDAR	Leak Detection and Repair
LiDAR	Light Detection and Ranging
LNG	Liquified Natural Gas
LULUCF	Land-Use, land use change and forestry
M&A	Merger and Acquisition
MACC	Marginal Abatement Cost Curve

Source: Rystad Energy research and analysis

Glossary (2/2)

Key abbreviations

Term	Definition
MAUD	Million Australian Dollars
MRV	Measurement, Reporting and Verification
Mt	Million Tonne
NDC	Nationally Determined Contribution
NGER	National Greenhouse and Energy Reporting
NOC	National Oil Company
O&G	Oil and Gas
OGI	Optical Gas Imaging
OGMP	Oil and Gas Methane Partnership
R&D	Research and Development
RCO	Regenerative Catalytic Oxidizer
ROM	Run-of-mine
RTO	Regenerative Thermal Oxidation
SMC	Safeguard Mechanism Credit
UAV	Unmanned Aerial Vehicle
UNFCC	United Nations Framework Convention on Climate Change

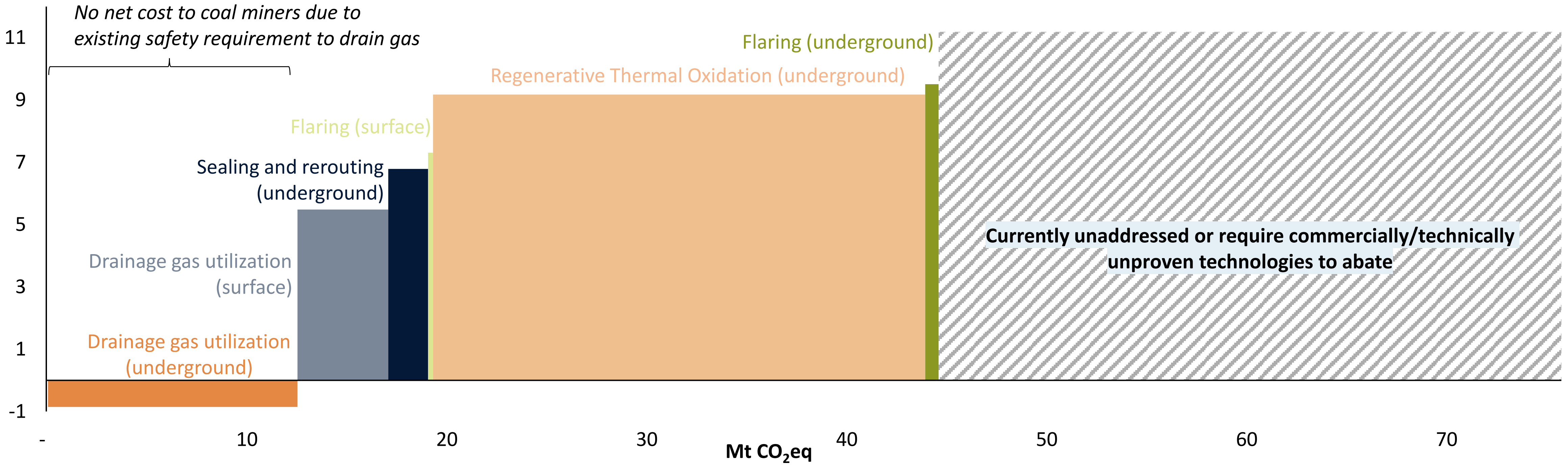
Term	Definition
USA	United States of America
USD	United States Dollar
UV	Ultra-violet
VAM	Ventilation Air Methane
VRU	Vapor Recovery Unit
YTD	Year to Date

Source: Rystad Energy research and analysis

Over 40Mt CO2eq. of coal mine methane emissions could be abated for less than 10 USD/t CO2eq

Methane marginal abatement cost curve (MACC) for coal mining sector

AUD / tCO_2eq



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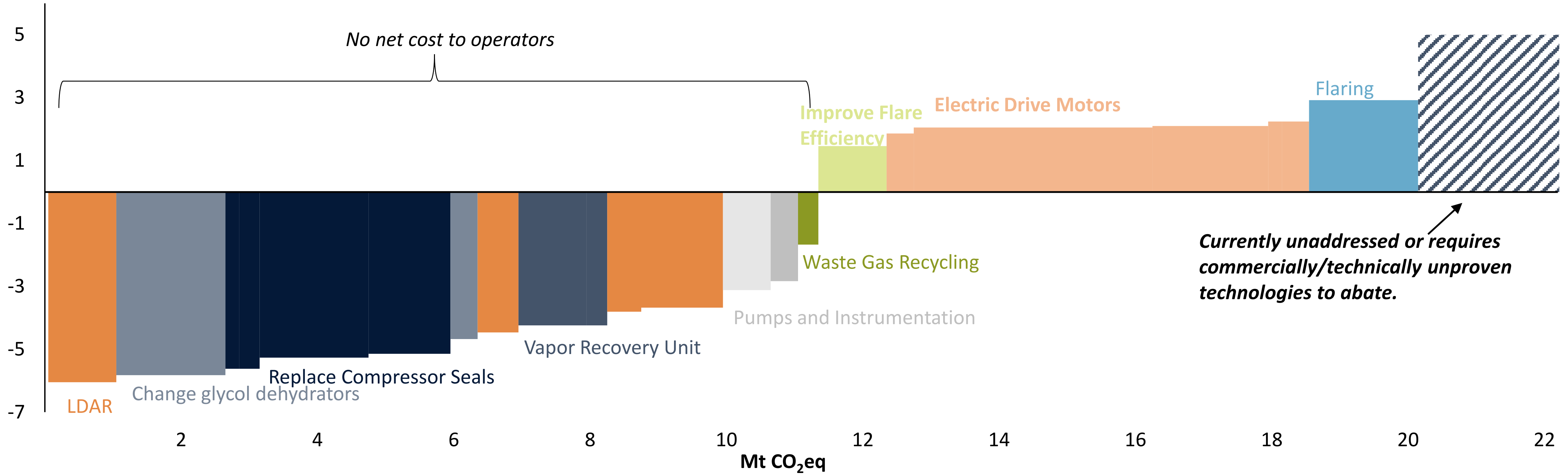
Flaring assumed to be enclosed
Effects of Safeguard Mechanism (ACCU/SMC generation) not considered
20-year IPCC AR6 global warming potential of 82.5 applied

Source: Rystad Energy research and analysis; industry interviews

Over 7Mt CO2eq. of O&G methane emissions could be abated for less than 5 USD/t CO2eq

Methane marginal abatement cost curve (MACC) for oil and gas sector

AUD / tCO_2eq



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Effects of Safeguard Mechanism (ACCU/SMC generation) not considered; 20-year IPCC AR6 global warming potential of 82.5 applied

Source: Rystad Energy research and analysis; industry interviews; EPA; CCAC OGMP Technical Guidance Documentation

RystadEnergy

Navigating the future of energy

Rystad Energy is an independent energy consulting services and business intelligence data firm offering global databases, strategic advisory and research products for energy companies and suppliers, investors, investment banks, organizations, and governments.

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