Technical Appendix: An All-In Pathway To 2030: U.S. Methane Emissions Reduction Potential

Methane Overview

Energy Sector

The U.S. energy sector accounted for 37% of overall methane emissions in 2020.[i] The oil and gas industry offers the largest cost-effective abatement potential given current cost estimates and policy opportunities. Methane emissions from oil and gas sources make up close to 80% of methane emissions in the energy sector, and they are largely released through extraction, processing and distribution.[ii] Coal mine methane (CMM) makes up the remaining emissions from the energy sector.[iii]

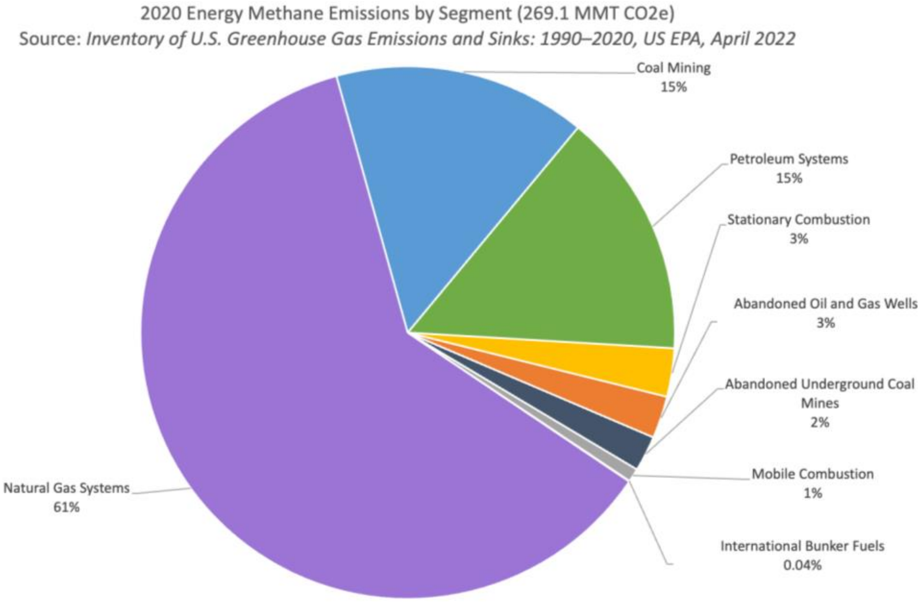
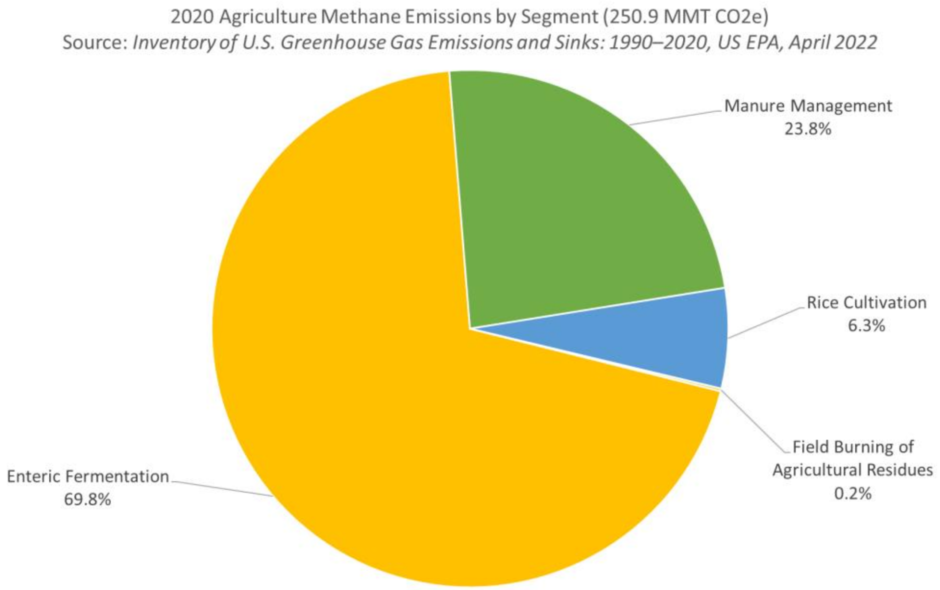


Figure 2. Energy sector methane emissions in 2020, based on EPA inventory

Agriculture Sector

Many abatement opportunities in agriculture exist, but solutions are not yet commercially available and implementation is more complex and costly. Methane emissions from agriculture in the U.S. currently account for 40% of methane emissions and arise mainly from enteric fermentation or the digestion of food from animals such as cows, manure, and rice cultivation.



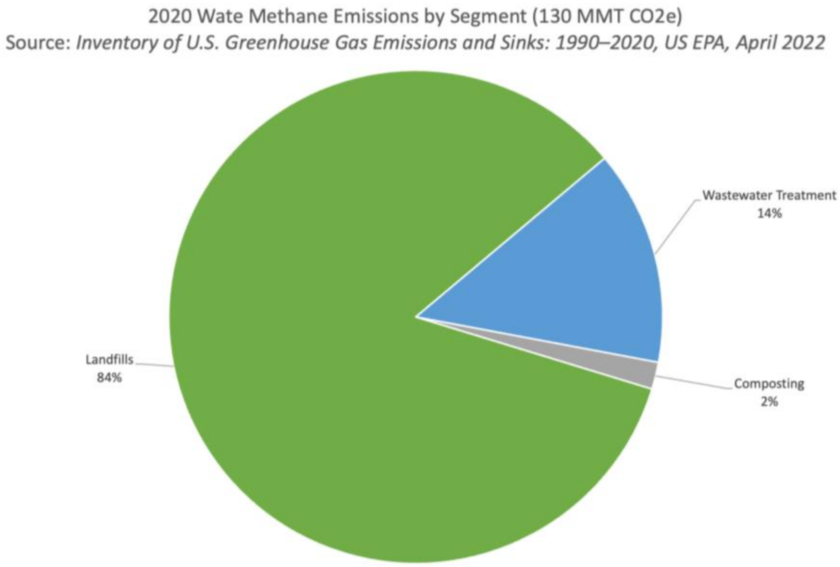
2020 Agriculture Methane Emissions by Segment (250.9 MMT CO2e)
Source: *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2020, US EPA, April 2022*

Figure 3. Agriculture sector methane emissions in 2020, based on EPA inventory

Waste Sector

Following energy and agriculture, waste is the third largest source of methane emissions, accounting for close to 17% of methane emissions in 2020.[iv] Landfills—of which organic waste is a predominant component—and wastewater are the two primary sources of methane emissions.[v] Organic waste, which typically includes paper, yard, wood and food wastes, comprises more than 60% of the total solid waste in the U.S.[vi,vii]

Wastewater treatment and discharge come from both domestic and industrial sources.[viii] Domestic sources account for emissions from septic systems as well as off-site treatment systems.[ix] Within industrial wastewater sources, the meat and poultry industry accounted for three fourths of methane emissions in 2020.[x]



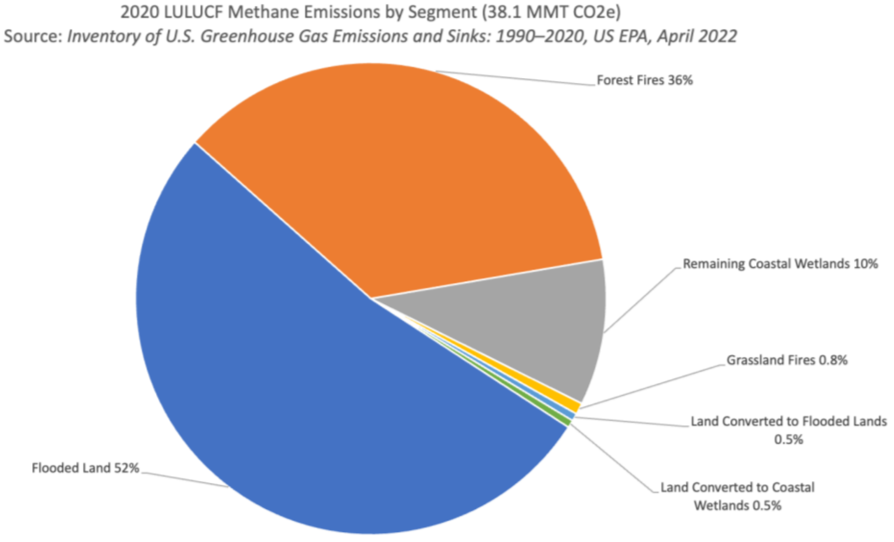
2020 Wate Methane Emissions by Segment (130 MMT CO2e)

Source: *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2020, US EPA, April 2022*

Figure 4. Waste sector methane emissions in 2020, based on EPA inventory

Other Sources of Methane Emissions

Other sources of methane emissions come from other land-use change and industrial processes, which make up 6% and less than 1% of methane emissions, respectively. Methane emissions from other land-use change generally occur from forest and grassland fires, as well as the decomposition of organic matter in wetlands.[xi] Industrial processes related to the production of iron and steel and chemicals also generate methane emissions, which are additional to emissions associated with fuel use.[xii]



2020 LULUCF Methane Emissions by Segment (38.1 MMT CO2e)

Source: *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2020, US EPA, April 2022*

Figure 5. Other land-use sector methane emissions in 2020, based on EPA inventory

Using EPA Inventory and Baseline Data

For the historical methane emissions from all sectors in the United States from 2005-2020, we use the EPA GHG Inventory.[xiii] Data for Baseline projections of methane emissions in all sectors at the state level was obtained from the data annex to the EPA's 2022 report, *U.S. State-level Non-CO2 Greenhouse Gas Mitigation Potential: 2025-2050*.[xiv] Also included in the report data annex are the marginal abatement cost (MAC) curve reductions in 2030 in all sectors at the state-level, corresponding to their respective Baseline projections in 2030.

Developing our Bottom-Up and All-In Scenarios

The Tier system was developed to differentiate states based on their climate action and policies. The Tiers are evaluated based on the ambition of the state's general climate action, energy policies, agricultural policies, and waste policies. Tier 1 is classified as the Leaders with the most ambitious policies, [followed] by Tier 2 Followers with less ambitious but climate-forward policies, with Tier 3 Laggards with the least ambitious or no policies within the Tier categories.

Tier 1 States		Tier 2 States	Tier 3 States	
California	Nevada	Arizona	Alabama	Mississippi
Colorado	New Hampshire	Louisiana	Alaska	Nebraska
Connecticut	New Jersey	Michigan	Arkansas	North Dakota
Delaware	New Mexico	Missouri	Florida	Oklahoma
Hawaii	New York	Montana	Georgia	South Carolina
Illinois	Oregon	North Carolina	Idaho	South Dakota
Maine	Pennsylvania	Ohio	Indiana	Tennessee
Maryland	Rhode Island	Utah	Iowa	Texas
Massachusetts	Vermont	Virginia	Kansas	West Virginia
Minnesota	Washington	Wisconsin	Kentucky	
		Wyoming		

Energy

Bottom Up

Using the EPA's state-level MAC curves, we assume that Tier 1 states achieve all methane emission reductions that are economically viable at a cost of \$1,500/tCH_4 (\$60/tCO_2e) in both oil & natural gas systems and coal mining. For Tier 2 states, we assume that they achieve only reductions achievable at negative cost (i.e., below a cost of \$0/tCH_4). We assume that no reductions in methane emissions are made in Tier 3 states from the EPA's Baseline scenario.

In the bottom-up scenario for the energy sector, we also account for reductions in methane emissions resulting from lower levels of fossil fuel production and consumption resulting from decarbonization in other sectors of the economy. Our previous analysis has shown a 48% reduction in coal consumption and 7% reduction in oil and gas consumption in 2030.[xv] We assume that methane emissions from the production and consumption of oil and gas are reduced by 7% as well. For coal, we also calculate the resulting increase in methane emissions from abandoned mines from the closure of active mines to offset 19% of the decrease in coal mine methane, assuming that one-third of the closed mines will flood naturally over time, with the other two-thirds of closed mines remaining dry.[xvi] The resulting activity reduction driver for coal mining is a net 29% reduction from the EPA's baseline projection 2030. Overall, the contribution of these activity reduction drivers for methane emissions from oil & natural gas systems and coal mining amount to reductions of 0.6 $MtCH_4$ and 0.4 $MtCH_4$, respectively.

We assume that the MAC curve reductions in the energy sector are proportionately reduced by the size of the activity reduction drivers for both oil & natural gas systems and coal mining. We first convert the national-level activity reduction drivers to state-level activity reduction drivers. To do this, each state takes on a share of the national-level activity reduction driver equivalent to its share of national-level methane emissions in each of oil & natural gas systems and coal mining. The resulting state-level activity reduction driver in each state is then converted to a percent reduction from the baseline emissions for each sector in each state. We then downscale the size of the MAC curve reductions in each sector in each state according to the following relation:

$$\begin{aligned} Downscaled\ MAC\ curve\ reduction = {} & Baseline\ emissions - (Baseline\ emissions \\ & * (1 - Activity\ reduction\ driver\ as\ \%\ reduction\ from\ Baseline\ emissions) \\ & * (1 - MAC\ curve\ reduction\ as\ \%\ reduction\ from\ Baseline\ emissions)) \\ & - Activity\ reduction\ driver \end{aligned}$$

In the bottom-up scenario, the residual emissions in the energy sector in 2030 are estimated to be 8.5 $MtCH_4$ or 21% below 2020 levels.

Half of the reductions in methane emissions from oil & natural gas systems are achieved through changing operational practices (including leak detection and repair), while most of the other half of reductions come from modifying or upgrading existing equipment, and the remainder from installing new equipment. In coal mining, reductions are achieved through capture of methane from coal mines, with three-quarters of it being injected into pipelines, and the remainder being used for power generation or process heat.

All In

In the All-In scenario, we assume that all states collectively achieve all reductions in methane emissions that are economically viable at a cost of \$1,500/tCH$_4$ (\$60/tCO$_2$e) in both oil & natural gas systems and coal mining.

Again, we account for reductions in methane emissions resulting from lower levels of fossil fuel production and consumption associated with decarbonization in other sectors of the economy. Our previous analysis has shown a 86% reduction in coal consumption and 14% reduction in oil and gas consumption in 2030.[xvii] We assume that methane emissions from the production and consumption of oil and gas are reduced by 14% as well. For coal, we employ the same assumptions as described above for the bottom-up scenario, and after accounting for an increase in abandoned mine methane (35%), the net activity driver reduction for coal mining is 51% below the EPA's baseline projection in 2030. Overall, the contribution of these activity reduction drivers for methane emissions from oil & natural gas systems and coal mining amount to reductions of 1.0 MtCH$_4$ and 0.8 MtCH$_4$, respectively. The size of the MAC curve reductions are downscaled according to the size of the activity reduction drivers for both oil & natural gas systems and coal mining using the same calculations used above for the bottom-up scenario. In the all-in scenario, the residual emissions in the energy sector in 2030 are estimated to be 5.3 MtCH$_4$ or 44% below 2020 levels.

Over 60% of the reductions in methane emissions from oil & natural gas systems are achieved through changing operational practices (including leak detection and repair), with the remaining reductions achieved via modifying or upgrading existing equipment, and installing new equipment. In coal mining, three-quarters of the reductions are attributable to the use of ventilation air methane, and remaining reductions come from flaring or capture of coal mine methane for pipeline injection, power generation, or process heat.

Agriculture

Bottom Up

Using the EPA's state-level MAC curves, we assume that Tier 1 states achieve all methane emission reductions that are economically viable at a cost of \$1,500/tCH$_4$ (\$60/tCO$_2$e) in both livestock and rice cultivation. For Tier 2 states, we assume that they achieve only reductions achievable at negative cost (i.e., below a cost of \$0/tCH$_4$). We assume that no reductions in methane emissions are made in Tier 3 states from the EPA's Baseline scenario. In the bottom-up scenario, the residual emissions in the agriculture sector in 2030 are estimated to be 8.8 MtCH$_4$ or 13% below 2020 levels.

For livestock, reductions come from both enteric fermentation and livestock manure management, with the bulk of reductions attributable to practices that reduce methane emissions from enteric fermentation. In rice cultivation, emissions of methane are lowered through changing tilling practices, applying fertilizers, and different strategies for paddy flooding.

All In

In the All-In scenario, we assume that all states collectively achieve all reductions in methane emissions that are economically viable at a cost of \$1,500/tCH (\$60/tCO_2e) in both livestock and rice and rice cultivation. In the all-in scenario, the residual emissions in the agriculture sector in 2030 are estimated to be 7.1 MtCH_4 or 29% below 2020 levels.

For livestock, increased reductions are achieved through feeding strategies that reduce methane emissions from enteric fermentation and manure management, with a significant increase in reductions achieved via manure management from the Bottom-up scenario. In rice cultivation, emissions of methane are lowered through a combination of incorporating crop residues, changing tilling practices, applying fertilizers, direct seeding, and different paddy flooding strategies.

Waste

Bottom Up

Using the EPA's state-level MAC curves, we assume that Tier 1 states achieve all methane emission reductions that are economically viable at a cost of \$1,500/tCH_4 (\$60/tCO_2e) in both landfills and wastewater (according to the EPA's state-level MAC curves, no methane emissions reductions from wastewater are economically viable below \$2,500/tCH_4, or \$100/tCO_2e). For Tier 2 states, we assume that they only make the reductions achievable at negative cost (i.e., below a cost of \$0/tCH_4). We assume that no reductions in methane emissions are made in Tier 3 states from the EPA's Baseline scenario.

We also account for reductions in methane emissions resulting from state- and city-level organic waste diversion policies. We assume that Tier 1 states follow California's lead of achieving 75% organic waste diversion compared to 2014 (equivalent to a 7.3% reduction in methane emissions relative to 2020 levels, based on a conservative estimate), and implement similar policies.[xviii] We assume that Tier 2 states also implement waste diversion policies, though a lower ambition level, achieving a 3% methane emissions reduction relative to 2020 levels. We assume that Tier 3 states do nothing on organic waste diversion. The MAC curve reductions were downscaled according to the size of these activity reduction drivers using the same calculation that was used for the energy sector. In the bottom-up scenario, the residual emissions in the waste sector in 2030 are estimated to be 5.0 MtCH_4 or 5% below 2020 levels.

In addition to the waste diversion policies mentioned above, reductions are achieved via capturing landfill gas or using it for energy generation.

All In

In the All-In scenario, we assume that all states collectively achieve all reductions in methane emissions that are economically viable at a cost of \$1,500/tCH_4 (\$60/tCO_2e) in both landfills and wastewater (According to the EPA's state-level MAC curves, no methane emissions reductions from wastewater are economically viable below \$2,500/tCH_4, or \$100/tCO_2e).

We also account for reductions in methane emissions that result from achieving the EPA target of a 50% reduction in organic waste below 2016 levels.[xix] We assume that organic landfill waste in all states is halved as a result of federal funding and technical support for waste diversion infrastructure and programming. The MAC curve reductions were downscaled according to the size of these activity reduction drivers using the same calculation that was used for the energy sector. In the all-in scenario, the residual emissions in the waste sector in 2030 are estimated to be 4.4 MtCH_4 or 15% below 2020 levels.

In addition to the waste diversion policies mentioned above, reductions come from collection of landfill gas, of which approximately two-thirds is used for energy generation while the rest is flared.

Areas for further consideration

Sensitivity analysis for different measurements of fugitive methane emissions in oil and gas

To probe the impact of measurement differences for fugitive methane in the oil and gas sector, we conducted a sensitivity analysis on the sector's historical methane emissions, projected future methane emissions, and abatement potentials. We assume that the historical methane emissions and projected methane emissions in the oil and gas sector are 60% higher than in the EPA's GHG Inventory and in their baseline projections for methane emissions in 2030.[xx] For the first sensitivity analysis with higher historical and projected fugitive methane emissions in the oil and gas sector, we assume that the magnitude of reductions from the EPA MAC curves does not change. This "pessimistic" abatement scenario delivers an All-In reduction of 31.2% from 2020. In the standard abatement scenario, we assume that the magnitude of the EPA MAC curve reductions proportionally increases by 60%, resulting in a 35.9% reduction from 2020 in the All-In scenario by 2030.

Sensitivity analysis for different global warming potentials

The EPA typically uses the 100-year global warming potential (GWP) for methane from IPCC AR4.[xxi] We also include a sensitivity analysis for the updated 100-year GWP for methane in IPCC AR6 as well as for the most recently published 20-year GWP for methane.[xxii] In these calculations, the 2020 historical emissions from the EPA's GHG inventory are adjusted, as are the baseline projections and abatement potentials in 2030. The percentage reductions will differ slightly when using the GWPs from IPCC AR6 because the GWPs for methane differ depending on whether it comes from a fossil or non-fossil source. Converting all results using the IPCC AR6 100-year GWP, residual methane emissions in 2030 are 33.6% below 2020 levels in the all-in scenario. With the 20-year GWP for methane from IPCC AR6, we estimate the residual methane emissions in 2030 for the all-in scenario to be 31.5% below 2020 levels.

Sensitivity analysis for calculation of activity reduction drivers in the energy sector

In the All-In scenario, we assume that the activity reduction drivers for coal mine methane and fugitive methane emissions in the oil and gas sector are proportional to the reduction in the domestic consumption of those fuels by the end of this decade.

In a sensitivity analysis, we assume that only half of the calculated emissions reductions are achieved from activity reduction drivers in the energy sector. Holding all else equal, this results in a lower overall abatement potential in the All-In scenario of 31.17% compared to 32.92% in our standard All-In scenario.

As an additional sensitivity analysis we recalculate the activity reduction drivers in the energy sector based on the reduction in production of these fuels by 2030 from our previous analysis.[xxiii] Accordingly, the reductions in methane emissions from the activity drivers are smaller in this case because most of the excess supply is assumed to be exported to other countries. Overall, this alternative approach to calculating the activity reduction drivers in the energy sector still delivers a 30.50% reduction in methane emissions by 2030 in the All-In scenario.

Calculation of percent progress toward achievement of 2030 NDC

For the standard bottom-up and all-in scenarios as well as the sensitivity analyses for higher fugitive methane emissions in the oil and gas sector and unit conversions for different GWPs for methane, we calculate the resulting percent contribution toward the US 2030 NDC. For the target of 50-52%, we use the absolute reduction in methane emissions from 2005 levels to our estimated 2030 residual methane emissions to calculate the percentage of the needed reduction for successful achievement of the NDC that is achieved from reduction in methane emissions alone. We estimate the needed reduction to 51% of 2005 GHG emissions in the US according to the EPA's GHG Inventory.[xxiv] When using IPCC AR6 values, the methane emissions from 2005 are adjusted accordingly. Results are shown in Table 2 of the paper.

Overview of GCAM-USA-AP

The estimates of oil and gas activity drivers from economy-wide emissions reductions in this analysis are based on a version of the Global Change Analysis model (GCAM) with a detailed representation of the U.S. energy system at the state level (GCAM-USA). We refer to the version of GCAM USA used in this study as GCAM-USA-AP.

The global version of GCAM is an Integrated Assessment Model that represents the energy and economic systems for 32 geopolitical regions, including the United States. GCAM represents land use and agriculture in 384 land regions nested within 235 water basins. GCAM tracks emissions of a range of greenhouse gasses (GHGs) and air pollutants from energy, agriculture, land use, and other systems.

GCAM-USA is a version of GCAM that disaggregates the U.S. energy and economy components into 50 states and the District of Columbia while maintaining the same level of detail in the rest of the world and for water and land sectors. The energy system formulation in GCAM-USA consists of detailed representations of depletable primary sources such as coal, gas, oil and uranium, in addition to renewable resources such as bioenergy, hydropower, wind, and geothermal.

GCAM-USA also includes representations of the processes that transform these resources to final energy carriers, such as refining and electric power. These energy carriers, in turn, are used to deliver services to end users in the buildings, transportation, and industrial sectors. The electric power sector includes representations of a range of power generation technologies, including those fueled by fossil fuels, renewables, bioenergy, and nuclear power.

GCAM-USA is a market equilibrium model. The equilibrium in each period is solved by finding a set of market prices such that supplies and demands are equal to one another in all markets as the actors in the model adjust the quantities of the commodities they buy and sell. GCAM operates in 5-year time-increments, with each new period starting from the conditions that emerged in the last.

GCAM-USA-AP is based on the open-source release of GCAM-USA 5.3. GCAM-USA-AP has been modified for the purposes of this study, for example to reflect the latest renewable energy costs and vehicle technology costs. It is also calibrated to the latest non-CO_2 marginal abatement cost curves from the U.S. Environmental Protection Agency.[1]

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