



Defining National Fossil Fuel Phase Out Roadmaps

A Colombian Case Study

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Foreword by Prof. Rachel Kyte

Special Representative for Climate, UK Government

The first summit on Transitioning Away from Fossil Fuels (TAFF) could not come at a more important time.

The war in Iran is threatening fossil supplies globally. Airports are running out of jet fuel and vital fertilizer shipments are being missed. The price of diesel and petrol has risen sharply, threatening livelihoods. Depending on fossil fuels to such an extent brings enormous risk – for security, economies and the environment.

This roadmap for Colombia – a collaboration between Colombian and UK experts – shows a clear path to economic and societal benefit. It builds off examples of successful implementation of policies in other countries. For example, the UK closed its last coal-fired power station last year. The roadmaps show that investment is needed to deliver change, but this investment brings rapid emission reduction and clear economic benefits by the 2030s.

We can learn from each other and the successes around the world. Climate councils such as the UK Climate Change Committee and its counterpart within the Colombian ministries have very important roles to play. They help get trusted evidence into the heart of government decision making, clearing the path towards a more prosperous and healthier planet.





Executive Summary (English)

The case for action

The climate is changing. Devastation caused by heatwaves and flooding in many areas of the world have become common occurrences. The long-term trend is 100% attributable to human causes. The unprecedented rate of temperature change is caused by global greenhouse gas emissions being at an all-time high, around 70% of these emissions are caused by the burning of fossil fuels.

At the same time shifting geopolitics is eroding multilateral cooperation, especially around climate and energy policy. Both climate and security risks are increasing. The First Conference on Transitioning Away from Fossil Fuels (TAFF), initiated by the Colombian and Netherlands governments comes at a crucial time and is a vital opportunity to forge new ways of cooperatively working together to reduce these risks.

The roadmap approach

In support of the TAFF Conference aims, we present a fossil-fuel phase-out roadmap for Colombia, covering both fossil fuel use within the country as well as production and exports. Contributors from Colombian government ministries provided Colombia-specific data, inputs from available models, and guidance on projections and national supply plans, ensuring that the perspectives and priorities relevant to Colombia were incorporated as much as possible. The roadmap approach builds upon a framework developed by the UK Climate Change Committee (CCC). It also uses evidence from the European Scientific Advisory Board on Climate Change and the Netherlands Scientific Climate Council. This roadmap is intended as a foundation for continued engagement with Colombian stakeholders. Their input will be essential to ensure that proposed pathways are feasible, aligned with national policy priorities, and support a genuinely just transition.

70% of global greenhouse emissions are caused by the burning of fossil fuels

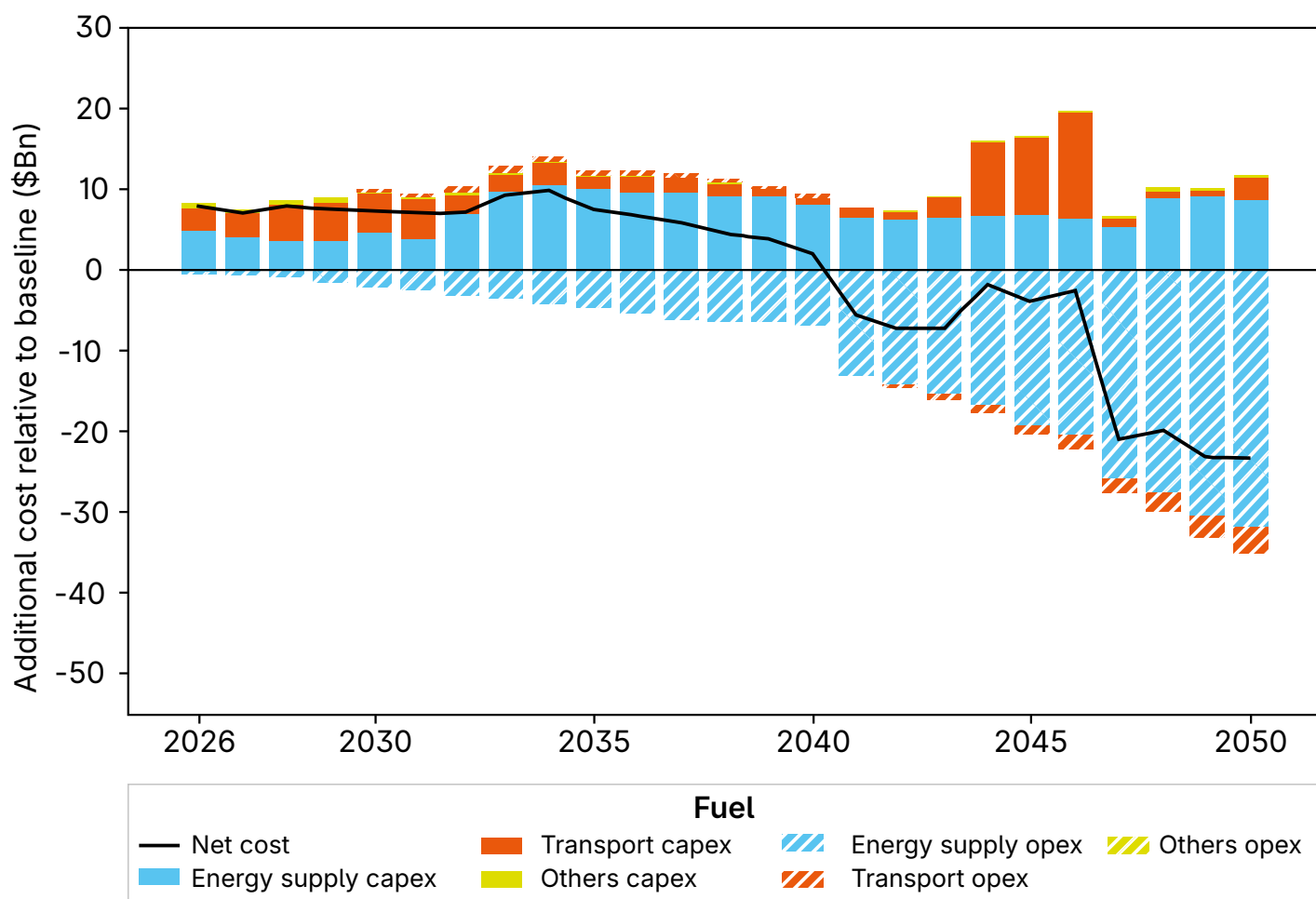
An Energy Transition Roadmap for Colombia

Costs and savings

Our roadmap for Colombia achieves a 90% reduction in primary fossil fuel demand relative to the base year (2026) and a 90% reduction in whole energy system emissions compared to 2015 levels, whilst expanding access to energy service demands. This can be achieved in a way that brings direct economic benefit, estimated as \$280 billion (BN) savings over the 2026-2050 period.

Considerable upfront investment is needed to achieve this transition, but by the early 2040s, this delivers annual net savings to the Colombian economy. Much of this investment is expected to come from the private sector. There would be additional economic benefits related to health impacts from improved air quality as well as those that come from reduced climate damages. Savings are achieved through a Real Zero transition where absolute emission reductions are prioritised.

Figure ES.1: Capital expenditure and operating costs for Colombia's transition away from fossil fuels relative to business-as-usual scenario.



Transforming supply and demand

In most parts of the economy, the path forward is clear. Fossil fuels can be phased out through energy efficiency measures, coupling renewable generation with energy storage and switching to electric technologies. With the right investment and finance framework such as contract for difference approaches adopted in the UK, Colombia can shift its electricity supply to renewables and especially solar PV, which is now the cheapest form of electricity generation. When combined with battery technology it can become a cheap, stable and secure source of power deployable at the community, state and national scale. Energy savings and measures to reduce demand are also an important contributor to the transition. Switching to electric cars, buses, vans, motorbikes and scooters can deliver almost immediate household cost savings and bring large air quality benefits to cities. Many industrial processes can now be electrified.

Supporting infrastructure, both physical and digital, will also play a critical role. On the physical side, modernising the electricity grid to support an increasingly electrified economy and creating the necessary network of charging points for EVs will be paramount to deliver a fossil fuel phase-out at pace. On the digital side, real-time data platforms will unlock significant savings by efficiently managing supply and demand while enabling the tracking of progress towards a decarbonised economy.

Switching to electric cars, buses, vans, motorbikes and scooters can deliver almost immediate household cost savings and bring large air quality benefits to cities.



Table ES.1: Sector targets to guide decarbonisation planning aligned with the modelled FFT scenario.

Target	2030	2040	2050
Power sector			
Share of electricity generated from renewables	90%	98%	100%
			
Electricity generated from solar, wind and geothermal	37%	60%	68%
			
Removal of coal from power sector		2045	
Removal of natural gas from power sector		2050	
Growth in the power generation to cover electrification (relative to 2026)	35%	167%	309%
			
Transport			
Electrification of road fleet	18%	59%	100%
			
Electrification of public transport fleet	13%	49%	100%
			

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Target	2030	2040	2050
Industry			
Share of heat demand from low-carbon sources	63%	80%	93%
[excluding biomass]	22%	47%	68%
Share of heat demand from hydrogen	0%	1%	1.8%
Buildings			
Phaseout of wood as heat source		2040	
Phaseout of natural gas		2045	
Share of electrification of end uses in housing	75%	100%	100%
Share of electrification of end uses in commercial & public sector	82%	96%	100%



Energy security

A fossil fuel phase-out can also reduce the risk of economic shocks caused by international conflicts or energy crises and increase national energy security. A low-carbon energy system is over twice as efficient as a fossil fuel based system. The UK CCC recently found that the total additional cost of a single fossil fuel price spike of 2022 magnitude is likely to be as large as the total net additional cost of meeting the UK's pathway to Net Zero across every year to 2050.

At present, Colombia exports \$25BN in oil and coal exports, roughly half its total export value. It imports roughly \$1BN of fossil fuel, mainly refined petroleum products. It is also beginning to import gas. Colombia exports coal, mainly to the Netherlands and Türkiye. These exports would be expected to decline rapidly even under a scenario where the world continues to rely on fossil fuels. With the current Iranian war, fossil prices are high meaning revenues are high, but also the cost of gas imports are high. While fossil fuel prices are notoriously volatile and challenging to predict, long-term revenues are expected to fall under a structurally declining sector.

Just transition

Under all scenarios considered, Colombia will need to plan for reduced revenue from fossil fuel exports, which roughly half by the mid 2030s. A fossil fuel phase out implementation plan could develop a structured transition for the affected communities and look to replace some lost revenue with other sources. For example, a revenue source may be through rapidly expanding the export of critical minerals such as copper. The communities affected will likely require significant support and training. There are few examples globally of successful industry transitions. Colombia has an opportunity to lead the way. The expanding critical mineral market is worth over \$400BN globally.

To develop a credible and fair roadmap that can be implemented in an evolving way to achieve a long-term sustained transition, a strong governance framework is needed. A range of stakeholders will need to be consulted within a multi-layer governance framework, covering affected communities and industries, state and national government and international development organizations. Such collaboration is needed to overcome barriers that may slow the pace of the transition, such as Investor-state dispute settlement (ISDS) proceedings where investors' interests may introduce legal risks for governments.

The case for standardised, national fossil fuel roadmaps

National climate councils efforts can be scaled within a country and through international cooperation via organizations such as the International Climate Councils Network to provide a supporting framework for producing country-specific evidence based energy transition roadmaps that can be implemented within differing national policy frameworks and circumstances.

We therefore make the case for developing standardised fossil fuel phase out roadmaps at a national scale produced by a network of national

climate councils. These should focus on the country-specific economic and societal wellbeing case for phase out. Such a set of roadmaps will enable governments to plan and execute near term fossil fuel phase out based on the best available science with local knowledge of country-specific challenges and opportunities.

A framework for delivery and aggregation of standardized national roadmaps would strengthen global assessments and multilateral processes by providing rigour to the tracking and delivery of Nationally Determined Contributions (NDCs) as well as to the TAFF process.





Executive Summary (Spanish) – Resumen Ejecutivo

Argumentos para la acción

El clima está cambiando. Los estragos causados por las olas de calor y las inundaciones en numerosas regiones del mundo se han convertido en fenómenos habituales. La tendencia a largo plazo es atribuible en un 100% a causas humanas. La actual tasa de cambio de temperatura sin precedentes es consecuencia de que las emisiones mundiales de gases de efecto invernadero se encuentran en su nivel más alto de la historia; aproximadamente el 70% de dichas emisiones provienen de la quema de combustibles fósiles.

Al mismo tiempo, los cambios geopolíticos están erosionando la cooperación multilateral, especialmente en materia de política climática y energética. Tanto los riesgos climáticos como los de seguridad van en aumento. La Primera Conferencia sobre la Transición hacia el Abandono de los Combustibles Fósiles (TAFF, por sus siglas en inglés), impulsada por los gobiernos de Colombia y los Países Bajos, llega en un momento crucial y representa una oportunidad vital para forjar nuevas formas de cooperación que permitan reducir estos riesgos.

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El enfoque de la hoja de ruta

En apoyo a los objetivos de la Conferencia TAFF, presentamos una hoja de ruta para la eliminación progresiva de los combustibles fósiles en Colombia, que abarca tanto su uso doméstico como su producción y exportación. Funcionarios de ministerios del Gobierno colombiano aportaron datos específicos del país, contribuciones de modelos disponibles y dirección sobre proyecciones y planes nacionales de suministro, garantizando que las perspectivas y prioridades colombianas quedaran incorporadas en la mayor medida posible. El enfoque de esta hoja de ruta se fundamenta en un marco desarrollado por el Comité de Cambio Climático del Reino Unido (CCC). Asimismo, incorpora evidencia del Consejo Científico Consultivo Europeo sobre Cambio Climático y del Consejo Científico del Clima de los Países Bajos. Esta hoja de ruta está concebida como base para una interlocución continua con actores colombianos, cuya participación será esencial para garantizar que las trayectorias propuestas sean viables, estén alineadas con las prioridades de política nacional y respalden una transición verdaderamente justa.

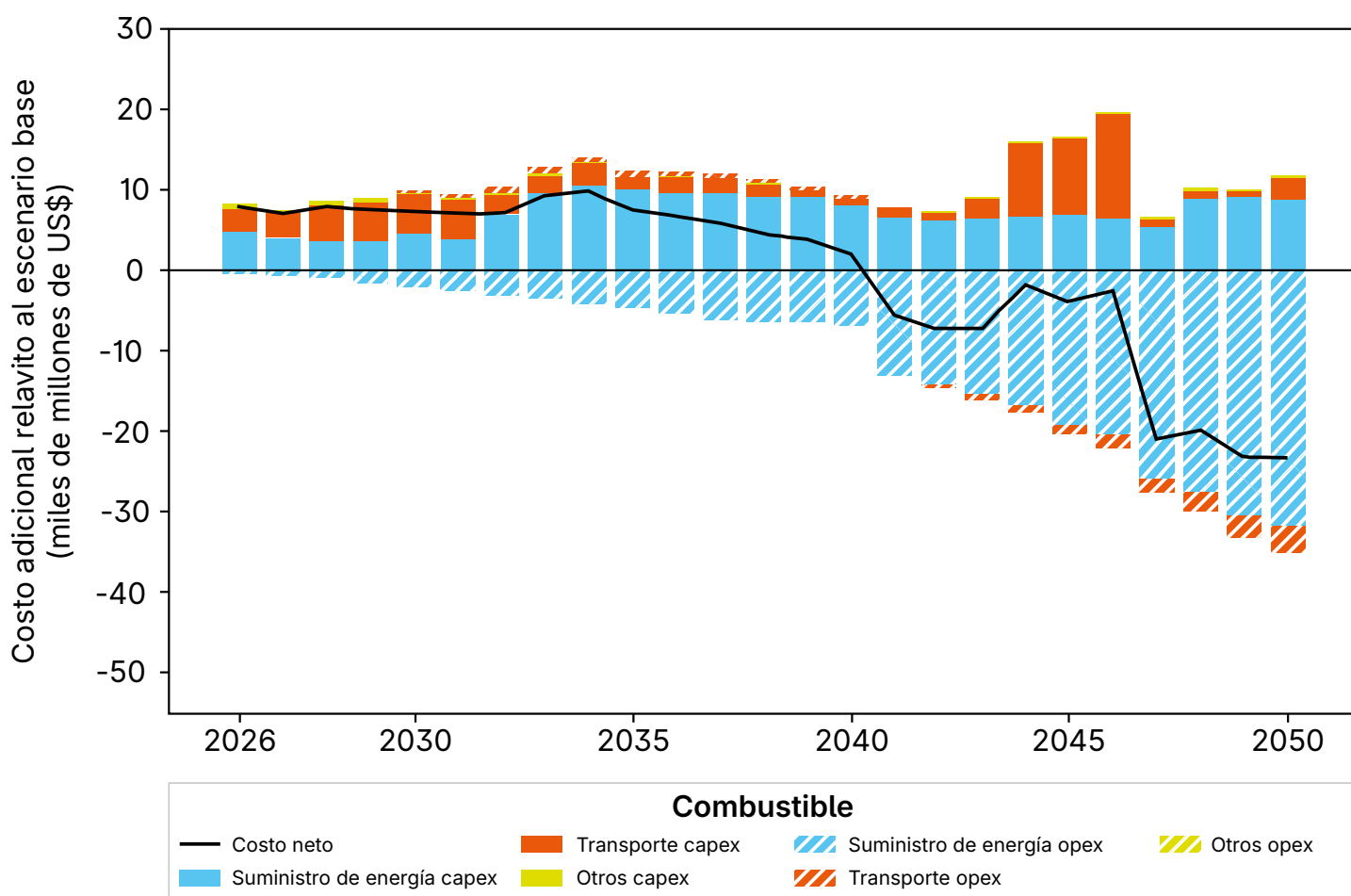
Una hoja de ruta para la transición energética en Colombia

Costo y ahorro

Nuestra hoja de ruta para Colombia logra una reducción del 90% en la demanda primaria de combustibles fósiles con respecto al año base (2026) y una reducción del 90% en las emisiones del sistema energético global en comparación con los niveles de 2015, al tiempo que amplía el acceso a los servicios energéticos. Este objetivo puede alcanzarse de una manera que genere beneficios económicos directos, estimados en 280.000 millones de dólares de ahorros durante el período 2026-2050.

La transición requiere una inversión inicial considerable, pero a principios de la década de 2040 comenzará a generar un ahorro anual neto para la economía colombiana. Se espera que gran parte de esta inversión provenga del sector privado. A ello se sumarían beneficios económicos adicionales derivados de las mejoras en la salud pública gracias a una mejor calidad del aire, así como los beneficios asociados a la reducción de los daños climáticos. El ahorro se logra mediante una transición hacia la neutralidad de carbono real, en la que se priorizan las reducciones absolutas de emisiones.

Figura ES.1: Inversión de capital (capex) y costos operativos (opex) para la eliminación de combustibles fósiles en Colombia en relación con el escenario de referencia (business-as-usual).



Transformación de la oferta y la demanda

En la mayoría de los sectores económicos, el camino a seguir es claro. Los combustibles fósiles pueden eliminarse progresivamente mediante medidas de eficiencia energética, la integración de generación renovable con almacenamiento de energía y la adopción de tecnologías eléctricas. Con el marco adecuado de inversión y financiación —como los mecanismos de contratos por diferencia adoptados en el Reino Unido— Colombia puede transformar su suministro eléctrico hacia el uso de fuentes de energía renovables y, en particular, hacia la energía solar fotovoltaica, que es actualmente la forma más económica de generación eléctrica. Combinada con tecnología de baterías, puede convertirse en una fuente de energía asequible, estable y segura, desplegable a escala comunitaria, departamental y nacional. El ahorro energético y las medidas de reducción de la demanda constituyen también una contribución importante a la transición. La adopción de automóviles, autobuses, furgonetas, motocicletas y scooters eléctricos puede generar un ahorro casi inmediato para los hogares y reportar importantes beneficios en la calidad del aire en las ciudades. Numerosos procesos industriales pueden electrificarse en la actualidad.

La infraestructura de apoyo, tanto física como digital, también desempeñará un papel fundamental. En el plano físico, la modernización de la red eléctrica para sostener una economía cada vez más electrificada y la creación de la red necesaria de puntos de carga para vehículos eléctricos serán aspectos primordiales para acometer la eliminación de los combustibles fósiles a un ritmo adecuado. En el plano digital, las plataformas de datos en tiempo real permitirán obtener un ahorro significativo mediante la gestión eficiente de la oferta y la demanda, a la vez que facilitarán el seguimiento de los avances hacia una economía descarbonizada.



La adopción de automóviles, autobuses, furgonetas, motocicletas y scooters eléctricos puede generar un ahorro casi inmediato para los hogares y reportar importantes beneficios en la calidad del aire en las ciudades.

Tabla ES.1: Objetivos sectoriales para orientar la planificación de la descarbonización alineados con el escenario FFT modelado.

Objetivo	2030	2040	2050
Sector eléctrico			
Participación de electricidad generada a partir de fuentes renovables	90%	98%	100%
Electricidad generada a partir de fuentes solar, eólica y geotérmica	37%	60%	68%
Eliminación del carbón en el sector eléctrico		2045	
Eliminación del gas natural en el sector eléctrico		2050	
Crecimiento de la generación eléctrica para cubrir la electrificación (relativo a 2026)	35%	167%	309%
Transporte			
Electrificación de la flota de vehículos de carretera	18%	59%	100%
Electrificación del transporte público	13%	49%	100%

Tabla ES.1: Objetivos sectoriales para orientar la planificación de la descarbonización alineados con el escenario FFT modelado.

Objetivo	2030	2040	2050
Industria			
Demanda de calor cubierta por fuentes bajas en carbono	63%	80%	93%
[excluyendo biomasa]	22%	47%	68%
Demanda de calor cubierta por hidrógeno	0%	1%	1.8%
Edificios			
Eliminación de la leña como fuente de calor		2040	
Eliminación del gas natural		2045	
Electrificación de los usos finales en viviendas	75%	100%	100%
Electrificación de los usos finales en el sector comercial y público	82%	96%	100%



Seguridad energética

La eliminación progresiva de los combustibles fósiles también puede reducir el riesgo de shocks económicos derivados de conflictos internacionales o crisis energéticas, e incrementar la seguridad energética nacional. Un sistema de bajas emisiones es más del doble de eficiente que uno basado en combustibles fósiles. El CCC del Reino Unido concluyó recientemente que el costo adicional total de un único episodio de aumento de precios de los combustibles fósiles de una magnitud similar al de 2022 es probablemente tan elevado como el costo neto adicional total de cumplir la trayectoria total del Reino Unido hacia la neutralidad de carbono hasta 2050.

En la actualidad, Colombia exporta 25.000 millones de dólares en petróleo y carbón, lo que representa aproximadamente la mitad del valor total de sus exportaciones. Importa alrededor de 1.000 millones de dólares en combustibles fósiles, principalmente productos refinados del petróleo. Asimismo, está comenzando a importar gas. Colombia exporta carbón principalmente a los Países Bajos y Turquía. Se prevé que estas exportaciones disminuyan rápidamente incluso en un escenario en el que el mundo continúe dependiendo de los combustibles fósiles. Con la actual guerra en Irán, los precios de los combustibles fósiles son elevados, lo que se traduce en altos ingresos, pero también en un mayor costo de las importaciones de gas. Si bien los precios de los combustibles fósiles son notoriamente volátiles y difíciles de prever, se espera que los ingresos a largo plazo desciendan en el marco de un sector estructuralmente en declive.

Transición justa

En todos los escenarios considerados, Colombia deberá prepararse para una reducción de los ingresos provenientes de las exportaciones de combustibles fósiles, que se reducirán aproximadamente a la mitad hacia mediados de la década de 2030. Un plan de implementación para la eliminación progresiva de los combustibles fósiles podría desarrollar una transición estructurada para las comunidades afectadas y buscar sustituir parte de los ingresos perdidos con otras fuentes. Por ejemplo, una fuente potencial de ingresos podría ser la rápida expansión de la exportación de minerales críticos como el cobre. Las comunidades afectadas probablemente requerirán un apoyo significativo y programas de formación. A nivel mundial, existen pocos ejemplos de transiciones industriales exitosas. Colombia tiene la oportunidad de emerger como líder en la materia. El mercado global en expansión de minerales críticos tiene un valor superior a los 400.000 millones de dólares a nivel mundial.

Para desarrollar una hoja de ruta creíble y equitativa que pueda implementarse de manera adaptativa y lograr una transición sostenible a largo plazo, es necesario contar con un sólido marco de gobernanza. Será necesario consultar a una amplia gama de actores dentro de un esquema de gobernanza multinivel, que incluya comunidades e industrias afectadas, gobiernos regionales y nacional, y organizaciones internacionales de desarrollo. Dicha colaboración es indispensable para superar los obstáculos que pueden ralentizar el ritmo de la transición, como los procedimientos de arbitraje de diferencias inversor-estado (ISDS, por sus siglas en inglés), en los que los intereses de los inversores pueden introducir riesgos jurídicos para los gobiernos.

Hacia un marco de hojas de ruta nacionales estandarizadas para la eliminación progresiva de los combustibles fósiles

Los esfuerzos de los consejos climáticos nacionales pueden ampliarse dentro de cada país y a través de la cooperación internacional mediante organizaciones como la Red Internacional de Consejos Climáticos, a fin de proporcionar un marco de apoyo para la elaboración de hojas de ruta de transición energética basadas en datos específicos de cada país y adaptadas a sus características particulares, que puedan implementarse dentro de distintos marcos de política y contexto nacional.

Por ello, planteamos la necesidad de desarrollar hojas de ruta estandarizadas para la eliminación progresiva de los combustibles fósiles a escala

nacional, elaboradas por una red de consejos climáticos nacionales. Estas deben centrarse en el análisis específico de cada país sobre los beneficios económicos y de bienestar social asociados a la eliminación progresiva de los combustibles fósiles. Este conjunto de hojas de ruta permitirá a los gobiernos planificar y ejecutar, en el corto plazo, la eliminación progresiva de los combustibles fósiles con base en la mejor evidencia científica disponible y el conocimiento local sobre los desafíos y oportunidades propios de cada país.

Un marco de implementación y agregación de hojas de ruta nacionales estandarizadas fortalecería las evaluaciones globales y los procesos multilaterales al aportar mayor rigor al seguimiento y cumplimiento de las Contribuciones Determinadas a Nivel Nacional (NDC, por sus siglas en inglés), así como al proceso TAFF.



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This draft roadmap is based on learnings and data from the Colombian Government and its ministries, the UK Climate Change Committee, the Netherlands Scientific Climate Council, the European Scientific Advisory Board on Climate Change and the International Climate Councils Network.

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We welcome open discussion and collaboration to further develop this roadmap for Colombia and the approach to future national roadmaps.

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Executive Summary (Spanish) - Resumen Ejecutivo

Argumentos para la acción

El clima está cambiando. Los estragos causados por las olas de calor y las inundaciones en numerosas regiones del mundo se han convertido en fenómenos habituales. La tendencia a largo plazo es atribuible en un 100% a causas humanas. La actual tasa de cambio de temperatura sin precedentes es consecuencia de que las emisiones mundiales de gases de efecto invernadero se encuentran en su nivel más alto de la historia; aproximadamente el 70% de dichas emisiones provienen de la quema de combustibles fósiles.

Al mismo tiempo, los cambios geopolíticos están erosionando la cooperación multilateral, especialmente en materia de política climática y energética. Tanto los riesgos climáticos como los de seguridad van en aumento. La Primera Conferencia sobre la Transición hacia el Abandono de los Combustibles Fósiles (TAFF, por sus siglas en inglés), impulsada por los gobiernos de Colombia y los Países Bajos, llega en un momento crucial y representa una oportunidad vital para forjar nuevas formas de cooperación que permitan reducir estos riesgos.

El enfoque de la hoja de ruta

En apoyo a los objetivos de la Conferencia TAFF, presentamos una hoja de ruta para la eliminación progresiva de los combustibles fósiles en Colombia, que abarca tanto su uso doméstico como su producción y exportación. Funcionarios de ministerios del Gobierno colombiano aportaron datos específicos del país, contribuciones de modelos disponibles y dirección sobre proyecciones y planes nacionales de suministro, garantizando que las perspectivas y prioridades colombianas quedaran incorporadas en la mayor medida posible. El enfoque de esta hoja de ruta se fundamenta en un marco desarrollado por el Comité de Cambio Climático del Reino Unido (CCC). Asimismo, incorpora evidencia del Consejo Científico Consultivo Europeo sobre Cambio Climático y del Consejo Científico del Clima de los Países Bajos. Esta hoja de ruta está concebida como base para una interlocución continua con actores colombianos, cuya participación será esencial para garantizar que las trayectorias propuestas sean viables, estén alineadas con las prioridades de política nacional y respalden una transición verdaderamente justa.

Una hoja de ruta para la transición energética en Colombia

Costo y ahorro

Nuestra hoja de ruta para Colombia logra una reducción del 90% en la demanda primaria de combustibles fósiles con respecto al año base (2026) y una reducción del 90% en las emisiones del sistema energético global en comparación con los niveles de 2015, al tiempo que amplía el acceso a los servicios energéticos. Este objetivo puede alcanzarse de una manera que genere beneficios económicos directos, estimados en 280.000 millones de dólares de ahorros durante el período 2026-2050. La transición requiere una inversión inicial considerable, pero a principios de la década de 2040 comenzará a generar un ahorro anual neto para la economía colombiana. Se espera que gran parte de esta inversión provenga del sector privado. A ello se sumarían beneficios económicos adicionales derivados de las mejoras en la salud pública gracias a una mejor calidad del aire, así como los beneficios asociados a la reducción de los daños climáticos.

Transformación de la oferta y la demanda

En la mayoría de los sectores económicos, el camino a seguir es claro. Los combustibles fósiles pueden eliminarse progresivamente mediante medidas de eficiencia energética, la integración de generación renovable con almacenamiento de energía y la adopción de tecnologías eléctricas. Con el marco adecuado de inversión y financiación —como los mecanismos de contratos por diferencia adoptados en el Reino Unido— Colombia puede transformar su suministro eléctrico hacia el uso de fuentes de energía renovables y, en particular, hacia la energía solar fotovoltaica, que es actualmente la forma más económica de generación eléctrica. Combinada con tecnología de baterías, puede convertirse en una fuente de energía asequible, estable y segura, desplegable a escala comunitaria, departamental y nacional. El ahorro energético y las medidas de reducción de la demanda constituyen también una contribución importante a la transición. La adopción de automóviles, autobuses, furgonetas, motocicletas y scooters eléctricos puede generar un ahorro casi inmediato para los hogares y reportar importantes beneficios en la calidad del aire en las ciudades. Numerosos procesos industriales pueden electrificarse en la actualidad.

La infraestructura de apoyo, tanto física como digital, también desempeñará un papel fundamental. En el plano físico, la modernización de la red eléctrica para sostener una economía cada vez más electrificada y la creación de la red necesaria de puntos de carga para vehículos eléctricos serán aspectos primordiales para acometer la eliminación de los combustibles fósiles a un ritmo adecuado. En el plano digital, las plataformas de datos en tiempo real permitirán obtener un ahorro significativo mediante la gestión eficiente de la oferta y la demanda, a la vez que facilitarán el seguimiento de los avances hacia una economía descarbonizada.

Seguridad energética

La eliminación progresiva de los combustibles fósiles también puede reducir el riesgo de *shocks* económicos derivados de conflictos internacionales o crisis energéticas, e incrementar la seguridad energética nacional. Un sistema de bajas emisiones es más del doble de eficiente que uno basado en combustibles fósiles. El CCC del Reino Unido concluyó recientemente que el costo adicional total de un único episodio de aumento de precios de los combustibles fósiles de una magnitud similar al de 2022 es probablemente tan elevado como el costo neto adicional total de cumplir la trayectoria total del Reino Unido hacia la neutralidad de carbono hasta 2050.

En la actualidad, Colombia exporta 25.000 millones de dólares en petróleo y carbón, lo que representa aproximadamente la mitad del valor total de sus exportaciones. Importa alrededor de 1.000 millones de dólares en combustibles fósiles, principalmente productos refinados del petróleo. Asimismo, está comenzando a importar gas. Colombia exporta carbón principalmente a los Países Bajos y Turquía. Se prevé que estas exportaciones disminuyan rápidamente incluso en un escenario en el que el mundo continúe dependiendo de los combustibles fósiles. Con la actual guerra en Irán, los precios de los combustibles fósiles son elevados, lo que se traduce en altos ingresos, pero también en un mayor costo de las importaciones de gas. Si bien los precios de los combustibles fósiles son notoriamente volátiles y difíciles de prever, se espera que los ingresos a largo plazo desciendan en el marco de un sector estructuralmente en declive.

Transición justa

En todos los escenarios considerados, Colombia deberá prepararse para una reducción de los ingresos provenientes de las exportaciones de combustibles fósiles, que se reducirán aproximadamente a la mitad hacia mediados de la década de 2030. Un plan de implementación para la eliminación progresiva de los combustibles fósiles podría desarrollar una transición estructurada para las comunidades afectadas y buscar sustituir parte de los ingresos perdidos con otras fuentes. Por ejemplo, una fuente potencial de ingresos podría ser la rápida expansión de la exportación de minerales críticos como el cobre. Las comunidades afectadas probablemente requerirán un apoyo significativo y programas de formación. A nivel mundial, existen pocos ejemplos de transiciones industriales exitosas. Colombia tiene la oportunidad de emerger como líder en la materia. El mercado global en expansión de minerales críticos tiene un valor superior a los 400.000 millones de dólares a nivel mundial.

Para desarrollar una hoja de ruta creíble y equitativa que pueda implementarse de manera adaptativa y lograr una transición sostenible a largo plazo, es necesario contar con un sólido marco de gobernanza. Será necesario consultar a una amplia gama de actores dentro de un esquema de gobernanza multinivel, que incluya comunidades e

industrias afectadas, gobiernos regionales y nacional, y organizaciones internacionales de desarrollo. Dicha colaboración es indispensable para superar los obstáculos que pueden ralentizar el ritmo de la transición, como los procedimientos de arbitraje de diferencias inversor-estado (ISDS, por sus siglas en inglés), en los que los intereses de los inversores pueden introducir riesgos jurídicos para los gobiernos.

Hacia un marco de hojas de ruta nacionales estandarizadas para la eliminación progresiva de los combustibles fósiles

Los esfuerzos de los consejos climáticos nacionales pueden ampliarse dentro de cada país y a través de la cooperación internacional mediante organizaciones como la Red Internacional de Consejos Climáticos, a fin de proporcionar un marco de apoyo para la elaboración de hojas de ruta de transición energética basadas en datos específicos de cada país y adaptadas a sus características particulares, que puedan implementarse dentro de distintos marcos de política y contexto nacional.

Por ello, planteamos la necesidad de desarrollar hojas de ruta estandarizadas para la eliminación progresiva de los combustibles fósiles a escala nacional, elaboradas por una red de consejos climáticos nacionales. Estas deben centrarse en el análisis específico de cada país sobre los beneficios económicos y de bienestar social asociados a la eliminación progresiva de los combustibles fósiles. Este conjunto de hojas de ruta permitirá a los gobiernos planificar y ejecutar, en el corto plazo, la eliminación progresiva de los combustibles fósiles con base en la mejor evidencia científica disponible y el conocimiento local sobre los desafíos y oportunidades propios de cada país.

Un marco de implementación y agregación de hojas de ruta nacionales estandarizadas fortalecería las evaluaciones globales y los procesos multilaterales al aportar mayor rigor al seguimiento y cumplimiento de las Contribuciones Determinadas a Nivel Nacional (NDC, por sus siglas en inglés), así como al proceso TAFF.

1.Introduction. The evidence base

The heating of the climate system is accelerating and global warming will exceed 1.5°C above pre-industrial levels within a few years (Forster et al., 2025; WMO, 2024). Devastation caused by heatwaves and flooding in many areas of the world have become common occurrences that are impacting economies, societies and ecosystems. The long-term climate trend is 100% attributable to human causes. The unprecedented rate of temperature change is caused by global greenhouse gas emissions being at an all-time high of $53.6 \pm 5.2 \text{ Gt CO}_2\text{e yr}^{-1}$ over the last decade. Around 70% of these emissions are from the burning of fossil fuels (Forster et al., 2025; UNEP, 2025).

The devastation from climate change is already common – and increasing in severity and frequency in many parts of the world. Recent research has attributed around a quarter of observed heatwaves since 2000 to anthropogenic emissions (Quilcaille et al., 2025). Economic losses are set to rise even further as heat stress disrupts labour productivity, health systems and supply chains, particularly in manufacturing bases such as China and the USA (Sun et al., 2024)

In spite of geopolitical stresses and limited progress through the United Nations Framework Convention on Climate Change's (UNFCCC) negotiations, which require unanimous agreement between parties, an ambitious movement to accelerate the transition away from fossil fuels is building. Through the Belém Declaration and the COP30 Presidency's commitment to develop a global roadmap on fossil fuels phaseout, there is growing recognition that the world must accelerate action.

The scientific foundation for this pathway is well established. Integrated assessment model pathways and IPCC approaches consistently show that deep, near-term GHG emissions reductions are essential for keeping 1.5°C within reach (Riahi et al., 2022). However, Nationally Determined Contributions submitted by parties are either not as ambitious as needed and/or lack a framework for national implementation (UNFCCC, 2025)

Increasingly, as 1.5°C is about to be breached, near term action becomes even more imperative, tackling not just carbon dioxide, but also methane, especially from fossil fuel use, which can make a difference in the shorter term (Gohar et al., 2026). The recent International Court of Justice (ICJ) ruling emphasizes the need to limit climate harm, emphasising the need for immediate actions rather than reliance on carbon removal efforts later in the century (Rogelj and Rajamani, 2025). Transition pathways that account for common but differentiated responsibilities and respective capabilities, in light of different national circumstances, give the same message when intergenerational equity is considered (Pelz et al., 2025b).

Taken together, the synergies between addressing climate change and promoting social justice point strongly to the rapid phasing out of fossil fuel technologies. The case becomes even stronger when economic and practical considerations are factored in. Renewable energy, battery storage and other technologies are more efficient, scalable and generally cheaper than the fossil fuel technologies they can replace. Their costs have been falling fast, whereas carbon capture and storage technologies have proved to be uneconomic, hard to scale and challenging to implement (Kazlou et al., 2024). Likewise, offsets have been decisively shown to not deliver effective emission reductions (Probst et al., 2024). The evidence shows that a realistic, economic and effective mitigation strategy should focus on absolute emission reduction by phasing out fossil fuel usage as fast as possible.

Ideally, the transition should be designed across countries with different levels of responsibility, capacity, development needs, and energy security concerns. A credible global roadmap must therefore pair a shared direction of travel with differentiated national pathways. These pathways will need to account for issues such as affordability, employment, fiscal dependence, industrial structure, and energy system resilience, while remaining aligned with the pace of decarbonisation required to limit the exceedance of 1.5°C.

To develop a national roadmap for Colombia, we draw expertise developed by national climate councils as well as the IPCC's enabling conditions framework, first developed in Chapter 4 of the IPCC SR1.5 report (de Coninck et al., 2018), which stresses the importance of multi-level governance, institutional capacity, behavioural change, innovation, policy instruments, and finance.

A UK example - as a box

The UK passed its Climate Change Act in 2008, becoming the first country in the world to establish a framework for setting legally-binding emission reduction targets. This also established the UK's CCC, as an independent advisor to Government on the recommended level of future targets. Over 70 countries now have somewhat similar governance structures.

In the UK, interim targets, known as carbon budgets (CB1-7), are set 12 years in advance covering future 5-year periods. To inform the approval process, the CCC provides a roadmap to show that delivery of the target is feasible and that it can be met in a cost-effective way. Successive UK governments have been required to introduce green policies to meet these targets, and setting them 12 years in advance helps provide policy and investor consistency. To date, six carbon budgets have been legislated and, since the framework was introduced, the pace of UK decarbonisation has doubled, while the UK economy grew. Coal has been completely phased out and oil and gas use is declining. The UK's last coal-fired power station closed in 2025 and UK

emissions have halved from their 1990 levels (see Figure 1). License issuance for the exploitation of new oil and gas fields was frozen in 2025. In the CCC's latest advice, it showed that for every pound spent on achieving Net Zero, the benefits are estimated to be 2.2 to 4.1 times greater. The largest gains come from avoiding climate-related damages, with projected savings of many billions by 2050. Energy efficiency also improves significantly, with system losses halved. Alongside these economic benefits, the transition brings substantial improvements in health and wellbeing from cleaner air, more comfortable homes, more active travel, and healthier diets (CCC, 2026).

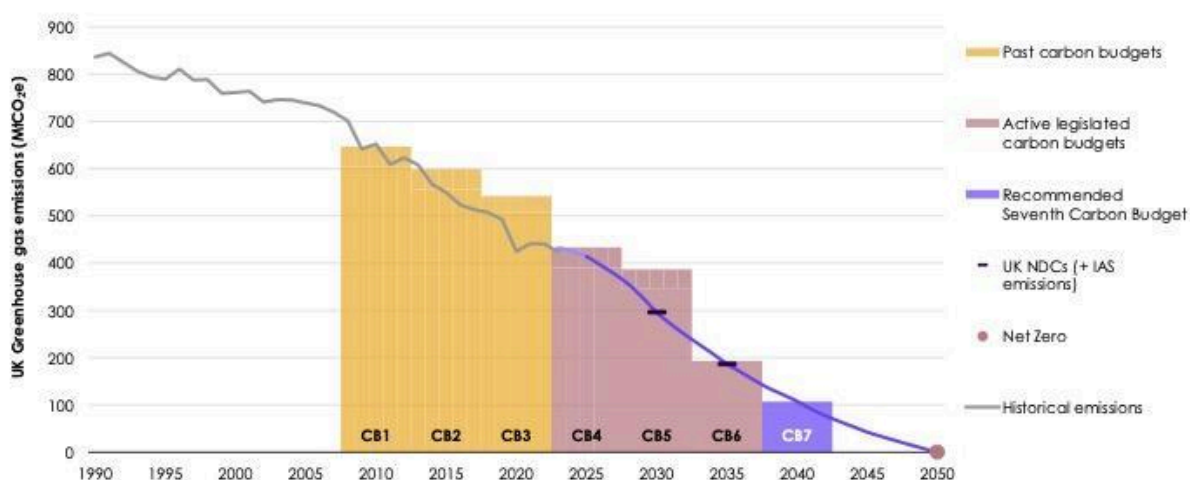


Figure 1. UK Carbon budget framework and the UK's historical territorial emissions (CCC, 2025, Figure 1.1). IAS stands for international aviation and shipping.

**** END UK example *****

Colombia is emerging as a climate leader, e.g. through its membership of the Fossil Fuel Non-Proliferation Treaty (FFNPT) and the Beyond Oil and Gas Alliance (BOGA). The launch of the first fossil fuel transition roadmap in Santa Marta will help define what a credible and practical transition can look like in a major fossil fuel producing country. These roadmaps can provide an early model for others, helping to shape both the content and the political ambition of any future global roadmap or treaty. Colombia's leadership matters not only because of its domestic significance, but because it can help set the tone for how fossil fuel phase-out is discussed internationally: not as an abstract ambition, but as a managed, just, and implementable process.

We note that the roadmap is focused on the energy transition, not agriculture, land-use change or embodied emissions. Restoring and managing forests and reducing emissions from agriculture remain an important part of national transition plans. A fuller

roadmap analysis could consider fossil fuel based fertilizers and the risks of offsetting and Article 6 trading, which could be used contrarily to prolong fossil fuel use. It could also consider the use of fossil fuels in material production, particularly petrochemicals, and explore the most effective pathways for transitioning to more sustainable alternatives.

The Santa Marta conference is structured around three pillars: overcoming economic dependency, transforming supply and demand and advancing international cooperation and multilateralism. We deliberately structure this report in the same way, starting with economic dependency.

For such roadmaps to be effective, they must be co-developed alongside stakeholders in the countries concerned. This report was drafted in collaboration with representatives from the Colombian government and is intended to serve as a foundation for further dialogue and input from Colombian counterparts and stakeholders. In particular, further feedback is sought on what a genuinely just transition could look like in the Colombian context, the feasibility of the key assumptions underpinning our analysis, and further alignment with the Colombian government's policy priorities. The analysis could also be strengthened over time by drawing on lessons from comparable exercises undertaken through the International Climate Council Network (ICCN), including, where relevant, case studies from the Powering Past Coal Alliance Solutions Bank.

2. Overcoming economic dependence: ensuring a fair, secure, and cost-effective transition

Colombia's economy remains significantly dependent on fossil fuel revenues for export, and it also relies on fossil fuels for its energy needs. Yet this model becomes increasingly untenable in a context of structurally declining global demand. In a decarbonising world aligned with international climate goals, global demand for coal, oil and natural gas is projected to decline by approximately 95%, 60% and 45%, respectively, by 2050 relative to 2019 levels (IPCC, 2022). Declines could be even steeper under more conservative assumptions regarding carbon dioxide removal potential (Achakulwisut et al., 2023). In such a scenario, fossil fuel exports would become progressively uneconomical, posing substantial risks in the form of stranded assets, employment losses and declining public revenues. A managed phase-out of fossil fuels is therefore not only an environmental necessity, but also a strategic economic imperative to safeguard long-term prosperity and resilience.

Extractive industries currently account for approximately 10% of Colombia's GDP and government revenues, with oil production representing the largest share (DANE, 2025). Fossil fuels constituted roughly half of total exports in 2024, with coal playing a particularly prominent role, placing Colombia ninth in the Coal Transitions Exposure Index (IEA, 2022). This high degree of market concentration increases the country's exposure to transition-related risks. Maintaining current production levels for oil and gas would require substantial capital expenditure across all fossil fuels e.g. mature oil fields require continued capex investment to maintain output levels as they get depleted. At the same time, the government announced in 2023 that it would halt the issuance of new oil and gas exploration licences, signalling a strategic pivot toward a more diversified and sustainable economic model.

Clean energy investment has accelerated in recent years. In 2025, clean energy accounted for approximately half of total energy-sector investment, amounting to around USD 8 billion (IEA, 2025a). Sustaining and scaling this momentum will be essential to align Colombia's development pathway with its international climate commitments and the best available scientific evidence.

A well-financed transition does not only require scaling renewable energy deployment, but also promoting emerging green industries that generate opportunities for communities negatively affected by the transition. Potential growth areas include selected manufacturing sectors (EVs and solar PV modules), renewable or green hydrogen and associated fertiliser production, the mining of key transition minerals such as copper using renewable energy, and sustainable biofuel production.

Colombia's 2050 climate strategy already identifies the bioeconomy as a strategic export sector with significant long-term potential (Gobierno de Colombia, 2021).

Delivering a fossil fuel phase-out at pace will also require addressing a range of challenges, including high costs of capital in high-debt economies, fossil fuel subsidies, insufficiently widespread and ambitious carbon pricing schemes, regulatory barriers including permitting bottlenecks and Investor-State Dispute Settlement (ISDS) risks, which can introduce legal liabilities for governments. Foreign investors affected by the phase-out may challenge policy measures that reduce the value of their assets or expected future profits. This risk is especially important when distinguishing between projects that are already at Final Investment Decision, and therefore effectively locked in under an ISDS regime, and earlier-stage projects that may still be more responsive to policy change. If a roadmap assumes rapid phase-out without accounting for these legal and contractual constraints, it may overstate how quickly governments can act and understate the possibility of delays, compensation claims, or policy rollback.

To inform our report, two alternative pathways for Colombia's energy system were modelled: a business-as-usual (BAU) scenario, characterised by limited deployment of low-carbon technologies, and a fossil fuel transition (FFT) scenario, based on the large-scale rollout of low-carbon solutions to reduce energy system emissions to below 10 MtCO_{2e}. A cost analysis of the FFT scenario relative to the BAU is presented below, with details about the evolution undergone by the different economic sectors provided in Section 3. Full details of the modelling framework used and the assumptions underpinning each scenario are presented in the appendix.

2.1 Costs and savings of phasing-out fossil fuel consumption

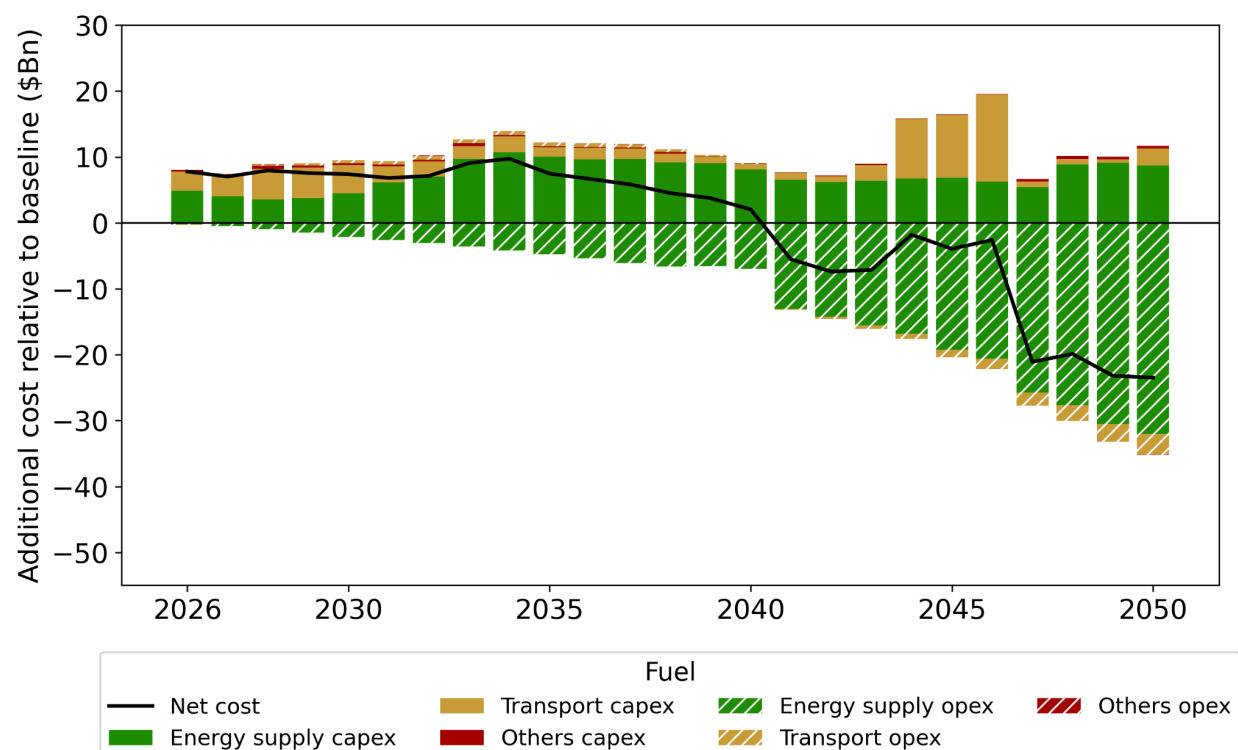


Figure 2. Capital expenditure (capex) and operating costs (opex) for Colombia's fossil fuel transition (FFT) scenario relative to business-as-usual (BAU). Note this does not account for changes in revenue from fossil fuel exports, which would need to be considered separately. Source: own analysis.

The transition away from fossil fuel consumption in the Colombian economy will require substantial upfront investment over the next 25 years, but drives savings almost immediately in energy supply operating costs. Our analysis, which contrasts FFT and BAU scenarios, projects net savings by the early 2040s, as illustrated in Figure 2. Detailed projections of capital and operational expenditures are provided in the appendix. This evidences that phasing out fossil fuels is not only environmentally necessary, but also economically advantageous over the medium and long term. However, who bears the burden for this investment is an important consideration, see Section 2.4.

Investment needs are concentrated in two sectors: energy supply and road transport (international aviation and shipping are excluded in this cost analysis). These sectors account for most upfront capital expenditure, enabling both the expansion and decarbonisation of electricity generation and the transition to a low-carbon transport system. Annual capital investments in these sectors are estimated at USD 10.2 billion

and USD 14.1 billion, respectively, through to 2050, which roughly translates to 2.4 per cent and 3.4 per cent of Colombia's 2024 GDP. This represents an increase of approximately USD 7.2 billion in energy supply and USD 3.1 billion in transport relative to the BAU scenario (1.7% and 0.7% of GDP), and broadly aligns with Colombia's government projections (MME, 2024).

Other sectors require comparatively modest investment to decarbonise. Combined annual capital expenditure for industry and buildings is estimated at USD 1.6 billion, around USD 0.3 billion above business-as-usual levels.

The transition to more efficient, low-carbon energy sources also reduces overall energy waste, generating significant cost savings across the system. These savings are most pronounced in the energy supply sector, where substantially lower operating costs relative to fossil fuel alternatives begin to materialise early in the transition. As a result, the overall transition delivers net economic savings from the 2040s onward.

A similar, though more gradual, effect is observed in the transport sector, where lower operating costs for vehicles contribute to savings over time. By 2050, annual operational cost savings are projected to reach USD 32 billion in energy supply and USD 3.1 billion in transport.

2.2 Financing the phase-out

A well-financed transition will require coordinated action by public institutions, private actors and international partners. As in similar decarbonisation pathways (Climate Change Committee, 2025; IEA, 2025a), the majority of investment is expected to come from the private sector, with the public sector playing a catalytic role in establishing the regulatory framework, de-risking projects and providing strategic backstops. Households are expected to contribute a relatively modest share of total investment (around 30% by 2035, a similar level to IEA, 2025), with the bulk of capital expenditure undertaken by state-owned enterprises and private corporations.

Access to affordable long-term finance remains a structural constraint for both the public and private sectors. Financing costs are roughly three times higher in Colombia than in the European Union and the United States (IEA, 2025a). Elevated lending rates reduce risk-adjusted returns on green infrastructure projects dampening investment. Mobilising both domestic and international capital at a lower cost will therefore be essential. Recent initiatives point in this direction, including the creation of the nuam exchange, integrating the Colombia, Santiago and Lima stock exchanges, and the Plataforma País initiative, designed to attract international investment and develop technical capabilities within Colombia to support the green transition.

The public sector plays a central role as a financier, regulator and risk mitigator. It currently accounts for approximately 25% of total energy financing, mainly through the equity portion of state-owned enterprise investments. Increased public investment will be required to accelerate low-carbon power generation, expand public transport systems, increase energy access coverage and incentivise building efficiency and EV adoption. Public resources will also be necessary to advance less mature technologies such as low-emissions fuels, as well as critical infrastructure projects including grid expansions and battery storage. These investments can be structured through a combination of equity injections and debt instruments.

Nevertheless, our analysis indicates that private capital will represent the dominant share of financing. Commercial investment is particularly critical for scaling renewable power generation, low-carbon fuels, energy efficiency improvements and vehicle electrification. However, mobilising capital at the required scale remains a challenge. Policy reforms will therefore be needed to facilitate these investments, including an investor-friendly regulatory environment, streamlined permitting procedures, an expanded energy grid able to accommodate new capacity and demand, and long-term clarity on carbon pricing and energy policy. Public-private partnerships (PPP) can further support risk-sharing and capital mobilisation, particularly when combined with development finance institutions (DFI) that often require sovereign participation. Colombia's experience with PPs in road infrastructure demonstrated the potential of this model, and similar programmes could be particularly valuable in more remote regions where purely commercial financing is unlikely to materialise.

International support will play a complementary but comparatively smaller role. International public finance, mainly DFIs, are expected to average approximately USD 0.9 billion annually over the period 2026-2035 (IEA, 2025a). These resources should focus on renewable energy deployment (PV and wind), grid expansion and storage in remote areas, as well as the development of wind potential in La Guajira, where social, environmental and connectivity challenges increase project risk and financing needs.

The transition will also have significant fiscal implications. Revenues from fossil fuel extraction and exports will decline under a phase-out scenario, requiring alternative sources of public funding. The continued reform of fossil fuel subsidies, which reached 2.5% GDP in 2022 (Gutierrez et al., 2024), offers an important opportunity to free fiscal space while strengthening price signals for energy efficiency and electrification. Given that approximately 80% of energy subsidies benefit non-poor households (Lora and Mejía, 2021), improved targeting and subsidy efficiency could protect vulnerable groups while releasing resources for transition investments.

Further reforms to carbon pricing and energy taxation could generate additional public revenues. These revenues could be recycled to shield low-income households from distributional impacts through targeted energy subsidies, while simultaneously supporting capital investment via grants, concessional loans or subsidies. In the near term, charges on domestic fossil fuel consumption and continued revenues from net fossil fuel exports may provide transitional funding streams to finance the shift toward a diversified, low-carbon economy.

2.3 Energy Security

A phase-out of fossil fuels presents a strategic opportunity to strengthen Colombia's energy security and independence. The country possesses significant low-carbon energy potential, of which the non-hydro resource is yet to be fully exploited. Once developed, it could meet domestic demand while supporting a competitive export portfolio. However, as the energy system transitions away from fossil fuels, new sources of system flexibility and resilience need to be introduced to ensure a secure, reliable, and affordable supply. A diversified portfolio of solutions encompassing an array of power generation types, energy storage, demand response measures and grid modernisation will therefore be essential to support the green transition.

Colombia's renewable energy resources are significant, though geographically uneven. Solar and onshore wind sources are particularly abundant in the central and northern regions, while offshore wind potential along the Caribbean coast is estimated at 50 GW (MME, 2022), roughly double the country's installed generation capacity. Colombia is also an established biofuel producer and one of the largest biofuel markets in Latin America and the Caribbean. This position provides a good foundation for expanding bioenergy production for both domestic consumption and export markets. National plans to produce more than 1.7 billion litres of sustainable aviation fuel (SAF) by 2050 (Presidencia de la República, 2025) could position Colombia as a net exporter in this emerging market. Expansion should prioritise rural development objectives and maximise the use of crop residues, forestry by-products, and organic waste to minimise land-use pressures.

In addition, the department of La Guajira holds significant potential for highly competitive, low-emissions hydrogen and other low carbon fuel production. This fuel could serve hard-to-electrify sectors domestically, while surplus production could support export markets and enable higher value-added industrial activities such as ammonia production for fertilisers. Geothermal resources, concentrated in the Andean volcanic region, are estimated at approximately 1 GW and could provide a stable and dispatchable source of low-emissions electricity in Colombia by 2050 (IEA, 2025a).

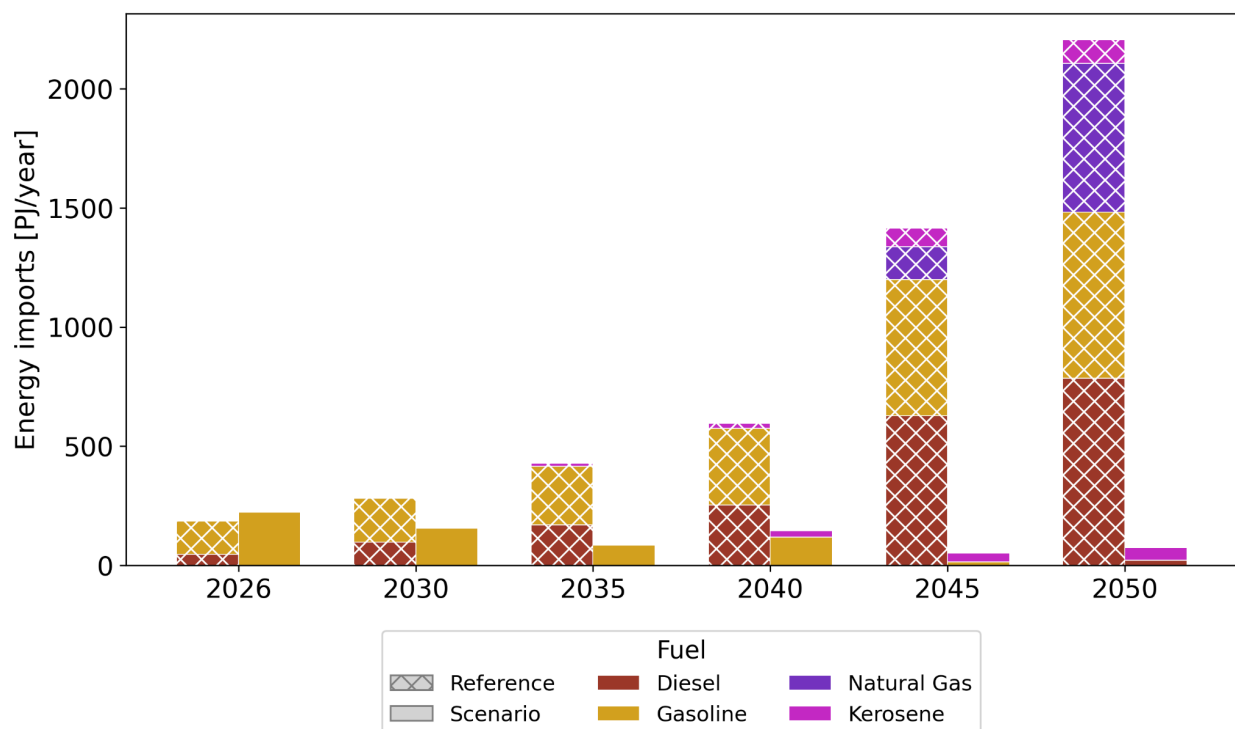


Figure 3. Colombia’s fossil fuel energy imports under a business-as-usual (hashed) and FFT (solid) scenarios.

Developing these resources would allow Colombia to substantially reduce its dependence on energy imports. In contrast to the BAU scenario, where Colombia is projected to depend on energy imports for about 58% of its needs by 2050, a decarbonised Colombia would be able to limit this dependence to just 2.9% of supply (Figure. 3). This would help shield its economy from external shocks and maintain energy affordability. However, this transition will require significant investment, not least in the electricity grid to give universal access to electricity, support the electrification of all sectors, and enable transport of energy from energy-rich areas to the rest of the country.

Achieving the pace of renewable energy deployment required for the transition will depend on close and sustained collaboration among all stakeholders. Initiatives such as the *Estrategia 6GW* (UPME, 2025c) are expected to play a central role in accelerating progress. This strategy aims to stimulate the expansion of renewable projects within Colombia’s energy matrix by identifying and addressing key barriers, including environmental licensing processes and grid connection constraints. It also emphasises the importance of coordinating actors across the public, private, and civil society spheres, fostering dialogue and engagement to align interests and facilitate more efficient project development and implementation.

An energy system dominated by variable renewable generation will necessitate enhanced flexibility across multiple timescales. The network must be able to respond to changes in supply and demand from the millisecond to the interannual scales, as well as to adapt to cross-regional differences (IEA, 2023; IEA, 2024a). Solar PV and wind generation, which are expected to constitute the backbone of future energy supply, must be complemented by dispatchable low-emissions technologies capable of ramping up generation on-demand. While hydropower will continue to offer valuable long-term flexibility, expansion potential is constrained. Additional low-emission options should therefore be developed such as bioenergy, geothermal and green hydrogen. Shorter-timescale flexibility can be provided through energy storage solutions such as batteries and pumped hydropower. Battery technology in particular can deliver a wide range of system services while benefiting from declining costs and high scalability and modularity. These benefits include split-second responsiveness, energy shifting, synthetic inertia, frequency regulation and voltage support. Seasonal energy storage and demand response measures will also play a critical role in balancing supply and demand in a cost-effective manner. Measures such as flexible EV charging and heat pump usage can shift consumption towards periods of abundant renewable generation, provided appropriate market incentives and regulatory frameworks are established.

System resilience must also be strengthened in the face of increasing physical and digital risks. Climate change is projected to intensify extreme weather events, with potential implications for hydropower output and grid reliability. Under high-emissions scenarios, hydropower capacity could decline by up to 25% by the end of the century due to droughts associated by stronger El Niño events (IEA, 2025a). Half of Colombia's national grid is built in areas expected to experience a wildfire every ten years or less (IEA, 2025a). Future-proofing the energy system will require enhanced contingency planning and physical system hardening (IEA, 2021a). Additionally, as electrification and digitalisation advance, cybersecurity risks will increase. Robust cybersecurity strategies will be necessary to safeguard critical infrastructure against malicious actors (IEA, 2021b).

A limited number of thermal power plants may remain in operation to provide secure capacity during peak demand or prolonged supply shortfalls. However, their role will shift from baseload generation to strategic reserve capacity. Where retained, these facilities should be equipped with carbon capture and storage (CCS) technologies to mitigate their emissions.

Finally, the green transition will depend on a reliable supply of critical minerals. These include copper, lithium, nickel, cobalt and rare earths that are essential for many clean technologies. International cooperation and appropriate regulations will be essential to provide those materials in a fair and sustainable manner. Where economically and environmentally viable, domestic production could create new industrial opportunities,

facilitate a just transition for regions historically dependent on fossil fuel extraction, and reduce dependence on imports.

2.4 Just transition

Domestically, Colombia faces several challenges in the transition away from fossil fuels in a way that ensures fairness and improves social outcomes for citizens, whilst structural interdependencies act as an initial barrier to decarbonisation. At the core of this challenge is Colombia's dependence on fossil fuel exports, which reduces fiscal revenues and limits the state's ability to simultaneously finance both the energy transition and social programmes. This creates a double bind: Colombia must decarbonise both its energy production and consumption whilst relying on the fossil fuel revenue that enables public investment in the first place.

This dependence exposes the Colombian economy to wider macroeconomic vulnerabilities. A widening trade deficit and reduced foreign exchange can contribute towards increased risk of currency depreciation, high unemployment, increasing public debt and dwindling international reserves in the absence of export diversification and reindustrialisation (Godin et al., 2023). In response, new, high-potential economic sectors, such as agro-products and renewable energy value chains (e.g. hydrogen production, critical mineral production and biofuels) have been identified (IEA, 2025), which can provide new sources of capital inflow and revenue replacement. However, key risks include existing institutional lock-in (which favours extractive sectors) and time-lags, in which new sectors take time to develop, whereas revenue loss may occur earlier. This makes early and proactive support for diversification essential.

These national-level dynamics translate into uneven regional impacts. Coal-dependent exporting regions, such as Cesar and La Guajira, where mining is a major source of employment, are likely to be disproportionately affected, with implications for local jobs, indirect employment effects, and municipal government revenues. Many of these regions have high potential for renewable energy generation, however these are unlikely to fully offset the impacts of declines in coal production and structural/geographical factors affect these regions' ability to decarbonise (Vega-Araújo et al., 2023; Arond et al., 2024).

Furthermore, these distributional challenges are further compounded by long-standing institutional constraints. Investments in fossil fuel infrastructures over a period of decades have not resulted in reduced poverty or improved productivity due to a lack of institutional capabilities (to collect revenues, manage budgets and implement infrastructural and social programmes) (SEI, 2023). Paradoxically, this has reinforced regional dependence on coal, deepening local vulnerabilities and weakening trust

between communities and the state, thereby increasing resistance to the energy transition (Vega-Araújo and Heffron, 2022).

Taken together, these dynamics highlight a significant risk: without deliberate intervention, the energy transition could reproduce or even exacerbate existing inequalities. This risk is particularly acute if new low-carbon sectors replicate the extractive patterns of fossil fuel industries - characterised by limited employment generation, geographic concentration of benefits, weak integration into local economies, and potential land conflicts affecting Indigenous communities. Therefore, it is crucial to develop bespoke, place-specific transition plans that address the local issues of revenue replacement, employment, infrastructure and clean energy access. Many studies have highlighted key policy priorities to ensure a just transition in Colombia:

- Fiscal planning for municipalities and departments that are expected to lose royalties from fossil fuel extraction (Godin et al., 2023; Moreno et al., 2024).
- Institutional capacity building to ensure the delivery of public services and the implementation of new regulatory frameworks
- Greater participation in decision-making, especially with indigenous communities, accounting for procedural justice (who decides), distributive justice (who benefits) and recognition justice (whose norms and authority counts) (Godinho et al., 2024).
- Community-owned renewable energy systems to enhance democratisation, governance and energy access to secure remote energy access (Garces et al., 2023).
- Targeted labour strategies to ensure that retraining, skills and education programmes are not concentrated exclusively amongst men, urban residents and highly-educated
- A comprehensive understanding of energy poverty beyond access indicators (Esquivel García and Toro-García, 2024).

Understanding Colombia's allocation of the remaining global carbon budget is key to guiding national fossil fuel phaseout pathways. A fair share carbon budget extends justice concerns beyond domestic socioeconomic impacts to questions of equitable allocation of the remaining global carbon budget across nations and populations. Carbon budgets can be based on several factors, such as population, historical responsibility and capacity to decarbonise.

In Figure 4 we allocate the global remaining CO₂-FFI (fossil fuel and industry) carbon budget under 1.5°C at 50 per cent probability (Smith et al., 2025) to Colombia using three equity interpretations (Pelz et al., 2025b)¹: (i) equal per capita from 2015; (ii) Common But

¹ Calculated using <https://github.com/setupelz/fair-shares>

Differentiated Responsibilities and Respective Capabilities (CBDR-RC) via cumulative per capita accounting from 1990 with a capability adjustment; and (iii) CBDR-RC with additional pre-1990 historical responsibility rescaling. After subtracting Colombia's actual cumulative CO₂-FFI from each allocation year through 2023, the remaining national budget from 2024 is approximately 1,998 Mt CO₂ under equal per capita (linear reduction to zero by the mid-2060s) and 4,060-4,254 Mt CO₂ under both CBDR-RC interpretations (gradual transition to zero by 2100). Under a net-zero carbon debt framework interpretation (Pelz et al., 2025a), and assuming a just and orderly fossil phase-out pathway, Colombia will likely hold a substantial carbon credit at net-zero CO₂, where its cumulative emissions remain well below its fair share allocations. This does not motivate lowering ambition; all countries should pursue the highest possible ambition per the Paris Agreement (Schönfeld and Rogelj, 2025). Rather, the gap between Colombia's highest possible ambition pathway and its fair share allocation quantifies the extent to which Colombia contributes beyond what considerations of international equity require, providing a transparent basis for deliberations over international cooperation and financial assistance to meet its domestic just transition requirements.

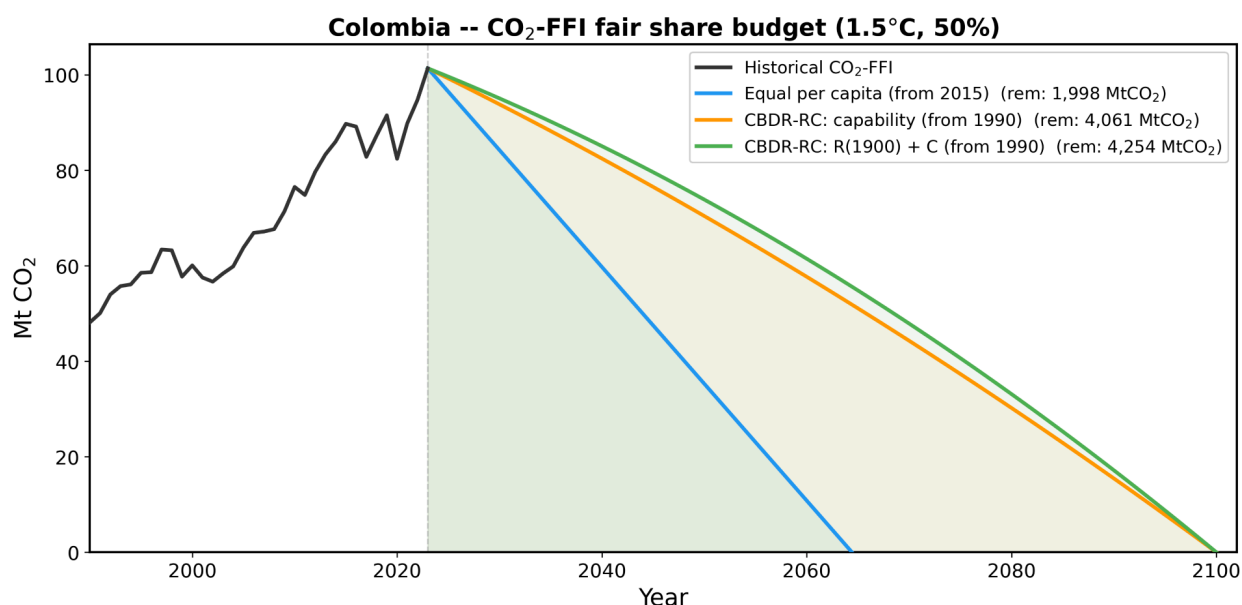


Figure 4. Global remaining fossil fuel and industry carbon budget under 1.5°C at 50 per cent probability (Smith et al., 2025) to Colombia using three equity interpretations (Pelz et al., 2025b): (i) equal per capita from 2015; (ii) Common But Differentiated Responsibilities and Respective Capabilities (CBDR-RC) via cumulative per capita accounting from 1990 with a capability adjustment; and (iii) CBDR-RC with additional pre-1990 historical responsibility rescaling

Although they are not directly comparable², Colombia's cumulative emissions out to 2050 in the fossil fuel phaseout pathway (Section 3.3) amount to 1,431 MtCO₂eq, suggesting a substantial notional carbon credit relative to fair share allocations. The remaining carbon space can therefore be interpreted as being allocated across (a) the remaining years between 2050 and prior to full decarbonisation and (b) emissions from industrial processes, which are not explicitly represented within the pathway presented below.

² The OSeMOSYS-COL model used to estimate the fossil fuel phaseout pathway reports emissions in CO₂-equivalent, aggregating all greenhouse gases as well as excluding industrial process emissions. In contrast, Figure 4 is calculated using CO₂ only but includes industrial process emissions. We also assume that emissions stay constant from historical levels from 2023-2025.

3. Transforming supply and demand: a fossil fuel phase-out roadmap

3.1 Colombia today: the current energy and emissions context

Colombia's energy system, including both supply and end uses, accounted for 31% of the country's territorial emissions, at 91MtCO₂eq in 2021. Overall, fossil fuels play a significant role in the Colombian energy system. Coal, natural gas and oil products dominate, accounting for 14%, 21% and 43% of primary energy supply, respectively (UPME, 2024). Not only this, but fossil fuel use has grown by 86% between 2000 to 2024.

As a middle-income country that has seen substantial growth in average incomes over the last two decades, Colombia's energy demand has almost doubled from 2000-2024. Although the proportion of demand from fossil fuels has remained relatively flat over this period, reaching 2,027 PJ in 2024 (IEA, 2025), this has resulted in the vast majority of new demand being met by fossil fuels - at around 76%.

Greater mobility and the growth of the transport sector has led to a significant increase in oil consumption, driven by travel needs largely being met by internal combustion engine vehicles. Whilst this has partially been offset by the introduction of biofuel mandates, and more recently strong developments in the EV market, Colombia's increased domestic oil production has fallen short of the increase in demand (IEA, 2025).

A similar story is observed in the residential sector, where larger, more energy-intensive dwellings have led to increases in demand for heating, cooling, lighting and domestic appliances. There has been a slow but marked reduction in traditional biomass use, alongside increased access to electricity and natural gas for heating and cooking needs, representing an important energy transition. This shift has enhanced end-use efficiency and substantially reduced exposure to household air pollutants, with pronounced benefits for women and children who face higher levels of exposure (WHO, 2025).

The increase in the electrification of end-use energy services in buildings and industry has resulted in strong growth in electricity generation, growing from 43 TWh in 2000 to over 88 TWh in 2024. The power sector in Colombia has long been dominated by hydropower, which represented 58% of all generation in 2024. Other low carbon sources, such as wind, solar and biofuels, constitute just 7.1% of generation, but have rapidly expanded from a small base in the last few years. The remainder is made up of

fossil fuels - predominantly gas (19%) and coal (12%), growing from a combined 11 TWh to 31 TWh from 2000-2024.

Against the backdrop of growing demand, supply pressures and climate impacts, this context represents an important juncture for Colombia's energy system. The country's reliance on hydropower as the backbone of the power system leaves the power sector vulnerable to fluctuations due to climatic variations, such as global El Niño events and worsening droughts due to anthropogenic climate change (Ochoa et al., 2025). Simultaneously, natural gas has become increasingly embedded in the energy system, with approximately 80% of households connected to the gas grid, increased industrial use and a key source of dispatchable electricity generation - acting as a backstop for hydropower.

However, as domestic production continues to decrease (IEA, 2025), Colombia is now a net-importer of natural gas, with a supply deficit projected as early as 2030 (Suárez et al., 2025). This leaves Colombia highly exposed to (a) highly volatile international markets and (b) energy supply shortfalls. As such, an energy transition, premised upon energy efficiency, demand reduction and renewables can help ensure supply in the short-term, reduce long-term dependency and lock-in whilst reducing the country's contribution to global greenhouse gas emissions.

Simultaneously, the Colombian economy is structurally dependent on the export of fossil fuels - primarily coal and oil. Colombia exports the second-most energy in South America, totalling 65% of domestic energy production, increasing 52% from 2000-2024 (IEA, 2026). Although exports have decreased since 2017, total energy exports still amounted to 3,079 PJ in 2024. Colombia is, therefore, substantially reliant on fossil fuel production and trade for fiscal revenue and economic growth. As we detail below, this source of revenue may dramatically change in a decarbonising world with reduced fossil fuel demand.

3.2. The future of Colombian energy exports in a decarbonising world

Energy exports have long been critical to Colombia's economy. In 2010, they accounted for 57 per cent of total exports, with this share reducing to 45 per cent in 2024, of which oil contributed most, at 30 per cent (IEA, 2025a).

Domestic oil production stands at around 0.75 mb/d in 2025, about half of which is exported. Its production is in decline, from a peak of over 1 mb/d in 2013. This decline is expected to continue, with the majority of production from mature or semi-mature fields, and limited CAPEX investment going into new exploration. Gas, unlike oil, is

predominantly used in the domestic energy sector, with Colombia recently becoming a net importer due to declining production since the 2013 peak, and growing domestic demand (IEA, 2025a). There is some prospect for increasing gas production based on the new Sirius project, a joint venture by Ecopetrol and Petrobras, which more than doubles currently discovered gas resources. This project has been subject to legal challenge, and has not yet been granted approval for production.

After oil, coal constitutes the next most significant export revenue earner for Colombia, with around 90% of production exported, primarily to European and Mediterranean markets (notably Turkey). However, coal exports have been in decline over the last 10 years, with future prospects challenging as countries shift away from coal.

The high dependency of the Colombian economy on export revenues makes it particularly vulnerable to declining fossil fuel export markets - and a need to manage such transition risks in a global economy that is moving towards electrification based on an increasing share of renewable generation. In their scenario of limited climate ambition, the Stated Policies Scenario (STEPS), the IEA projects that global oil demand will peak by 2030, largely due to the uptake of electric vehicles, led by China (IEA, 2025b). The question will be the speed of decline post-2030, and its impact on oil prices. Coal, also under STEPS, suggests peak demand in the very near term, with a more rapid decline of almost 20% by 2035, relative to current levels. This decline is even more rapid in the European markets that Colombia currently exports to. The IEA's Net Zero roadmap for Colombia sees production of coal at very low levels in 2050 under their APS scenario, driven by the net zero commitments in the economies they export to (IEA, 2025a).

Given the importance of oil historically as a generator of export revenue, we focus on assessing transition risks associated with this export commodity. We consider projected global oil demand under scenarios published by the IEA in WEO 2024 (IEA, 2024b), and assess what this means for Colombian production over the next 25 years. WEO 2024 is chosen due to the diversity of scenarios, reflecting different levels of climate ambition.

We use a dynamic recursive global oil model that assesses the commerciality of Colombian production under the prevailing oil price, which is set by the global demand for oil and the supply cost of meeting it (see Annex for a brief description of the model). Global demand projections from the IEA scenarios are shown in Figure 5 below.

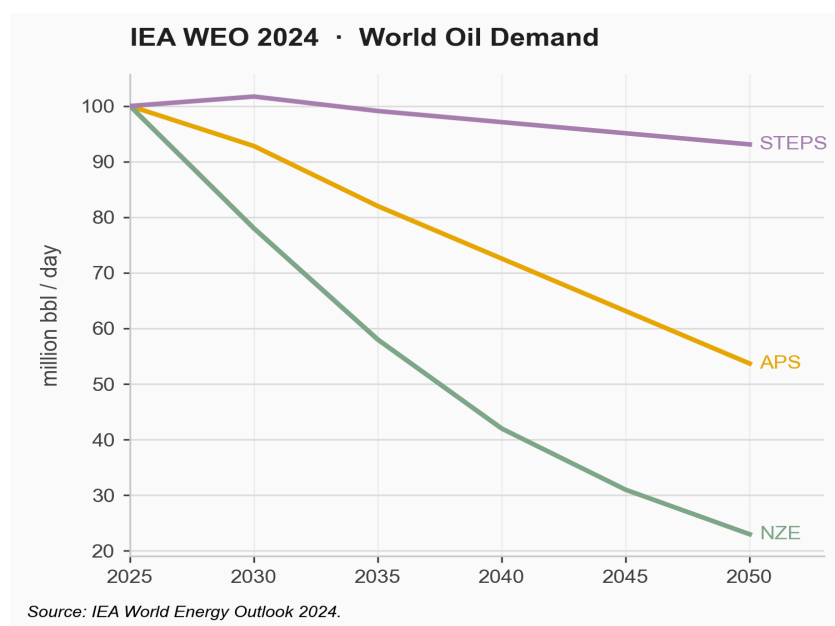


Figure 5: Global demand trajectories for oil under three IEA scenarios from WEO 2024: Stated Policies Scenario (STEPS), Announced Pledged Scenario (APS) and Net Zero Emissions Scenario (NZE).

Colombia's oil production declines in all scenarios, but at different rates. This is not unexpected; as shown by the projections from Ministry of Mines and Energy (UPME, 2025a), even under an optimistic scenario (3), production declines to around 0.4 mb/d by 2035, and 0.2 mb/d by 2040.

In STEPS, where global demand remains relatively flat through 2050, Colombia's production falls by almost 50% in 2035, with a lower decline thereafter out to 2050, at around 0.25 mb/d (Figure 6). Remaining production output is driven mainly by currently producing fields, with only limited offset from new developments or undiscovered resources.

As climate ambition strengthens under APS and especially NZE, the decline in production is more rapid, with plotted reduction thresholds reached increasingly early. This implies that as global demand reduces, lowering prices, the commerciality of Colombia's oil exports will also reduce.

Under APS, production in 2035 is around 0.2 mb/d, and almost at 25% of 2025 production levels. This contrasts with the IEA scenario, which put Colombian production in 2035 at 0.35 mb/d, the same level as domestic demand needs. It is likely that the model used here is overestimating decline by using breakeven prices as the basis for production decisions, and not enabling short run marginal cost-based operation. It also

does not consider domestic demand levels. The NZE scenario sees an even more rapid decline, with production levels at under 0.1 mb/d in 2035.

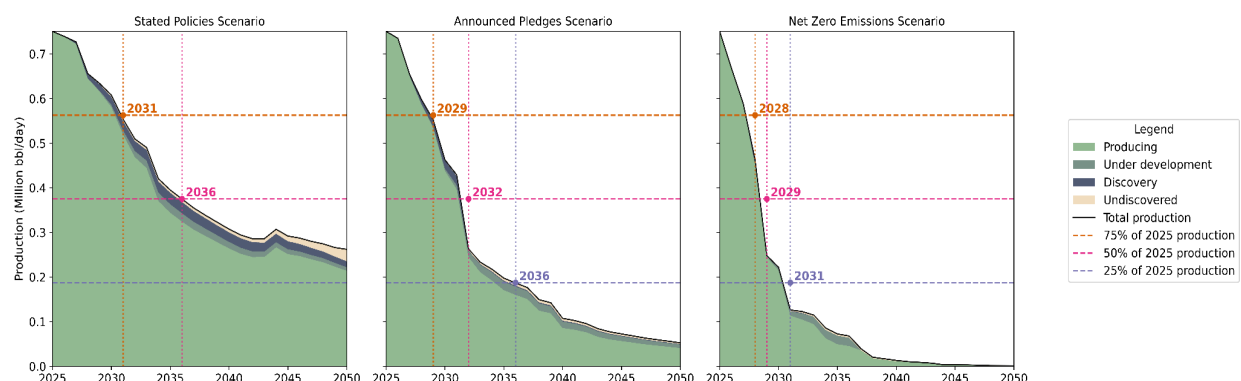


Figure 6: Production of Colombia's oil production under selected IEA scenarios. The horizontal dashed lines show when production hits decline thresholds, set at 75% down to 25% of 2025 production levels, and the corresponding year.

Combining the above production profiles with the modelled prices in each year, it is possible to estimate the change in revenues over time (Figure 7). Note that these revenues measure total revenues from all production, and do not differentiate between oil used domestically and exported. These also do not indicate the level of government take, which will depend on the fiscal regime in play. Current breakeven costs of Colombia's production reflect the current tax regime in place today.

While the production profiles provide an important insight into future earning potential, associated transition risks are magnified when we convert production into potential revenue. Declining global market prices, driven by falling demand, lead to relatively steeper falls in revenue compared to the rates of reduction observed for production.

Revenue losses are front-loaded, with net revenue (accounting for costs of production) falling faster than gross revenue in every scenario. Colombia reaches 50% of 2025 net revenue by 2029 in STEPS, 2028 in APS, and 2027 in NZE, earlier than the equivalent gross revenue thresholds of 2032, 2030, and 2028.

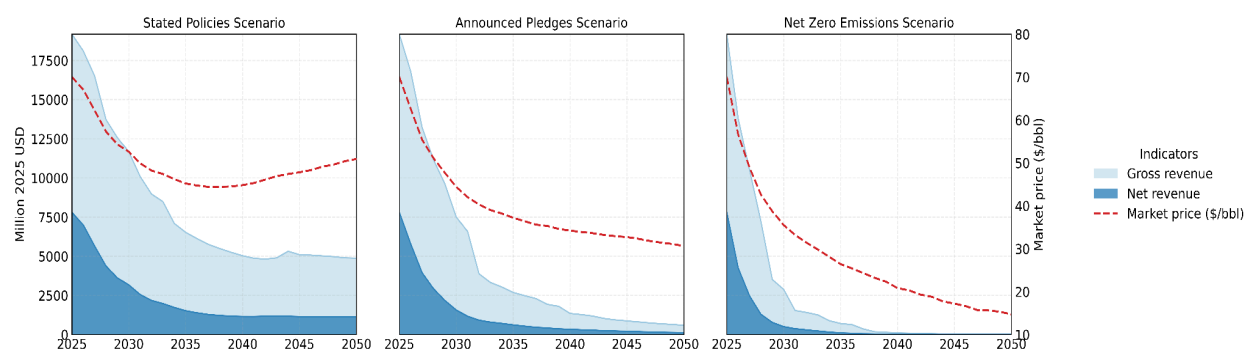


Figure 7: Estimated gross and net revenues from Colombia's oil production under selected IEA scenarios, based on modelled prices.

Given the criticality of fossil fuels as a generator of export revenues, it is crucial that Colombia can plan strategically to fill this gap over the next 15-20 years. By 2040, revenues are 25% of 2025 levels in STEPS and much lower in APS and NZE. Diversification could come in the form of clean energy sector growth, including critical minerals, green hydrogen, and clean tech manufacture, as well as the development of other sectors e.g. tourism, agriculture. Any strategy will also need to account for the location of current energy sector employment, notably from coal and oil, and ensure that any strategy is spatially targeted to ensure a just transition.

Note that these calculations are based on long-term estimates of fossil fuel prices resulting from structural change in demand. Current prices are much higher than these long-term prices due to the war in Iran. For a country such as Colombia, where half the export revenues are from fossil fuel exports, a robust implementable roadmap needs to factor in that prices may or may not stay high for quite some time. A near term high price outlook might actually mean that Colombia can keep revenues high with reducing fossil fuel production. However, it is important to underline that a short term uptick in prices does not change the picture from the modelling which shows that long-term declining fossil fuel revenues are expected under all scenarios, roughly halving by the early 2030s.

3.3 Colombia tomorrow: phasing out fossil fuel consumption

Our FFT scenario projects a deep decarbonisation across all sectors of the economy, fundamentally driven by electrification powered by renewables. The transition to a more efficient, electrified energy system progresses steadily to 2050. In areas where electrification remains challenging, mainly heavy industry, green or renewable hydrogen emerges as a complementary solution in the medium-term.

Overall final energy demand grows only moderately despite economic and population growth, increasing by around 16% by 2050 compared to 2025. This reflects significant efficiency gains and the impact of demand-side measures. At the same time, the energy mix undergoes a profound transformation: fossil fuels are largely displaced, falling from a dominant share of final energy demand to a marginal role, while electricity becomes the backbone of the system, supplying more than 81% of final energy by mid-century.

This shift is enabled by a rapid expansion of the power sector, where generation increases nearly fourfold and is overwhelmingly supplied by renewable sources, particularly solar and wind. Complementary investments in storage, dispatchable

low-carbon generation, and grid infrastructure ensure system reliability and resilience as variability increases.

The pace of change varies by sector. The residential sector undergoes rapid electrification over the next decade, while progress in commercial and transport sectors is more gradual. Industrial decarbonisation, in contrast, accelerates after 2040, reflecting the energy-intensive nature of the sector and the time required for relevant low-carbon technologies to mature.

A significant shift toward higher-efficiency appliances is projected over the next decade, emerging as a key near-term opportunity. Many efficiency improvements require only modest upfront premiums and offer short payback periods. Existing policies are already supporting this transition and should be strengthened, including minimum energy performance standards, building codes, and national efficiency strategies such as the PROURE plan (PAI PROURE).

Digital infrastructure plays a key role. For example, the expansion of renewables, storage, and demand response would require real-time data platforms and smart grid systems to balance supply and demand across regions. Similarly, the scale-up of EV infrastructure and flexible charging could be significantly accelerated through digital coordination tools that optimize charging patterns and reduce grid stress. In industry and buildings, digital monitoring systems are key for energy efficiency gains by enabling circularity and providing continuous performance tracking. From an economic perspective, digitalization also strengthens the investment case. It acts as the “information layer” that ensures capital is allocated efficiently, risks are managed proactively, and emissions reductions are measurable. Without such a layer, there is a risk that investments (particularly in energy supply and transport) will not deliver fully.

3.3.1 Emissions

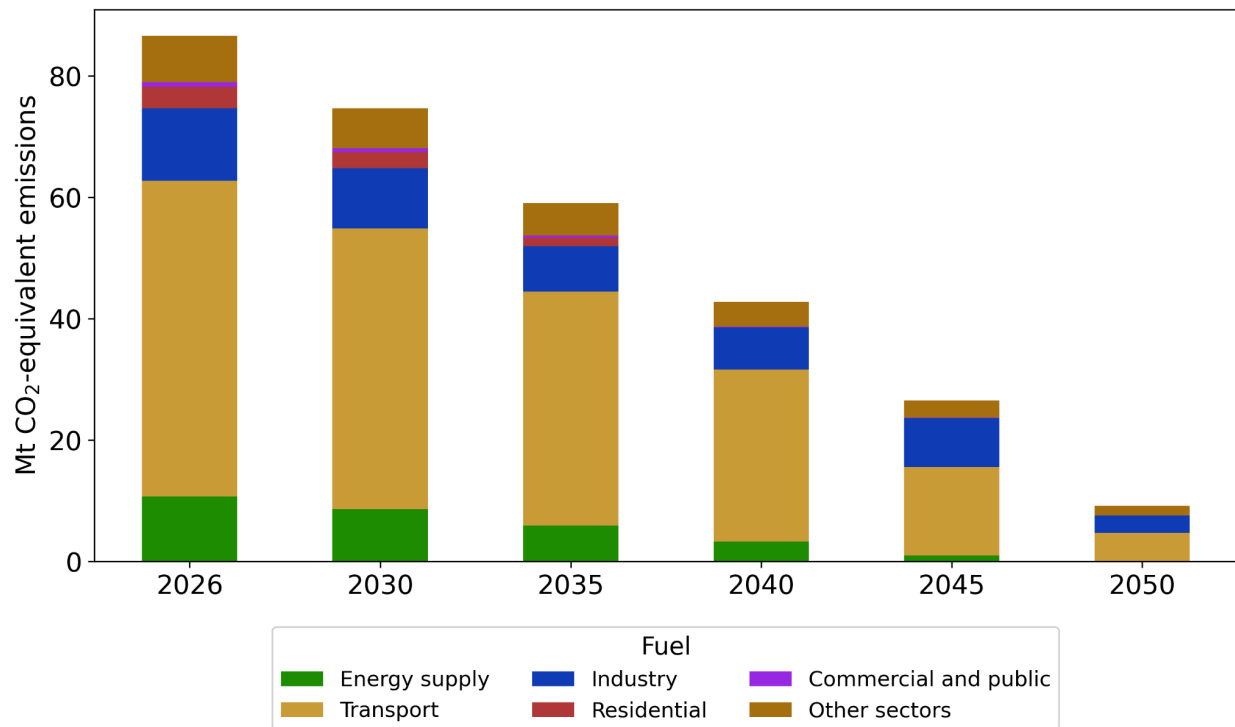


Figure 8: Emissions projections for the 2026-2050 period in Megatonnes (Mt) of equivalent CO₂ by sector in the modelled FFT scenario.

Under the FFT scenario, emissions associated with energy consumption in Colombia decline from 86.6 MtCO₂e in 2026 to 9.2 MtCO₂eq in 2050, a 90% reduction, broadly aligned with the targets set out in Colombia's Long-Term Strategy E2050 (Gobierno de Colombia, 2021). Emissions decrease steadily across all sectors, reaching 74.7 MtCO₂eq in 2030, 59.1 MtCO₂eq in 2035 and 42.8 MtCO₂eq in 2040.

The transition is primarily driven by the deployment of already cost-competitive technologies, particularly renewable energy and electrification of end-use sectors. The electrification of transport plays a central role, reducing emissions in the sector from 52 MtCO₂e in 2026 to 4.7 MtCO₂e in 2050. Alongside this, demand-side measures and the use of hydrogen as a low-carbon fuel in hard-to-electrify industrial processes enable continued growth while emissions decline.

Under this pathway, the residential sector reaches near-zero emissions in 2040 and the commercial and public, and energy sectors in 2050. By mid-decade, emissions are produced primarily in the transport (4.7 MtCO₂e) and industry (2.8 MtCO₂e) sectors. The timing of these reductions is not fixed and could shift depending on policy priorities. For example, accelerated decarbonisation of the power sector over the next decade

could support more rapid emissions reductions, while greater emphasis on end-use sectors could be deferred to the 2035-2050 period, as suggested in comparable national roadmaps (Climate Change Committee, 2025; IEA, 2025).

By 2050, around half of remaining energy-related emissions are projected to come from international aviation (4 MtCO₂e) and shipping (0.75MtCO₂eq), which remain hard to decarbonise. These emissions could be further reduced if Colombia's ambitions to develop the national production of sustainable aviation fuel (SAF) and green hydrogen and ammonia are realised. This scenario does not include engineered carbon dioxide removal technologies, reflecting current uncertainties around the feasibility of their large-scale deployment. However, their future use could further reduce net emissions if they become economically viable.

3.3.2 Energy demand

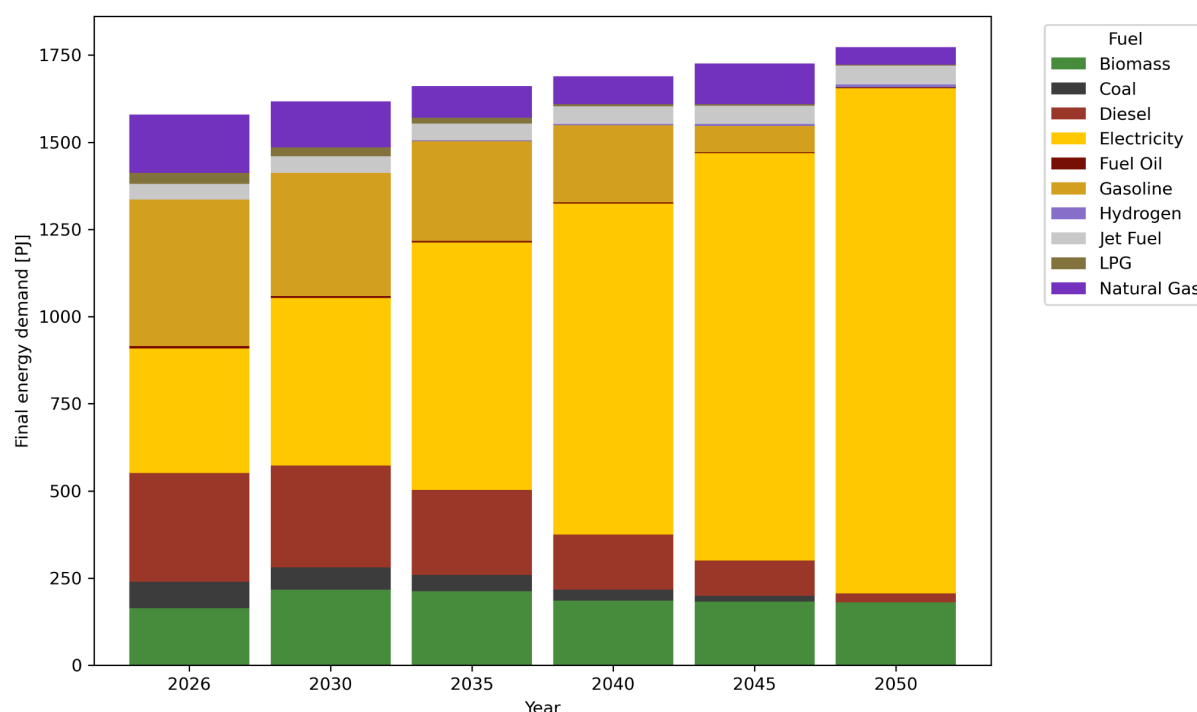


Figure 9: Final energy demand (2020-2050) by fuel carrier in the modelled FFT scenario.

Despite continued population growth and economic expansion, overall energy demand increases only moderately over the next 25 years in the FFT scenario. This reflects substantial efficiency gains associated with electrification, alongside the impact of demand-side management measures. By 2050, total final energy demand is projected to rise by approximately 12% relative to 2026 levels.

Electrification plays a central role in reducing reliance on fossil fuels across end-use sectors. The share of final energy demand met directly by fossil fuels (i.e. excluding fossil fuels used in power generation) declines sharply, from around 66% in 2026 to less than 8% by 2050. The remaining fossil fuel use is largely concentrated in the transport sector, where gasoline, diesel and jet fuel continue to be used in international shipping and aviation. Demand for coal and diesel begins to decline immediately, while the decline for gasoline and natural gas accelerates in the 2040s. In contrast, electricity expands significantly, increasing its share of final energy demand from approximately 22.8% to over 81% by mid-century.

Alternative fuels are progressively deployed in sectors that are more difficult to electrify. Modern biofuels increasingly replace traditional forms of bioenergy, with bioenergy accounting for around 10% of final energy demand in 2050. Traditional biomass use in residential cooking is phased out by 2040. However, sustainable biofuels continue to play an important role in specific applications, including industrial heat, international aviation and shipping, and power generation. Biogas could be explored as a substitute for natural gas, leveraging existing infrastructure and assets. To minimise land-use pressures, liquid biofuel production should transition, at least partially, from crop-based feedstocks to agricultural and forestry residues.

Hydrogen is likely to become an important component of Colombia's decarbonisation pathway. The country has strong potential to produce low-cost green hydrogen, particularly in regions such as La Guajira. If developed strategically, both by promoting the local industrial base and creating governance frameworks for effective multilateral collaboration (Caiafa et al., 2025), hydrogen could create significant economic opportunities at both regional and national levels. In the near term, the development of this sector is expected to be driven primarily by export markets, as domestic demand remains limited to certain hard-to-electrify industrial processes. Over time, hydrogen and its derivatives could also contribute to further emissions reductions in international aviation and shipping, sectors where fossil fuel demand is otherwise expected to persist. In addition, hydrogen production could stimulate the growth of downstream industries, including ammonia production for fertilisers, further supporting economic diversification.

3.3.3 Power sector

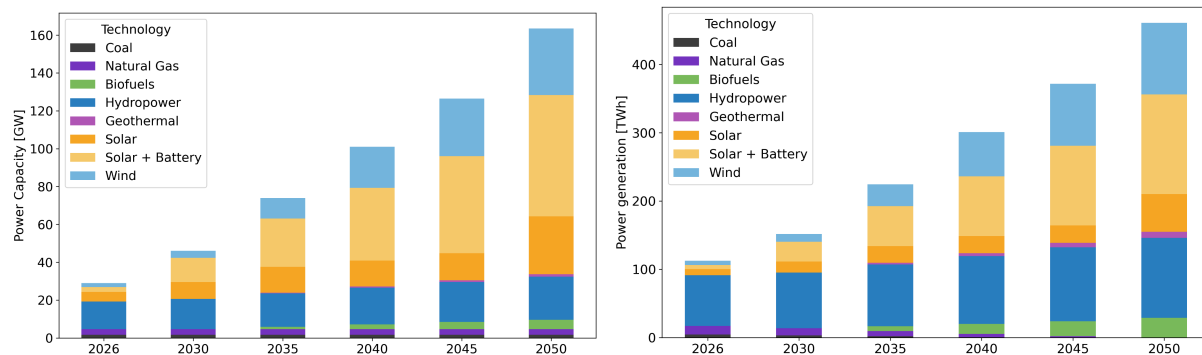


Figure 10: Power capacity (left) and electricity generation (right), broken down by power source in the modelled FFT scenario.

Electricity generation expands substantially to support the electrification of Colombia's economy. By 2050, total generation increases nearly fourfold, reaching approximately 461 TWh, supported by around 163 GW of installed capacity. This corresponds to an average annual growth rate of roughly 6% over the period.

This expansion is driven primarily by the rapid deployment of renewable energy sources, particularly solar and wind, enabling the power sector to decarbonise while meeting rising electricity demand. At the same time, a portfolio of low-carbon, dispatchable generation including hydropower, biomass, and geothermal energy, plays a critical role in maintaining system reliability. In addition, large-scale battery storage, reaching approximately 64 GW by 2050, provides flexibility by shifting electricity supply across time and helping to balance variable renewable output.

Solar power emerges as the single largest source of electricity by mid-century. Installed capacity reaches approximately 94 GW by 2050, generating close to 200 TWh annually. This growth is sustained over the coming decades, with an intermediate milestone of around 39.2 GW and 83 TWh by 2035. Wind energy also expands significantly, reaching 10.8 GW by 2035 and 35.2 GW by 2050, supplying approximately 32.1 TWh and 104.8 TWh, respectively.

The scale-up of renewable generation enables the progressive phase-out of fossil fuel-based power. Coal-fired generation is eliminated by 2045, while natural gas is phased out by 2050. Some residual gas-fired capacity may remain available to support system adequacy during periods of low renewable output, although its utilisation is expected to be minimal.

Given the variability of solar and wind resources, system flexibility becomes increasingly important. Utility-scale battery storage, projected to reach around 64 GW by 2050, plays a central role in ensuring reliability by storing excess generation and redistributing it during periods of peak demand. While modelled in conjunction with solar generation, in practice these storage assets would operate across the system, supporting both solar and wind output.

Ensuring a resilient and reliable electricity system also requires a diversified generation mix. In this scenario, dispatchable low-carbon capacity is expanded through a combination of hydropower, geothermal, and biomass. Hydropower capacity increases by approximately 8 GW by 2050, while geothermal and biofuels contribute around 1 GW and 5 GW, respectively. Biofuel-based generation should operate employing agricultural and forestry residue as much as possible to minimise land-use impacts. Together, these sources provide approximately 155 TWh of dispatchable generation, strengthening system resilience.

By 2050, the electricity mix is projected to comprise approximately 43.6% solar, 25.4% hydropower, 22.8% wind, 6.3% biofuels, and 1.9% geothermal. Other technologies such as nuclear power could also be considered, particularly small nuclear reactors. However, due to ongoing uncertainties regarding their economic viability and deployment timelines, these were not included in our scenario.

Alongside generation capacity, substantial investment in electricity networks is required. Grid infrastructure must expand and modernise to accommodate higher electricity volumes and integrate geographically dispersed renewable resources. This includes upgrades to transmission and distribution systems including overhead lines, underground cables, transformers, and substations. The ability of the grid to support bidirectional power flows will also be important in a system dominated by renewables and batteries, as well as its resilience against climate-related risks. Existing studies suggest that total grid length in a decarbonised Colombia could increase by up to 90% by 2050, with network investments accounting for around 40% of total power sector expenditure (IEA, 2050).

3.3.4 Transport

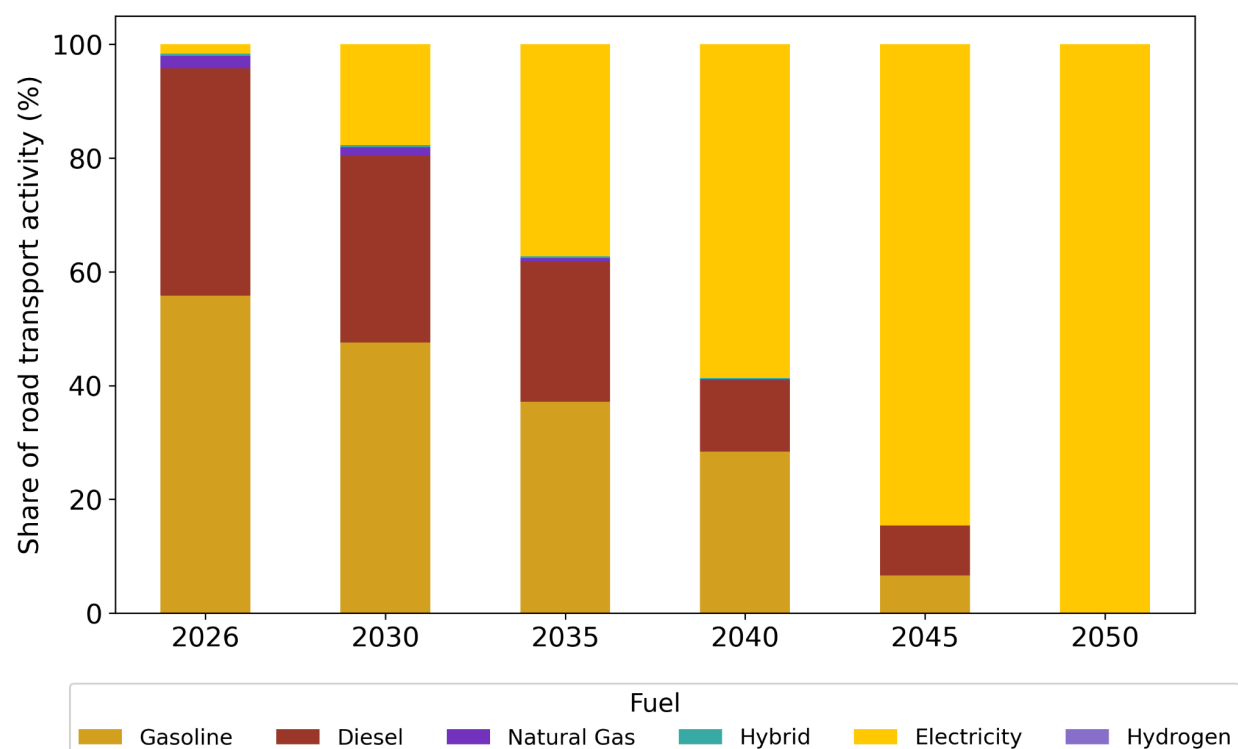


Figure 11: Share of transport sector activity broken down by fuel carrier in the modelled FFT scenario.

The electrification of road transport is the key driver of emissions reduction in the sector, which is currently the largest source of emissions in the Colombian economy. By 2050, the vehicle fleet is projected to be virtually electrified.

The transport sector dominates current energy demand in Colombia, and has the highest potential for energy demand reduction. It is the only sector that reduces the final energy demand in the pathway, falling from 710PJ in 2025 to 356 PJ in 2050 - despite increases in energy service demands across all transport types. This reduction is largely driven by a dramatic increase in final-to-useful efficiency of EVs in comparison to ICEVs.

Colombia has one of the highest rates of two- and three- wheeler ownership in the world, with nearly one in five people owning one. This segment is expected to decarbonise the fastest, with around half vehicles electrified by 2030. Electrification of light- and heavy-duty vehicles progresses more gradually, broadly aligning with the national zero-emissions vehicle target of 600,000 EVs by 2030 (excluding two/three-wheelers), equivalent to around 10% of the fleet. Internal combustion vehicles

are largely phased out during the 2040s, although some residual use may remain for journeys where electrification is more challenging.

This transition is ambitious but achievable. While improving cost-competitiveness of EVs against traditional modes of transport will drive much of the change, targeted government support will be required to accelerate uptake. Measures to increase fleet renewal such as incentives for early vehicle replacement could be particularly effective given the relatively old vehicle stock in Colombia.

The expansion of charging infrastructure and grid capacity will be critical to enable this transition. An estimated 8,000 new charging points per year will be needed, broadly comparable to recent deployment rates in Sweden (IEA, 2025). This expansion will support the uptake of EVs beyond major urban centres, where most EVs are currently concentrated (Fenaclo 2025). Delivering this infrastructure at the required scale and pace will require timely planning and development, as well as close coordination between the public and private sectors.

By 2050, demand for aviation and shipping is projected to grow by 42% and 50%, respectively. These sectors remain heavily reliant on fossil fuels by mid-century due to limited availability of low-carbon alternatives. As a result, they constitute most of the remaining transport emissions by 2050 and a significant fraction of economy-wide emissions. However, Colombia's plans to scale up hydrogen and SAF production (stated ambitions include 380 million litres of SAF by 2035 and 1.7 billion litres by 2050) could significantly reduce these emissions while simultaneously placing the country as a significant exporter of low-carbon fuels.

3.3.5 Industry

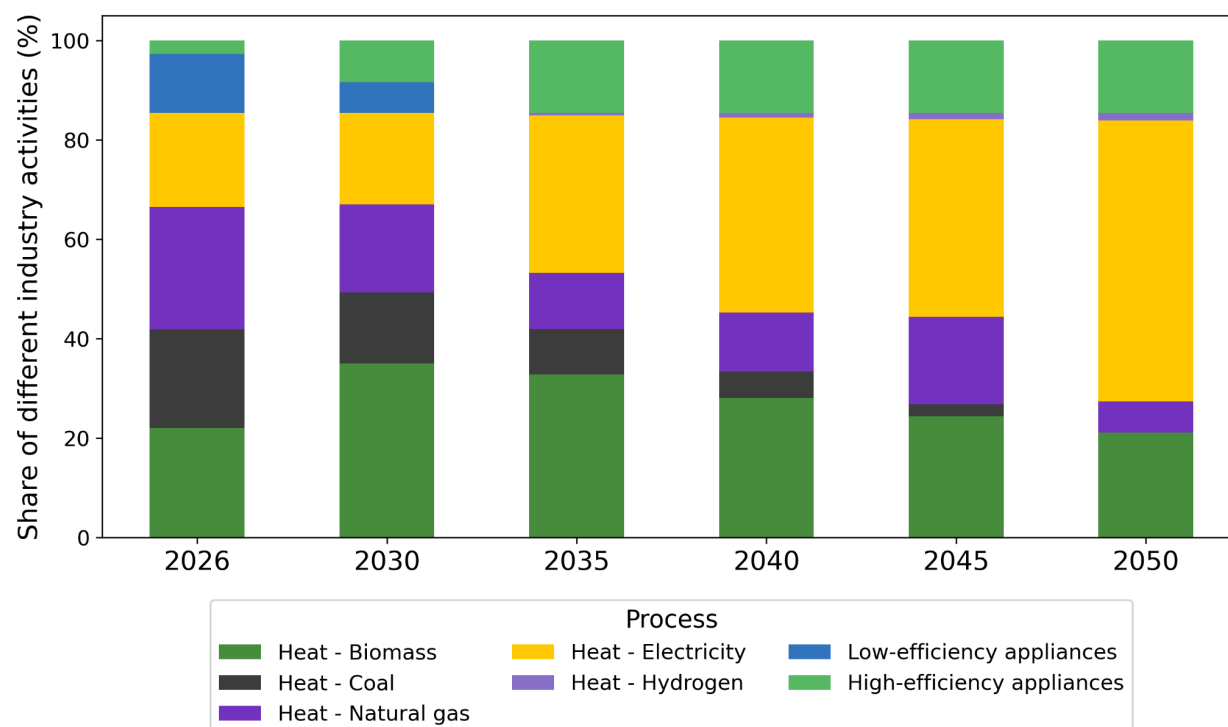


Figure 12: Share of total industry energy used by different processes broken down by type and carrier in the modelled FFT scenario.

The diversity of processes and technologies involved in the industrial sector makes its decarbonisation particularly complex. Different industries are likely to transition at different speeds, depending on their energy intensity and technological alternatives.

At the same time, industrial energy demand is projected to increase substantially, from 341 PJ in 2025 to 629 PJ by mid-century. This growth is partially offset by improvements in energy and material efficiency, including increased recycling and better product design.

In the near term, progress is gradual due to technological constraints. Coal use declines steadily to 2050, replaced in part by biomass, which expands from their traditional use in light industries to more energy-intensive applications. Efficiency improvements also begin to take effect.

After 2030, electrification accelerates, particularly for low- and medium-temperature processes, as technologies such as electric boilers and heat pumps become economically viable. Heat pumps, in particular, are expected to reach cost parity on a levelised basis with conventional boilers around 2030 (IEA, 2025).

Certain processes within energy-intensive industries such as steel and cement production may remain difficult to electrify until the 2040s. As a result, coal and particularly natural gas remain a substantial share of the industrial energy mix for the next two decades to allow for this possibility. To address this, low-carbon hydrogen begins to play a role from the mid-2030s, supporting emissions reductions in these hard-to-abate sectors. Combined with further electrification, this drives a significant acceleration in Colombia’s industrial decarbonisation during the 2040s.

By 2050, emissions from the industrial sector are projected to reach 2.8 MtCO₂e, a 76% reduction from 2026. Most processes are electrified or powered by low-carbon energy sources such as hydrogen or other synthetic fuels made from renewable energy or biomass. Coal is phased-out by 2050.

Achieving this transition will require strong policy support, including financial incentives and targeted support for emerging technologies. At the same time, investment in supply chains and workforce skills will be essential to enable widespread deployment.

3.3.6 Buildings

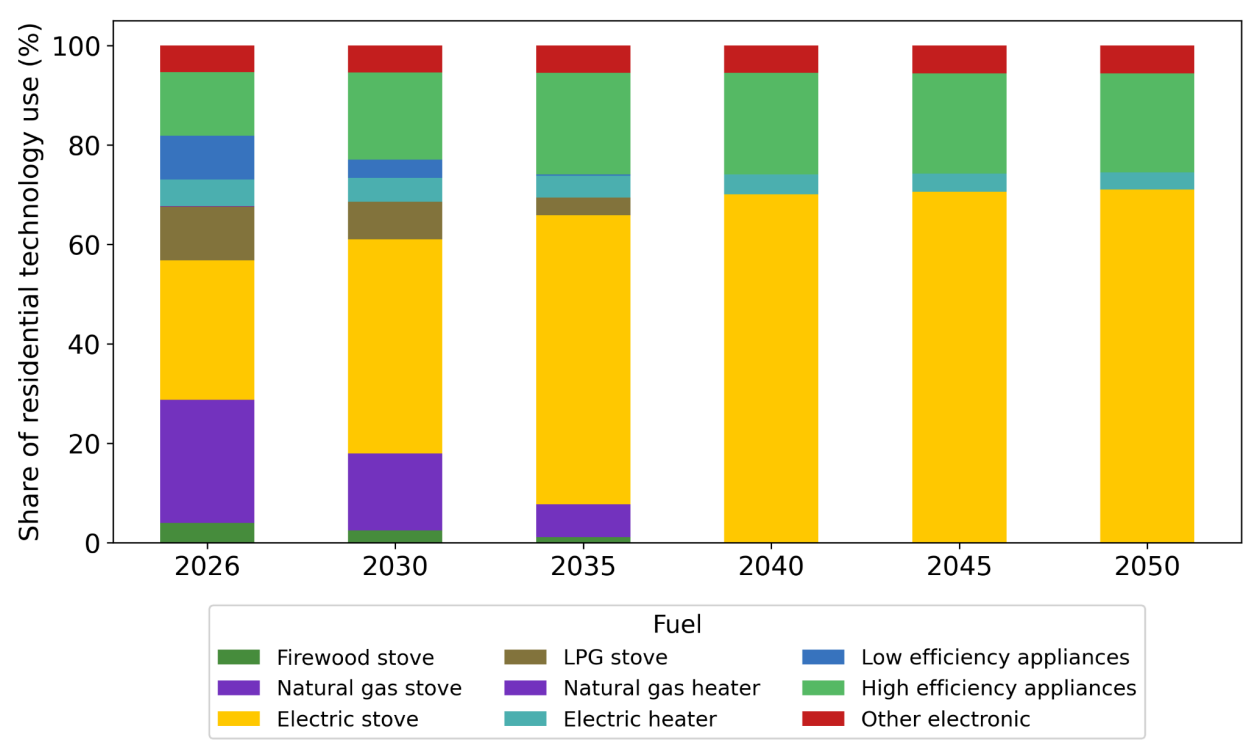


Figure 13: Share of total residential building energy used broken down by type and carrier in the modelled FFT scenario.

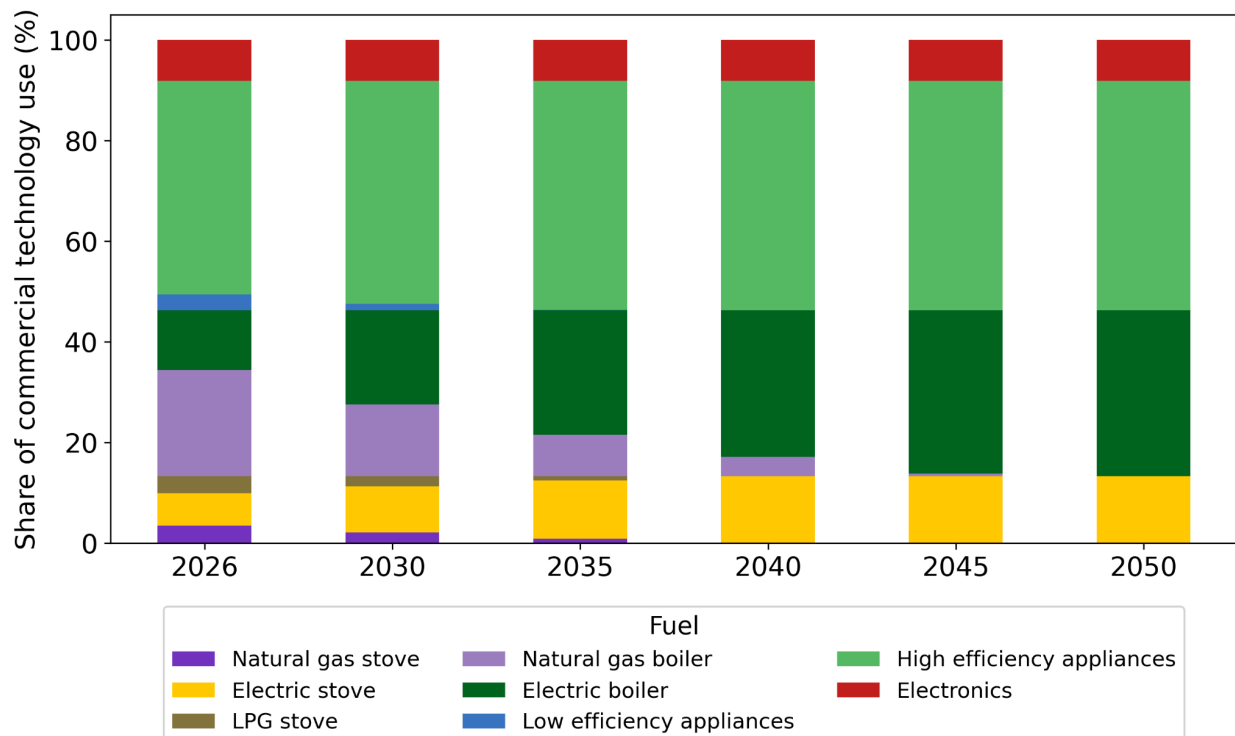


Figure 14: Share of total commercial building energy used broken down by type and carrier in the modelled FFT scenario.

Energy demand in buildings is projected to increase, with residential and commercial demand rising at different rates. Residential demand remains broadly stable, with a 3% increase by 2050 relative to the 2025 baseline (from 242 PJ to 250 PJ), while commercial demand rises significantly with a 95% growth by 2050 (from 82PJ to 160 PJ). This disparity reflects the comparatively higher efficiency already achieved in the commercial sector and the demand management measures introduced in the residential sector (e.g. higher energy intensity in buildings, behavioural changes).

Electrification is the main driver of emissions reductions in this sector, complemented by stronger energy efficiency standards. The widespread adoption of electric cooking technologies places a central role, replacing natural gas, LPG, and traditional biomass. This transition also enables universal access to clean cooking by 2040, in line with national and international development goals (UN Sustainable Development Goal 7, Colombia's "Plan Nacional de Sustitución de Leña" (UPME, 2025b)) and delivering significant health and social benefits. This shift in cooking practices is particularly pronounced in the residential sector, mitigating the leading source of emissions from households.

The second largest source of energy demand in the buildings sector is space heating and cooling. As with cooking, electric heaters and boilers progressively replace natural

gas systems across both residential and commercial buildings. On the cooling side, strengthening efficiency standards will be essential to ensure AC efficiency rates track those of comparable countries, as current levels lag behind similar economies such as Brazil and India. This will help moderate the expected growth in cooling energy demands, which are projected to increase significantly due to rising incomes and higher temperatures associated with climate change.

More broadly, a sector-wide shift towards high-efficiency appliances will be critical to limit overall energy demand. While these technologies often involve higher upfront costs, they typically deliver lower lifetime costs. High-efficiency standards are already implemented in new buildings through Colombia's National Roadmap for Net Zero Carbon Buildings (CCCS, 2021). However, uptake in existing buildings remains more challenging, particularly in the residential sector where efficiency levels are substantially lower than in commercial buildings. To address this, a range of policy measures including subsidies, early scrappage schemes, and low interest financing will be needed to support adoption, particularly among lower-income households. Combined with minimum energy standards, these measures can accelerate the transition while delivering net cost savings for consumers over time, especially given Colombia's relatively high electricity prices.

Table 1. Sector targets to guide decarbonisation planning aligned with the modelled FFT scenario.

Target	2030	2040	2050
Power sector			
Share of electricity generated from renewables	90%	98%	100%
Electricity generated from solar, wind and geothermal	37%	60%	68%
Removal of coal from power sector	2045		
Removal of natural gas from power sector	2050		
Growth in the power generation to cover electrification (relative to 2026)	35%	167%	309%

Transport			
Electrification of road fleet	18%	59%	100%
Electrification of public transport fleet	13%	49%	100%
Industry			
Share of heat demand from low-carbon sources	63%	80%	93%
[excluding biomass]	22%	47%	68%
Share of heat demand from hydrogen	0%	1%	1.8%
Buildings			
Phaseout of wood as heat source	2040		
Phaseout of natural gas	2045		
Share of electrification of end uses in housing	75%	100%	100%
Share of electrification of end uses in commercial & public sector	82%	96%	100%

4. Advancing international cooperation and multilateralism

COP30 showed both that multilateralism is functioning still, but that the UNFCCC process, which hinges on consensus, is also suffering from a lack of international cooperation. The declarations made in Belém on both fossil fuels and nature can be framed as a novel approach to preserve multilateral cooperation without the need for unanimous agreement between all parties.

It is important to integrate TAFF into existing multilateral processes so that it can effectively support UNFCCC. This would also help to give it a structure and formality so its ambition survives beyond that of many past COP initiatives. The Global Methane Pledge stands out as a model of what effective cooperation can achieve, as the countries involved in the pledge have used existing multilateral organizations such as the Climate and Clean Air Coalition (CACC) to progress actions.

The current co-chairing of the CACC by Brazil and the UK presents an opportunity to increase national regulatory frameworks around commitment to reduce methane emissions resulting from fossil fuel production. Trade deals, regulation and potentially Methane Border Adjustment Mechanisms (MBAMs) could be used to reduce the spread of some of the worst fossil fuels in terms of emission intensity and air quality impact. Care is needed so that such mechanisms are inclusive, so they can raise global ambition rather than fragment it.

At the same time, the transition cannot succeed if it ignores the realities facing fossil fuel-dependent economies. Countries such as Nigeria and Guyana illustrate a fundamental tension: those most reliant on fossil fuel revenues are often among the most exposed to climate impacts. The lesson for the international community is straightforward, calls for transition must be matched with finance, technology transfer, and economic diversification strategies. Without this, global agreements will lack both fairness and durability.

Non-state actors are already shaping the transition, but their role must be sharpened and aligned with public goals. Businesses within Colombia can take advantage of opportunities around the transition but they will require supportive policies. They will also need support from financial institutions such as development banks to accelerate change through investment, innovation, and supply chain transformation. Clear standards, regulation, and accountability are needed to ensure that private sector activity delivers real emissions reductions at scale.

International cooperation must also deliver in practical terms. Technology sharing, reformed trade frameworks, and expanded Just Energy Transition Partnerships (JETPs) are critical to enabling developing countries to move beyond fossil fuels without sacrificing development. These mechanisms must be scaled rapidly and designed to reduce risk, unlock investment, and build long-term capacity.

Stronger governance is essential to close the gap between promises and outcomes. Independent climate councils are already giving advice around NDCs and their implementation (ICCN, 2025). They can help anchor decision-making in evidence, hold governments accountable, and provide continuity across political cycles. Scaling up these institutions, nationally and through international coordination, would significantly strengthen credibility and delivery.

We recommend that an international structure with a multi-layered governance framework is created to deliver evidence-based roadmaps to support national implementation. This process could co-create national roadmaps with support from the International Climate Council Network and national climate councils, working with a range of policy makers to make sure that roadmaps were both relevant and country-specific enough to be implementable and accepted within existing national policy frameworks. Yet, the roadmaps could share elements of common design and framing as well as access to the latest evidence on climate science and the energy transition.

References

- Achakulwisut, P., Erickson, P., Guivarch, C., Schaeffer, R., Brutschin, E. and Pye, S. 2023. Global fossil fuel reduction pathways under different climate mitigation strategies and ambitions. *Nature Communications*. **14**(1), p.5425.
- Arond, E., Vega-Araújo, J., Peña-Niño, J. and Patzy, F. 2024. Just transitions from coal in Colombia: between policy and reality. *SEI Working Paper*. Stockholm Environment Institute.
- CCC 2025. *Progress in reducing emissions - 2025 report to Parliament* [Online]. [Accessed 31 March 2026]. Available from: <https://www.theccc.org.uk/publication/progress-in-reducing-emissions-2025-report-to-parliament/>.
- CCC 2026. *Supplementary analysis of the Seventh Carbon Budget* [Online]. [Accessed 8 April 2026]. Available from: <https://www.theccc.org.uk/publication/supplementary-analysis-of-the-seventh-carbon-budget/>.
- Climate Change Committee 2025. *The Seventh Carbon Budget* [Online]. [Accessed 24 February 2026]. Available from: <https://www.theccc.org.uk/publication/the-seventh-carbon-budget/>.
- de Coninck, H., Revi, A., Babiker, P., Bertoldi, P., Buckeridge, M., Cartwright, A., Dong, W., Ford, J., Fuss, S., Hourcade, J.-C., Ley, D., Mechler, R., Newman, P., Revokatova, A., Schultz, S., Steg, L. and Sugiyama, T. 2018. Strengthening and Implementing the Global Response. In: V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor and T. Waterfield, eds. *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Online]. Cambridge, UK and New York, NY, USA: Cambridge University Press. Available from: <https://doi.org/10.1017/9781009157940.006>.
- DANE 2025. Producto Interno Bruto (PIB) nacional trimestral. [Accessed 24 February 2026]. Available from: <https://www.dane.gov.co/index.php/estadisticas-por-tema/cuentas-nacionales/cuentas-nacionales-trimestrales/pib-informacion-tecnica>.
- Esquivel García, C.L. and Toro-García, G.L. 2024. Multidimensional energy poverty in Colombia: A department-level review from 2018 to 2022. *Heliyon*. **10**(14), p.e34395.

- Forster, P.M., Smith, C., Walsh, T., Lamb, W.F., Lamboll, R., Cassou, C., Hauser, M., Hausfather, Z., Lee, J.-Y., Palmer, M.D., von Schuckmann, K., Slangen, A.B.A., Szopa, S., Trewin, B., Yun, J., Gillett, N.P., Jenkins, S., Matthews, H.D., Raghavan, K., Ribes, A., Rogelj, J., Rosen, D., Zhang, X., Allen, M., Aleluia Reis, L., Andrew, R.M., Betts, R.A., Borger, A., Broersma, J.A., Burgess, S.N., Cheng, L., Friedlingstein, P., Domingues, C.M., Gambarini, M., Gasser, T., Gütschow, J., Ishii, M., Kadow, C., Kennedy, J., Killick, R.E., Krummel, P.B., Liné, A., Monselesan, D.P., Morice, C., Mühle, J., Naik, V., Peters, G.P., Pirani, A., Pongratz, J., Minx, J.C., Rigby, M., Rohde, R., Savita, A., Seneviratne, S.I., Thorne, P., Wells, C., Western, L.M., van der Werf, G.R., Wijffels, S.E., Masson-Delmotte, V. and Zhai, P. 2025. Indicators of Global Climate Change 2024: annual update of key indicators of the state of the climate system and human influence. *Earth System Science Data*. **17**(6), pp.2641–2680.
- Garces, E., Franco, C.J., Tomei, J. and Dyner, I. 2023. Sustainable electricity supply for small off-grid communities in Colombia: A system dynamics approach. *Energy Policy*. **172**, p.113314.
- Gobierno de Colombia 2021. *Estrategia climática de largo plazo de Colombia E2050 para cumplir con el Acuerdo de París* [Online]. [Accessed 4 February 2026]. Available from: <https://unfccc.int/documents/311208>.
- Godin, A., Yilmaz, D., Andrade, J., Barbosa, S., Guevara, D., Hernandez, G. and Rojas, L. 2023. Can Colombia cope with a Global Low Carbon transition? *AFD Research Papers*. (285), pp.1–60.
- Godinho, C., De Vivero, G. and de Grandpré, J. 2024. *A just transition in Colombia*. New Climate Institute.
- Gohar, L., Mathison, C., Sanderson, B., Sandstad, M., Smith, C., Walsh, T., Gillett, N., Ribes, A., Kikstra, J., Nicholls, Z., Thiery, W., Schleussner, C.-F. and Rogelj, J. 2026. Updated scenarios show 1.5°C overshoot is unavoidable but limitable.
- Gutierrez, M.B., Araújo, J.V. and Arond, E. 2024. A strategic phase-out of Colombia's diesel subsidy to support the energy transition.
- ICCN 2025. From ambition to implementation: climate councils propel progress. [Accessed 31 March 2026]. Available from: <https://www.climatecouncils.org/iccn-work/from-ambition-to-implementation-climate-councils-propel-progress/>.
- IEA 2025a. *An Energy Sector Roadmap to Net Zero Emissions in Colombia* [Online]. [Accessed 5 February 2026]. Available from: <https://www.iea.org/reports/an-energy-sector-roadmap-to-net-zero-emissions-in-colombia>.
- IEA 2021a. *Climate Resilience* [Online]. [Accessed 23 February 2026]. Available from: <https://www.iea.org/reports/climate-resilience>.

- IEA 2022. *Coal in Net Zero Transitions: Strategies for Rapid, Secure and People-centred Change* [Online]. OECD. [Accessed 24 February 2026]. Available from: https://www.oecd.org/en/publications/coal-in-net-zero-transitions_5873f7bb-en.html.
- IEA 2026. Colombia - Countries & Regions. *IEA*. [Online]. [Accessed 13 April 2026]. Available from: <https://www.iea.org/countries/colombia/energy-mix>.
- IEA 2021b. *Enhancing cyber resilience in electricity systems* [Online]. [Accessed 23 February 2026]. Available from: <https://www.iea.org/reports/enhancing-cyber-resilience-in-electricity-systems>.
- IEA 2023. *Managing Seasonal and Interannual Variability of Renewables* [Online]. [Accessed 23 February 2026]. Available from: <https://www.iea.org/reports/managing-the-seasonal-variability-of-electricity-demand-and-supply>.
- IEA 2024a. *Managing the Seasonal Variability of Electricity Demand and Supply* [Online]. [Accessed 23 February 2026]. Available from: <https://www.iea.org/reports/managing-the-seasonal-variability-of-electricity-demand-and-supply>.
- IEA 2024b. *World Energy Outlook 2024* [Online]. Paris: IEA. [Accessed 31 March 2026]. Available from: <https://www.iea.org/reports/world-energy-outlook-2024>.
- IEA 2025b. *World Energy Outlook 2025* [Online]. Paris: IEA. [Accessed 31 March 2026]. Available from: <https://www.iea.org/reports/world-energy-outlook-2025>.
- IPCC (ed.). 2022. Summary for Policymakers *In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, NY, USA: Cambridge University Press, pp.1–48.
- Kazlou, T., Cherp, A. and Jewell, J. 2024. Feasible deployment of carbon capture and storage and the requirements of climate targets. *Nature Climate Change*. **14**(10), pp.1047–1055.
- Lora, E. and Mejía, L.F. 2021. Reformas para una Colombia post-COVID-19. Hacia un nuevo contrato social.
- MME 2024. Análisis de inversiones requeridas para la Transición Energética Justa.
- MME 2022. *Colombia's offshore wind roadmap - Executive summary*.
- Moreno, A., Guevara, D., Andrade, J., Pierros, C., Godin, A., Yilmaz, S.D. and Valdecantos, S. 2024. Low-Carbon Transition and Macroeconomic Vulnerabilities: A Multidimensional Approach in Tracing Vulnerabilities and Its

- Application in the Case of Colombia. *International Journal of Political Economy*. **53**(1), pp.43–66.
- Ochoa, A., Rivera, J.J. and Cantor, D. 2025. El Niño and La Niña signatures on daily inflows to colombian hydropower reservoirs. *International Journal of Energy and Water Resources*. **9**(4), pp.2743–2753.
- Pelz, S., Ganti, G., Lamboll, R., Grant, L., Smith, C., Pachauri, S., Rogelj, J., Riahi, K., Thiery, W. and Gidden, M.J. 2025. Using net-zero carbon debt to track climate overshoot responsibility. *Proceedings of the National Academy of Sciences*. **122**(13), p.e2409316122.
- Pelz, S., Ganti, G., Pachauri, S., Rogelj, J. and Riahi, K. 2025. Entry points for assessing ‘fair shares’ in national mitigation contributions. *Environmental Research Letters*. **20**(2), p.024012.
- Presidencia de la República 2025. Colombia definió hoja de ruta para producir combustible sostenible de aviación SAF. *Presidencia de la República*. [Online]. [Accessed 23 February 2026]. Available from: <https://www.presidencia.gov.co/prensa/Paginas/Colombia-definio-hoja-de-ruta-para-producir-combustible-sostenible-de-aviacion-SAF-250122.aspx>.
- Probst, B.S., Toetzke, M., Kontoleon, A., Díaz Anadón, L., Minx, J.C., Haya, B.K., Schneider, L., Trotter, P.A., West, T.A.P., Gill-Wiehl, A. and Hoffmann, V.H. 2024. Systematic assessment of the achieved emission reductions of carbon crediting projects. *Nature Communications*. **15**(1), p.9562.
- Riahi, K., Schaeffer, R., Arango, J., Calvin, K., Guivarch, C., Hasegawa, T., Jiang, K., Kriegler, E., Matthews, R., Peters, G.P., Rao, A., Robertson, S., Sebbit, A.M., Steinberger, J., Tavoni, M. and van Vuuren, D.P. 2022. Mitigation pathways compatible with long-term goals *In*: P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz and J. Malley, eds. *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, NY, USA: Cambridge University Press, pp.295–408.
- Rogelj, J. and Rajamani, L. 2025. The pursuit of 1.5°C endures as a legal and ethical imperative in a changing world. *Science*. **389**(6757), pp.238–240.
- Schönfeld, J.K. and Rogelj, J. 2025. A framework to assess highest possible ambition in nationally determined contributions under Article 4 of the Paris Agreement. *Environmental Research Letters*. **20**(11), p.114081.
- Smith, C., Walsh, T., Gillett, N., Hauser, M., Krummel, P., Lamb, W., Lamboll, R., Mühle, J., Palmer, M., Ribes, A., Schumacher, D., Seneviratne, S., Slangen, A., Trewin, B., von Schuckmann, K. and Forster, P. 2025. Indicators of Global Climate

- Change 2024. [Accessed 13 April 2026]. Available from: <https://zenodo.org/records/15744430>.
- Suárez, W., Parra Rodas, J.F., Vásquez, M.P. and Valencia, V. 2025. *Unlocking the energy transition in Colombia: Strategies to reduce gas dependency*. Ember.
- UNEP, U.N. 2025. Emissions Gap Report 2025: Off target - Continued collective inaction puts global temperature goal at risk. [Accessed 31 March 2026]. Available from: <https://www.unep.org/resources/emissions-gap-report-2025>.
- UNFCCC 2025. *Nationally determined contributions under the Paris Agreement. Synthesis report by the secretariat*. [Online]. [Accessed 8 April 2026]. Available from: <https://unfccc.int/documents/650664>.
- UPME 2024. *Balance Energético Colombiano* [Online]. [Accessed 13 April 2026]. Available from: <https://www.upme.gov.co/simec/planeacion-energetica/balance-minero-energetico-colombiano/>.
- UPME 2025a. *Plan indicativo de abastecimiento de combustibles líquidos 2025-2040* [Online]. Colombia. Available from: https://docs.upme.gov.co/SIMEC/Hidrocarburos/Publicaciones_SIPG/PIACL_2025-2040_VF_20032026.pdf.
- UPME 2025b. *Plan Nacional de Sustitución de Leña* [Online]. [Accessed 8 April 2026]. Available from: https://docs.upme.gov.co/SIMEC/Hidrocarburos/Publicaciones_SIPG/Hacia_la_implementacion_del_PNSL_y_otros_CIAC_para_la_coccion_domestica_de_alimentos_VF.pdf.
- UPME 2025c. *Resiliencia energética: Acciones para la entrada en operación de proyectos de generación FNCER*.
- Vega-Araújo, J., Peña Niño, J., Arond, E. and Patzy, F. 2023. Navigating a just energy transition from coal in the Colombian Caribbean. *SEI Working Paper*. Stockholm Environment Institute.
- WHO 2025. Household air pollution. [Accessed 31 March 2026]. Available from: <https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health>. Available from: <https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health>.

Appendix

A1 - The OSeMOSYS energy system model

A1.1 - Description of energy system model

This modelling exercise utilised the Open Source Energy Modelling System (OSeMOSYS) framework. The OSeMOSYS framework is designed to be simple and accessible - designed to support energy system transition planning at the national level. The Colombian version of the OSeMOSYS model was developed by Plazas-Niño et al. (2023a).

OSeMOSYS is a bottom-up linear programming cost-optimisation model³. The model solves for the least-cost evolution of the energy system given a series of assumptions, namely energy service demand projections, techno-economic data (operational and capital costs, efficiencies, operational lifetimes, capacity factors and energy potentials), an effective carbon tax and an emissions constraint.

The model has four main components: primary energy sources, transformation processes, transport and distribution and end uses. Primary energy sources are broken down into renewable sources (solar, wind, hydropower and geothermal), nuclear resources (uranium), fossil fuels (coal, natural gas, crude oil), imports of secondary fuels (LPG, gasoline, diesel etc.) and biomass. Transformation processes are broken down into power generation (centralised and decentralised), fossil fuel processing (regasification, refinery), hydrogen production (SMR, electrolysis) and biofuel production and blending. The transport and distribution network represents the transport and distribution of natural gas, coal, LPG, hydrogen, biofuels, as well as power transmission and distribution network (including charging stations for electric vehicles).

Four end use sectors are represented in detail - transport, industry, residential and commercial and public sector. The end use sectors represent various end use energy services, which can be met by a variety of technologies. The transport sector has a detailed representation of various modes of private (private cars, light duty vehicles, four wheel drive motorcycles) and public transportation (taxis, buses, microbuses, rail). Shipping and freight are also included. Industrial energy demands include direct heat and indirect heat (both available with direct CCS) as well as electricity demand. Residential and commercial building energy demands include cooking, refrigeration, water and space heating/cooling and electrical appliances. There is an additional sector

³ Full documentation of the OSeMOSYS modelling framework can be found here: <https://osemosys.readthedocs.io/en/latest/>

for other demands that cannot be otherwise classified. In total, the Colombian energy system is represented by 169 technologies and 77 commodities.

A1.2 - Scenario overview

Two pathways were developed for this report, which explored detailed energy system scenarios for the Colombian context:

- **A business-as-usual (BAU) scenario** was implemented using data from Plazas-Niño et al. (2023a). This scenario explores a least-cost trajectory for the energy system without an emissions constraint, whereby supply meets increasing energy demands with limited deployment of novel, low carbon technologies and a continuation of historical trends for energy carriers.
- **A fossil fuel transition (FFT) scenario**, premised upon demand reduction, rapid electrification and the deployment of renewable energy, is also implemented. An emissions target of 10 MtCO₂eq in 2050 is solved for, achieved via linear annual reductions from the base year. CCS is excluded from this pathway due to concerns regarding the rapid deployment of the suite of carbon capture technologies (Kazlou et al., 2024), geological storage capacity (Gidden et al., 2025) and mitigation deterrence (McLaren, 2020; Grant et al., 2021; Carton et al., 2023).

Techno-economic cost data is taken from an open source energy dataset specific to Colombia Plazas-Niño et al. (2023b) and remains unchanged for both scenarios, with the exception of vehicle capex numbers (see Table A1.3 for details).

A1.3 - Demand reduction

Energy service demand projections are presented in Table A1.1. The FFT scenario introduces energy service demand reductions across each end use sector (relative to the BAU scenario). Further reductions in final energy demand are also achieved as a result of final-to-useful efficiencies are determined endogenously in OSeMOSYS through technology choice. Reductions in activity levels for transport and housing are taken from Grubler et al. (2018), whilst activity level reductions are taken from the useful energy projections for Colombia's NDC (Gobierno de Colombia, 2020).

Demand for energy services are still expected to rise across Colombia as the country's GDP per capita increases. However, there are still opportunities to limit the proliferation of energy service demands in fast-developing Global South countries, such as Colombia. Table A.2 gives an overview of sufficiency-based energy demand reduction measures, which are assumed to be implemented in our FFT scenario, aimed at reducing overall activity levels.

In Colombia, the transport sector has the greatest potential for energy demand reduction - making up 42% of current total final energy demand. Currently, the transport sector is dominated by gasoline and diesel consumption, with road transport making up the majority (91%) of the sector's demand.

The full OSeMOSYS model and the Colombian scenarios can be found here⁴.

⁴ https://github.com/alejandrromeroprieto/colombia-ff-phase-out/tree/main/new_input_files

Table A1.1 - Energy service demand projects by scenario

			BAU						FFT					
Sector	Activity	Unit	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
Industry	Direct heat	PJ	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.21	1.42	1.62	1.83	2.04
	Indirect heat	PJ	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.21	1.42	1.62	1.83	2.04
	Industry electricity	PJ	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.21	1.42	1.62	1.83	2.04
Residential	Cooking demand	PJ	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.21	1.42	1.63	1.84	2.05
	Refrigeration demand	PJ	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.21	1.42	1.63	1.84	2.05
	Lightening demand	PJ	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.21	1.42	1.63	1.84	2.05
	Air conditioning demand	PJ	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.04	1.08	1.13	1.17	1.21
	Water heating demand	PJ	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.04	1.08	1.13	1.17	1.21
	TV demand	PJ	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.21	1.42	1.63	1.84	2.05
	Washer demand	PJ	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.21	1.42	1.63	1.84	2.05
	Fan demand	PJ	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.04	1.08	1.13	1.17	1.21

	Other electronics demand	PJ	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.21	1.42	1.63	1.84	2.05
	NIZ demand	PJ	1.00	1.70	1.99	2.33	2.73	3.19	1.00	1.08	1.17	1.25	1.33	1.42
Transport	Light duty vehicle	Gpk m	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.48	1.96	2.45	2.93	3.41
	Four wheel drive	Gpk m	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.48	1.96	2.45	2.93	3.41
	Motorcycle	Gpk m	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.37	1.74	2.11	2.47	2.84
	Taxi	Gpk m	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.13	1.26	1.39	1.52	1.65
	Microbus	Gpk m	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.10	1.19	1.29	1.39	1.49
	Bus	Gpk m	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.04	1.08	1.12	1.16	1.20
	Truck freight	Gtkm	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.13	1.26	1.39	1.52	1.65
	Semi-trailer truck freight	Gtkm	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.13	1.26	1.39	1.52	1.65
	Air transport	Gpk m	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.04	1.08	1.12	1.16	1.19
	Maritime transport	Gtkm	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.13	1.26	1.39	1.52	1.65
	Railroad transport	Gpk m	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.20	1.41	1.61	1.82	2.02

CPS	Cooking demand	PJ	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.24	1.49	1.73	1.97	2.21
	Indirect heat demand	PJ	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.24	1.49	1.73	1.97	2.21
	Air conditioning demand	PJ	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.24	1.49	1.73	1.97	2.21
	Refrigeration demand	PJ	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.24	1.49	1.73	1.97	2.21
	Lightening demand	PJ	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.24	1.49	1.73	1.97	2.21
	Electronics demand	PJ	1.00	1.17	1.37	1.60	1.88	2.20	1.00	1.24	1.49	1.73	1.97	2.21

Table A1.2 - Sufficiency-based energy demand reduction measures in the Colombian context.

Sector	Measures
Transport	Smaller, lightweight vehicle use (including two/three wheelers, micromobility) Increased teleworking Active travel High-speed rail Integrated urban public transport systems
Industry	Lightweighting Shared economy (car clubs, library of things) Repair and refurbishment Product longevity Increased recycling rates
Buildings	Lower per-capita floor space Re-use of existing structures to displace new construction Extending building lifetimes Adapting thermal comfort (increased acceptable range of temperatures) Better natural ventilation to reduce AC use Shared services and appliances (e.g. communal laundry)
Cross-sectoral	Compact urban design (limiting travel requirements, increases floor space per capita) Less materially intensive construction Limiting urban sprawl Fewer cars

The BAU scenario assumes a uniform increase across all energy services. For the FTT scenario, firstly, we assume an across-the-board reduction of 25% in road transport activity levels relative to the BAU - in line with Grubler et al. (2018) assumptions for the Global South. However, Colombia already has quite a high share of road transport activity that is provisioned for by public transport (predominantly buses) - approximately 77% according to Plazas-Niño et al. (2023a). Thus, we assume that as Colombia develops, there is a constrained, but persistent increase in private vehicle ownership and use. Therefore, we assume that 25% of the growth in bus travel (both microbus and regular buses) is absorbed by two-wheel vehicles (5%) and passenger cars (20%). Furthermore, for similar reasons, we assume that 20% of the growth in two-wheel vehicle activity is absorbed by passenger cars. This actually leads to an increase in passenger car activity levels of 241% relative to 2025, which is much higher than the 120% increase observed in the BAU.

Finally, we assume that much of the growth in domestic aviation can be offset by the implementation of a high speed, intercity rail and public transit system. As such, 20% of the growth in aviation is absorbed by rail (15%) and bus (5%).

A1.4 - Techno-economic assumptions

Table A1.3 presents an overview of the energy system technology assumptions made in the FTT scenario. Accounting for these parameters, the model achieves the given emissions target adopting the least-cost pathway. All other technology assumptions were adopted from the ADPS scenario from Plazas-Niño et al. (2023a).

Table A1.3 - Technology parameters in the FTT scenario

Parameter	Description				
End-use technologies					
Sector	Description				
Buildings	Natural gas boilers are phased out by 2045				
	Natural gas stoves are phased out by 2039				
	LPG stoves are phased out by 2040.				
Transport	Internal combustion engine (gasoline, diesel, natural gas and hybrid) vehicles are phased out by 2050.				
	Hydrogen for use in heavy road vehicles are excluded from the pathway.				
	CAPEX data from BEVs is taken from the CCC (2025). Battery electric vehicles are expected to reach price parity for cars in 2029 and vans in 2027. BEV savings relative to ICEVs for each vehicle are below:				
	Vehicle	2025	2030	2040	2050
	Car	+14%	-6%	-10%	-12%
	Van	+8%	-8%	-12%	-15%
HGV	+102%	+57%	+33%	+30%	
Industry	Natural gas boilers are phased out by 2050				
	Natural gas furnaces can only supply 28 PJ of energy service demands by 2050.				
Energy supply					

Parameter	Description
Hydropower	Expanded from its current base to ensure a greater level of dispatchable power capacity. Approximately 9GW of additional capacity is installed by 2050 - starting in 2025 and increasingly linearly. This equates to ~111 TWh of electricity generation, roughly in line with IEA (2025).
Solar PV + batteries	A battery storage capacity equivalent to the same proportion of non-dispatchable renewable electricity generation is assumed, consistent with IEA (2025). Within the OSeMOSYS framework, storage capacity is represented with solar PV technologies. Therefore, all battery charging is assumed to be supplied by solar generation.
Geothermal	1GW of geothermal power capacity is assumed to be implemented from 2030 onwards.
Biomass	Approximately 5GW of biomass-based electricity generation by 2050, which is introduced linearly from 2030 onwards. Biomass generation has an emissions factor of zero, suggesting a fully functioning and sustainable supply chain from the base year.
Hydrogen	Low-carbon hydrogen is introduced for use in industry from 2035 onwards - equating to 8.4 PJ of production by 2050. Production is split equally between PEM and alkaline electrolysis. Other scenarios, such as the IEA (2025), have much greater levels of hydrogen production. However, this is not primarily utilised to satisfy domestic industrial demand, but rather aviation, shipping and exports, which are currently not represented in OSeMOSYS-COL.
Carbon capture and storage	CCS technologies were excluded from the modelling
Nuclear	Nuclear power generation was excluded based on concerns regarding time constraints and costs

Tables A1.4-6 includes the cost assumptions for technologies available within the OSeMOSYS-COL model. Most of the data is taken from Plazas-Niño et al. (2023a), except for the electric vehicle costs, which are described above.

Table A1.4 - Capital cost assumptions. All units are in MUSD/PJ, except for road/aviation transport (MUSD/Gpkm) and freight transport (MUSD/Gtkm).

Technology	Code	2025	2030	2035	2040	2045	2050
High efficiency air conditioning	AIRHIG	9.2	9.2	9.2	9.2	9.2	9.2
High efficiency air conditioning	AIRHIG002	9.2	9.2	9.2	9.2	9.2	9.2
Low efficiency air conditioning	AIRLOW	8.0	8.0	8.0	8.0	8.0	8.0
Low efficiency air conditioning	AIRLOW002	8.0	8.0	8.0	8.0	8.0	8.0
Biomass boiler	BAGBOI	30.6	30.6	30.6	30.6	30.6	30.6
Biomass boiler + CCS	BAGBOICCS	100.9	100.9	101.1	101.4	101.7	102.1
Biomass furnace	BAGFUR	32.2	32.2	32.2	32.2	32.2	32.2
Biomass furnace + CCS	BAGFURCCS	102.5	102.6	102.7	103.0	103.3	103.7
Bio-blended diesel transport and distribution	BBDDST	0.9	0.9	0.9	0.9	0.9	0.9
Bio-blended gasoline transport and distribution	BBGDST	1.0	1.0	1.0	1.0	1.0	1.0
Coal boiler	COABOI	14.1	14.1	14.1	14.1	14.1	14.1
Coal boiler + CCS	COABOICCS	72.3	64.5	56.0	49.5	47.4	45.3
Coal transport and distribution	COADST	0.4	0.4	0.4	0.4	0.4	0.4
Coal furnace	COAFUR	15.4	15.4	15.4	15.4	15.4	15.4

Coal furnace + CCS	COAFURCCS	73.6	65.7	57.3	50.7	48.6	46.5
Diesel bus	DSLBUS	5.7	5.7	5.7	5.7	5.7	5.7
Diesel four wheel drive	DSLFWDD	3903.4	3903.4	3903.4	3903.4	3903.4	3903.4
Diesel light duty vehicle	DSLLEDV	1524.6	1524.6	1524.6	1524.6	1524.6	1524.6
Diesel microbus	DSLMIC	24.7	24.7	24.7	24.7	24.7	24.7
Diesel motorcycle	DSLMOT	127.9	127.9	127.9	127.9	127.9	127.9
Diesel ships	DSLSDP	4558.9	4558.9	4558.9	4558.9	4558.9	4558.9
Diesel semi-trailer truck	DSLSTT	100.1	100.1	100.1	100.1	100.1	100.1
Diesel taxi	DSLTXD	96.1	96.1	96.1	96.1	96.1	96.1
Diesel truck	DSLTKK	207.5	207.5	207.5	207.5	207.5	207.5
Diesel technology	DSLTEC	0.0	0.0	0.0	0.0	0.0	0.0
Electricity boiler	ELCBOI	12.7	12.7	12.7	12.7	12.7	12.7
Electricity boiler	ELCBOI002	12.7	12.7	12.7	12.7	12.7	12.7
Electricity bus	ELCBUS	14.0	10.9	10.1	9.2	9.1	9.0
Electricity furnace	ELCFUR	32.2	32.2	32.2	32.2	32.2	32.2
Electricity four wheel drive (BEV)	ELCFWD	2878.5	2373.5	2323.0	2272.5	2247.3	2222.0
Electricity light duty vehicle (BEV)	ELCLDV	750.6	618.9	605.7	592.5	586.0	579.4
Electricity meter	ELCMET	72.6	72.6	72.6	72.6	72.6	72.6

Electricity microbus	ELCMIC	120.5	87.5	69.9	54.6	39.6	24.7
Electricity motorcycle	ELCMOT	147.2	121.4	118.8	116.2	114.9	113.6
Electricity semi-trailer truck	ELCSTT	165.4	128.6	119.6	108.9	108.1	106.5
Electrical stove	ELCSTV	12.1	12.1	12.1	12.1	12.1	12.1
Electrical stove	ELCSTV002	12.1	12.1	12.1	12.1	12.1	12.1
Electricity taxi	ELCTAX	47.3	39.0	38.2	37.3	36.9	36.5
Electricity truck	ELCTCK	419.1	325.8	302.9	276.0	273.9	269.7
Electricity technology	ELCTEC	0.0	0.0	0.0	0.0	0.0	0.0
Electrical water heater	ELCWHT	6.1	6.1	6.1	6.1	6.1	6.1
Other electronic	ELEDEM	153.4	153.4	153.4	153.4	153.4	153.4
Electronics	ELEDEM002	153.4	153.4	153.4	153.4	153.4	153.4
High efficiency fan	FANHIG	26.6	26.6	26.6	26.6	26.6	26.6
Low efficiency fan	FANLOW	17.6	17.6	17.6	17.6	17.6	17.6
Fuel oil technology	FOLTEC	0.0	0.0	0.0	0.0	0.0	0.0
Gasoline bus	GSLBUS	6.9	6.9	6.9	6.9	6.9	6.9
Gasoline four wheel drive	GSLFWD	2525.0	2525.0	2525.0	2525.0	2525.0	2525.0
Gasoline light duty vehicle	GSLLDV	658.4	658.4	658.4	658.4	658.4	658.4
Gasoline microbus	GSLMIC	29.9	29.9	29.9	29.9	29.9	29.9

Gasoline motorcycle	GSLMOT	129.1	129.1	129.1	129.1	129.1	129.1
Gasoline semi-trailer truck	GSLSTT	81.9	81.9	81.9	81.9	81.9	81.9
Gasoline taxi	GSLTAX	41.5	41.5	41.5	41.5	41.5	41.5
Gasoline truck	GSLTCK	401.2	401.2	401.2	401.2	401.2	401.2
Gasoline technology	GSLTEC	0.0	0.0	0.0	0.0	0.0	0.0
Hydrogen boiler	HDGBOI	9.1	9.1	9.1	9.1	9.1	9.1
Hydrogen bus	HDGBUS	97.2	97.2	74.6	52.1	29.5	6.9
Hydrogen transport by road	HDGDST	12.8	12.4	12.0	11.7	11.3	11.0
Hydrogen furnace	HDGFUR	33.5	33.5	33.5	33.5	33.5	33.5
Hydrogen four wheel drive (FCEV)	HDGFWD	14717.1	14717.1	11669.1	8621.1	5573.1	2525.1
Hydrogen light duty vehicle (FCEV)	HDGLDV	12793.3	12793.3	9758.3	6723.3	3688.3	653.3
Hydrogen microbus	HDGMIC	424.2	424.2	325.7	227.1	128.6	30.0
Hydrogen motorcycle	HDGMOT	1367.1	1367.1	1057.6	748.1	438.6	129.1
H2 Refuelling station	HDGRST	37.1	35.8	34.6	33.4	32.2	31.1
Hydrogen semi-trailer truck	HDGSTT	398.6	398.6	319.6	240.6	161.6	82.6
Hydrogen taxi	HDGTAX	806.3	806.3	615.2	424.0	232.9	41.7
Hydrogen truck	HDGTCK	2297.7	2297.7	1777.7	1257.7	737.7	217.7
Hydrogen pipeline	HDGTRN	6.7	6.7	6.6	6.5	6.4	6.4

Hybrid four wheel drive (PHEV)	HYBFWD	3867.4	3602.4	3337.4	3072.4	2807.4	2542.4
Hybrid light duty vehicle (PHEV)	HYBLDV	2620.9	2230.9	1840.9	1450.9	1060.9	670.9
Hybrid taxi	HYBTAX	165.2	141.2	117.2	93.2	69.2	45.2
High efficiency illumination	ILUHIG	2.6	2.6	2.6	2.6	2.6	2.6
High efficiency illumination	ILUHIG002	2.6	2.6	2.6	2.6	2.6	2.6
Low efficiency illumination	ILULOW	0.6	0.6	0.6	0.6	0.6	0.6
Low efficiency illumination	ILULOW002	0.6	0.6	0.6	0.6	0.6	0.6
Electric appliances high efficiency	INDHIG	30.2	30.2	30.2	30.2	30.2	30.2
Electric appliances low efficiency	INDLOW	15.1	15.1	15.1	15.1	15.1	15.1
Jet fuel airplanes	JETAIR	6342.9	6342.9	6342.9	6342.9	6342.9	6342.9
LPG transport and distribution	LPGDST	0.9	0.9	0.9	0.9	0.9	0.9
LPG stove	LPGSTV	3.6	3.6	3.6	3.6	3.6	3.6
LPG stove	LPGSTV002	3.6	3.6	3.6	3.6	3.6	3.6
LPG technology	LPGTEC	0.0	0.0	0.0	0.0	0.0	0.0
Natural gas boiler	NGSBOI	4.7	4.7	4.7	4.7	4.7	4.7
Natural gas boiler	NGSBOI002	4.7	4.7	4.7	4.7	4.7	4.7
Natural gas boiler + CCS	NGSBOICCS	39.8	36.2	32.5	29.5	27.8	26.2
Natural gas bus	NGSBUS	71.5	71.5	71.5	71.5	71.5	71.5

Natural gas furnace	NGSFUR	6.0	6.0	6.0	6.0	6.0	6.0
Natural gas furnace + CCS	NGSFURCCS	41.1	37.5	33.8	30.8	29.1	27.5
Natural gas four wheel drive	NGSFWD	3928.6	3928.6	3928.6	3928.6	3928.6	3928.6
Natural gas light duty vehicle	NGSLDV	2693.3	2693.3	2693.3	2693.3	2693.3	2693.3
Natural gas microbus	NGSMIC	311.9	311.9	311.9	311.9	311.9	311.9
Natural gas motorcycle	NGSMOT	95.6	95.6	95.6	95.6	95.6	95.6
Natural gas semi-trailer truck	NGSSTT	293.1	293.1	293.1	293.1	293.1	293.1
Natural gas stove	NGSSTV	5.5	5.5	5.5	5.5	5.5	5.5
Natural gas stove	NGSSTV002	5.5	5.5	5.5	5.5	5.5	5.5
Natural gas taxi	NGSTAX	220.7	220.7	220.7	220.7	220.7	220.7
Natural gas truck	NGSTCK	1689.5	1689.5	1689.5	1689.5	1689.5	1689.5
Natural gas technology	NGSTEC	0.0	0.0	0.0	0.0	0.0	0.0
Natural gas transport and distribution	NGSTRN	0.9	0.9	0.9	0.9	0.9	0.9
Natural gas water heater	NGSWHT	7.1	7.1	7.1	7.1	7.1	7.1
Biomass power plant (agriculture and forestry residues)	PWRAFR	125.4	121.3	117.3	113.2	109.1	105.1
Biomass power plant + CCS (agriculture and forestry residues)	PWRAFRCCS	195.6	191.6	187.7	183.9	180.2	176.5
Coal power plant	PWRCOA	74.1	69.7	66.2	63.9	61.6	59.3

Coal power plant + CCS	PWRCOACCS	132.3	120.0	108.1	99.2	94.8	90.5
CSP power plant	PWRCSP	165.2	132.5	129.0	125.6	122.2	118.8
Hydro power plant (dam)	PWRDAM	122.1	122.1	122.1	122.1	122.1	122.1
Distribution electricity technology	PWRDST	47.3	47.3	47.3	47.3	47.3	47.3
Geothermal power plant	PWRGEO	644.9	546.6	533.0	519.8	507.0	494.4
Distributed PV network	PWRMCG	126.1	116.1	106.9	98.4	90.6	83.4
Natural gas power plant	PWRNGS	27.2	26.4	25.8	25.2	24.7	24.2
Natural gas power plant + CCS	PWRNGSCCS	62.3	57.9	53.6	50.0	47.8	45.8
Nuclear power plant (SMR)	PWRNUC	209.2	202.4	195.7	188.9	182.2	175.4
Offshore wind power plant	PWROFW	80.6	74.2	70.3	67.4	65.2	63.4
Onshore wind power plant	PWRONW	36.8	29.0	27.5	26.1	24.6	23.2
Hydro power plant (run-of-river)	PWRROR	104.6	104.6	104.6	104.6	104.6	104.6
Recharging station	PWRRST	31.0	28.0	25.3	22.9	20.7	18.7
Individual photovoltaic solution (Rooftop PV)	PWRRTP	35.3	32.5	29.9	27.6	25.4	23.4
Solar PV Utility	PWRSOL	30.4	23.3	22.2	21.2	20.2	19.1
Solar PV utility + battery system	PWRSOLBAT	47.7	33.0	31.4	29.8	28.1	26.5
Diesel plant standalone	PWRSTD	23.8	23.8	23.8	23.8	23.8	23.8
Transmission electricity technology	PWRTRN	23.7	23.7	23.7	23.7	23.7	23.7

Biomass power plant (wood)	PWRWOO	125.4	121.3	117.3	113.2	109.1	105.1
Biomass power plant + CCS (wood)	PWRWOCCS	195.6	191.6	187.7	183.9	180.2	176.5
High efficiency refrigerator	REFHIG	69.7	69.7	69.7	69.7	69.7	69.7
High efficiency refrigerator	REFHIG002	69.7	69.7	69.7	69.7	69.7	69.7
Low efficiency refrigerator	REFLOW	60.8	60.8	60.8	60.8	60.8	60.8
Low efficiency refrigerator	REFLOW002	60.8	60.8	60.8	60.8	60.8	60.8
High efficiency TV	TVUHIG	118.5	118.5	118.5	118.5	118.5	118.5
Low efficiency TV	TVULOW	17.8	17.8	17.8	17.8	17.8	17.8
ALK Electrolyzer	UPSALK	38.8	34.1	30.1	26.5	23.3	20.0
Blending diesel-biodiesel	UPSBDDB	0.0	0.0	0.0	0.0	0.0	0.0
Biodiesel plant	UPSBDL	19.0	19.0	19.0	19.0	19.0	19.0
Blending gasoline-bioethanol	UPSGBB	0.0	0.0	0.0	0.0	0.0	0.0
Distillery	UPSDET	27.4	27.4	27.4	27.4	27.4	27.4
LPG plant	UPSLPG	6.7	6.7	6.7	6.7	6.7	6.7
PEM Electrolizer	UPSPEM	54.2	47.2	41.0	35.7	31.0	26.2
Refinery	UPSREF	15.9	15.9	15.9	15.9	15.9	15.9
Regasification Plant	UPSREG	6.1	6.1	6.1	6.1	6.1	6.1
Steam Methane Reforming plant	UPSSMR	20.2	19.5	18.9	18.3	17.7	17.1

Steam Methane Reforming plant + CCS	UPSSMRCCS	33.6	32.9	32.3	31.6	31.0	30.4
Wood stove	WOOSTV	11.6	11.6	11.6	11.6	11.6	11.6
Wood technology	WOOTEC	0.0	0.0	0.0	0.0	0.0	0.0
High efficiency washer	WSHHIG	37.6	37.6	37.6	37.6	37.6	37.6
Low efficiency washer	WSHLOW	37.6	37.6	37.6	37.6	37.6	37.6

Table A1.5 - Fixed cost assumptions (MUSD/PJ).

Technology	Code	2025	2030	2035	2040	2045	2050
High efficiency air conditioning	AIRHIG	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
High efficiency air conditioning	AIRHIG002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Low efficiency air conditioning	AIRLOW	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Low efficiency air conditioning	AIRLOW002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Biomass boiler	BAGBOI	0.0507	0.0507	0.0507	0.0507	0.0507	0.0507
Biomass boiler + CCS	BAGBOICCS	0.3397	0.4311	0.5206	0.6083	0.6942	0.7784
Biomass furnace	BAGFUR	0.0507	0.0507	0.0507	0.0507	0.0507	0.0507
Biomass furnace + CCS	BAGFURCCS	0.3397	0.4311	0.5206	0.6083	0.6942	0.7784
Bio-blended diesel transport and distribution	BBDDST	0.0279	0.0279	0.0279	0.0279	0.0279	0.0279

Bio-blended gasoline transport and distribution	BBGDST	0.0288	0.0288	0.0288	0.0288	0.0288	0.0288
Coal boiler	COABOI	0.0507	0.0507	0.0507	0.0507	0.0507	0.0507
Coal boiler + CCS	COABOICCS	1.6679	1.5411	1.3825	1.2557	1.2557	1.2557
Coal transport and distribution	COADST	0.0123	0.0123	0.0123	0.0123	0.0123	0.0123
Coal furnace	COAFUR	0.0507	0.0507	0.0507	0.0507	0.0507	0.0507
Coal furnace + CCS	COAFURCCS	1.6679	1.5411	1.3825	1.2557	1.2557	1.2557
Diesel bus	DSLBUS	0.1144	0.1144	0.1144	0.1144	0.1144	0.1144
Diesel four wheel drive	DSLFWDD	117.1008	117.1008	117.1008	117.1008	117.1008	117.1008
Diesel light duty vehicle	DSLFDV	45.7368	45.7368	45.7368	45.7368	45.7368	45.7368
Diesel microbus	DSLMIC	0.4949	0.4949	0.4949	0.4949	0.4949	0.4949
Diesel motorcycle	DSLMOT	3.8374	3.8374	3.8374	3.8374	3.8374	3.8374
Diesel ships	DSLSDP	136.7679	136.7679	136.7679	136.7679	136.7679	136.7679
Diesel semi-trailer truck	DSLSTT	2.0017	2.0017	2.0017	2.0017	2.0017	2.0017
Diesel taxi	DSLTD	2.8826	2.8826	2.8826	2.8826	2.8826	2.8826
Diesel truck	DSLTDK	4.1499	4.1499	4.1499	4.1499	4.1499	4.1499
Diesel technology	DSLTD	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Electricity boiler	ELCBOI	0.1903	0.1903	0.1903	0.1903	0.1903	0.1903
Electricity boiler	ELCBOI002	0.1903	0.1903	0.1903	0.1903	0.1903	0.1903

Electricity bus	ELCBUS	1.1870	0.9780	0.7690	0.5600	0.3510	0.1420
Electricity furnace	ELCFUR	0.0412	0.0412	0.0412	0.0412	0.0412	0.0412
Electricity four wheel drive (BEV)	ELCFWD	50.7486	45.6486	40.5486	35.4486	30.3486	25.2486
Electricity light duty vehicle (BEV)	ELCLDV	31.0933	26.1933	21.2933	16.3933	11.4933	6.5933
Electricity meter	ELCMET	2.1775	2.1775	2.1775	2.1775	2.1775	2.1775
Electricity microbus	ELCMIC	2.2313	1.9013	1.5713	1.2413	0.9113	0.5813
Electricity motorcycle	ELCMOT	3.9985	3.4985	2.9985	2.4985	1.9985	1.4985
Electricity semi-trailer truck	ELCSTT	6.1806	6.1806	5.0406	3.9006	2.7606	1.6206
Electrical stove	ELCSTV	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Electrical stove	ELCSTV002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Electricity taxi	ELCTAX	1.9587	1.6487	1.3387	1.0287	0.7187	0.4087
Electricity truck	ELCTCK	13.2218	13.2218	10.9568	8.6918	6.4268	4.1618
Electricity technology	ELCTEC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Electrical water heater	ELCWHT	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Other electronic	ELEDEM	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Electronics	ELEDEM002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
High efficiency fan	FANHIG	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Low efficiency fan	FANLOW	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Fuel oil technology	FOLTEC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Gasoline bus	GSLBUS	0.1383	0.1383	0.1383	0.1383	0.1383	0.1383
Gasoline four wheel drive	GSLFWD	75.7500	75.7500	75.7500	75.7500	75.7500	75.7500
Gasoline light duty vehicle	GSLLDV	19.7516	19.7516	19.7516	19.7516	19.7516	19.7516
Gasoline microbus	GSLMIC	0.5979	0.5979	0.5979	0.5979	0.5979	0.5979
Gasoline motorcycle	GSLMOT	3.8731	3.8731	3.8731	3.8731	3.8731	3.8731
Gasoline semi-trailer truck	GSLSTT	1.6378	1.6378	1.6378	1.6378	1.6378	1.6378
Gasoline taxi	GSLTAX	1.2448	1.2448	1.2448	1.2448	1.2448	1.2448
Gasoline truck	GSLTCK	8.0239	8.0239	8.0239	8.0239	8.0239	8.0239
Gasoline technology	GSLTEC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Hydrogen boiler	HDGBOI	0.1807	0.1807	0.1807	0.1807	0.1807	0.1807
Hydrogen bus	HDGBUS	1.9440	1.9440	1.4925	1.0410	0.5895	0.1380
Hydrogen transport by road	HDGDST	1.8392	1.8392	1.8392	1.8392	1.8392	1.8392
Hydrogen furnace	HDGFUR	0.6088	0.6088	0.6088	0.6088	0.6088	0.6088
Hydrogen four wheel drive (FCEV)	HDGFWD	441.5143	441.5143	350.0743	258.6343	167.1943	75.7543
Hydrogen light duty vehicle (FCEV)	HDGLDV	383.8000	383.8000	292.7500	201.7000	110.6500	19.6000
Hydrogen microbus	HDGMIC	8.4840	8.4840	6.5130	4.5420	2.5710	0.6000
Hydrogen motorcycle	HDGMOT	41.0134	41.0134	31.7284	22.4434	13.1584	3.8734

H2 Refuelling station	HDGRST	0.1649	0.1649	0.1649	0.1649	0.1649	0.1649
Hydrogen semi-trailer truck	HDGSTT	7.9728	7.9728	6.3928	4.8128	3.2328	1.6528
Hydrogen taxi	HDGTAX	24.1891	24.1891	18.4546	12.7201	6.9856	1.2511
Hydrogen truck	HDGTCK	45.9532	45.9532	35.5532	25.1532	14.7532	4.3532
Hydrogen pipeline	HDGTRN	0.9196	0.9196	0.9196	0.9196	0.9196	0.9196
Hybrid four wheel drive (PHEV)	HYBFWD	38.6740	36.0240	33.3740	30.7240	28.0740	25.4240
Hybrid light duty vehicle (PHEV)	HYBLDV	26.2091	22.3091	18.4091	14.5091	10.6091	6.7091
Hybrid taxi	HYBTAX	1.6522	1.4122	1.1722	0.9322	0.6922	0.4522
High efficiency illumination	ILUHIG	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
High efficiency illumination	ILUHIG002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Low efficiency illumination	ILULOW	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Low efficiency illumination	ILULOW002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Diesel imports	IMPDSL	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Fuel oil imports	IMPFOL	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Gasoline imports	IMPGSL	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Jet Fuel/Kerosene imports	IMPJET	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Natural gas imports (LNG)	IMPLNG	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LPG imports	IMPLPG	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Crude oil imports	IMPOIL	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Electric appliances high efficiency	INDHIG	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Electric appliances low efficiency	INDLOW	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Jet fuel airplanes	JETAIR	190.2857	190.2857	190.2857	190.2857	190.2857	190.2857
LPG transport and distribution	LPGDST	0.0282	0.0282	0.0282	0.0282	0.0282	0.0282
LPG stove	LPGSTV	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LPG stove	LPGSTV002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LPG technology	LPGTEC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Agriculture and forestry residues production	MINAFR	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Bagasse production	MINBAG	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Coal extraction	MINCOA	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Solar CPS potential	MINCSP	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Hydro potential (dam)	MINDAM	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Geothermal resources	MINGEO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Natural gas extraction	MINNGS	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Offshore wind potential	MINOFW	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Crude oil extraction	MINOIL	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Onshore wind potential	MINONW	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Oilpalm dedicated production (biodiesel)	MINOPL	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Hydro potential (run of river)	MINROR	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sugarcane dedicated production (bioethanol)	MINSGC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Solar PV potential	MINSOL	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Uranium production	MINURN	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Wood extraction	MINWOO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Natural gas boiler	NGSBOI	0.0444	0.0444	0.0444	0.0444	0.0444	0.0444
Natural gas boiler	NGSBOI002	0.0444	0.0444	0.0444	0.0444	0.0444	0.0444
Natural gas boiler + CCS	NGSBOICCS	1.1542	1.1225	1.0908	1.0591	1.0591	1.0591
Natural gas bus	NGSBUS	1.4294	1.4294	1.4294	1.4294	1.4294	1.4294
Natural gas furnace	NGSFUR	0.0444	0.0444	0.0444	0.0444	0.0444	0.0444
Natural gas furnace + CCS	NGSFURCCS	1.1542	1.1225	1.0908	1.0591	1.0591	1.0591
Natural gas four wheel drive	NGSFWD	117.8571	117.8571	117.8571	117.8571	117.8571	117.8571
Natural gas light duty vehicle	NGSLDV	80.8000	80.8000	80.8000	80.8000	80.8000	80.8000
Natural gas microbus	NGSMIC	6.2382	6.2382	6.2382	6.2382	6.2382	6.2382
Natural gas motorcycle	NGSMOT	2.8674	2.8674	2.8674	2.8674	2.8674	2.8674
Natural gas semi-trailer truck	NGSSTT	5.8624	5.8624	5.8624	5.8624	5.8624	5.8624
Natural gas stove	NGSSTV	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Natural gas stove	NGSSTV002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Natural gas taxi	NGSTAX	6.6202	6.6202	6.6202	6.6202	6.6202	6.6202
Natural gas truck	NGSTCK	33.7891	33.7891	33.7891	33.7891	33.7891	33.7891
Natural gas technology	NGSTEC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Natural gas transport and distribution	NGSTRN	0.0276	0.0276	0.0276	0.0276	0.0276	0.0276
Natural gas water heater	NGSWHT	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Biomass power plant (agriculture and forestry residues)	PWRAFR	4.7834	4.7834	4.7834	4.7834	4.7834	4.7834
Biomass power plant + CCS (agriculture and forestry residues)	PWRAFRCCS	4.4945	4.4031	4.3136	4.2259	4.1400	4.0558
Coal power plant	PWRCOA	2.3148	2.2514	2.2197	2.2197	2.2197	2.2197
Coal power plant + CCS	PWRCOACC S	3.9320	3.7418	3.5515	3.4247	3.4247	3.4247
CSP power plant	PWRCSP	1.9442	1.7955	1.7910	1.7864	1.7819	1.7774
Hydro power plant (dam)	PWRDAM	0.6104	0.6104	0.6104	0.6104	0.6104	0.6104
Distribution electricity technology	PWRDST	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Geothermal power plant	PWRGEO	11.9223	11.0276	11.0276	11.0276	11.0276	11.0276
Distributed PV network	PWRMCG	2.5223	2.3222	2.1379	1.9682	1.8120	1.6683
Natural gas power plant	PWRNGS	0.8879	0.8879	0.8879	0.8879	0.8879	0.8879

Natural gas power plant + CCS	PWRNGSCC S	1.9977	1.9660	1.9343	1.9026	1.9026	1.9026
Nuclear power plant (SMR)	PWRNUC	3.6149	3.6149	3.6149	3.6149	3.6149	3.6149
Offshore wind power plant	PWROFW	2.6878	2.4587	2.3052	2.1896	2.0968	2.0192
Onshore wind power plant	PWRONW	1.2993	1.2351	1.1888	1.1425	1.0961	1.0498
Hydro power plant (run-of-river)	PWRROR	0.5232	0.5232	0.5232	0.5232	0.5232	0.5232
Recharging station	PWRRST	1.2341	1.1170	1.0110	0.9150	0.8282	0.7496
Individual photovoltaic solution (Rooftop PV)	PWRRTP	0.7065	0.6504	0.5988	0.5513	0.5075	0.4673
Solar PV Utility	PWRSOL	0.5760	0.4827	0.4668	0.4511	0.4356	0.4202
Solar PV utility + battery system	PWRSOLBAT	0.9662	0.7436	0.7165	0.6895	0.6628	0.6363
Diesel plant standalone	PWRSTD	0.7293	0.7293	0.7293	0.7293	0.7293	0.7293
Transmission electricity technology	PWRTRN	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Biomass power plant (wood)	PWRWOO	4.7834	4.7834	4.7834	4.7834	4.7834	4.7834
Biomass power plant + CCS (wood)	PWRWOCC S	4.4945	4.4031	4.3136	4.2259	4.1400	4.0558
High efficiency refrigerator	REFHIG	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
High efficiency refrigerator	REFHIG002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Low efficiency refrigerator	REFLOW	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Low efficiency refrigerator	REFLOW002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

High efficiency TV	TVUHIG	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Low efficiency TV	TVULOW	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
ALK Electrolyzer	UPSALK	1.9377	1.7064	1.5027	1.3233	1.1653	1.0004
Blending diesel-biodiesel	UPSBDDB	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Biodiesel plant	UPSBDL	0.5708	0.5708	0.5708	0.5708	0.5708	0.5708
Blending gasoline-bioethanol	UPSGBB	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Destillery	UPSDDET	1.9343	1.9343	1.9343	1.9343	1.9343	1.9343
LPG plant	UPSLPG	0.2700	0.2700	0.2700	0.2700	0.2700	0.2700
PEM Electrolizer	UPSPEM	3.7970	3.3017	2.8711	2.4966	2.1709	1.8357
Refinery	UPSREF	0.6013	0.6013	0.6013	0.6013	0.6013	0.6013
Regasification Plant	UPSREG	0.1585	0.1585	0.1585	0.1585	0.1585	0.1585
Steam Methane Reforming plant	UPSSMR	0.7972	0.7709	0.7454	0.7207	0.6969	0.6739
Steam Methane Reforming plant + CCS	UPSSMRCCS	1.3371	1.3113	1.2859	1.2610	1.2366	1.2127
Wood stove	WOOSTV	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Wood technology	WOOTEC	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
High efficiency washer	WSHHIG	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Low efficiency washer	WSHLOW	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table A1.6 - Variable cost assumptions. All units are in MUSD/PJ, except for road/aviation transport (MUSD/Gpkm) and freight transport (MUSD/Gtkm).

Technology	Code	2025	2030	2035	2040	2045	2050
High efficiency air conditioning	AIRHIG	0	0	0	0	0	0
High efficiency air conditioning	AIRHIG002	0	0	0	0	0	0
Low efficiency air conditioning	AIRLOW	0	0	0	0	0	0
Low efficiency air conditioning	AIRLOW002	0	0	0	0	0	0
Biomass boiler	BAGBOI	0.46944 4	0.46944 4	0.46944 4	0.46944 4	0.46944 4	0.46944 4
Biomass boiler + CCS	BAGBOICCS	7.47867 2	7.47867 2	7.47867 2	7.47867 2	7.47867 2	7.47867 2
Biomass furnace	BAGFUR	0.46944 4	0.46944 4	0.46944 4	0.46944 4	0.46944 4	0.46944 4
Biomass furnace + CCS	BAGFURCCS	9.81002 2	9.81002 2	9.81002 2	9.81002 2	9.81002 2	9.81002 2
Bio-blended diesel transport and distribution	BBDDST	0	0	0	0	0	0
Bio-blended gasoline transport and distribution	BBGDST	0	0	0	0	0	0
Coal boiler	COABOI	0.46944 4	0.46944 4	0.46944 4	0.46944 4	0.46944 4	0.46944 4

Coal boiler + CCS	COABOICCS	6.56394 5	6.56394 5	6.56394 5	6.56394 5	6.56394 5	6.56394 5
Coal transport and distribution	COADST	0	0	0	0	0	0
Coal furnace	COAFUR	0.46944 4	0.46944 4	0.46944 4	0.46944 4	0.46944 4	0.46944 4
Coal furnace + CCS	COAFURCCS	8.25784 5	8.25784 5	8.25784 5	8.25784 5	8.25784 5	8.25784 5
Diesel bus	DSLBUS	0	0	0	0	0	0
Diesel four wheel drive	DSLFWDD	0	0	0	0	0	0
Diesel light duty vehicle	DSLLEDV	0	0	0	0	0	0
Diesel microbus	DSL MIC	0	0	0	0	0	0
Diesel motorcycle	DSL MOT	0	0	0	0	0	0
Diesel ships	DSL SHP	0	0	0	0	0	0
Diesel semi-trailer truck	DSLSTT	0	0	0	0	0	0
Diesel taxi	DSL TAX	0	0	0	0	0	0
Diesel truck	DSL TCK	0	0	0	0	0	0
Diesel technology	DSL TEC	0	0	0	0	0	0
Electricity boiler	ELCBOI	0.16666 7	0.16666 7	0.16666 7	0.16666 7	0.16666 7	0.16666 7
Electricity boiler	ELCBOI002	0.16666 7	0.16666 7	0.16666 7	0.16666 7	0.16666 7	0.16666 7

Electricity bus	ELCBUS	0	0	0	0	0	0
Electricity furnace	ELCFUR	0.166667	0.166667	0.166667	0.166667	0.166667	0.166667
Electricity four wheel drive (BEV)	ELCFWD	0	0	0	0	0	0
Electricity light duty vehicle (BEV)	ELCLDV	0	0	0	0	0	0
Electricity meter	ELCMET	0	0	0	0	0	0
Electricity microbus	ELCMIC	0	0	0	0	0	0
Electricity motorcycle	ELCMOT	0	0	0	0	0	0
Electricity semi-trailer truck	ELCSTT	0	0	0	0	0	0
Electrical stove	ELCSTV	0	0	0	0	0	0
Electrical stove	ELCSTV002	0	0	0	0	0	0
Electricity taxi	ELCTAX	0	0	0	0	0	0
Electricity truck	ELCTCK	0	0	0	0	0	0
Electricity technology	ELCTEC	0	0	0	0	0	0
Electrical water heater	ELCWHT	0	0	0	0	0	0
Other electronic	ELEDEM	0	0	0	0	0	0
Electronics	ELEDEM002	0	0	0	0	0	0
High efficiency fan	FANHIG	0	0	0	0	0	0
Low efficiency fan	FANLOW	0	0	0	0	0	0

Fuel oil technology	FOLTEC	0	0	0	0	0	0
Gasoline bus	GSLBUS	0	0	0	0	0	0
Gasoline four wheel drive	GSLFWD	0	0	0	0	0	0
Gasoline light duty vehicle	GSLLDV	0	0	0	0	0	0
Gasoline microbus	GSLMIC	0	0	0	0	0	0
Gasoline motorcycle	GSLMOT	0	0	0	0	0	0
Gasoline semi-trailer truck	GSLSTT	0	0	0	0	0	0
Gasoline taxi	GSLTAX	0	0	0	0	0	0
Gasoline truck	GSLTCK	0	0	0	0	0	0
Gasoline technology	GSLTEC	0	0	0	0	0	0
Hydrogen boiler	HDGBOI	0	0	0	0	0	0
Hydrogen bus	HDGBUS	0	0	0	0	0	0
Hydrogen transport by road	HDGDST	0	0	0	0	0	0
Hydrogen furnace	HDGFUR	0	0	0	0	0	0
Hydrogen four wheel drive (FCEV)	HDGFWD	0	0	0	0	0	0
Hydrogen light duty vehicle (FCEV)	HDGLDV	0	0	0	0	0	0
Hydrogen microbus	HDGMIC	0	0	0	0	0	0
Hydrogen motorcycle	HDGMOT	0	0	0	0	0	0

H2 Refuelling station	HDGRST	0	0	0	0	0	0
Hydrogen semi-trailer truck	HDGSTT	0	0	0	0	0	0
Hydrogen taxi	HDGTAX	0	0	0	0	0	0
Hydrogen truck	HDGTCK	0	0	0	0	0	0
Hydrogen pipeline	HDGTRN	0	0	0	0	0	0
Hybrid four wheel drive (PHEV)	HYBFWD	0	0	0	0	0	0
Hybrid light duty vehicle (PHEV)	HYBLDV	0	0	0	0	0	0
Hybrid taxi	HYBTAX	0	0	0	0	0	0
High efficiency ilumination	ILUHIG	0	0	0	0	0	0
High efficiency ilumination	ILUHIG002	0	0	0	0	0	0
Low efficiency ilumination	ILULOW	0	0	0	0	0	0
Low efficiency ilumination	ILULOW002	0	0	0	0	0	0
Diesel imports	IMPDSL	7.7513	8.66275	9.74606 6	10.6205 3	11.7057 8	12.7910 3
Fuel oil imports	IMPFOL	10.9635	13.2738 6	15.4337 7	17.0744 8	19.1539 8	21.2334 8
Gasoline imports	IMPGSL	9.35461 3	11.0414 3	13.2291 4	14.9250 3	17.0334 4	19.1418 5
Jet Fuel/Kerosene imports	IMPJET	19.5837 8	23.3927 5	27.6875 9	31.1502 7	35.3832	39.6161 4

Natural gas imports (LNG)	IMPLNG	6.98357 1	8.56850 5	10.0660 7	11.3222	12.8794 6	14.4367 1
LPG imports	IMPLPG	18.3574 3	22.3095 9	27.0170 3	30.6752 2	35.2797	39.8841 8
Crude oil imports	IMPOIL	11.6794 6	12.8950 6	13.8098 2	14.5625 8	15.4710 6	16.3795 4
Electric appliances high efficiency	INDHIG	0	0	0	0	0	0
Electric appliances low efficiency	INDLOW	0	0	0	0	0	0
Jet fuel airplanes	JETAIR	0	0	0	0	0	0
LPG transport and distribution	LPGDST	0	0	0	0	0	0
LPG stove	LPGSTV	0	0	0	0	0	0
LPG stove	LPGSTV002	0	0	0	0	0	0
LPG technology	LPGTEC	0	0	0	0	0	0
Agriculture and forestry residues production	MINAFR	1.7	1.7	1.7	1.7	1.7	1.7
Bagasse production	MINBAG	2.55	2.55	2.55	2.55	2.55	2.55
Coal extraction	MINCOA	2.84107 5	2.84107 5	2.84107 5	2.84107 5	2.84107 5	2.84107 5
Solar CPS potential	MINCSP	0	0	0	0	0	0
Hydro potential (dam)	MINDAM	0	0	0	0	0	0
Geothermal resources	MINGEO	0	0	0	0	0	0

Natural gas extraction	MINNGS	4.2	4.2	4.2	4.2	4.2	4.2
Offshore wind potential	MINOFW	0	0	0	0	0	0
Crude oil extraction	MINOIL	1.56887 2	1.56887 2	1.56887 2	1.56887 2	1.56887 2	1.56887 2
Onshore wind potential	MINONW	0	0	0	0	0	0
Oilpalm dedicated production (biodiesel)	MINOPL	10.5	10.5	10.5	10.5	10.5	10.5
Hydro potential (run of river)	MINROR	0	0	0	0	0	0
Sugarcane dedicated production (bioethanol)	MINSGC	5.7	5.7	5.7	5.7	5.7	5.7
Solar PV potential	MINSOL	0	0	0	0	0	0
Uranium production	MINURN	0.3431	0.3431	0.3431	0.3431	0.3431	0.3431
Wood extraction	MINWOO	3.66	3.66	3.66	3.66	3.66	3.66
Natural gas boiler	NGSBOI	0.14722 2	0.14722 2	0.14722 2	0.14722 2	0.14722 2	0.14722 2
Natural gas boiler	NGSBOI002	0.14722 2	0.14722 2	0.14722 2	0.14722 2	0.14722 2	0.14722 2
Natural gas boiler + CCS	NGSBOICCS	3.66428 8	3.66428 8	3.66428 8	3.66428 8	3.66428 8	3.66428 8
Natural gas bus	NGSBUS	0	0	0	0	0	0
Natural gas furnace	NGSFUR	0.14722 2	0.14722 2	0.14722 2	0.14722 2	0.14722 2	0.14722 2
Natural gas furnace + CCS	NGSFURCCS	4.53918	4.53918	4.53918	4.53918	4.53918	4.53918

Natural gas four wheel drive	NGSFWD	0	0	0	0	0	0
Natural gas light duty vehicle	NGSLDV	0	0	0	0	0	0
Natural gas microbus	NGSMIC	0	0	0	0	0	0
Natural gas motorcycle	NGSMOT	0	0	0	0	0	0
Natural gas semi-trailer truck	NGSSTT	0	0	0	0	0	0
Natural gas stove	NGSSTV	0	0	0	0	0	0
Natural gas stove	NGSSTV002	0	0	0	0	0	0
Natural gas taxi	NGSTAX	0	0	0	0	0	0
Natural gas truck	NGSTCK	0	0	0	0	0	0
Natural gas technology	NGSTEC	0	0	0	0	0	0
Natural gas transport and distribution	NGSTRN	0	0	0	0	0	0
Natural gas water heater	NGSWHT	0	0	0	0	0	0
Biomass power plant (agriculture and forestry residues)	PWRAFR	1.61111 1	1.61111 1	1.61111 1	1.61111 1	1.61111 1	1.61111 1
Biomass power plant + CCS (agriculture and forestry residues)	PWRAFRCCS	17.685	17.685	17.685	17.685	17.685	17.685
Coal power plant	PWRCOA	2.22222 2	1.94444 4	1.94444 4	1.94444 4	1.94444 4	1.94444 4
Coal power plant + CCS	PWRCOACCS	13.1152 2	13.1152 2	13.1152 2	13.1152 2	13.1152 2	13.1152 2

CSP power plant	PWRCSP	0.80833 3	0.80833 3	0.80833 3	0.80833 3	0.80833 3	0.80833 3
Hydro power plant (dam)	PWRDAM	0	0	0	0	0	0
Distribution electricity technology	PWRDST	0	0	0	0	0	0
Geothermal power plant	PWRGEO	0	0	0	0	0	0
Distributed PV network	PWRMCG	0	0	0	0	0	0
Natural gas power plant	PWRNGS	0.55555 6	0.55555 6	0.55555 6	0.55555 6	0.55555 6	0.55555 6
Natural gas power plant + CCS	PWRNGSCCS	6.41526 1	6.41526 1	6.41526 1	6.41526 1	6.41526 1	6.41526 1
Nuclear power plant (SMR)	PWRNUC	1	1	1	1	1	1
Offshore wind power plant	PWROFW	0	0	0	0	0	0
Onshore wind power plant	PWRONW	0	0	0	0	0	0
Hydro power plant (run-of-river)	PWRROR	0	0	0	0	0	0
Recharging station	PWRRST	0	0	0	0	0	0
Individual photovoltaic solution (Rooftop PV)	PWRRTP	0	0	0	0	0	0
Solar PV Utility	PWRSOL	0	0	0	0	0	0
Solar PV utility + battery system	PWRSOLBAT	0	0	0	0	0	0
Diesel plant standalone	PWRSTD	0	0	0	0	0	0
Transmission electricity technology	PWRTRN	0	0	0	0	0	0

Biomass power plant (wood)	PWRWOO	1.61111 1	1.61111 1	1.61111 1	1.61111 1	1.61111 1	1.61111 1
Biomass power plant + CCS (wood)	PWRWOOCCS	17.685	17.685	17.685	17.685	17.685	17.685
High efficiency refrigerator	REFHIG	0	0	0	0	0	0
High efficiency refrigerator	REFHIG002	0	0	0	0	0	0
Low efficiency refrigerator	REFLOW	0	0	0	0	0	0
Low efficiency refrigerator	REFLOW002	0	0	0	0	0	0
High efficiency TV	TVUHIG	0	0	0	0	0	0
Low efficiency TV	TVULOW	0	0	0	0	0	0
ALK Electrolyzer	UPSALK	0	0	0	0	0	0
Blending diesel-biodiesel	UPSBDB	0	0	0	0	0	0
Biodiesel plant	UPSBDL	0	0	0	0	0	0
Blending gasoline-bioethanol	UPSBGB	0	0	0	0	0	0
Destillery	UPSDET	0	0	0	0	0	0
LPG plant	UPSLPG	0.67	0.67	0.67	0.67	0.67	0.67
PEM Electrolizer	UPSPEM	0	0	0	0	0	0
Refinery	UPSREF	0.71775	0.71775	0.71775	0.71775	0.71775	0.71775
Regasification Plant	UPSREG	0	0	0	0	0	0
Steam Methane Reforming plant	UPSSMR	0	0	0	0	0	0

Steam Methane Reforming plant + CCS	UPSSMRCCS	2.73403 9	2.73403 9	2.73403 9	2.73403 9	2.73403 9	2.73403 9
Wood stove	WOOSTV	0	0	0	0	0	0
Wood technology	WOOTEC	0	0	0	0	0	0
High efficiency washer	WSHHIG	0	0	0	0	0	0
Low efficiency washer	WSHLOW	0	0	0	0	0	0

A1.5 - Limitations of the model

There are several limitations to the OSeMOSYS-COL model that should be addressed. Generally, the OSeMOSYS modelling framework is not immune to many of the general criticisms that can be levelled at energy system optimisation models (ESOMs). First, ESOMs make unrealistic assumptions regarding the perfect rationality and perfect foresight of agents, which results in the least cost, optimal solution being chosen. In reality, there are many factors (beyond cost minimisation) that affect energy system planning and decision-making (e.g. infrastructural inertia, behavioural biases, institutional barriers, equity, and political and financial preferences). Similarly, many of the assumptions that are made are actually highly uncertain, such as future demand, fuel prices and technology costs, which can profoundly affect decision making.

Second, OSeMOSYS framework is a simple modelling environment. Computational simplifications and aggregations are made in the representation of the energy system. As such, to remain solvable, the Colombian version adopted omits several important factors that could affect results. For example, there is only a single annual time slice, there is no spatial resolution and there is a lack of technological detail. This can omit issues with renewable intermittency, network capacity constraints. Further work to assess the feasibility of intra/inter day/seasonal intermittency is a crucial next step and would give greater insights into feasible pathways for the power sector. The model can also improve from better energy system detail (e.g. green ammonia production, energy exports).

Third, the demand assumptions that were adopted do not account for country-specific barriers, idiosyncrasies and infrastructure constraints. This was predominantly due to a lack of available data. Instead, we utilised generic projections for the Global South from an international study. Further research into energy demand reduction potential in the Colombian context would be indispensable for future energy scenarios.

Fourth, our analysis only presents a pathway for the Colombian energy system, which only contributes towards approximately 30% of the country's territorial emissions. The modelling framework that we adopted does not represent Land Use, Land Use Change and Forestry (LULUCF), which make up the majority of Colombia's emissions and will be crucial for Colombia to achieve its emissions targets. Similarly, there is a lack of linkages in the OSeMOSY-COL model with land use, including interactions between land availability, biomass potential and agriculture, as well as residual emissions from the energy system and sequestration from nature-based solutions.

Finally, we adopted techno-economic assumptions from Plazas-Niño et al. (2023a, 2023b). Any long-term cost assumptions have a high degree of uncertainty and can change dramatically over a short period of time as they rely on assumptions that are

constantly evolving (technology improvement/innovation, price volatility, finance, demand). ESOMs are highly sensitive to cost assumptions in particular, so these should be updated with the latest available data to - however, this was outside the remit of this analysis due to time constraints.

As such, whilst this modelling exercise can provide valuable insights for strategic energy system planning in Colombia's, the outputs should be treated as a decision-support tool, rather than a predictive forecast. Further work can enhance the realism of the FTT pathway and ensure it is policy-relevant for Colombian decision-makers.

A2. Global oil model used to model production

The model adopts a field-level, bottom-up representation of the global oil market. It assumes market conditions that are underpinned by profit-driven investment, focusing on both oil and gas demand at the global level. In effect, the model solves in a dynamic recursive fashion to meet demand based on prioritising the lowest breakeven cost assets. The supply-side dataset, including field-level production and economic parameters, is sourced from Rystad UCube, while demand trajectories are drawn from the IEA World Energy Outlook 2024 under the Stated Policies (STEPS), Announced Pledges (APS), and Net Zero Emissions (NZE) (IEA, 2023b; IEA, 2024b).

The model incorporates a comprehensive representation of the geological and economic characteristics of upstream oil resources, including field-level production profiles and breakeven prices. After basic data cleaning of the Rystad UCube database, such as excluding seasonal/abandoned fields or fields reporting negative production or cost values, we model over 46,000 oil and 18,000 gas fields across 158 countries. The dataset includes fields at different life-cycle stages (producing, under development, discovered, and undiscovered) and covers different resource categories from conventional to unconventional.

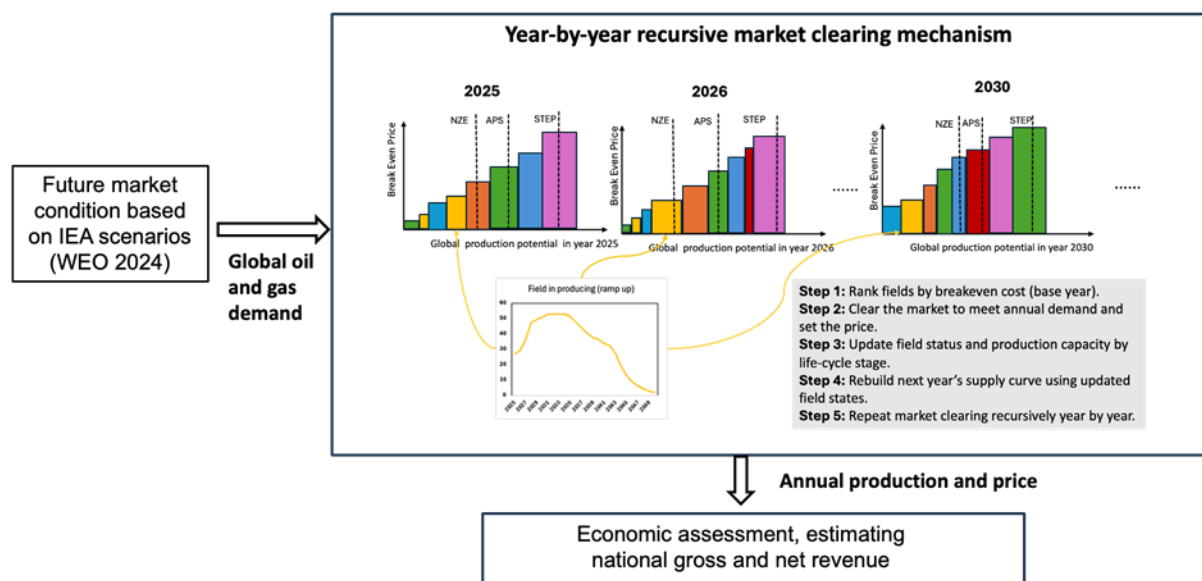


Figure A2.1. Global dynamic oil and gas supply mechanism diagram

The model illustrated in Figure A2.1 above employs a recursive market-clearing mechanism to simulate the annual equilibrium between global supply and demand for oil from 2026 to 2050. In each year:

- Active fields are ranked by breakeven cost to construct an annual supply curve.
- Demand for a given year is met by producing fields below a marginal or clearing price, which is set by the breakeven cost of the field(s) producing the last unit of global demand in that specific year.
- Fields with breakeven costs above this price are considered uneconomic and are deactivated in subsequent iterations, where demand decreases, or may be brought back in to supply if demand increases.
- Production capacities of active fields are updated according to their life-cycle stage to generate the next year's supply curve (as illustrated for a specific field in Figure 1), while the productive capacities of inactive fields are frozen once they become uneconomic and cease to deplete.

This dynamic recursive process enables the model to track how field level production (aggregated by country) and prices evolve over time under different global demand pathways. Figure A2.2 below depicts oil market-clearing outcomes for 2030, 2040, and 2050 under the STEPS and NZE scenarios as an illustrative example.

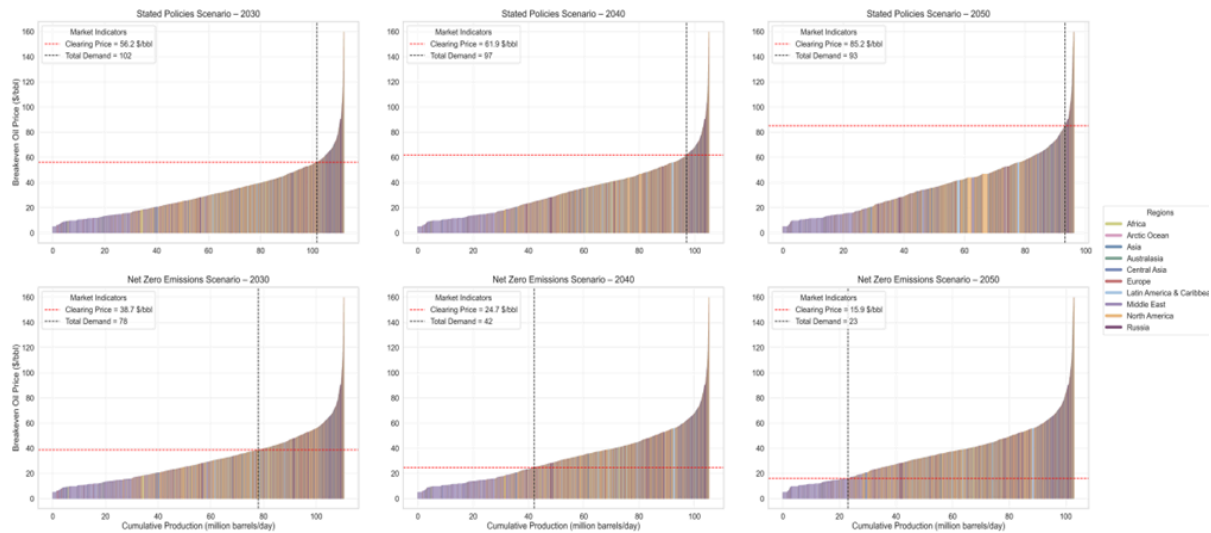


Figure A2.2. Oil market clearing outcomes for 2030, 2040 and 2050 under STEPS and NZE scenarios. Each coloured 'line'(block) represents production from an individual field of specific region, at a specific breakeven cost. The breakeven costs are the levelised costs of production of that field in a given year, to include annualised capital, operating costs and upstream fiscal regime. Fields to the left of demand line change over time according to their life-cycle stages. Fields to the right of the demand line are uneconomic in this scenario; once excluded from demand, their production is frozen and no longer depleted. The price is solved annually through a market-clearing process, ensuring that total supply meets demand in each year. This clearing price is where the black vertical dashed line, representing demand, intersects with the marginal project – and is represented by the red horizontal dashed line.

There are a number of key limitations to the current approach that need to be recognised -

- The current fiscal regime is incorporated into the breakeven costs. It could be that a country such as Colombia might decide to change this regime in future years, altering project economics.
- This model version is not dynamic to being in a lower price world. In reality, projects would reconsider their operational decisions based on market prices, shifting to a short run marginal cost basis if needed, away from a full breakeven cost basis. Furthermore costs of supply could also reduce, as suppliers responded to a lower price world.
- The model does not account for production requirements

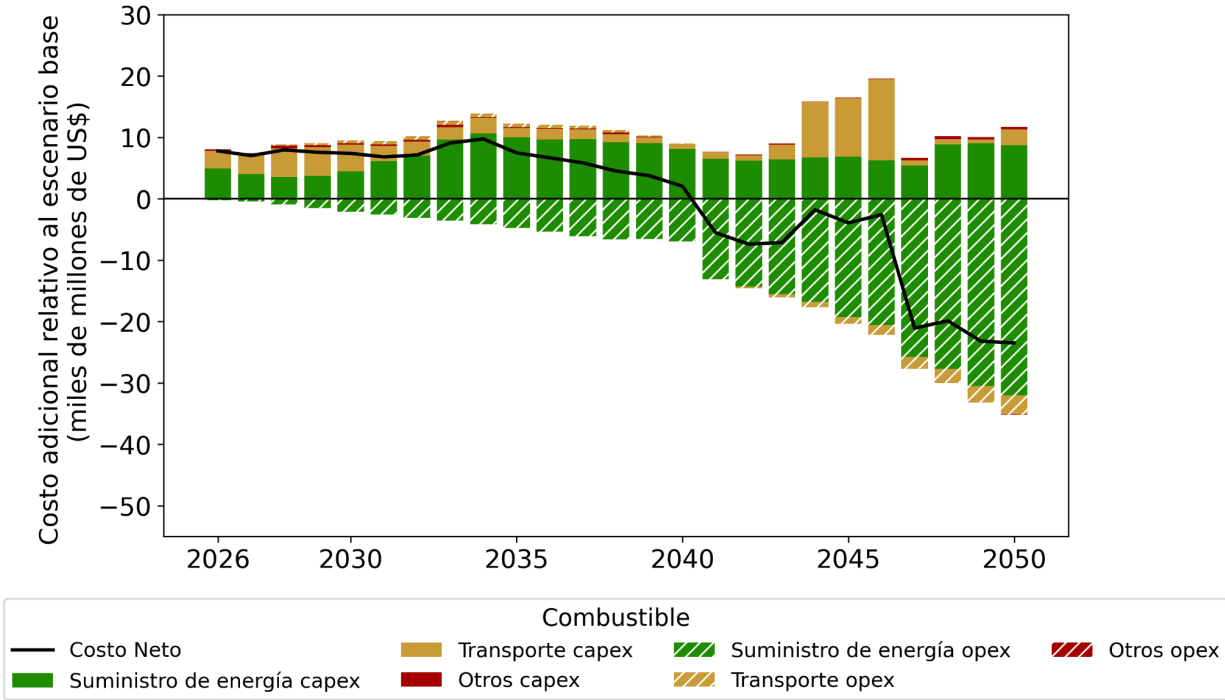
A3. Spanish translations of ES Figure and Table

Tabla A3.1. Objetivos sectoriales para orientar la planificación de la descarbonización alineados con el escenario FFT modelado.

Objetivo	2030	2040	2050
Sector eléctrico			
Participación de electricidad generada a partir de fuentes renovables	90%	98%	100%
Electricidad generada a partir de fuentes solar, eólica y geotérmica	37%	60%	68%
Eliminación del carbón en el sector eléctrico	2045		
Eliminación del gas natural en el sector eléctrico	2050		
Crecimiento de la generación eléctrica para cubrir la electrificación (relativo a 2026)	35%	167%	309%
Transporte			
Electrificación de la flota de vehículos de carretera	18%	59%	100%
Electrificación del transporte público	13%	49%	100%
Industria			
Demanda de calor cubierta por fuentes bajas en carbono	63%	80%	93%
[excluyendo biomasa]	22%	47%	68%
Demanda de calor cubierta por hidrógeno	0%	1%	1.8%

Edificios			
Eliminación de la leña como fuente de calor	2040		
Eliminación del gas natural	2045		
Electrificación de los usos finales en viviendas	75%	100%	100%
Electrificación de los usos finales en el sector comercial y público	82%	96%	100%

Figura A3.1. Inversión de capital (capex) y costos operativos (opex) para la eliminación de combustibles fósiles en Colombia en relación con el escenario de referencia (business-as-usual).



References

- Carton, W., Hougaard, I., Markusson, N., Lund, J.F., 2023. Is carbon removal delaying emission reductions? WIREs Climate Change 14, e826. <https://doi.org/10.1002/wcc.826>
- [Climate Change Committee, 2025. The Seventh Carbon Budget.](#)
- Gidden, M.J., Joshi, S., Armitage, J.J., Christ, A.-B., Boettcher, M., Brutschin, E., Köberle, A.C., Riahi, K., Schellnhuber, H.J., Schleussner, C.-F., Rogelj, J., 2025. A prudent planetary limit for geologic carbon storage. Nature 645, 124–132. <https://doi.org/10.1038/s41586-025-09423-y>
- Gobierno de Colombia, 2020. Actualización de la Contribución Determinada a Nivel Nacional de Colombia (NDC).
- Grant, N., Hawkes, A., Mittal, S., Gambhir, A., 2021. Confronting mitigation deterrence in low-carbon scenarios. Environ. Res. Lett. 16, 064099. <https://doi.org/10.1088/1748-9326/ac0749>
- Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., Mccollum, D.L., Rao, N.D., Riahi, K., Rogelj, J., Stercke, S.D., Cullen, J., Frank, S., Fricko, O., Guo, F., Gidden, M., Havlík, P., Huppmann, D., Kiesewetter, G., Rafaj, P., Schoepp, W., Valin, H., 2018. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. <https://doi.org/10.1038/s41560-018-0172-6>
- IEA, 2025. An Energy Sector Roadmap to Net Zero Emissions in Colombia.
- Kazlou, T., Cherp, A., Jewell, J., 2024. Feasible deployment of carbon capture and storage and the requirements of climate targets. Nat. Clim. Chang. 14, 1047–1055. <https://doi.org/10.1038/s41558-024-02104-0>
- McLaren, D., 2020. Quantifying the potential scale of mitigation deterrence from greenhouse gas removal techniques. Climatic Change 162, 2411–2428. <https://doi.org/10.1007/s10584-020-02732-3>

- Plazas-Niño, F.A., Yeganyan, R., Cannone, C., Howells, M., Quirós-Tortós, J., 2023a. Informing sustainable energy policy in developing countries: An assessment of decarbonization pathways in Colombia using open energy system optimization modelling. *Energy Strategy Reviews* 50, 101226. <https://doi.org/10.1016/j.esr.2023.101226>
- Plazas-Niño, F.A., Ortiz-Pimiento, N.R., Quirós-Tortós, J., 2023b. Supporting energy system modelling in developing countries: Techno-economic energy dataset for open modelling of decarbonization pathways in Colombia. *Data in Brief* 48, 109268. <https://doi.org/10.1016/j.dib.2023.109268>

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