The Razor's Edge

The 1.5°C goal of the Paris Climate Agreement is still feasible but the window is closing

OEreCM Part I

Energy & Industry-related Mitigation

Part I: Energy & Industry Mitigation

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The Razor's Edge: the 1.5°C goal of the Paris Climate Agreement is still feasible but the window is closing (Part I)

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Highlights

- Global energy and industry emissions peaked in 2024 and are expected to decline further in 2025.
- Renewables have ramped up at a far greater pace than previously anticipated and are on track to providing nearly 100% of new installed power capacity well before 2030.
- A more rapid reduction in carbon emissions is required to keep the 1.5°C window, requiring significant investments in renewable infrastructure and energy efficiency.
- LULUCF emissions must be phased out by 2035 to keep the 1.5°C window.
- The potential for nature-based carbon removal is significant, but Afforestation, Reforestation, and Revegetation (ARR) efforts need to rapidly increase.
- The OE 'razor's edge' Climate Model (OEreCM) puts forth a scenario in which global emissions are reduced 41% by 2035, 81% by 2045, and 98% by 2055.
- Versus a BAU baseline (~2.3°C), OEreCM avoids 6103.8 GtCO2 emissions between 2025 and 2055.
- GMST reaches a peak of 1.63°C above pre-industrial levels in 2043, declining to 1.38°C in 2100 (using an 11-year running mean) for a 2025-2100 average of 1.50°C.
- It is projected that land sinks will roughly double in capacity by 2040 then gradually decline, while ocean sinks will steadily decline throughout the century.

Abstract

Many high-ambition climate models underestimate the volume of post-Covid 19 carbon dioxide emissions, overestimate the potential for engineered carbon dioxide removal, or both. The One Earth 'razors's edge' Climate Model (OEreCM), incorporates the latest real economy data on fossil fuel and renewable energy deployments 2019-2024 to build a realistic, yet ambitious scenario to decarbonize the global economy across all sectors by 2055. The model has four phases: 'Warm-up' (2025-2030); 'Low-hanging Fruit' (2030-2040); 'Ramp-up' (2040-2050); and 'Deep Decarbonization' (2050-2055). Total Final Energy is 403 EJ in 2055 with an additional 41 EJ for hydrogen and E-fuel, met almost entirely by renewable energy sources. 197 EJ of avoided energy demand is provided by energy efficiency measures. To achieve the long term 1.5°C goal of the Paris Climate Agreement, 200 GtCO2 of nature-based carbon dioxide removal is required between 2025 and 2055 (with a long tail of additional removal through 2100). MAGICC7.5, a prime reduced-complexity model to determine radiative forcing of greenhouse gases and projected global temperature rise, establishes a peak of 1.6°C in global temperature rise 2035-2055, declining to 1.4°C 2070-2100, using an 11-year running mean.

Introduction

1a. Background & Summary

Several recent developments have called into question the feasibility of the 1.5°C goal of the Paris Climate Agreement. First, the Remaining Carbon Budget (RCB) established in Working Group 1 (WG1) of the IPCC Sixth Assessment Report (AR6) was subsequently adjusted downwards to incorporate changes in historic aerosol emissions, estimates of permafrost emissions, and other factors used to calibrate prime reduced-complexity models, including MAGICC7.5 [1]. Few, if any, climate mitigation models use the newly updated carbon budget.

Second, after a drop in global fossil fuel emissions in 2020 due to the Covid-19 pandemic, emissions quickly rebounded, remaining comparable to 2019 levels through 2024 [2]. While substantial pledges were made at the twenty-eighth UNFCCC Conference of Parties (COP28) – to triple renewable power generation and cut net CO2 emissions in half by 2030 -- it is unlikely these goals will be achieved. Most high-ambition mitigation scenarios depict a steep decline in emissions commencing in 2020 [3], which clearly did not occur, and it is likely that institutional constraints could further curtail their timely implementation [4].

Third, recent efforts utilizing Global Dynamic Vegetative Models (GDVMs) to determine the technical potential of Carbon Dioxide Removal (CDR) from Afforestation, Reforestation and Revegetation (ARR) under 1.5°C and 2°C of global average temperature rise, have constrained the extent of nature-based CDR in both forest and non-forest biomes [5]. The quantity of CDR used in many climate mitigation scenarios far exceeds the total available when considering demand for other land uses such as agriculture, forestry, and urban development [6].

The One Earth 'razor's edge' Climate Model (OEreCM) presents a comprehensive climate mitigation scenario that takes into account all three of these factors – a reduced RCB; increased CO2 emissions to 2024 (minus the Covid-19 drop in 2020); and constrained CDR potential – to render an estimate of cumulative CO2 emissions by year, from 2020 to 2055. The model depicts a rapid decarbonization of energy and industry sectors, alongside a ramp-up of nature-based CDR and other natural climate solutions within estimated constraints.

The results indicate that humanity is now walking on a "razor's edge" of climate mitigation potential. Even with a rapid decarbonization of energy and industry commencing in 2030 – an average of approximately 5.1% per annum (~1.6 GtCO2) between 2030-2045 – combined with a rapid ramp-up of nature-based CDR commencing in 2025 (totaling ~160 GtCO2 removed by 2050 and ~440 GtCO2 removed by 2100) – the model just barely achieves the central goal of the Paris Climate Agreement, resulting in a long term Global Mean Surface Temperature (GSMT) of 1.5°C for the years 2025-2100 (> 50% probability). The scenario requires a 20-year overshoot to approximately 1.6°C (2035-2055), before returning to 1.4°C towards the end of the century (Figure 1).

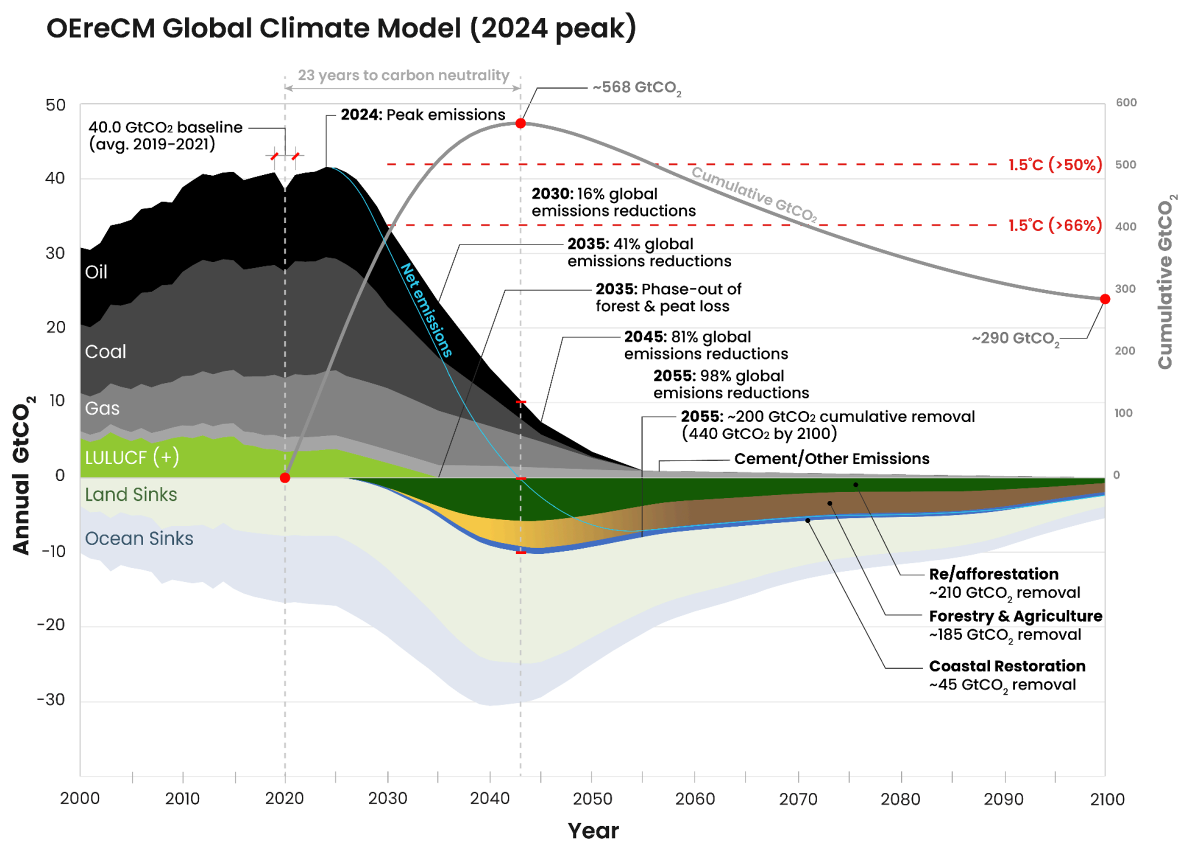

Figure 1. The One Earth 'razor's edge' Climate Model (OEreCM). Cumulative anthropogenic emissions above 2020 levels peak at 568 GtCO2 in 2043, declining to 290 GtCO2 by 2100 in line with a long term rise in Global Surface Mean Temperature (GSMT) to 1.5°C above early-industrial levels (c. 1850-1900). This is achieved by (1) a rapid reduction in fossil fuel emissions (gray and black) through the rapid deployment of renewable energy sources, meeting 98% of total projected energy demand by 2055; and (2) a full phaseout of deforestation and peat loss by 2035, alongside 200 GtCO2 of carbon removal by 2055 and 440 GtCO2 by 2100 through 10 ecosystem restoration pathways (green, brown, gold, blue). The greenhouse gas scenario was run with MAGICC7.5, a prime reduced-complexity model to determine radiative forcing and projected global temperature rise, based on IMAGE quantification of the SSP1-Baseline scenario in the IPCC SR1.5 database. The model projects that natural land carbon sinks (light green) and ocean carbon sinks (light blue) continue to function through 2100, but their capacity to absorb additional carbon declines in the second half of the century. The model results in an overshoot to ~1.6°C 2035-2055 with a fair likelihood (>50% chance) of returning to ~1.4°C by 2100. (Note: The drop in fossil fuel emissions due to the COVID-19 pandemic appears to occur before 2020 in the scenario timeline; this is due to the standard practice of plotting average annual emissions and does not affect final modeling outcomes). Credit: One Earth

1b. Understanding the 1.5°C goal

It is important to clarify that the adopted goal of the Paris Climate Agreement includes the possibility of temporarily exceeding 1.5°C Global Mean Surface Temperature (GMST) to “well below 2°C” before returning to “below 1.5°C” by no later than 2100 [7]. The general public remains extremely confused about this point. Many believe the Paris Agreement contains two alternative goals, 1.5° or 2°C, presenting a range of options from which countries can choose. This is not the case.

To reiterate, the ‘1.5°C goal’ should be understood as the long term objective to bring global average temperature rise – defined as the average of combined land surface air and sea surface temperatures measured uniformly across the entire globe – to below 1.5°C by the end of the century and sustained consistently over multiple decades, as compared with the average GMST from the early industrial era (circa 1850-1900).

Overshoots in the Paris Agreement are allowed, and as shown in this paper, likely unavoidable. However, the overshoot must be limited in extent and duration. An overshoot to “well below 2°C” is still open to interpretation by UNFCCC parties, but overshoot models are now commonly divided in two groups – “low overshoot” with approximately 1.6°C in global temperature rise, and “medium to high” overshoots in the range of 1.7°C to 1.9°C in temperature rise [8]. Models that go beyond 1.8°C are considered by many to be misaligned with the Paris Agreement, as there would likely be insufficient time and CDR potential to return to 1.5°C by the end of the century.

Another point of confusion is the duration of global average temperature rise associated with the 1.5°C goal. Recent news articles could lead readers to believe that the world will surpass the 1.5°C limit within the next few years, or even that we have already done so. For example, in 2023 El Niño conditions led to a temporary GMST of 1.5°C, causing many reporters and NGOs to misstate that the 1.5°C limit had been breached. Others have incorrectly surmised that when the 1.5°C carbon budget (> 50% likelihood) is surpassed, it will no longer be possible to achieve the Paris Agreement goal [9].

An understanding of ‘centered running means’ is helpful in clearing up these misconceptions. While multi-decadal centered running means of 20 years or more are common in climate models, an 11-year centered running mean, while more sensitive, has been shown to be effective in establishing global average temperature rise from anthropogenic sources, screening out variations in non-anthropogenic warming from solar forcing [10]. In some ways, the 11-year running mean could be thought of as the smallest unit of time for measuring historic temperature anomalies. OEreCM uses an 11-year running mean to plot GSMT rise, arriving at a peak temperature of 1.63°C in 2043, averaging years 2038-2048.

Based on the results of OEreCM -- which factors in reduced carbon budgets; limits to the speed of industrial decarbonization; constraints in nature-based carbon removal; as well as anticipated declines in the background rate of carbon absorption from natural land and ocean sinks -- we conclude that a temporary overshoot of approximately 1.6°C in this scenario would still allow the world to return to 1.4°C by the end of the century, achieving the 1.5°C goal of the Paris Climate Agreement. There is, however, an increasingly small window to do so.

1c. Energy & Industry Modeling

The OEreCM energy transition scenario is based on the One Earth Climate Model (OECM), which developed a global decarbonization framework based on 'just transition' principles in line with 1.5°C and 2°C pathways, using data on socioeconomic shifts as well as critical mineral constraints, projecting final energy demand for electricity, heat, and transport energy in 2050 by fuel type across ten global regions published in the book A*chieving the Paris Climate Agreement Goals*: *Global and Regional 100% Renewable Energy Scenarios* [11]. The model was subsequently refined in a series of papers [12, 13,14], detailing sector-specific transitions required to achieve the goal of limiting long term GMST to 1.5°C above early industrial levels, which were then integrated in a new model (OECM 2.0) published in the book *Achieving the Paris Climate Agreement Goals: Part 2,* supporting target setting for the finance industry [15].

OECM 2.0 provided, for the first time, detailed transition pathways covering Scope 1, 2 and 3 emissions across several major industry sectors using the Global Industry Classification Standard (GICS) with the goal of achieving net-zero emissions across all sectors globally by 2050, including Aluminum, Steel, Cement, Chemicals (Pharmaceutical, Agricultural, Inorganic, Fibers/Rubber, Organic), and Leather & Textiles. It also modeled four major services sectors – Agriculture & Food products; Forestry & Wood products; Fisheries; and Water/Waste Utilities. The model was further refined to develop science-based sectoral emissions targets at the national level (for G20 countries) [16].

The OECM model architecture consists of three discrete modules – Energy System Model (EM); Transport Energy Model (TRAEM); and the Power Systems Analysis model [R]E 24/7 – that when merged into a unified framework allow a detailed simulation of the global electricity system in 1-hour increments, including power distribution and storage infrastructure requirements. In addition, a fourth model – High Efficiency Buildings (HEBs) – is leveraged to create bottom-up demand scenarios for residential and commercial construction.

To reach nearly 100% renewables globally by 2050, nine proven power generation sources were considered in the One Earth transition scenario – Solar PV, Concentrating solar (CSP), Geothermal power, Onshore wind, Offshore wind, Ocean energy, Hydropower, Biomass power, and Hydrogen power -- with an allocation of Electricity for E-fuel production. Four direct heating sources were used – Solar heat, Geothermal heat, Hydrogen heat, and Sustainable biomass – with an allocation of heat production from District heating and Combined Heat & Power (CHP). Three fuel sources were included – Sustainable biofuels, Sustainable E-fuel, and Green hydrogen. For both Heat and Transport, electricity is also considered a fuel source, with the share of renewable electricity increasing commensurate with overall power generation mix.

Utilizing these models, the OECM transition scenario published in 2023 established a total final energy demand of 440 EJ in 2050 (including 73 EJ of electricity for hydrogen and E-fuel production), with an additional 46 PJ equivalent of fossil fuel feedstocks for non-energy use. The model established an upper limit to the share of total energy demand met exclusively through renewable electricity, due largely to limits on the availability and recycling potential of critical minerals – meeting approximately 69% of total energy demand directly through renewable electricity, 25% through direct heating sources, and 6% through portable fuels.

Modifications in OEreCM. The original OECM scenario, like most high-ambition decarbonization models, rendered a steep decline in fossil fuel emissions pursuant to the dip in production during the Covid-19 pandemic in 2020, a decline that did not transpire. Fossil fuel emissions rebounded in 2021 and continued to rise in 2022 and 2023. However, the rate of growth decreased in 2024, which some are hailing as a potential global peak in fossil fuel emissions [17]. The new OEreCM transition scenario presented here incorporates these recent developments, presenting a gradual and more feasible decline in fossil fuel production in the years 2025-2029. From 2030, it follows similar pathways used in the original OECM scenario, but shifted five years into the future, with a steep emissions decline in the years 2030-2045 (~5.1% per annum average). Instead of achieving zero energy-related emissions by 2050, OEreCM achieves a 98% reduction in combined energy and industry emissions (including cement) by 2055, which gradually tapers to zero in 2100.

In addition to these overarching changes in the OEreCM energy transition scenario, many additional adjustments were made to align more closely with recent trends in renewable and fossil fuel energy development, incorporating new data sets and refined calculation methods. These adjustments include:

- Updated CAGRs for all RE sources developed based on data plotting actual growth rates between 2019 and 2024
- Updated CAGRs for FF generation based on data plotting actual growth rates between 2019 and 2024
- Reduced H2 production and more accurate estimates of power demand for hydrogen and E-fuel production
- Increased power demand for both IT sector and desalination sectors
- Inclusion of some advanced nuclear power capacity rather than a full phaseout of nuclear in the original OECM model
- Small amount of CCS/CCU factored in as part of the heavy industry transition scenario
- Updated curtailment model for Variable Renewable Energy (VRE) sources based on new research by IEA plotting technical curtailment values for 10 countries
- Revised CAGRs for road & rail electrification trends
- Revised CAGR for aviation trends
- Reduction in peak biomass heat from 54 EJ per OECM to 48 EJ, declining to 46 EJ by 2055
- Updated pipeline energy estimates incorporating hydrogen distribution

1d. Energy Transition Summary

The resulting OEreCM energy transition scenario establishes total final energy demand of 444 EJ in 2055, including 41 EJ for hydrogen and E-fuel production (Figure 2). While the total is comparable to final energy demand in the original OECM scenario (440 EJ in 2050), one major difference is a significant reduction in electricity for hydrogen and E-Fuel. In the OEreCM scenario, renewable power capacity triples from 2020 levels by 2029 (roughly in line with the COP28 pledge). From that point on, the transition becomes very rapid, achieving approximately 67% of total energy demand met by renewables in 2040 and 93% by 2050. From 2019 levels, total fossil fuel consumption is reduced by approximately 31% in 2035 and by 90% in 2050. A full fossil fuel phaseout for energy is complete by 2055.

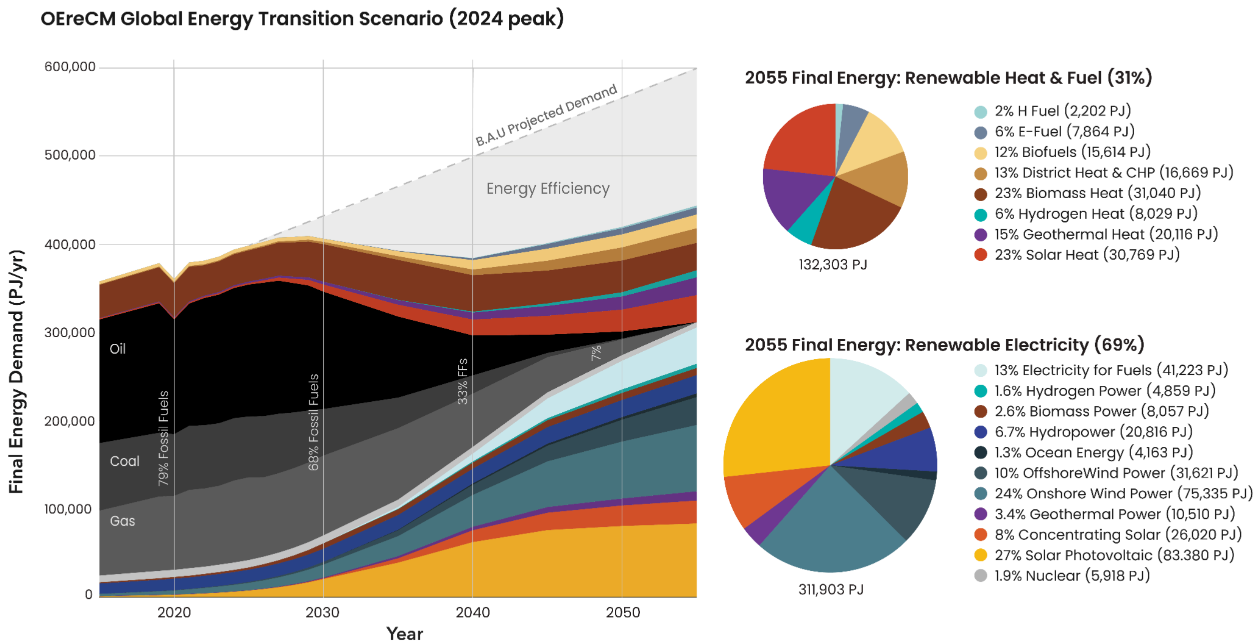

Figure 2. (Left) Final global energy delivery by modality and source in the OEreCM transition scenario, expanding from 379 exajoules in 2019 to 444 exajoules in 2055. The lower portion of the chart depicts final energy delivery met through electricity by power generation source. Electricity for sustainable E-fuel production is delineated as its own category, assumed to be a proportional mix of all ten renewable power generation sources. The central portion of the chart depicts final energy demand met through fossil fuels, which diminishes to zero by 2055. The upper portion of the chart depicts final energy demand met through non-electrical modalities, including both direct heating and portable fuels. Significant energy efficiency measures are required across all sectors to reduce total energy demand, with a BAU energy demand estimate of 600 exajoules by 2055. (Right) Final energy mix ratios in 2055 for renewable electricity and heat & fuel sources. Credit: One Earth, 2025.

In the scenario, by 2055 approximately 70.2% of total energy demand is met through renewable electricity (311.9 EJ), the majority of which is provided by wind and solar – 34% and 35% of total power respectively. Electricity used to produce hydrogen and E-fuel is typically classified as secondary energy, but it is included here in the final energy balance to highlight the significant power capacity required to produce these portable fuels. Direct use of hydrogen, E-fuel, and biofuel meet another 5.8% of total final energy demand (25.7 EJ). The remaining 24.0% of total final energy demand is met through direct heating sources, predominately solar heating and biomass – both of them meeting approximately 29% of total heat demand.

2. OEreCM Energy Transition

The sections below describe methods used for the revised energy transition scenario organized by three major supply modules – Electricity Generation (2a-1) and Installed Capacity (2a-2); Transport (2b); and Heat (2c) – with a discussion on Energy Efficiency potential (2d). This is followed by a summary of Final Energy consumption by sector (2e); and lastly total Primary Energy demand (2f-1) and resulting Energy & Industry CO2 emissions (2f-2).

2a. Electricity Generation & Installed Capacity

The renewable power sector appears to have reached a tipping point [18, 19]. Rapidly descending prices combined with increasing demand and more flexible transmission and storage options, suggest that the next 10 years will see exponential growth in renewable power capacity. Renewables made up 92.5% of global power expansion in 2024, and it is likely that nearly 100% of new power capacity will be provided by renewables before 2030 [20]. In addition, recent political conflicts have exposed the vulnerability of fossil fuel supply chains, further driving public investment in renewable generation [21].

Given these recent developments, one key objective of the OEreCM was to gather up-to-date global statistics on deployment rates for both renewable and non-renewable electricity generation between 2019-2023, developing estimated Compound Annual Growth Rates (CAGRs) to support a realistic forecast of power sector deployments in 2024 and 2025. For the years 2019-2022, actual statistics for power generation were taken from IEA World Energy Balances [22], which provide data for both installed capacity and electricity generation. The Statistical Review of World Energy provided actual statistics for 2023 installed capacity [23], and using average ratios of installed capacity to electricity generation (see Table 3), 2023 electricity generation values were derived. These were cross-referenced with other sources, including IRENA Renewable Energy Statistics [24], Ember Global Electricity Review [25], and Windpower Engineering & Development [26], in order to derive estimated CAGRs for each power source as shown in Table 1.

RE Power Growth (2019-2023)	*2024 CAGR*	Nuclear & FF Power Growth (2019-2023)	*2024 CAGR*
Solar - combined	*21.95%*	Coal % increase	*1.35%*
Solar - PV	22.31%	Lignite % increase	*0.30%*
Solar - CSP	4.02%		
Wind - combined	*17.44%*	Natural Gas % increase	*1.77%*
Wind - onshore	11.57%		
Wind - offshore	23.47%	Oil % increase	*-3.06%*
Wave power	0.00%	Diesel % increase	*-3.63%*
Geothermal power	1.45%		
Hydropower	1.11%	Nuclear % increase	*-0.30%*
Biomass/Biofuel Electricity	6.50%		

Table 1. Estimated Compound Average Growth Rates for renewable electricity generation (left) and nuclear & fossil fuel electricity generation (right) used in the OEreCM energy transition scenario, inferring annual growth in measured capacity above 2019 levels through 2023.

2a-1. Global Electricity Generation

The CAGR rates developed for the OEreCM scenario were applied to create 2024 and 2025 values for all electricity generation sources. For hydropower, wind power, and PV power, the CAGR rates were applied through 2030. For biomass, geothermal, and concentrating solar power (CSP), we expect a faster rate of growth to 2030, so the original more ambitious OECM values were used (shifted to 2030). The OECM values for ocean power and hydrogen power, however, were lowered in 2030, given the low penetration rates of these technologies. For fossil fuels the original OECM values were used (shifted to 2030). Exponential growth steps were applied to the intermediary years 2026, 2027, 2028, 2029 (13.0%, 16.5%, 20.0%, and 23.5% respectively) to bridge between the 2025 and 2030 targets. During the course of writing this manuscript, BloombergNEF released new primary energy statistics for 2024 [17], indicating a significant slowdown in coal production and increase in natural gas relative to the previously modeled CAGR estimates. These statistics were factored into slightly revised electricity generation values as shown in Table 2.

Electricity generation (TWh/a)	2015	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Fossil Fuels	**16,217**	**17,646**	**17,899**	**17,975**	**18,410**	**18,350**	**17,858**	**17,229**	**16,191**	**15,015**	**13,531**
Hard coal (& non-RE waste)	7,813	8,789	8,902	8,972	9,049	8,906	8,837	8,387	7,578	6,671	5,507
Lignite & Subbituminous coal	1,823	1,574	1,671	1,627	1,645	1,618	1,505	1,313	1,081	808	494
Natural Gas	5,557	6,560	6,525	6,634	7,004	7,137	6,819	6,834	6,851	6,872	6,896
Oil Products	866	607	648	628	601	584	595	598	588	577	553
Diesel	158	116	153	114	110	105	102	98	93	87	80
Hydrogen	-	-	-	0.01	0.04	0.25	2	3	5	8	11
Nuclear	2,570	2,808	2,685	2,744	2,735	2,735	2,744	2,754	2,767	2,783	2,800
Renewables	**5,510**	**7,948**	**8,559**	**9,208**	**9,960**	**10,835**	**12,008**	**13,408**	**15,073**	**17,046**	**19,381**
Biomass/Biofuel (& RE waste)	3,893	4,293	4,350	4,398	4,447	4,496	4,546	4,596	4,647	4,699	4,751
Hydropower	798	1,726	1,950	2,175	2,427	2,708	3,021	3,371	3,760	4,195	4,681
Wind onshore	36	138	170	210	259	320	395	488	602	743	918
Wind offshore	245	1,020	1,295	1,583	1,936	2,368	2,897	3,543	4,333	5,300	6,482
Ocean energy	446	659	683	727	775	825	975	1,164	1,395	1,665	1,975
PV	81	96	97	99	100	102	126	157	194	238	289
Solar thermal power plants	10	15	14	14	15	15	46	86	134	190	255
Geothermal	1	1	1	1	1	1	2	4	8	16	31
Total Electricity generation	**24,297**	**28,402**	**29,143**	**29,927**	**31,105**	**31,920**	**32,612**	**33,394**	**34,036**	**34,852**	**35,723**
% CHP generation	*15.4%*	*15.5%*	*15.0%*	*14.8%*	*14.6%*	*14.2%*	*14.1%*	*13.8%*	*13.4%*	*12.9%*	*12.3%*

Table 2. Electricity generation in terawatt-hours per year (TWh/a) for power plants by fuel type with actual values for 2015-2023, estimated 2025 values, and modeled OEreCM generation values for 2025-2030, including percentage of generation from Combined Heat & Power (CHP).

This provides a 2025 start year for the OEreCM electricity transition, revealing significant progress made in the decade since the Paris Climate Agreement was signed. The use of biomass (including the combustion of renewable waste products) more than doubled between 2015 and 2025 to 516 TWh. Onshore wind more than tripled and offshore wind saw 10x growth. Solar photovoltaic (PV) power was the biggest winner of the past ten years, with nearly 10x growth reaching 2368 TWh in 2025. Hydropower, Solar thermal and geothermal power plants also saw significant growth. This reflects a quadrupling of Variable Renewable Energy (VRE), which made up 4.4% of total electricity generation in 2015 and now makes up an estimated 16.9% of electricity generation.

The OEreCM scenario shows a continued growth in generation from power plants by 2030, reaching 31,312 TWh, plus an additional 4,410 TWh from CHP (see below), as fossil fuel generation declines. All VRE sources increase – most notably Solar PV that increases 173% to 6482 TWh and onshore wind that increases 73% to 4681 TWh by 2030. Nuclear and hydropower increase only slightly, while CSP, Geothermal, and Ocean power begin a gradual climb that will accelerate post-2030. According to the scenario, by 2030 VRE will make up 33.9% of all electricity generation, and carbon-free sources (all renewables plus nuclear) will make up 62.1% of electricity generation. This is roughly inline with recent ‘100% Clean Electricity by 2035’ scenarios developed by the National Renewable Energy Lab (NREL) for the U.S. [27].

In the 2030-2040 time period, there is a significant jump in electricity generation to keep up with an increasingly electrified world. Electric vehicles, electric cooktop appliances, electric heat pumps, and a transition to electrified industrial processes are a few of the many innovations that will allow traditionally fossil fuel-based technologies to be decarbonized. OEreCM optimizes for a fast transition away from carbon-intensive coal power generation, with OECD countries ceasing coal-fired electricity generation by 2035, and all countries following suit by 2050. Oil-fired power generation currently plays a limited role globally and is expected to be entirely phased out before 2050. Natural gas is set to play a gradually diminishing role in power generation, until a full phaseout in 2055. Meanwhile, solar and wind generation will climb steeply providing 78% of power generation capacity by 2055. The renewable energy transition, shown in Figure 3, is projected to rely primarily on solar and wind with support from a mix of other renewable energy solutions suitable for specific geographic contexts.

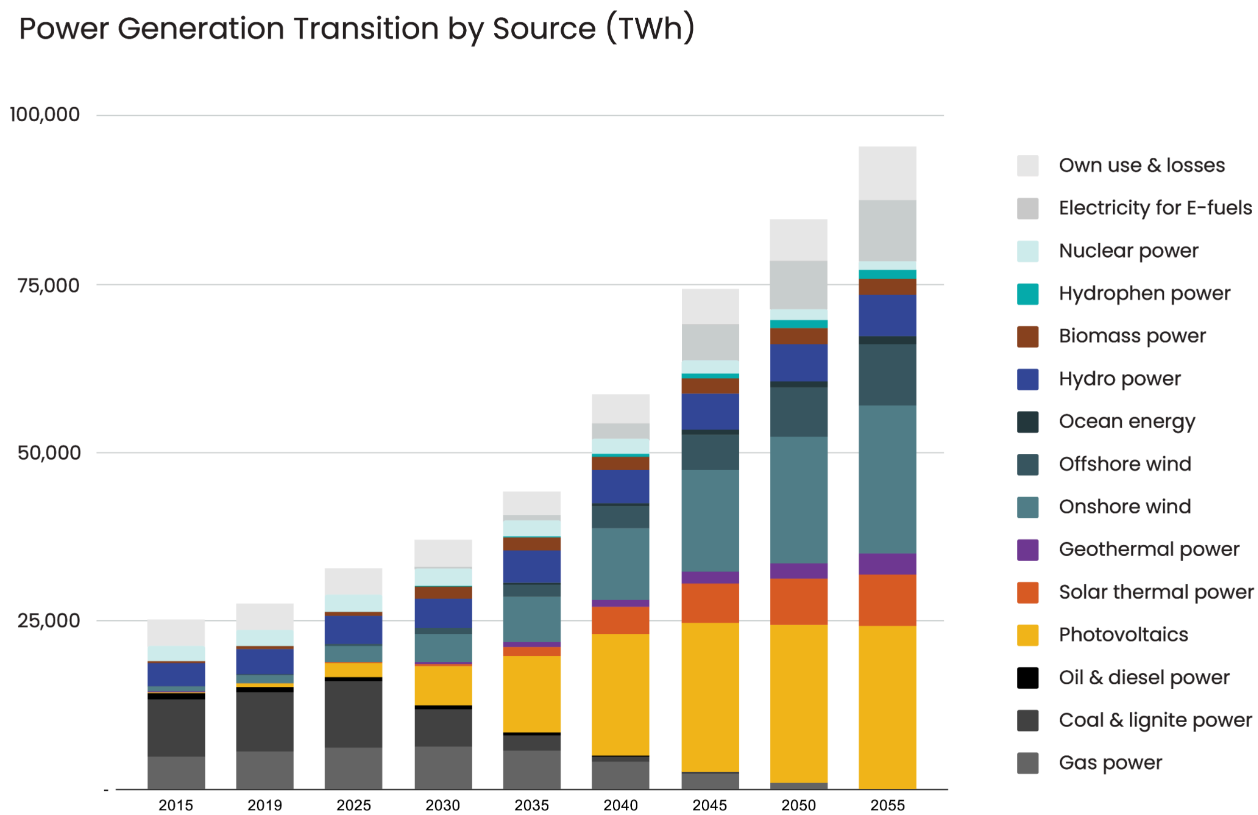

Figure 3. Power generation by energy source. In 2019 power generation provided 26,969 terrawatt-hours (TWh), with renewables playing a relatively small role (26.1% of total electricity generation). In 2055, power generation is projected to reach 96,051 TWh, with renewables providing 97.8% of total electricity generation (the balance met by nuclear). Electricity for hydrogen and E-fuel fuel production is broken out as a secondary energy category, assumed to

be a proportional mix of all ten renewable power generation sources (including some nuclear generation). Transmission losses and 'own consumption' also increase over time, but as a reduced share of total electricity generation. Credit: Spencer Scott, One Earth

Approximately 85% of total power generation is currently provided by dedicated power plants and another 15% by Combined Heat & Power (CHP) generation. Long term transitions for both are developed – with CHP gradually declining from 4410 TWh in 2030 to 2351 TWh in 2055 as CHP generation converts to 100% renewables, while power plant generation triples from 31,312 TWh in 2030 to 93,700 TWh in 2055. Distribution losses and 'own consumption' continue to be significant, though the rate of loss declines from 16.2% of total electricity generated in 2019 to 9.8% in 2055. By 2055, total final electricity consumption in OEreCM (excluding own consumption, losses, and electricity for E-fuels) is 75.2 TWh, significantly higher than the original OECM scenario with total final electricity consumption of 65.0 TWh.

2a-2. Installed Capacity

To estimate the extent of installed capacity required to meet electricity generation demand per OEreCM, accurate efficiency ratios are required. These were developed by importing actual installed capacity statistics from IRENA [24] and IEA [22] for the years 2015, 2019, 2020, 2021, 2022. Efficiency ratios for the years 2023-2025 were created by averaging 2021 and 2022 and efficiency ratios for each energy source. Similar to OECM, gradual efficiency improvements are applied in 5-year steps to 2050 as shown in Table 3. For example, it is estimated that natural gas plants will become 50% more efficient and onshore wind 37% more efficient between 2025 and 2050. Oil and biomass become somewhat less efficient due to a major reduction in feedstocks. Solar thermal and ocean power are assumed to be slightly less efficient given uncertainties around wear and tear over time.

TWhs generated per GW of Installed Capacity			
	2025	2050	*% increase*
Fossil Fuels (weighted average)	***3.940***	***5.319***	***35%***
- Hard coal (& non-renewable waste)	4.915	4.993	*2%*
- Lignite	3.759	4.993	*33%*
- Gas (w/o H2)	3.546	5.319	*50%*
- Oil	1.638	1.137	*-31%*
- Diesel	2.284	1.521	*-33%*
Nuclear	7.223	7.671	*6%*
Hydrogen	2.000	3.151	*58%*
Renewables (weighted average)	***2.187***	***2.305***	***5%***
- Hydropower	3.135	3.500	*12%*
- Wind onshore	2.271	3.100	*37%*
- Wind offshore	2.625	4.000	*52%*
- PV	1.181	1.450	*23%*
- Biomass (& renewable waste)	4.641	4.374	*-6%*
- Geothermal	6.629	7.355	*11%*
- Solar thermal power plants	2.301	2.250	*-2%*
- Ocean energy	1.866	1.851	*-1%*
All sources (weighted average)	***3.190***	***2.322***	***-27%***

Table 3. Electricity generated (TWh) per GW of Installed Capacity by energy source. 2025 ratios are based on average of actual installed capacity and electricity generated. Efficiencies are anticipated for most energy sources by 2050, with the corresponding percentage increases shown on the right.

In the OEreCM scenario, almost all fossil fuel plants will be shuttered by 2050 with the exception of limited natural gas capacity (220 GW). Nuclear capacity will decrease somewhat (to 274 GW) as legacy reactors are taken offline, while some regions historically reliant upon oil and gas for power generation will see a significant rise in hydrogen power (1095 GW). Renewables will account for over 40 TW of installed capacity – 2.1 TW hydropower; 8.6 TW and 2.8TW onshore and offshore wind power respectively; 20.4 TW and 4.1 TW solar PV and CSP respectively; 0.6 TW biomass power; 0.5 TW geothermal power; and 0.8 TW ocean power.

As noted above, the OEreCM transition scenario requires an additional 10 TWh of final electricity versus the OECM 2.0 scenario. This is due in part to increased electrification of industrial processes and transport (described below), but it is also due to two other factors – rapid growth in the IT sector as a result of AI computing and increased demand for water desalination stemming from expected aridification of croplands. The original OECM scenario had almost no growth in the IT sector and a modest 18% increase in energy for desalination by 2050. Recent developments have put both these assumptions into question.

In 2022, data servers accounted for only 300 TWh of electricity demand [28] and by 2024 this grew to 450 TWh, with 945 TWh projected for data servers and AI by 2030 [29]. One scenario by Wood Mackenzie anticipates approximately 4500 TWh for the IT sector globally by 2050 [30], and some governments are modeling even higher demand [31]. It is possible that AI could drive energy and industry efficiencies resulting in an overall reduction in electricity demand [32], but further research is required to attribute specific efficiency gains to the AI sector. OEreCM uses a mid-range estimate of approximately 1800 GW by 2055, or 4186 TWh (reducing the Wood Mackenzie estimate by 7% anticipating some efficiency gains from colocation), estimating a CAGR of 6.135% starting in 2030 as shown in Table 4a.

Growth in generation for the IT sector	2025	2030	2035	2040	2045	2050	2055
IT sector electricity demand *(GW)*	160	346	541	787	1,044	1,356	1,803
IT sector installed capacity (TWh)	*509*	*945*	*1,273*	*1,714*	*2,308*	*3,109*	*4,186*

Table 4a. OEreCM scenario anticipated growth in electricity demand from the IT sector from 2025-2055.

Concurrently, new research on cropland aridification due to climate change indicates that the human population reliant upon desalination could triple by 2050, requiring a large increase in installed electricity capacity above today's levels (150 GW), ranging from 1.7x to 4.4x over current capacity, with a mid-range estimate of a 3x increase that assumes significant irrigation efficiency by mid-century [33]. OEreCM uses the mid-range estimate of 450 GW of installed capacity required for desalination in 2055, or 1044 TWh, estimating a CAGR of 2.635% as shown in Table 4b.

Growth in generation for Desalination	2025	2030	2035	2040	2045	2050	2055
Desalination electricity demand *(GW)*	150	199	264	324	364	400	450
Desalination installed capacity (TWh)	*479*	*545*	*621*	*707*	*805*	*917*	*1,044*

Table 4b. OEreCM scenario anticipated growth in electricity demand for desalination from 2025-2055.

Combined, this represents an additional 5.2 TWh required compared to the original OECM scenario. To help meet this increased demand, OEreCM includes a curtailment model to estimate the potential of additional uncaptured electricity from VRE. Technical curtailment can vary widely depending upon the region and energy mix. Germany (with 52% VRE) curtails only 1.9% for solar and 3.2% for onshore wind, but offshore wind has an extremely high curtailment rate of 25% [34]. California (with 45% VRE) has an effective curtailment rate of 9% [35], and other models indicate an average curtailment approaching 10% for a VRE mix of 45% [36]. The most comprehensive study to date by IEA plots VRE shares in generation and technical curtailment for 10 major economies, finding an approximately linear correlation between VRE total and increased curtailment [37]. Though speculative, extending this correlation out to 70% VRE (the OEreCM 2050 projection), we would expect an average 8.5% curtailment rate, resulting in the surplus generation rates shown in Table 5 for 2020-2055.

Variable RES Curtailment Estimates	2030	2035	2040	2045	2050	2055
Variable RES % for calculations	33.9%	50.2%	62.4%	67.6%	70.5%	71.9%
Linear curtailment estimate	4.38%	6.22%	7.60%	8.18%	8.52%	8.67%
Total surplus generation (TWh)	**555**	**1,468**	**3,019**	**4,506**	**5,617**	**6,550**
Apply 1/3 used for co-located computer servers	*185*	*489*	*1,005*	*1,501*	*1,870*	*2,181*

Table 5. Variable Renewable Energy (VRE) curtailment projected to 2055 per OEreCM energy transition scenario, increasing from an average of 4.38% in 2030 (555 TWh) to 8.67% in 2055 (6550 TWh).

Colocating server farms near utility-scale VRE plants is an effective strategy to reduce operational costs, and in the OEreCM scenario we assume that one-third of potential curtailed power could be recaptured for this purpose, realizing a net gain of approximately 2180 TWh to help meet increased IT sector power demand.

2b. Global Transport

In 2023 the transportation sector comprised close to 31% of total global energy consumption. Road transit is the biggest culprit, accounting for more than 75% of transportation emissions globally, with shipping and aviation responsible for 9% and 10% respectively. In the United States, the transportation sector emits more greenhouse gasses than any other sector, and in other regions transportation demand is on the rise. In order to solve the climate crisis and achieve the 1.5°C goal of the Paris Climate Agreement, decarbonizing the transportation sector by mid-century is essential. This is a difficult task, as approximately 96% of energy demand for transport is currently met by fossil fuels.

OEreCM follows an energy transition scenario for the transportation sector similar to OECM 2.0 (with a 5-year delay), organized in five major transport categories – Road (including heavy equipment), Rail, Navigation (marine), Aviation, and Pipelines. The model optimizes a rapid transition away from fossil fuels for each modality commencing in 2030, utilizing four clean energy delivery pathways—Green Hydrogen, Sustainable E-fuel, Sustainable Biofuel, and Electrification. Overall, OEreCM lands on a higher value of 47.1 EJ in total transportation energy demand by 2055 (see Figure 4) versus OECM 2.0. OEreCM includes significantly more energy for Road & Heavy Equipment, totaling 20.3 EJ in 2055. Navigation is somewhat lower (10.8 EJ) and Aviation somewhat higher (11.6 EJ) for 2055. OEreCM also breaks out an additional category for Pipeline energy required for the transport of natural gas, transitioning to hydrogen gas by mid-century (1.4 EJ in 2055).

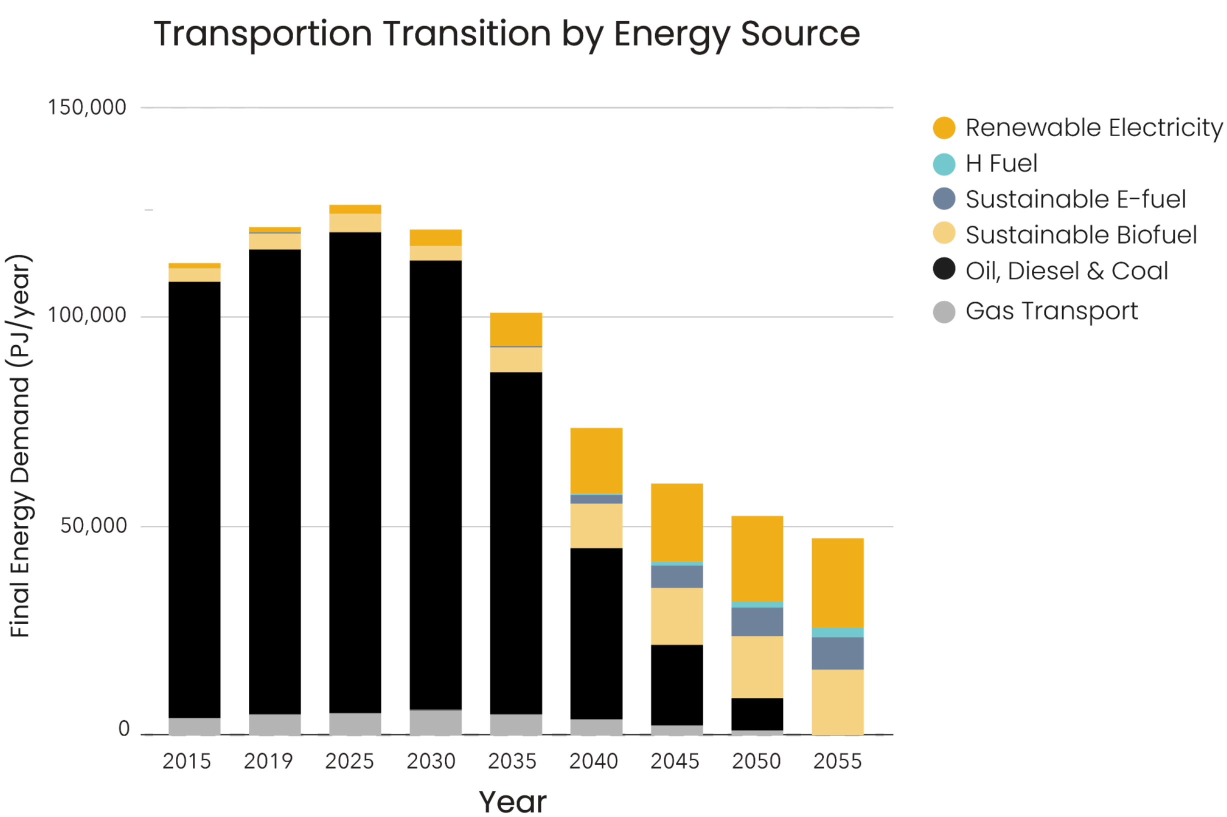

Figure 4. Transformation of total fuel sources across all global transport modalities in five-year steps per the OEreCM, illustrating a dramatic reduction of total energy demand due primarily to fuel switching (PJ units).

Electrification of both Road and Rail transport are central to OEreCM. CAGRs were developed for each based on recent data, establishing more precise estimates for the 2025-2030 timeframe. EV growth has been remarkably fast to date – growing from less than 1 million vehicles on the road in 2013 to more than 40 million in 2023 [38]. While there was a significant drop in EV production and electric rail projects during the Covid-19 pandemic, both dramatically rebounded in 2021. EVs saw an average CAGR of 25.8% growth 2021-2023 [39] with a projected CAGR of 21.85% for 2025. Currently, one out of every five road vehicles purchased is an EV. Electric rail has also steadily grown led by China [40], with a projected CAGR of 21.85% for 2025.

While some had thought that LNG would ramp up as it is considered a lower-emissions “bridge fuel” to replace oil, the market for LNG has largely collapsed. With a jump in oil export capacity and competition from the EV market due to dramatically decreased battery costs, LNG demand growth is expected to face economic, political, financial, and logistical challenges that an oversupplied environment may not fully resolve [41]. OEreCM still does include some modest growth for LNG by 2030 but then models a gradual decline through 2050. Energy demand for EVs is expected to grow dramatically to 3.8 EJ in 2030, roughly doubling from 2024 levels. Concurrently, a gradual decline in oil consumption begins in 2026, returning to 2022 levels by 2030.

From 2030 a rapid transition to 100% clean road transport by 2055 is modeled, with energy for road and heavy equipment reduced from 83.7 EJ in 2030 by approximately half in 2040, then half again by 2055 (20.3 EJ). While OEreCM has a modest reduction of passenger miles traveled by road (approximately 14% less passenger miles in 2055 versus 2025 offset by increased rail transport) most of the total reduction in energy is from efficiency gains due to fuel switching. By 2055, 45.5% of all road transport is electrified. Because of the enormous inefficiencies in the internal combustion engine, switching to EV transport results in 4.4 times more miles traveled per petajoule of energy than by an equivalent fossil fuel based vehicle [42].

Hydrogen fuel cells also feature prominently in OEreCM (approximately 10.9% of all road transport in 2055), providing 2.5 times more miles traveled per petajoule of energy [43]. Biofuels play a significant role in road transport though they are greatly reduced from 4.2 EJ in 2025 to only 1.1 EJ in 2055, most of which would be met by marine algae fuels. Competition for cropland will increase due to growing human populations and climate-driven cropland aridification [44], so OEreCM does not consider it feasible to to expand crop-based biofuel production.

While passenger miles traveled by road decrease somewhat between 2030 and 2055, rail miles dramatically increase in the OEreCM transition scenario in line with OECM 2.0 – roughly 250% growth above 2020 levels for passenger miles and 200% growth for tonnage of materials shipped by rail (see Figure 5). Despite this growth, total rail energy demand barely increases between 2025 (2.8 EJ) and 2055 (3.1 EJ), due to increasing electrification which yields higher efficiencies.

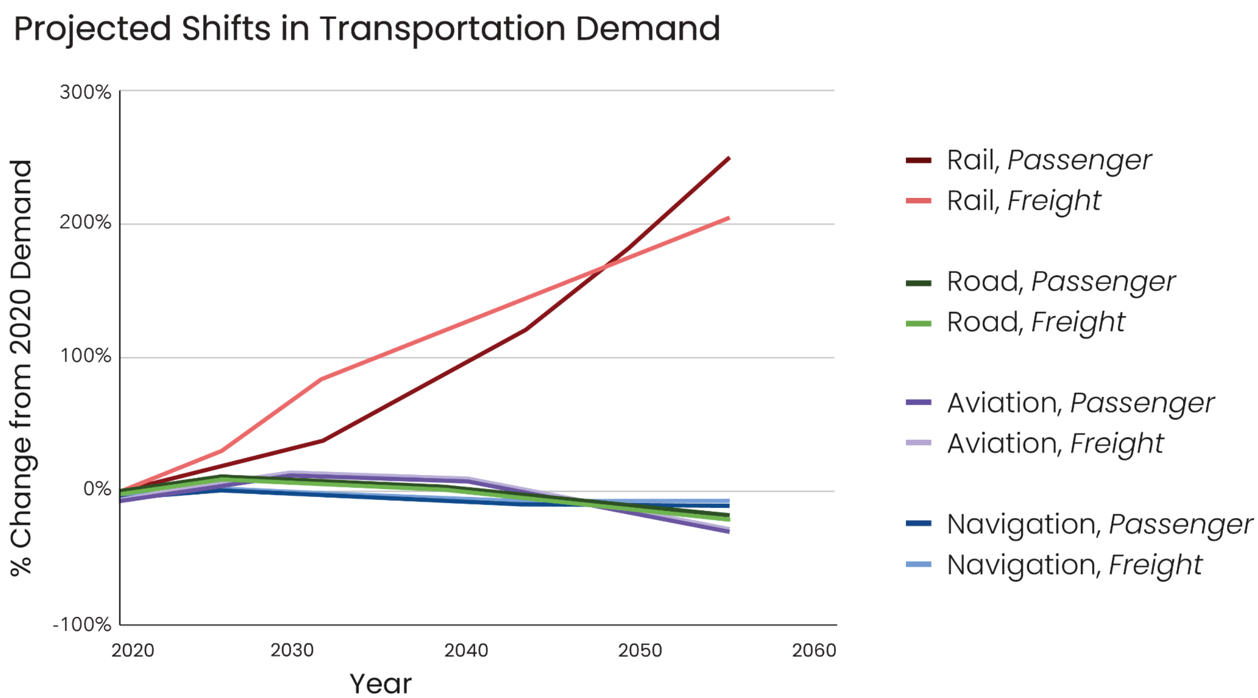

Figure 5. Changes in transportation demand by transit mode from a 2020 baseline per OEreCM. Demand for passenger and freight rail increases 2.2x by 2055 from the 2019-2021 baseline. All modes of transport demand decrease during the same time frame. Passenger demand is measured in passenger-kilometre units (pkm) and freight demand is measured in tonne-kilometer units (tkm).

As seen in Figure 4, both passenger and freight demand for marine transport (aka Navigation) and aviation are reduced. The aviation sector was hard hit during the Covid-19 pandemic and still has yet to recover fully. The industry currently forecasts a modest 26% growth in air travel by 2027 above 2019 levels, far lower than the pre-pandemic forecast of 40% [45]. Inflation and increasing global conflict are also likely to dampen future growth, while the airlines continue to gradually increase the efficiency of their aircraft in order to reduce operational expenses (approximately 1% increase in efficiency every five years) [46]. Taking these factors into consideration, OEreCM includes an increase in air travel through 2035 (18 EJ), followed by a very gradual decline through 2055 (11.6 EJ).

In the OECM 2.0 and OEreCM transition scenarios, oil products are gradually replaced by biofuel and E-fuel. E-fuels, or synthetic fuels, are required due to the biophysical constraints on biofuel production and the need for an equivalent liquid fuel, particularly important for the aviation industry. There are numerous potential methods to develop E-fuel, depending on the CO2 and hydrogen sources and the intermediate steps used. OEreCM references a common approach for the first generation of plants currently in development, the DAC-RWGS-RT route [47]. Electrolysis is used to produce hydrogen, and Direct Air Capture is used to create a stream of CO2 gas from which solid carbon can be extracted by converting CO2 to Carbon Monoxide (CO) using the Reverse Water Gas Shift (RWGS) reaction. This CO is then synthesised into wax and hydrocarbon condensate using the Fischer-Tropsch (FT) process, and these products are then hydrocracked to produce liquid fuels (see Figure 6).

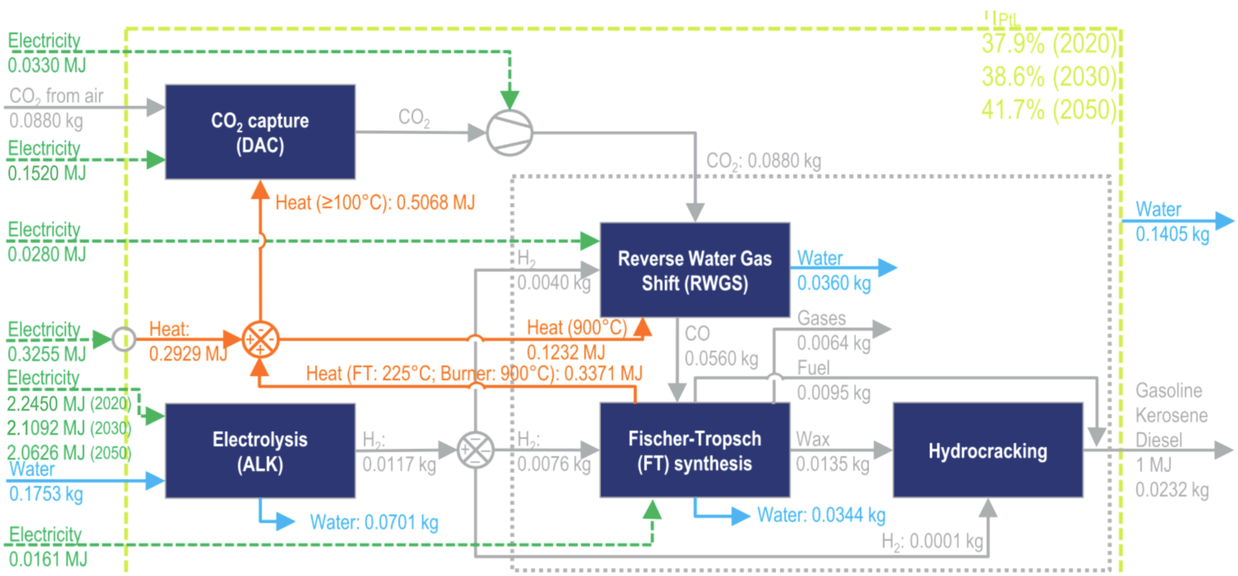

Figure 6. The DAC-RWGS-FT route for producing E-fuels using only renewable energy. Electrical inputs (left) are shown in dark green. Heat inputs are shown in orange, and water in light blue. Diagram adapted from Concawe/Aramco (2024). Note: OEreCM increases the baseline energy input for Electrolysis to 2.245 MJ and for DAC to 0.152 MJ in 2020, for a total of 2.8 MJ required to produce 1 MJ of liquid fuel.

As the global electricity supply shifts to renewables, it will become possible to manufacture a liquid fuel with similar characteristics to diesel or jet fuel entirely with clean energy. OEreCM uses an estimate of 2.800 MJ of input required to produce 1 MJ of liquid E-fuel, and it is anticipated the process will become increasingly efficient as the technology scales, with only 2.545 MJ required to produce 1 MJ in 2055. This reflects increased efficiency in hydrogen production, requiring 1.455 MJ of energy to produce 1 MJ of hydrogen in 2030 and only 1.290 MJ in 2055.

Altogether, OEreCM calls for approximately 7.7 EJ in the form of E-fuels for marine shipping and aviation (including the production of hydrogen for the DAC-RWGS-FT process), in addition to 2.2 EJ in direct hydrogen use for road transport by 2055. Lastly, OEreCM factors in energy for pipeline distribution of fuels (mostly natural gas transitioning to hydrogen), which reduces from 3.2 EJ required in 2025 to 1.4 EJ in 2055. See Figure 7 for the transition of each transport sub-category between 2019 and 2055.

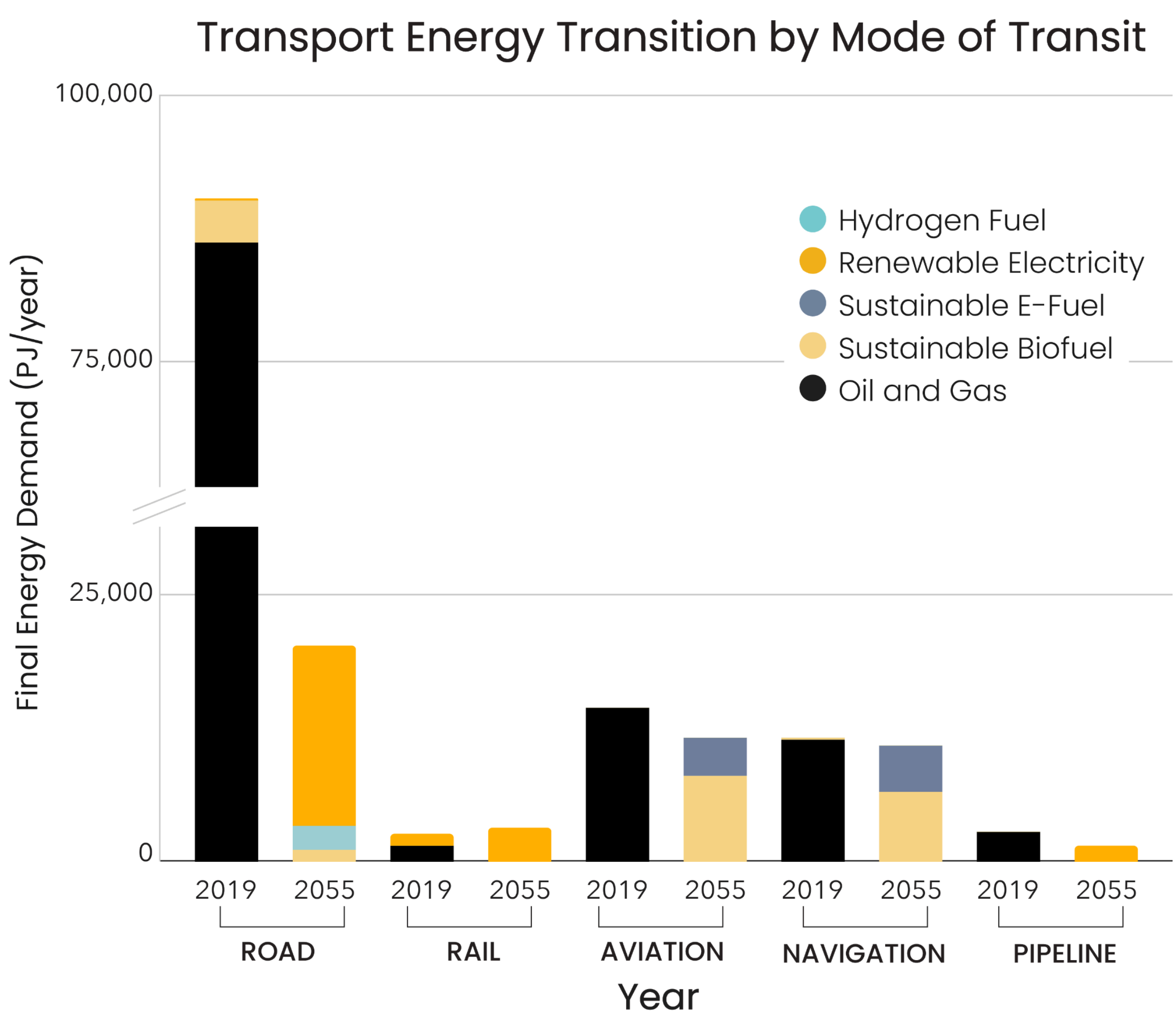

Figure 7. Total energy demand for the five major transport sub-categories – Road (including heavy equipment), Rail, Aviation, Navigation (or marine shipping), and Pipeline – by fuel source organized. Electricity required to produce hydrogen fuel and synthetic E-fuel is also shown, though it is secondary energy.

In summary, total energy required for transport reduces in OEreCM from the 2019 baseline of 121.5 EJ to 47.1 EJ in 2055. Road transport reduces from 90.3 EJ to 20.3 EJ as rail increases from 2.5 EJ to 3.1 EJ, providing 4x the number of passenger miles. Aviation reduces from 14.1 EJ to 11.6 EJ, becoming 6% more efficient, while marine shipping reduces only slightly from 11.5 EJ to 10.8 EJ. Pipeline energy is reduced by half from 2.8 EJ in 2019 to 1.4 EJ in 2055 as it becomes 100% electrified.

2c. Global Heat Supply & Air Conditioning

Direct heating is required to warm our homes, boil water and cook food, create construction materials, process food, and formulate chemicals. Decarbonizing our global heating supply is no small task as heat accounts today for approximately 45% of total global energy consumption, dwarfing electricity (25%) and transport (30%). It is also highly varied in its use. Industrial processes, including the manufacturing of steel and cement, can require temperatures exceeding 1000˚C. While lower temperatures required in homes and commercial buildings to heat air or water rarely exceed 100˚C in output. And the need for heating in buildings is widely distributed, with approximately 40% of households worldwide requiring some form of space heating [48].

In OEreCM, global heat demand is expected to increase from 187 EJ in 2019 to 207 EJ in 2055. Total energy used for heating buildings is expected to decline significantly as electrification and other technologies reduce demand. Heat required for industrial processes however will significantly increase. Energy efficiency measures are unlikely to compensate for increasing manufacturing demand as GDP rises through 2055 when fossil fuels, which are highly efficient carriers of heat, are eventually phased out [15].

Transitioning away from our fossil-fuel dependent heating supply to renewable sources of heat (including electricity generated from renewable power plants) will be a defining challenge of the next thirty years. Currently, 73% of heat is supplied through the direct combustion of fossil fuels (138.6 EJ). An additional 6% of heat is supplied from electricity (11.8 EJ), and less than half of this energy is generated from renewable sources. But the transition is underway with renewable heating increasing significantly over the past several years. Since 2015, solar heating has more than tripled, and geothermal heating has more than doubled in capacity.

One key objective of the OEreCM was to gather up-to-date global statistics on deployment rates for both renewable and non-renewable heat supply sources between 2019-2023, developing estimated Compound Annual Growth Rates (CAGRs) to support a realistic forecast of heat supply in 2024 and 2025. For the years 2019-2022, actual statistics for heat supply were taken from IEA World Energy Balances [22], breaking out estimates for direct heating, district heating, and heat from CHP. The Statistical Review of World Energy provided actual statistics for 2023 primary energy [23], and using average ratios of primary to final heat, estimated 2023 heat supply values were derived. These were cross-referenced with other sources, including IRENA Renewable Energy Statistics [24], IEA Solar Heating & Cooling Programme [49], IRENA Global Geothermal Market [50], and where data was not available (RE district heat, electric heat pumps, and electric direct heating) values were derived from OECM 2.0 to establish growth rates in these heat supply modalities between 2015 and 2019 [15]. CAGRs for heat supply modalities referenced in OEreCM are presented in Table 6.

RE Heat Growth (2019-2023)	***2024 CAGR***	**Electric & FF Heat Growth (2019-2023)**	***2024 CAGR***
RE District heat supply	*5.75%*	Electric Heat pumps	*11.50%*
RE CHP heat supply	4.60%	Electric Direct heating	*3.82%*
Solar heat	*4.38%*	Coal & Non-RE waste	*-2.13%*
Geothermal heat	10.84%	Natural Gas	*1.47%*
Biomass heat	0.74%	Oil products	*1.44%*

Table 6. Estimated Compound Average Growth Rates (CAGRs) for renewable heat supply (left) and electric & fossil fuel heat supply (right) used in the OEreCM energy transition scenario, inferring annual growth in measured capacity above 2019 levels through 2023.

The CAGR rates developed for the OEreCM scenario were applied to create 2024 and 2025 values for all heating supply sources. During the course of writing this manuscript, BloombergNEF released new primary energy statistics for 2024 [17], indicating a significant slowdown in coal production and increase in natural gas relative to the previously modeled CAGR estimates. These statistics were factored into slightly revised heat supply values. Total Heat Supply is shown in Table 7, including percentages of District heat and heat from CHP.

Heat supply (PJ/a)	2015	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Fossil Fuels	**133,259**	**139,423**	**138,506**	**137,648**	**139,190**	**138,650**	**135,712**	**133,882**	**130,172**	**126,121**	**120,501**
Hard coal, lignite, non-RE waste	47,667	41,274	39,514	38,493	37,861	37,557	37,308	37,219	36,282	35,474	34,010
Natural Gas	52,787	63,902	63,685	63,913	66,011	66,275	63,383	63,280	63,160	63,017	62,840
Oil Products	32,805	34,247	35,307	35,242	35,318	35,818	35,021	33,383	30,730	27,630	23,650
Hydrogen	-	-	0.001	0.002	0.004	0.025	6	13	21	31	43
Renewables	**40,056**	**42,933**	**38,490**	**38,996**	**39,537**	**40,098**	**42,214**	**44,908**	**48,190**	**52,068**	**56,563**
Biomass & RE waste	38,287	40,192	35,553	35,849	36,163	36,477	37,561	38,945	40,638	42,650	44,997
Geothermal Heat	519	1,200	1,315	1,466	1,619	1,789	1,989	2,242	2,549	2,909	3,325
Solar Heat	1,250	1,541	1,622	1,681	1,755	1,832	2,664	3,721	5,003	6,509	8,241
Electric Heat	**7,884**	**10,136**	**10,390**	**10,607**	**10,775**	**10,896**	**11,761**	**12,859**	**14,189**	**15,753**	**17,549**
Electric Heat pumps	189	363	405	451	503	561	1,403	2,471	3,766	5,287	7,035
Electric direct heating	6,925	8,673	8,873	9,023	9,123	9,173	9,034	8,857	8,643	8,392	8,103
Electric industrial process	770	1,100	1,112	1,133	1,149	1,162	1,324	1,531	1,780	2,074	2,411
Total Heat Supply	**181,199**	**192,492**	**187,386**	**187,251**	**189,502**	**189,644**	**189,693**	**191,662**	**192,572**	**193,973**	**194,656**
% District heat	*6.3%*	*7.6%*	*8.0%*	*8.1%*	*8.1%*	*8.1%*	*8.2%*	*8.1%*	*8.1%*	*8.1%*	*8.2%*
% CHP heat	*2.8%*	*3.0%*	*3.1%*	*3.1%*	*3.1%*	*3.1%*	*3.2%*	*3.3%*	*3.3%*	*3.5%*	*3.6%*

Table 7. Global Heat Supply in petajoules per year (PJ/a) by fuel type with actual values for 2015-2023, estimated 2025 values, and modeled OEreCM generation values for 2026-2030, including percentages of heat from Combined Heat & Power (CHP) and District Heating.

OEreCM develops targets for Direct Heat, as well as District and CHP heat supply for 2030-2055 using the IEA World Energy Balances taxonomy. The final targets for 2055 are comparable to the OECM 2.0 targets for 2050, though they are formatted somewhat differently, with electricity for industrial process heat delineated as a separate category – scaling from only 1.2 EJ in 2025 to 38.1 EJ in 2055 – as well as a delineation between electric heat pumps and direct electric heating for buildings. Altogether, electric heat scales rapidly from 10.9 EJ in 2025 to 56.2 EJ in 2040 and 100.5 EJ in 2055, when it provides nearly half of total global heat demand.

Three direct renewable heating sources – biomass, solar thermal, and geothermal – also play a central role in the global heat supply transition. Biomass heat in OEreCM is significantly lower than OECM 2.0 with a peak of 48.2 EJ in 2035 declining to 45.8 EJ in 2055. Solar and geothermal heat grow rapidly from only 2.4 EJ combined in 2019 to 26.6 EJ in 2040 and 52.7 EJ in 2055. Hydrogen heat plays a modest but important role in industrial process heat, growing from nearly zero in 2025 to 1.2 EJ in 2040 and 8.0 EJ in 2055. See Figure 8 for the global heat supply transition by energy source.

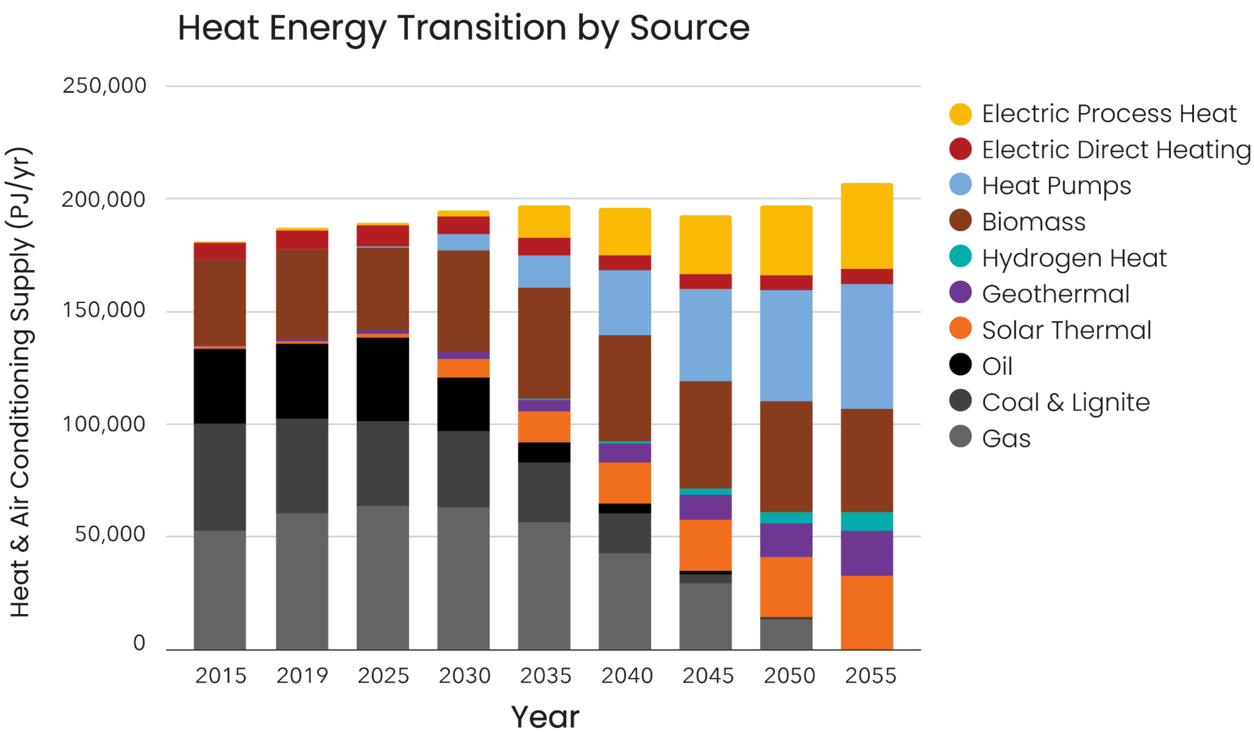

Figure 8. Global Heat and air conditioning supply by energy source from 2019 to 2055. Secondary electricity required to produce hydrogen for industrial process heat is also shown for reference.

The OEreCM transition assumes an eventual phaseout of window air conditioning units by mid-century, replaced by heat pumps which meet both heating and cooling demand. It should be noted that there is limited global electricity data specifically for window air conditioning units, swamp coolers, and fans, as most analyses focus on electricity demand for space cooling overall. These devices are considered portable appliances, as are refrigerators, and the additional electricity associated with these devices is not included in the Heat Supply transition described above, but rather is incorporated into the total electricity demand for Buildings (see Final Energy summary).

2d. Energy Efficiency

In just the past two decades, energy efficiency measures in IEA member countries have generated over 27 EJ of energy savings, equivalent to 20% of total current energy demand – 15.8 EJ Industry & Services (including commercial buildings), 6.6 EJ Residential Buildings, 4.8 EJ Transportation (mostly passenger transport) [51.] This illustrates that even with modest investments, energy efficiency is one of the greatest potential levers to mitigate climate change, with the ability to provide as much as a 4% annual gain in primary energy intensity this decade [52].

The main objective of energy efficiency is to decrease total final energy consumption without reducing quality of life, effectively meeting the same end-use demand with fewer per capita resources. On the supply side, governments and companies can increase efficiency through incentivizing and funding technological innovation and smart infrastructure. On the demand side, promoting efficient technologies and positive end-use behaviors will allow countries to achieve and maintain high standards of living with far less material and energy inputs than are required today. However, the highest rate of global efficiency improvement to date has been approximately 2% in 2022. Reaching 4% per year or higher in efficiency gains, will require a whole-systems approach, instead of focusing exclusively on singular technology substitutions within the existing system [53].

OEreCM and other high-ambition climate mitigation scenarios incorporate demand-side mitigation responses categorized into three broad strategies (technology adoption, infrastructure design/use, and socio-cultural shifts) applied across five main sectoral categories – Industry & Services, Transport, Buildings, Electricity, and Food – in line with the IPCC Sixth Assessment Report (AR6), Working Group III [54]. Summarizing over 500 bottom-up studies representing all global regions, AR6 finds a median estimate of ~26 $GtCO_2$ mitigation potential in 2050 for the first four categories – 4.5 $GtCO_2$ Industry (17.3%), 6.5 $GtCO_2$ Transport (25%), 7.0 G tCO_2 Buildings (26.9%), and 8.0 EJ Electricity (30.8%) – versus the median emissions baseline of 46.75 $GtCO_2$. Note: food systems mitigation measures are covered in Non-CO_2 Emissions (Part II).

The vast majority of these energy savings come from the adoption of new technologies. Our current energy system is highly inefficient due to a reliance on fossil fuels. The U.S. for example loses 67.3% of its primary energy to waste heat through the combustion of fossil fuels in thermoelectric power plants. [55] Fossil fuels themselves also demand enormous energy inputs to extract, refine, and transport fuel stocks, and combustion-based vehicles are extremely wasteful, losing an average of 79% of potential energy stored in a gallon of gasoline [56]. Globally (2019), 29.2% of all primary energy is lost to energy production with 3.1% is required for fuel transport, and another 30.2% is lost at the time of use (e.g. combustion engines) [57]. Shifting to a nearly 100% renewable electricity supply by mid-century while electrifying the majority of end-use sectors could decrease global energy demand by 36% compared to a world reliant upon fossil fuel combustion [58].

In addition to technological shifts, the design and use of highly efficient infrastructure is key to the net-zero transition – from modern residential community planning and low-energy buildings to development of commuter rail and the deployment of high-voltage transmission lines. But even with these infrastructure advances, socio-cultural shifts are required so that people choose to adopt new products and technologies. Behavioral changes, like using buses or bicycles for commuting, or opting for smaller more energy-efficient homes, are essential to achieving the 1.5°C goal of the Paris Agreement.

To establish estimates for final energy demand reduction in the OEreCM across these three major efficiency strategies, the IPCC median efficiency estimates are used with the OEreCM Business as Usual (BAU) baseline of 600.1 EJ final energy demand in 2055, projecting an average annual growth rate of 1.4% for energy consumption 2013-2023 as documented in the Statistical Review of World Energy through 2055 [23]. While baselines for final energy vary widely across net-zero scenarios, the median range for >2°C models is 450 EJ to 750 EJ in 2050 (600 EJ) [59], aligning exactly with the OEreCM baseline.

The OEreCM energy transition scenario establishes a total Final Energy demand of 403 EJ (see Final Energy below) plus an additional 41 EJ for electricity for hydrogen and E-fuel, totaling 444 EJ in 2055. Using the 600 EJ baseline, this yields a total conserved energy savings estimate of 156 EJ, which can be broadly divided into technological shifts, infrastructure shifts, and social-cultural shifts per IPCC. These can be further divided by applying AR6 energy efficiency ratios for each of the four energy demand reduction categories (Table 8).

Energy-related effiency by category applied to OERECM (AR6 ratios)			
	IPCC	% of Sub-total	Avoided Final E (PJ est.)
Technological shifts	***16.4***	**96,925**	
- Industry & Services	*3.0*	*18.2%*	*17,601*
- Transportation	*3.1*	*18.8%*	*18,192*
- Built Environment	*3.6*	*21.9%*	*21,263*
- Electricity Supply	*6.8*	*41.1%*	*39,869*
Infrastructure shifts	***6.2***	**36,856**	
- Industry & Services	*0.8*	*12.7%*	*4,666*
- Transportation	*2.3*	*36.5%*	*13,467*
- Built Environment	*1.9*	*29.6%*	*10,927*
- Electricity Supply	*1.3*	*21.2%*	*7,797*
Socio-cultural shifts	***3.7***	**22,029**	
- Industry & Services	*0.9*	*23.6%*	*5,197*
- Transportation	*1.3*	*34.0%*	*7,501*
- Built Environment	*1.6*	*42.4%*	*9,331*
*- Electricity Supply**		*NA*	
TOTAL efficiency mitigation		**155,811**	

Table 8. Energy-related demand reduction (avoided Final Energy) in OEreCM is estimated by applying AR6 median energy efficiency values by strategy subdivided by end-use category. Note: Electricity Supply efficiency is excluded under Socio-cultural strategies, as shifts in end-use demand for power are captured in the Industry & Services, Transportation, and Built Environment categories.

Industrial Process Efficiency. Shifts in industrial processes could avoid approximately 27.5 EJ in final energy demand by 2055 in OEreCM, with more than 64% of these savings due to the adoption of new, energy efficient technologies and processes. Every industrial sector – from agriculture and textiles, to pharmaceuticals and cement production – will need to reduce energy demand through more efficient technologies and innovative processes. Aluminum, steel, and cement are three industry sub-sectors that currently require extremely large amounts of heat energy. In the case of aluminum and steel, using recycled metals as input material can reduce the total energy required to make new steel by up to 72% [60].

In addition to greatly improving recycling capabilities, AR6 highlights the need to source low-carbon or carbon neutral feedstocks, for example raw materials of biological rather than petrochemical origin to replace, for example, emissions intensive cow leather with leather produced from fungi. Socio-cultural changes will also play a key role, for example shifting demand away from cheaply made consumer goods to longer-lived, repairable products.

Transportation Efficiency. Shifts in transportation could avoid approximately 39.2 EJ in final energy demand in OEreCM, roughly half due to technology shifts and more than one-third due to better infrastructure design. The mere act of electrification – switching from fossil powered motors to electrical motors – will make the global energy system drastically more efficient as electric motors are up to 4.4x more efficient than internal combustion engines [40], and hydrogen fuel cell vehicles are 2.5x more efficient [41].

However, fuel switching is not the only solution to transforming the transportation sector. Behavior and technological choices drive a large part of current energy demand. North America, for example, only accounts for 7% of the global population, yet its overreliance on automobiles requires 34% of global transport energy [11]. This suggests that both behavior and infrastructure play a large part in shifting energy demand for the transportation sector. A broad suite of behavioral, infrastructural and technological changes that move more people with less energy is required. This includes infrastructure investments in public rail, busing, bicycles, walkability, and PEVs to reduce the dependence on low-efficiency travel like automobiles and airplanes. It could also include policies like remote working, which reduces commuting, as well as policies that limit vehicle weights (lighter vehicles need less energy per passenger mile).

Lastly, reducing transport energy demand will require socio-cultural shifts – more compact urban planning, increasing local production of goods, and innovating transport logistics. Increasing the walkability and bikeability of cities, policies that encourage remote work, streamlining freight logistics, and moving production closer to areas of demand are all ways to facilitate the transportation transition. Shifting to more energy-efficient transport modes largely means moving from road to rail for both passenger and freight transit, as well as replacing aviation with marine and rail transport (see Global Transport above).

Built Environment Efficiency. Shifts in building efficiency can avoid approximately 41.5 EJ in final energy demand, roughly half due to technology and one-quarter due to infrastructure policies. Built structures—homes, commercial buildings, government facilities, roads, bridges, and factories—represent a large portion of total energy use. It is possible to significantly reduce the materials needed for construction and the energy needed to heat, cool, operate, and illuminate those structures. Smaller homes, for example, require fewer materials to build and less energy to heat and cool. Buildings can also be designed to be passively heated or cooled, significantly reducing total energy demand. And more efficient appliances, like induction ovens and heat pumps will play a major role in the global energy transition, both of which are 3-5x more efficient than traditional gas heat [61].

Electricity Demand Efficiency. The optimization of global electricity supply will avoid approximately 47.7 EJ in final energy demand, with more than 84% of energy savings provided by switching from fossil fuels to renewable energy sources for electricity generation. While more ubiquitous than fossil fuels, the potential for renewable energy is not evenly spread throughout the world. Certain areas are sunnier than others, and some are windier. As a necessary aspect of the renewable energy transition, power may be generated far from where it is being consumed. Advances in high-voltage transmission technology will be necessary to reduce 'line loss'—the loss of power between the point of production and the point of consumption. Variable renewables (solar and wind) also mean that, unlike fossil fuel plants, renewable plants are not operating 24/7 and may vary seasonally in their output. Utility-scale energy storage becomes an integral part of a renewable energy future, allowing for delayed dispatch of energy, ramping up and down supply as needed to meet demand.

Several other technologies will be required to modernize the electrical grid to function reliably with an increased share of VRE. Sophisticated load management systems can deliver an additional 16% efficiency in the electricity sector. These can include smart grids, which function on the supply side to predict and respond to demand fluctuations, smart meters that allow users to customize their energy use (e.g. setting the time of day EV charging), and load shedding systems that allow the grid to curtail excess electricity if demand approaches total supply. Another innovative solution is the 'Virtual Power Plants' (VPP) – aggregations of small-scale energy resources like electric vehicles, smart thermostats, building batteries, and microgenerators – that could, for example, supply as much as 60 GW of on-peak generation capacity in the U.S. by 2030 [62]. Together these technologies will enable a far more efficient energy distribution system than we have today, as global renewable electricity production ramps up.

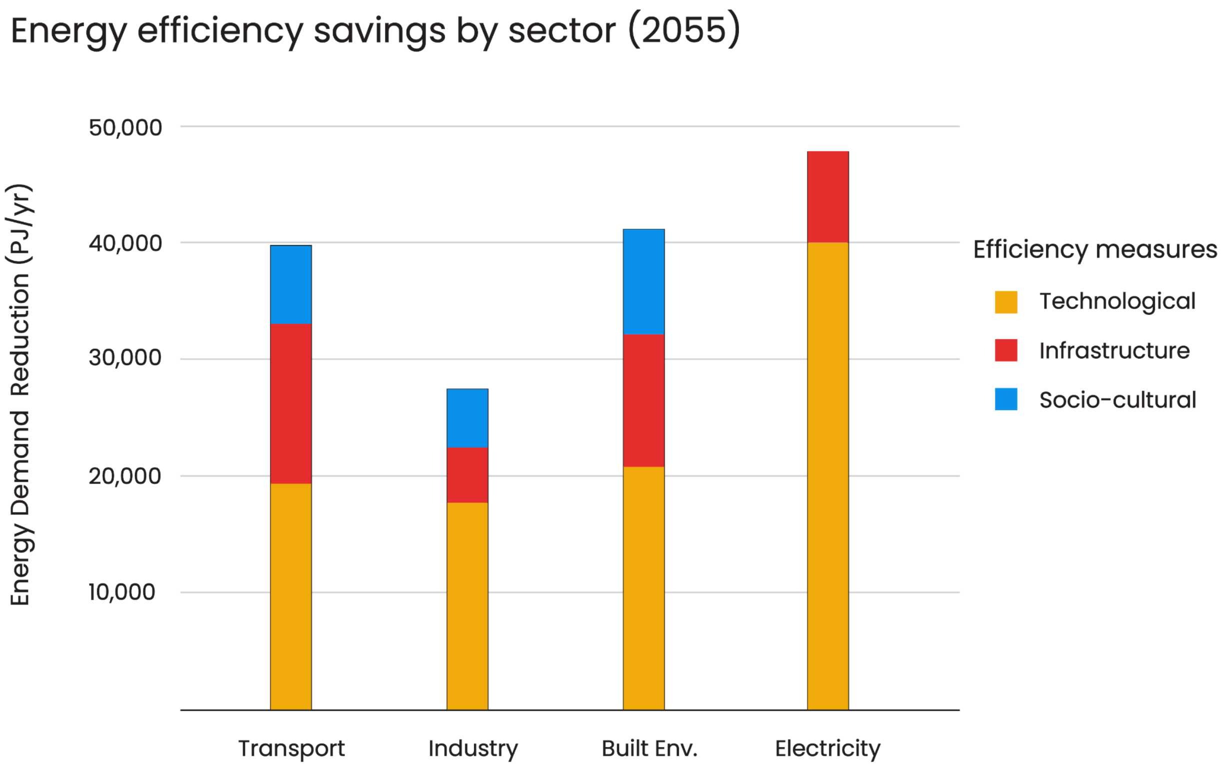

Figure 9. OEreCM Final energy demand and energy conservation across four major mitigation categories in 2055 – Industry, Transport, Built Environment, and Electricity Supply. Blue rectangles represent the extent of avoided energy use by category based on median estimates of Socio-cultural demand reduction measures per AR6. Red rectangles indicate the extent of efficiency gains derived from Infrastructure improvements. Orange rectangles indicate the extent of efficiency gains from fuel switching and the adoption of efficient technologies.

We are on the cusp of the AI era, and some believe that artificial intelligence could result in even deeper efficiency cuts than what is described above [63]. It is important, however, to keep in mind that energy efficiency is intrinsically tied to issues of environmental justice and social equity [64]. The poorest countries have done the least to cause the climate crisis and are the most at risk from the harmful impacts of climate change. High rates of energy consumption in wealthy nations, including accelerated consumption of energy for the IT sector, could result in a faster breach of the 1.5°C global carbon budget. Since OECD countries use nearly 10x more energy than low-income countries per capita, it's essential for wealthier nations that have greater access to capital to rapidly deploy as many efficiency measures as possible. If OECD countries succeed in reducing their total energy demand in the next decade, they will give the rest of the world the possibility to develop higher standards of living, while protecting the world's most vulnerable communities from the impacts of climate change.

2e. Final Energy Demand

The OEreCM energy scenario depicts a transition to nearly 100% renewables (with some nuclear power) for all purposes by 2055. It is defined in four phases:

- The 'Warm-up' phase (2025-2030) begins after a peak in total global fossil fuel emissions in 2024, and is defined by a gradual acceleration of renewable energy deployments with 100% of new power capacity met by renewable sources by 2030.

- The 'Low-hanging Fruit' phase (2030-2040) sees a decline in total Final Energy – from 406.4 EJ in 2030 to 375.7 EJ in 2040 – achieved through widespread energy efficiency measures across all sectors and electrification of transport and heat, reducing fossil fuel combustion by more than half.

- The 'Ramp-up' phase (2040-2050) sees Final Energy demand increase to 387.4 EJ in 2050 as renewable deployment ramps up across all RE generation types (with additional electricity for hydrogen and E-fuel production increasing from 9.8 EJ in 2040 to 33.1 EJ in 2050).

- The 'Deep Decarbonization' phase (2050-2055) represents the final push to decarbonize even the hard-to-abate industrial sectors and sees Final Energy demand jump to 403 EJ in 2055 (with additional electricity for hydrogen and E-fuel production ramping up to 41.2 EJ in 2055).

See Figure 10 for the share of total Final Energy across the three major sectors, sub-divided into Direct Heat, Electric Heat, and Electric Power.

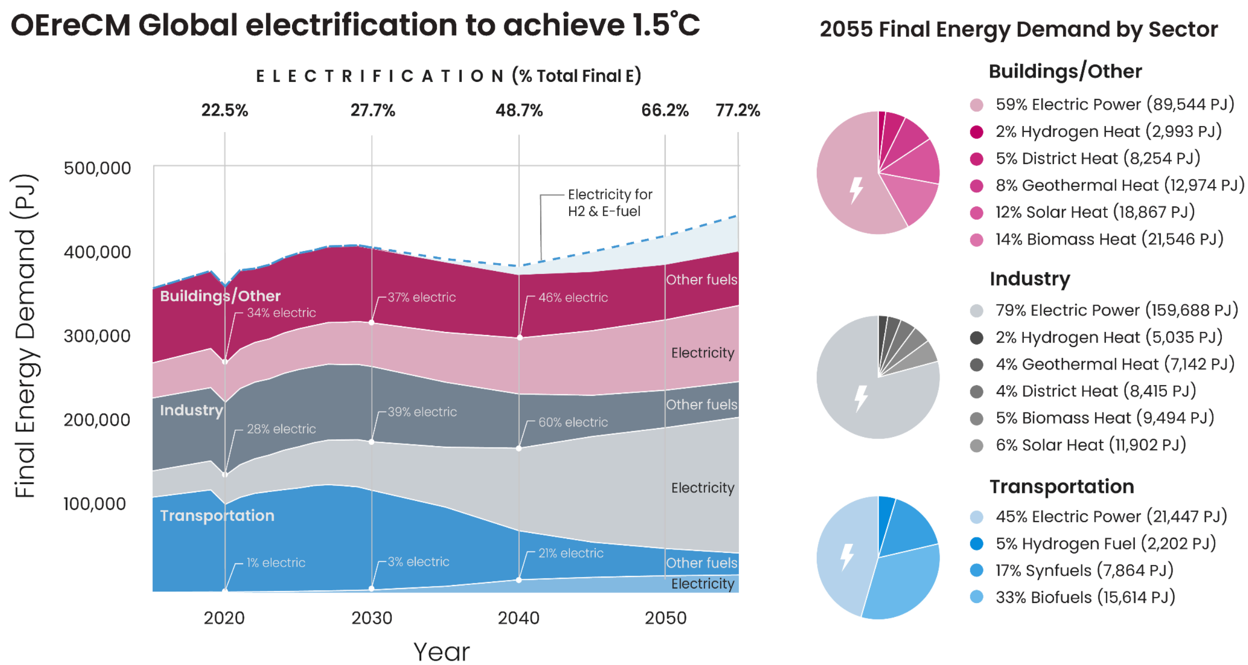

Figure 10. Final Energy across three major sectors – Transport, Built Environment, and Industry – all of which are increasingly electrified through 2055. Transportation shifts from 1.8% electrification in 2025 to 45.5% in 2055. Electrification of the Built Environment shifts from 35% electrification in 2025 to 58% in 2055. Industry shifts from 34.8% electrification in 2025 to 79% in 2055, with direct heat and process heat met largely through electrified heating sources. An additional 42 EJ of electricity is required to produce hydrogen and E-fuel (dashed line).

Transport demand. Final Energy for transportation in OEreCM is met almost entirely by fossil fuels in 2025 (117.2 EJ), with 4.1 EJ met by renewable fuels (biofuels) and 2.2 EJ met by electricity. By 2040 this changes dramatically when total Final Energy demand is reduced to 73.4 EJ, primarily through the replacement of internal combustion engines with EVs, leaving only 44.7 EJ of fossil fuels required for direct mobility energy. Renewable fuels also increase dramatically to 13 EJ by 2040, as electrified transport increases to 15.3 EJ. By 2055, total Final Energy for transport reduced to 47.1 EJ with 25.7 EJ of transport demand met by renewable fuels (including hydrogen and E-fuels), and 21.5 EJ met by electricity.

Built environment. Final Energy for buildings and infrastructure in OEreCM, including the IT sector, rises only gradually from 136.8 EJ in 2025 to 141.5 EJ in 2040 and 154.2 EJ in 2055, and is sub-divided into demand for heating & cooling (not including plug-in cooling appliances) and demand for end-use power covering all lighting, appliances, and other equipment. Fossil fuel heating is reduced by more than half between 2025 and 2040 (from 59.7 EJ to 25.2 EJ) before being entirely phased out in 2055. Renewable heat for buildings (including biomass, RE district heat, solar heat, and geothermal heat) more than doubles from 29.3 EJ in 2025 to 64.6 EJ in 2055, including a modest amount of direct hydrogen use (3 EJ). Electricity for heat, largely in the form of heat pumps), scales rapidly from 9 EJ in 2025 to 25.8 EJ in 2040 and 49.7 EJ in 2055. End-use electricity is assumed to be relatively constant (39.8 EJ between 2030 and 2055) as significant energy efficiency improvements in appliances and equipment keep pace with expanding housing and commercial building stocks.

Industry energy. The transition to 100% clean energy for all industry sectors in OEreCM is aggressive and requires the adoption of numerous innovative technologies. While electricity for low-temperature building heat can be achieved with heat pumps or solar collectors, temperatures over 500°C required in many industrial processes, generally rely upon combustion. Beyond 2030, technologies like electric resistance heat and electric arc furnaces will increase to help replace fossil fuels currently required for industrial process energy. And a switch from energy-dense fossil fuels to biofuel, hydrogen, and synthetic fuels will supply the high-temperature process heat required for chemical and metallurgical industries that are more difficult to abate.

Overall Final Energy demand for Industry increases from 139.2 EJ in 2025 to 160.8 EJ in 2040 and 201.7 EJ in 2055. Fossil fuels provide 80.0 EJ for industrial heat in 2025, dropping to 38.8 EJ in 2040 before phasing out entirely in 2055. Renewable heat sources (biomass, solar heat, geothermal) met another 10.8 EJ in 2025, more than doubling to 25.0 EJ in 2040 then scaling to 42.0 EJ in 2055. Electrical heating is very limited in 2025 (2.3 EJ) but ramps up rapidly to 30.2 EJ in 2040 and 50.8 EJ in 2055. End-use power demand also grows very quickly from 46.2 EJ in 2025 to 66.7 EJ in 2040 and 108.9 EJ in 2055. This large increase accounts for advanced electrical processes such as high-temperature electric arc welding, industrial lasers, compression, metal forming, robotics, cryogenic infrastructure, and other industrial systems.

To better understand the OEreCM Final Energy breakdown for 2055 by energy modality – Transport, Heat, and Power – Table 9 provides the total Final demand for each including electrification as well as electricity for hydrogen and E-fuels:

OERECM Final Energy demand by modality incl. electricity for fuels						
	PJ Final 2019	*% share*	PJ Final 2055	*E for fuel*	2055 Total	*% share*
Transport Energy	**121,487**		**47,127**		**70,764**	
- FFs	*116,243*	*95.68%*			0	*0.0%*
- Green H2	*0*	*0.00%*	2,202	*3,620*	5,822	*8.2%*
- E-fuel	*6*	*0.00%*	7,864	*20,017*	27,881	*39.4%*
- Biofuel	*3,853*	*3.17%*	15,614		15,614	*22.1%*
- Electric	*1,385*	*1.14%*	21,447		21,447	*30.3%*
Heat Energy (Industry & Bldgs.)	**180,786**		**207,093**		**220,290**	
- FFs	*129,452*	*71.61%*			0	*0.0%*
- Solar heat	*1,400*	*0.77%*	30,769		30,769	*14.0%*
- Geothermal heat	*926*	*0.51%*	20,116		20,116	*9.1%*
- Sustainable biomass	*38,615*	*21.36%*	31,040		31,040	*14.1%*
- Green H2	*0*	*0.00%*	8,028	*13,197*	21,225	*9.6%*
- RE District heat	*955*	*0.53%*	16,669		16,669	*7.6%*
- Electric heat	*9,438*	*5.22%*	100,471		100,471	*45.6%*
Electricity (excl. Heat & Transport)	**70,569**		**148,761**		**153,150**	
- FFs	44,861	*63.57%*	0		0	*0.0%*
- Solar PV	1,790	*2.54%*	45,824		45,824	*29.9%*
- Solar thermoelectric	37	*0.05%*	14,300		14,300	*9.3%*
- Geothermal power	241	*0.34%*	5,776		5,776	*3.8%*
- Onshore wind	3,518	*4.99%*	41,403		41,403	*27.0%*
- Offshore wind	222	*0.31%*	17,378		17,378	*11.3%*
- Wave energy	3	*0.00%*	2,288		2,288	*1.5%*
- Sustainable hydropower	11,088	*15.71%*	11,440		11,440	*7.5%*
- Sustainable biomass	1,509	*2.14%*	4,429		4,429	*2.9%*
- Green H2	0	*0.00%*	2,670	*4,389*	7,060	*4.6%*
- Advanced nuclear	7,301	*10.35%*	3,252		3,252	*2.1%*

Table 9. Final Energy demand organized by energy modality – Transport, Heat, Power – for 2019 and 2055 in the OEreCM energy transition scenario, showing the breakdown of each category by energy source. Estimates for electricity for fuel production (hydrogen and E-fuel) are added (right) to create adjusted totals inclusive of electrical fuels. The portion of electricity used for Heat and Transport is deducted from total final Electricity added to the attributed modality.

Overall, the OEreCM energy transition scenario includes a significant reduction of total Transport energy from 121.5 EJ in 2019 to 70.8 EJ in 2055 (inclusive of 23.6 EJ of electricity for fuels). Energy for Heat increases somewhat from 180.8 EJ in 2019 to 220.3 EJ in 2055 (inclusive of 13.2 EJ of electricity for fuels). Electricity for direct end-use power demand more than doubles in the scenario from 70.6 EJ in 2019 to 153.2 EJ in 2055 (inclusive of 4.4 EJ of electricity for fuels), reflecting the significant increase in electricity required to decarbonize all industrial sectors.

As can be seen, the success of a net zero global energy transition is predicated upon large-scale electrification across all sectors as well as a build-up of the hydrogen economy. Hydrogen, and

E-fuels made from hydrogen, are critical especially for hard-to-abate sectors, providing more than one–fifth of energy for transportation, 4% of heat energy, and even 2% of end-use electricity, which is required in particular for small island nations and other regions with limited capacity to produce electricity from VRE sources. 2024 marked a turning point for hydrogen, with the establishment of the world's latest clean hydrogen incentive in the U.S. and a series of multi-billion-dollar investments in green hydrogen, green ammonia, and green steel projects [65]. Equally important, the inclusion of a significant volume of hydrogen in the 2055 scenario supports a 'just transition' strategy, providing employment for hundreds of thousands of people currently working in the fossil fuel industry.

2f. Primary Energy and Energy-related CO2 Emissions

For the OEreCM energy transition scenario, primary energy and corresponding emissions factors were developed from recent historic data for the years 2019-2024 [22]. During the course of writing this manuscript, BloombergNEF released new primary energy statistics for 2024 [17], indicating a significant slowdown in coal production and an increase in natural gas production relative to the previous estimates. These statistics were factored into to create slightly revised primary energy totals as described below.

2f-1. Primary Energy

Total primary energy in OEreCM grows from 568.9 EJ in 2019 to 603.3 EJ in 2025, then drops to 587.4 EJ by 2030 and 518.6 EJ in 2040. Primary energy then increases to 536.6 EJ in 2055 due largely to the need for additional energy in hard-to-abate sectors. Fossil fuels make up roughly 78% of all primary energy in 2025, dropping to 35% by 2040 and zero in 2055. There is still, however, a significant and ongoing need for fossil fuels for non-energy uses, for example chemical feedstocks. In 2025 90.5 Mt of coal, 7.8 Tcf of natural gas, and 5.6B bbl of oil is required for non-energy use (2.7 EJ, 8.2 EJ, and 34.6 respectively in energy equivalents). This increases somewhat by 2055 when 99.0 Mt of coal, 9.1 Tcf, of natural gas and 5.5B bbl of oil is required (2.9 EJ, 9.6 EJ, and 33.8 EJ respectively in energy equivalents). See Table 10 for a breakdown of Primary Energy by fuel type in OEreCM in 5-year steps.

Primary Energy (PJ	2025	2030	2035	2040	2045	2050	2055
Fossil Fuels	**469,216**	**400,172**	**298,010**	**183,352**	**91,531**	**36,567**	**-**
Hard coal (& non-RE waste)	148,743	116,220	73,449	42,357	9,911	1,742	-
Lignite & Subbituminous coal	17,700	6,421	5,971	3,564	847	10	-
Natural Gas	142,964	135,794	120,936	89,560	58,932	26,240	-
Oil Products	159,809	141,737	97,654	47,871	21,841	8,575	-
Nuclear	**29,612**	**30,312**	**28,370**	**26,484**	**24,653**	**23,004**	**21,566**
Renewables	**104,310**	**156,725**	**223,942**	**308,641**	**385,785**	**450,860**	**514,841**
Hydro	16,152	17,102	19,373	19,984	23,160	24,394	26,592
Wind (onshore & offshore)	12,763	20,155	33,900	56,536	85,837	112,480	136,633
Solar (PV & thermal)	10,413	32,492	64,433	108,391	140,199	156,628	172,240
Biomass	58,954	74,832	83,708	88,300	83,206	87,323	84,430
Geothermal	6,024	12,033	21,860	33,653	50,626	66,376	89,627
Ocean energy	4	111	668	1,777	2,757	3,659	5,319
Additional District Heat & Power	**152**	**155**	**157**	**160**	**162**	**165**	**167**
TOTAL Primary Energy	**603,290**	**587,364**	**550,479**	**518,637**	**502,131**	**510,596**	**536,574**
RE share	*22.2%*	*31.8%*	*45.8%*	*64.6%*	*81.7%*	*92.8%*	*100.0%*

Table 10. OEreCM Primary Energy by fuel type in 5-year steps – growing from 22.2% renewable energy share to 64.6% by 2040 and 100% by 2055 – not including fossil fuels for non-energy use.

In 2055, nuclear energy declines somewhat in OEreCM, as legacy reactors (GEN III and earlier) are entirely shuttered by mid-century. Additions to nuclear generation capacity are expected to be met by advanced technologies, such as Generation IV reactors [66], small modular reactors, and potentially even fusion reactors. Primary energy also includes a small amount of heat and power from District utilities. Altogether, the share of renewables and nuclear supplying Primary Energy increases from 22.2% in 2024 to 64.6% in 2040 and 100% by 2055.

2f-2. Energy-related & Industry CO2 Emissions

CO2 emissions factors (MtCO2/PJ) for 2015, 2019-2023 are derived from recorded historic emissions data by fuel type [67]. The factor for lignite/sub-bituminous coal is derived from OECD data that finds these fuels generate 13.2% more emissions than hard coal [68]. 2022 and 2023 values are used to create an estimate for 2024 emissions values, which are assumed to be constant through 2050:

- Coal *0.0885 MtCO2/PJ*
- Lignite *0.1002 MtCO2/PJ*
- Gas *0.0581 MtCO2/PJ*
- Oil *0.0762 MtCO2/PJ*

For Industry-related direct emissions, a factor for estimated flaring emissions associated with oil & gas production is also derived based on recorded data for 2023 and 2023 – 3.37% additional emissions above oil production volumes, which is also assumed to be constant through 2050. Energy-related emissions are projected through 2055 based on the OERECEM transition scenario, as shown in Table 11a.

CO2 Emissions (MtCO2/yr)	2019-2021	2025	2030	2035	2040	2045	2050	2055
Energy-related CO2	**34,040**	**35,413**	**29,611**	**21,559**	**12,953**	**6,047**	**2,331**	**-**
Coal total	14,698	14,941	10,932	7,100	4,107	962	155	-
Bituminous	*12,953*	*13,167*	*10,288*	*6,502*	*3,750*	*877*	*154*	-
Lignite/Sub-bituminous	*1,745*	*1,774*	*643*	*598*	*357*	*85*	*1*	-
Oil products	11,635	12,171	10,795	7,437	3,646	1,663	653	-
Nat Gas	7,707	8,301	7,884	7,022	5,200	3,422	1,523	-
Industry CO2	**2,348**	**2,255**	**2,141**	**1,931**	**1,705**	**1,391**	**1,103**	**900**
Flaring (add to Gas)	413	411	364	251	123	56	22	-
Cement	1653	1,575	1,600	1,625	1,650	1,550	1,450	1,350
Other Industry/Bunkers	301	300	300	300	300	300	300	300
CCU/CCS removals (from cement, gas, coal)	19	31	123	245	368	515	669	750
Add'l energy demand (TWh)	*23.2*	*36.6*	*147.0*	*294.0*	*441.0*	*617.4*	*802.6*	*900.0*
TOTAL Energy & Industry CO2 Emissions	**36,388**	**37,668**	**31,752**	**23,490**	**14,658**	**7,438**	**3,434**	**900**

Table 11a. Annual energy-related CO2 emissions and Industry CO2 emissions by fuel type in OEreCM in 5-year steps, including estimates for CCU/CCS. Total CO2 emissions c. 2020 were 36.4 GtCO2 (2019-2021 average), rising to 37.7 GtCO2 in 2025 and declining to 0.9 GtCO2 by 2055. Electricity demand for CCU/CCS rises from 36.6 TWh in 2025 to 900 TWh in 2055.

Energy-related emissions were 34.7 GtCO2 in 2019, which then dropped to 32.8 GtCO2 in 2020 due to the Covid-19 pandemic, then rebounded to 34.6 GtO2 in 2021. The average of 2019-2021 values (34.0 GtCO2) is used to create a c. 2020 global baseline against which future decarbonization can be measured. Energy-related emissions in 2022 and 2023 were very similar – 35.0 GtCO2 and 35.1 GtCO2 respectively – and then increased to 35.6 GtCO2 in 2024. Based on data from BloombergNEF, 2024 appears to represent the global historic peak in energy-related emissions, with a slight reduction to 35.4 GtCO2 anticipated for 2025.

Industry-related direct emissions – Flaring, Cement, and Other Industry (including Bunkers) — decline gradually, contributing an additional 2,255 MtCO2 net emissions in 2025, declining 1,705 MtCO2 in 2040 and 900 MtCO2 in 2055, driven mostly by the elimination of flaring emissions associated with oil & gas production. Cement emissions are expected to increase through 2040, at which point a variety of efficiency measures and improved processes will begin to reduce the CO_2 intensity of cement production – from 1,650 $MtCO_2$ in 2040 to 1,350 $MtCO_2$ by 2055. Other direct industry-related emissions are assumed to be constant through 2055. The OEreCM greenhouse gas scenario starts with 37.7 $GtCO_2$ in total emissions in 2025, ramping down to 34.8 $GtCO_2$ by 2030. From that point onwards emissions decline rapidly – 26% reduction by 2035, 54% by 2040, 77% by 2045, 89% by 2050, and 97% by 2055.

Residual emissions from cement production and other industry emissions totaling approximately 1,650 $MtCO_2$ remain, and are assumed to gradually decline to zero by 2100 as new technologies to create zero-emissions cement and solutions for extremely hard-to-abate industrial processes are invented. Some carbon capture technologies are required to reduce total Industry-related emissions. OEreCM focuses particularly on Carbon Capture and Utilization (CCU), which can provide the necessary CO_2 feedstock for many industrial processes, including the production of E-fuel, ammonia, and other chemicals.

Some progress has been made in deploying Carbon Capture and Storage (CCS) technology within fossil fuel power plants, reducing some emissions associated with the combustion of fuels for electricity, but this is likely to play a very modest role in the energy transition. Currently, there is capacity to remove 50 $MtCO_2$ per year, but these plants function at approximately 50% capacity due to high costs. Significant investments have been made in CCS, CCU, and also Direct Air Capture (DAC), and the current pipeline of projects could potentially increase carbon removal capacity 9x by 2030 [69]. It should be noted that these technologies require significant additional energy inputs for the operation of equipment, compression of CO_2, and transportation and storage of chilled or liquified carbon. For every tonne of CO_2 harvested from DAC, for example, 1.2 MWh of electricity is required [70]. For this reason, CCS/CCU plays only a limited role in OEreCM, with 0.75 $GtCO_2$ removed in 2055.

To understand the role of each of the three main energy demand categories in driving global carbon emissions – Transport, Heat, and End-use Electricity – emissions estimates were attributed based on the share of fossil fuels consumed within each sector. This gives us an estimation for cumulative emissions loads for each, as shown in Table 11b.

CO2 Emissions (MtCO2/yr)	2025	2030	2035	2040	2045	2050	2055	*Cumulative CO2 (2025-2055)*
Electricity Generation CO2	**9,888**	**6,518**	**3,753**	**2,043**	**1,016**	**304**		***96,841***
Transport-Coal & lignite	7,499	4,244	1,743	656	197	-	-	*57,041*
Transport-Oil products	201	185	125	24	7	-	-	*2,241*
Transport-Natural gas	2,188	2,089	1,885	1,363	812	304	-	*37,559*
Transport CO2 (excl. Electricity)	**9,539**	**9,206**	**7,031**	**3,611**	**1,731**	**704**	**-**	***136,804***
Transport-Coal & lignite	7	7	4	2	1	-	-	*87*
Transport-Oil products	9,063	8,694	6,621	3,302	1,544	624	-	*128,175*
Transport-Natural gas	469	505	406	307	186	80	-	*8,542*
Heat Supply CO2 (excl. Electricity)	**15,986**	**13,886**	**10,776**	**7,299**	**3,301**	**1,323**	**-**	***224,975***
Heat-Coal & lignite	7,435	6,681	5,354	3,449	765	155	-	*101,887*
Heat-Oil products	2,907	1,916	691	320	112	29	-	*23,746*
Heat-Natural gas	5,644	5,289	4,731	3,530	2,424	1,139	-	*99,342*
Total Energy-related CO2 emissions	**35,413**	**29,610**	**21,560**	**12,953**	**6,048**	**2,331**	**-**	***458,620***
Additional Industry direct emissions*	**2,256**	**2,142**	**1,931**	**1,706**	**1,392**	**1,104**	**900**	***49,427***

*Table 11b. Cumulative direct CO2 emissions organized by energy supply category – Electricity Generation, Heat, Transport – per OEreCM in 5-year steps. Note: Emissions specifically associated with electricity for Heat and Transport categories are not included in those sub-totals but rather bundled into total Electricity Generation in this chart. Cumulative emissions 2025-2055 by category are shown (right). *Additional Industry-related direct emissions are shown as net emissions with the total reduced from CCU/CCS carbon removal per Table 11a.*

Global heat supply is by far the largest contributor to cumulative CO2 emissions in the OEreCM transition scenario. Heat, including industrial process heat, is responsible for 16.0 GtCO2 in 2025, dropping to 7.3 GtCO2 in 2040 and zero in 2050. Total transportation-related emissions are 9.5 GtCO2 in 2025, dropping to 3.6 GtCO2 in 2040. Electricity generation emissions are quite low, due to the significant share of renewables currently on the grid (42.5% in 2025), and the rapid speed of adoption of VREs in the power sector. Electricity emissions total 9.9 GtCO2 in 2025, declining to 2.0 GtCO2 in 2040 before phasing out in 2050. Heat supply accounts for 225.0 GtCO2 in cumulative emissions 2025-2055. Transport energy accounts for 136.8 GtCO2 and Electricity generation another 96.8 GtCO2, totaling 458.6 GtCO2 in cumulative energy-related emissions. An additional 49.4 GtCO2 of emissions are associated with Industry-related direct emissions.

A simple BAU baseline scenario was created to establish an estimate for total avoided emissions attributable to each of the major energy supply categories starting in 2025. The BAU scenario maintains 2025 emissions as a constant through 2055, as total Final Energy grows to 600 EJ, in line with recent data showing that new energy demand is now being met almost entirely by clean energy [71]. The BAU scenario results in cumulative Energy-related emissions of 1062.4

GtCO2 by 2055. Industry-related direct emissions for the BAU scenario are assumed to be the same as the OEreCM scenario (49.4 GtCO2). Thus, the OEreCM scenario avoids 603,770 MtCO2 above 2025 levels.

The OEreCM Final Energy mix delivers 444 EJ in 2055 (including hydrogen and E-fuel electricity) with zero emissions, resulting in 458,620 MtCO2 of energy-related emissions 2025-2055. Based on cumulative energy emissions (Table 11b), the Transportation scenario avoids 149.4 GtCO2 (24.7% of total avoided emissions); the Heat scenario avoids 254.6 GtO2 (42.2%); and the Electricity Generation scenario avoids 199.8 GtCO2 (33.1%). But this achievement is predicated upon a large amount of conserved Final Energy due to efficiency measures (155.8 EJ in equivalent avoided demand) providing approximately 156,787 MtCO2 in avoided emissions.

To account for the benefit of energy efficiency in total avoided emissions, the values attributed to Transportation, Heat, and Electricity are refactored according to the share of total mitigation delivered. Initially, this results in 110.6 GtCO2 in avoided emissions from the Transportation scenario; 188.5 GtCO2 from Heat; and 147.9 GtCO2 from Electricity. However, this does not yet factor in the share of electricity used for the Heating and Transport sectors. It also ignores the efficiency gains from electricity due solely from fuel switching. To correct for these measures, a split attribution method assigns 50% of electricity for heat and transport as well as 50% of electricity for hydrogen and E-fuel production based on the proportion of hydrogen and E-fuel used in the Heating, Transport, and Electricity categories. In addition, 50% of net efficiency gains resulting from a 100% clean power grid are shifted to the Electricity category, resulting in the following attribution of avoided emissions by energy category:

- Transport *100,036 MtO2*
- Heating *149,278 MtCO2*
- Electricity *217,728 MtCO2*
- Efficiency *109,092 MtCO2*

Using Final Energy ratios for each category, an attribution of avoided emissions per solution sub-category can be provided as a share of total avoided CO2 emissions, shown in Table 12.

Avoided CO2 emissions by energy sub-category	Avoided CO2	% share	Avoided CO2 emissions by energy sub-category	Avoided CO2	% share
Transport Energy	**100,036**	***16.6%***	**Electricity (excl. Heat & Transport)**	**217,728**	***36.1%***
- Green H2	12,476	*2.1%*	- Solar PV	65,311	*10.8%*
- E-fuel	25,761	*4.3%*	- Solar thermoelectric	20,381	*3.4%*
- Biofuel	36,637	*6.1%*	- Geothermal power	8,232	*1.4%*
- Electric transport	25,162	*4.2%*	- Onshore wind	59,009	*9.8%*
			- Offshore wind	24,769	*4.1%*
			- Wave energy	3,261	*0.5%*
Heat Energy (Industry & Bldgs.)	**149,278**	***24.7%***	- Sustainable hydropower	16,305	*2.7%*
- Solar heat	28,005	*4.6%*	- Sustainable biomass	6,311	*1.0%*
- Geothermal heat	18,309	*3.0%*	- Green H2	9,513	*1.6%*
- Sustainable biomass	28,251	*4.7%*	- Advanced nuclear	4,635	*0.8%*
- Green H2	13,818	*2.3%*			
- RE District heat	15,172	*2.5%*	**Efficiency**	**136,729**	**22.6%**
- Electric heat	45,722	*7.6%*	- Built Environment	41,782	*6.9%*
			- Transport	39,405	*6.5%*
			- Transmission & Storage	27,905	*4.6%*
			- Industry/Services	27,637	*4.6%*
603,770 MtCO2					
Total Avoided CO2 emissions					

Table 12. Avoided CO2 emissions by energy supply category and sub-category versus a BAU scenario of 1,062,390 MtCO2 in cumulative emissions (2025-2055), factoring in net efficiency gains distributed across Transport, Heat, and End-use electricity categories per OEreCM ratios. Emissions associated with electricity generation for Heat and Transport categories are calculated as a 50% share of total Electricity emissions. These values are deducted from total Electricity emissions to derive estimated emissions specifically associated with end-use electricity demand.

Based on this attribution model, it can be theorized that out of the 603,770 MtCO2 of total avoided emissions projected, investments in Transport energy (including electrification) account for approximately 16.6% of the avoided emissions benefit by 2055, and investments in Heat supply (including electrification) account for another 24.7% of avoided emissions. End-use Electricity investments provide 36.1% of avoided emissions, alongside investments in Energy Efficiency, which provide 22.6% of the total mitigation achieved 2025-2055 due to the full implementation of the OEreCM energy transition scenario.

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