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Global Decarbonization: Current Status and What It Will Take to Achieve Net Zero by 2050

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Abstract: A review of global CO_2 emissions over the last century shows that emissions from 80 economies contributed to 95% of global emissions. Among them, 55 economies were decarbonizers, where CO_2 emissions had either plateaued or were declining, while 25 economies were polluters, where CO_2 emissions were still increasing. In 2021, the global CO_2 emissions were 37.1 Gtpa, with 56% coming from polluters and 39% from decarbonizers. If current trends continue, global CO_2 emissions will reach 49.6 Gtpa by 2050, with 81% coming from polluters and 14% from decarbonizers. Only 14 economies will reach net zero. The decarbonization target, over and above current efforts, to achieve net zero is calculated for each economy. Decarbonizers need to mitigate 230 Mtpa CO_2 and polluters 1365 Mtpa CO_2 beginning in 2021 to reach the net-zero target by 2050. This target will increase each year decarbonization is delayed. Analyses show that renewable energies' share in the total final energy consumption in most economies increased by an average of only 4 percentage points in the last decade, which is inadequate for achieving net zero by 2050. Other means of decarbonization, including low-carbon fossil solutions through carbon capture and storage, will be needed. Pathways to accelerate decarbonization are proposed and their policy implications are discussed.

Keywords: decarbonization; net zero; CO_2 emissions; carbon capture and storage; low-carbon fossil fuels

Citation: Lau, H.C.; Tsai, S.C. Global Decarbonization: Current Status and What It Will Take to Achieve Net Zero by 2050. *Energies* **2023**, *16*, 7800. https://doi.org/10.3390/en16237800

Academic Editors: Federica Raganati and Paola Ammendola

Received: 3 November 2023
Revised: 20 November 2023
Accepted: 21 November 2023
Published: 27 November 2023

1. Introduction

Since the signing of the Paris Agreement in 2015, 196 countries have agreed to reduce their anthropogenic greenhouse gas (GHG) emissions in order to maintain the global rise of atmospheric temperature below 1.5 °C above pre-industrial times [1]. This is driven by the belief of many scientists that global warming is caused by anthropogenic GHG emissions [2–4]. Among GHGs, CO_2 is the most important due to its vast quantity and greenhouse gas effect. Some scientists believe the effect of CO_2 on global warming is irreversible [5,6].

In the last 120 years, global CO_2 emissions from the combustion of fossil fuels have grown 19-fold from 1.95 Gtpa in 1900 to 37.1 Gtpa in 2022 [7]. To achieve the 1.5 °C target, many climate scientists believe that global GHG emissions should be reduced by 45% by 2030 and reach net zero by 2050 [8]. Hitherto, over 70 countries have pledged to achieve net zero by 2050 [9,10]. They include the biggest emitters, such as China [11], the USA [12], India [13] and the European Union [14], and cover 76% of global emissions. Today, more and more businesses are committed to achieving net zero by 2050, as this has become a license to operate in many countries [15–20].

Global decarbonization has received much attention in the academic literature in the last five years. In a recent review paper on energy transition, Lau et al. (2021) argued that decarbonization should be considered according to energy-consumption sectors, with power (electricity), transport and industry being the three major ones [21]. Furthermore, each country will choose an energy transition pathway depending on its particular energy and social context. A recent report by the McKinsey (2022) consulting firm predicted that future capital investment in physical assets for energy and land-use systems will reach USD 9.2 trillion per year in 2050 or USD 3.5 trillion per year more than in 2021, with most of the investment concentrated on the power, transport and industry sectors [22]. Jackson et al. (2018) argued that the current global energy growth is outpacing decarbonization [23]. They identified 19 countries whose GDP grew and whose CO_2 emissions declined over the last decade. However, their efforts were outpaced by CO_2 emissions from other countries. Rockstrom et al. (2017) proposed a simple carbon law, namely, halving anthropogenic CO_2 emissions every decade, as a roadmap for achieving net zero by 2050 [24]. However, Urpelainen (2017) argued that this roadmap, though mathematically possible, is unrealistic because it is not based on the energy and social context of individual countries [25]. To be useful, decarbonization roadmaps need to be tailored to local conditions and address the barriers to policy implementation. Several country-specific decarbonization roadmaps for Singapore [26,27], Malaysia, Indonesia [28], Thailand [29,30], Vietnam [31], Taiwan [32] and Canada [33,34] were published recently with due consideration given to the unique energy landscape of each country.

Various agencies published their energy forecast scenarios to predict sectorial or global CO_2 emissions under different future scenarios. For example, the US Renewable Energy National Laboratory (NREL) published its standard scenarios for the US power sector, which are updated annually based on US energy policies [35,36]. Several international oil companies, such as Shell, ConocoPhillips, Exxon and BP, published energy scenarios based on their respective outlook of the energy future [37–40]. The International Energy Agency (IEA) published scenarios capturing current government policies, what was pledged and what will be needed to achieve net-zero emissions by 2050 or soon afterward [41–43]. In this study, rather than advocating for any of the aforementioned energy scenarios, we assumed that the current energy trend of each country will continue till 2050 and determine what more is needed to meet the net-zero goal by 2050.

Hitherto, the debate on global decarbonization seems mostly centered on the increased use of renewable energies [8,44], and increasingly, more people are advocating for a total ban on fossil fuels [45–48]. However, this approach is rather one-sided and does not consider the limit to the pace at which renewable energy capacities can be added and the contributions from low-carbon fossil energies, such as fuel switching, and the use of carbon capture and storage (CCS) [21]. In this study, we examined historical CO_2 emissions and the pace of global decarbonization over the last two to three decades to understand the current status. We then forecasted global CO_2 emissions by 2050 and what decarbonization targets, over and above current efforts, will be needed to achieve net zero by 2050. Then, we discuss options to achieve these targets.

2. Objectives and Methodology

The objectives of this study were threefold. First, a look back at global CO_2 emissions over the last 120 years was conducted to understand the historical trend and current status. Second, using recent historical trends, we forecasted CO_2 emissions by 2050 and determined the extra decarbonization efforts, over and above current efforts, that will be needed to achieve net zero by 2050 for the top 80 CO_2 emitters of the world. Third, we discuss pathways to accelerate decarbonization for various economies and their policy implications.

A linear history matching and forecasting method was used to analyze CO_2 emissions data. The methodology is illustrated in Figure 1. From the global database of CO_2 emissions from Our World in Data [7], we selected the top 80 CO_2 emitters and classified them into two groups. The first group was called decarbonizers and consisted of economies where CO_2 emissions had either peaked or were in decline. The second group was called polluters and consisted of economies where CO_2 emissions were still increasing. In this study, economies were either countries or territories that reported accurate data on CO_2 emissions. After determining the historical CO_2 increase rate from the historical data, we extended the historical CO_2 emissions trends linearly into the future to determine the CO_2 emissions by 2050. We also calculated the CO_2 decline rate needed to achieve net zero by 2050 using the CO_2 emissions rate in 2021. The difference between this rate and the historical rate gave the target decarbonization rate in 2021, over and above current efforts, to achieve net-zero emissions by 2050. Assuming decarbonization was delayed beyond 2021, the decarbonization target was recalculated based on the CO_2 emissions forecast. Thus, we determined the decarbonization targets for every polluter and decarbonizer between 2021 and 2050. We then grouped economies into coal-dominated, gas-and-oil-dominated, and non-fossil-energy-dominated economies and discussed their respective decarbonization pathways and policy implications.

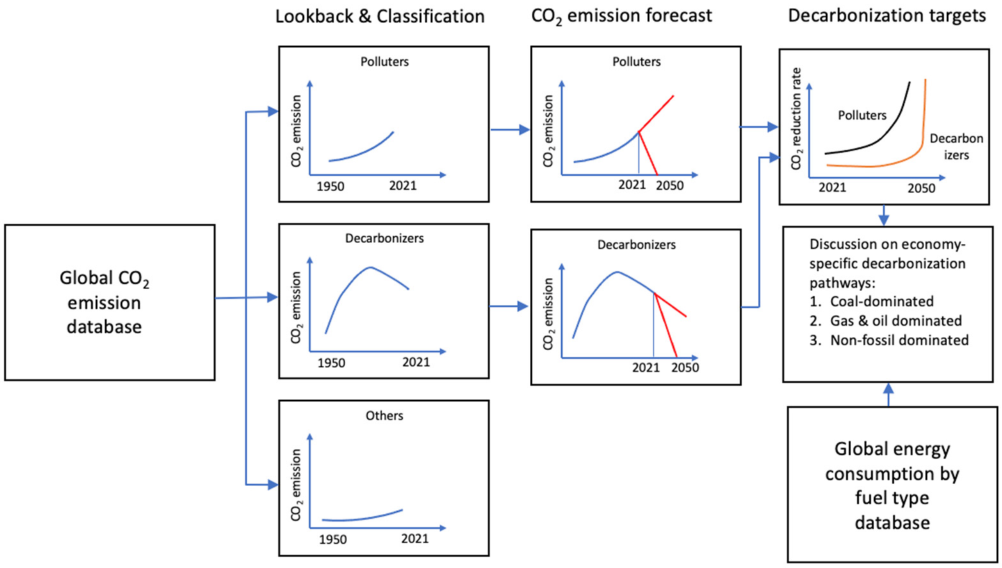

Figure 1. Methodology of study.

Comparison of Study Methodology with IEA Scenarios

It is worthwhile to compare our forecast methodology with the four global energy forecast scenarios proposed by the IEA (Figure 2). The business-as-usual (BAU) scenario assumes that few or no steps are taken to limit greenhouse gas emissions. Therefore, unabated CO_2 emissions will continue to increase with the increased use of fossil energies due to the growth in population and prosperity. The second is the stated policies scenario (STEPS), which reflects the current policy settings of each country as of August 2023 [42]. The announced pledges scenario (APS) assumes that all climate commitments made by governments and industries as of August 2023 will be met [41]. The sustainable development scenario (SDS) assumes that significant actions will be taken to limit the global temperature increase to 1.5 °C and thereby reduce global CO_2 emissions to about 10 Gtpa by 2050 [43]. The net-zero (NZE) scenario assumes that net zero will be achieved by 2050 [49]. Although the IEA scenarios are global scenarios, they may be adapted to individual countries or economies.

Figures 3 and 4 show how our forecast method fits in the context of IEA's four scenarios for a decarbonizer and polluter, respectively. Our forecast did not assume any of the four IEA scenarios for any economy. It just extrapolated the current trend into the future. For a decarbonizer, the current trend may lie between STEPS and APS (Figure 3), which still falls short of the NZE scenario. Our forecasting method showed what it will take to accelerate the current trend to meet net zero by 2050 by assuming different years for the start of this acceleration. Each year a decarbonizer delays in starting the extra effort will make it more difficult to achieve the net-zero goal by 2050. For a polluter, the current trend may fall between BAU and STEPS (Figure 4). Our forecasting method calculated the extra effort needed to achieve the NZE scenario by beginning the extra effort at different years. The extra effort to achieve net zero by 2050 will be much greater for a polluter than a decarbonizer. The validity of our forecast was based on the length of time used to establish the current trend, which was at least one decade and may be as long as three decades. See figures in Section 5 for the USA and China, respectively.

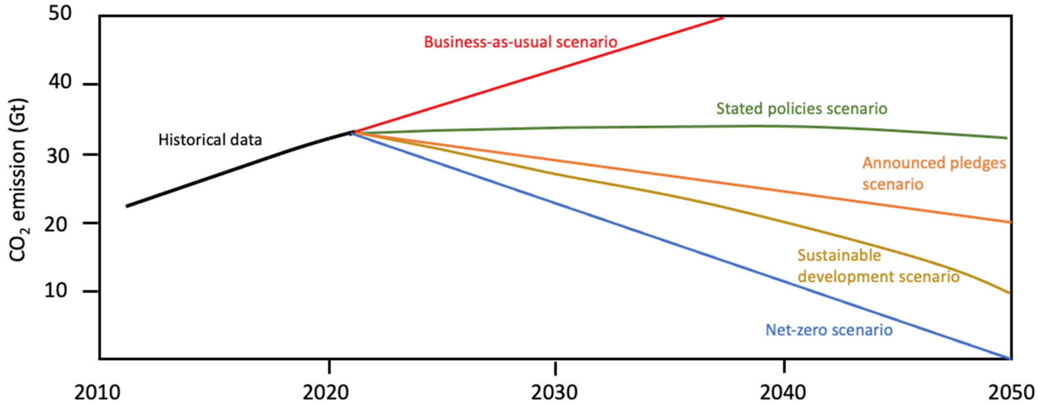

Figure 2. Forecast scenarios by International Energy Agency (IEA).

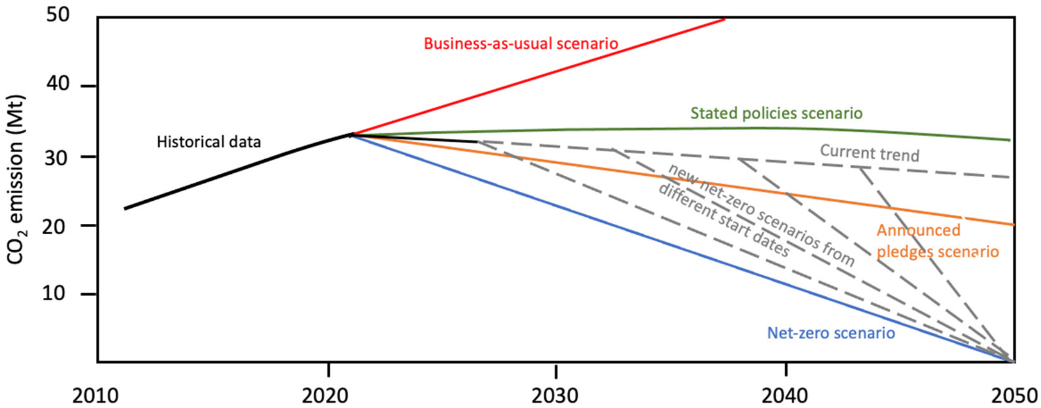

Figure 3. Comparison of current trend study methodology with IEA scenarios for a decarbonizer.

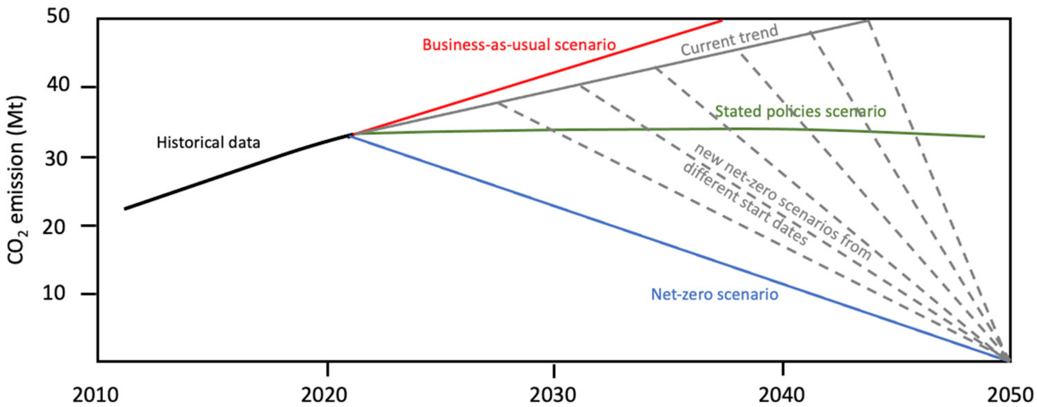

Figure 4. Comparison of current trend study methodology with IEA scenarios for a polluter.

3. Look Back and Classification

Figure 5 shows the annual CO_2 emissions history for decarbonizers over the last 120 years [7]. There were 55 economies where CO_2 emissions had either peaked or were declining. The complete list is given in Table 1. Among the decarbonizers, the biggest CO_2 emitters were the USA, Japan, Germany, South Korea, Canada, Brazil, South Africa, Mexico, Australia and the United Kingdom (UK).

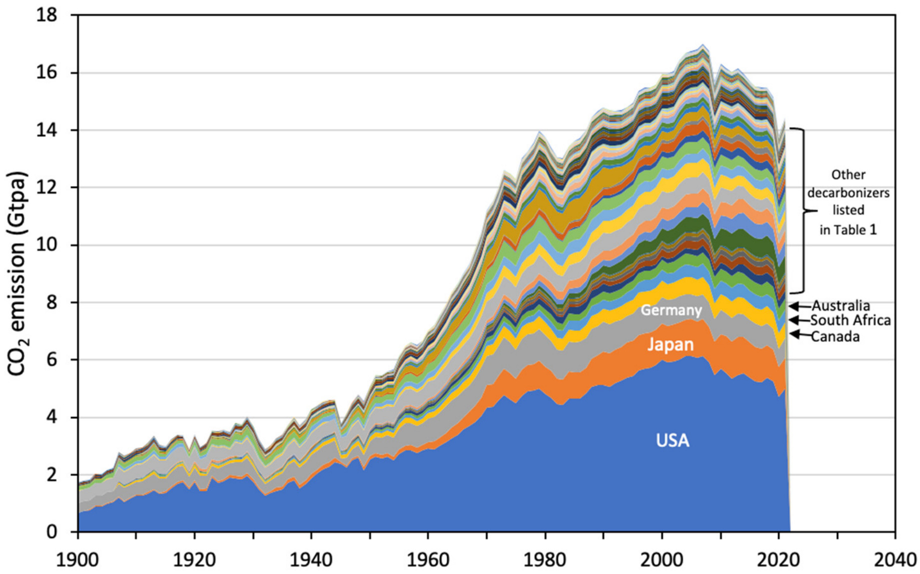

Figure 5. Annual CO_2 emission from decarbonizers [7].

Table 1. CO_2 emissions forecast and decarbonization targets for decarbonizers.

	Economy	CO_2 Emissions in 2021 (Mtpa) [7]	Estimated Net-Zero Date	Est. CO_2 Emissions in 2050 (Mtpa)	Current CO_2 Increase Rate (Mtpa)	CO_2 Increase Rate to Reach Net Zero by 2050 (Mtpa)	Decarbonization Target in 2021 to Achieve Net Zero by 2050 (Mtpa)	Confidence Level of Forecast *
1	USA	5007	2091	2900	−71.40	−172.67	−101.27	M
2	Japan	1067	2050	60	−33.80	−36.81	−3.01	M
3	Germany	674	2108	510	−8.50	−23.27	−14.77	H
4	South Korea	616	2050	0	−19.41	−19.41	0.00	L
5	Brazil	489	2074	215	−8.90	−16.86	−7.96	M
6	Mexico	407	2064	132	−9.60	−14.04	−4.44	M
7	UK	347	2045	0	−14.10	−11.96	2.14	H
8	Italy	329	2047	0	−11.90	−11.33	0.57	H
9	Poland	329	2083	147	−4.51	−11.33	−6.82	L
10	France	306	2060	80	−7.60	−10.55	−2.95	H
11	Thailand	278	2100	177	−3.50	−9.60	−6.10	L
12	Spain	234	2042	0	−10.00	−8.06	1.94	M
13	UAE	202	2098	126	−2.60	−7.04	−4.44	L
14	Ukraine	204	2042	0	−9.70	−6.96	2.74	L
15	The Netherlands	141	2097	91	−1.90	−4.86	−2.96	L
16	Czechia	97.1	2061	25	−2.40	−3.35	−0.95	M
17	Belgium	95.7	2069	36	−1.90	−3.30	−1.40	M
18	Columbia	91.7	2100	58	−1.14	−3.16	−2.02	L
19	Venezuela	79.5	2027	0	−14.10	−2.75	11.35	M
20	Romania	79.3	2055	11	−2.04	−2.74	−0.71	M
21	Austria	64.6	2114	45	−0.70	−2.23	−1.53	L

Table 1. *Cont.*

	Economy	CO_2 Emissions in 2021 (Mtpa) [7]	Estimated Net-Zero Date	Est. CO_2 Emissions in 2050 (Mtpa)	Current CO_2 Increase Rate (Mtpa)	CO_2 Increase Rate to Reach Net Zero by 2050 (Mtpa)	Decarbonization Target in 2021 to Achieve Net Zero by 2050 (Mtpa)	Confidence Level of Forecast *
22	Belarus	59.6	NA	60	0.00	−2.06	−2.06	L
23	North Korea	56.4	NA	56	0.00	−1.94	−1.94	L
24	Greece	56.3	2035	0	−4.10	−1.94	2.16	H
25	Israel	54.5	2055	8	−1.60	−1.88	−0.28	L
26	Hungary	48.4	2088	26	−0.67	−1.67	−1.00	L
27	Bulgaria	42.6	2068	15	−0.85	−1.47	−0.62	M
28	Ecuador	41.3	NA	41	0.00	−1.42	−1.42	L
29	Norway	40.9	2077	20	−0.73	−1.41	−0.69	L
30	Portugal	40.8	2047	0	−1.56	−1.41	−0.15	M
31	Finland	37.6	2040	0	−2.10	−1.30	0.80	H
32	Ireland	37.5	2076	17	−0.66	−1.29	−0.63	L
33	Trinidad & Tobago	36.1	2047	0	−1.40	−1.25	0.15	M
34	Sweden	35.8	2063	12	−0.95	−1.24	−0.29	M
35	Slovakia	35.3	2070	13	−0.65	−1.22	−0.57	M
36	Switzerland	34.9	2060	8	−0.88	−1.20	−0.32	M
37	Serbia	30.9	2050	0	−1.33	−1.06	0.26	L
38	Denmark	29.6	2036	0	−1.90	−1.02	0.88	H
39	Syria	27.0	NA	27	0.00	−0.93	−0.93	L
40	Sri Lanka	20.8	2086	12	−0.33	−0.72	−0.39	L
41	Croatia	17.7	2057	3.2	−0.48	−0.61	−0.13	M
42	Lithuania	13.9	NA	13.9	0.00	−0.48	−0.48	L
43	Slovenia	12.5	2057	2.6	−0.36	−0.43	−0.07	L
44	Estonia	10.4	2035	0	−0.82	−0.36	0.46	L
45	Luxembourg	8.4	2058	1.9	−0.23	−0.29	−0.06	M
46	Canada	545	NA	NA	0.00	−18.81	−18.81	L
47	South Africa	436	NA	NA	0.00	−15.03	−15.03	L
48	Australia	391	NA	NA	0.00	−13.49	−13.49	L
49	Taiwan	283	NA	NA	0.00	−9.75	−9.75	L
50	Kazakhstan	277	NA	NA	0.00	−9.54	−9.54	L
51	Argentina	186	NA	NA	0.00	−6.43	−6.43	L
52	Uzbekistan	122	NA	NA	0.00	−4.19	−4.19	L
53	New Zealand	33.8	NA	NA	0.00	−1.17	−1.17	L
54	Singapore	32.5	NA	NA	0.00	−1.12	−1.12	L
55	Hong Kong	31.7	NA	NA	0.00	−1.09	−1.09	L
	Total	14,310			−261	−492	−230	

* L—low, M—moderate, H—high, NA—not available

Figure 6 shows the CO_2 emissions history for polluters over the last 120 years [7]. There were 25 economies where CO_2 emissions were still increasing. The complete list is given in Table 2. Among the polluters, the biggest CO_2 emitters were China, India, Russia, Iran, Saudi Arabia, Indonesia, Turkey, Vietnam, Malaysia and Egypt.

Figure 7 shows the aggregate CO_2 emissions for polluters, decarbonizers and the rest of the world (others). It can be seen that between 2001 and 2021, CO_2 emissions have dropped by 1.520 Gtpa for decarbonizers but have increased by 12.49 Gtpa for polluters. The net change between the two was 10.97 Gtpa. Global CO_2 emissions were still increasing at 407 Mtpa in 2021, as calculated from the slopes of the curves for polluters, decarbonizers and "others" in Figure 7

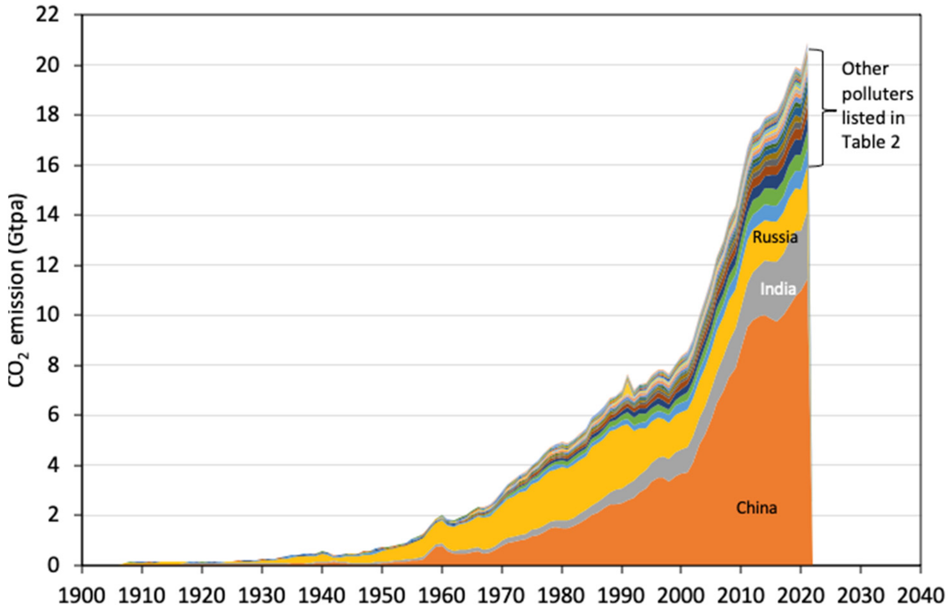

Figure 6. Annual CO_2 from polluters [7].

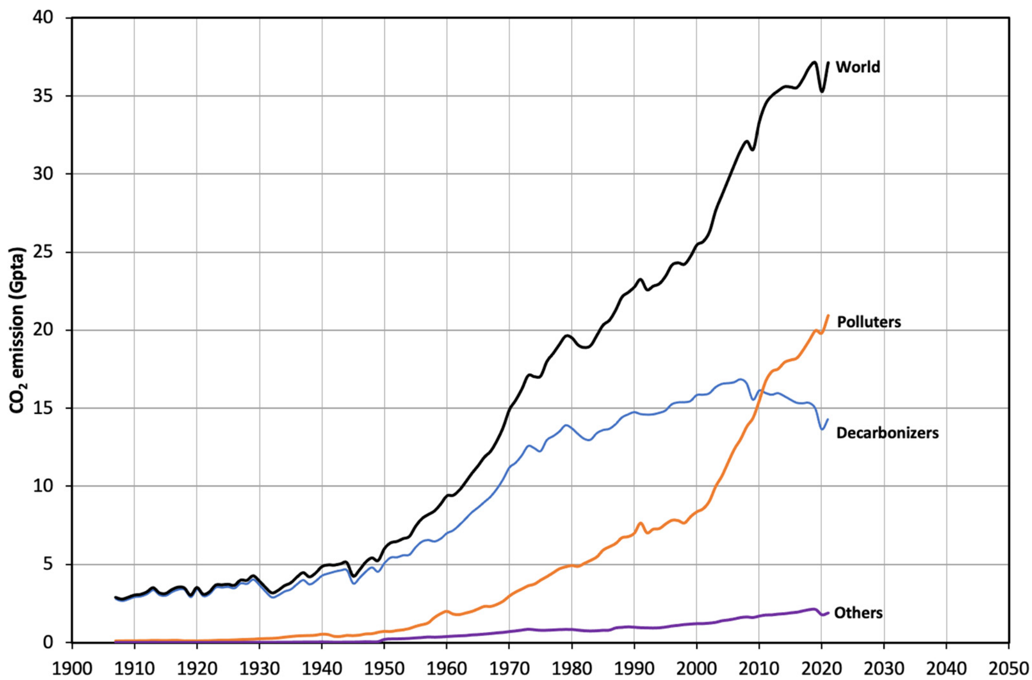

Figure 7. Global CO_2 emissions.

Table 2. CO_2 emissions forecast and decarbonization targets for polluters.

	Economy	CO_2 Emissions in 2021 (Mtpa) [7]	Est. CO_2 Emissions in 2050 (Mtpa)	Current CO_2 Increase Rate (Mtpa)	CO_2 Increase Rate to Reach Net Zero by 2050 (Mtpa)	Decarbonization Target in 2021 to Achieve Net Zero by 2050 (Mtpa)	Confidence Level of Forecast *
1	China	11,472	22,400	375.80	−395.60	−771.40	M
2	India	2710	5900	106.70	−93.44	−200.14	H
3	Russia	1756	2100	12.00	−60.54	−72.54	M
4	Iran	749	1250	17.30	−25.82	−43.12	H
5	Saudi Arabia	672	1360	21.60	−23.19	−44.79	H
6	Indonesia	619	1210	19.00	−21.35	−40.35	H
7	Turkey	446	760	10.71	−15.39	−26.10	H
8	Vietnam	326	840	17.78	−11.24	−29.02	M
9	Malaysia	256	490	7.25	−8.83	−16.08	M
10	Egypt	250	480	7.04	−8.61	−15.65	M
11	Pakistan	229	370	5.00	−7.91	−12.91	M
12	Iraq	186	522	10.00	−6.40	−16.40	L
13	Algeria	176	328	4.96	−6.08	−11.04	M
14	Philippines	144	295	5.28	−4.97	−10.25	M
15	Nigeria	137	252	3.98	−4.71	−8.70	L
16	Kuwait	106	156	1.90	−3.66	−5.56	M
17	Qatar	95	200	3.30	−3.30	−6.60	M
18	Bangladesh	93	190	3.33	−3.21	−6.54	H
19	Chile	85	154	0.20	−2.95	−3.15	H
20	Turkmenistan	83	168	2.83	−2.86	−5.69	M
21	Oman	81	167	2.93	−2.79	−5.72	H
22	Libya	75	108	1.18	−2.57	−3.75	L
23	Morocco	71	118	1.70	−2.43	−4.13	H
24	Peru	56	94	1.28	−1.94	−3.22	L
25	Azerbaijan	38	53	0.47	−1.33	−1.80	L
	Total	20,913	39,965	644	−721	−1365	

* L—low, M—moderate, H—high, NA—not available

4. Global CO_2 Emissions Forecast

For each economy, we used a straight line to best fit the CO_2 emissions data for the last two to three decades. We extended this line into the future to determine the CO_2 emission by 2050 and the net-zero time for decarbonizers. The results are given in Table 1 for decarbonizers and Table 2 for polluters. When the results for all 55 decarbonizers were summed, we obtained the CO_2 emissions forecast for decarbonizers, as shown in Figure 8. The same was done for the 25 polluters, with the results given in Figure 9. It is worthwhile to emphasize that a linear trend appeared to be the best fit for historical CO_2 emissions data for most countries. A nonlinear history match was usually not a good match and gave an unreliable forecast.

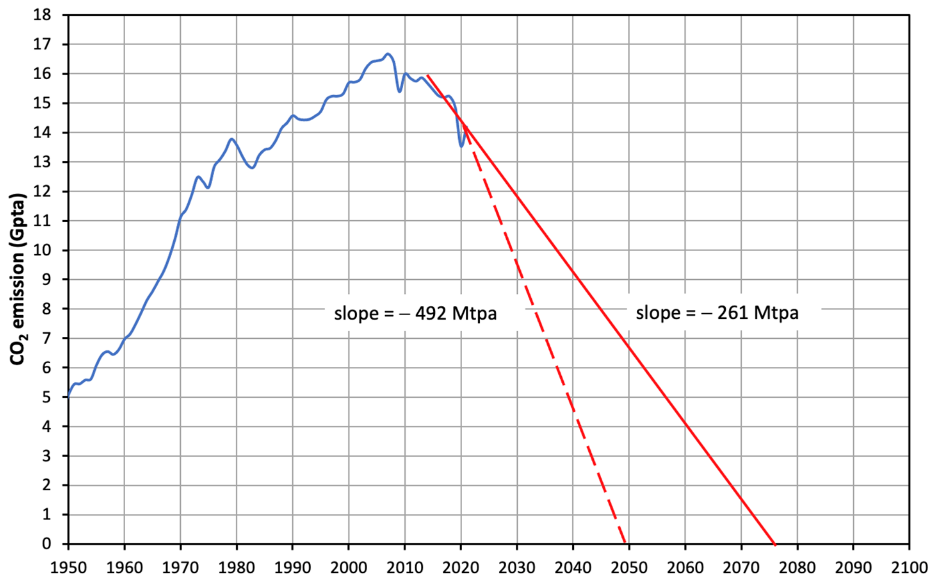

Figure 8. CO_2 emissions forecast for decarbonizers.

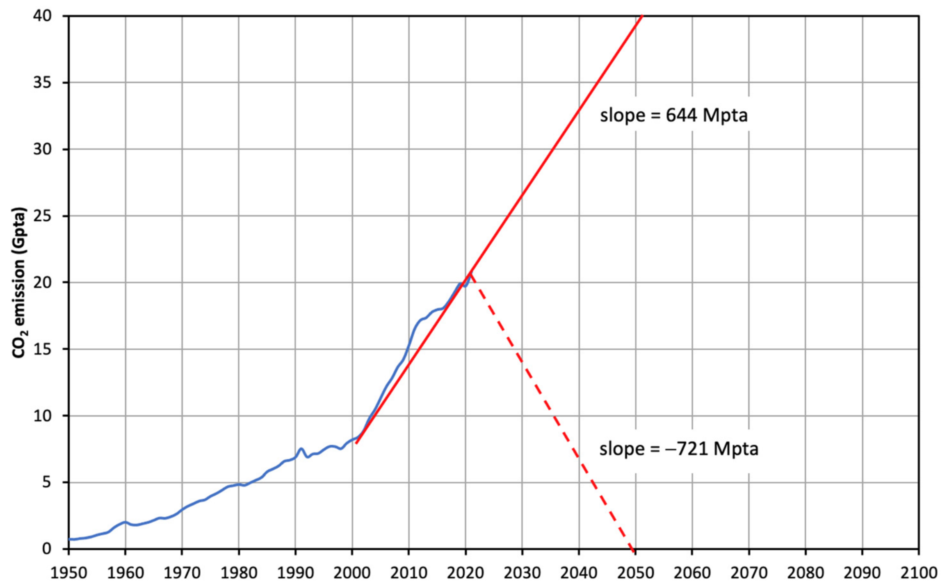

Figure 9. CO_2 emissions forecast for polluters.

Using this methodology, we estimated that the CO_2 emissions for decarbonizers, as a group of economies, were changing at a rate of −261 Mtpa. Thus, their CO_2 emissions will reach 6.74 Gtpa by 2050 and net zero will be reached by 2076 (Figure 8). Similarly, our calculations show that the CO_2 emissions for polluters will increase at a rate of +644 Mtpa and will reach 39.6 Gtpa by 2050 (Figure 9). Using this method, we estimated that the CO_2 emission for other economies was increasing at a rate of 23.7 Mtpa and will reach 2.6 Gtpa by 2050 (Figure 10). As of 2021, the global CO_2 emissions were 37.1 Gtpa, with 56% coming from polluters, 39% from decarbonizers and 5% from other economies (Figure 11a). If current CO_2 emission rates continue, our study forecasted that the global CO_2 emissions will increase to 49.3 Gtpa in 2050 (Figure 11b), with 80% coming from polluters, 14% from decarbonizers and 5% from other economies. Consequently, the current emission rates of CO_2 will not allow the world to achieve peak CO_2 emissions by 2050, let alone reach net zero, as evidenced by Figure 7. In short, the increasing CO_2 emissions by polluters will more than offset the CO_2 abatement by decarbonizers, and the world as a whole is losing ground on decarbonization.

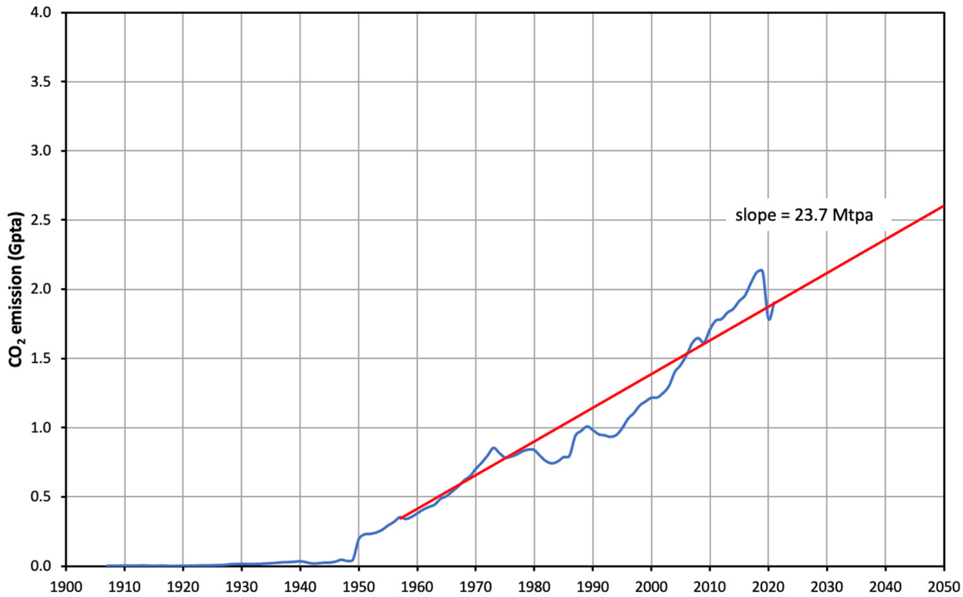

Figure 10. CO_2 emissions forecast for "other" economies.

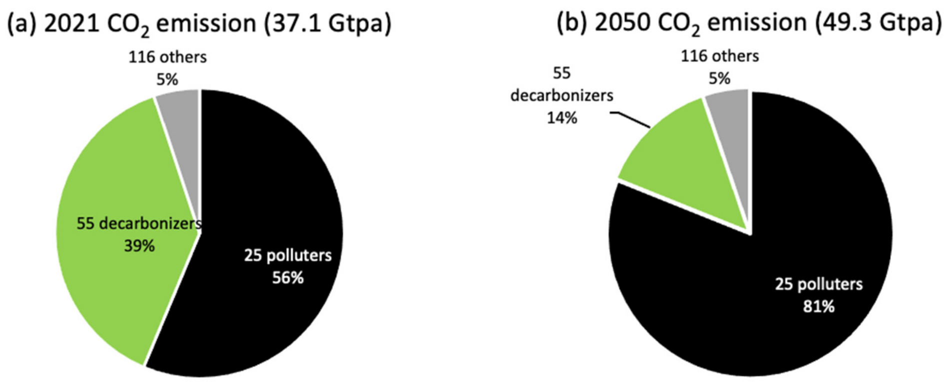

Figure 11. Global CO_2 emissions in (**a**) 2021 and (**b**) 2050 (forecast).

Our calculations showed that if current CO_2 emission rates continue, only 14 economies will achieve net zero by 2050. They were the UK, Italy, Spain, Ukraine, Greece, Portugal, Finland, Serbia, Denmark, Estonia, Trinidad and Tobago, Venezuela, South Korea and Japan. Together they contributed only 8.4% of the global CO_2 emissions in 2021. Therefore, a drastic change in the way economies tackle decarbonization will be needed over and beyond what they are doing, if they are to achieve net zero by 2050.

5. Decarbonization Target to Achieve Net Zero by 2050

To quantify what efforts, over and above current ones, will be needed to meet the net-zero target by 2050, for each of the 80 economies, we estimated the decarbonization target rate to achieve this. The method to calculate this is illustrated for a decarbonizer (USA) in Figure 12 and a polluter (China) in Figure 13. In these figures, we drew a straight line connecting the emissions in 2021 to the x-axis at 2050. This is the decarbonization rate needed to achieve net zero by 2050 assuming the 2021 CO_2 rate was neither increasing nor decreasing. This rate was −172.7 Mtpa for USA (Figure 12) and −395.6 Mtpa for China (Figure 13). The target decarbonization rate in 2021 to achieve net zero by 2050 was the difference between this rate and the current decarbonizing rate in 2021. This target rate was −101.3 Mtpa for the USA (Figure 12) and −771.4 Mtpa for China (Figure 13). To obtain the target decarbonization rate for subsequent years, we drew a straight line from the CO_2 emissions forecast for subsequent years to the x-axis at 2050 and repeated the same calculations.

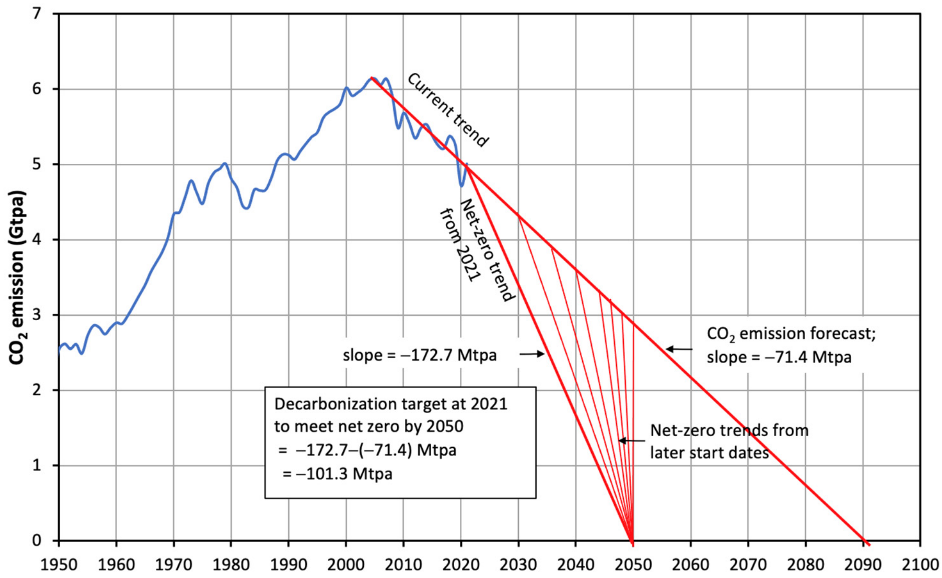

Figure 12. Graphical method to determine decarbonization targets between 2021 and 2050 for USA.

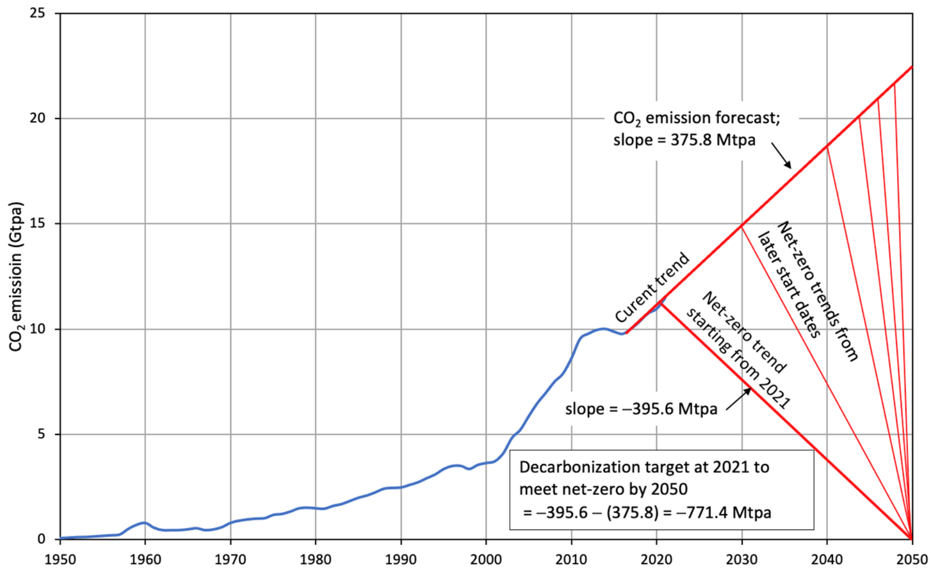

Figure 13. Graphical method to determine decarbonizer targets between 2021 and 2050 for China.

Figure 14 shows the target decarbonization rates for decarbonizers and polluters as groups of economies. For decarbonizers, the target decarbonization rate started at 230 Mtpa in 2021 and increased to 500 Mtpa by 2030. As time approaches 2050, this target rate will increase rapidly. For polluters, the target decarbonization rate started at 1365 Mtpa in 2021 and will increase to 2000 Mtpa for the year 2030 and 4400 Mtpa for the year 2040. Thereafter, it will increase sharply as 2050 was approached. The target decarbonization rates for economies with the biggest targets are shown in Figure 15. Figures 14 and 15 show clearly that there was a big difference in target decarbonization rates to achieve net zero by 2050 between polluters and decarbonizers. Polluters required a much bigger target decarbonization than decarbonizers. For both, the target decarbonization rate will increase with time. As 2050 approaches, the target decarbonization rate will be too high to be achievable. This means that decarbonization must begin as soon as possible. Each year of delay in beginning decarbonization will make subsequent decarbonization more difficult and expensive.

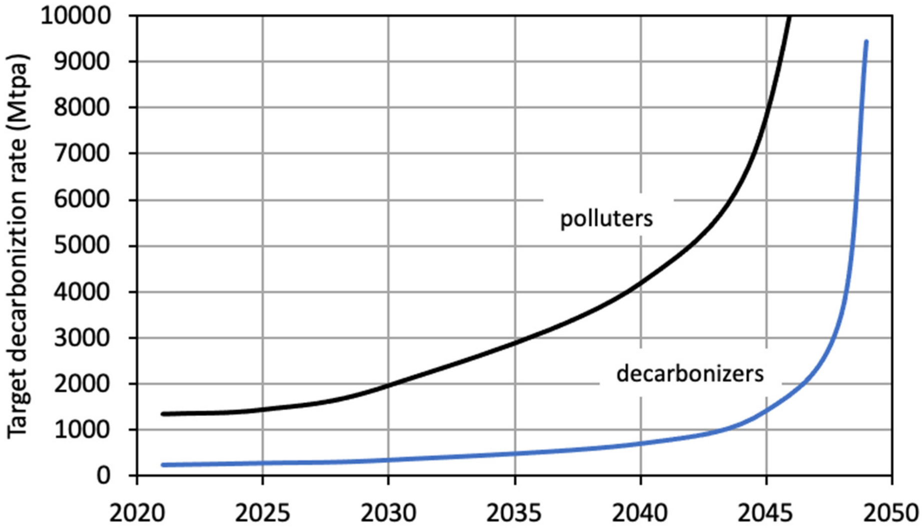

Figure 14. Target decarbonization targets for polluters and decarbonizers.

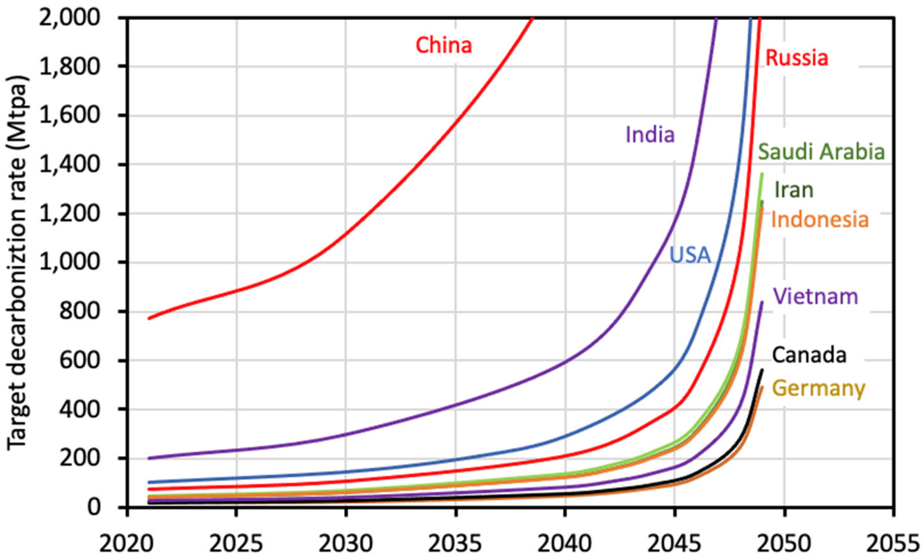

Figure 15. Target decarbonization targets for various countries.

6. Decarbonization Pathways

The target decarbonization rates in 2021 to achieve net zero by 2050 are shown in the second-to-last column in Tables 1 and 2. Figure 16 compares the target decarbonization rates in 2021 for 20 economies with the highest targets. The economies with the highest decarbonization targets are China, India, the USA, Russia, Saudi Arabia, Iran and Indonesia. Their efforts will be critical for global decarbonization. It is worthwhile to note that there are some big CO_2 emitters, e.g., Japan, South Korea, the UK and Italy, that do not appear on this list because they have low decarbonization targets since their current decarbonization rates are relatively high.

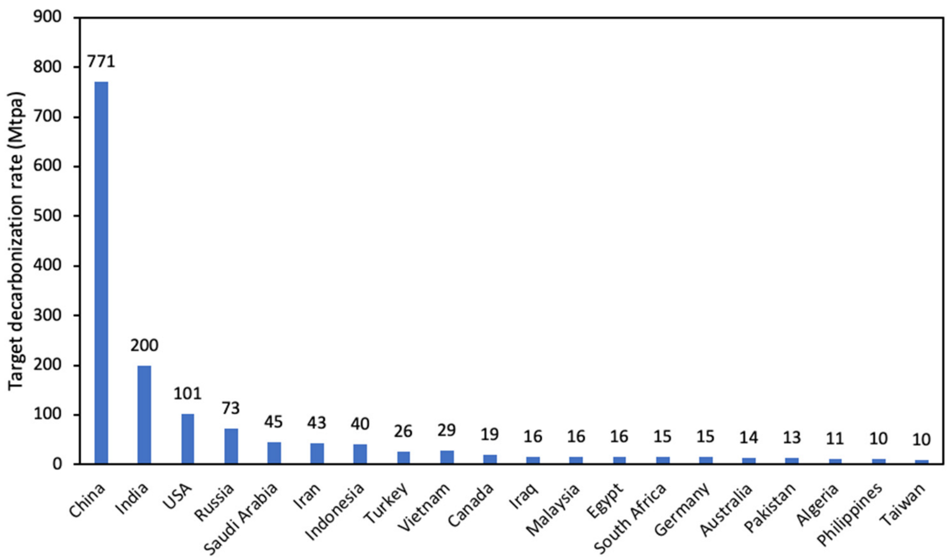

Figure 16. Target decarbonization rate in 2021 to achieve net zero by 2050.

To determine the pathways for decarbonization, we divided economies into three categories: coal-dominated (Table 3), gas-and-oil-dominated (Table 4), and non-fossil-dominated (Table 5) and discuss decarbonization pathways for each. Out of the 80 economies included in the aforementioned analysis, only 66 reported data on their composition of total final energy consumption (TFEC) in 2021 [50]. Hence, in the following sections, we focus on these 66 economies.

Table 3. Composition of TFEC in coal-dominated economies in 2021 [50].

Number	Country	Coal's Share of TFEC (Fraction)	Oil's Share of TFEC (Fraction)	Gas's Share of TFEC (Fraction)	RE's Share of TFEC (Fraction)	Nuclear's Share of TFEC (Fraction)	CO_2 Emissions (Mtpa)	ΔRE Share of TFEC (2011–2021) (pp)
1	South Africa	0.710	0.209	0.028	0.034	0.018	436	3.02
2	India	0.567	0.266	0.063	0.093	0.011	2710	2.34
3	China	0.547	0.194	0.086	0.150	0.023	11,470	8.26
4	Kazakhstan	0.544	0.220	0.195	0.042	0.000	277	1.19
5	Vietnam	0.497	0.217	0.060	0.226	0.000	326	8.03
6	Poland	0.423	0.311	0.189	0.077	0.000	329	4.93
7	Philippines	0.401	0.416	0.061	0.122	0.000	144	−3.70
8	Indonesia	0.395	0.341	0.160	0.104	0.000	619	6.58
9	Taiwan	0.336	0.386	0.197	0.030	0.050	283	1.11
10	Czechia	0.321	0.244	0.196	0.071	0.167	97	3.28
11	Morocco	0.320	0.567	0.031	0.082	0.000	71	NA
12	Australia	0.284	0.337	0.248	0.131	0.000	391	9.36
13	Ukraine	0.284	0.138	0.281	0.063	0.234	202	4.39
14	Japan	0.271	0.373	0.210	0.116	0.031	1067	5.98
15	Turkey	0.255	0.277	0.302	0.166	0.000	446	5.52
							18,868 [a]	4.31 [b]

[a]—total, [b]—average. NA = not available

Table 4. Composition of TFEC in oil-and-gas-dominated economies in 2021 [50].

Number	Country	Coal's Share of TFEC (Fraction)	Oil's and Gas's Share of TFEC (Fraction)	RE's Share of TFEC (Fraction)	Nuclear's Share of TFEC (Fraction)	CO_2 Emissions (Mtpa)	ΔRE Share of TFEC (2011–2021) (pp)
1	Turkmenistan	0.000	1.000	0.000	0.000	83	0.00
2	Qatar	0.000	1.000	0.000	0.000	95	0.00
3	Kuwait	0.000	1.000	0.000	0.000	106	NA
4	Trinidad & Tobago	0.000	1.000	0.000	0.000	36	0.00
5	Saudi Arabia	0.000	0.999	0.001	0.000	672	0.09
6	Oman	0.007	0.993	0.000	0.000	81	NA
7	Singapore	0.009	0.988	0.003	0.000	33	0.29
8	Algeria	0.008	0.988	0.004	0.000	176	0.16
9	Iraq	0.000	0.986	0.014	0.000	186	NA
10	Azerbaijan	0.000	0.985	0.015	0.000	38	0.90
11	Iran	0.006	0.979	0.013	0.002	749	0.09
12	UAE	0.015	0.951	0.011	0.022	202	1.10
13	Uzbekistan	0.036	0.939	0.026	0.000	122	−1.86
14	Egypt	0.013	0.924	0.063	0.000	250	NA
15	Belarus	0.027	0.919	0.009	0.045	60	0.90
16	Bangladesh	0.085	0.909	0.006	0.000	93	−0.63
17	Mexico	0.034	0.844	0.106	0.016	407	4.89
18	Argentina	0.020	0.840	0.111	0.029	186	−0.40
19	Hong Kong	0.172	0.828	0.000	0.000	32	0.00
20	The Netherlands	0.066	0.801	0.124	0.009	141	9.68
21	Israel	0.152	0.790	0.057	0.000	55	5.71
22	Italy	0.036	0.780	0.184	0.000	329	7.88
23	Thailand	0.159	0.771	0.070	0.000	278	3.84
24	Russia	0.109	0.760	0.066	0.064	1756	1.19
25	UK	0.029	0.734	0.180	0.057	347	13.98
26	Greece	0.067	0.733	0.200	0.000	56	13.77
27	Hungary	0.059	0.723	0.218	0.000	48	4.38
28	Venezuela	0.000	0.714	0.286	0.000	80	7.21
29	Belgium	0.037	0.702	0.092	0.169	96	5.87
30	Malaysia	0.212	0.702	0.086	0.000	256	6.14
31	USA	0.114	0.700	0.107	0.080	5007	5.39
32	Pakistan	0.174	0.683	0.106	0.036	229	NA
33	Ecuador	0.000	0.671	0.329	0.000	41	15.47
34	Peru	0.041	0.669	0.289	0.000	41	4.65
35	Portugal	0.011	0.663	0.326	0.000	41	9.68
36	Spain	0.029	0.657	0.224	0.091	234	8.93
37	Romania	0.121	0.621	0.186	0.071	79	8.26

Table 4. *Cont.*

Number	Country	Coal's Share of TFEC (Fraction)	Oil's and Gas's Share of TFEC (Fraction)	RE's Share of TFEC (Fraction)	Nuclear's Share of TFEC (Fraction)	CO_2 Emissions (Mtpa)	ΔRE Share of TFEC (2011–2021) (pp)
38	Sri Lanka	0.154	0.615	0.231	0.000	21	NA
39	South Korea	0.179	0.607	0.037	0.114	616	3.05
40	Canada	0.034	0.607	0.299	0.060	545	2.78
41	Columbia	0.068	0.602	0.330	0.000	545	1.45
42	Germany	0.168	0.587	0.195	0.049	674	13.77
43	Chile	0.156	0.575	0.269	0.000	85	8.50
44	Austria	0.075	0.551	0.374	0.000	65	10.40
45	New Zealand	0.083	0.512	0.405	0.000	34	0.99
						11,024 [a]	4.58 [b]

[a]—total, [b]—average. NA = not available

Table 5. Non-fossil's share of TFEC in non-fossil-dominated economies in 2021 [50].

Number	Country	Coal's Share of TFEC (Fraction)	Oil's and Gas's Share of TFEC (Fraction)	RE's Share of TFEC (Fraction)	Nuclear's Share of TFEC (Fraction)	Non-Fossil's Share of TFEC (Fraction)	CO_2 Emissions (Mtpa)	ΔRE Share of TFEC (2011–2021) (pp)
1	Norway	0.015	0.260	0.725	0.000	0.725	41	7.88
2	Sweden	0.026	0.258	0.507	0.210	0.717	36	12.83
3	Finland	0.103	0.362	0.345	0.190	0.536	38	14.99
4	Switzerland	0.000	0.467	0.374	0.159	0.533	35	9.38
5	France	0.024	0.473	0.138	0.364	0.502	306	10.45
6	Brazil	0.056	0.471	0.462	0.010	0.472	489	6.98
							944 [a]	10.42 [b]

[a]—total, [b]—average.

6.1. Decarbonization Technologies

Decarbonization technologies can be divided into demand-side and supply-side technologies. On the energy demand side, increasing energy efficiency [51] and reducing demand [52] are key areas but are outside the scope of this paper. Decarbonization technologies on the energy supply side can be classified into four types (Table 6). The first type is renewable energies (REs), including wind, solar, bioenergy, geothermal and hydroelectricity [53]. They are mostly applied to the power (electricity) sector but can be applied to the transport sector through the use of electric vehicles, which have been gaining acceptance in recent years. In fact, renewable energies have been applied in many economies and contributed to 27.9% of global electricity and 13.5% of global total final energy consumption (TFEC) in 2021 [50]. Hitherto, most of the efforts on decarbonization have been focused on RE.

The second type of decarbonization technology is low-carbon fossil energies. They include (1) switching from coal to gas for power and heat generation (coal → gas), applying CCS to coal-fired power plants (CP-CCS), gas-fired power plants (GP-CCS) and industrial plants (Ind-CCS) [28,54,55]. Coal → gas is a mature technology and has the potential to halve CO_2 emissions in power generation, as the combustion of gas produces approximately half the CO_2 compared with coal [56]. It has been implemented in many advanced and growing economies. CCS has been applied commercially in Norway [57,58] and is currently being implemented in tens of projects worldwide [59], especially in countries that have a carbon tax or credit. It has been gaining momentum in the USA, where economic incentives have been increased through the 45Q tax regulations [60]. Another type of low-carbon fossil decarbonization technology is carbon capture and utilization, which seeks to turn anthropogenic CO_2 into useful commercial products [61]. However, these technologies are still in the R&D stage and not ready for commercialization [61].

The third type of decarbonization technology is hydrogen. Though hydrogen is not an energy source, it is an energy carrier like electricity. It can be used to generate electricity through a hydrogen fuel cell or combusted to produce heat. Consequently, hydrogen can be used for the transport sector through the use of hydrogen fuel cell vehicles or used to replace fossil fuels for industrial heating and power generation. Green hydrogen is produced via the electrolysis of fresh water with renewable electricity. It is called "green" because this process does not produce CO_2 [62]. However, this is the most expensive form of hydrogen and currently costs USD 3–7/kg [63]. Blue hydrogen is produced from natural gas through steam methane reforming or coal through coal gasification with emitted CO_2 mitigated by CCS. Both processes are technologically mature [21]. Currently, blue hydrogen is roughly half (USD 1.5–2.3/kg) as expensive as green hydrogen [63]. Besides being used to fuel hydrogen fuel cell vehicles, hydrogen can be used to replace coal or gas in industries requiring high temperatures (over 1000 °C), such as steelmaking, cement manufacturing, natural gas processing and raw material in the petrochemical processes. Hydrogen is therefore useful to decarbonize the "hard-to-decarbonize" industrial sector. At present, neither green nor blue hydrogen is manufactured at a commercial scale.

The fourth type of decarbonization technology is nuclear energy. The use of conventional nuclear energy is a country-specific issue. Some countries, e.g., France and Ukraine, favor the use of nuclear energy, whereas many others, e.g., Southeast Asian countries, do not. Conventional nuclear energy suffers from a long lead time from proposal to government approval, which could take up to a decade. In addition, the disposal of nuclear waste is also an issue. Recently, there has been interest in the use of advanced small modular reactors (SMRs) of capacity up to 300 MW_e, which are faster to build and deploy and can be used for industrial applications or remote areas with limited grid capacity. However, SMRs are still in the research and development stage [64].

Table 6. Supply-side decarbonization technologies.

	Renewable Energies	**Low-Carbon Fossil Energies**	**Nuclear Energy**	**Hydrogen**
Main types	• Wind • Solar • Bioenergy • Geothermal • Hydroelectricity	• Coal → gas • CP-CCS • GP-CCS • Ind-CCS	• Conventional • Advanced small modular reactor (SMR) [64]	• Green H_2 • Blue H_2 (coal → H_2-CCS; gas → H_2-CCS)
Main use	• Power sector • Transport sector through EV	• Power sector • Industry sector	• Power sector	• Transport sector • Industry sector • Power sector
Comments	• Applied in many economies	• Technologically mature; commercial applications increasing	• Application is country-specific • SMRs in R&D stage	• Green H_2 requires renewable electricity and fresh water • Blue H_2 comes from gas or coal with CCS

6.2. Slow Pace of Addition of Renewable Energy Capacity

In the last column of Tables 3–5, we have listed the change in RE's share of TFEC over the last decade (2011 to 2021) [50]. For coal-dominated economies, Australia's gain in RE's share of TFEC was 9.36 percentage points (pp) over a decade and was the largest (Table 3). This was still less than 1 pp per year. The average increase was only 4.31 pp over a decade. For oil-and-gas-dominated economies, European economies had the biggest gain in RE in the last decade (Table 4). The biggest gain was achieved by the UK (13.98 pp), Germany (13.77 pp), Greece (13.77 pp), Austria (10.39 pp) and the Netherlands (9.68 pp). Ecuador was the only economy in South America with a sizeable gain in RE (15.47 pp). Both the USA and Canada achieved small gains of 5.39 pp and 2.78 pp, respectively. The average increase in RE's share of TFEC was 4.58% over a decade (Table 4). All non-fossil-dominated economies exhibited sizable gains in the RE share of TPEC in the last decade, ranging from 7 pp to 15 pp (Table 5). The average increase in RE's share of TFEC was 10.42 pp over a decade (Table 5). These numbers show that the pace of the addition of RE's share of TFEC was relatively slow and was about 0.4 pp per year for most economies. Even if this rate were tripled, the goal of a near 100% in RE's share of TFEC by 2050 cannot be achieved. There are two reasons for this slow growth in RE's share of TFEC. First, renewable energies' (RE) share of TFEC will only increase if the growth in RE is larger than the growth in fossil fuels. However, in many economies, the growth in the fossil fuel capacity surpasses that of the RE capacity. Therefore, unless more RE capacity is installed, the overall growth in the RE share of TPEC is negative. Second, wind and solar have a lower capacity utilization rate (<20%) than fossil fuel (>40%) in power generation [55]. Therefore, replacing fossil power generation capacity with wind and solar requires a much higher wind or solar capacity.

6.3. Decarbonization for Coal-Dominated Economies

These are economies where coal's share of TFEC was 25% or higher in 2021 [65]. There were 15 economies in this group. They included China, India, Australia, Indonesia and Japan, which are some of the biggest CO_2 emitters in the world. The compositions of TFEC by fuel type in these economies are listed in Table 3. In these economies, the majority of CO_2 is emitted by the combustion of coal. Consequently, the decarbonization effort should be directed at reducing CO_2 emissions from the combustion of coal.

In general, there are two demonstrated ways to decarbonize coal-dominated economies. The primary way is to replace the use of coal for power and heat generation with gas. This has the potential to reduce CO_2 emissions by one-half [56]. To achieve this, coal-fired power plants have to be repurposed for using gas as fuel. An alternative decarbonization method is to install CCS in coal-fired power plants to mitigate the emitted CO_2. This will require compressing the captured CO_2 and transporting it to nearby oil or gas reservoirs, or using saline aquifers for permanent storage. A recent study by Lau showed a potentially large contribution of retrofitting CCS in existing coal-fired power plants in several Asian countries [66]. Which method is preferred will depend on the availability of gas to replace coal and the availability of suitable subsurface storage sites for CO_2 storage. The secondary decarbonization method is to install CCS in gas-fired power plants to further reduce CO_2 emissions.

6.4. Decarbonization of Gas-and-Oil-Dominated Economies

These are economies where the share of oil and gas in TFEC was 50% or higher in 2021. There were 45 economies in this group. The aggregate CO_2 emissions from them were only 58% of that of coal-dominated economies (Tables 3 and 4). The compositions of TFEC in 2021 for these economies are given in Table 4. In these economies, gas was used mostly for power and heat generation, whereas oil was mostly used as fuel for transport. The main decarbonization pathway was to use CCS in natural gas-fired power plants (GP-CCS) and, secondarily, CCS in industry plants (Ind-CCS) and coal-fired power plants (CP-CCS). For road transport, the main decarbonization pathway was to use electric vehicles (EVs) to replace internal combustion engine vehicles. This will shift mobile CO_2 emissions from vehicles to stationary emissions at power plants. The latter may be mitigated by CCS if fossil fuels are used for power generation.

The biggest CO_2 emitters from this group are the USA, Russia, the UK, Iran, Saudi Arabia, Germany and South Korea (Table 4). Except for Belgium and South Korea, nuclear energy's share of TFEC in 2021 in this group of economies was less than 10%.

6.5. Decarbonization of Non-Fossil-Energy-Dominated Economics

These economies were dominated mostly by renewable and nuclear energies and their aggregate share of TFEC was larger than 45%. There were six economies in this category and their compositions of TFEC in 2021 are given in Table 5. Among them, France was the one with the most nuclear energy (36.4%). Other economies were mostly dominated by renewable energies. Among them, Brazil and France were the biggest CO_2 emitters in 2021. Decarbonization of these economies will require the further expansion of nuclear power, possibly by using SMR [64] and renewable electricity, to replace gas for power generation. The secondary decarbonization pathway is the further electrification of road transport to replace gasoline with electricity as a transportation fuel.

7. Discussion

The decarbonization pathways for an economy will vary according to the composition of its TFEC. The suggested pathways are summarized in Table 7. It should be emphasized that these pathways are over and above current efforts to increase energy efficiency and install renewable energy capacities. Many of these pathways can be classified as low-carbon fossil pathways that include switching from coal to gas for power and heat generation (coal → gas) and mitigating CO_2 emission from the combustion of fossil fuels using CCS (CP-CCS, GP-CCS, Ind-CCS). Given the urgency for decarbonization, there is a need to use all available tools in our toolkit to accelerate decarbonization. Low-carbon fossil solutions should be considered, together with RE and nuclear energy. The optimal path for each economy will likely depend on the availability of fossil, renewable, and nuclear energy resources and CCS options. It should also be noted that the decarbonization pathways in Table 7 are only suggestions and could be incomplete. Other decarbonization options can be included depending on their technology and commercial readiness level.

Table 7. Suggested decarbonization pathways for various classes of economies.

	Coal-Dominated Economies	**Oil-and-Gas-Dominated Economies**	**Non-Fossil-Energy-Dominated Economies**
Number of economies	15	45	6
Characteristics	Coal's share of TFEC > 25%	Oil and gas share of TFEC > 50%	Non-fossil-energy's share of TFEC > 45%
Biggest CO_2 emitters	China, India, Australia, Indonesia, Japan	USA, Russia, UK, Iran, Saudi Arabia, Germany, South Korea	Brazil, France
Primary decarbonization pathway	• Coal → gas • CP-CCS	• GP-CCS • EVs	• Nuclear • Renewables
Secondary decarbonization pathway	• GP-CCS • Ind-CCS	• CP-CCS • Ind-CCS	• EVs

8. Policy Implications

If current CO_2 emission rates continue, our analysis shows that only 14 economies will achieve net zero by 2050. There is, therefore, an urgent need for most economies to accelerate the pace of decarbonization over and above the current pace of the addition of RE capacity. Consequently, low-carbon fossil solutions, including switching from coal to gas for power and heat generation (coal → gas) and installing CCS in coal- and gas-fired power plants (CP-CCS, GP-CCS) and industrial plants (Ind-CCS) will be needed. According to the Global CCS Institute, as of September 2022, there were 30 CCS projects operating in the world mitigating 43 Mtpa; another 164 projects are in various phases of development and will add 201 Mtpa of CCS capacity [59]. Moreover, CCS has been gaining momentum over the last few years. The already sanctioned Longship project in Norway will be in operation by 2024 and will sequester 0.8 to 5.0 Mtpa CO_2 [67,68]. It may become the first cross-border CCS project in the world. The Porthos [69,70] and Aramis [71] CCS projects in the Netherlands will sequester 2.5 Mtpa and 5.0 Mtpa CO_2, respectively. The East Coast Cluster CCS project in the UK will sequester 26 Mtpa CO_2, almost 50% of CO_2 emissions from the UK's industrial sector [72,73]. Talos Oil has started operations in the first offshore CCS project in the Gulf of Mexico near Port Arthur, Texas, in cooperation with several other companies [74–76]. The Houston CCS Alliance plans to sequester 100 Mtpa CO_2 by 2040 [77]. These projects are all located in countries that have imposed a substantial carbon tax or credit. In 2022, the carbon taxes in Norway, the Netherlands and the UK were USD 88, USD 46 and USD 24, respectively [78]. In 2022, the US government increased the carbon credit from USD 45 to USD 85 per tonne CO_2 [79]. Outside of Europe and North America, most countries do not have a carbon tax or credit. However, Aramco has announced it will establish a CCUS hub in Jubail [80–83]. Malaysia already has several CCS projects under development [84–86] and Indonesia has expressed interest in CCS projects and passing related regulations [87,88]. China is also aggressively installing CCS projects, both onshore and offshore [11,89,90]. Imposing a credible carbon tax or credit will be the most important energy policy to incentivize companies to reduce their CO_2 emissions. Next, the passing of CCS regulations on CO_2 injection and monitoring will be needed. Furthermore, the transfer of long-term liability from the operator to the government will be needed to de-risk CCS projects and to obtain financing [21,72,73]. More public engagement on the benefits of CCS will also be needed to raise the level of public acceptance of CCS. Government funding of CCS R&D should include subsurface characterization of saline aquifers for CO_2 storage [28].

In the transport sector, there appears to be a consensus among economies to replace the use of internal combustion engine vehicles with electric vehicles (EVs) [91,92]. This will drastically reduce CO_2 emissions if the electricity used for EVs is generated using renewable energy or low-carbon fossil fuels. If the latter, CCS will be needed. To encourage the wider use of EVs, policies need to be enacted to incentivize the building of charging facilities [91,93], upgrading of the electric grid [94] and R&D of battery technologies [95].

In the longer-term future, the use of hydrogen to replace the use of fossil fuels to decarbonize the "hard-to-decarbonize" industrial sector will be needed [63]. Therefore, national governments will need to propose a hydrogen strategy or roadmap to underpin the increased use of hydrogen [96–98]. Since green hydrogen currently costs twice as much as blue hydrogen, it will probably not be available in large quantities for some time [63]. The use of blue hydrogen should therefore be considered [99].

9. Conclusions

The following may be concluded from this study:

1. The top 80 CO_2 emitters contributed 95% of the global emissions in 2021. Among them, 55 were decarbonizers, where emissions had either peaked or were in decline; 25 were polluters, where emissions were increasing.
2. A linear history matching and forecasting method was applied to historical CO_2 emissions data. The results show that global CO_2 emissions will increase from 37.1 Gtpa in

2021 to 49.3 Gtpa in 2050 with polluters contributing to 81% and decarbonizers 14% of global CO_2 emissions. Furthermore, only 14 economies will achieve net zero by 2050. They are the UK, Italy, Spain, Ukraine, Greece, Portugal, Finland, Serbia, Denmark, Estonia, Trinidad and Tobago, Venezuela, South Korea and Japan.
3. The target decarbonization rates to achieve net zero by 2050, over and above current efforts, were estimated for the 80 economies. These rates will increase rapidly as 2050 is approached. Therefore, decarbonization must start as soon as possible and any delay will only make future efforts more costly and difficult.
4. China, India, the USA, Russia, Saudi Arabia, Iran, Indonesia, Turkey, Vietnam and Canada have the largest decarbonization targets. Their efforts will determine the future of global decarbonization.
5. The average increase in RE's share in TFEC was 0.4 pp per year for most economies over the last decade. Even if this rate were tripled, it is still inadequate to allow RE's share in TFEC to approach 100% by 2050. Therefore, other decarbonization methods are urgently needed. They will vary with each country's energy mix. Pathways for coal-dominated, gas-and-oil-dominated, and non-fossil-energy-dominated economies are suggested and their policy implications are discussed.

Author Contributions: Investigation, S.C.T.; Investigation and writing original draft, H.C.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: Hon Chung Lau and Steve C. Tsai were employed by Low Carbon Energies LLC. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Nomenclature

APS	IEA's announced pledges scenario
BAU	Business-as-usual scenario
CCS	Carbon capture and storage
Coal $\rightarrow$ gas	Switching from coal to gas in power generation
CP-CCS	Use of CCS in coal-fired power plants
Coal $\rightarrow$ H_2-CCS	Production of blue hydrogen through coal gasification and CCS
Gas $\rightarrow$ H_2-CCS	Production of blue hydrogen through steam methane reforming and CCS
GP-CCS	Use of CCS in gas-fired power plants
GHG	Greenhouse gas
IEA	International Energy Agency
Ind-CCS	Use of CCS in industrial plants
NA	Not available
NREL	National Renewable Energy Laboratory
NZE	IEA's net-zero scenario
pp	Percentage point
RE	Renewable energy
R&D	Research and development
SDS	IEA's sustainable development scenario
SMR	Advanced small modular nuclear reactor
STEP	IEA's stated policies scenario
TFEC	Total final energy consumption
UK	United Kingdom
Gtpa	10^9 tonnes per annum
Mtpa	10^6 tonnes per annum

References

1. The Paris Agreement. United Nations. Available online: https://www.un.org/en/climatechange/paris-agreement (accessed on 18 November 2023).
2. Climate Change: Atmospheric Carbon Dioxide. NOAA. Available online: https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide (accessed on 21 March 2023).
3. Climate Change: Evidence and Causes. Royal Society. Available online: https://royalsociety.org/topics-policy/projects/climate-change-evidence-causes/basics-of-climate-change/ (accessed on 21 March 2023).
4. Home—Climate Science, Risk & Solutions. Available online: https://climateprimer.mit.edu/ (accessed on 21 March 2023).
5. Solomon, S.; Plattner, G.K.; Knutti, R.; Friedlingstein, P. Irreversible Climate Change Due to Carbon Dioxide Emissions. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 1704–1709. [CrossRef]
6. Princiotta, F.T. The Climate Mitigation Challenge—Where Do We Stand? *J. Air Waste Manag. Ass.* **2021**, *71*, 1234–1250. [CrossRef] [PubMed]
7. CO_2 Emissions—Our World in Data. Available online: https://ourworldindata.org/co2-emissions (accessed on 21 March 2023).
8. Renewable Energy—Powering a Safer Future. United Nations. Available online: https://www.un.org/en/climatechange/raising-ambition/renewable-energy (accessed on 21 March 2023).
9. Net Zero Targets. Climate Action Tracker. Available online: https://climateactiontracker.org/methodology/net-zero-targets/ (accessed on 22 March 2023).
10. Net Zero Coalition. United Nations. Available online: https://www.un.org/en/climatechange/net-zero-coalition (accessed on 22 March 2023).
11. International Renewable Energy Agency. *China's Route to Carbon Neutrality: Perspectives and the Role of Renewables*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2022; ISBN 9789292604493.
12. The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050—United States Department of State. Available online: https://www.state.gov/tackling-the-climate-crisis-together/longtermstrategy-3/ (accessed on 18 November 2023).
13. COP26: India PM Narendra Modi Pledges Net Zero by 2070—BBC News. Available online: https://www.bbc.com/news/world-asia-india-59125143 (accessed on 17 November 2023).
14. An EU Energy Scenario Compatible with the Paris Agreement—CAN Europe. Available online: https://caneurope.org/an-eu-energy-scenario-compatible-with-paris-agreement/ (accessed on 18 November 2023).
15. Achieving Net-Zero Emissions. Shell Global. Available online: https://www.shell.com/powering-progress/achieving-net-zero-emissions.html (accessed on 22 March 2023).
16. Reaching Net Zero by 2050—Equinor. Available online: https://www.equinor.com/magazine/our-plan-the-energy-transition (accessed on 22 March 2023).
17. Chevron Sets Net Zero Aspiration and New GHG Intensity Target—Chevron. Available online: https://www.chevron.com/newsroom/2021/q4/chevron-sets-net-zero-aspiration-and-new-ghg-intensity-target (accessed on 22 March 2023).
18. ExxonMobil Announces Ambition for Net Zero Greenhouse Gas Emissions by 2050. ExxonMobil. Available online: https://corporate.exxonmobil.com/News/Newsroom/News-releases/2022/0118_ExxonMobil-announces-ambition-for-net-zero-greenhouse-gas-emissions-by-2050?utm_source=google&utm_medium=cpc&utm_campaign=XOM+%7C+Corp+%7C+Traffic+%7C+OT+%7C+Brand+%7C+Greenhouse+Gas&utm_content=OT+%7C+Brand+%7C+Net+Zero&utm_term=exxon+net+zero&gclid=Cj0KCQjw8e-gBhD0ARIsAJiDsaWtga359jZeiaTRybenUGpjgVi5QanErFgsjNm99nMwnX52awSTsxkaAsJqEALw_wcB&gclsrc=aw.ds (accessed on 22 March 2023).
19. Net Zero in 2050, Together with Society. Available online: https://totalenergies.com/company/transforming/ambition/net-zero-2050 (accessed on 22 March 2023).
20. Getting to Net Zero: Climate Advocacy in the US. Who We Are. Home. Available online: https://www.bp.com/en_us/united-states/home/who-we-are/advocating-for-net-zero-in-the-us.html?utm_source=google&utm_medium=cpc&utm_campaign=us_netzero_direct&utm_term=net%20zero%20gas&gclid=Cj0KCQjw8e-gBhD0ARIsAJiDsaVzzv2_9FzxfKpjedU7D-sBCKoybrfaQAPRflH6VKWGHEezvr5bhoEaAu8rEALw_wcB (accessed on 22 March 2023).
21. Lau, H.C.; Ramakrishna, S.; Zhang, K.; Radhamani, A.V. The Role of Carbon Capture and Storage in the Energy Transition. *Energy Fuels* **2021**, *35*, 7364–7386. [CrossRef]
22. The Net-Zero Transition What It Would Cost, What It Could Bring McKinsey Global Institute in Collaboration with McKinsey Sustainability and McKinsey's Global Energy & Materials and Advanced Industries Practices. 2022. Available online: https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/the%20net%20zero%20transition%20what%20it%20would%20cost%20what%20it%20could%20bring/the-net-zero-transition-what-it-would-cost-and-what-it-could-bring-final.pdf (accessed on 1 October 2023).
23. Jackson, R.B.; Le Quéré, C.; Andrew, R.M.; Canadell, J.G.; Korsbakken, J.I.; Liu, Z.; Peters, G.P.; Zheng, B. Global Energy Growth Is Outpacing Decarbonization. *Environ. Res. Lett.* **2018**, *13*, 120401. [CrossRef]
24. Rockström, J.; Gaffney, O.; Rogelj, J.; Meinshausen, M.; Nakicenovic, N.; Schellnhuber, H.J. A Roadmap for Rapid Decarbonization. *Science* **2017**, *355*, 1269–1271. [CrossRef] [PubMed]
25. Urpelainen, J. The Limits of Carbon Reduction Roadmaps. *Science* **2017**, *356*, 1019. [CrossRef] [PubMed]

26. Lau, H.C.; Ramakrishna, S.; Zhang, K.; Hameed, M.Z.S. A Decarbonization Roadmap for Singapore and Its Energy Policy Implications. *Energies* **2021**, *14*, 6455. [CrossRef]
27. Lau, H.C.; Ramakrishna, S. A Roadmap for Decarbonization of Singapore and Its Implications for ASEAN Opportunities for 4IR Technologies and Sustainable Development. *Asian Pac. Tech Monit.* **2021**, *38*, 29–39.
28. Lau, H.C. Decarbonization Roadmaps for ASEAN and Their Implications. *Energy Rep.* **2022**, *8*, 6000–6022. [CrossRef]
29. Lau, H.C. Decarbonizing Thailand's Economy: A Proposal. *Energies* **2022**, *15*, 9498. [CrossRef]
30. Zhang, K.; Bokka, H.K.; Lau, H.C. Decarbonizing the Energy and Industry Sectors in Thailand by Carbon Capture and Storage. *J. Pet. Sci. Eng.* **2022**, *209*, 109979. [CrossRef]
31. Bokka, H.K.; Lau, H.C. Decarbonising Vietnam's Power and Industry Sectors by Carbon Capture and Storage. *Energy* **2023**, *262*, 125361. [CrossRef]
32. Lau, H.C.; Tsai, S.C. A Decarbonization Roadmap for Taiwan and Its Energy Policy Implications. *Sustainability* **2022**, *14*, 8425. [CrossRef]
33. Zhang, K.; Lau, H.C.; Chen, Z. Regional Carbon Capture and Storage Opportunities in Alberta, Canada. *Fuel* **2022**, *322*, 124224. [CrossRef]
34. Zhang, K.; Lau, H.C.; Chen, Z. Using Blue Hydrogen to Decarbonize Heavy Oil and Oil Sands Operations in Canada. *ACS Sustain. Chem. Eng.* **2022**, *10*, 10003–10013. [CrossRef]
35. Archive. ATB. NREL. Available online: https://atb.nrel.gov/archive (accessed on 18 November 2023).
36. Gagnon, P.; Brown, M.; Steinberg, D.; Brown, P.; Awara, S.; Carag, V.; Cohen, S.; Cole, W.; Ho, J.; Inskeep, S.; et al. 2022 Standard Scenarios Report: A U.S. Electricity Sector Outlook. 2022. Available online: https://www.nrel.gov/docs/fy23osti/84327.pdf (accessed on 1 October 2023).
37. Scenario Analysis. ConocoPhillips. Available online: https://www.conocophillips.com/sustainability/managing-climate-related-risks/strategy/scenario-analysis/ (accessed on 18 November 2023).
38. Scenario Analysis and Resiliency. Exxon Mobil Corporation (XOM). Available online: https://investor.exxonmobil.com/esg/climate/scenario-analysis-and-resiliency (accessed on 18 November 2023).
39. Energy Economics. Home. Available online: https://www.bp.com/en/global/corporate/energy-economics.html (accessed on 18 November 2023).
40. New Energy Security Scenarios Explore How the World Could Evolve. Shell Global. Available online: https://www.shell.com/media/news-and-media-releases/2023/new-energy-security-scenarios-explore-how-the-world-could-evolve.html (accessed on 18 November 2023).
41. Understanding GEC Model Scenarios—Global Energy and Climate Model—Analysis—IEA. Available online: https://www.iea.org/reports/global-energy-and-climate-model/understanding-gec-model-scenarios (accessed on 17 November 2023).
42. Stated Policies Scenario (STEPS)—Global Energy and Climate Model—Analysis—IEA. Available online: https://www.iea.org/reports/global-energy-and-climate-model/stated-policies-scenario-steps (accessed on 17 November 2023).
43. Introducing the Sustainable Development Scenario—Event—IEA. Available online: https://www.iea.org/events/introducing-the-sustainable-development-scenario (accessed on 17 November 2023).
44. Renewable Energy 101. National Geographic—YouTube. Available online: https://www.youtube.com/watch?v=1kUE0BZtTRc&ab_channel=NationalGeographic (accessed on 21 March 2023).
45. End New Oil, Gas and Coal Funding to Reach Net Zero, Says IEA. Reuters. Available online: https://www.reuters.com/business/environment/radical-change-needed-reach-net-zero-emissions-iea-2021-05-18/ (accessed on 22 March 2023).
46. Pathway to Critical and Formidable Goal of Net-Zero Emissions by 2050 Is Narrow but Brings Huge Benefits, According to IEA Special Report—News—IEA. Available online: https://www.iea.org/news/pathway-to-critical-and-formidable-goal-of-net-zero-emissions-by-2050-is-narrow-but-brings-huge-benefits (accessed on 22 March 2023).
47. We Must Stop Fossil Fuels Causing Global Warming, before the World Stops Using Fossil Fuels—Prof Myles Allen. University of Oxford. Available online: https://www.ox.ac.uk/news/2022-11-10-we-must-stop-fossil-fuels-causing-global-warming-before-world-stops-using-fossil-fuels (accessed on 22 March 2023).
48. 8 Reasons Why We Need to Phase Out the Fossil Fuel Industry—Greenpeace USA. Available online: https://www.greenpeace.org/usa/research/8-reasons-why-we-need-to-phase-out-the-fossil-fuel-industry/ (accessed on 22 March 2023).
49. International Energy Agency. *Net Zero by 2050—A Roadmap for the Global Energy Sector*; International Energy Agency: Paris, France, 2021.
50. bp Statistical Review of World Energy 2022. Available online: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf (accessed on 1 October 2023).
51. Tsai, W.-H.; Sundaramoorthy, S.; Kamath, D.; Nimbalkar, S.; Price, C.; Wenning, T.; Cresko, J. Energy Efficiency as a Foundational Technology Pillar for Industrial Decarbonization. *Sustainability* **2023**, *15*, 9487. [CrossRef]
52. Li, J.; Xu, G. Circular Economy towards Zero Waste and Decarbonization. *Circ. Econ.* **2022**, *1*, 100002. [CrossRef]
53. Boyle, G. *Renewable Energy: Power for Sustainable Future*, 3rd ed.; Oxford University Press: Oxford, UK, 2012.
54. Lau, H.C. Evaluation of Decarbonization Technologies for ASEAN Countries via an Integrated Assessment Tool. *Sustainability* **2022**, *14*, 5827. [CrossRef]
55. Lau, H.C. Decarbonization of ASEAN's Power Sector: A Holistic Approach. *Energy Rep.* **2023**, *9*, 676–702. [CrossRef]

56. U.S. Energy Information Administration—EIA—Independent Statistics and Analysis. Available online: https://www.eia.gov/environment/emissions/co2_vol_mass.php (accessed on 22 March 2023).
57. Maldal, T.; Tappel, I.M. CO_2 Underground Storage for Snøhvit Gas Field Development. *Energy* **2004**, *29*, 1403–1411. [CrossRef]
58. Zhang, K.; Lau, H.C.; Chen, Z. Extension of CO_2 Storage Life in the Sleipner CCS Project by Reservoir Pressure Management. *J. Nat. Gas Sci. Eng.* **2022**, *108*, 104814. [CrossRef]
59. Global Status of CCS 2022—Global CCS Institute. Available online: https://www.globalccsinstitute.com/resources/global-status-of-ccs-2022/ (accessed on 22 March 2023).
60. Section 45Q Credit for Carbon Oxide Sequestration—Policies—IEA. Available online: https://www.iea.org/policies/4986-section-45q-credit-for-carbon-oxide-sequestration (accessed on 22 March 2023).
61. Bui, M.; Adjiman, C.S.; Bardow, A.; Anthony, E.J.; Boston, A.; Brown, S.; Fennell, P.S.; Fuss, S.; Galindo, A.; Hackett, L.A.; et al. Carbon Capture and Storage (CCS): The Way Forward. *Energy Environ. Sci.* **2018**, *11*, 1062–1176. [CrossRef]
62. The Colors of Hydrogen: An Overview. EWE AG. Available online: https://www.ewe.com/en/shaping-the-future/hydrogen/the-colours-of-hydrogen (accessed on 22 March 2023).
63. Lau, H.C. The Role of Fossil Fuels in a Hydrogen Economy. In Proceedings of the International Petroleum Technology Conference, Virtual, 23–25 March 2021. [CrossRef]
64. Advanced Small Modular Reactors (SMRs). Department of Energy. Available online: https://www.energy.gov/ne/advanced-small-modular-reactors-smrs (accessed on 21 March 2023).
65. Total Final Consumption—Energy Education. Available online: https://energyeducation.ca/encyclopedia/Total_final_consumption (accessed on 22 March 2023).
66. Lau, H.C. The Contribution of Carbon Capture and Storage to the Decarbonization of Coal-Fired Power Plants in Selected Asian Countries. *Energy Fuels* **2023**, *37*, 15919–15934. [CrossRef]
67. Longship CCS Project—Gassnova. Available online: https://gassnova.no/en/full-scale-ccs (accessed on 22 March 2023).
68. Northern Lights—CCUS around the World in 2021—Analysis—IEA. Available online: https://www.iea.org/reports/ccus-around-the-world-in-2021/northern-lights (accessed on 18 November 2023).
69. Porthos—The CCUS Hub. Available online: https://ccushub.ogci.com/focus_hubs/rotterdam-porthos/ (accessed on 22 March 2023).
70. Porthos Carbon Capture and Storage Project, Rotterdam, Netherlands. Available online: https://www.nsenergybusiness.com/projects/porthos-carbon-capture-and-storage-ccs-project/ (accessed on 22 March 2023).
71. Aramis—The CCUS Hub. Available online: https://ccushub.ogci.com/focus_hubs/aramis/ (accessed on 22 March 2023).
72. East Coast Cluster. Available online: https://eastcoastcluster.co.uk/ (accessed on 22 March 2023).
73. East Coast Cluster—The CCUS Hub. Available online: https://ccushub.ogci.com/focus_hubs/east-coast-cluster/ (accessed on 22 March 2023).
74. Joint Venture Bayou Bend CCS Finalized—Chevron. Available online: https://www.chevron.com/newsroom/2022/q2/chevron-talos-and-carbonvert-announce-closing-of-joint-venture-expansion (accessed on 18 November 2023).
75. Equinor Joins Chevron, Talos on Bayou Bend CCS Project. Offshore. Available online: https://www.offshore-mag.com/energy-transition/article/14298218/equinor-joins-chevron-talos-on-bayou-bend-ccs-project (accessed on 18 November 2023).
76. Talos Eyes Big Carbon Capture Role in the US and Beyond. Available online: https://jpt.spe.org/talos-eyes-big-carbon-capture-role-in-the-us-and-beyond (accessed on 18 November 2023).
77. Houston CCS Alliance. Available online: https://houstonccs.com/?gclid=Cj0KCQjw8e-gBhD0ARIsAJiDsaVMT6IFCHW8LrSSjrza_8HAuJy2c69pcTBQGCT7MWPRJj542mntP0saAnJIEALw_wcB (accessed on 22 March 2023).
78. 2022 Carbon Tax Rates in Europe. European Countries with a Carbon Tax. Available online: https://taxfoundation.org/carbon-taxes-in-europe-2022/ (accessed on 22 March 2023).
79. 45Q Carbon Capture Credit Raised to $85 From $50—Carbon Herald. Available online: https://carbonherald.com/45q-carbon-capture-tax-credit-raised-to-85/ (accessed on 1 October 2023).
80. Aramco Jubail—The CCUS Hub. Available online: https://ccushub.ogci.com/focus_hubs/aramco-jubail-ccs-hub/ (accessed on 18 November 2023).
81. Saudi Aramco Identifying Fields for EOR with CO_2 Injection from Jubail CCS Plant. S&P Global Commodity Insights. Available online: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/oil/022023-saudi-aramco-identifying-fields-for-eor-with-co2-injection-from-jubail-ccs-plant (accessed on 18 November 2023).
82. Saudi Aramco Poised to Tender Huge Carbon Capture Project Targeting Multiple Gas Plants. Upstream Online. Available online: https://www.upstreamonline.com/exclusive/saudi-aramco-poised-to-tender-huge-carbon-capture-project-targeting-multiple-gas-plants/2-1-1389566 (accessed on 18 November 2023).
83. Carbon Capture, Utilization & Storage. Aramco. Available online: https://www.aramco.com/en/sustainability/climate-change/managing-our-footprint/carbon-capture-utilization-and-storage?gclid=CjwKCAiAgeeqBhBAEiwAoDDhnwDoK2iYlz7CXovyBuBEDLgY_fFU0tg6Hfys4VpfcIO5WfEo9DSDghoCp7wQAvD_BwE (accessed on 18 November 2023).
84. Malaysia Energy Carbon Capture and Storage. Available online: https://www.trade.gov/market-intelligence/malaysia-energy-carbon-capture-and-storage (accessed on 18 November 2023).
85. Kasawari Carbon Capture and Sequestration (CCS) Project, Malaysia. Available online: https://www.nsenergybusiness.com/projects/kasawari-carbon-capture-and-storage-project/ (accessed on 18 November 2023).

86. Topics. Mitsui Concludes Agreement on the Joint Development of CCS Project in Malaysia—MITSUI & Co., Ltd. Available online: https://www.mitsui.com/jp/en/topics/2023/1246779_13949.html (accessed on 18 November 2023).
87. Indonesia Regulates Carbon Capture and Storage in Upstream Operations. Upstream Online. Available online: https://www.upstreamonline.com/carbon-capture/indonesia-regulates-carbon-capture-and-storage-in-upstream-operations/2-1-1435246 (accessed on 18 November 2023).
88. Indonesia to Be the Pioneer of CCS in the Region: Collaboration in Maintaining Growth towards Low Emission Future. Available online: https://www.prnewswire.com/apac/news-releases/indonesia-to-be-the-pioneer-of-ccs-in-the-region-collaboration-in-maintaining-growth-towards-low-emission-future-301917455.html (accessed on 18 November 2023).
89. Chinese Energy Giant Strives for Carbon Neutrality, Launching Mega Carbon Capture Project-Xinhua. Available online: https://english.news.cn/20230603/ee847bb037b142a182152f1a0485348c/c.html (accessed on 18 November 2023).
90. Wang, P.; Shi, B.; Li, N.; Kang, R.; Li, Y.; Wang, G.; Yang, L. CCUS Development in China and Forecast Its Contribution to Emission Reduction. *Sci. Rep.* **2023**, *13*, 17811. [CrossRef]
91. Is It Time to Go "All In" on Electric Vehicles? Econofact. Available online: https://econofact.org/is-it-time-to-go-all-in-on-electric-vehicles (accessed on 22 March 2023).
92. Global EV Outlook 2023—Analysis—IEA. Available online: https://www.iea.org/reports/global-ev-outlook-2023 (accessed on 18 November 2023).
93. Alternative Fuels Data Center: Developing Infrastructure to Charge Electric Vehicles. Available online: https://afdc.energy.gov/fuels/electricity_infrastructure.html (accessed on 22 March 2023).
94. Electric Cars Will Challenge State Power Grids. The Pew Charitable Trusts. Available online: https://www.pewtrusts.org/en/research-and-analysis/blogs/stateline/2020/01/09/electric-cars-will-challenge-state-power-grids (accessed on 22 March 2023).
95. Ahmed, S.; Bloom, I.; Jansen, A.N.; Tanim, T.; Dufek, E.J.; Pesaran, A.; Burnham, A.; Carlson, R.B.; Dias, F.; Hardy, K.; et al. Enabling Fast Charging—A Battery Technology Gap Assessment. *J. Power Sources* **2017**, *367*, 250–262. [CrossRef]
96. Global Hydrogen Strategies. ITM Power. Available online: https://itm-power.com/global-h2-strategies (accessed on 22 March 2023).
97. International Renewable Energy Agency. *Geopolitics of the Energy Transformation: The Hydrogen Factor*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2022.
98. Countries Roll Out Green Hydrogen Strategies, Electrolyzer Targets. Available online: https://www.powermag.com/countries-roll-out-green-hydrogen-strategies-electrolyzer-targets/ (accessed on 22 March 2023).
99. Lau, H.C. The Color of Energy: The Competition to Be the Energy of the Future. In Proceedings of the International Petroleum Technology Conference, Online, 23–25 March 2021.