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# Evaluating US CO2 Emissions Targets: Statistical Models and Strategic Solutions

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## Abstract

Climate change caused by the increasing greenhouse emissions is one of the biggest threats impacting the world. One of the primary contributors to $CO_2$ emissions is energy production. The energy demand is expected to rise in the developing countries too because of the rising living standards and growing population. In developed countries such as the US, this growth is driven by technological advancements in AI (Artificial Intelligence) leading to expansion in data centers. The United States has set intermediate targets to meet its long-term net-zero target, i.e., no net $CO_2$ emissions by 2050. Our hypothesis is that the US is not on track to meet intermediate targets such as about 50% reduction in greenhouse gases compared to 2005 and carbon-free electricity by 2035. We assessed the progress against these targets using statistical models and public data for energy related $CO_2$ emissions since they cover about 80% of total emissions. Although the US is making progress on decarbonization through production and application of renewable energy, we found that they are not on track to meet either of these intermediate targets. $CO_2$ emissions are reducing by about 30% by 2030 compared to 2005 and electricity generation still has 30% carbon emissions compared to 2022. To bridge these gaps, the US needs to reduce dependence on fossil fuel energy and move towards electrification through electric vehicles and improving the fuel economy which bridges about 3% of the decarbonization gap. If solar and wind generation is increased by 20% on top of projected increase, the decarbonization gap is reduced further by about 4%. Even with these initiatives, the US is unable to meet its 2030 or 2035 targets. Thus, the US needs to explore and implement other decarbonization options such as sustainable fuels for aviation and maritime applications, hydrogen for heavy duty transportation, or carbon capture for industrial use as a couple of other options to get closer to these targets. Reaching this target will involve researchers, business leaders, policy makers and the public to work collectively to solve this impending challenge.

Keywords: CO2 emissions; renewable energy; renewable power; electric vehicles

## Introduction

Global warming is one of the most pressing challenges our humanity faces today. This is caused by trapping the sun's heat in the Earth's atmosphere due to carbon dioxide ($CO_2$) or other greenhouse emissions. This phenomenon leads to several unintended, uncontrollable, and fatal consequences such as changes in the typical weather patterns (Arrhenius, 1896; United Nations, n.d.). These volatile weather patterns include rising sea levels, unpredictable storm patterns, and overall disruption to the ecosystems (Environmental Protection Agency, 2023a). These emissions impact air quality causing health issues, impact wildlife and decrease agricultural productivity which can affect our food sources (US EPA, n.d.). This is why research institutions, businesses, and governments across the globe are trying to combat an increase in $CO_2$ emissions (United Nations, n.d.). A reduction in $CO_2$ emissions will help in a more sustainable, resilient future, safeguarding natural resources and ensuring a habitable climate for future generations. One of the primary contributors to $CO_2$ emissions is energy production. The energy demand is expected to rise in developing countries to improve lifestyle and serve growing populations. In developed countries, the increase is driven in part by the increasing need for data centers to support rapid expansion of AI applications. In this paper, we evaluated the US emission targets and provided strategies to combat this pressing challenge.

Various research institutions, businesses, and governments across the globe have been actively working together to solve this complex emissions challenge (United Nations, n.d.). Ma et al. (2012) investigated how electric vehicles compared to regular internal combustion engine powered cars help in reducing greenhouse gases emissions. They found that electric vehicles result in about half of the carbon emissions of internal combustion engines. Significant reductions in emissions come from non-usages of fossil fuel and electricity for energy, but some emissions in electric vehicles are due to charging of the batteries using electricity, and the manufacturing of the vehicle. Similarly, Ellabban, Abu-Rub, & Blaabjerg (2014) showed that power electronics and smart grids can increase the use of renewable resources which can satisfy the world's energy demand while being good for the environment. Huisingh et al. (2014). augmented the findings of Ellabban, Abu-Rub, & Blaabjerg (2014) that renewable resources are key for emission reductions. They found that although drastic societal changes are required for clean energy, renewables are the most viable solution to reduce carbon emissions. ASEAN (Association of Southeast Asian Nations) also has a similar power sector goal as the US (Handayani *et al.*, 2022) and they observed that it is possible for ASEAN to reach its goal if it uses multiple renewable resources such as hydro, hydrogen, and especially solar.

To solve this pressing challenge, most countries, international organizations, business and research organizations are working on this problem. To be able to measure progress, various targets are set and tracked by these organizations. One of these targets was through the Paris Agreement in 2015 where countries around the world agreed to cooperate to reduce the effects of carbon emissions (Unfccc, n.d.). Their targets were to limit the temperature increase from pre-industrial levels to $2^{o}$C through nationally determined contributions (NDCs), i.e., having a national climate action plan. Each successive NDC is suggested to have an increasingly higher degree of ambition compared to the previous one to limit global warming through reduced emissions. This led to a tremendous amount of focus towards solving this problem, and leaders around the world to set goals for their country to do their part. For example, the EU is striving to achieve net zero greenhouse gas emissions by 2050, have a 40% renewable energy source by 2030, and to have at least a 55% reduction in greenhouse gas emissions by 2030 compared to 1990 (European Climate Law, n.d.). The US is also committed to achieving net-zero by 2050. The US under the Obama administration has taken actions to build the foundation for a clean energy economy to tackle climate change and protect the environment (National Archives and Records Administration, n.d.). The Biden administration revised emission goals to have carbon free electricity by 2035 and greenhouse gas emissions to be 50-52% below 2005 levels in 2030 (The United States Government, n.d.). So far, the US has made tremendous progress through increased renewable energy and the use of fossil fuels steadily decreasing (EIA Energy change, 2023). In this paper, we assess our hypothesis that the US is not on track to meet their goals at their current rate, but we will suggest some options how they can.

Several researchers have assessed the US emissions and power targets. On the overall emissions target, Bistline et al. (2022) found that the US is not on track to meet 2030 emissions goal and proposed six paths for the US to reduce their emissions by 50% by 2030 through various models . They found that the US needs to triple its historic carbon emission reductions. The William and Flora Hewlett Foundation and the Linden Trust for Conservation commissioned Rhodium Group (Larsen *et al.*, 2021) assessed the possibility of meeting the US emissions target for 2030. They found that with current policies they will be able to reduce emissions by 25%, not 50-52% with respect to 2005, as per the target. They suggested that acting across renewable electricity, transport, industrial, and carbon removal can enable the US to meet the target. Subsequently, the Rhodium Group (Larsen *et al.*, 2022) expanded the analysis by considering the Inflation Reduction Act in 2022 and found that the 2030 emissions will be down by 32-42% with respect to 2005.

Recently, Keerthana *et al.* (2023a) used a linear regression to assess the US emissions and track its progress for the 2050 goal. They identified emissions drivers and found that decarbonization in the US is hard driven by its large economy. On the power sector emissions target, Evergreen Collaborative group (Harper *et al.,* 2023) assessed the power sector target, and they found that the US is not on track to meet that goal. National Renewable Energy Laboratory (Denholm *et al.,* 2022 ) presented supply side options to achieve 100% emissions free power. To the best of authors' knowledge, there is no statistical analysis-based assessment for power sector emission. We are thus expanding prior works by assessing both US 2030 emissions and 2035 power sector targets using statistical models. We estimate gaps and propose options to reduce them in the US. Options to reduce emissions include adoption of electric vehicles, fuel economy standards, and greater penetration of renewable energy in the power sector. Statistical methods are based on real data and thus these methods offer a realistic view for gap assessment and develop potential resolutions. We first estimate the US overall emissions and also for the power sector using statistical models developed based on historical data. Once we have an emissions estimate, we then compare it with the US emissions targets for overall $CO_2$ reduction and for the power sector (The United States Government, n.d.). These comparisons help us in assessing how the US is progressing to meet these targets. Additionally, we perform deeper analysis on power and transport sectors while evaluating the US targets and developing pathways since power and transport are two key sectors contributing about 70% of $CO_2$ emissions related to energy. They offer a set of options to create a greater impact on $CO_2$ emissions. This paper is organized as follows: description of data collection and methodology in the data & methodology section, analysis of findings in the results section, and a summary of findings in the conclusion section.

## Data and Methodology

### Data

We gathered the energy sector data to assess the 2030 and 2035 goals for the United States. We sourced the historical and forecast energy, power mix (forecast only) and transport data from Energy Information Administration (US EIA, 2024a; US EIA, 2024b; US EIA, n.d., US EIA projections, n.d.; US EIA new, n.d.; US EIA Outlook, 2023). Quarterly historical power mix data is from Carnegie Mellon University's emission index website (US EIA Outlook, 2023).

### Methodology

We developed statistical models to forecast $CO_2$ emissions related to energy, power sector $CO_2$ emissions and then gasoline motor $CO_2$

emissions using statistically significant variables with p-value less than 0.01. Before utilizing the regression equation, we validated the model by performing a blind test using 20% of a random data set before estimating the impact of independent variables. We found that for the energy overall and power sector emission estimations, the linear regression model is the best model with the highest R-square and better predictability. In the case of US gasoline model emission, the linear regression has reasonable R-square and uses both independent variables in forecasting. Thus, we again selected the linear regression model. We then used the regression equation to forecast $CO_2$ emissions to assess whether the US meets the targets or not assuming external factors will be similar to the past. Subsequently, we suggested resolution options and estimated potential reduction in the gap. Since the gap between the US emissions target and the estimated emissions persisted, we proposed further optionality. We assumed that an EV reduces emissions by 80% compared to gasoline vehicles (US Power CMU, n.d.) when considering emissions due to power.

### Validation using external sources

We leveraged prior works to validate $CO_2$ emission reduction to gain confidence in the model and forecasts. The estimates were successfully compared against prior articles.

## Results

Energy-related activities are the main sources of U.S. anthropogenic greenhouse gas emissions. Based on 2021 EIA data (Environmental Protection Agency, 2023b), these emissions account for 82% of the total greenhouse gas emissions on a $CO_2$ equivalent basis. The energy-related $CO_2$ emissions alone constitute 76.6% of the US greenhouse gas emissions from all sources on a $CO_2$-equivalent basis, while the remaining 5.4% is non-$CO_2$ emissions from energy-related activities. The emissions account for 96.5, 41.6, and 10.0 percent of the nation's $CO_2$, methane ($CH_4$), and nitrous oxide ($N_2O$) emissions, respectively. Thus, energy related $CO_2$ is the main component of emissions, and we focus on the energy related $CO_2$ emissions in this paper. We first presented the existing historical data for $CO_2$ emissions between 1990 and 2023 related to energy in Figure 1 (U.S. Energy Information Administration, 2024a). We found that the two key dominant sectors are transport and electric power. These two sectors contribute about 70% of $CO_2$ emissions related to energy. Between 1990 and 2005, $CO_2$ emissions increased with a rate of 1.2% driven by power and transport. These two sectors increased annually about 2%. Between 2005 and 2023, $CO_2$ emissions started decreasing annually by 1.2%. This is primarily driven by the power sector, which is declining annually about

3% due to renewable power such as solar and wind. The transport sector is also decreasing annually by 0.4%.

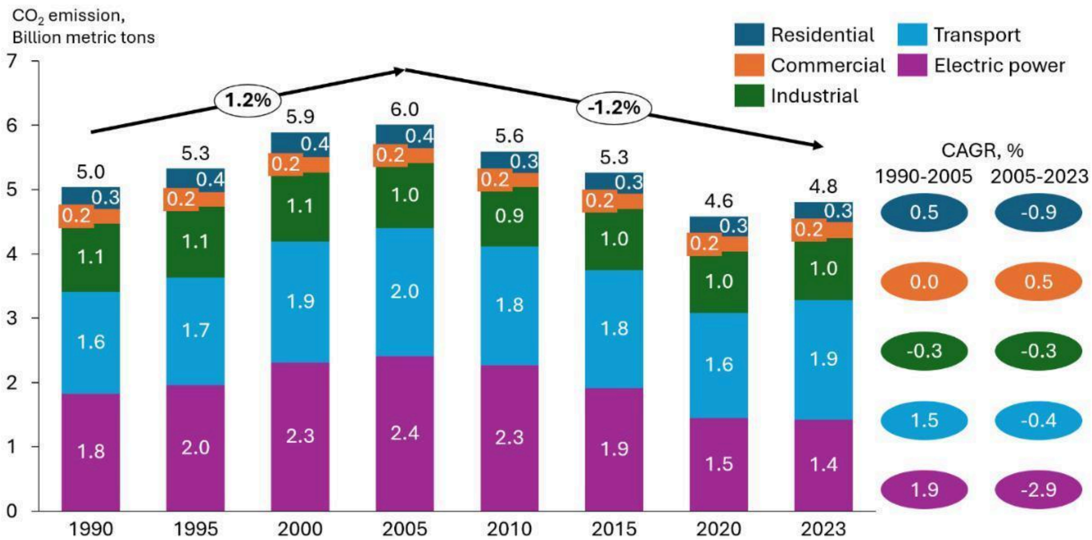


FIGURE 1: *Historical US CO2 emissions related to energy and its distribution across different sources.*

## US CO2 emission assessment

We first developed a statistical model using historical energy sources and associated emissions data starting with 1965 and until 2023. All energy sources such as coal, natural gas, petroleum oil, renewable and nuclear were significant variables with p-values less than 0.005. We kept all fossil fuel energy sources different due to their different carbon emission intensities but combined renewable and nuclear since they emit nearly no $CO_2$ emissions. The output of the regression was multiple R as 0.999, R Square as 0.999 adjusted R Square as 0.999, and std. error as 19.653. The model predicted estimates were then compared with actual $CO_2$ emissions, which were not used in developing the model. They match reasonably well, as shown in Figure 2, with variability between the actual and forecasted data being less than 1%. It is noteworthy to mention that we did not account for autocorrelation while developing the model since energy mix and emissions are linearly related regardless of the previous year. To validate the assumption further, we added a pseudo variable year in the model to account for autocorrelation impact and that did not improve the prediction capability suggesting a time-series model is not required. The regression equation is:

$$US\ CO2\ emissions = -84.5 + 96.5 * Coal + 51.6 * Nat\ Gas + 69.2 * Oil - 5.40 * (Renewable + Nuclear) \quad (1)$$

In equation (1), the US $CO_2$ emissions are in million metric tons. Coal, natural gas, oil, and renewable & nuclear are different energy sources and their emissions are in quadrillion British Thermal Units (BTU). The coefficients in equation (1) are in an order of their $CO_2$ emissions and the coefficient is positive if a fuel is emitting $CO_2$ else is negative. Thus, the equation is physically consistent along with statistically.

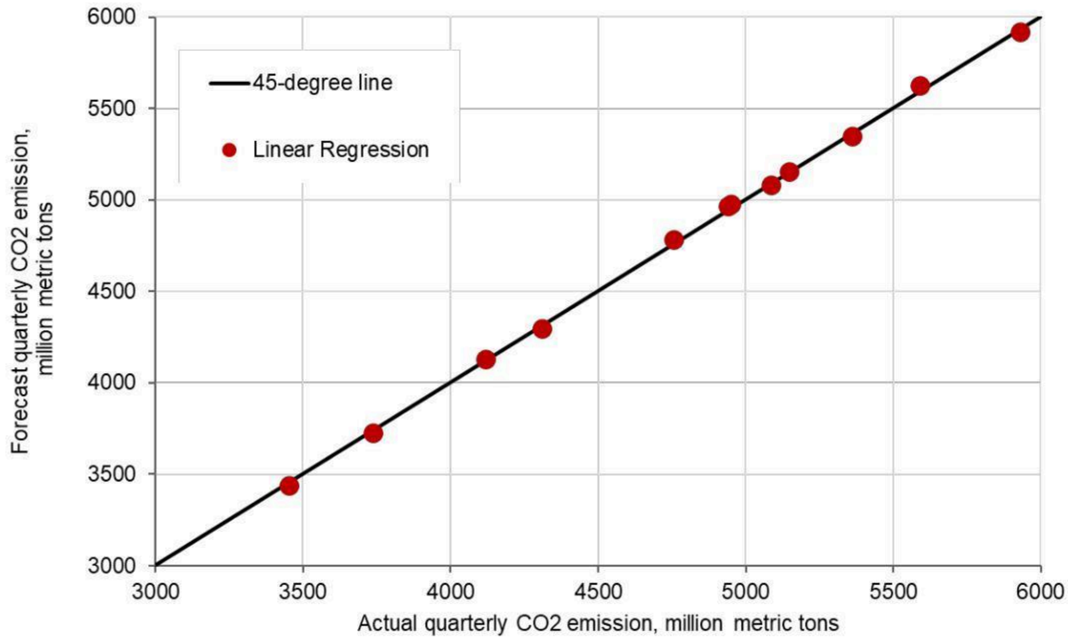


FIGURE 2: *US actual and forecast annual CO2 emissions based on developed regression equation (1). The bullets are data points, and the solid line is a 45-degree line.*

We then forecasted $CO_2$ emissions for the future using EIA projections for energy sources data and presented in Figure 3. $CO_2$ emissions were increasing until 2005 and then started to decrease. Emissions are decreasing at an annual rate of -1.5% between 2005 and 2030. There is a significant drop in emission until 2030, but then it stabilizes until 2035 and also until 2050. They may be a result of the energy forecast not accounting for technological advancement and policies, as they are still evolving. As mentioned earlier, the US set a target of 50-52% reduction in emissions by 2030 compared to 2005 (The United States Government, n.d.). The $CO_2$ emissions for energy in 2030 are predicted to be 4,153 million metric tons whereas 2005 emissions were compared to 6017 million metric tons. Thus, the expected reduction is 31%, not 50%. This is in line with the findings of Rhodium Group (Larsen *et al.*, 2022). Thus, this validates our hypothesis that the US is not on track to meet the target and needs to act. We will share some options in the subsequent sections.

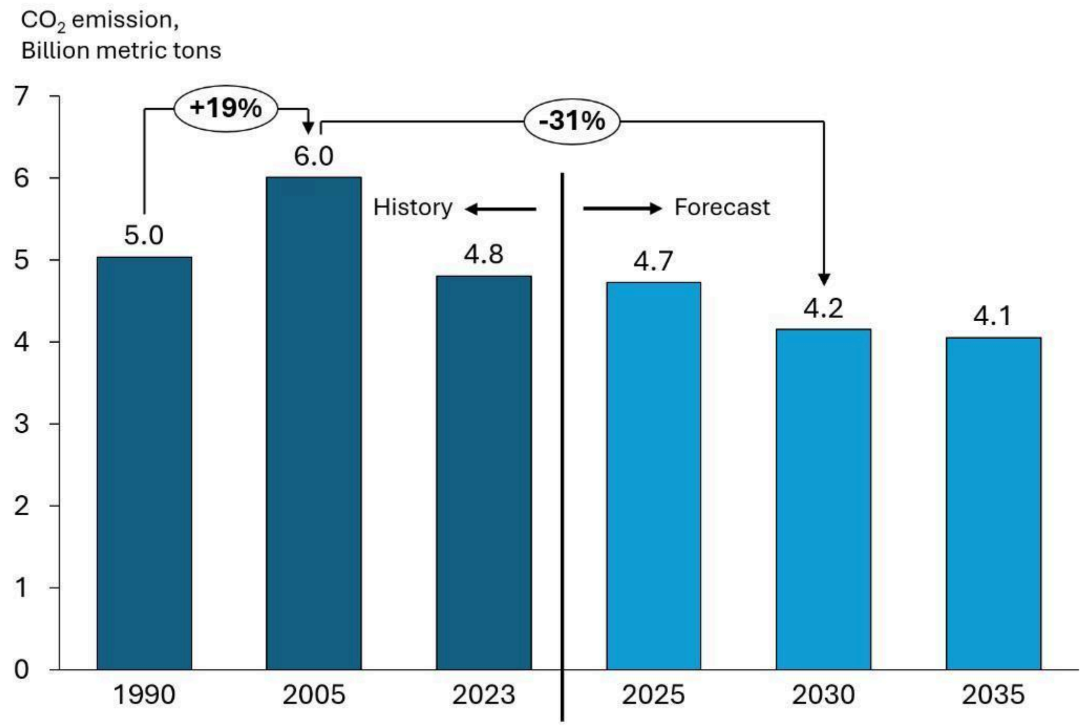


FIGURE 3: *US annual forecast CO2 emissions based on developed regression equation (1).*

## US power sector CO2 emission assessment

Similar to the US $CO_2$ emissions forecast, we first developed a statistical model using the quarterly historical power mix and associated emissions data between 2001 and 2022. Again, we kept coal and natural gas separately and then combined others based on $CO_2$ emission intensity. We found that statistically significant variables are coal, natural gas, renewable, nuclear & hydro, and others with p-values less than about 0.05. The output of the regression is multiple R as 0.998, R square as 0.996, adjusted R square as 0.996, and std. error as 6.49. The model predicted estimates were then compared with the actual $CO_2$ emissions (not used in model development) from the power sector. They match reasonably well, as shown in Figure 4, with variability between the actual and forecasted data being less than 1%. It is noteworthy to mention that we did not account for autocorrelation by performing a time-series model since the power mix and emissions are linearly related regardless of the previous year. To validate this assumption further, we added a pseudo variable year in the model to account for autocorrelation impact and that did not improve the prediction capability suggesting a time-series model is not required. The regression equation is:

$$\textit{US CO2 Emissions in Power Sector} = 25 + 0.975 * \textit{Coal} + 0.495 * \textit{Nat Gas} - 0.127 * (\textit{Nuclear} + \textit{Hydro}) - 0.14 * \textit{Renewable} + 1.26 * \textit{Other} \quad (2)$$

In equation (2), the US CO2 emissions in the power sector are in million metric tons, and coal, natural gas, renewable, nuclear & hydro and others are in billion kilowatt-hr. Other contains other sources used in generation. The coefficients in equation (2) are in order of their CO2 emissions and the coefficient is positive if a fuel is emitting CO2 else is negative. Thus, it is physically consistent along with statistically.

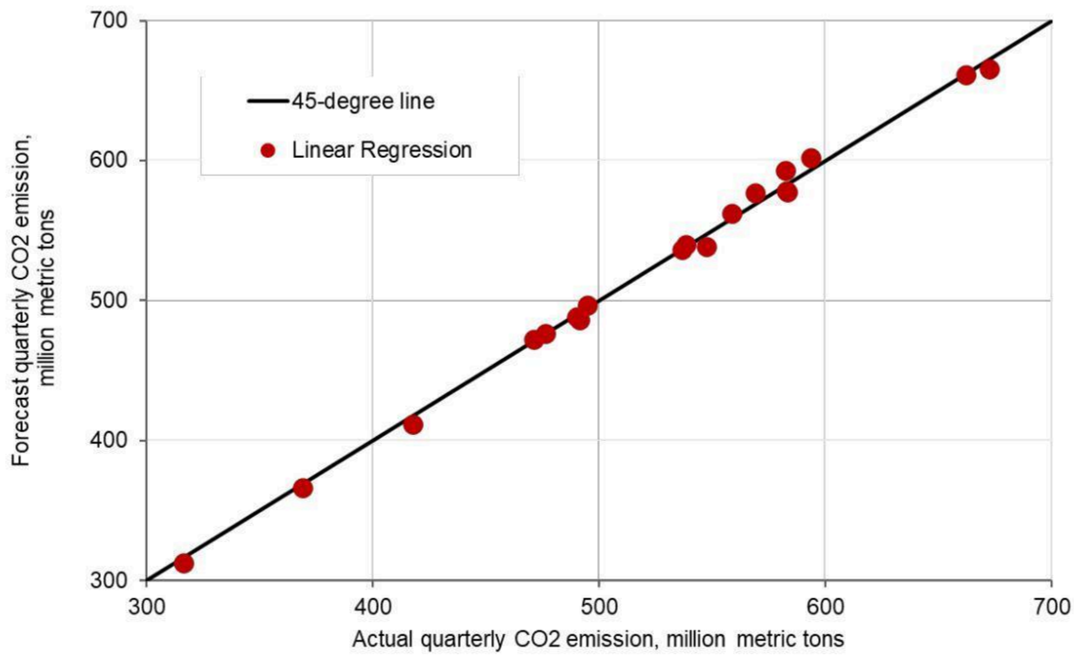


FIGURE 4: *Actual and forecast quarterly US power sector $CO_2$ emissions based on regression equation (2). The bullets are data points, and the solid line is a 45-degree line.*

We used the forecasted power mix and predicted $CO_2$ emission in the power sector and presented it in Figure 5. $CO_2$ emissions reduced between 2001 and 2022 annually at the rate of about 2%, but between 2022 and 2035, it is expected to reduce by over 9% annually primarily driven by the penetration of solar and wind and displacement of coal with natural gas. Given this is one of the key sectors contributing to emissions and relatively easy to decarbonize, the Biden administration set an aggressive target of carbon-free electricity by 2035 in the US (The United States Government, n.d.). They have made significant progress to date since the power sector $CO_2$ emissions in 2022 are down by 33% compared to 2002.

$CO_2$ emissions in 2030 are about 63% reduction compared to 2022, which is in line with the estimate of researchers (Harper *et al.,* 2023) of 66%. It is expected to reduce further and the 2035 $CO_2$ emission will be about 15% of that in 2001 and expect about 25% of that in 2022. Still, the power sector is not expected to be carbon free, and it needs further action. This again validates our initial hypothesis that the US is not on track to meet these targets.

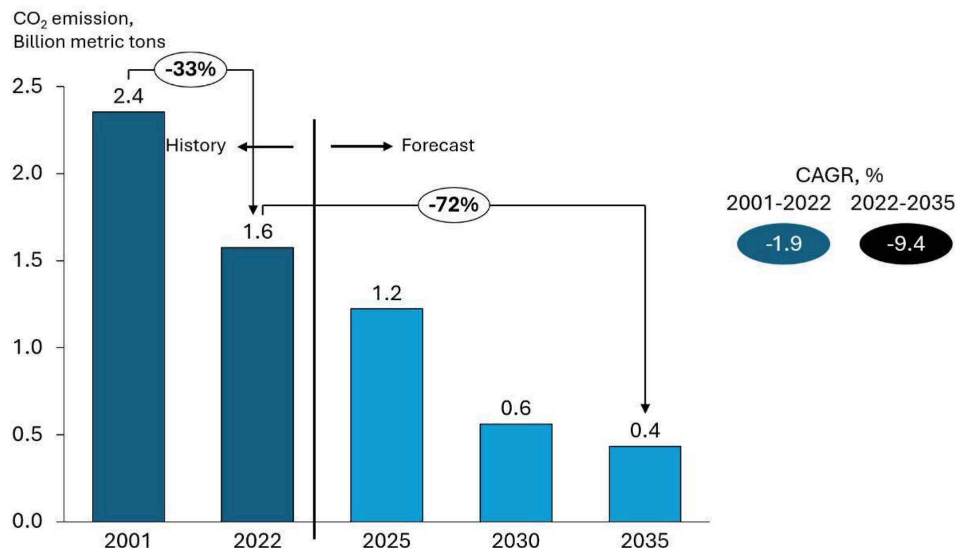


FIGURE 5: *US annual forecast power sector CO2 emissions based on developed regression equation (2).*

## Evaluation of options to bridge the gap between the target and emissions based on current trajectory

We explored two pathways to bridge the gap. The first pathway is about improving the fuel economy and electrification of the transport sector. For example, the penetration of electrical vehicles in the gasoline motor sector is impactful. The second pathway includes increasing electrification in all sectors by having a greater proportion of power in residential, commercial and industrial sectors.

### Improve fuel economy and penetration of electric vehicle

We found in the earlier section that the US has made significant progress on the power sector decarbonization. One of the ways to reduce total $CO_2$ emissions is by transferring energy sources from fossil fuel sources to electricity. The transport sector offers an opportunity. Thus, to keep the focus, we considered only gasoline light vehicles in this subsection, although the transport sector has various sub-sectors such as heavy-duty vehicles, aviation, maritime and others. Two significant efforts to decarbonize gasoline light vehicles are (i) increasing the fuel economy and (ii) adoption of electric vehicles. We developed a statistical model using historical data and used the model with better forecast capability. We found that $CO_2$ emissions of gasoline light vehicles depend on gasoline consumption and fuel economy, as expected. They are statistically significant variables and the variability between estimated and actual data is less than 3%, as shown in Figure 6. Those models (gradient boosting and random forest) use only gasoline consumption. The output is multiple R as 0.950, R-square as 0.903, adjusted R-square as 0.894, std. error as 21.055. It is noteworthy to mention that we did not account for autocorrelation by performing a time-series model since fuel consumption and economy impact transport emissions linearly related regardless of the previous year. To validate the assumption further, we added a pseudo variable year in the model to account for autocorrelation impact and that did not improve the prediction capability suggesting a time-series model is not required. The regression equation is:

$$US\ motor\ gasoline\ CO2\ emissions = 825.407 + 3.489 * Gasoline\ consumption - 43.340 * Fuel\ economy \quad (3)$$

In equation (3), the US motor gasoline $CO_2$ emissions are in million metric tons, gasoline consumption in million gallons per day and fuel economy in miles per gallon. The signs of the two terms in equation (3) are physically consistent, i.e., having greater gasoline consumption should increase emissions and have a positive coefficient. In contrast, better fuel economy reduces emissions and thus a negative coefficient. For a given fuel economy, the first term of equation (3) can be reduced by using electric vehicles. The second term is for fuel economy.

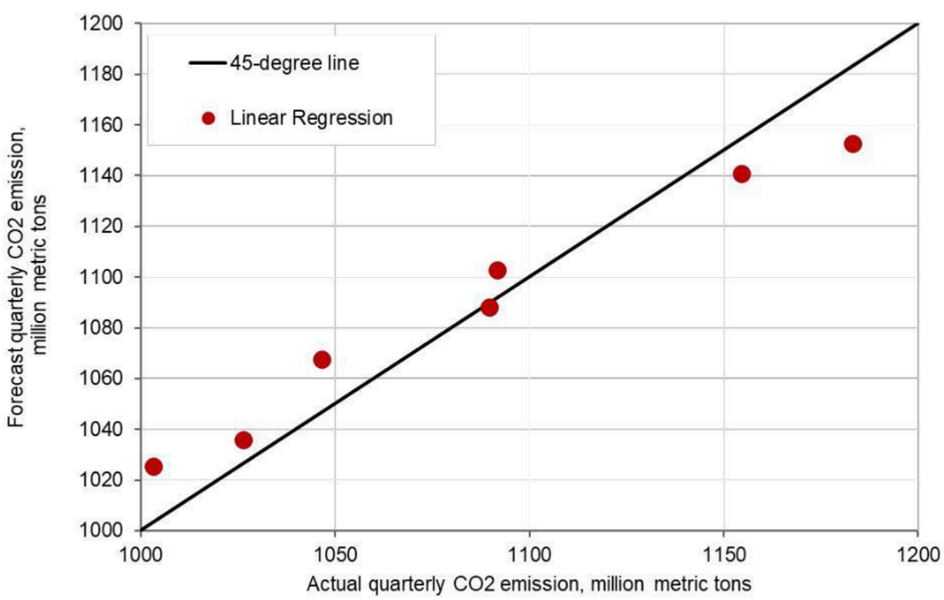

FIGURE 6: *US annual gasoline motor CO2 emissions based on regression equation (3). The bullets are data points, and the solid line is a 45-degree line.*

We leveraged equation (3) and estimated the impact in Figure 7 using the achievable fuel economy increase (Total Energy Monthly Data – US EIA, 2024b) and EV penetration (US EIA, n.d.) by 2030. It is noteworthy to mention that we are adding this reduction on top of what is already considered in the energy and power mix. We found in Figure 7 that we reduced energy related $CO_2$ emissions by 210 million tons, which is an approximately 3% reduction of total $CO_2$ due to energy with 10% further increase in fuel economy and additional 10% of electric vehicles by 2030. The greater impact of the fuel economy since most vehicles are gasoline and only about 10% EVs are expected by 2030. That is significant but is not enough to bridge the gap of about 20%. These can be facilitated through government policies for stringent fuel economy standards and subsidies for electric vehicles and infrastructure including funding for research and development.

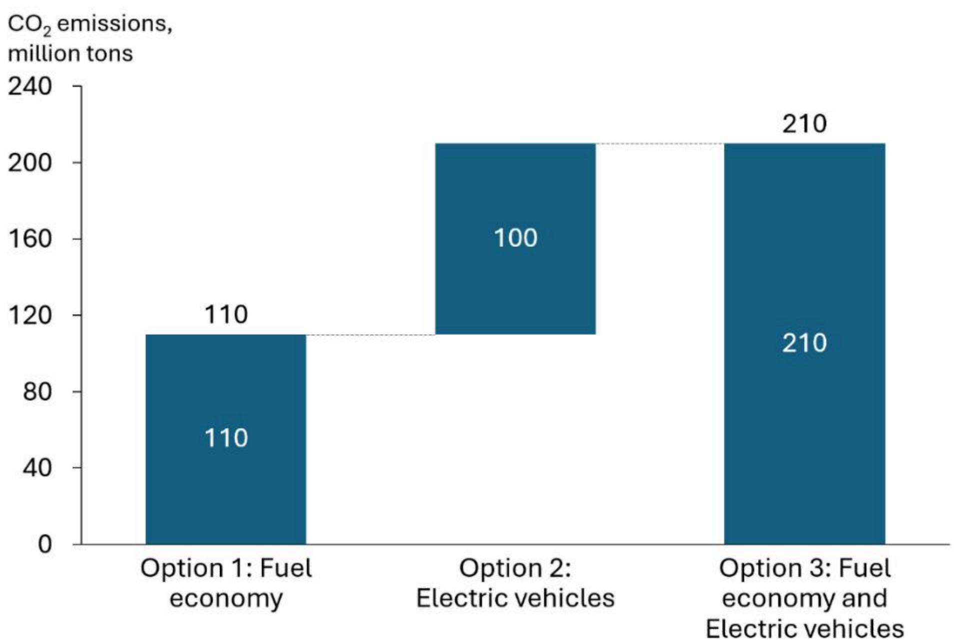


FIGURE 7: *CO2 emissions reduction due to fuel economy increase and penetration of electric vehicles in transport by 2030.*

Increase wind and solar contribution in power mix

Decarbonization using wind and solar reduces $CO_2$ emissions greatly. Currently, these two sources and hydro cover around 25% of the power mix and are expected to double by 2030. If this power-mix increases to 60%, the $CO_2$ emissions due to power reduces by over 40% further in

2035, but the overall $CO_2$ emission reduction is about 4%. This alone again is not enough to bridge the 20% gap. This is driven by the fact that the grid has 50% renewable by 2030 and further increase in renewable helps but is not enough. This will also require grid modernization and energy storage and can be augmented by policies promoting clean energy standards including funding for research and development. In addition, the increasing use of data centers in the US will increase power demand. The data center power demand is expected to increase by 15-20% annually until 2030 with about 50GW demand in 2024 increasing to over 130 GW (Tarasov, 2024). In 2030, the data center power demand will be about 16% of total US power demand (Tarasov, 2024).The assessment of these two pathways suggests that combined impact of these two pathways reduces the emissions by 7%. This is 1/3rd of the total gap of 20%. Thus, further options need to be evaluated. The options include decarbonization of heavy-duty vehicles, maritime and aviation using biofuels and hydrogen in the transport sector. Subsequently, we should further penetrate industrial sectors energy and feedstocks using green hydrogen (Harnessing hydrogen NPC, 2024) or hydrogen produced through renewable sources such as solar or wind. In addition, one of the simplest ways for emission reduction is to reduce energy consumption through societal/ behavioral changes using existing technology. Smil and his collaborators (Smil, 2004; ; Smil, 2016; Voosen, 2018.; Smil, 2014) suggest multiple options such as reducing vehicle weight, using public transport, food waste, and energy loss in homes for heating and cooling. Combination of these can reduce energy related emission by about 3% with about 1% from each. The average vehicle weight has increased by two-times in the last 40 years. Reduction in vehicle weight by 25% can reduce energy by about 1%. Similarly reducing food waste by 50% can save another 1%. The average home size in the US increased by 2-times in the last 50 years leading to greater energy needs for heating and cooling. Reducing the home size and having better insulation can save another 1% of $CO_2$ emissions. These will be slow but effective and require no new technology.

## Conclusion

In this paper, we developed statistical models to assess the US emissions targets. The models identified key variables as statistically significant and successfully predicted the blind test forecast data within +/-3% difference. The model predictions were then compared with the US targets. As per our hypothesis, both targets, i.e., 50-52% emission reduction compared to 2005 and carbon free electricity by 2035 are not expected to meet based on the current EIA forecasted energy and power mix data. One viable alternative is to shift energy consumption from fossil fuels to electricity in the transportation sector through increased policy mandates towards electric vehicles. However, this might not be enough since with current projected penetration of electric vehicles and fuel economy, these two factors could reduce the $CO_2$ emissions due to energy activities by about 3%. The second option is to further increase wind and solar in the power mix by 20%, this again reduces emissions by 4% further. However, the gap seems to be around 20% and these two alone cannot bridge the gap. Also, the US power demand is expected to increase with the revolution in data center driven by AI. Thus, additional actions will be needed across sectors such as transport, residential, commercial and industrial. Electrification of these sectors coupled with application of high energy density solutions such as hydrogen in industry or heavy-duty transportation, increased adoption of sustainable/lower carbon fuels such as ammonia in the aviation and marine sector and large-scale carbon capture may offer breakthroughs. In addition, societal/behavioral changes such as reducing vehicle weight, public transportation, home size and food waste can help reduce greenhouse gas significantly. These do not require new technology but have barriers such as our resistance to change.

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