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A near-term to net zero alternative to the social cost of carbon for setting carbon prices

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The social cost of carbon (SCC) is commonly described and used as the optimal CO_2 price. However, the wide range of SCC estimates provides limited practical assistance to policymakers setting specific CO_2 prices. Here we describe an alternate near-term to net zero (NT2NZ) approach, estimating CO_2 prices needed in the near term for consistency with a net-zero CO_2 emissions target. This approach dovetails with the emissions-target-focused approach that frames climate policy discussions around the world, avoids uncertainties in estimates of climate damages and long-term decarbonization costs, offers transparency about sensitivities and enables the consideration of CO_2 prices alongside a portfolio of policies. We estimate illustrative NT2NZ CO_2 prices for the United States; for a 2050 net-zero CO_2 emission target, prices are US\$34 to US\$64 per metric ton in 2025 and US\$77 to US\$124 in 2030. These results are most influenced by assumptions about complementary policies and oil prices.

Economists overwhelmingly support pricing CO_2 emissions[1]. How much to charge for each ton of emissions is perhaps the most important element of a carbon pricing policy, yet little consensus exists among economists about the appropriate level for CO_2 prices[2].

To find optimal CO_2 prices, economists have long focused on a metric called the social cost of carbon (SCC), an estimate of the marginal damages of an additional ton of CO_2 emissions. However, the SCC cannot be credibly estimated with sufficient precision to provide practical assistance to policymakers setting CO_2 prices. The SCC approach is also disconnected from real-world policy discussions that position CO_2 prices as one element of a strategy to avoid the risks of exceeding thresholds of global warming.

In the face of these constraints, this paper introduces an alternative approach. It starts with policymakers selecting a net-zero CO_2 emissions target informed by the best available science and economics. Then, near-term to net zero (NT2NZ) CO_2 prices are combined with a broader policy strategy to achieve an emissions pathway consistent with the net-zero target in the near term, when the projections of energy–economic models are most useful.

Helping policymakers set CO_2 prices

In textbooks, optimal CO_2 prices are identified with perfect precision. Net benefits to society are largest if the government taxes an activity that creates a negative externality (such as CO_2 emissions) at the rate that equalizes the marginal social benefits and marginal social costs of emissions reductions[3].

Economists have long recognized that, in the real world, approaches for developing optimal policies can be constrained by various uncertainties and measurement difficulties[4,5], including imprecision, ambiguity, intractability and indeterminacy[6]. Therefore, in addition to maximizing net benefits, analysts should strive to identify CO_2 prices using approaches with the following attributes:

- Credible precision. The approach produces a range of CO_2 prices that provides policymakers with valuable information to incorporate into policy design decisions. For example, if adding complexity to a model injects disproportionate uncertainty, it can be more informative to use a simpler framework[7].
- Transparency. The approach enables policymakers to understand the causes of relatively high or low estimates within the range of CO_2 prices identified.
- Consistency with policy objectives. The approach produces CO_2 prices that fit the objectives of the policy. The most common rationale for a CO_2 price is to reduce emissions as part of a broader global response to the risks of climate change.

Policymakers setting CO_2 prices are also concerned with additional factors that are outside our scope, such as public health benefits from reducing air pollution, energy security, competitiveness, the expected actions of other jurisdictions and (perhaps most importantly) political viability.

Challenges with setting CO_2 prices using SCC estimates

The SCC, commonly used as the optimal CO_2 price that maximizes net benefits to society[8], is estimated with projections of the following parameters: global emissions over the next few centuries, the effects of emissions on temperatures and other climate impacts, and the impacts of climate change on the economy and human welfare, using economic methods that aggregate centuries of impacts into a single value representing the net benefits of emissions reductions[9].

Unfortunately, the degree of uncertainty in SCC estimates spans virtually any conceivable stringency level for a CO_2 pricing policy. Meta-analyses find recent SCC estimates that range from under US\$0 per ton of CO_2 to over US\$2,000 per ton (excluding outliers still leaves a range of hundreds of dollars)[8,10].

SCC estimates will continue to improve[9,11,12], but methodological advancements are unlikely to narrow the range of SCC estimates much. After all, large uncertainties come from parameters that are inherently uncertain, such as the appropriate discount rates[9], risk aversion levels[13], issues around inequality[14] and attempts to assign monetary values to non-economic climate damages[15]. In addition, methodological improvements often involve incorporating new

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uncertain elements that were omitted from previous estimates, which can widen the range of SCC estimates[16,17].

The advantage of the SCC approach is that it attempts to perfectly maximize net benefits to society; however, the SCC approach provides limited practical value to policymakers setting specific CO_2 prices due to its difficulty satisfying the desired attributes identified in the previous section. First, the range of SCC estimates is too wide to credibly support the use of any single CO_2 price. (In contrast, the US government developed SCC estimates for use in the separate context of benefit–cost analysis, where a wide range can be incorporated[9].) Second, the differences in SCC estimates hinge partly on assumptions that are not usually transparent to policymakers (such as the value placed on future generations by discount rates). Third, the SCC approach is disconnected from constraining global warming beyond specific levels—the goal of most policymakers setting CO_2 prices. For example, William Nordhaus's 2018 Nobel Prize Lecture shows an optimal pathway of 4 °C of warming by the mid-2100s as the implication of his SCC estimates[18], an outcome far outside the bounds of the Paris Agreement's goals (which other analyses have found would pass a cost–benefit test[19]). Helping policymakers set CO_2 prices in practice therefore necessitates an approach that balances benefits and costs only imperfectly, such as the NT2NZ approach described in the next section.

The classic alternate approach in the face of this sort of uncertainty is a cap-and-trade programme, which involves mandating emissions targets. We assume that policymakers have other reasons for selecting a price instrument, such as the interactions with complementary policies, a desire for certainty in business planning, concerns about market manipulation or political economy considerations[20].

The NT2NZ approach

NT2NZ CO_2 prices are designed to accommodate uncertainties and measurement difficulties and to align with real-world policy objectives. They are estimated using the following four steps:

Step 1: select a net-zero CO_2 emissions date. While the international climate change negotiations have focused primarily on temperature targets, policymakers are increasingly shifting to net-zero emissions targets for both substantive and political reasons[21–24]. A global net-zero CO_2 emissions target has a science-based rationale: surface temperatures will continue to increase until the sources and sequestration of CO_2 are equal, at which point temperatures will roughly stabilize[25,26] (reductions in non-CO_2 GHGs and land-use change emissions are required for full stabilization[24], but we focus on CO_2 emissions, which are the bulk of what would be covered by a CO_2 price). Views differ on what threshold of global warming should not be exceeded, but failing to achieve net-zero CO_2 emissions implies ever-increasing temperatures, which will eventually reach unacceptably high levels regardless of one's threshold. Net-zero targets also naturally scale to any jurisdiction, because achieving global net zero requires, on average, all jurisdictions to achieve net zero.

Policymakers must balance a range of factors to set net-zero targets, including the risks of even-higher temperature changes and the additional costs of decarbonizing faster. International climate agreements recognize that countries have the responsibility to decarbonize at different paces[27], which means that jurisdictions will set different net-zero target dates. Like estimating an SCC, setting a net-zero target involves judgements about concern for future generations, willingness to tolerate risks and aversion to inequality (among other factors). Under the NT2NZ approach, these trade-offs are made by the governing officials selecting the target.

Step 2: select an emissions pathway to the net-zero target. An infinite number of pathways are conceivable between current emissions levels and a future net-zero target. Some frameworks emphasize the benefits of reducing near-term disruption and enabling innovation to bring down technology costs, which argue for a slower initial rate of reductions[28]. Other frameworks emphasize the importance of near-term deployments in reducing costs and avoiding technology lock-in[29–31], as well as benefits from reducing cumulative emissions and respecting intergenerational equity.

Policymakers, weighing these considerations as well as technical and political constraints, may choose a straight-line pathway to net zero for simplicity and transparency, or a different trajectory that fits the circumstances of the jurisdiction (such as a developing country with a peak-and-decline pathway)[32].

Step 3: estimate CO_2 prices consistent with the emissions pathway in the near term. Energy–economic models can be used to estimate the CO_2 prices required to reduce emissions on a desired pathway under a given set of assumptions about future technologies, prices and behaviour[33]. Unlike the SCC approach, energy–economic models enable analysts to combine CO_2 prices with other policy measures to overcome multiple market barriers to emissions reductions.

While net-zero emissions is the long-term goal, the NT2NZ approach focuses on the near term (the next decade, for example). Models that simulate economic and energy systems are built using historical data on production, consumption and market dynamics, which may be a reasonable assumption in the near term. After all, most energy technologies and consumer behaviours evolve relatively slowly. But such models become less useful as the time horizon of the exercise lengthens[34]. Changes in technologies, preferences and policies will inevitably impact energy systems in unexpected ways in a rapidly decarbonizing country—just as advancements in solar energy technologies and the shale revolution in the United States were almost entirely unforeseen decades ago[35].

Focusing on the near term means that CO_2 price estimates should not be unduly influenced by assumptions about the highly uncertain long-term evolution of technologies and behaviour. Analysts often use models with 'foresight', which means that decisions are contingent on assumed future changes to the energy system. For example, if the costs of breakthrough low-carbon technologies are assumed to remain prohibitively high, models with foresight may suggest that the cost-effective pathway involves higher near-term CO_2 prices, so that additional emissions reductions can be achieved in sectors where stock turnover is slow. In contrast, if the costs of breakthrough technologies are assumed to fall precipitously, the same model may suggest a cost-effective pathway that involves relatively less near-term mitigation (see Supplementary Information, Appendix 2).

Step 4: periodically update Steps 1–3. Knowledge about climate science and the costs of mitigation technologies will continue to change rapidly, especially given the substantial social and economic shifts associated with decarbonization. This calls for an adaptive management strategy[36] whereby the analysis described above is repeated periodically. Using emissions outcomes and other relevant metrics (such as deployment rates of low-carbon infrastructure and progress in hard-to-decarbonize sectors[30]), both the CO_2 price pathway and the broader climate policy strategy can be revised and extended, capturing the most up-to-date information.

Adaptive management can enable jurisdictions to stay close to the desired emissions pathway without making policy details contingent on assumptions about highly uncertain long-term variables. Various mechanisms for periodically updating policies have been proposed in recent years[37], including CO_2 prices that are contingent on emissions outcomes (that is, if emissions exceed target levels, price increases accelerate in future years).

Illustrative NT2NZ CO_2 prices for the United States

We demonstrate the approach described above to produce illustrative NT2NZ CO_2 prices for the United States. For this analysis we

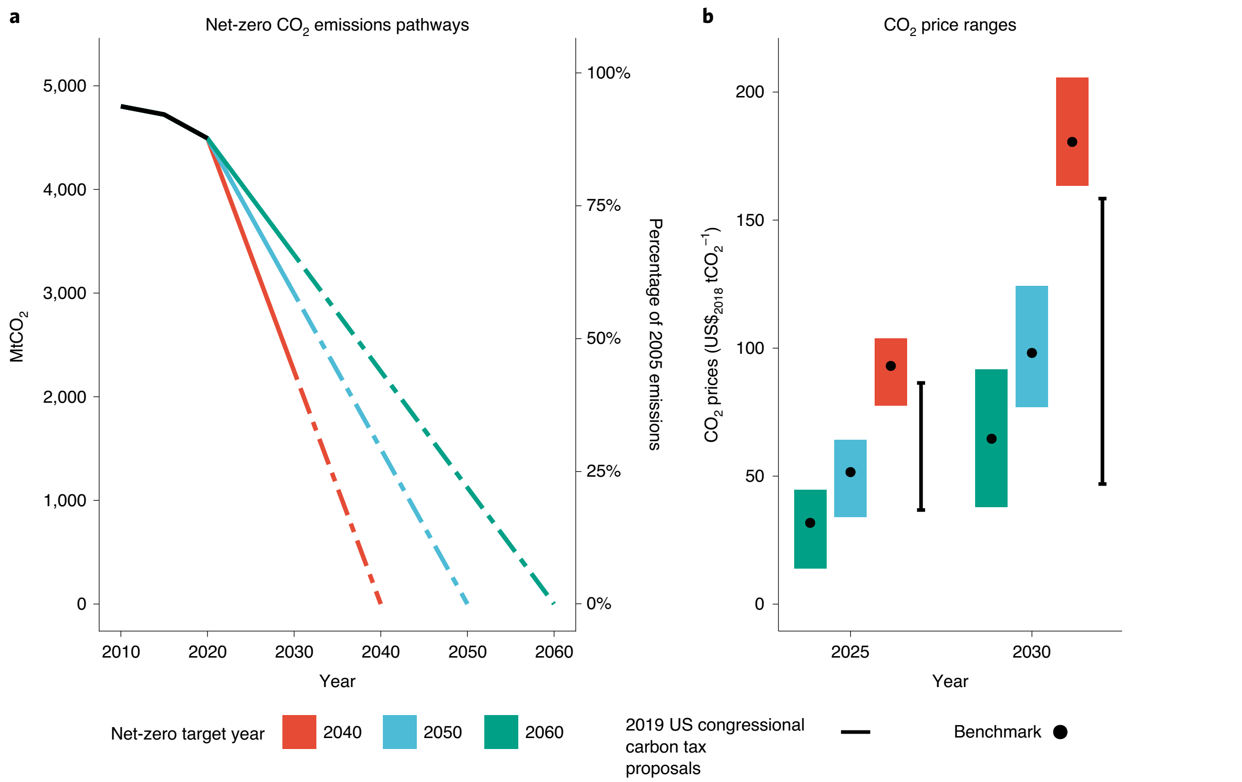

Fig. 1 | US CO_2 emissions pathways to net zero and associated NT2NZ CO_2 prices. **a**, Historical emissions (black) and CO_2 emissions pathways consistent with a straight-line path to net-zero CO_2 in the target year. **b**, Illustrative ranges of CO_2 prices in 2025 and 2030 needed to reduce US net CO_2 emissions on each of the three emissions pathways (NT2NZ CO_2 prices; bars). The black dots reflect benchmark scenario NT2NZ CO_2 prices. The whiskers represent the ranges of CO_2 prices in proposals to the US Congress in 2019.

use the 50-state version of the Global Change Assessment Model (GCAM-USA), an integrated assessment model of energy–economy–environment systems, and data available as of 2019 (Methods). Real-world policy design should be informed by multiple analytic tools using the most up-to-date available information[32].

We begin with three straight-line annual emissions pathways from current (2020) levels to net-zero CO_2 emissions targets in 2060, 2050 and 2040 (Fig. 1a) to reflect a range of emissions pathways discussed in recent years by US policymakers. In the absence of a consensus favouring larger or smaller near-term emissions reductions[38,39], an illustrative straight-line emissions pathway for the United States may be appealing due to its simplicity and transparency. These pathways correspond to 2030 CO_2 emissions of 35%, 42% and 57% below 2005 levels, respectively. Consistent with both economic theory and policy practice, we assume that the CO_2 price is surrounded by complementary policies that address separate market failures[40]: efficiency policies, air pollution regulations and early-stage support for the deployment of low-carbon technologies (such as electric vehicles).

For our benchmark scenario, we find NT2NZ CO_2 prices in 2025 of US$32, US$52 and US$93 per metric ton (in 2018 dollars) for consistency with net-zero targets in 2060, 2050 and 2040, respectively. The NT2NZ CO_2 prices in 2030 are roughly two times larger (Fig. 1b), reflecting a much higher annual growth rate than typical CO_2 price estimates based on the SCC or rising at the rate of interest (see Supplementary Information, Appendix 2).

For each emissions pathway, we show a range of NT2NZ CO_2 prices from sensitivity scenarios that intend to capture uncertainty in influential model inputs (Methods). Figure 2 shows that compared with our benchmark scenario (with a 2050 target), more stringent and successful complementary policies (that is, air quality regulations that lead to higher coal retirements, more aggressive energy efficiency measures and more aggressive early-stage deployment support for certain low-carbon technologies) lowered the CO_2 prices by US$10–US$20 per ton. The prices rise by about the same amount with less aggressive complementary policies. Changing the future oil price trajectory from a pathway to either US$45 or US$176 per barrel in 2030 leads to a swing in CO_2 prices of US$40 per ton in 2030. Figure 2 also displays the impacts on NT2NZ CO_2 prices from changing inputs related to natural gas prices, innovation and economic growth. Appendix 1 in the Supplementary Information provides additional results.

For a 2050 target, the range of NT2NZ CO_2 prices is largely consistent with the range of CO_2 prices in legislation proposed to the US Congress in 2019 (Fig. 1). However, the prices are on the lower end of the range of CO_2 prices that global energy–economic models have identified as consistent with constraining average global temperature increases to 1.5 and 2 degrees Celsius[41] for at least three reasons. First, NT2NZ CO_2 prices will differ by jurisdiction, and the United States has a large amount of coal-fired electricity generation that can be replaced at a relatively low cost. Second, while many studies assume that the CO_2 price is implemented without other policies, we assume that multiple policies are implemented to address multiple market barriers to emissions reductions. Third, the actors within GCAM do not have foresight, so their energy consumption is based on their myopic vision of current market conditions and not based on long-term projections of technological progress (see Supplementary Information, Appendix 2 and Extended Data Fig. 1).

Discussion and policy implications

Economists have long referred to the SCC as the optimal CO_2 price. The use of the SCC as a CO_2 price has become commonplace

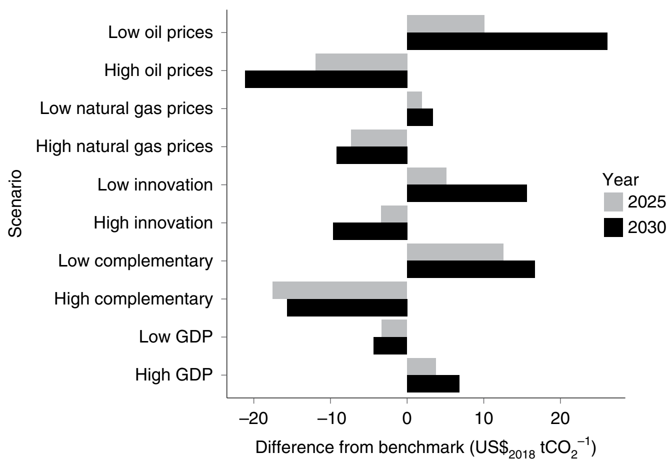

Fig. 2 | US NT2NZ CO_2 prices for a net zero by 2050 pathway: comparison of sensitivity scenarios to the benchmark scenario. The light and dark bars reflect the differences between the NT2NZ CO_2 prices for a given sensitivity scenario compared with the benchmark scenario in 2025 and 2030, respectively. The complementary scenarios reflect proxies for policies that surround the CO_2 price and address non-price-related market barriers (see Methods for a description of the sensitivity scenarios).

in recent years, including in federal carbon tax proposals and state-level subsidies for clean electricity generation in the United States (see Supplementary Information, Appendix 3). Using the NT2NZ approach instead offers several advantages.

First, CO_2 prices can be estimated with more precision. All of the uncertainties in the CO_2 prices estimated using the NT2NZ approach—such as near-term clean energy innovation and fossil fuel prices—are also uncertainties using the SCC approach. But the NT2NZ approach avoids much larger uncertainties, including assigning monetary values to climate change damages. The NT2NZ approach focuses on the most important and (relatively) better understood aspects of the problem.

Second, while any approach can be transparent, the NT2NZ approach focuses on changes to the energy system in the near future, which should enable policymakers to better understand the rationale for selecting CO_2 prices of varying levels. An NT2NZ analysis enables external stakeholders to assess whether a jurisdiction's policies are consistent with its targets and how the outcomes are influenced by key assumptions about technology costs and energy prices (Fig. 2). While the full range of our estimates is ~US$40 per ton for any given target, policymakers are not likely to regard all sensitivities as equally likely and can choose within that range accordingly. By comparison, the complexity of modelling the SCC can make it more difficult to communicate why estimates differ (often by hundreds of dollars per ton under different plausible assumptions about discounting, adaptation and so on).

Third, the NT2NZ approach is more consistent with the objectives of most policymakers implementing CO_2 prices. While economists have traditionally recommended a harmonized global CO_2 price to maximize efficiency, national annual emissions targets have long been the lingua franca of international negotiations on climate change. The illustrative example in the previous section shows how US policymakers could use the NT2NZ approach to help design a federal carbon price as an element of its 2030 Nationally Determined Contribution to the Paris Agreement. Other countries, groups of countries or subnational jurisdictions could do the same. The NT2NZ approach also enables the CO_2 price to be one piece of a broader policy strategy to address multiple market failures around climate, which better aligns with economic theory compared with a CO_2-price-alone approach[40]. It also better aligns with the real-world practice of combining CO_2 prices with a range of other (often sectoral)[42] policies, recognizing that preparation for deep decarbonization[31] requires adaptive management using an ecosystem of policies. For example, passenger vehicle decarbonization might include goals and policy measures to encourage electric vehicles, charging infrastructure, fuel economy and modal shifts away from single-occupancy vehicle travel[43].

Pairing a long-term emissions target with a set of iterative near-term policies is not novel. The United Kingdom, for example, has adopted a national target of net-zero GHG emissions by 2050 and sets five-year carbon budgets to act as stepping-stones[44]. Indeed, the Paris Agreement encourages this framework by calling on nations to produce long-term development strategies for low GHG emissions and near-term Nationally Determined Contributions that are updated every five years[26].

The NT2NZ approach does not attempt to set CO_2 prices by perfectly balancing costs and benefits, so it does not satisfy the definition of an 'optimal CO_2 price' found in economics textbooks. Instead, it enables policymakers to consider both qualitative and quantitative information about climate science and economics when selecting a net-zero target. Models can then estimate the CO_2 prices for cost-effective reductions in the near term, when their projections are most useful, with the understanding that policy details can be updated as uncertainties are resolved.

We describe our results as illustrative because no single model should inform policy setting. The NT2NZ approach should be implemented across a suite of models to further characterize uncertainties, identify results that are robust across methods[34] and explore how prices are best combined with other policies. Future work should also examine the roles of the domestic land-use sink and non-CO_2 GHG emissions.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-020-0880-3.

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Methods

Overview of the model. To numerically estimate CO_2 prices using the NT2NZ approach, we use GCAM-USA. GCAM is an economy-wide global integrated assessment model representing the energy and land sectors linked with a climate model; GCAM is used to explore the interactions of emissions-reducing investments and activities across the US and global economies. We begin with the same version of the model and the standard assumption set used for the US Mid-century Strategy (MCS)[45]. The technical assumptions used in the US MCS are documented in the MCS technical appendix[46]. We have also made updates and changes reflecting the developments in the energy markets and policies as of late 2019, when this analysis was conducted (before the COVID-19 crisis). These are described in detail below. More detail on GCAM can be found in the Supplementary Information.

Key updated assumptions. Most of the assumptions follow the benchmark scenario described in the MCS technical appendix. We updated key assumptions to align the model with the changing market dynamics in the past several years, using the sources in Supplementary Table 3. Given the uncertain and influential nature of these assumptions, our sensitivity scenarios are designed by selecting low, benchmark and high assumptions for each.

Innovation and low-carbon energy technologies. To reflect the rapidly falling costs of renewable energy, we have updated the renewable energy costs to those from the National Renewable Energy Laboratory's (NREL) Annual Technology Baseline[47]. To reflect uncertainties in the evolution of future energy markets as well as concerted research, development and deployment policies to further reduce low-carbon energy costs, we conduct a sensitivity analysis using the high, medium and low estimates of solar, wind and nuclear costs. The detailed cost assumptions are summarized in Supplementary Table 4.

Oil and gas prices. To reflect future uncertainty in oil and gas prices, we have updated the oil and gas price trajectories consistent with the Energy Information Administration's (EIA) oil and gas price trajectories from Annual Energy Outlook 2019 (ref. [48]). Each five-year price point in GCAM is based on a three-year running average of prices to avoid short-term fluctuations. We conduct a sensitivity analysis using the high, medium and low estimates of the oil and gas price trajectories. The detailed assumptions are summarized in Supplementary Table 5. We note that oil prices have fallen considerably since our analysis was performed, and we probably will not know how projections for 2025 or 2030 will be influenced until after the immediate COVID-19 crisis subsides.

Population and GDP. We conducted a sensitivity analysis using high, medium and low estimates of population and GDP. Medium population projections are based on US Census Bureau National Population Projections Tables[49]. The high population growth scenario assumes 0.1% per year additional growth, and the low population growth scenario assumes 0.1% per year less growth. The GDP variations are based on Annual Energy Outlook 2019, which provides high, medium and low variants of GDP growth projections. The COVID-19 pandemic will considerably depress GDP growth in the near term and has the potential to do so through 2025—future analysis with updated projections from the EIA (or another source) should take this effect into account. The detailed population and GDP data used are tabulated in Supplementary Table 6.

Complementary policies. We developed three complementary policy scenarios (detailed below), both to reflect policies needed to overcome market barriers left unaddressed by CO_2 prices and to reflect the uncertain future of sectoral policies that influence CO_2 emissions.

Coal retirements. Coal-fired power plants release not only CO_2 emissions but also various other air pollutants, such as particulate matter and ozone. Policymakers have long recognized the need for regulations to protect constituents from the harmful impacts of these pollutants. Coal-fired power plants have been rapidly retiring in the United States due to changing market dynamics and concerted efforts to reduce emissions of CO_2 and other air pollutants. To capture the potential impact of future environmental regulations on coal generation, we developed high, medium and low coal-retirement scenarios. These coal-retirement pathways assume no CO_2 emission mitigation policy; they thus serve as a starting point for our CO_2 price scenarios. The low trajectory tracks the EIA Annual Energy Outlook 2018 coal-retirement reference case projections[48]. The medium (benchmark) trajectory roughly tracks the US Environmental Protection Agency Integrated Planning Model May 2019 reference case[50] (which also assumes no new policy). The high trajectory tracks the Integrated Planning Model reference case to 2021 and then assumes a trajectory that is consistent with the Enhanced Engagement scenario in the America's Pledge Report[51] (this post-2021 rate is consistent with a capacity retirement rate between the medium and average retirement rates since 2012). The impact of these coal-retirement trajectories on generation is shown in Table M5. In addition to scheduled retirements, GCAM allows the power plants to prematurely retire when they are no longer profitable in the market. Sufficiently high CO_2 prices can therefore force coal power plants out of the market (Supplementary Fig. 3).

Energy demand. A CO_2 price alone is often insufficient to encourage consumers to take advantage of all cost-effective opportunities to reduce energy usage due to market barriers including informational failures and consumer short-sightedness. To reflect uncertainty in the future growth of energy demand, including policies to reduce the rate of energy demand growth, we developed high, medium and low scenarios for future demand growth in key energy sectors using assumptions from the Smart Growth scenario of the MCS report[45]. Specifically, our low and medium energy demand scenarios assume less vehicle travel and greater efficiency in the buildings sector than does the Benchmark scenario. The detailed energy demand differences are shown in Supplementary Table 7.

Early-stage deployment support for low-carbon technologies. In addition to the lack of a CO_2 price, numerous market barriers stand in the way of a large-scale shift to products that do not directly burn fossil fuels (such as electric vehicles and electric heat pumps). To reflect the highly uncertain future of electrification, including policies designed to support electrification, we develop high, medium and low sensitivity scenarios for electrification in buildings and transportation, drawn from the NREL Electrification Futures Study[52]. The electrification rates are shown in Supplementary Table 7.

Land-sector sink assumptions. We develop three net-zero emissions targets (2040, 2050 and 2060) (Fig. 1). In our analysis, net CO_2 emissions are constrained to linearly decrease to zero in the specified target years. In 2030, this formulation corresponds to an emissions range of 3,400 $MtCO_2$ to 2,200 $MtCO_2$ (35–57% below the 2005 emission level). For simplicity, we assume the CO_2 emissions from land-use change are constant at current levels: 714 $MtCO_2$ (ref. [53]). The US MCS has considered multiple possible pathways for CO_2 emissions from land-use change, but given the large fluctuations in year-by-year estimates for land-use change emissions, we did not find other estimates to be of additional value that warrants the additional complexity. A decrease in the land sink over time would require additional emissions reductions from fossil fuel combustion beyond what we model here.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

All data generated or analysed during this study are from publicly available sources and are either included in this article (and its Supplementary Information files) or available from the corresponding author on reasonable request. Source data are provided with this paper.

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Author contributions

N.K., A.R.B., H.M. and P.M. contributed to the design of the research. W.K. and H.M. conducted the modelling. All authors contributed to the analysis of the results. N.K., A.R.B., H.M. and P.M. wrote the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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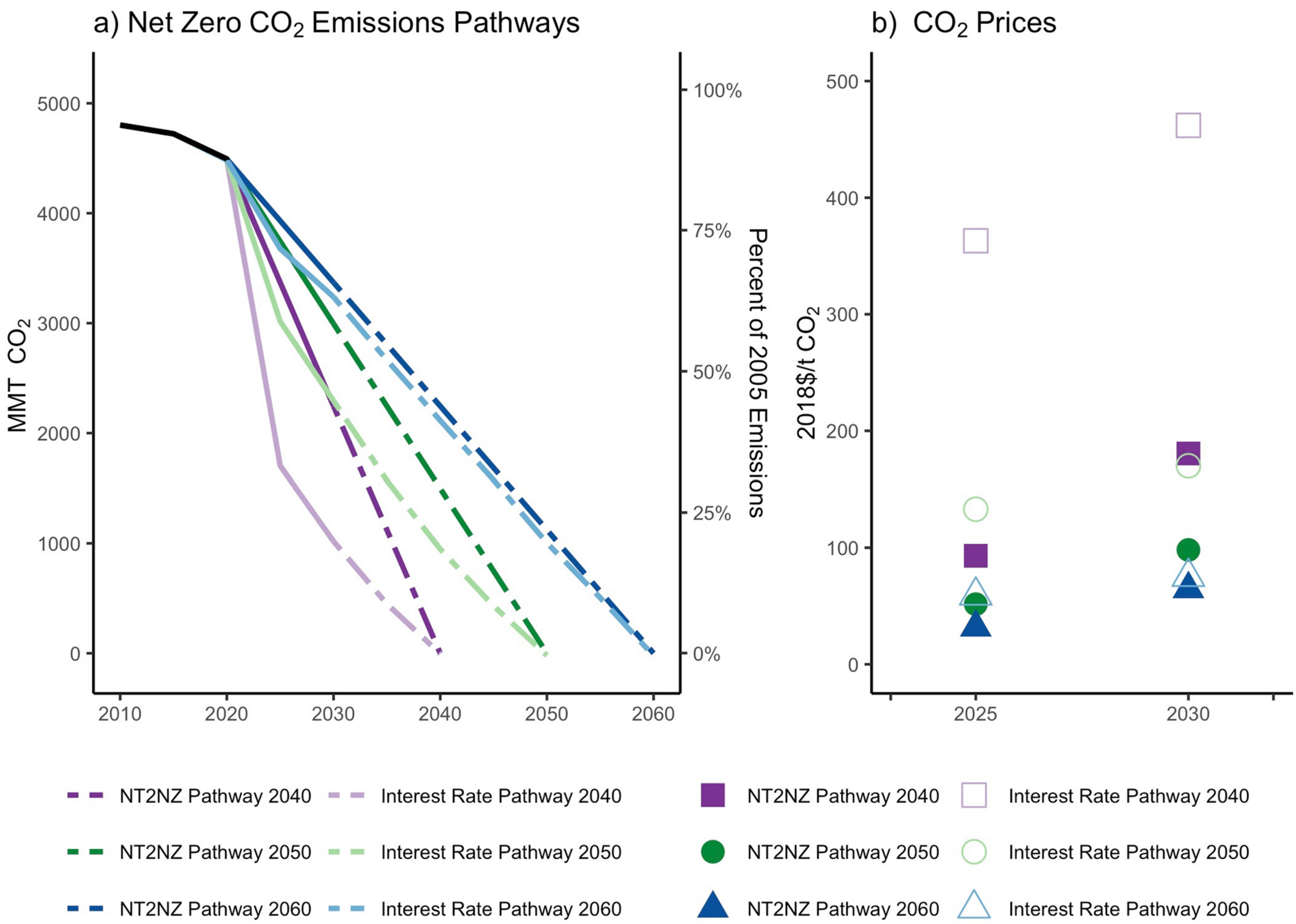

Extended Data Fig. 1 | SI Figure 4. NT2NZ versus CO2 Prices Rising at the Interest Rate. a, Linear emissions reduction pathways to net zero targets (dark lines) vs emissions reduction pathways when the price is constrained to grow at the interest rate (as a rough proxy for perfect foresight). **b**, CO2 prices for the linear pathways (closed symbols) and interest rate-constrained pathways (open symbols) in the year 2025 and 2030 for net zero targets in 2040 (squares), 2050 (circles), and 2060 (triangles), respectively.

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