The Macroeconomics of Net Zero*

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Abstract

This paper examines the macroeconomic cost and implications of transitioning to net zero emissions. The macroeconomic cost of achieving net zero is a combination of lower output due to higher energy prices and higher investment due to more costly technology. Along the transition path, a net zero target operates as both an anticipated negative productivity shock and a negative capital shock. Thus, for monetary policy, net zero is a negative aggregate demand shock that lowers the natural rate of interest. Using projected technology costs and net zero modeling scenarios, decarbonization of US electric power generation is estimated to cost less than 0.2% of steady state consumption.

Keywords: Climate change, net zero, energy transition

JEL Classification: E22, E23, Q43, Q54

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1 Introduction

In the wake of the Paris climate accords in 2015, the goal of net zero greenhouse gas emissions has increasingly become the organizing principle around climate change. In the Paris accords, countries agreed that to limit warming to 2 degrees Celsius or, preferably, 1.5 degrees Celsius would require achieving net zero greenhouse gas emissions by around mid century. Major emitters - including the US, European Union, China and Japan - have taken meaningful steps since the Paris accords to lower emissions. The Inflation Reduction Act (IRA), passed in 2022, represents the largest US effort to address climate change via broad-based subsidies for clean energy investment, though recent legislation has largely reversed its major provisions on electric vehicles and deployment of solar and wind energy.

The growing ambition around targeting net zero emissions and concrete steps taken in many advanced and developing economies toward decarbonization have prompted questions about the macroeconomic effects of the climate transition and its implications for monetary and fiscal policy. The investment and fiscal expenditures required to transition an economy from fossil to clean technologies across power generation, transportation, and industry have raised concerns that interest rates may move structurally higher, with implications for both public debt dynamics and monetary policy. Some have argued that direct fiscal costs on the energy transition may either raise interest rates or stoke inflation.[1]

In particular, the macroeconomic costs of getting to net zero are highly uncertain. At one level, the complete remaking of the world's energy system over 30 years would appear on its face to be an expensive undertaking. For some countries, the macroeconomic cost of getting to net zero emissions is projected to be modest. The UK Treasury estimated that getting to net zero emissions for UK would cost roughly 1-2% of GDP per year. The IEA estimated in 2021 that global annual energy sector investment would have to roughly double in a net zero scenario, implying a one percentage point of global GDP increase in investment (see International Energy Agency (2021)).

However, other estimates are significantly higher. The DICE model's abatement function has a net zero cost of 11% of global GDP in 2020, falling to 5.1% in 2050 (see Appendix E in Barrage and Nordhaus (2023)). Morris et al. (2023) calculate that achieving global net zero would lower consumption by 10-15% of GDP yearly while Smil (2023), drawing from a 2021 McKinsey Global Institute study (Mckinsey Global Institute (2021)), estimates that investment required to reach net zero would require a staggering 15-25% of GDP per year for high income countries.

In this paper, I examine the costs of getting to net zero emissions and the implications for monetary and fiscal policy. Specifically, I consider the macroeconomic consequences of the transition to net zero emissions through the lens of simple analytical model and through a quantitative ap-

[1] Bistline, Mehrotra and Wolfram (2023) find that the climate provisions of IRA could results in expenditures of up to $1.2 trillion over ten years.

plication to decarbonization of the electric power sector in the US. In considering the transition to next zero, two dimensions are key: the shift in technology from fossil to clean (zero emissions) and the turnover in the capital stock. The approach taken in this paper seeks to more directly drawn upon energy systems modeling, which has been influential in specifying the technology pathways to net zero emissions.

I start with a simple analytical model that is sufficiently general to consider decarbonization for any particular sector (i.e. power generation, transportation, etc.) or for any country. The planner invests in clean and fossil fuel capital that produces energy used in the production of a final good. Clean and fossil fuel capital differ in their capital cost, productivity, and depreciation rates. To render net zero feasible, there must exist a technology (or suite of technologies) that at some price could fully substitute for the incumbent fossil fuel technology. I show that, in the long-run, the macroeconomic cost of achieving net zero depends on the difference in consumption when fossil fuel capital is available or is banned. The sacrifice in consumption in the net zero case can be decomposed into an output cost and an investment cost. Output is lower under net zero since the cheaper fossil technology is not available, lowering production. Additionally, steady state investment also increases as some combination of more costly or less productive clean capital is needed on an ongoing basis.

Turning to the transition path, I show that a net zero target is analogous to a composite shock: an anticipated negative productivity shock and an anticipated negative capital shock. In effect, the shift to a zero emissions technology is a shift to a more costly or less efficient technology for energy. The higher cost of energy shifts inward the production possibilities frontier. The planner smooths out the effect of the negative productivity shock by gradually reducing consumption. This equivalence is shown analytically in the case of full depreciation.

Additionally, a net zero target may also materialize as a negative capital shock. If capital cannot be reallocated by the net zero date due to, for example, irreversibility, part of the capital stock is rendered obsolete and output falls. Consumption falls at the point the capital stock is rendered obsolete (relative to the previous period). From that point forward, the clean energy capital stock rises towards its steady state level. Importantly, the negative effect on consumption during the transition can still materialize even if there is very little long-run cost of attaining net zero. If, for example, the capital cost of clean and fossil fuel capital are similar, steady state consumption will be comparable, but consumption will fall during transition due to premature capital destruction.

The transition path for consumption has clear implications for the real interest rate during the climate transition that run contrary to conventional wisdom. Both a negative productivity shock and a negative capital shock imply a decline in consumption from the initial date to the net zero date. This negative consumption growth implies a declining real interest rate during the climate transition. This decline in consumption emerges despite a *rise* in investment. Importantly this result suggest that, generically, one should not expect the climate transition to be an upward force on the interest rate relevant for monetary policy (i.e. natural rate of interest r_t^n). Moreover, for stabilization purposes, the climate transition represents a *negative* aggregate demand shock.

The analytical model also has implications for fiscal policy. Net zero emissions can be achieved via some combination of a carbon tax or clean energy subsidy, but optimal policy relies solely on a carbon tax and sets the subsidy to zero.[2] If a subsidy is used to achieve net zero emissions, then electricity production will be unchanged (relative to baseline) but at the cost of excessive investment. In the net zero steady state, the carbon tax raises zero revenue but a subsidy represents an ongoing cost. To the extent that the subsidy is financed by distortionary taxation on other factors of production, the overall macroeconomic cost of achieving net zero also includes an additional fiscal cost from distortionary taxation.

The cost of net zero under a subsidy-only approach provides a useful upper bound on the long-run cost of getting to net zero. An upper bound on the cost of net zero is the clean technology premium multiplied by the energy investment share in GDP. This upper bound shows why that macroeconomic cost of getting to net zero is likely to be low. When fuel costs are explicitly modeled, this upper bound may be negative (i.e. consumption may *rise* is the long-run due to lower fuel costs). Key clean energy technologies - solar and wind, batteries, and electric vehicles - have become markedly cheaper in recent years, shrinking the premium relative to incumbent fossil fuel technologies. Moreover, the energy investment share is low for advanced economies; for instance electric power generation investment is roughly 0.5% of GDP in the US.

Using the simple expression derived from the analytical model, I provide estimates for an upper bound on decarbonization of US transportation and buildings. Together with electricity production, these three sectors account for 2/3 of US emissions. Light-duty vehicles account for the largest share of investment in energy capital but are also expected to see electric vehicles become cheaper on a lifecycle basis relative to internal combustion vehicles. Therefore, the switch to zero emissions vehicles produces a macroeconomic *savings* that offsets the cost of decarbonizing the rest of transportation (medium/heavy-duty vehicles and aviation) and buildings (residential and commercial space and water heating). While the zero emissions technology carries a substantial premium for aviation and buildings, the level of investment is very low relative to GDP meaning the macroeconomic cost is small and "paid for" by savings from switching to electric light-duty vehicles.

To further assess the quantitative implications of transitioning to net zero in electric power generation, I enrich the analytical model to include adjustment costs, non-energy capital, and a more realistic model of electric power generation. Though the unsubsidized cost of clean power sources like wind and solar are now competitive with natural gas fired power generation, these intermittent sources of power are imperfect substitutes for dispatchable sources of power that are

[2]The optimal subsidy may be non-negative if there are learning-by-doing externalities where the price of clean energy capital drops with the capital stock as noted in Bistline, Mehrotra and Wolfram (2023).

needed to ensure reliability. To capture this property of power generation, I assume that electric power is produced via a variable elasticity of substitution (VES) production function. When intermittent power is a low share of total power generation, it is a strong substitute for dispatchable (fossil) power generation. But as its share increases, intermittent (clean) power becomes less substitutable for fossil power making further decarbonization with intermittent sources increasingly costly. Data on current and future capital costs and baseline projections from energy systems models are used to estimate the parameters of the VES electricity production function.

This electricity production function is calibrated to baseline scenarios from energy system models. These models choose the optimal mix of clean, unabated fossil, and fossil with carbon capture to both ensure reliability and minimize cost. Net zero scenarios are considered where taxes or subsidies are imposed to drive the unabated fossil share down to the average levels in net zero scenarios. I find that the macroeconomic cost of achieving net zero emissions for US power generation is less than 0.1% of consumption under the assumption that energy and non-energy inputs are moderate complements. With Cobb-Douglas final good production, consumption losses are less than 0.2% of consumption. At these costs, decarbonization of the electricity sector likely passes cost-benefit analysis on the basis of conventional (non-greenhouse gas pollution) abatement. Even in the extreme scenario of no technological progress to 2050, long-term consumption losses are still less than 1%. Quantitatively, transition path results modestly attenuate these consumption costs as discounting effects dominate adjustment costs.

Though limited to only quantifying the cost of decarbonization of US electric power production, these magnitudes are an order of magnitude lower than many estimates of the cost of attaining net zero. This is largely a function of technological progress and of the small share of electricity production in overall output and energy investment as a share of overall investment. The quantitative model does not consider the benefits from mitigating carbon emissions, but the magnitude of the consumption costs suggests that the reduction in conventional air pollutants alone would justify the cost of attaining net zero. The costs are also likely low enough to justify unilateral decarbonization as most of the social cost of carbon is borne outside the US.

The rest of the paper is organized as follows. Section 1.1 below outlines the related literature in energy systems modeling and macro/climate models. Section 2 describes the simple analytical model of the transition to net zero and describes the upper bound on decarbonization. Section 3 presents the quantitative model and calibration strategy for the US electric power sector. Section 4 provides results on the long-run and transition costs of attaining net zero emissions in the US electric power generation. Section 5 concludes.

1.1 Related Literature

This paper seeks to bring the results of energy system modeling into a conventional macroeconomic growth framework. Energy systems models have been used to describe pathways for net zero emissions for the US economy and to quantify the effects of recent US policy changes such as the Inflation Reduction Act (IRA). Bistline, Mehrotra and Wolfram (2023) use the EPRI-REGEN model to analyze the impact of the Inflation Reduction Act on US electric power generation, electric vehicle adoption adoption, carbon dioxide emissions, and electricity prices. Bistline et al. (2023) offers a comparison across nine energy systems models to examine the energy market impacts of IRA. Jenkins et al. (2021) provide several scenarios for the US to achieve net zero emissions by 2050, while Huppmann et al. (2023) compare net zero scenarios across a range of energy systems models for the National Climate Assessment. These models do not consider the macroeconomic impacts of the energy transition or provide an estimate of the macroeconomic cost of getting to net zero.

An extensive literature in macroeconomics has sought to incorporate climate change damages and mitigation into a standard macroeconomic framework. Nordhaus (1993) provided that first integrated assessment model with more recent updates of the DICE model in Barrage and Nordhaus (2023). Golosov et al. (2014) characterize the optimal carbon tax in macro growth model with climate damages, while Barrage (2020) studies the interaction between carbon taxes and other distortionary taxes. This work does not model mitigation in detail, taking a reduced form approach. This paper focuses more closely on mitigation technologies and, in particular,, takes into account the turnover the capital stock needed to achieve net zero and on the modeling electric power generation to account for imperfect substitutability between intermittent and firm sources of electric power.

Lastly, this paper is related to macroeconomic models with energy production. Arkolakis and Walsh (2023) examines the economic growth and spatial activity impacts of the falling price of clean energy capital, finding a rapid increase in US clean energy power generation even accounting for limited interregional transmission capacity. Fried (2018) quantitatively examines how a carbon tax induces innovation in clean energy in a model with clean, fossil and non-energy capital. Casey, Jeon and Traeger (2023) study the implications of subsidies to clean energy relative to a carbon tax in a dynamic macroeconomic model where clean and fossil energy are complements. Mehrotra and Srivastava (2025) adapts the framework developed here to the energy transition in a small open economy. Mehrotra (2025) consider how spillovers from frictions in electricity pricing affect end-use decarbonization and, in particular, establishes that an economywide carbon tax may not implement optimal policy. Carton et al. (2023) outline a large-scale open economy macro model with energy production and trade; this model is used in Voigts and Paret (2023) to assess the energy and macroeconomic impact of IRA. Relative to these papers, I focus on dynamics of the capital stock in net zero scenarios, allow for variable elasticity of substitution across clean and fossil energy, and use evidence and approaches from energy system models to quantify the cost of the transition.

2 Analytical Model

I begin by outlining a simple neoclassical model with clean and fossil capital to highlight the key macroeconomic forces from a net zero emissions target. The model here follows closely the framework introduced in Bistline, Mehrotra and Wolfram (2023) that was used to characterize the macroeconomic impacts of the climate provisions of IRA. This section introduces the model, characterizes the steady state and transition path, and considers implications for monetary and fiscal policy.

2.1 Planner's Problem

The model introduced here is a neoclassical growth model with energy production. The planner chooses consumption and investment in two types of capital to maximize the discounted present value of flow utility from consumption. The clean capital stock K_t^c and the fossil fuel capital stock K_t^f produce energy E_t from a generation function $G(\cdot, \cdot)$ that takes both types of capital as input. The planner can invest in new clean or fossil fuel capital at relative prices p_t^c and p_t^f. The final good production function is assumed to be constant returns to scale, with decreasing returns in each input and satisfies the Inada conditions. Labor supply is inelastic at $\bar{N}$.

$$\max \sum_{t=0}^{\infty} \beta^t u(C_t)$$

$$\begin{aligned} C_t + p_t^c I_t^c + p_t^f I_t^f &= F\left(E_t, \bar{N}\right) \\ E_t &= G\left(K_t^c, K_t^f\right) \\ K_{t+1}^i &= I_t^i + (1-\delta_i) K_t^i \quad i \in \{c, f\} \\ K_{t+1}^i &\geq 0 \end{aligned}$$

The model presented here parsimoniously captures the essential features of the energy transition: the choice between fossil and clean energy technologies with different costs and underlying productivity, the importance of energy as an input into final goods production and the need to turnover a energy-producing capital stock that depreciates slowly. This setup is sufficiently general to capture decarbonization outside of electric power generation. For example, decarbonization of transportation likewise reflects a shift in transportation capital from fossil fuel power to clean fuel with transportation services (instead of E_t) as an input to overall final goods production. Decarbonization of buildings and industry likewise require the production of alternative fuels (i.e. hydrogen, synthetic natural gas) or a shift towards capital that can be electrified.[3]

The possibility of attaining net zero emissions depends on the energy generation function $G(\cdot,\cdot)$.[4] Typically, macro/climate or macro/energy models specify a constant elasticity of substitution across these two types of technologies (see, for example, Fried (2018) and Golosov et al. (2014)). With constant elasticity of substitution, full decarbonization is infeasible since both types of capital are essential. To allow for a net zero allocation (i.e. $K_t^f = 0$), non-negativity constraints on capital are imposed.

The optimal allocation of clean and fossil capital satisfies the following intertemporal Euler equations:

$$
\begin{aligned}
p_t^c \lambda_t + \mu_t^c &= \beta \lambda_{t+1} \left[p_{t+1}^e G_c \left(K_{t+1}^c, K_{t+1}^f \right) + p_{t+1}^c (1 - \delta_c) \right] \\
p_t^f \lambda_t + \mu_t^f &= \beta \lambda_{t+1} \left[p_{t+1}^e G_f \left(K_{t+1}^c, K_{t+1}^f \right) + p_{t+1}^f (1 - \delta_f) \right] \\
\lambda_t &= u_c(C_t) \\
p_t^e &= F_e \left(E_t, \bar{N} \right) \\
0 &= \mu_t^i K_{t+1}^i
\end{aligned}
$$

For an interior solution, the optimal level of investment in each type of capital equations the price of capital today to the sum of the discounted value of undepreciated capital in the next period and the marginal product of capital. The marginal product of clean or fossil fuel capital depends on the value of energy in the production function p_t^e and the incremental energy from another unit of clean or fossil capital.

The model can be easily generalized to allow for endogenous labor supply. Assume that period utility is now a function of utility less disutility from labor supply: $u(C_t) - v(N_t)$ with the disutility of labor supply $v(\cdot)$ increasing and convex. The optimal labor allocation equates the marginal cost of supplying labor with the marginal benefit:

$$
\frac{v_n(N_t)}{u_c(C_t)} = F_n(E_t, N_t)
$$

[3] In the simple model, I do not model the consumption or provision of fossil fuel. Effectively, the model assumes costless supply of fossil fuel and Leontif demand for fuel for energy production. This may neglect efficiency gains where emissions and fuel usage can be reduced for a given level of energy production.

[4] The DICE model features a reduced form abatement function; the fraction of emissions abated directly reduces production available for consumption. See Barrage and Nordhaus (2023) for details.

2.2 Net Zero Steady State

A sufficient condition for ensuring the feasibility of a net zero allocation is perfect substitutability and constant returns to scale for the energy production function $G(\cdot,\cdot)$:

$$G\left(K_t^c, K_t^f\right) = G^c\left(K_t^c\right) + G^f\left(K_t^f\right)$$
$$G^i\left(K_t^i\right) = A_i K_t^i$$

If this functional form is assumed, then, in steady state, all energy capital will be allocated to either clean or fossil capital. The choice between clean and fossil capital satisfies the following condition:

$$\frac{p_f}{\theta_f}\left(r+\delta_f\right) - \tilde{\mu}_f = \frac{p_c}{\theta_c}\left(r+\delta_c\right) - \tilde{\mu}_c$$

The assumption perfect substitutability may appear strong and deserves further discussion. First, no restriction is placed on how much more expensive the clean technology pathway p_c is be relative to the fossil pathway p_f. Second, perfect substitutability is the tacit assumption in energy systems modeling, which lays out pathways through which fossil fuel use can be replaced by some combination of electrification, alternative fuels, or carbon capture and sequestration. Third, for hard-to-abate sectors, a feasible though perhaps costly decarbonization strategy is always to simply capture or offset the unabated emissions.

The assumption of constant returns also merits further discussion. There is little reason a priori to think that zero carbon energy pathways require inputs in fixed supply. Land is an important input for biofuels or negative emissions technologies like bioenergy with carbon capture; however, higher cost options that are not land-constrained are available for both zero carbon fuels and carbon capture. Labor input to energy production is comparatively small as a share of the total labor force. Existing production of raw materials like lithium and copper are likely insufficient to cover the energy transition, but there is little reason to think that production could be increased through further exploration and production.

If the productivity and depreciation-adjusted price of fossil fuel capital (adjusted for productivity) is less than that of clean energy capital, only fossil fuel capital is used and $\tilde{\mu}_c > 0$. In the opposite case, only clean energy capital is used. The steady level of energy generation, output and consumption satisfy the following conditions:

$$\frac{p_i}{A_i}\left(r+\delta_i\right) = F_e\left(A_i K_i, \bar{N}\right)$$
$$Y = F\left(A_i K_i, \bar{N}\right)$$
$$C = Y - \delta_i p_i K_i$$

where i is the lowest cost energy production technology and $r = 1/\beta - 1$. From these expressions, it is clear that a net zero steady state is feasible and that, if clean energy capital is more costly than fossil fuel capital, energy generation, total output and consumption will be lower while the price of energy will rise. The implications for investment are ambiguous, as higher investment may be needed due to a higher capital stock or higher relative price of capital. From these expressions, the long-run cost of attaining net zero emissions is simply the difference in consumption between the clean and fossil fuel steady states.

Under net zero, the switch from fossil to clean energy reduces the marginal product of labor - a negative labor demand shock - reducing the labor input as wages fall. So long as the income effect is not too strong, labor input falls and output falls by more relative to the case of inelastic labor supply.

An upper bound to the consumption loss from a net zero target can also be derived under conditions of perfect substitutability and constant returns. A feasible allocation is one in which energy production is kept constant between the net zero and fossil fuel steady state. In this case, output remains unchanged across the two steady states and consumption is only lower because of the higher required investment needed to maintain energy production. The consumption cost of net zero ΔC_{nz} expressed as a share of GDP is:

$$\Delta C_{nz}/Y = \left(\frac{p_c}{p_f}\frac{\delta_c}{\delta_f}\frac{\theta_f}{\theta_c} - 1\right) p_{k,f} I_f / Y \tag{1}$$

The consumption loss is proportional to the productivity and depreciation adjusted price premium in capital cost between clean and fossil fuels and is linear in the initial level of energy investment. Consumption losses will be modest in the long run if capital costs, productivity differences are small and/or steady state energy investment I_f as a share of GDP is low.

2.2.1 Extension to Fuel

The simple model presented here can be easily generalized to include the production and use of fossil fuel. As a practical matter, energy production requires the combination of fossil fuels (coal, natural gas, oil) with fossil capital for the production of useful energy services. I assume that fossil fuels can be extracted at a constant marginal cost p_f and are combined with fossil capital in constant proportions: for each unit of fossil capital K_f, κF units of fossil fuel are required.[5] The resource constraint now becomes:

$$C_t + p_f F_t + \sum_i p_k^i I_t^i = F\left(E_t, \bar{N}\right)$$

where p_f is the extraction cost of fossil fuel or equivalently the world price of fossil fuel that is imported (assuming balanced trade). Optimality conditions for clean and fossil power are largely

[5] In general, the clean energy source may also have a fuel cost as in the case of nuclear power or carbon capture. However, here we maintain the general assumption that clean power has higher capital cost or lower capacity.

unchanged; one can derive a steady state expression for the cost of each type energy that is analogous to the levelized cost of electricity. The cost of energy is its fuel cost plus its fuel-adjusted capital cost:

$$p_e = \kappa p_f + \frac{r + \delta_f}{\theta_f} p_{k,f}$$
$$p_e = \frac{r + \delta_c}{\theta_c} p_{k,c}$$

p_e is the price of energy (the marginal product with respect to energy). Higher fuel costs p_f, lower capacity factors A_i and higher capital cost $p_{k,i}$ raise the price of energy.

As before, under the assumption that energy use is kept constant, a generalized bound on the consumption cost of zero emissions can be derived:

$$\Delta C_{nz}/Y = \left(\frac{p_c}{p_f} \frac{\delta_c}{\delta_f} \frac{\theta_f}{\theta_c} - 1 \right) p_{k,f} I_f / Y - F/Y$$

where F/Y is the share of GDP spent on fossil fuels. As can be seen from the above expression, the steady-state consumption cost of net zero can now be negative - consumption may indeed rise in the long-run due to lower fuel costs. In the net zero steady state, the household no longer faces any flow cost for energy as renewable energy replaces fossil fuels. Note that it is simultaneously possible for consumption to rise in the long run and the price of energy to rise under a net zero target. The price of energy includes the time cost r that does not appear in the resource constraint; put another way, a net zero target that raises long-run consumption is equivalent to a forced saving policy that requires the household to sacrifice current consumption for higher future consumption.[6]

2.3 Net Zero Transition Path

I now turn to characterizing the transition path to net zero. The net zero transition path is the planner's choice of clean and fossil capital between date 0 and date T_{nz} after which point fossil fuel capital can no longer be utilized (i.e. $K_t^f = 0$ or $\theta_f = 0$). The optimal allocation of capital is a constrained version of the optimality conditions shown above:

$$p_t^c + \mu_t^c = \frac{\beta \lambda_{t+1}}{\lambda_t} \left[p_{t+1}^e G_c \left(K_{t+1}^c, K_{t+1}^f \right) + p_{t+1}^c (1 - \delta_c) \right] \quad t < T_{nz}$$
$$p_t^f = \frac{\beta \lambda_{t+1}}{\lambda_t} \left[p_{t+1}^e G_f \left(K_{t+1}^c, K_{t+1}^f \right) + p_{t+1}^f (1 - \delta_f) \right] \quad t < T_{nz}$$
$$p_t^c = \frac{\beta \lambda_{t+1}}{\lambda_t} \left[p_{t+1}^e G_c \left(K_{t+1}^c, 0 \right) + p_{t+1}^c (1 - \delta_c) \right] \quad t \geq T_{nz}$$

[6]The prospect that consumption may rise in a zero emissions economy makes the social discount factor an important parameter in assessing whether energy policy is optimal even absent pollution or climate change externalities. This debate is central in assessments of the optimal carbon tax - see, for example, Stern (2006)

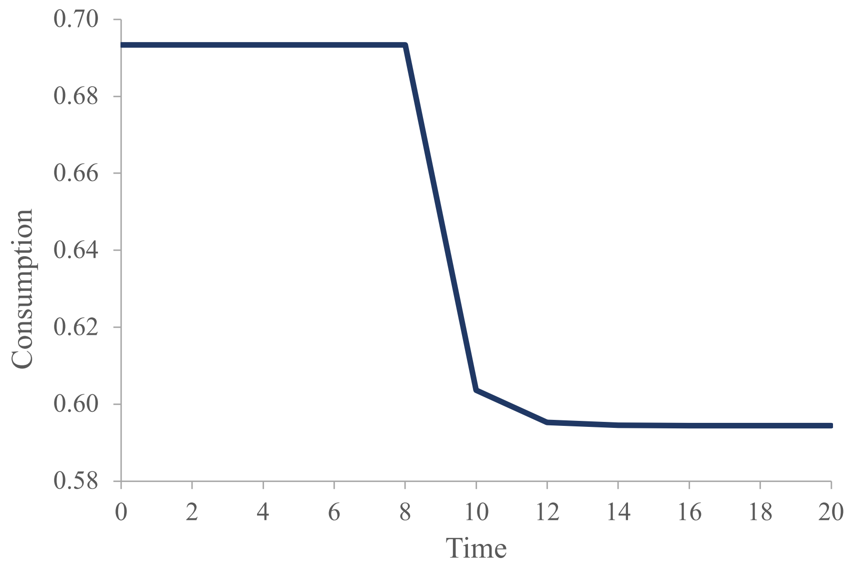

Figure 1: Transition path: Anticipated productivity shock

For $t \geq T_{nz}$, the transition path is analogous to a standard neoclassical growth model with one type of capital. But prior to the net zero date, the planner can generically invest in both forms of capital.

In general, it will be difficult to characterize the transition paths for output, consumption and capital stocks analytically without strong assumptions. However, to illustrate the key forces at work in the transition, I consider two specific cases.

As shown earlier, assuming that the clean technology is more costly than the fossil technology, consumption must be lower in the net zero steady state. With full depreciation, the technology shift around net zero requires a discrete shift to the more costly technology. The following proposition summarizes the dynamics of consumption:

Proposition 1. *If $\delta = 1$ and $p_c > p_f$, consumption starts above its long run level and falls monotonically to its net zero consumption level C_{nz}.*

The case of full depreciation illustrates how the net zero transition mimics an anticipated negative productivity shock. The intuition is straightforward in this case - future consumption must be lower since energy production will be more costly. While the productivity change is abrupt around the net zero date, the drop in consumption is gradual as the planner smoothes out the consumption response along the transition. Since the timer period is arbitrary in this simple model, a net zero transition with a relatively long transition period can best approximated by the full depreciation case.

In the case of log consumption, full capital depreciation and Cobb-Douglas production, the model is isomorphic to an RBC model with productivity shocks and full depreciation. Saving and investment are a constant share of output. From the initial steady state with only fossil capital, energy can only be produced by clean energy capital after T_{nz}. Prior to the net zero date, consumption, output and investment are at their pre-net-zero steady state level and clean energy capital is zero. At $T_{nz} - 1$, investment shifts to clean energy capital, but that level of investment is insufficient for output to remain unchanged in T_{nz}, resulting in a decline in consumption. This result is summarized in the following lemma, with Figure **??** illustrating the transition path:

Lemma 1. *If utility function is log and the final good production function is Cobb-Douglas, then the saving rate is constant and consumption falls monotonically to* $C_{nz} < C_0$

The alternative case is the case of no depreciation $\delta_f = \delta_c = 0$, irreversibility and $p_c = p_c + \epsilon$. In this case, steady state consumption with and without a net zero target are comparable, since the underlying technologies are similar in cost. However, the transition dynamics around the net zero target will be pronounced. At the net zero date, the economy experiences a negative capital shock and fall in output. By investing in clean energy capital prior to the net zero date T_{nz}, the planner can mitigate the fall in output. However, to do so, returns on capital must therefore be depressed prior to T_{nz} and consumption must be falling. After T_{nz} the clean energy capital stock grows to its long-run value just as in a standard capital accumulation model after a capital destruction shock. This result is summarized by the following proposition and illustrated in Figure 2:

Proposition 2. *If* $\delta = 0$ *and capital is irreversible, consumption growth is weakly negative before the net zero date* T_{nz}

The case of no depreciation and irreversibility captures a key element of the climate transition: stranded assets. Fossil fuel capital is long-lived and may need to be retired before the end of its economic life. This premature retirement of economic useful assets functions like a negative capital shock (or a war shock). Since this shock is anticipated, the consumption response is smoothed out and consumption declines to the net zero date and must approach the eventual steady state level of consumption from below.

To summarize, these cases illustrate how the climate transition is the composition of an anticipated negative productivity and capital shock.

2.4 Implications for monetary and fiscal policy

The characterization above of the energy transition path has clear implications for the behavior of the natural rate of interest (i.e. the interest rate that monetary policy wishes to track). The interest

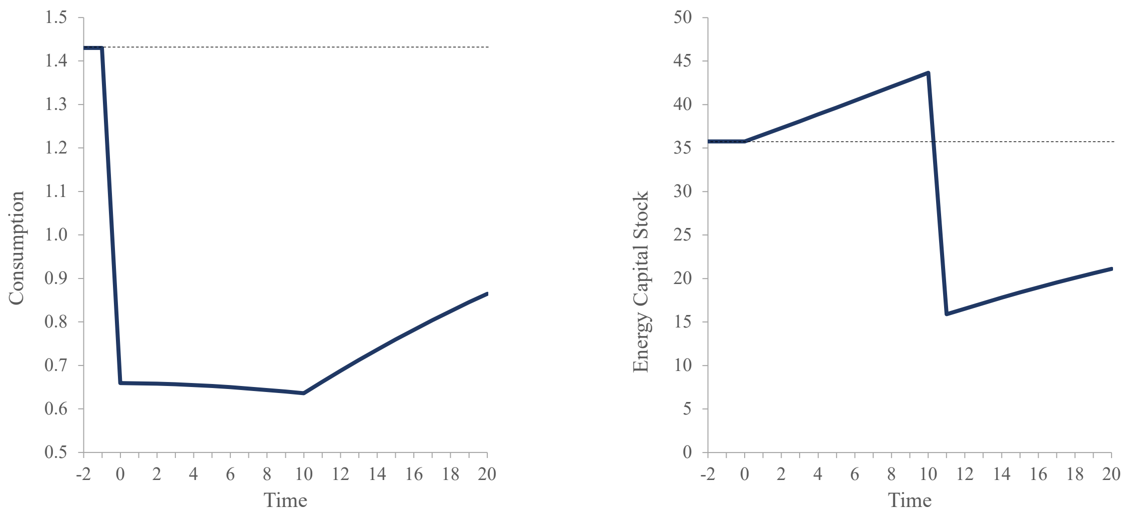

Figure 2: Transition path: Anticipated capital shock

rate over the climate transition is derived below:

$$1 + r_{0,T_{nz}} = \prod_{j=0}^{T} (1 + r_{j,j+1})$$

$$1 + r_{t,t+1} = \frac{1}{\beta} \frac{u_c(C_t)}{u_c(C_{t+1})}$$

$$\Rightarrow = \frac{1}{\beta^T} \frac{u_c(C_0)}{u_c(C_T)}$$

In both the cases of a negative productivity shock and negative capital shock, consumption growth is negative between the initial date and the net zero date. Since consumption growth is negative, on average, the real interest rate over this period falls below its steady state level (i.e. $1/\beta - 1$). The generic decline in the real interest rate along the transition path stands in sharp contrast to conventional wisdom among central bankers and monetary policymakers that interest rates may be structurally higher due to the investment demands of the climate transition.[7] Interestingly, this intuition holds after the net zero date where the clean energy capital stock continues growing to its steady state level.

In the presence of pricing frictions in the labor market, a net zero target acts as a negative shock to aggregate demand (hence the decline in the natural rate). If monetary policy fails to track the declining natural rate, consumption demand will fall but investment demand will not rise commensurately, resulting in lower labor demand and higher unemployment. While the productivity component is a negative demand shock, the negative capital shock component turns to a positive aggregate demand shock after the net zero date T_{nz} as the marginal product of capital rises. It is worth emphasizing that expectation effects on current consumption would need to be quite strong

[7]See, for example, a Peterson Institute discussion on the future of interest rates or this Wall Street Journal piece.

to induce a negative output gap from the adoption of a net zero target.

This result could potentially be reversed to the extent that the net zero economy is actually more productive than the baseline case; one way this may be true if clean energy investment benefits from learning-by-doing that drives down capital costs or boost productivity of clean energy capital. The result of a declining natural rate could also be reversed if emission damages are sufficiently reduced to raise future consumption relative to the baseline. If emissions reductions are small relative to global emissions, then the mitigation of climate damages on interest rates is likely to be modest.

The implications for fiscal policy are likewise clear. The planner can implement the net zero allocation by either raising the relative cost of fossil capital or lowering the relative cost of clean energy capital. The combination of a carbon tax τ_f and clean energy subsidy τ_c that implements the net zero allocation must ensure that the after tax cost of capital is higher than the after subsidy cost of clean energy capital. The expression below shows this condition:

$$\frac{p_f}{\theta_f - \tau_f}\left(r + \delta_f\right) = \frac{p_c}{\theta_c + \tau_c}\left(r + \delta_c\right)$$

In steady state, the carbon tax that implements the net zero allocation raises zero revenue and has no broader economic impacts via fiscal policy. However, if implemented solely with a clean energy subsidy, the subsidy will be strictly positive in steady state to keep fossil capital uncompetitive and output and energy will be unchanged relative to the fossil case. Any output costs from distortionary capital or income taxes represent an additional macroeconomic cost of attaining net zero due to fiscal implementation. It can be shown that the optimal fiscal implementation both in the long-run and along the transition path is solely via a carbon tax (see Bistline, Mehrotra and Wolfram (2023) for extensive discussion).

Consider a distortionary labor tax that is used to finance a clean energy subsidy that renders fossil capital uncompetitive. In steady state, the labor tax must collect sufficient revenues to fund the subsidy to clean energy capital as shown below:

$$\tau N = \tau_c \delta_c K_c$$

Both N and K_c are decreasing in the labor income tax so long as labor supply is not completely inelastic. As a result, a non-zero labor income tax lowers both employment N and clean energy capital K_c, lowering output. The steady state cost of attaining net zero can be expressed as the sum of the upper bound consumption cost without distortionary taxes (see equation (1)) and a second term that reflects the additional steady state output lost from the fiscal instrument used to implement the net zero allocation:

$$\Delta C_{nz,\tau} = \left(\frac{p_c}{p_f}\frac{\delta_c}{\delta_f}\frac{\theta_f}{\theta_c} - 1\right) p_f I_f - \left(Y_{nz} - Y_{nz,\tau}\right)$$

2.5 Bound on steady state cost

As noted earlier, equation (1) provides a useful upper bound on the macroeconomic cost of zero emissions in steady state. In the presence of a subsidy that leaves energy usage unchanged, equation (1) states that the macroeconomic cost of getting to net zero is the additional investment needed in steady state for the clean energy pathway. This additional investment can be expressed as the cost premium multiplied by fossil fuel investment as a share of GDP. For most advanced economies, fossil fuel investment is a small share of GDP and, therefore, the only way for the steady state cost of net zero to be large is that there is a large premium on clean energy pathway relative to the fossil fuel pathway.

Table 1 provides bounds using equation (1) on the steady state cost of decarbonizing US transportation and buildings emissions. The cost of decarbonizing electricity production is modeled in more detail in the following section. Together with electricity generation, transportation and building emissions account for roughly 2/3 of US emissions; industrial and agriculture/land-use related emissions are excluded. The first column of Table 1 shows 2022 emissions by sector in millions of tons. Transportation emissions are largely concentrated in road transportation, while US building emissions are dominated by space and water heating. The second and third columns show the capital stock and annual investment (as a percent of GDP) of light-duty and medium/heavy duty vehicles and buildings with fossil fuel space and water heating.[8]

As the bottom of column 3 shows, total investment in vehicles and building heating equipment is 3.5 percent of GDP and mostly concentrated in light-duty vehicles (approximately 15 million light-duty vehicles are sold in the US annually). Investment in residential and commercial space and water heating is very low - just 0.06 percent of GDP or around $ 2-3 billion.[9] The fossil fuel capital stock however is sizable: 270 million light-duty vehicles, 11 million medium and heavy duty vehicles, and around 60 million residential buildings with fossil fuel based space and water heating.

The fourth column estimates the current or future cost premium for the clean energy pathway relative to the fossil fuel pathway. For vehicles and buildings, this premium consists mostly of the difference in the initial capital outlay for electric vehicles or heating systems relative to the fossil fuel counterpart. The cost premium for vehicles is the 2050 estimate of the lifecycle cost of driving for light and medium/heavy vehicles. Sharp declines in the cost of batteries are expected to make electric light-duty vehicles *cheaper* than conventional gasoline powered vehicles. For buildings, we use current cost estimates for the difference in electric versus fossil fuel powered space and

[8]The stock of fossil fuel space and water heating is a count a buildings with fossil fuel space and water heating drawn from the most recent Residential Energy Consumption Survey and the Commercial Buildings Energy Consumption Survey compiled by the Energy Information Administration.

[9]The overall HVAC market is larger, but this calculation excludes air conditioning and electric space and water heating along with industrial applications.

	CO2 emissions	Stock	Sales	Cost premium	Cost bound
	Millions of tons, 2022	Thousands of units, 2022	Basis points of GDP		Basis points of GDP
Transportation	1751				
Light-duty vehicles	1013	272200	276.3	0.7	-70.2
Medium/heavy-duty vehicles	429	11200	44.2	1.0	0.6
Aviation	166		23.9	2.9	45.7
Other	143				0.2
Buildings	593				
Commercial	259				
Space heating	177	2587	1.1	3.0	2.2
Water heating	26	1885	0.2	1.9	0.2
Other	55				0.1
Residential	334				
Space heating	227	62710	2.8	2.2	3.3
Water heating	85	59330	1.9	1.3	0.5
Other	22				0.0
Total	2344		350.5	1.9	-17.3

Table 1: Steady state upper bound on cost of decarbonization, US transportation and buildings, basis points of GDP.

water heating. For aviation, we use estimates from NREL Annual Technology Baseline for the cost premium for sustainable aviation fuel.

The last column multiplies the cost premium in column 4 with the investment share in column 3 to extract an upper bound on steady state cost of decarbonization. For buildings, the 2-3X cost premium for electric space and water heating has very small steady state costs given the negligible share of investment in fossil heating. Even if these cost premia are off by a factor of 10 (for instance, some older buildings may be require more extensive upgrades to ductwork, electric panels, etc. to retrofit), the investment share is so low that it is difficult to decarbonization costs that are of macroeconomic relevance.

For transportation, decarbonization of aviation carries a larger cost (though still less than 0.5% of GDP) that is nearly fully offset by *savings* from transitioning to electric vehicles. The expected decline in battery costs and improvement in energy density along with the intrinsic efficiency advantages of electric motors imply that, over their lifecycle, electric vehicles will generate macroeconomic savings. In short, cheaper fuel and less maintenance offset the higher upfront cost and lower the resources needed for a given level of transportation services. The macroeconomic savings from electric light-duty vehicles more fully offsets the costs of both building and transportation decarbonization.[10]

To summarize Table 1 shows how the low share of investment in fossil fuel capital and antic-

[10]The cost of decarbonizing the remaining "other" categories in both transportation and buildings is computed by assuming carbon capture at $400 per ton.

ipated decline in the cost of electric vehicles together implies a low (or possibly negative) cost of decarbonizing transportation and buildings. Together with low costs for decarbonizing electric power generation, these calculations suggest that roughly 2/3 of US emissions can be eliminated at very low cost. The bounding calculation here has some limitations: 1) transition costs may exceed steady state costs depending on degree to which assets are stranded and short-term adjustment costs, 2) adoption and coordination frictions are not included (i.e. charging infrastructure, building out distribution, etc.), 3) estimates rely, in part, on technology cost estimates that are uncertain and for technologies that, today, have limited deployment. In the next section, we model the full transition for decarbonization in electric power generation.

3 Quantitative Model and Calibration

In this section, I present the full quantitative model used to analyze decarbonization in US electric power generation. The quantitative model includes both energy and non-energy capital, capital adjustment costs and several distinct energy capital stocks. This section also describes in some detail the way that electric power generation is represented in the model and the mapping between energy systems models of decarbonization and the aggregate production function used here.

3.1 Full Model

A representative household maximizes the discounted present value of consumption subject to an aggregate resource constraint and electric power production functions. The planner's problem is given below:

$$\max \sum_{t=0}^{\infty} \beta^t u\left(C_t\right)$$

$$C_t + \sum_i p_t^i I_t^i + S\left(I_t^i, K_t^i\right) = F\left(K_t^{ne}, E_t, \bar{N}\right)$$

$$E_t = G\left(K_t^c, E_t^{dis}\right)$$

$$E_t^{dis} = G^{dis}\left(K_t^f, K_t^{ccs}\right)$$

$$K_{t+1}^i = I_t^i + \left(1-\delta_i\right) K_t^i$$

There are four types of capital: unabated fossil fuel capital K_t^f, abated fossil fuel (carbon capture) capital K_t^{ccs}, clean energy capital K_t^c, and non-energy capital K_t^{ne}. Each capital stock has a relative price given by p_t^i and is subject to capital adjustment costs given by the function $S_i\left(I_t^i, K_t^i\right)$. Adjustment costs appear in the aggregate resource constraint. Capital accumulation equations for each type of capital are standard but capital may differ in depreciation rates. Electricity production is a nested function of the three types of energy capital and is discussed in further detail in the next section.

The optimality conditions for the planner's problem are given below:

$$
\begin{aligned}
u_c\left(C_t\right) &= \lambda_t \\
\lambda_t^e &= \lambda_t F_e\left(K_t^{ne}, E_t, \bar{N}\right) \\
\lambda_t^e G_2\left(K_t^c, E_t^{dis}\right) &= \lambda_t^{dis} \\
\mu_t^i &= \lambda_t\left(p_t^i + S_1\left(I_t^i, K_t^i\right)\right) \\
\mu_t^{ne} - \beta\mu_{t+1}^{ne}\left(1-\delta_{ne}\right) &= \beta\lambda_t\left(F_k\left(K_{t+1}^{ne}, E_{t+1}, \bar{N}\right) - S_2\left(I_{t+1}^{ne}, K_{t+1}^{ne}\right)\right) \\
\mu_t^c - \beta\mu_{t+1}^c\left(1-\delta_c\right) &= \beta\lambda_t^e G_1\left(K_{t+1}^c, E_{t+1}^{dis}\right) - \beta\lambda_t S_2\left(I_{t+1}^c, K_{t+1}^c\right) \\
\mu_t^f - \beta\mu_{t+1}^f\left(1-\delta_f\right) &= \beta\lambda_t^{dis} G_1^{dis}\left(K_{t+1}^f, K_{t+1}^{ccs}\right) - \beta\lambda_t S_2\left(I_{t+1}^f, K_{t+1}^f\right) \\
\mu_t^{ccs} - \beta\mu_{t+1}^{ccs}\left(1-\delta_{ccs}\right) &= \beta\lambda_t^{dis} G_2^{dis}\left(K_{t+1}^f, K_{t+1}^{ccs}\right) - \beta\lambda_t S_2\left(I_{t+1}^{ccs}, K_{t+1}^{ccs}\right)
\end{aligned}
$$

where μ_t^i are the Lagrange multipliers on the capital accumulation equation, λ_t is the Lagrange multiplier on the aggregate resource constraint, and λ_t^e and λ_t^{dis} are the Lagrange multipliers on the nests of the electricity production function. The quantitative model simplifies to the analytical model considered earlier if adjustments costs are zero and there is no non-energy capital or abated fossil energy capital.

3.2 Electricity Production

The modeling of electric power production merits further discussion. The most cost competitive clean sources of electric power generation are solar and wind power. These sources of electric power generation are classified as intermittent because the times at which they produce power (and the quantity produced) cannot be adjusted to meet demand. Intermittent power sources stand in contrast to dispatchable power - power generation sources that can be adjusted up or down to meet fluctuations in demand. To model electricity power generation, it is necessary to account for the need of dispatchable power generation to meet fluctuations in demand or periods in which solar and wind sources are not producing.[11]

Given the importance of dispatchable generation, I rely on a variable elasticity of substitution production function to represent aggregate electric power generation. The variable elasticity of substitution production function was introduced by Revankar (1971) and used in the context of substitution between clean and fossil energy in Fries (2023). I assume that electric power generation is a variable elasticity of substitution aggregate of intermittent E_t^{int} and dispatchable power

[11]Solar and wind power generation can be made less intermittent by pairing these sources with storage. Lithium batteries can provide short-term storage (typically 2-4) hours. Longer term storage is significantly more expensive at current prices (i.e. pumped hydro power or fuel conversion).

E_t^{dis}:

$$E_t = \left(E_t^{dis}\right)^{\alpha} \left(E_t^{int} + \alpha\rho E_t^{dis}\right)^{1-\alpha}$$

where ρ is a parameter that determines how the elasticity of substitution varies as the share of dispatchable generation varies.

As can be seen in the expression below, an increase in intermittent power generation relative to dispatchable generation lowers the elasticity of substitution when $\rho > 0$.

$$\sigma_t = \left(1 + \rho \frac{E_t^{dis}}{E_t^{int}}\right)$$

The variable elasticity of substitution production function has constant returns to scale, decreasing returns to each type of power generation, and has the feature that intermittent power generation is not essential for production (i.e. $E_t^{int} = 0$, $E_t > 0$ is feasible). This can also be seen by looking at the expression for the elasticity of substitution σ_t, which has the property that $\sigma_t \to \infty$ as $E_t^{dis}/E_t^{int} \to 0$.

In steady state, the share of intermittent and dispatchable power will depend on relative prices. Assume that dispatchable power is unabated fossil energy and intermittent power is clean energy. In steady state and with constant returns, a simple relationship between the relative price of fossil versus clean energy and their share in power generation can be derived:

$$\frac{p_f}{p_c} = \frac{A_f}{A_c} \frac{\alpha}{1-\alpha} \left(\frac{E_{int}}{E_{dis}} + \rho\right) - \tilde{\mu}_c$$

where $\tilde{\mu_c}$ is a Lagrange multiplier on the constraint that clean energy capital must be non-negative. When $\rho > 0$, the Lagrange multiplier is binding if productivity-adjusted clean energy capital $p_c/A_c > p_f/A_f$. Intuitively, clean energy generation will only be utilized if its price is less than dispatchable generation because of the intermittency penalty. As clean energy capital becomes cheaper, more intermittent energy is utilized but its market penetration is limited by a growing intermittency penalty.

In the quantitative application, clean energy capital generates intermittent power and some combination of unabated fossil or fossil energy with carbon capture is used to generate dispatchable power. Full decarbonization of the power sector is not feasible with clean intermittent sources alone. There is a range of non-fossil dispatchable generation that could be utilized: hydropower, nuclear power, and geothermal power are all potential zero-carbon dispatchable generation. However, these technologies generally play a limited role in energy systems modeling of net zero pathways due to cost (as shown below) or frictions in siting/permitting new generation.

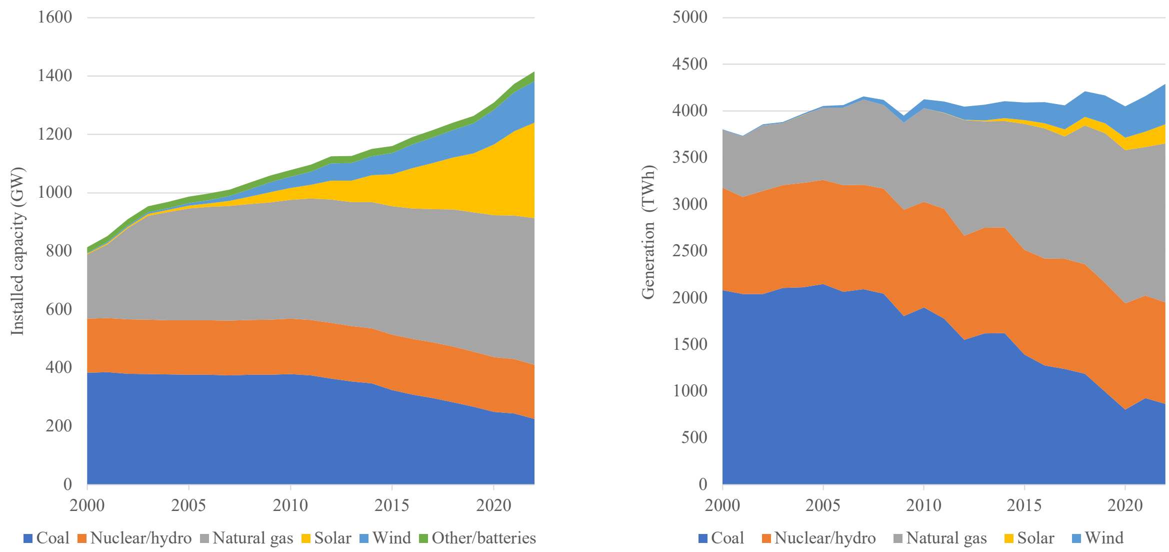

Figure 3: Nameplate capacity and generation by technology

The remaining functional forms for the quantitative model are given below:

$$u(C) = \ln(C)$$

$$F(K_{ne}, E, N) = K_{ne}^{\kappa} E^{\nu} N^{1-\kappa-\nu}$$

$$\text{or} \quad F(K_{ne}, E, N) = \left(\eta E^{\nu} + (1-\eta)\left(K_{ne}^{\kappa} N^{1-\kappa}\right)^{\nu}\right)^{\frac{1}{\nu}}$$

$$G^{dis}(K_f, K_{ccs}) = \left(\eta_e A_f K_f^{\epsilon} + (1-\eta_e)(A_{ccs} K_{ccs})^{\epsilon}\right)^{\frac{1}{\epsilon}}$$

$$S_i(I, K) = \frac{\gamma_i}{2}\left(\frac{I - \delta K}{K}\right)^2 K$$

I assume log consumption and quadratic capital adjustment costs. The final good production function is assumed to be Cobb-Douglas with electricity, non-energy capital, and labor as inputs. I also consider the case where final good production is a constant elasticity of substitution aggregate between electricity and non-electricity inputs. In this case, energy and non-energy inputs are assumed to be moderate complements. The production function for dispatchable electric power generation is assumed to be a constant elasticity of substitution aggregate of unabated fossil fuel and carbon capture fossil fuel power generation.[12]

3.3 Data

Calibration of the model requires choosing key parameters such as the relative price of energy capital, the productivity of energy capital, and the parameters in the variable elasticity of substitution

[12]It would be natural to assume perfect substitutability, but most decarbonization scenarios rely on a mix of carbon-capture technologies and unabated fossil energy that serves as backup generation.

production function. To do this, we draw on both historic electric power capacity and power generation data from the Energy Information Administration and projections from energy system modeling for how electric power generation is likely to evolve in a business-as-usual scenario and with a net zero target.

The capital stocks K_t^i for different types of energy capital and the productivity of these technologies are taken from historical data on electric power generation capacity and generation data from the Energy Information Administration. Figure 3 shows the evolution of the electric power capacity and generation since 2000 in the US. Capacity is a quantity measure of the capital stock K_t^i, representing the rated maximum output for by technology (measured in gigawatts); generation $E_t^i = G_i\left(K_t^i\right)$ is the electric power output over a year (measured in terawatt hours). Clean technologies like solar and wind differ from fossil technologies in that their share of generation lags their share in capacity. Capacity factors A_t^i are generally substantially higher for fossil power compared to wind and solar, with wind and solar logging capacity factors of 0.3 or 0.4.[13]

As the left-hand panel of Figure 3 shows, wind and solar capacity have grown markedly as share of installed capacity since 2000 and particularly in the last decade. Installed wind and solar capacity now exceeds that of coal, hydropower, and nuclear. However, as a share of power generation (shown in the right panel), the gains have been more modest, with wind power accounting for the bulk of increased non-hydro renewable power generation. Overall electricity production has remained flat since 2005. The clearest trend evident in this figure is the displacement of coal by natural gas, which accounts for much of the reduction in carbon dioxide emissions from the power generation sector since its peak in 2005.

Energy systems models are used to project the future evolution of electric power capacity and generation based on projections for electricity demand, technology costs, fuel costs, and policy. These energy systems models are also used to study the impact of policies like the Inflation Reduction Act and model power generation under a net zero emissions target. Figure 4 shows projected capacity and generation in a business-as-usual scenario and in a net zero scenario, drawing from six energy systems models.[14] The first bar in both panels shows US electric power capacity and generation in 2020 across four categories: clean (solar and wind), NG (natural gas), NG CCS (natural gas with carbon capture), Exo (all other - mostly legacy hydropower, nuclear, and coal). The remaining bars in each panel show projections for electric power capacity and generation across the six models in 2050 under a business-as-usual case.

Absent a net zero target, projected declines in cost ensure that solar and wind become a larger

[13]For example, a gigawatt of installed wind power could theoretically generate 8760 = 365 x 24 gigawatt hours (8.8 terawatt hours) of electric power over the course of a year with constant maximum wind speed and no downtime. Of course, in reality, wind speeds are variables and therefore realized power generation is closer to 3-4 terawatt hours.

[14]These energy systems models are drawn from the 5th National Climate Assessment and include prominent models from the RIO-REPEAT Net Zero America study and the EPRI's REGEN model used in Bistline, Mehrotra and Wolfram (2023) and Bistline et al. (2024).

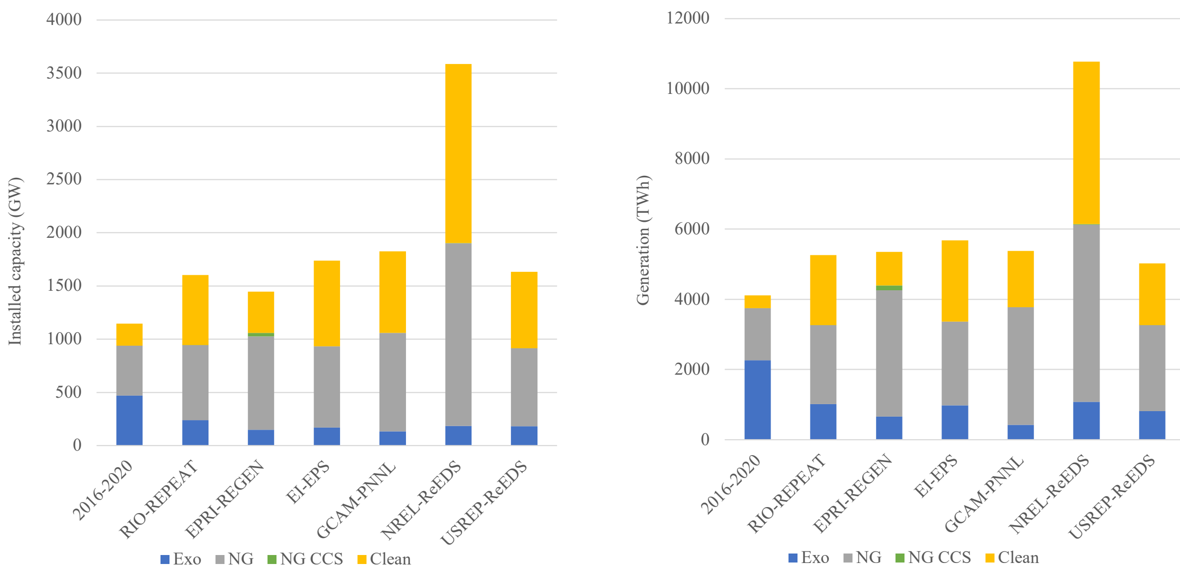

Figure 4: Business-as-usual projections for electric power capacity and generation

share of capacity and generation. However, natural gas still accounts for about 50% of power generation. Across models, projections see declines in legacy power generation (coal and nuclear) and see very little role for carbon capture and sequestration. The business-as-usual projections show large variations in both capacity and generation (relative to 2020 levels), with most modeling seeing a more than 40% increase in capacity and 30% increase in power generation. Differences in capacity and generation levels are driven by different assumptions about underlying electricity demand and pace of electrification of final energy use.

Capacity and generation are shown in the net zero scenarios in Figure 5. As before, the first bar shows capacity (or generation) in 2020 and the remaining bars show projections for 2050 for different models in a net zero scenario. Across models, capacity is projected to more than double relative to current levels by 2050 and generation is rises sharply as electrification boosts demand. As in the baseline model, natural gas capacity remains significant, with carbon capture playing a more role in both capacity and generation. As the generation figure shows, installed natural gas capacity is used less intensively than in the business-as-usual, with natural gas capacity serving as a backup for intermittent solar and wind power. Carbon capture also accounts for a significant share of generation in some models.

Finally, I assemble data on the current and projected costs of different power generation technology. Table 2 shows the current and projected capital cost of different types of generation technology. The table also shows the current and projected levelized cost of electricity for these different technologies. Levelized cost of electricity is a measure of the breakeven price of electricity needed to recoup the initial capital expenditure and fixed and variable costs, including fuel costs over the lifetime of a project. Table 2 is sorted from lowest to highest current levelized cost. Tech-

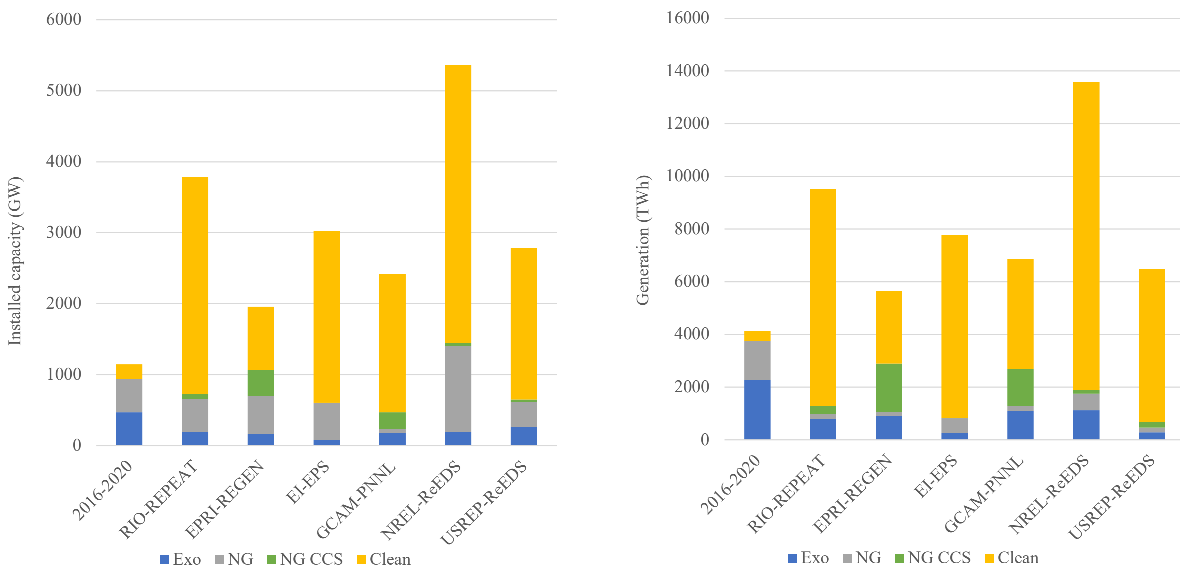

Figure 5: Net zero projections for electric power capacity and generation

nology cost data is obtained from the National Renewable Energy Laboratories (NREL) Annual Technology Baseline and are reported in constant 2023 dollars.[15]

As this table shows, wind and solar are the lowest cost current technologies while natural gas is lowest cost fossil technology. Capital costs and levelized cost are projected to fall across all technologies in 2050, with solar showing the biggest drop in capital cost. As noted earlier, other zero emissions dispatchable sources of power - hydropower, nuclear, and geothermal - are as or more expensive than the cheapest form of natural gas with carbon capture. Bioenergy with carbon capture is the most expensive option but, importantly for some net zero scenarios, is a negative emissions technology.

3.4 Calibration Strategy

The calibration strategy use historical data, technology cost projections, and energy systems modeling projections to calibrate the parameters of the quantitative model. Current and future technology costs shown in Table 2 are used to obtain paths for the relative price of energy capital p_t^i.[16] Time paths for energy capital productivity A_t^i can be taken directly from both historical and projected paths for installed capacity and generation.

[15]NREL Annual Technology Baseline is available from https://atb.nrel.gov/electricity/2023/technologies using default technologies and moderate assumption for cost reductions from learning-by-doing. Capital cost and levelized cost of electricity for bioenergy CCS obtained from Fajardy et al. (2020).

[16]Since fuel and other operating costs are not present in the model, capital cost in Table 2 is adjusted to include the net present value of fuel and other variable and fixed costs. This adjustment is akin to levelized cost of electricity but does not include an adjustment for capacity factor.

Technologies	Emissions	Levelized cost of electricity ($/MWh) 2023	2050	Capital cost ($2022/kW) 2023	2050
Wind	0	30	19	1447	924
Solar	0	39	18	1331	632
Natural Gas	+	48	42	1271	985
Hydro	0	78	75	3008	2887
Natural Gas CCS	0	83	66	2521	1630
Nuclear	0	87	73	8811	6668
Coal	+	112	99	3530	2824
Geothermal	0	128	77	12931	7334
Distributed solar	0	149	58	2842	1119
Biomass	0	157	145	5031	3871
Coal CCS	0	180	149	5960	4256
Bioenergy CCS	-	270	270	10000	10000

Table 2: Electric power generation, technology costs

The parameters ρ and α in the variable elasticity of substitution electric power production function are chosen to match the share of intermittent (clean) power generation in the business-as-usual scenarios from an range of energy systems models. Specifically, I use the equation below to estimate values of α and ρ to fit model projections of intermittent energy share, capital costs, and capacity factors:

$$\frac{p_f}{p_c} = \frac{A_f}{A_c}\frac{\alpha}{1-\alpha}\left(\frac{E_{int}}{E_{dis}} + \rho\right)$$

I rely on two modeling exercises. First, I use baseline capacity and generation projections from 11 energy systems models discussed in a recent multi-systems analysis of the energy market effects of the Inflation Reduction Act shown in Bistline et al. (2023). The baseline projections show the share of solar and wind power projected in 2035 absent any IRA subsidies. Second, I use business-as-usual projections shown in Figure 4 obtained from the Fifth National Climate Assessment. Given a vector of intermittent energy share and relative price of clean versus fossil energy, the two parameters in the variable elasticity of substitution power generation function are estimated by minimizing the sum of squared errors.

The remaining energy capital parameters are fairly standard. Fossil, clean and carbon capture capital are all assumed to depreciate over 40 years (i.e. $\delta_i = 0.025$). While this is at the longer end of assumed payback periods, a lower depreciation rate for energy capital is needed to match the share of aggregate investment in electric power generation in US data. The price of fossil capital is normalized to unity in the baseline, with 2020 prices of clean and carbon capture and 2050 prices of fossil, clean, and carbon capture expressed as relative to the 2020 price of fossil capital. The

	Baseline (2016-2020)	BAU (2050)	Net zero (2050)	CCS subsidy (2050)	Energy subsidy (2050)	No technological progress (2050)
	(1)	(2)	(3)	(4)	(5)	(6)
Aggregates:						
Output (% dev. from baseline)	0.00	0.12	0.02	0.22	0.12	-0.76
Consumption (% dev. from baseline)	0.00	0.17	0.08	0.18	0.13	-0.80
Investment rate (% of GDP)	0.1510	0.1506	0.1505	0.1513	0.1509	0.1513
Power generation:						
Elec. investment rate (% of GDP)	0.0060	0.0055	0.0055	0.0061	0.0062	0.0071
Fossil tech price (2020 = 100)	1.00	0.95	1.20	0.95	0.95	2.21
Clean tech price (rel. to 2020 fossil)	0.49	0.34	0.34	0.34	0.27	0.69
Tax/subsidy	-0.30		0.27	-0.22	-0.21	1.21
Electricity production	0.0	5.8	1.0	11.1	13.6	-25.8
Ratio of clean to fossil capital	0.2	1.2	4.9	3.9	4.9	3.6

Table 3: Steady state macro and energy outcomes

elasticity of substitution

The capital share and electricity share in the aggregate production function κ and ν are set to match non-energy investment share of GDP of 14.5% and an electric power expenditure share of GDP of 1.5%. The rate of time preference is set so that the real interest rate is 4 percent annually. The price of non-energy capital p_{ne} is normalized to unity. Capital adjustment costs γ_i are assumed to be symmetric for all types of capital and are set at $\gamma_i = 2$, consistent with business cycle estimates of quadratic capital adjustment costs (see, for example, Canzoneri et al. (2006)).

4 Results

In this section, I present the results from the full quantitative model that is calibrated to US electric power generation. This section shows how macroeconomic aggregates and electric power sector indicators change in a net zero scenario. For the US, net zero scenarios in 2050 shows small losses - less than 0.2% in consumption - relative to the reference case of no net zero emissions target.

4.1 Steady State

Table 3 shows the business as usual and net zero steady state under moderate complementarity between electricity and non-electricity inputs in final good production. The elasticity of substitution between electricity and non-electricity inputs is set at 0.5. As before, the top rows show output, consumption (expressed as percent deviations from the current period) and the investment rate while the bottom rows show measures of power sector investment and production. In the baseline period (column (1)), 18% of the energy capital stock is in clean technologies (solar and wind).

Column (2) shows the business as usual case. In this case, the price of both fossil and clean energy capital are expected to fall 5% and 31% relative to current levels. Both fall due to underlying declines in unsubsidized capital cost. The price decline in clean energy is mitigated since our calibration assumes that there is a 30% subsidy in the the baseline period to account for currently installed wind and solar energy. The decline in both fossil and clean capital prices imply higher electricity production (an 6% rise) and a slight decline in energy sector investment.[17] Higher energy production raises output and consumption by 12 and 17 basis points respectively.

Column (3) shows the net zero scenario. In this scenario, a tax on fossil capital is imposed such that the share of electric power generation from fossil capital equals the average of the six net zero model scenarios shown in the previous section.[18] A 27% tax on fossil capital is needed to achieve this level of generation from fossil capital; the required tax on fossil capital represents an effective carbon tax of $31 per ton in 2050.[19] The ratio of clean to fossil capital triples relative to the business as usual case and electric power generation rises by 1%.

Overall, the results in column (3) suggest very mild impacts in steady state from achieving net zero in electricity production. The difference in steady state output and consumption between the net zero and BAU case are just 10 and 9 basis points respectively. Even under the net zero scenario, consumption rises relative to current levels due to declines in the relative price of both clean and fossil capital. Lower fossil capital costs lower required investment in energy capital.

Columns (4) and (5) consider alternative scenarios in which unabated fossil use is mitigated through subsidies for carbon capture or subsidies for both carbon capture and clean energy. A roughly 20% subsidy to CCS is sufficient to reduce the fossil generation share to the net zero target. In column (5), the subsidy is chosen to ensure that output match the BAU case. By subsidizing CCS and clean energy capital, electric power production rises substantially in each case by 11 to 14%. The energy investment rate is also slightly higher than in the BAU or net zero scenarios. Output and consumption are higher in the subsidized case than in the net zero scenario but are comparable to the BAU case.

Column (6) considers the case of no technological progress between now and 2050; both capital costs and productivity in power generation are fixed at current levels. This case sees the largest drops in output, consumption, and electricity production. Absent technological progress, a substantial tax on fossil capital is required to induce switching to clean energy capital and carbon capture technologies. The implied carbon tax required is $170 per ton and price of natural gas (including the tax) rises from $2.50 per MMBtu to $11.50 per MMBtu. Electricity production becomes substantially more expensive and falls by almost a quarter relative to the current period. This drop

[17]If electricity and non-electricity inputs are complements, a lower relative price for energy capital lowers the investment share and vice versa.

[18]Importantly, fossil capital also includes legacy nuclear and hydropower that continue to provide dispatchable zero-carbon power generation across the six energy systems models considered in the previous section.

[19]The levelized cost of electricity for natural gas is $42 per MWh and assumes a price of natural gas of $2.50 per MMBtu. The carbon dioxide emission coefficient for natural gas is 52.9 kg/MMBtu.

	Baseline (2016-2020)	BAU (2050)	Net zero (2050)	CCS subsidy (2050)	Energy subsidy (2050)	No technological progress (2050)
	(1)	(2)	(3)	(4)	(5)	(6)
Aggregates:						
Output (% dev. from baseline)	0.00	0.21	0.04	0.39	0.21	-1.09
Consumption (% dev. from baseline)	0.00	0.24	0.09	0.30	0.20	-1.01
Investment rate (% of GDP)	0.1510	0.1510	0.1510	0.1510	0.1510	0.1510
Power generation:						
Elec. investment rate (% of GDP)	0.0060	0.0060	0.0060	0.0060	0.0060	0.0060
Fossil tech price (2020 = 100)	1.00	0.95	1.20	0.95	0.95	2.21
Clean tech price (rel. to 2020 fossil)	0.49	0.34	0.34	0.34	0.27	0.69
Tax/subsidy	-0.30		0.27	-0.22	-0.21	1.21
Electricity production	0.0	11.9	2.0	23.4	28.4	-44.7
Ratio of clean to fossil capital	0.2	1.2	4.9	3.9	4.8	3.6

Table 4: Steady state macro and energy outcomes, with Cobb-Douglas production

in electricity production reduces output and consumption by about 70 basis points. Compared to the BAU case, the drop in output and consumption is close to 1 percentage point. This case underscores how expected cost reductions in both clean and carbon capture technologies substantially mitigate the macroeconomic cost of achieving net zero.

It should be noted that the modest macroeconomic cost, even in the most pessimistic case of no technological progress and with moderate complementarity, is due to small share of electric power investment relative to total investment or GDP. The carbon tax required to achieve the net zero target is large, particularly in the case no technological progress. Moreover, energy investment in steady state increases 20%. However, this additional investment remains small and subtracts only modestly from household consumption.

Table 4 shows a comparison of steady states from the 2016-2020 current period to 2050 with and without a transition to net zero emissions under the assumption of Cobb-Douglas final good production.Golosov et al. (2014) argue that energy shares are fairly constant over time and, therefore, the elasticity of substitution over a moderate time horizon is unity for energy versus non-energy inputs. In this case, the investment share in electric power generation is constant as relative price changes are offset by proportional changes in quantities. In the BAU case, output and consumption rises 0.2% relative to its 2020 level due to projected price declines in both clean and fossil technology costs. Electricity production rises by 12% and the ratio of clean capacity to fossil capacity rises from 0.2 to 1.2; the change in ratios of clean to fossil production is the same as the base case of moderate complementarity.

Column (3) shows the net zero scenario calibrated using the average net zero pathway. The fossil energy tax needed to drive the capacity share of fossil to its net zero level is the same as in the Cobb-Douglas case (i.e. 27%), as capacity and generation shares are independent of assumptions on final good production. On net, electricity production rises because of the price decline in clean

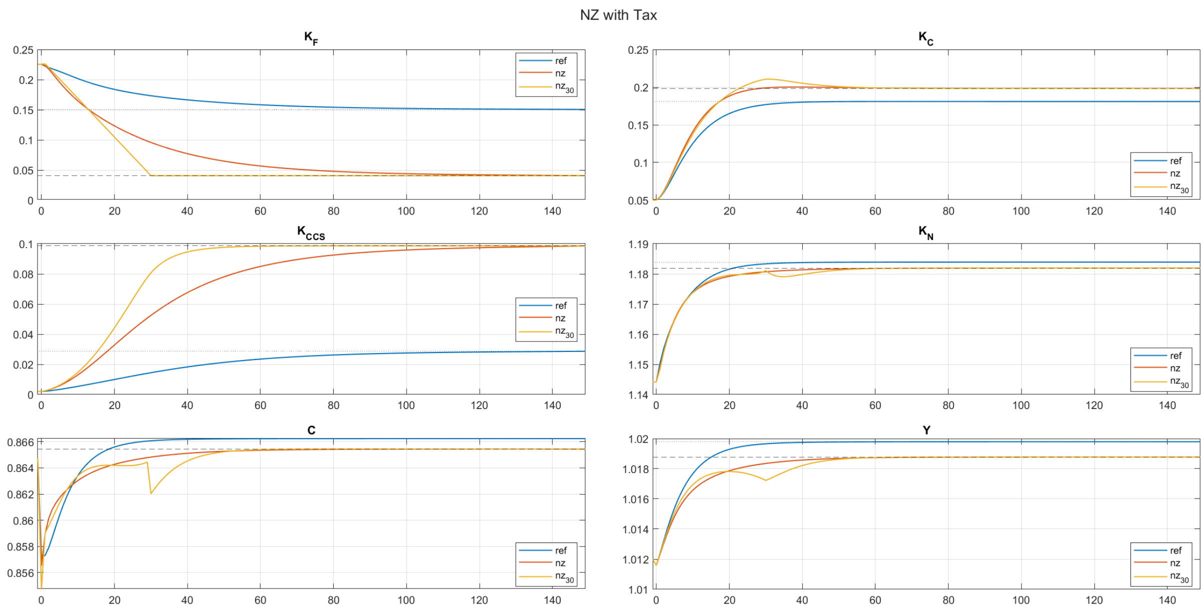

Figure 6: Transition path to net zero

energy capital. Under Cobb-Douglas, electricity production rises 2% (as opposed to only 1% under moderate complementarity), and output rises by 4 basis points. Consumption rises by 9 basis points, similar to the consumption increase under moderate complementarity.

Columns (4) and (5) show the impact of policies with subsides to carbon capture or subsidies to both clean energy and carbon capture. Electricity production rises 23% and 28% respectively with Cobb-Douglas production, roughly double the increase from the case of complementarity. Output and consumption also rise by larger magnitudes, as non-energy inputs are more elastic. A reduction in the price of energy thereby increases the non-energy capital stock, raising output and consumption.

Lastly, column (6) looks at the case of no technological progress. The large increase in the fossil capital tax results in a 40% decline in electric power generation. Reductions in output and consumption exceed 1 percentage point relative to 2020 levels; output and consumption are 1.2 percentage points lower than the BAU case.

4.2 Transition Path

Figure 6 shows the transition path of the economy in the net zero scenario. The orange line shows the transition path for a carbon tax that rises to its steady state level over 30 years. Energy and non-energy inputs are moderate complements, and the x-axis shows time in years. Technology prices drop smoothly over the first 30 periods and clean energy productivity improves over the same time horizon.

The path of clean energy capital is similar in both the baseline and net zero scenario. The

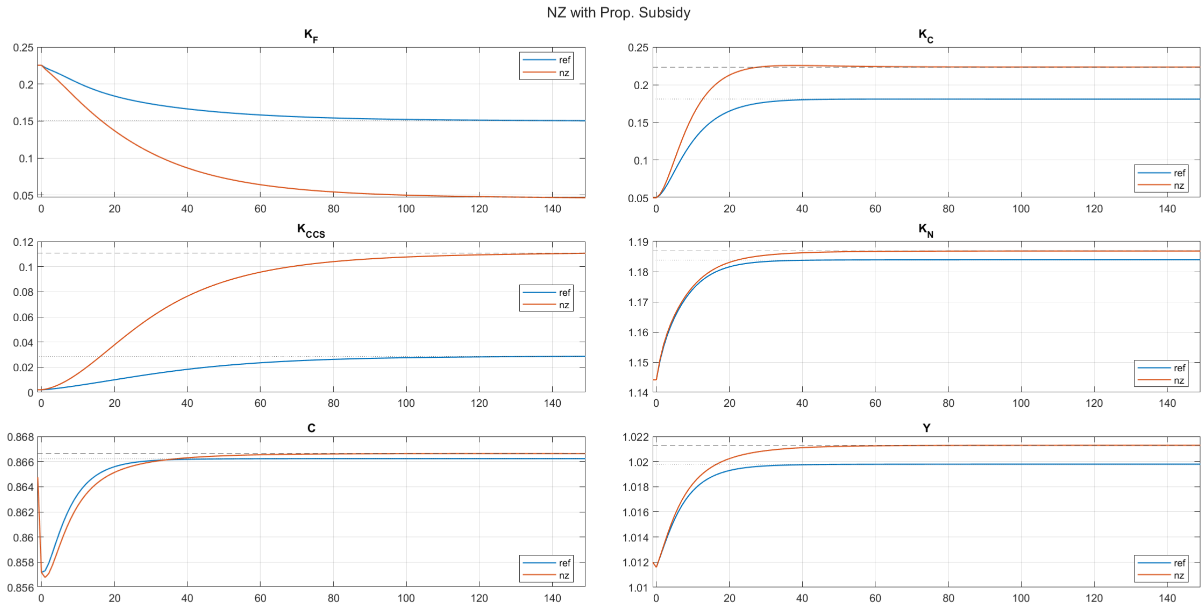

Figure 7: Transition path to net zero with subsidy

biggest differences across the baseline and net zero scenarios are in the evolution of unabated fossil capital versus carbon capture capital. The level of fossil capital falls sharply in the net zero scenario but also falls in the BAU case. Given adjustment costs, fossil and carbon capture capital stocks are still somewhat above (below) their steady state values. Consumption falls initially and gradually rises under both transition paths, with the difference in the consumption paths largely driven by long-run (steady state) differences. The dynamics for output and non-energy capital are similar.

The yellow lines displays the transition path under a more aggressive carbon tax that ramps up towards the net zero date. This more aggressive carbon tax path is chosen to ensure that the fossil capital stock converges to its net zero value in 30 years. Relative to the transition under the less aggressive carbon tax, the transitions are faster for both carbon capture and clean energy capital, with the latter overshooting its long-run steady state value. The transition paths for consumption, output and non-energy capital are more volatile but the fluctuations are small relative to long-run differences.

For each transition path, I compute the Lucas consumption-equivalent welfare cost. The consumption cost of the gradual net zero transition (orange line) is just 4 basis points of steady-state BAU consumption and just 8 basis points for the net zero transition that attains the 2050 target (yellow target). The welfare cost is lower than what is shown in Tables 3 and 4 due to discounting; the consumption cost of getting to net zero is largely dominated by the long-run differences in consumption between net zero and BAU that are only realized in the future.

Figure 7 shows the transition path to net zero under a subsidy for carbon capture technologies.

The transition path for energy capital is broadly similar to the transition under a carbon tax. Fossil capital falls smoothly towards its steady state value with carbon capture (or, more generally, clean firm) capital replacing it. Clean energy capital rises more quickly, with the transition to its new steady state values largely completed by the net zero date. Output and consumption rise in the net zero case in the long-run due to the subsidy, however consumption is lower over much of the intermediate transition (relative to the BAU case). Indeed, the Lucas consumption cost under the subsidy is 5 basis points of steady-state BAU consumption, higher than under a carbon tax. This verifies quantitatively the finding in Bistline, Mehrotra and Wolfram (2023) that a carbon tax is generically preferred to a clean energy subsidy absent learning-by-doing or innovation externalities.

It is worth emphasizing that at these consumption costs, decarbonization of electricity production may pass the cost-benefit test simply on based on conventional (non-greenhouse gas) air pollution abatement. Studies estimate that coal-fired air pollution in the US results in premature mortality of approximately 1600 persons per year as of 2021.[20] With a conventional value of statistical life of $1-$10 million, electric-sector decarbonization saves $1.6 - $16 billion per year, or about 1-10 basis points of current US consumption.

5 Conclusion

In this paper, I analyze the macroeconomic consequences of achieving net zero greenhouse gas emissions. I introduce a simple analytical model to consider the long-run (steady state) and transitional dynamics of a net zero emissions target. Through the lens of this simple model, the macroeconomic cost of achieving net zero emissions is function of technology costs between clean and fossil fuel capital. The reduction in consumption in the long-run can be decomposed into a component from higher energy prices leading to lower output and higher required investment in more costly capital. The model provides an upper bound for the steady state cost of attaining net zero that is proportional to the energy investment share of GDP and the cost premium of the decarbonized technology relative to the fossil technology.

The transition path for consumption and investment in a net zero scenario can also be characterized. The announcement of a net zero target date operates as a combination of a negative technology shock and a negative capital shock. Both of these shocks mean that consumption must decrease up to the net zero date, implying a decline in the real interest rate along the transition path. Importantly this decline in consumption occurs alongside an *increase* in investment. As a result, the natural rate of interest generically falls during the energy transition in contrast

[20] Overall air pollution in the US from all sources is estimated to result in excess mortality of 50,000 to 100,000 persons per year. Economywide decarbonization would carry potentially much greater benefits by reducing (though not eliminating) transportation based emissions and indoor air pollution effects from burning natural gas.

to conventional wisdom. Since a net zero transition is both an anticipated negative technology shock and an anticipated negative capital shock, the net zero transition is a negative aggregate demand shock. In the presence of price rigidities and imperfect stabilization, these negative demand shocks would lower output and employment.

To quantify the cost of decarbonizing electric power generation in the US, power generation is modeled via a variable elasticity of substitution production function between intermittent (clean) and dispatchable (fossil or other ”clean-firm”) power generation. The power generation model is calibrated using a range of scenarios for US electric power capacity and generation from energy systems modeling and estimates of current and future technology costs.

I find that, in a net zero scenario, consumption falls by less than 0.1% relative to the scenario of no net zero target. Output declines and consumption declines are larger to the extent that energy and non-energy inputs are Cobb-Douglas instead of moderate complements. These costs suggest that electric sector decarbonization may be beneficial even just considering conventional air pollution abatement and ignoring climate change. The largest macroeconomic costs occur in scenarios where lower capital costs for solar, wind and CCS do not materialize, but even in this scenario that macroeconomic cost of net zero in electricity production is comparatively modest, despite a relatively high carbon tax needed to attain net zero.

Future work will broaden the quantitative model to take into account decarbonization in transportation and buildings, which, alongside power generation, account for over 60% of US greenhouse gas emissions. A preliminary analysis based on investment shares and technology costs suggest that the cost of decarbonization in these sectors may actually be *negative*. Lifecycle costs for light-duty electric vehicles, space and water heating are already comparable to that of fossil fuel incumbents and expected to continue to fall. The intrinsic efficiency gains of electric motors and heat pumps will also lower primary energy demand. Capital lifetimes are also shorter than those for power generation lowering the likelihood of stranded capital.

Technology costs, particularly for dispatchable clean power, are particularly important for the long-term macroeconomic costs of net zero emissions. How quickly learning-by-doing can drive down costs for these technologies is an open question. Solar and wind power have seen impressive cost declines in recent decades, and the costs, speed of transition, and nature of optimal climate policy hinge on how strong these learning effects are for nascent technologies like carbon capture, batteries and other long duration storage.

Lastly, future work should also focus on open economy considerations for the net zero transition. The framework developed here could be applied to other countries or regions where the capital and industry mix and underlying technology costs may be different and can inform efforts to speed up decarbonization efforts outside of advanced economies. Decarbonization in advanced economies may have significant ramifications for global prices for oil, natural gas and coal (see, for example, Bistline et al. (2024)). Major fossil fuel exporters like the US and Australia may seek to limit fossil fuel exports to lower global emissions. Lower demand for fossil fuels in Europe and China could increase fossil fuel demand elsewhere and mitigate emissions reductions in those regions. Incentives to decarbonize globally could be at odds with developing country aims of industrializing and growing their manufacturing base.

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