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THE SENSITIVITY OF CO_2 EMISSIONS UNDER A CARBON TAX TO ALTERNATIVE BASELINE FORECASTS

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Future carbon dioxide (CO_2) emissions under a carbon tax depend on the time-path of the economy under baseline (business-as-usual) conditions as well as the extent to which the policy reduces emissions relative to the baseline. Considerable uncertainties surround the baseline forecasts for fuel prices, energy efficiency (energy-GDP ratios), and GDP, as evidenced by the significant ranges in the forecasts by government agencies and research institutions in the U.S. This paper assesses the significance of these uncertainties to the path of CO_2 emissions under a carbon tax. We do this by examining the emissions levels and quantities of abatement that result from the E3 general equilibrium model under a range of alternative baseline forecasts for fuel prices, energy efficiency, and GDP, where the different baselines are produced through suitable changes to key model parameters. In addition, we consider how the time-profile of the carbon tax needed to achieve specified CO_2 abatement targets is affected by such forecast-linked changes in parameters.

We find that the sensitivity of baseline emissions to alternative forecasts depends on the particular forecasted variable under consideration. Baseline CO_2 emissions are highly sensitive to alternative scenarios related to the rate of energy efficiency improvements in the nonenergy sector and the rate of general economic growth. In contrast, such emissions are much less sensitive to alternative scenarios related to the productivity of fossil fuel production. The extent of abatement from the baseline is generally fairly insensitive to changes in the scenarios for time-paths of fuel prices, energy-efficiency and GDP. We also find that short-term emissions targets can be achieved with relatively moderate carbon taxes under all of the baseline scenarios considered.

Keywords: Carbon tax; CGE modeling; emissions sensitivity; climate.

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1. Introduction

Future carbon dioxide (CO_2) emissions under a carbon tax depend on the time-path of the economy under baseline (business-as-usual) conditions as well as the extent to which the policy reduces emissions relative to the baseline. What is referred to as the baseline is multi-dimensional, including business-as-usual forecasts of oil prices, natural gas prices, renewables costs, energy efficiency (energy-GDP ratios), GDP, and other economic variables.

There is a great deal of uncertainty about each of these forecast elements. For example, long-run fossil fuel price forecasts by the US Energy Information Administration's (EIA) Annual Energy vary considerably. In AEO 2016, natural gas prices were predicted to grow at an annual rate of 1.4% from 2015–2040 under the central case forecasts; yet under the high oil and gas resource case, natural gas prices were forecast to fall at an annual rate of 0.3% over the same timeframe. Moreover, in AEO 2017 the EIA predicted natural gas prices to rise at an annual rate of 1.6% through 2040 under the revised central case forecast and rise (not fall) at an annual rate of 0.5% under the high oil and gas resource scenario.

A key objective of EMF32 is to evaluate how CO_2 emissions paths and economic outcomes vary across different types of models. By comparing results for a given policy across a range of models, the EMF effort yields important information about the implications of the differing structural assumptions across models. In particular, the range of results generated by the different models provides a sense of the magnitude of uncertainty in the impacts of given policies.

However, EMF studies generally do not consider the implications of uncertainties in baseline forecasts to model results. Even if the various models were to generate very similar impacts of a given policy under their central-case parameters, there would be considerable uncertainty about those impacts if the confidence intervals for the parameters were quite wide.

This paper assesses the significance of uncertainties in baseline forecasts to the path of CO_2 emissions under a carbon tax. We do this by altering model parameters in order to generate a range of baseline forecasts, and observing the impacts of a carbon tax imposed under these alternative conditions. In particular, we consider baselines that differ according to the projected time-profiles of the prices of oil, natural gas, and non-fossil energy, and of energy-GDP ratios and GDP. We achieve each of these alternative baseline time-paths by altering model parameters that are significant determinants of the baseline variable of interest.[1]

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[1] For example, to achieve alternative time-paths of natural gas prices, we alter the time-path for the parameter in the model that determines the productivity of the natural gas production function. It may be noted that for any given dimension of a baseline (e.g., the time-path of natural gas prices), the time-path is determined in general equilibrium and thus cannot be entirely attributed to any single parameter in model. In order to alter these time-paths, we focus on the model parameters that seem to be especially significant determinants of the baseline element in question.

We find that the sensitivity of baseline emissions to alternative forecasts depends on the particular forecasted variable under consideration. Baseline CO_2 emissions are highly sensitive to alternative scenarios as to the rate of energy efficiency improvements in the nonenergy sector and the rate of general economic growth. In contrast, such emissions are much less sensitive to alternative scenarios regarding the productivity of fossil fuel production. The extent of abatement from the baseline is generally fairly insensitive to changes in the scenarios for time-paths of fuel prices, energy-efficiency and GDP.

After the historic Paris Agreement in 2015, the Obama administration announced a greenhouse gas target for 2025: 26–28% below 2005 levels. After the announcement, there was tremendous interest in determining the costs of meeting these targets through alternative mechanisms.[2] This motivates the second main focus of our paper. In addition to comparing the impacts of a given carbon tax under alternative baselines, we examine what different baselines imply about the carbon taxes needed to achieve specified CO_2 abatement targets. This component of the paper extends prior work by Chen and Hafstead (2016), which evaluated the carbon tax paths required to meet the targets to which the U.S. had pledged under the historic 2015 Paris agreement. In the present paper, we find that the 2025 emissions targets can be achieved through relatively modest carbon taxes across a fairly wide range of forecast assumptions.

To address the implications about uncertainties about baselines for future CO_2 emissions, this paper applies the Goulder–Hafstead environment-energy-economy (E3) model. We decompose carbon tax emissions into baseline emissions and abatement. Let emissions in year t under a carbon tax policy be denoted by e_t^p. These emissions are a function of baseline (or reference case) emissions, e_t^r, and abatement, a_t, expressed as the change in emissions as a percent of baseline emissions: $e_t^p = (1 + a_t)e_t^r$.[3] We consider the sensitivity of baseline emissions, as well as the extent of abatement from the baseline, to the various changes in model parameters associated with alternative assumptions about baseline variables such as fuel prices or GDP growth.

Our analysis contributes to the literature by identifying the sensitivity of carbon tax impacts to alternative assumptions about baseline time-paths. By identifying, in particular, the baseline assumptions that have especially large implications for emissions, this work can help indicate what sorts of future research aimed to reduce uncertainties might be especially valuable. In addition, this paper helps broaden our understanding of the carbon taxes needed to achieve target emissions reductions by identifying the needed tax levels under a range of assumptions about important baseline variables.[4]

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[2] In June 2017, President Trump indicated that the U.S. would pull out of the Paris Agreement, claiming that emissions reductions would involve very high costs to the economy. Nevertheless, there remains significant interest in determining the level of economic impact associated with emissions reductions consistent with the U.S. target.

[3] We use the term abatement to refer to the percent change in emissions relative to baseline. When a reduction in emissions occurs, abatement a will be negative. This is slightly different from an alternative, and more common, definition of abatement in which abatement is positive when emissions reductions occur (-1*a).

[4] Our analysis cannot suggest optimal mechanisms to narrow emissions uncertainty. See Hafstead *et al.* (2017) for a discussion on mechanisms to add emissions certainty to a carbon tax.

The rest of the paper is organized as follows. Section 2 briefly describes the E3 model, including its key features and parameters. We then describe how baseline forecasts for fossil fuel prices, renewable costs, energy efficiency, and GDP growth are introduced into the model. In Sec. 3, we evaluate the emissions paths under a carbon tax under a range of baseline forecasts and key model parameters, decompose emissions sensitivity to determine the source of the sensitivity, and solve for tax levels to meet the Obama era 2025 emissions targets. In Sec. 4, we offer key takeaways and suggestions for future research.

2. Model Overview

The E3 model is a dynamic multi-sector model of the US economy with international trade. A collection of representative forward-looking agents — 35 distinct domestic industries, a foreign industry, domestic and foreign households, and domestic and foreign governments — interact to supply and demand commodities and factors. The model solves for intertemporal equilibrium prices for each period such that factor and commodity supply and demands equate each period and agents' expectations of future prices match realized prices (perfect foresight expectations). The benchmark period for the model is 2013 and the length of each period is one year. In both the business-as-usual reference case and the policy cases, we jointly solve for the new steady state balanced growth path and the transition over 151 years to the new steady state path. For the purposes of the EMF32 exercise, we primarily focus on results through either 2040 or 2050.

Two key features distinguish the E3 model from (most) other CGE models. First, we combine a detailed description of domestic energy supply and demand with a detailed treatment of the US tax system to allow for a careful examination of the interactions between climate and fiscal policies. These interactions fundamentally shape the economic impacts of carbon taxation. Second, the model introduces capital adjustment costs to consider the dynamics of investment and disinvestment in physical capital. These costs critically affect both the pace of the transition and the size of stranded assets across industries.[5]

2.1. *General description of the E3 model*

The E3 model is fully documented in Goulder and Hafstead (2017). Here, we offer a general overview of the model with a focus on key model parameters and indicate how we introduce baseline forecasts of fossil fuel prices, renewable costs, energy efficiency, and GDP growth into the E3 model to match AEO 2016 emissions forecasts.

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[5] Other CGE models may also include some or all of these details. For example, the G-Cubed model (see McKibbinen and Wilcoxen, 2013) includes energy sector disaggregation, sector-specific adjustment costs, and a relatively detailed tax system. However, that model also fixes long-run labor supply and assumes an *ad-hoc* liquidity constraint in the short run, elements that are not included in the E3 model.

2.1.1. *Producer behavior*

Production is divided into 35 industry groups, with a focus on energy supply and demand. Primary fuel producers — crude oil extraction, natural gas extraction, and coal mining — supply fuels to both secondary energy producers — electricity generators, natural gas distributors, and petroleum refineries — and other industries. Electricity, natural gas, and petroleum products are then sold to domestic and foreign industries, households, and governments. While the E3 model does not include a bottom-up engineering approach to electricity modeling, the top-down structure approximates more detailed electricity model by introducing three types of generators: coal-fired generators, other fossil generators (primarily natural gas-fired generation), and nonfossil (or renewable) generators. The electric transmission and distribution utility purchases electricity from the three wholesale generators and distributes retail electricity to the final electricity consumers (industries, household, government). Table 1 lists the 35 industries along with the value of output and energy inputs for each industry.

A representative firm in each industry combines variable inputs — labor, energy, and materials — and capital stocks — structures and equipment/intellectual property products — to produce a distinct output. Figure 1 displays the nested production structure. At each node, a constant returns to scale constant-elasticity-of-substitution (CES) function creates a composite of the inputs immediately below that node. The CES functions generally take the following form:

$$X = \gamma^{\frac{1}{\rho}} \left[\sum_{i=1}^{n} \alpha_i x_i^{\rho} \right]^{\frac{1}{\rho}}, \tag{1}$$

where γ represents a scale parameter, α_i represent share parameters (such that $\sum_{i=1}^{n} \alpha_i = 1$) and ρ is a translation on the elasticity of substitution $\sigma : \rho = \frac{\sigma-1}{\sigma}$. Given the elasticity of substitution, the γ and α parameters are calibrated to be consistent with benchmark data inputs. As explained in Sec. 2.2, we will alter these parameters over time in key industries and nodes to match key AEO 2016 forecasts.

At the bottom of the nest, industry-specific commodities $E_1 \ldots E_{N_e}$ and $M_1 \ldots M_{N_m}$ are created by aggregating the good produced by the domestic industry and the good produced by its foreign counterpart. The elasticities of substitution at this level are derived from Armington trade elasticities estimated by Feenstra *et al.* (2014). At the next level, the industry-specific energy and material commodities are aggregated into energy and material composites, $E = e(E_1 \ldots E_{N_e})$ and $M = m(M_1 \ldots M_{N_m})$. With a few exceptions, the industry-specific elasticities of substitution across energy goods and material goods are derived from trans-log price elasticities estimated by Jorgenson *et al.* (2013) and converted into CES elasticities.[6] The exceptions are the electricity industries.

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[6] The authors are grateful to Peter J. Wilcoxen for providing the price elasticities from Jorgenson *et al.* (2013) and for providing an algorithm for converting the trans-log price elasticities into CES elasticities.

Table 1. Benchmark output and energy inputs by industry.

Industry	Output[a]	Pct of total output (%)	Energy input[b]	Pct of output (%)
Oil extraction	264.6	1.0	8.6	3.2
Natural gas Extraction	110.5	0.4	2.9	2.7
Coal mining	40.5	0.2	2.5	6.1
Electric transmission and distribution	358.9	1.4	200.0	55.7
Coal-fired electricity generation	69.5	0.3	22.0	31.6
Other fossil electricity generation	64.3	0.3	35.7	55.6
Nonfossil electricity generation	53.4	0.2	0.1	0.1
Natural gas distribution	125.7	0.5	46.8	37.2
Petroleum refining	691.8	2.7	560.9	81.1
Pipeline transportation	38.8	0.2	3.1	8.0
Mining support activities	217.7	0.9	6.8	3.1
Other mining	47.4	0.2	5.9	12.5
Farms, Forestry, Fishing	423.5	1.7	25.1	5.9
Water utilities	77.1	0.3	1.7	2.2
Construction	1512.0	5.9	61.4	4.1
Wood products	94.4	0.4	2.9	3.1
Nonmetallic mineral products	106.1	0.4	6.4	6.0
Primary metals	287.7	1.1	18.7	6.5
Fabricated metal products	339.0	1.3	7.2	2.1
Machinery and Misc. manufacturing	1372.1	5.4	13.1	1.0
Motor vehicles	584.6	2.3	4.4	0.8
Food and beverage	773.1	3.0	12.7	1.6
Textile, apparel, leather	84.2	0.3	1.5	1.7
Paper and printing	227.0	0.9	11.9	5.3
Chemicals, plastics, and rubber	992.4	3.9	63.1	6.4
Trade	2384.8	9.4	34.3	1.4
Air transportation	157.1	0.6	35.3	22.5
Railroad transportation	99.7	0.4	6.5	6.5
Water transportation	50.6	0.2	9.3	18.4
Truck transportation	284.1	1.1	49.4	17.4
Transit and ground passenger transportation	55.9	0.2	5.3	9.5
Other transportation and warehousing	287.1	1.1	16.0	5.6
Communication and information	1143.1	4.5	4.9	0.4
Services	9641.5	37.9	112.4	1.2
Real estate and owner-occupied housing	2364.8	9.3	92.10	3.9
Total	25425.1	100.0	1490.8	5.9

Notes: [a]In billions of 2013 dollars. [b]In billions of 2013 dollars. Energy inputs include fossil fuels, electric power sectors, natural gas distribution and petroleum refining.

To prevent unrealistic shifts in inputs, we impose very low (0.2) elasticities for generation industries. For the electric utility industry, we choose an elasticity of 3 to mimic changes, on average, in generation from the bottom-up electricity model Haiku from Resources for the Future. The energy and material composites are aggregated into an intermediate input composite, $h(E, M)$, and the intermediate input composite is aggregated with labor to

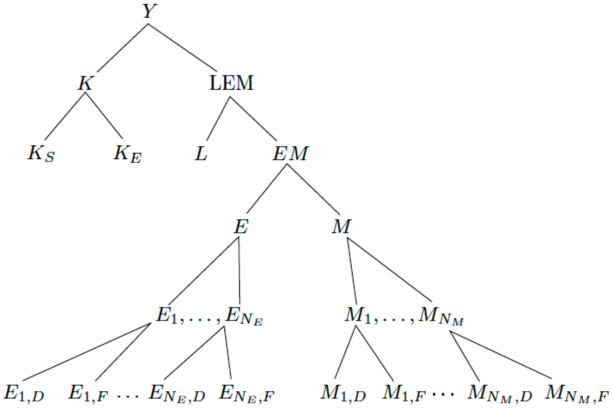

Figure 1. Diagram of the E3 nested production function

create the variable input composite, $g(L, h(E, M))$. Elasticities at these nodes are derived from Jorgenson *et al.* (1996). At each nest, the producers choose inputs to minimize the unit cost of each composite.

Let $\bar{g} = g(L, h(E, M))$ denote the level of the variable input composite. At the top of the production nest, capital (a composite of structure fixed assets K^s and equipment/intellectual property product fixed assets K^e) is combined with the variable input composite to create gross output, X:

$$X = f(k(K^s, K^e), \bar{g}). \tag{2}$$

Capital adjustment costs are modeled as lost output associated with the process of installing (or uninstalling) new capital. Net output, Y, is equal to gross output less the cost of capital adjustments,

$$Y = X - \phi^s(I^s/K^s) \bullet I^s - \phi^e(I^e/K^e) \bullet I^e, \tag{3}$$

where $\phi(I/K)$ is a convex function of the rate of investment,

$$\phi(I/K) = \frac{(\xi/2)(I/K - \delta)}{I/K}. \tag{4}$$

The parameter δ represents economic depreciation of the capital stock and ξ is the adjustment cost parameter. This key adjustment cost parameter determines the slope of the supply curve in each industry in the short-run by preventing large investment or disinvestment in each period. Few studies estimate industry-level adjustment costs. Earlier studies such as Summers (1981) found large aggregate adjustment costs (around 20) and more recent studies such as Hall (2004) suggest aggregate adjustment costs are negligible. Cooper and Haltiwanger (2006) also found small convex firm-level adjustment costs (around 1).[7] We choose a

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[7] Cooper and Haltiwanger (2006) also found evidence for nonconvex firm-level adjustment costs to explain within industry investment heterogeneity. However, within firm-level heterogeneity is beyond the scope of the E3 model and therefore we utilize convex adjustment costs to proxy for all forms of industry-level adjustment costs.

compromise value of 7 for the industry-level adjustment cost parameter across all industries and types of capital.

The treatment of firms' financial decisions is richer in E3 than in other environmental CGE models. Investments are both debt and equity financed. Firms are required to hold a constant level of debt, relative to their capital stock, and pay interest payments to the owners of the debt (the household). Owners of firm equity (also the household) receive dividends, a constant fraction of after-tax profits, and capital gains, both realized and unrealized, in return for owning equity.[8] A no-arbitrage condition requires that firms offer an after-tax rate of return on equity comparable to the after-tax rate of return on owning private or public debt. We apply a marginal corporate tax rate on firm profits of 40%, with adjustments allowed for property taxes, interest payments, and investment deductions.[9] Firm managers, subject to the financing constraints, choose variable inputs and capital investment to maximize the value of the firm. See Goulder and Hafstead (2017) for a complete derivation of the firm problem.

Technological progress is in the form of labor-augmenting Harrod-neutral technological change. Thus, the effective hours worked are actual hours worked adjusted for annual productivity gains. For the EMF32 study, we assume an annual rate of increase of 2% such that all variables, including GDP, grow at 2% per year on the balanced growth path.[10] This rate of growth in labor productivity applies to all industries equally, though as explained in Sec. 2.3, we also introduce exogenous technological change in total factor productivity in certain energy industries to reflect differential growth (and changes in relative prices) in these sectors over time.[11]

Carbon dioxide emissions are linked to the purchase of crude oil, natural gas, and coal as intermediate inputs into production. This accounting method assigns emissions to the purchaser of fossil fuels (e.g., generators or petroleum refiners) even if actual emissions in the real economy occur further downstream (e.g., refined petroleum products such as gasoline and diesel). Fixed carbon coefficients convert the quantity of fuels purchased into emissions and are calibrated to match EIA energy-related carbon dioxide emissions by fuel and source in the benchmark year. Emissions are adjusted to account for downstream products that are imported or exported. The E3 model also implements carbon taxes as taxes on the input of fossil fuels (domestic or foreign) into production and tariffs are (optionally) imposed on the import of downstream products whose consumption leads to domestic CO_2 emissions (e.g., gasoline). Firms may

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[8] Marginal tax rates on dividend income, capital gains, and interest income are average marginal federal and state tax rates on each income source. We obtain rates from NBER's TAXSIM database.

[9] Following the rules of the General Depreciation System (GDS), firms are allowed to deduct investment expenditures on structures over 39 years and investment expenditures on equipment over 7 years.

[10] The model does not include population growth; hence technological progress is the sole source of growth in the economy over time.

[11] McKibbin *et al.* (2009) show that differences in long-run technological progress across industries can change the impact of a carbon tax. This is in keeping with the fact that these differences imply changes in relative prices over time. Differences in long-run technological growth across industries is beyond the scope of this paper.

respond to carbon taxes in a number of manners, including shifts away from fossil fuel inputs (or energy inputs more generally). Carbon-intensive firms may decrease investment and carbon-free firms may increase investment. Investment behavior may change further if cuts to capital taxes, which affect firm value, are included in the carbon policy.

2.1.2. *Consumer behavior*

The E3 model utilizes a representative household to capture consumer behavior and captures several aspects of consumer choice that may be relevant to climate policy: a labor-leisure choice, the choice between current consumption and saving for future consumption, and the allocation consumption expenditure across various goods and services. Here, we briefly describe the household's utility function and the key parameters that determine its optimal choices of consumption, labor supply, and savings.

The representative household chooses full consumption and savings to maximize expected lifetime utility,

$$U_t = \sum_{s=t}^{\infty} \beta^{s-t} \frac{1}{1-\sigma} C_s^{1-\sigma}, \tag{5}$$

where β represents the discount factor and σ is the coefficient of relative risk aversion. With this functional form, σ also represents the inverse of the intertemporal elasticity of substitution in consumption. The discount factor is calibrated to be consistent with the steady state growth rate (induced from the Harrod-neutral technological change assumption) and the coefficient of relative risk aversion is 2 (which implies an intertemporal elasticity of substitution of 0.5). Full consumption is a composite of a consumption bundle $\bar{C}$ and leisure ℓ:

$$C = \left[\bar{C}^{\frac{\eta-1}{\eta}} + \alpha_\ell^{\frac{1}{\eta}} \ell^{\frac{\eta-1}{\eta}}\right]^{\frac{\eta}{\eta-1}}. \tag{6}$$

The elasticity of substitution parameter η and the leisure preference parameter α_ℓ are calibrated such that the implicit compensated elasticity of labor supply is 0.3 and the uncompensated elasticity of labor supply is 0.1.

The consumption bundle is a nested consumption composite of 24 consumer goods. Figure 2 displays the nesting and Table 2 displays the benchmark level of spending for each good. At the lowest nest, the household uses a CES function to aggregate domestically and foreign supplied goods from producers. At the next level of the nest, a Leontief aggregation function is used to add transportation and trade costs (provided by domestic transportation and trade industries) to the final cost of the consumption good. At the top level of the nest, a Cobb-Douglas function aggregates the consumption of each good into the composite good,

$$\bar{C} = \prod_{j=1}^{24} \tilde{C}_j^{\alpha_j^c}, \tag{7}$$

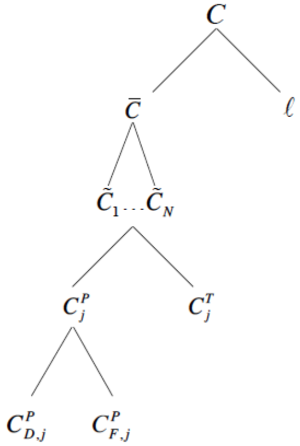

Figure 2. Diagram of the E3 nested consumption function

Table 2. Benchmark expenditures by cosumption good.

Consumption category	Consumption[a]	Pct of total consumption (%)
Motor vehicles	549.0	4.8
Furnishings and household equipment	394.5	3.4
Recreation	1022.1	8.9
Clothing	425.8	3.7
Health care	2372.1	20.7
Education	277.1	2.4
Communication	283.1	2.5
Food	750.3	6.5
Alcohol	124.7	1.1
Motor vehicle Fuels (and Lubricants and Fluids)	381.8	3.3
Fuel oil and other fuels	26.6	0.2
Personal care	245.3	2.1
Tobacco	108.0	0.9
Housing	1780.9	15.5
Water and waste	136.4	1.2
Electricity	169.1	1.5
Natural gas	51.2	0.4
Public ground	42.3	0.4
Air transportation	49.5	0.4
Water transportation	3.2	0.0
Food services and accomodations	714.7	6.2
Financial services and insurance	826.7	7.2
Other services	700.5	6.1
Net foreign travel	44.2	0.4
Total	11478.9	100.0

Note: [a]In billions of 2013 dollars.

where $\tilde{C}_j$ represents final consumption good j (inclusive of transportation and trade costs). Given the Cobb–Douglas aggregation function, the household has a unit elasticity of substitution between all goods and spends a constant fraction of its total spending on each good, $\frac{\tilde{p}_j \tilde{C}_j}{\bar{P}\bar{C}} = \alpha_j^c$, where $\tilde{p}_j$ represents the after-tax and subsidy price of final consumption good j and $\bar{p}$ is the unit price of the consumption bundle.[12]

Households do not directly pay carbon taxes in the E3 model but will face higher prices of carbon-intensive goods, $\tilde{p}_j$, as a result of carbon taxation. In different policy scenarios, households may receive carbon dividend payments as described above or receive reductions in the rates on capital and labor income.

2.1.3. *Government*

Government behavior is that of a single agent representing a combination of federal, state, and local governments. The government uses tax revenue and debt to finance spending on goods and services, labor, and transfers. The government budget constraint requires total expenditures to equal total revenue plus new debt issue. The real debt level is assumed to grow exogenously at the steady state growth rate. Tax revenues are comprised of household income taxes (on capital and labor), sales taxes on consumer goods and services, taxes on firms (corporate income taxes and employer payroll taxes), net border taxes, and carbon revenue. Carbon taxes may shrink the size of noncarbon tax bases and we therefore adjust lump-sum taxes on households each period to satisfy the government budget constraint. A carbon policy is revenue-neutral when the adjustments to lump-sum taxes are zero (on a discounted present value basis).

The government is required to deliver a fixed amount of government services to the households. Because publicly provided services do not enter the household's utility function, we hold the level of public services fixed across policies. Publicly provided services are created from a production function that utilizes capital, labor, and intermediate inputs. To simplify the government investment decision, we hold government investment fixed over time (and across policies), but we do allow the government to shift its basket of variable inputs (labor and intermediate inputs) to minimize the cost of providing the public service using a Cobb–Douglas aggregation function.

2.1.4. *The foreign economy*

The foreign economy largely mirrors the domestic economy. The modeling of the foreign household and government matches that of their domestic counterparts; we assume the foreign households and governments have the same preferences and spending patterns, but we assume larger endowments to reflect the larger size of the

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[12] A Cobb–Douglas consumer demand system with unitary elasticities might imply unrealistically large reductions in consumer demand for carbon-intensive goods. Previously, we explored a beta version of an Almost Ideal Demand (AID) system. In that version of the model, household energy demand changes were smaller. The smaller change in demand had a very small impact on overall abatement. This was in keeping with the fact that household spending on carbon-intensive goods such as electricity, natural gas, and refined petroleum products accounts for only 20–40% of economy-wide consumption of these goods.

foreign economy. A single representative firm produces all foreign intermediate inputs, consumer goods, and capital goods, with the exception of crude oil. This industry uses capital and labor to produce foreign goods (using a Cobb–Douglas production function) and we simplify the production nest by requiring a fixed intermediate input to output ratio. Otherwise, the foreign firm problem is identical to the domestic firm problem: the firm manager chooses variable inputs (in this case only labor) and investment to maximize the value of the firm.

The foreign economy also produces oil and sells it to the domestic economy at an exogenous world oil price in return for a basket of domestically produced producer goods. If the value of the foreign imported oil exceeds the value of the oil-related exports, then the foreign household receives lump-sum oil rents. In EMF32, we utilize a simplification of the full E3 model described in Goulder and Hafstead (2017) such that oil imports are imperfect substitutes for domestically produced oil.[13]

Although foreign goods are a relatively small fraction of domestic intermediate inputs or domestic consumption, Armington trade elasticities will determine the relative trade impacts of a US-only carbon policy. As described previously, we use Feenstra *et al.* (2014) estimates for trade elasticities.

2.2. *Benchmark calibration*

The E3 model combines benchmark year data — in the form of a Social Accounting Matrix (SAM) — with various parameters to create a consistent and fully parameterized model that is consistent with balanced growth: all quantities grow at the rate of technological change and relative prices across goods are unchanged over time. Data for the benchmark year (2013) are collected from various publicly available datasets and converted into a consistent SAM (see Goulder and Hafstead (2017) for details). We delineate between primary parameters — the ones that are specified exogenously — and secondary parameters — the ones that are derived to calibrate the model. Primary parameters are chosen based on empirical estimates from various studies.

2.3. *Reference case (central case baseline)*

The U.S. economy is not expected to exhibit balanced growth under business-as-usual conditions for a variety of reasons. For example, the AEO 2016 predicts the economy to grow at a rate of 2% per year over the interval 2016–2040. Under a balanced growth path, CO_2 emissions would also rise at 2% per year, but the AEO 2016 predicts relatively flat CO_2 emissions over the same time period. Accordingly, we introduce exogenous changes over time in share and scale parameters so that the paths of endogenous variables in the E3 model (e.g., fossil fuel prices, electric generation

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[13] In the full E3 model, foreign oil is a perfect substitute for domestic oil. The full E3 model also includes endogenous productivity in the domestic oil sector such that productivity is declining in cumulative output over time to represent stock effects. The endogenous productivity model also requires a backstop industry to replace the domestic oil sector over time. For EMF32, we treat oil productivity as exogenous and therefore do not introduce a backstop industry.

(a) Oil

(b) Natural Gas

Figure 3. Fossil fuel price forecasts, 2013–2040

shares, and economy-wide emissions) will match independent forecasts. Below we describe the procedure utilized to match AEO 2016 forecasts for economic growth, fossil fuel prices, electric generation shares and total emissions.

First, we set the exogenous technologically induced growth rate of the model economy to match the annual rate of growth in GDP from AEO 2016; the growth rate is set to 2%.[14] Because fossil fuel prices, with the exception of foreign oil prices, are endogenous in the E3 model, we linearly decrease the productivity of the fossil fuel producers to generate increases in the fossil fuel prices over time, where γ from equation (1) represents total factor productivity. The productivity parameter for crude oil extraction, natural gas extraction, and coal are decreased at an annual rate of 1.2%, 0.6%, and 0.4% respectively.[15] Figure 3 displays both the projected AEO 2016 and E3 prices for crude oil and natural gas through 2040. The differences in the forecasts, with smaller increases in prices in the E3 model, reflect the difficulties of projecting endogenous fossil fuel prices in a general equilibrium model. Because price changes are also functions of the other reference case assumptions described below, the E3 model predicts increases in crude oil and natural gas prices of about 1% and 0.6%, respectively, in our benchmark reference case.

To match emissions per unit of output projections and electric generation shares projections, we also adjust the total factor productivities (γ) for the three electric generators. The amount of electricity generated per unit of energy input in the coal-fired and natural gas generators are projected to change over time. Coal-fired generators are projected by EIA to become slightly less efficient and natural gas generators are projected to become much more efficient (due to the installation of efficient combined-cycle plants). We therefore decrease coal-fired generator productivity by about 0.4% annually and increase other-fossil productivity by about 0.9% annually.

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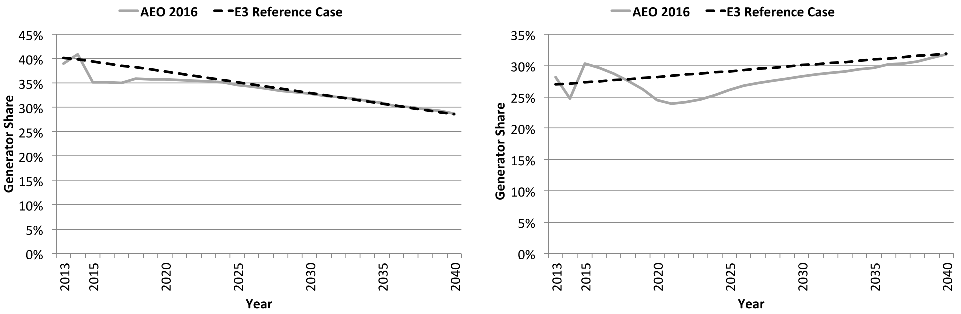
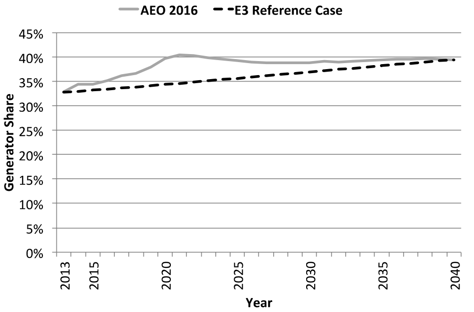
[14] As mentioned previously, the 2% growth rate applies to all sectors equally. Thus, we do not consider unbalanced growth.

[15] We also increase the price of foreign oil at an annual rate of 1.2% to maintain approximately the same ratio of domestic to foreign oil demand.



(a) Coal-Fired Generators (b) Other-Fossil Generators



(c) Nonfossil Generators

Figure 4. Generation share forecasts, 2013–2040.

EIA also projects that renewable costs will decline over time. There is no direct parameter in the E3 model to match projected changes in renewable costs; to match AEO 2016 projections for the share of electricity produced by nonfossil generators, we increase productivity in the nonfossil generation sector at a rate of 0.7% annually. Figure 4 displays the AEO 2016 and E3 generation share projections through 2040.[16]

Although the changes in fossil fuel and generation productivities increase energy prices, the E3 model predicts growing demand for household consumption of energy — motor vehicle fuels, fuel oils, electricity, and natural gas — and industrial consumption of energy in the absence of continued improvements in energy efficiency. For the households (and government), we exogenously decrease the expenditure share parameters (α_j^c) for motor vehicle fuels, fuel oils, electricity, and natural gas at annual rates of 1.1%, 2.1%, 1.3%, and 1.3%, respectively, to match the AEO projections for household consumption of these energy goods. Finally, to match the AEO aggregate emissions path, we assume a transition away from industrial energy consumption by

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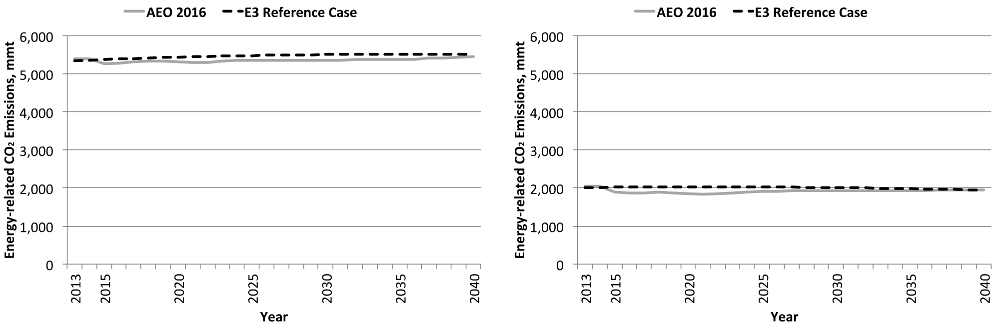
[16] Despite the changes in relative input prices and productivities, the E3 model predicts much more coal generation relative to natural gas generation compared to the AEO 2016 forecasts. To adjust for this, we also linearly adjust the share parameters in the electric utility's demand function for wholesale electricity to shift generation away from coal towards natural gas in the E3 model.



(a) Economy-Wide (b) Power-Sector

Figure 5. Carbon dioxide emissions forecasts, 2013–2040

nonenergy firms at a rate of 1.4% annually and refer to this as industrial energy efficiency improvements.[17]

Figure 5 displays the AEO 2016 and E3 economy-wide and power-sector energy-related CO_2 emissions paths. The E3 model, given the adjustments described above, generates CO_2 emissions paths that closely approximate the AEO 2016 forecasts. In 2025, the E3 model predicts 2.0 billion metric tons of power sector CO_2 emissions and 5.5 billion metric tons of economy-wide energy-related CO_2 emissions compared to the 1.9 billion and 5.4 billion metric tons projected by AEO 2016. In the following section, we examine how alternative reference case assumptions impact emissions under a carbon tax and decompose the impacts into changes in baseline emissions and abatement.

3. Emissions Time-Paths under a Carbon Tax

The first step in our assessment of the time-path of emissions under a carbon tax is to evaluate the carbon tax's impacts under model parameters that yield the central case forecast. We focus on one carbon tax scenario from EMF32: the \$25-5% household rebate scenario. Under this scenario, a carbon tax is introduced in 2020 at a level of \$25 per ton (in \$2010) and the tax rises at a rate of 5% year (above inflation). Though the E3 model can include anticipation effects by considering policies that are announced in advance, these simulations model the carbon tax as unanticipated in 2020. All revenues are returned through lump-sum rebates to the household. As shown in Goulder and Hafstead (2017), revenue uses in the E3 model significantly impact costs but do not significantly impact abatement. This finding is also consistent across models, as shown in Barron *et al.* (2018). Therefore, we focus on a single revenue use for the remainder of this exercise.

Figure 6 displays both emissions and emissions abatement levels under the \$25-5% carbon tax policy from 2020–2040. In the first year of the carbon tax, energy-related CO_2 emissions fall by about 15.8% relative to baseline. As the carbon tax increases in

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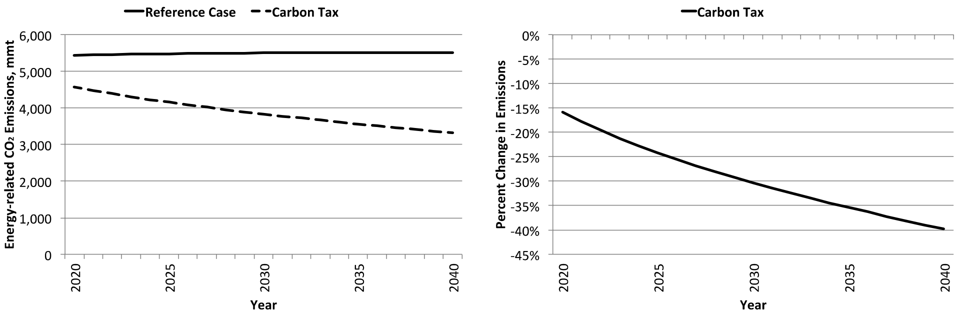
[17] This shift is caused by linearly adjusting the α share parameters in the nonenergy industry energy-material nest.



(a) Emissions (b) Abatement

Figure 6. Carbon tax emissions, 2020–2040

stringency over time, emissions continue to decline relative to baseline. In 2025, emissions are 24% below baseline emissions and by 2040, when the carbon tax is \$66.33 in \$2010, emissions under the carbon tax are 39.8% below baseline emissions. The level of emissions under this carbon tax path in 2025 is 4.2 billion metric tons, a 31% reduction in emissions relative to energy-related CO_2 emissions in the common benchmark year 2005. By 2040, emissions are 3.3 billion metric tons, a 45% reduction relative to 2005.

3.1. *Sensitivity of emissions paths to alternative forecast scenarios*

Table 3 displays the level of emissions in 2025 and 2040 for both business-as-usual and the \$25-5% carbon tax scenario across a range of alternative forecast scenarios. As

Table 3. Projected emissions across forecast scenarios.

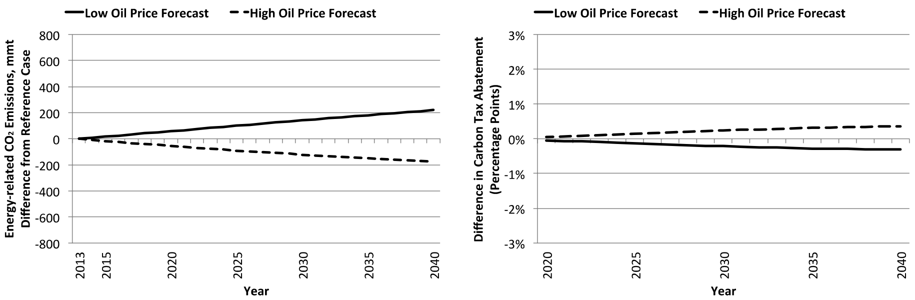
		Oil price	Gas price	Renewable cost	Energy efficiency	GDP growth
				(a) 2025		
Baseline	Low	5,581	5,505	5,457	5,710	5,182
	Central	5,480	5,480	5,480	5,480	5,480
	High	5,391	5,458	5,502	5,240	5,793
Carbon tax	Low	4,238	4,174	4,140	4,314	3,930
	Central	4,155	4,155	4,155	4,155	4,155
	High	4,079	4,137	4,169	3,989	4,391
				(b) 2040		
Baseline	Low	5,728	5,568	5,443	6,134	4,843
	Central	5,509	5,509	5,509	5,509	5,509
	High	5,335	5,460	5,566	4,807	6,264
Carbon tax	Low	3,463	3,347	3,281	3,643	2,915
	Central	3,314	3,314	3,314	3,314	3,314
	High	3,190	3,284	3,344	2,941	3,765

mentioned in the introduction, forecasted baselines are multi-dimensional, including predicted time paths for several variables including fuel prices, energy-output ratios, and GDP. Each of the alternative scenarios is a departure from the central scenario along one of these dimensions. We alter key parameters of the model so as to generate the scenario in question and evaluate the time-path of emissions under the carbon tax. Below, we explain each alternative scenario and decompose the resulting changes in emissions into the changes in baseline emissions and changes in abatement from the baseline.

3.1.1. *Oil prices*

As described in Sec. 2.2, because fossil fuels prices are endogenous in the E3 model, we calibrate the total factor productivity parameter (γ) for fossil fuel producers to match fossil fuel price forecasts. In our central case, oil prices rise at a rate of 1% annually. Here we consider, as alternatives, a "Low Oil Price Forecast" and "High Oil Price Forecast," in which oil prices rise at an annual rate of 0.57% and 1.44%, respectively. In the central case, the productivity factor for oil producers declined at 1.24% annually. To achieve the alternative oil price time-paths, the productivity parameter declines at annual rates of 0.62% and 1.84% in the low and high oil price scenarios, respectively.[18]

Figure 7 displays the change in baseline emissions and abatement relative to the reference case baseline emissions and the benchmark carbon tax abatement, respectively. Low oil prices encourage increased consumption of refined petroleum products, leading to higher baseline emissions. By 2040, baseline emissions are approximately 218 million metric tons higher in the "Low Oil Price Forecast" scenario than in the reference case, a 4% increase in baseline emissions. The "High Oil Price Forecast"



(a) Emissions (b) Abatement

Figure 7. Oil price forecast sensitivities

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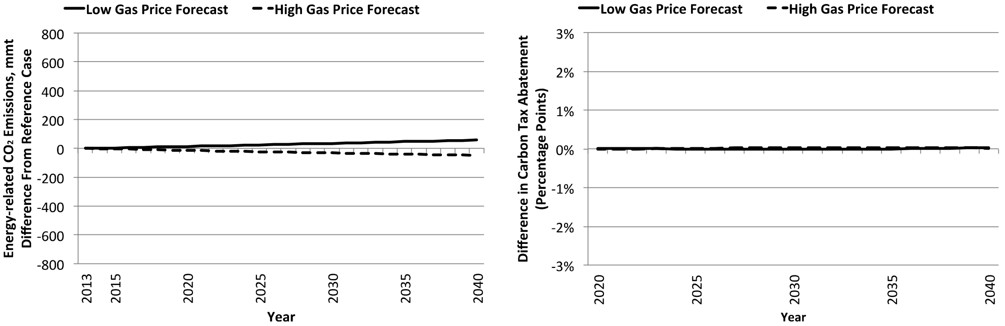
[18] Similar to the benchmark reference case, we also increase the exogenous foreign oil price to maintain approximately the same ratio of domestic to foreign oil inputs.

scenario largely mirrors the "Low Oil Price Forecast" scenario. Higher oil prices lead to lower baseline emissions: in 2040, baseline emissions are 3% lower than in the reference case. Figure 7(b) displays the change in abatement. Recall from Fig. 6(b) that abatement was about -15.8% in 2020 and -39.8% in 2040. Short-run abatement is virtually identical and long-run abatement changes by less than 0.4% points under the alternative oil price scenarios: by 2040, abatement is -39.5% under low oil prices and -40.2% under high oil prices.

3.1.2. *Natural gas prices*

In our reference case, we exogenously decreased natural gas extraction productivity at a rate of 0.6% annually to generate an average price increase of 0.59% over time. In the alternative "Low Natural Gas Price Forecast" scenario, we decrease productivity at a rate of 0.3% annually to match a price increase of 0.31%; in the "High Natural Gas Price Forecast" scenario, we match a price increase of 0.86% by decreasing productivity at a rate of 0.9% annually.

As shown in Fig. 8, the alternative natural gas price scenarios, when modeled through decreasing natural gas producer productivity, have almost no effect on either baseline emissions or abatement. High natural gas prices lead to a decrease in natural gas consumption and its corresponding emissions across all sectors. However, high natural gas prices also lead to a shift in generation within the electric power sector: both coal-fired generation and nonfossil generation increase when natural gas extraction is less efficient and natural gas prices are higher. The increase in coal emissions from the electric power sector partially, but not fully, offsets the decreases in natural gas emissions throughout the rest of economy. Alternatively, low natural gas prices lead to fewer power-sector coal emissions but this decline is not enough to cause economy-wide emissions to fall in response to lower natural gas prices.



(a) Emissions (b) Abatement

Figure 8. Natural gas price forecast sensitivities

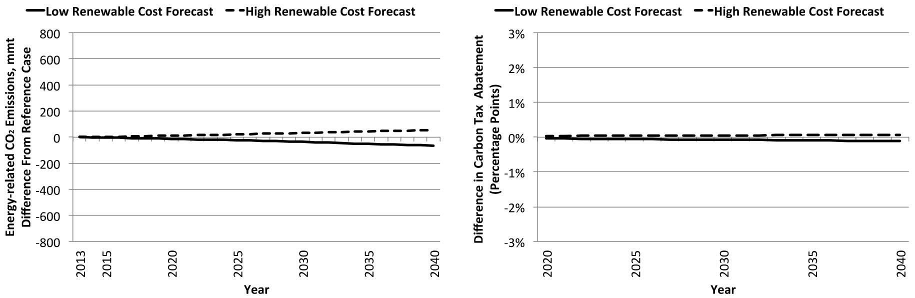
3.1.3. *Renewable costs*

In the E3 model, changes in the productivity of the nonfossil generation sector are a proxy for changes in renewable electricity costs.[19] In the reference case, we increased the productivity parameter (γ) at a rate of 0.7% annually to match long-run AEO 2016 predictions for nonfossil generation shares. To generate the "Low Renewable Cost Forecast" scenario, we increase productivity at a rate of 1.05% annually; for the "High Renewable Cost Forecast" scenario, we increase productivity at a rate of 0.35% annually.

As expected, the share of nonfossil generation is highest in the "Low Renewable Cost Forecast". This leads to a decline in baseline emissions from coal and natural gas in the power sector, as shown in Fig. 9. However, the impact on total baseline emissions is small. First, the shift in generation caused by alternative nonfossil generator productivity is relatively small. In the "Low Renewable Cost Forecast" scenario, the generation share increases from only 39.5% to 42.9%. It is possible that the alternative nonfossil productivity values in this exercise do not sufficiently represent the scale of uncertainty in renewable costs. Second, there is a *rebound* effect in the E3 model. Higher nonfossil productivity lowers the price of retail electricity and increases the quantity of electricity consumed in general equilibrium; therefore, reductions in emissions through shifts in generation are partially offset by increases in total generation. As was the case under the natural gas price scenarios, neither renewable cost scenario significantly affects abatement from the carbon tax policy.

3.1.4. *Energy efficiency*

In the E3 reference case, we alter the energy-intensive consumptions shares for households and the government and also reduce the energy input requirement for nonenergy industries to match forecasts of energy consumption and total emissions. Both of these could be interpreted as changes in energy-efficiency, but in this section



(a) Emissions (b) Abatement

Figure 9. Renewable cost forecast sensitivities

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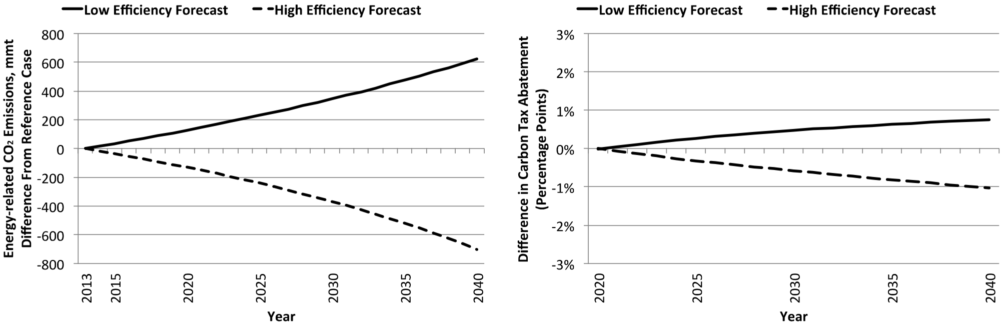
[19] This interpretation is consistent with changes in renewable costs through improvements in efficiency in the form of more power generated per mile per hour of wind or hour of sunlight. This interpretation is less consistent with changes in renewable costs through changes in fixed capital costs to install new capacity.



(a) Emissions (b) Abatement

Figure 10. Energy efficiency forecast sensitivities.

we focus solely on the sensitivity of baseline emissions and abatement from the baseline to changes in industrial energy input requirements. In the reference case, to maintain constant emissions over time, conditional on the other reference case assumptions, we imposed a 1.4% annual decrease in industrial energy input requirements through linear adjustments in the α share parameters in the nonenergy industry energy-material nest. In the "Low Efficiency Forecast" and the "High Efficiency Forecast" scenarios considered here, we decrease the energy input requirement by 0.7% and 2.1%, respectively.

These energy efficiency assumptions have large impacts on baseline emissions, as shown in Fig. 10. Baseline emissions are decreasing in efficiency (lower energy input requirement) and in 2040, baseline emissions are more than 10% higher or lower than baseline emissions in the reference case. Abatement is also decreasing in efficiency: higher baseline efficiency reduces some opportunities to increase efficiency through a carbon tax. However, the magnitude of the change in abatement is small: a 1% point decrease in abatement reduces abatement from -39.8% to -38.8%.

3.1.5. *Rate of economic growth*

As described in Sec. 2, economic growth in the model occurs through Harrod-neutral technological change and all quantity variables must grow at this exogenously specified growth rate on the balanced growth path. In the reference case, we chose a growth rate of 2% to match AEO 2016 GDP growth rate projections. In the "Low Growth Forecast" and "High Growth Forecast" scenarios here, we employ growth rates of 1.5% and 2.5%, respectively.

Other things equal,[20] changes in the rate of economic growth significantly affect baseline emissions. As seen in Fig. 11, emissions are significantly increasing in the

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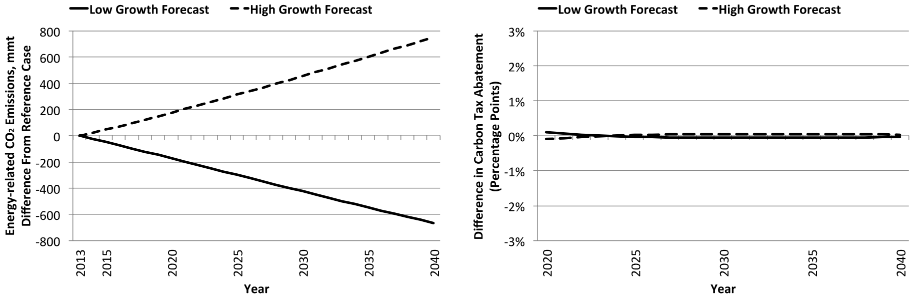
[20] Of course, changes in economic growth can be associated with other changes besides changes in the rate of Harrod-neutral technological change. Thus, it is important to note the particular elements underlying the changes in GDP growth.



(a) Emissions (b) Abatement

Figure 11. Economic growth forecast sensitivities

rate of GDP growth.[21] However, the level of abatement under the carbon tax is completely independent of the growth rate. In our balanced growth path model, relative changes in emissions under a carbon tax are not impacted by changes in the size of the economy over time.

3.1.6. *Summary*

We have demonstrated the sensitivity of emissions to five alternative forecasts of important prices and outputs. As part of this analysis, we have decomposed the impacts into the changes in baseline emissions and the changes in emissions reductions from the (new) baseline.

We find that natural gas prices and renewable costs have very little impact on emissions paths, as neither scenario significantly influences baseline emissions or abatement in the E3 model. It is worth noting that these two scenarios, considered separately here, are in fact closely linked with the power sector. Changes in the price of generation may cause offsetting changes in emissions from other generation sources and changes in retail electricity prices may lead to offsetting emissions through the rebound effect.[22]

Oil prices forecasts, modeled through changes in oil extraction productivity, have a moderate impact on projected emissions under a carbon tax: baseline emissions are decreasing in the price of oil, but abatement is largely independent of oil price forecasts.

Unsurprisingly, changes in energy efficiency and the rate of GDP growth have large impacts on the level of carbon tax emissions and baseline emissions in the E3 model. A 0.5% increase in the rate of growth leads to 6% higher baseline emissions in 2025 and

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[21] These results indicate emissions are impacted by long-run growth, but not necessarily short-term fluctuations in growth. Because the model does not have business cycle-like shocks, we cannot quantitatively predict the impact of short-term booms or recessions on emissions.

[22] It is also possible that we did not consider the full range of potential variation of future natural gas prices and renewable costs. With the "top-down" E3 model, we could consider additional scenarios involving simultaneous changes in emissions from the different types of generators. Moreover, with more detailed, "bottom-up" models of the power sector, this issue could be explored further.

14% higher baseline emissions in 2040. In contrast, we also find that changes in the rate of GDP growth, when these changes derive from changes in the rate of labor-augmenting technological change, have virtually no impact on abatement.

One of the most interesting findings from this analysis is that emissions abatement under a given carbon tax time-profile does not differ much across the different forecast scenarios for fossil fuels prices, renewable costs, the rate of energy efficiency improvements, and the rate of economic growth.

3.2. *Price paths to meet short-term annual targets*

Here, we consider the question: how does the ability of carbon taxes to meet specific reduction targets differ across the different forecast scenarios? As described in the introduction, EMF32 included a solve-to-match 26% 2025 carbon tax scenario. In our central case forecast and parameter scenario, we found that an initial price level of \$12.83 (in \$2010) in 2020, rising to \$16.37 (in \$2010) by 2025 would reduce energy-related CO_2 emissions by 23% relative to 2005 in the target year of 2025.[23] Here, we ask how the prices in the 26% 2025 scenario differ across the various forecast scenarios.

Table 4 displays the projected 2025 tax levels (in \$2010) to meet the target reduction of 23%, relative to 2005, in energy-related CO_2 (this also meets the 26% reduction in all greenhouse gases, given EMF32 assumptions on the paths of emissions for the other gases). We report the price in the year 2025 only; as shown in Chen and Hafstead (2016), the price in the target year is more important than the path to reach that price; hence we focus only on the price in the target year.

The qualitative impacts are as expected. Forecast scenarios that increase baseline emissions relative to the central case increase the required tax rates in 2025 required to

Table 4. Projected prices to meet 2025 INDC target tax level in 2025 (in \$2010) across alternative forecast scenarios.

	Oil price	Gas price	Renewable cost	Energy efficiency	GDP growth
Low	18.92	16.97	15.89	21.44	9.98
Central	16.37	16.37	16.37	16.37	16.37
High	14.19	15.81	16.82	11.39	23.88

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[23] There is an important distinction between the levels of energy-related carbon dioxide emissions reported by the EIA and by EPA's GHG Inventory. In 2005, the EIA reported approximately 6 billion metric tons of these emissions and the EIA reported 5.75 billion metric tons. The difference stems from different geographical definitions (whether to include territories or not) and the inclusion/exclusion of international bunker fuels. In the EMF32 exercise, this is important because the EMF32 26% 2025 scenario sets a target for energy-related CO_2 emissions of 4.45 billion metric tons, a 23% reduction relative to EPA's 2005 emissions levels. However, the E3 model is calibrated to EIA emissions inventories and therefore in this scenario we target a level of 4.62 billion metric tons, a 23% reduction relative to EIA's 2005 emissions levels. Models that are calibrated to EIA emissions but solved for the 4.45 billion ton target would require a larger carbon tax to meet the target.

meet a fixed emissions target. What seems more significant is that the magnitudes of the needed carbon taxes do not change substantially across scenarios. In particular, lower energy efficiency and a greater GDP growth rate imply required taxes of \$21 and \$24 (in \$2010), respectively.[24]

4. Conclusions

The future impacts of a carbon tax depend on the future economic circumstances upon which the carbon tax is imposed. Using the E3 model, we have measured the sensitivity of baseline emissions and emissions abatement from the baseline to alternative forecasts of the time-paths of fuel prices, energy-efficiency, and GDP. This sensitivity varies depending on the particular forecasted variable under consideration. Baseline CO_2 emissions are highly sensitive to alternative scenarios as to the rate of energy efficiency improvements in the nonenergy sector and the rate of general economic growth. In contrast, baseline emissions are much less sensitive to alternative scenarios regarding the productivity of fossil fuel production. The extent of abatement from the baseline is generally fairly insensitive to changes in the scenarios for time-paths of fuel prices, energy-efficiency and GDP.

We have also implemented the EMF32 solve-to-match 26% 2025 carbon tax policy in each of our alternative forecast scenarios. Within the E3 model, short-term emissions targets can be achieved with relatively moderate carbon taxes under all of the baseline scenarios considered.

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[24] If, for example, the US experienced high GDP growth and low energy efficiency improvements, then the price needed to hit short-term targets would be higher. For the price to meet an emissions target, we found that combining the GDP and energy efficiency scenarios is approximately additive (relative to the central baseline) and therefore a price of \$29 would be necessary to match the target under this combined scenario.

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