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U.S. energy sector impacts of technology innovation, fuel price, and electric sector CO_2 policy: Results from the EMF 32 model intercomparison study☆

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ABSTRACT

We study the impact of fuel prices, technology innovation, and a CO_2 emissions reduction policy on both the electric power and end-use sectors by comparing outputs from four U.S. energy-economic models through the year 2050. Achieving innovation goals decreases CO_2 emissions in all models, regardless of natural gas price, due to increased energy efficiency and low-carbon generation becoming more cost competitive. For the models that include domestic natural gas markets, achieving innovation goals lowers wholesale electricity prices, but this effect diminishes as projected natural gas prices increase. Higher natural gas prices lead to higher wholesale electricity prices but fewer coal capacity retirements. A CO_2 electric power sector emissions cap influences electric sector evolution under reference technology assumptions but has little to no incremental influence when added to innovation goals. Long-term, meeting innovation goals achieves a generation mix with similar CO_2 emissions compared to the CO_2 policy but with smaller increases to wholesale electricity prices. In the short-term, the relative effect on wholesale prices differs by model. Finally, higher natural gas prices, achieving innovation goals, and the combination of the two, increases the amount of renewable generation that is cost-effective to build and operate while slowing the growth of natural-gas fired generation, which is the predominant generation type in 2050 under reference conditions.

1. Introduction

Energy technology cost and performance, fuel prices, and electricity sector policies are major driving forces determining technology choice, cost, and environmental impacts in the electric sector. Understanding the interaction of these three drivers is a key question in environmental regulatory design for the electricity sector as well as research and development policy. Multi-model studies that use energy-economic models to examine sensitivities to future drivers and model design are important to separate out robust trends and understand differences between

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model projections. The last U.S. multi-model study to examine sensitivities to energy technology innovation and electricity sector greenhouse gas policy using a coordinated set of assumptions was Energy Modeling Forum (EMF) 24 (EMF, 2014). Since EMF 24, projections of future technology costs have decreased considerably (U.S. Energy Information Administration (EIA), 2017a; NREL, 2017), natural gas prices have dropped, and a national carbon dioxide (CO_2) emissions reduction policy was finalized for the electricity sector (40 C.F.R. § 60, 2015). Thus, EMF 32 provides an updated multi-model comparison of these drivers.

This study builds upon what is presented in the EMF 32 overview papers by taking a deeper and more comprehensive look at the impact of technology costs using four EMF 32 energy-economic models. We use an alternate set of more comprehensive and detailed U.S. technology cost and performance assumptions. Unlike the overview papers for EMF 32 (Creason et al., 2017; Bistline et al., 2017), which focus on either the technology or policy sensitivities, we explore the interaction of both.

Previous studies have focused on understanding the economic efficiency aspects of investing in research and development to more cost-effectively meet climate goals. For example, Fischer and Newell, 2008 and Bosetti et al., 2011 showed that climate goals can be achieved at lower cost by combining greenhouse gas reduction policies with investments in research and development compared to utilizing either policy in isolation. Major U.S. government analysis has highlighted the importance of research and development investment to spur innovation that enables environmental benefits (DOE, 2015e, 2016c, 2017c). For this analysis, we take it as given that investing in clean energy research and development is an important part of achieving climate goals. Instead, we focus on exploring the impacts of recent research and development investment and CO_2 policy, at different natural gas prices, on the energy sector using four commonly used energy-economic models.

This study is interested in the following primary questions.

1. How do technology choice, electricity price, and environmental impacts depend on: (a) fuel prices, and (b) technology innovation?
2. How do the electricity sector outcomes of achieving representative technology innovation goals compare to those when implementing a representative electricity sector CO_2 policy?
3. How much do the answers to the previous questions depend on model architecture and assumptions?

Section 2 introduces the models and scenarios. Section 3 discusses the results. Section 4 includes the main findings from this study.

2. Methodology

2.1. Participating models

Four models participated in this study: one economy-wide model (ReEDS-USREP), two partial equilibrium models with a full energy sector (EPSA-NEMS,[1] GCAM-USA), and an electricity sector-only model (ReEDS). These models differ in a number of ways that allow a diverse and informative perspective on how the model architecture affects the model results. Each model is designed to answer a certain subset of questions best, which necessitates trade-offs on spatial detail, temporal detail, technology detail, feedbacks with the economy, and model solution approach as outlined in Table 1.

Each of the models represents economic activity in a different way. ReEDS-USREP is a computable general equilibrium (CGE) model, meaning ReEDS-USREP includes all economic sectors and can examine how changes in the energy sector impact economic indicators, such as consumption and GDP. ReEDS-USREP couples the ReEDS electricity sector model with the U.S. Regional Energy Policy (USREP) CGE model. EPSA-NEMS and GCAM-USA include a representation of the economy but are partial-equilibrium models, meaning they include effects of how the economy impacts the energy sector with partial feedback between energy and economy. ReEDS does not represent economic interactions beyond the electricity sector; rather, it prescribes energy demand using regional load growth trajectories on base-year load data.

Temporal resolution and scope vary across models. The model time steps vary from one year (EPSA-NEMS) to five years (GCAM-USA). Important for this analysis, 3 of the 4 models solve to the year 2050, while EPSA-NEMS stops at the year 2040.[2] In each time step, each model must satisfy market and policy constraints within the sectors included in the model.

All four models include a detailed representation of the electricity sector, which was a pre-requisite to analyze the questions posed in EMF 32. ReEDS includes only the electricity sector, while the other models represent all energy sectors including production, transformation, and demand sectors (EPSA-NEMS, GCAM-USA, and ReEDS-USREP). Within the electricity sector, ReEDS and ReEDS-USREP have the most spatial and temporal detail, which is particularly important for resolving variable resource generation, such as solar and wind. EPSA-NEMS has a more aggregated spatiotemporal resolution in the electricity sector than ReEDS, but it still includes significant detail across both dimensions. The version of GCAM-USA used here has sub-national spatial but no sub-annual temporal detail. As a consequence, it does not have an explicit representation of sub-annual temporal integration of variable resources such as solar and wind with electricity demand.

All four models include detailed technology representations in the electricity sector, which is important for the technology sensitivities we explored. The models differ, however, in their implementation of technology types. A key strength of ReEDS is its characterization of variable renewables and transmission. ReEDS calculates expected value of variable renewable curtailment, capacity value, and forecast error-induced operating reserve requirements for each solve year, and renewable resources are differentiated by performance class and grid interconnection costs. ReEDS also models power flow between approximately 300 transmission lines with capacity limits and linearized direct current power flow between them. EPSA-NEMS represents all existing generating units and evaluates capacity additions, retirements and retrofits using a forward-looking expansion model as well as an annual dispatch model. Planning reserves, operating reserves, and various emission regulations must be met in addition to satisfying generation needs. Variable renewable resources and curtailments are represented but with much less spatial and temporal detail than in ReEDS. Future load shapes are endogenously determined based on end-use demand projection. The utilized version of GCAM-USA does not explicitly model capacity value and curtailment. GCAM-USA represents transmission and trade among US grid regions using a nonlinear logit formulation. Trade is calibrated to current conditions but can expand in the future when relative prices among regions changes, though there are diminishing returns to trade expansion.

An important difference among the models is the way they decide to maintain or retire existing generating capacity. EPSA-NEMS allows all existing power plants to remain in operation as long as they are able to cover their future operating costs. The other models assume that existing generating capacity is retired by two mechanisms: (1) scheduled retirements, and (2) the ability of generators to cover their future operating costs (see Table 1), with a few additional caveats. ReEDS and ReEDS-USREP retire additional coal-based capacity when a specified capacity factor threshold is not met. Moreover, ReEDS and ReEDS-USREP have no economic-based nuclear plant retirements. All nuclear plant retirements are scheduled. GCAM-USA does not include the capability for existing coal-fired power plants

[1] EPSA-NEMS is based on the National Energy Modeling System, a model developed by the U.S. Energy Information Administration, but is developed by OnLocation and does not represent the views of EIA.

[2] EPSA-NEMS is based on the version of NEMS used for the Annual Energy Outlook 2015 which has a projection period to 2040. The most recent version of NEMS (i.e., the Annual Energy Outlook 2017) has been modified by EIA to provide projections to the year 2050.

Table 1
Description of key model attributes.

Model name	EPSA-NEMS	GCAM-USA	ReEDS	ReEDS-USREP
Model version and overview	Modified National Energy Modeling System (NEMS) based on 2015 AEO (USEIA, 2016a, 2017b)	GCAM-USA implementation of GCAM 4.2 (Kraucunas et al., 2015; Zhou et al., 2014; PNNL, 2017)	U.S. electricity sector model (Cole et al., 2016; Eurek et al., 2016)	Coupled U.S. electricity sector and CGE models[a] (Rausch and Mowers, 2014; Eurek et al., 2016)
Model developer	OnLocation, Inc[b]	PNNL	NREL	NREL and MIT
Energy sectors represented	4 Energy production, 2 transformation and 4 demand sectors[c]	7 energy production, 3 transformation, and 3 demand sectors[d]	Electricity sector only	5 energy production and transformation sectors and 6 demand sectors[e]
Time horizon (all models start in 2010)	1-year increments through 2040	5-year increments to 2050 for this exercise	2-year time steps through 2050	Same as ReEDS
Electricity sector intra-annual resolution	9 time slices per year in electricity (three seasons with three diurnal periods)	One annual time slice	17 time slices per year in electricity (four seasons with four diurnal periods and one for peak load)	Same as ReEDS
Spatial regions	22 electricity regions representing the continental U.S.; 9 Census regions	50 states plus 31 international regions	134 U.S. balancing regions for most technologies; 356 wind and CSP resource regions	Same as ReEDS for electricity sector. Other sectors have 6 U.S. regions and 15 international regions
Representation of existing generators	Detailed plant-level database aggregated by plant characteristics and regions; no aggregation for coal-fired power plants	Existing capacity aggregated by fuel and technology category in each state[f]	Detailed plant-level database aggregated by fuel and technology category in each balancing region	Same as ReEDS
Power plant retirement algorithm(s)	Economic; no fixed plant lifetimes; includes announced retirements	Combined economic and fixed technology lifetimes[g]	Exogenously specified announced and lifetime-based retirements, with additional retirements of coal capacity with low usage[h]	Same as ReEDS
Utility and distributed generation technologies represented	Coal with and without CCS, NGCC with and without CCS, CT's, nuclear, utility and distributed PV, CSP, wind onshore & offshore, biomass, hydropower, existing pumped storage, geothermal, landfill gas, CHP	Same as EPSA-NEMS except no offshore wind or landfill gas	Same as EPSA-NEMS except includes CSP with and without thermal storage, compressed air energy storage, utility-scale battery storage, no landfill gas	Same as ReEDS
Demand representation	Endogenous; detailed stock and technology choice models for all end-use sectors	Endogenous; detailed stock models for all end-use sectors except for industry	Exogenous; demand is used from EPSA-NEMS	Endogenous; price-responsive demand of household consumption of goods, including electricity
Fuel supply	Coal, oil, and natural gas supply is endogenous; uranium supply is exogenous	Endogenous supplies, though U.S. natural gas prices are set exogenously to AEO	Coal, natural gas, and uranium are exogenously specified; oil is not represented due to its negligible use in the electricity sector	Endogenous; calibrated to AEO
Equilibrium approach	Partial equilibrium with macro feedback	Partial equilibrium with focus on energy and agriculture markets	Single sector model with no implied equilibrium.	Iterate between two models until converge in electricity sector; reaches general equilibrium in all sectors.
Intertemporal solution approach	Near-perfect foresight in electricity sector; myopic foresight in demand models	Myopic	Limited electricity model foresight	Limited electricity sector foresight. All other sectors myopic.

[a] These two models were previously linked to explore a limited set of clean energy policies (Rausch and Mowers, 2014), but the present analysis uses updated versions of both models for a larger scenario suite.
[b] EPSA-NEMS is based on NEMS, a model developed by EIA, but is developed by OnLocation and does not represent the views of EIA.
[c] Energy production sectors: oil, gas, coal, renewables; transformation sectors: electricity and liquid fuels; demand sectors: residential, commercial, industry, transportation.
[d] Energy production sectors: oil, gas, coal, nuclear, renewables; transformation sectors: electricity, liquid fuels, hydrogen; demand sectors: buildings, industry, transportation.
[e] Energy sectors: coal, natural gas, crude oil, refined oil, and electricity; demand sectors: manufacturing, services, agriculture, transportation, energy-intensive products, and other.
[f] Existing generating stock is calibrated to match historical totals and efficiencies for each of the 50 states. New investment assumes uniform generation efficiencies, costs, and technology availability across states.
[g] Assumed lifetimes: existing Coal – 60 years; existing CT/CC – 60 years; new CT/CC – 45 years; existing and new wind, solar, geothermal – 30 years; existing and new nuclear – 60 years; existing and new biopower - 60 years.
[h] Assumed lifetimes: existing coal <100 MW – 65 years; existing coal >100 MW and new coal – 75 years; all types of natural gas and oil-based units – 55 years; nuclear – 80 years; hydropower – 100 years; biopower – 45 years; wind – 24 years; solar – 30 years; geothermal – 30 years. Low capacity factor-based retirements use a threshold capacity factor of 0.01 in 2020 increasing linearly to 0.5 in 2040, where it remains thereafter.

Table 2
Eight cases modeled for this analysis.

Reference case (REF, Same as EMF 32 scenario 3.1.0.0): ReEDS and ReEDS-USREP were calibrated to 2016 Annual Energy Outlook (AEO) Reference case. GCAM-USA was calibrated to the AEO 2015 Reference case with select technology assumptions and natural gas prices calibrated to AEO 2016 Reference case. EPSA-NEMS REF is the 2015 AEO High Natural Gas and Oil Resource side case modified to include select updates to make EPSA-NEMS REF more similar to the AEO 2016 Reference case (EIA, 2015; U.S. Energy Information Administration (EIA), 2016).
High Natural Gas Price case (HighNG, Same as EMF 32 scenario 3.1.0.2): REF plus modifications that increase natural gas prices.
High-technology Goals case (HighTech): REF plus Fiscal Year 2017 U.S. Department of Energy technology cost and performance goals. A comparison of the model implementation of goals is shown in Table 3. Goals include technology cost and performance trajectories to the year 2040, with no change to technology costs after 2040.
High-technology Goals with High Natural Gas Price case (HighTech-HighNG): REF modified to include the same technology and natural gas resource or price assumptions as in the HighTech and HighNG cases.
CO_2 Policy Reference case (Pol-REF, Same as EMF 32 scenario 3.1.1.0): REF case modified to include a national power sector mass-based CO_2 emissions cap with targets of 1891, 1754, and 1644 million metric tons of CO_2 in 2020, 2025, and 2030, respectively, and a reduction in mean annual power sector emissions of 1.8% per year beyond 2030.
CO_2 Policy with High Natural Gas Price case (Pol-HighNG, Same as EMF 32 scenario 3.1.1.2): HighNG case overlaid with a power sector emissions cap as described in Pol-REF.
CO_2 Policy with High-technology Goals case (Pol-HighTech): HighTech case overlaid with a power sector emissions cap as described in Pol-REF.
CO_2 Policy with High-technology Goals and High Natural Gas Price case (Pol-HighTech-HighNG): HighTech-HighNG case overlaid with a power sector emissions cap as described in Pol-REF.

to increase dispatch beyond current levels. Lastly, EPSA-NEMS is the only model to include an endogenous representation of technology innovation, which reduces technology costs for new technologies as more capacity of each type is built.

Three models include an endogenous representation of energy demand (EPSA-NEMS, GCAM-USA, ReEDS-USREP), although the representation differs by model. EPSA-NEMS has the most detailed demand sector representation with stock and technology choice models in all end-use sectors. GCAM-USA also contains technology representation but at a more aggregate level. ReEDS-USREP represents sectors' and consumers' electricity demand using constant elasticity of substitution (CES) production and consumption functions, respectively. Said differently, electricity is treated as an input to the production of various goods and services as well as an item that provides utility for consumers. ReEDS uses exogenously specified electricity demand, which prevents it from exhibiting electricity demand response to price.

EPSA-NEMS and ReEDS-USREP include endogenous representation of oil, gas, and coal supplies, which allows these models to estimate fuel prices based on supply and demand response. GCAM-USA includes endogenous representation of all fuels as well, but for this analysis natural gas prices were set exogenously for the reference and higher natural gas price scenarios based on the EIA Annual Energy Outlook (AEO) projections. In ReEDS, coal and uranium fuel prices are exogenously parameterized using U.S. data derived from AEO, but natural gas prices are endogenously determined from linear, region-specific supply curves parameterized by regressing price-quantity pairs in AEO cases.

The models also vary in their solution method and in how they represent foresight. The electricity module within EPSA-NEMS is a linear program with a 30-year near-perfect foresight, which assumes that decision-makers have a near complete view of future energy prices and demand when they make capacity planning decisions.[3] The other models are dynamic-recursive models, which assume that all decisions are based on current conditions. ReEDS is a linear program model that minimizes the 20-year net present value of capital and operating costs of generation and transmission capacity in each time step. ReEDS-USREP also does not include foresight into economic conditions when solving the CGE. GCAM-USA is not a linear model, but rather it uses a non-linear logit formulation to model the distribution of economic shares of new investment among technology options as a function of relative costs.

2.2. Scenarios

Table 2 describes the 8 cases run for this analysis. The following sections describe the cases and their model implementation in more detail. The four cases with reference technology assumptions listed in Table 2 are part of EMF 32 scenario set, whereas the four High Technology Goals cases are unique to this analysis.

2.2.1. Reference case (REF, same as scenario 3.1.0.0 in EMF 32)

The benchmark for the Reference case in EMF 32 (scenario 3.1.0.0) is the 2016 Annual Energy Outlook (AEO) No Clean Power Plan side case, developed by the Energy Information Administration using NEMS (U.S. Energy Information Administration (EIA), 2016). The Reference case (REF) in this analysis was modified somewhat for each model depending on model architecture.

EPSA-NEMS REF is the 2015 AEO High Natural Gas and Oil Resource side case (U.S. EIA, 2015) with modifications to be more like the 2016 AEO, which had not been released in time for this analysis.[4] EPSA-NEMS used the AEO 2015 High Natural Gas and Oil Resource side case instead of the AEO 2015 Reference case to better approximate AEO 2016 natural gas prices. AEO 2016 natural gas prices are lower than AEO 2015 natural gas prices because natural gas prices are low compared to historic ranges (EIA, 2017c). In addition, EPSA-NEMS REF includes the 2015 wind and solar tax credit extensions (H.R. 2029, 2016) and updated solar and wind technology cost and performance estimates that are consistent with AEO 2016 Reference case. The EPSA-NEMS REF also includes updated carbon capture, utilization, and storage (CCUS) cost and performance estimates (Matuszewski and Chou, 2013; Turner and Pinkerton, 2013; Fout et al., 2015).

GCAM-USA REF utilizes GCAM 4.2 and calibrates key input variables that scale energy demand in the end-use sectors to AEO. These key variables include socioeconomics (population and gross domestic product), residential and commercial building floorspace, vehicle miles traveled, and technology cost and performance assumptions in all energy sectors. The year 2010 is the model base year with input values calibrated to International Energy Agency data, while the future trajectory of these input variables is calibrated to AEO. We calibrated residential and commercial floorspace and vehicle miles traveled according to the AEO 2015 Reference case, whereas we updated major drivers for EMF 32, including the socioeconomic assumptions, technology assumptions, and natural gas prices, to be consistent with the AEO 2016 Reference case. The natural gas price calibration is explained in more detail in the next section. Since AEO 2015 and 2016 end at the year 2040, beyond 2040 we extrapolated AEO projections to approach outcomes for the United States in the global version of GCAM. GCAM-USA REF also harmonizes several additional assumptions with AEO

[3] EPSA-NEMS model performs multiple cycles in reaching equilibrium, and the electricity model uses information about future energy prices and electricity demands from prior cycles, but does not have foresight about technology characteristics (i.e. future cost declines).

[4] This is the same reference case used for the second Quadrennial Energy Review (DOE, 2017a). We did not update to AEO 2016, because AEO 2016 was not released before we had implemented the technology cost sensitivities in EPSA-NEMS (see Table 3). EPSA-NEMS includes the most detailed representation of generation and end-use technologies of the models used in this study, but that same capability precluded transferring the work to a new AEO version of the model.

2016, including: power plant cost, power plant efficiencies, power plant capacity factors, building technology efficiencies, industrial fuel efficiencies, vehicle capital cost and efficiencies, and vehicle load factors. The version of GCAM-USA used in this analysis does not include representation of air quality regulations or state policies including the Mercury Air Toxics Standard and the Cross-State Air Pollution Rule, state renewable portfolio standards, and local CO_2 emissions limits imposed by California AB-32 and the Regional Greenhouse Gas Initiative. For more detail, see Iyer et al., 2017.

ReEDS REF calibrates both endogenous and exogenous variables to the AEO 2016 Reference case. Fossil, nuclear, and renewable technology cost projections along with electricity demand, coal prices, and uranium prices are exogenously specified to match the AEO 2016 Reference Case. Beyond the 2040 end year of input data, electricity demand continues to grow at the average 2031–2040 growth rate, and all other cost and price assumptions remain constant. Natural gas supply curves are developed using the AEO 2016 Reference Case but natural gas prices are endogenously determined. ReEDS uses linear, region-specific supply curves for natural gas that are parameterized by regressing price-quantity pairs from AEO scenarios so that gas usage can respond to price in scenarios with different electricity system evolution from AEO. As in the AEO 2016 Reference Case, retirements of nuclear facilities assume an 80-year life, but other technology retirements are defined using the ABB Velocity Suite (see Table 1 for assumed lifetimes). Major existing electricity sector policies represented in ReEDS include air quality regulations such as the Mercury Air Toxics Standard and the Cross-State Air Pollution Rule, state renewable portfolio standards, production and investment tax credits, and local CO_2 emissions limits imposed by AB-32 and the Regional Greenhouse Gas Initiative.

ReEDS-USREP largely adopts the same electricity sector assumptions for REF as just described for ReEDS. In addition, U.S. gross domestic product (GDP), electricity demand, CO_2 emissions, coal prices, and natural gas prices in REF are calibrated to closely match the AEO 2016 Reference Case forecasts. This calibration is performed by making adjustments to available energy reserves (for fossil fuel prices), autonomous energy efficiency improvement (AEEI, for emissions and energy demand), and productivity (for growth in gross domestic product). Energy and economy input data for USREP is largely derived from the Global Trade Analysis Project (GTAP) (Narayanan G. and Walmsley, 2008), the Impact Analysis for Planning (IMPLAN) data set (IMPLAN, 2008), the U.S. Census Bureau (Census Bureau, 2010), and the EIA (2009). Key inputs include production, trade, and population growth.

Due to the challenges inherent in linking two complex models, the ReEDS version used for the linked ReEDS-USREP model does not include some features included in the standalone ReEDS version described above. Key differences include: (1) the renewable electricity tax credit extensions of December 2015 are not included, (2) the updated hydropower formulation developed for the *Hydropower Vision* (DOE, 2016a) is not incorporated, (3) an older representation of state RPS constraints is used, and (4) historical calibration for 2010–2014 does not include improvements to better match generation and CO_2 emissions data. These differences somewhat reduce accuracy of the near-term solutions but should not substantially affect the broader long-term implications of this work.

2.2.2. High natural gas price case (HighNG, same as 3.1.0.2 in EMF 32)

The HighNG case is a scenario that explores the sensitivity of the models to natural gas prices, meant to reflect a reasonable alternative world in which natural gas prices are higher than current day prices but are still within the range of what has happened historically. Natural gas prices under REF assumptions are projected to be low by historical standards, so a sole high gas price scenario is chosen over an additional low gas price scenario to capture a broader range of model outcomes while maintaining a focused scenario suite. We modified REF using a variant of either AEO 2015 or 2016 (U.S. Energy Information Administration (EIA), 2015, 2016) natural gas prices. The AEO 2015 Reference case is most similar to the AEO 2016 Low Oil and Gas Resource side case, so these two scenarios are used to represent a high natural gas price future. Due to data availability at the time of this analysis, EPSA-NEMS HighNG is the 2015 AEO Reference case modified to include the same policy and technology cost updates as in EPSA-NEMS REF (EIA 2015).

GCAM-USA, ReEDS, and ReEDS-USREP HighNG are calibrated to the AEO 2016 Low Oil and Gas Resource side case (U.S. Energy Information Administration (EIA), 2016). The natural gas price trajectories for each model and case are in Fig. 2. While all three models calibrate to the AEO 2016 Low Oil and Gas Resource side case in the HighNG case (and the AEO 2016 Reference case in REF), the method of calibration varies, as does the endogenous representation of natural gas supply and demand. GCAM-USA calibrates natural gas prices by exactly matching AEO natural gas prices in the years 2030–2050, but linearly interpolating natural gas prices between 2010 and 2030. Thus, GCAM-USA uses two exogenously fixed price paths for all of the sensitivities in this study. ReEDS calibrates to AEO by using AEO to develop supply curves, but the actual supply and demand are endogenously calculated in the model. ReEDS-USREP calibrates to AEO by adjusting available energy reserves, and then allowing the model to endogenously calculate natural gas prices. Note that EPSA-NEMS HighNG includes changes to both natural gas and domestic oil prices, whereas ReEDS, ReEDS-USREP, and GCAM-USA modify only natural gas prices. However, oil prices have a limited effect on the electricity sector.

2.2.3. The high-technology goals (HighTech) and high-technology goals with high natural gas price (HighTech-HighNG) cases

The HighTech and HighTech-HighNG cases were run only by the models in this analysis and were not otherwise part of EMF 32. However, there are similarities between the HighTech cases and the renewable and end-use energy efficiency technology sensitivities included in EMF 32. HighTech aims to examine the impact that technology innovation can have on the energy system by addressing the following question: how does the energy system change if all fiscal year 2017 (FY 17) U.S. Department of Energy goals, including technology cost and performance goals, are met? The technology costs for HighTech and HighTech-HighNG follow Fiscal Year 2017 U.S. Department of Energy research, development, demonstration and deployment (RDD&D) goals. These include greater reductions in technology costs for many technologies, including nuclear and renewables, but not for all technologies such as natural gas and coal generation without CCUS (see Table 3), which may differ from total private sector RDD&D investment in generating technologies. Fossil technologies without CCUS follow REF technology projections; thus, we do not incorporate the possibility that these technologies receive indirect benefits from improvements made to renewable, nuclear, and CCUS technologies.[5]

The technology goals are based on detailed underlying analysis conducted to support the fiscal year 2017 budget planning process mainly from U.S. national laboratories. Table 3 references detailed studies that support the development of the DOE research, development, demonstration, and deployment (RDD&D) goals. DOE, 2017b Appendix C includes a graphical comparison of the technology goals. As part of the annual federal budget planning process, technology goals are revisited and either updated or retained based on changes to federal funding levels as well as changes in the market and to consumer preferences. DOE regularly publishes updates on the current state of technology innovation. These are either published as large collective efforts across all technologies (e.g. DOE, 2015e) or for individual technologies (e.g. DOE, 2014; DOE, 2016a, 2016b; Denholm et al., 2016). Each technology goal is developed independently with limited harmonization across the renewable generation technologies (NREL, 2017). Beyond this, the authors did not attempt to harmonize goals to be consistent among technologies,

[5] EPSA-NEMS includes component learning, so the costs of non-CCUS technologies could in theory be reduced through joint learning with similar technologies with CCUS, but these other components are relatively mature with little additional learning.

Table 3
High-technology goals case assumptions and implementation by model.

		Model name		
		EPSA-NEMS	GCAM-USA	ReEDS & ReEDS-USREP
End-use technologies	Biofuels	Reduced cost for biofuel conversion pathways, reduced biofuel refinery capital costs, biomass-to-liquid processing conversion efficiency improved, added 50 million gallons/year of advanced biofuel planned capacity by 2020	No change from REF	ReEDS: Elect-ricity demand same as EPSA-NEMS; ReEDS-USREP: Electricity demand same as REF
	Light-duty vehicles	Changes in LDV costs, improved fuel economy, and increased availability of electric hybrid, EVs, and fuel cell EVs (Moawad et al., 2016)	Updated costs and fuel economy following EPSA-NEMS. No updates to vehicle availability.	
	Heavy-duty vehicles	Modification of HDV classes to better represent U.S. Department of Energy Vehicle Technology Office HDV classifications, changes in HDV costs, increased fuel economy (Stephens et al., 2016)	Updated costs and fuel economy following EPSA-NEMS. No updates to vehicle classes.[a]	
	Hydrogen	\$7/kg-H2 ramping down to \$4/kg-H2[b] by 2020; constant thereafter	Not applicable	
	Buildings	For residential and commercial buildings, increased stringency of appliance standards and building codes, improved new building shell technology performance, introduced new cost effective energy efficient technologies, increased rate of building shell upgrades, and increased consumer acceptance of high efficiency products (represented by lowering hurdle rates to 7% by 2025 and removal of non-economic decision-making factors)	Increased stringency of residential and commercial appliance standards and building codes; lower cost and increased performance for equipment and appliances; increased availability of efficient technologies; improved new residential shell technology performance; increased consumer adoption of high efficiency products	
	Industry	AEO industrial high tech assumptions (EIA, 2014) (earlier availability, lower costs, and higher efficiency industrial equipment and a more rapid rate of improvement in the recovery of biomass byproducts from industrial processes) combined with technology improvements, which yields more efficient energy use for pulp and paper, iron and steel, petroleum refining, chemicals, and cement, and updated data on the use of recycled aluminum (DOE, 2015a, 2015b, 2015c, 2015d; U.S. Geological Survey (USGS), 2016).	Improved efficiency levels for all fuels, model has one industrial sector	
Electric sector	Carbon-capture, utilization and storage	Improvements to capital cost trajectories, heat rates, and fixed and variable operating and maintenance (O&M) costs for new full capture coal and NGCC CCUS plants, partial capture coal CCUS plants, and coal retrofits with CCUS	Same as EPSA-NEMS for new CCUS plants; model has no retrofit technology	Same as EPSA-NEMS
	Nuclear	New build times reduced from 6 to 5 years, 9% reduction in projected overnight capital costs for state-of-the art nuclear technology in 2025 and 32% by 2040 relative to reference. Assumes existing plants will operate for 80 years with no required early retirements	Reduced overnight capital and O&M costs for nuclear following EPSA-NEMS	Same as EPSA-NEMS
	Electric grid	Share of new transmission capacity applied to reserves increases from 75% to 85%, available transmission capacity increases from 75% to 85% on existing transmission lines, spinning reserve requirements for renewables decrease from 50% to 30% of generation, use of load shifting technologies tripled from 3.5% to 11% by 2040, and improvement in interconnection limitations for distributed generation in buildings accelerated by 10 years compared to reference case	No change from REF	No change from REF
	Solar	Cost reductions for utility-scale, commercial, and residential PV using the 2016 NREL ATB Low Case (NREL, 2016). CSP modified to include 6 h of electricity storage and changes to cost trajectory.	Reduced costs for utility-scale PV only following EPSA-NEMS	NREL 2016 ATB Low Case (NREL, 2016)
	Wind	Onshore and offshore wind capital costs reduced for best wind classes with more modest reductions for lower wind classes based on NREL 2016 ATB Low Case (NREL, 2016). Improvement in capacity factors for onshore and offshore wind. Increased construction time from 3 to 4 years and lengthened the onshore PTC eligibility schedule by 1 year.	Reduced costs for onshore wind only following EPSA-NEMS	NREL 2016 ATB Low Case (NREL, 2016)
	Hydropower	Improved site-specific costs, performance, and expanded resource availability with some upgrade options for existing sites (DOE, 2016a)	No change from REF	NREL 2016 ATB Low Case (NREL, 2016)
	Geothermal	Reduced site-specific costs for geothermal flash, binary, and enhanced by 12.5% by 2040 following NREL, 2016	No change from REF	NREL 2016 ATB Low Case (NREL, 2016)

[a] GCAM-USA has fewer vehicle classes than EPSA-NEMS.
[b] Gallon gasoline equivalent.

meaning the goals are not consistent relative to a standard statistical metric.

While best efforts are made to project future technology costs given 2017 RDD&D fiscal year funding levels, there are many factors that influence innovation. We note that individual technology goals included in this analysis may not be realized while other technology goals may be met sooner than expected (e.g. DOE, 2018). We recognize that there is a deep body of research focused on what drives innovation (e.g. DOE, 2017c). This analysis focuses on comparing across several output metrics, assuming the exogenous technology goals are realized.

DOE RDD&D goals were translated into model inputs for HighTech as described in Table 3.[6] For this scenario, technology learning is specified

[6] Note that the inputs listed in Table 3 represent national cost and performance technology goals.

Table 4
Electric power sector emissions cap.

Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030–2050
Million metric tons CO_2	1891	1846	1800	1800	1800	1677	1677	1677	1600	1600	1.8% decrease per year[a]

[a] Based on the average annual reduction from 2020 to 2030.

exogenously through the inputs described in Table 3. EPSA-NEMS implemented the most model changes, including cost reductions for generating and end-use technologies as well as efficiency and other performance improvements. GCAM-USA implemented a subset of cost and performance improvements for both generation and demand technologies. ReEDS and ReEDS-USREP implemented most of the cost and performance improvements for generating technologies, including some differences in grid and renewable technologies. The two models did not implement any of the HighTech demand technology assumptions, although ReEDS HighTech energy demand and fuel prices are benchmarked to energy demand from the EPSA-NEMS HighTech case. Using this case trajectory allows ReEDS to reflect assumed energy efficiency improvements that occur in EPSA-NEMS and GCAM-USA HighTech. Energy efficiency improvements are not implemented in ReEDS-USREP HighTech. More detail about the EPSA-NEMS and GCAM-USA HighTech technology assumptions are available in previous publications (DOE, 2017b; Iyer et al., 2017).[7] HighTech-HighNG uses the same natural gas assumptions as for HighNG and the same technology cost and performance metrics as for HighTech.

2.2.4. CO_2 Policy scenarios (Pol-REF, Pol-HighNG, Pol-HighTech, Pol-HighTech-HighNG)

The CO_2 Policy scenarios listed in Table 2 take the reference scenarios (REF, HighNG, HighTech, HighTech-HighNG) and add a representative power sector carbon dioxide (CO_2) emissions reduction policy. The CO_2 policy limits the maximum total quantity of CO_2 that can be emitted by the power sector on a national scale—a national mass-based emissions cap. The annual cap imposed in the models is shown in Table 4, and is modeled with national trading allowed across all sub-national regions. This is the same power sector national mass-based emissions cap implemented by the 3.1.1.x scenarios in EMF 32. The cap through 2030 is based on the U.S. Environmental Protection Agency's final Clean Power Plan regulatory impact analysis for the rate-based compliance pathway (EPA, 2015). CO_2 allowance banking is not modeled in this analysis.

Finally research, development, demonstration, and deployment (RDD&D) goals and a power sector CO_2 policy can have overlapping impacts on technological innovation. For example, a CO_2 policy can spur technological innovation. Most of the models, except for EPSA-NEMS, do not model this effect and thus most of the models isolate the effect of the CO_2 policy from assumptions about technological innovation.

3. Results

To compare across models, we selected output variables that are most relevant for analyzing energy sector evolution in these scenarios. These include: electricity generation, fossil fuel carbon dioxide (CO_2) emissions from the power sector, wholesale power prices, and energy consumption by end-use sectors. We describe the reference case first, followed by the impact of: changes in natural gas prices, changes in technology cost and performance metrics, and finally a policy that reduces CO_2 emissions from the power sector.[8]

[7] See Appendix C of DOE, 2017b for visualization of the scenario assumptions. The HighTech case run with the EPSA-NEMS model is the same as the "Advanced Technology" scenario in DOE, 2017b.

[8] Emissions of criteria air pollutants are also dependent on the type of technology used to generate electricity but are outside of the scope of this analysis.

3.1. The reference scenarios

3.1.1. The reference case (REF)

This section describes electricity sector outcomes for the reference case (REF), with sub-sections containing detailed descriptions of the resulting capacity expansion and dispatch, CO_2 emissions, and wholesale electricity prices. Overall projections for all models are characterized by rising electricity demand met by increasing amounts of natural gas-fired, solar, and wind generation while coal-fired generation decreases. The resulting CO_2 emissions are relatively constant for most REF model projections through 2040 but decrease after 2040. Trends in wholesale electricity prices differ by model.

3.1.1.1. Electric power sector generation. Electric power sector generation in REF has similar elements across all models (Fig. 1a). Total electricity generation increases over time. The majority of the REF case electricity generation in 2010 is from natural gas and coal-fired power plants, with a smaller percentage from nuclear and renewable power. By the final year of the projection, electricity is generated from a more diverse mix of technologies than the present in three models, EPSA-NEMS, ReEDS, and ReEDS-USREP. Natural gas becomes the dominant generation fuel, with electricity production increasing by 88–195% by 2040. However, greater diversification is achieved through a decline in coal-fired generation (54–51% by 2040), roughly constant hydropower and nuclear generation, and an increase in utility-scale solar photovoltaic (PV) and onshore wind power (combined increase of 407–450% by 2040).

Differences in electricity generation REF case trends include: (1) GCAM-USA modeling of future electricity demand in end uses results in a slightly higher increase in total generation than EPSA-NEMS to 2040, and noticeably higher than ReEDS and ReEDS-USREP by 2050, (2) GCAM shows a higher fraction of the growth met by natural gas-fired generation; and (3) more onshore wind power is built post-2040 in ReEDS and ReEDS-USREP. While ReEDS and ReEDS-USREP demand is based on EPSA-NEMS output, the EPSA-NEMS demand shown here is larger because it includes industrial combined heat and power generation that is not included in the ReEDS and ReEDS-USREP electric sector modeling frameworks. Though all models use common technology cost assumptions, more wind is deployed in ReEDS and ReEDS-USREP because these models utilize higher-resolution wind supply curves and a more detailed representation of variable renewable energy that allows a greater amount of wind resource to be competitive with natural gas-based capacity. On the other hand, GCAM-USA does not weight all generation technologies equally, with fossil-fuel fired generation preferred over renewable generation.

3.1.1.2. CO_2 emissions. The REF case trends for electricity sector CO_2 emissions are relatively consistent across models, hovering around 2000 MMT through 2040 before decreasing thereafter (Fig. 1b). The model differences in CO_2 emissions in the REF case are due to: (1) how much energy is demanded, (2) how quickly wind power is deployed, and (3) assumptions about power plant retirements. REF CO_2 emissions in EPSA-NEMS are almost flat, increasing slightly over time as energy demand increases, but are tempered by increased generation from zero-emitting sources. GCAM-USA REF emissions have a consistently decreasing trajectory because of assumed coal retirements and the competitiveness of lower-emitting (natural gas) and zero-emitting sources (renewables) for new investment. ReEDS REF emissions increase after

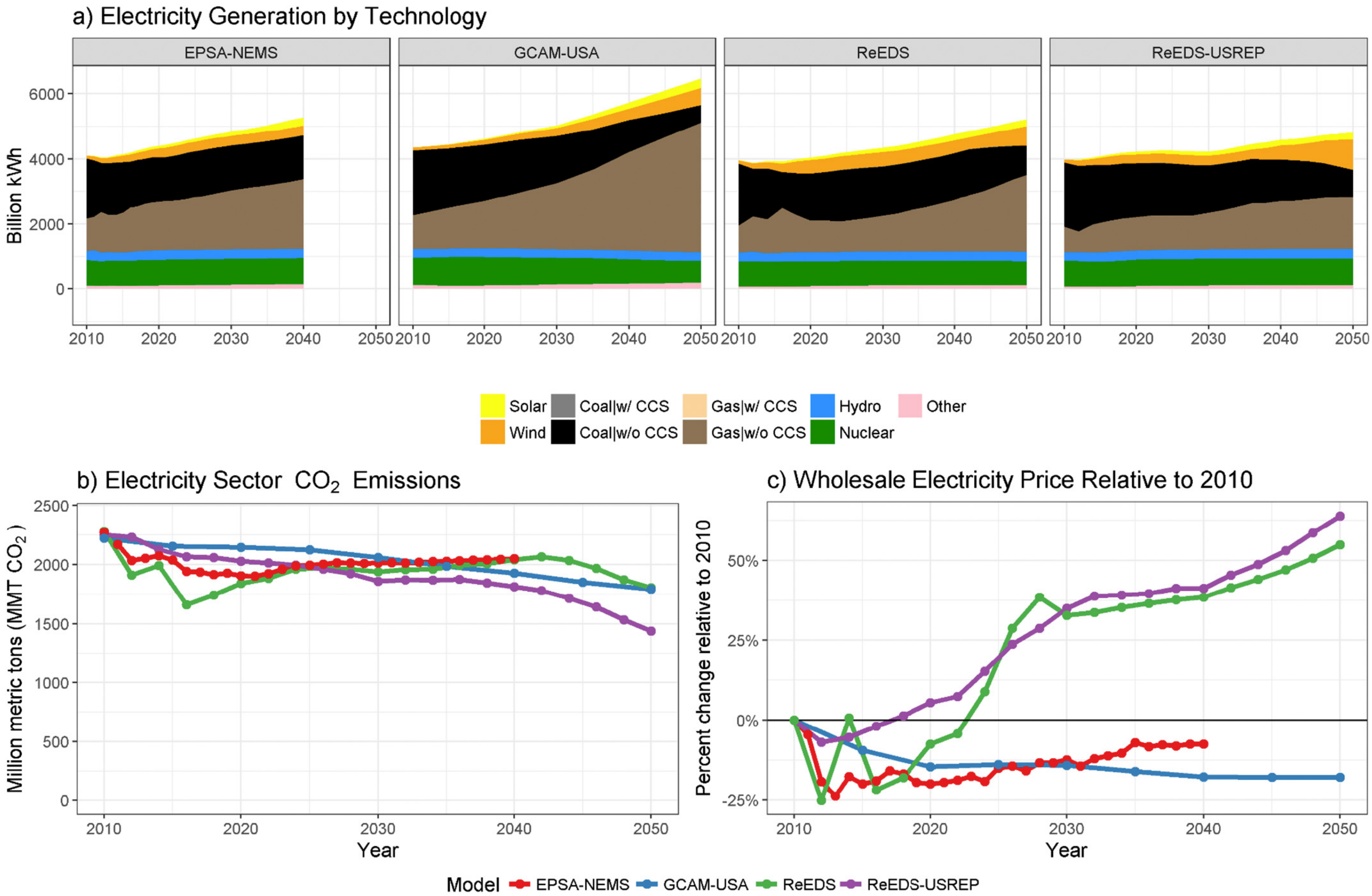

Fig. 1. Reference (REF) case outputs. The upper panel displays REF electricity generation by technology type. The lower two panels from left to right display: REF CO_2 emissions and REF wholesale electricity prices. Dots indicate model output years. CCS = carbon capture, utilization, and storage; hydro = hydropower, other = geothermal power, biomass power, and oil-fired generation.

2016 then remain relatively stable from the mid-2020s to 2040 when new natural gas capacity added to meet increasing demand is only somewhat offset by retiring coal capacity, then emissions fall when accelerated coal retirements coincides with more natural gas and wind deployment. ReEDS-USREP REF emissions decrease steadily because coal generation is steadily displaced by natural gas generation in the near-to-medium term and by wind deployment in the 2040s and beyond.

3.1.1.3. Wholesale electricity prices. Wholesale electricity price trends vary the most among the output metrics chosen for comparison in the study. Wholesale electricity prices differ between the models due to variations in: (1) natural gas prices, and (2) capacity market requirements. Wholesale electricity prices in Fig. 1c are shown as percent change from 2010 because the models have different definitions and reporting for wholesale prices.[9] In EPSA-NEMS and GCAM-USA, REF wholesale electricity price trends generally track natural gas price trends.[10] However, in ReEDS and ReEDS-USREP, a growing contribution of new capacity costs leads to a rapid price increase from 2016 to 2030 relative to natural gas price trends.[11] Initially, capacity costs contribute little to electricity prices in ReEDS and ReEDS-USREP because the practical constraints promoting actual announced projects are less fully represented in the model, meaning the generating capacity appears to be overbuilt. However, as power plants retire and demand grows, the models require new capacity to meet adequacy reserves, and wholesale electricity prices sharply increase. Beyond 2030, ReEDS and ReEDS-USREP REF wholesale electricity prices follow natural gas price trends. The transition between these two regimes is smoother for ReEDS-USREP than ReEDS because ReEDS is an electricity sector only model, and thus, projects more abrupt changes in wholesale electricity prices that cannot be buffered by feedbacks from other sectors.

3.1.2. The high natural gas price case (HighNG)

This section compares REF electricity sector outcomes with those in the HighNG case. When natural gas prices increase, all models reduce natural gas-based generation and increase renewable generation. Additionally, the models that include the capability dispatch existing coal-fired power plants more frequently than REF, since natural gas and coal are the most substitutable power sources. Higher natural gas prices can produce slight increased CO_2 emissions in the short-term, but CO_2 emissions are either the same or lower than REF CO_2 emissions in the long-term because greater renewable penetration and lower electricity demand offset greater emissions from coal. Higher natural gas prices lead to higher wholesale electricity prices in all models.

[9] EPSA-NEMS, ReEDS, and ReEDS-USREP calculate wholesale electricity prices as a combination of marginal energy and capacity market prices. REF energy market prices are driven primarily by natural gas price trends since natural-gas generation is often the marginal generating resource. Capacity market prices are driven by the need for new capacity to meet reserve margin requirements, which is largely met through capital investment in natural gas turbines. In GCAM-USA, the wholesale electricity price is defined in each period as the levelized cost of building and operating new power plants, which is similarly driven by the marginal cost of building and operating natural gas generation.

[10] GCAM-USA REF wholesale prices decrease slightly although REF natural gas prices remain flat, because the levelized cost of building new power plants decreases over time with technological change.

[11] The spike in 2014 ReEDS REF wholesale prices is due to difficulties in calibration to AEO.

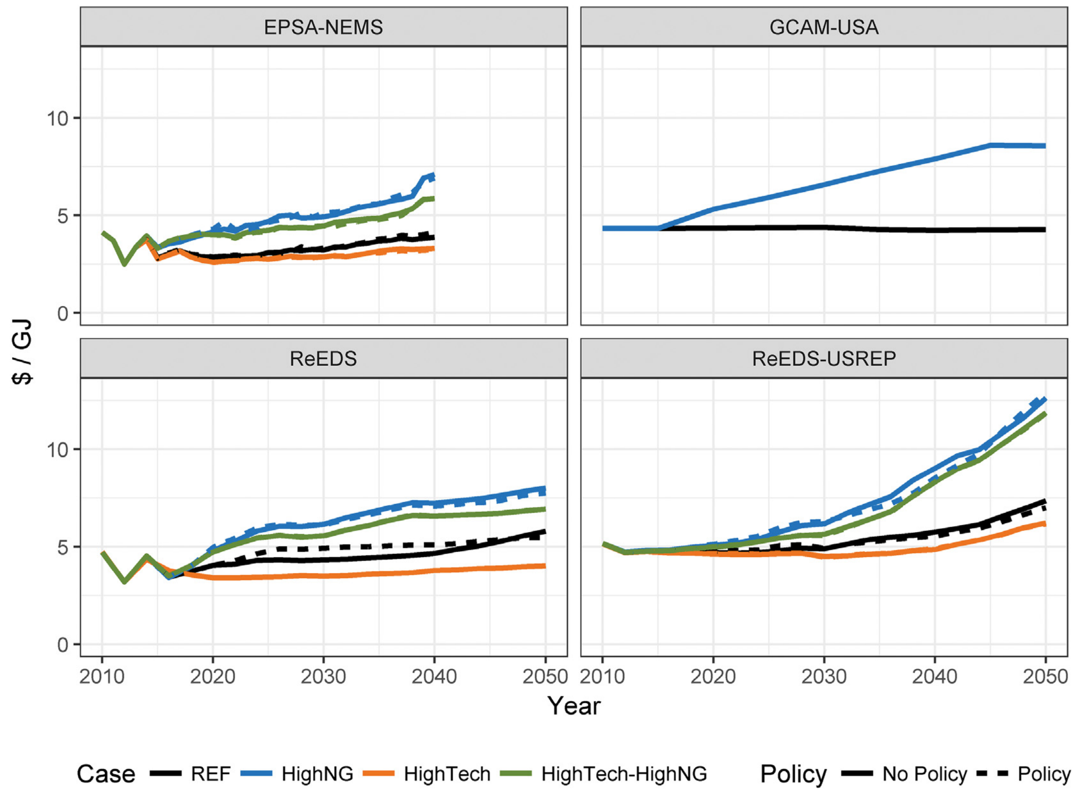

Fig. 2. National average natural gas prices electric utilities pay for delivered natural gas. Note that GCAM-USA has only two distinct natural gas prices. GCAM-USA HighTech, Pol-REF, and Pol-HighTech natural gas prices are the same as for REF, whereas GCAM-USA HighTech-HighNG, Pol-HighNG, and Pol-HighTech-HighNG natural gas prices are the same as for HighNG. All monetary values are expressed in 2010 U.S. dollars.

3.1.2.1. Natural gas prices. In the last 20 years, natural gas prices have fluctuated between approximately \$2/GJ (\$2/MMBtu, Henry Hub spot price) and \$13/GJ (EIA, 2017c). Over the last 5 years, however, natural gas prices have been almost continually low, under \$5/GJ. This wide variation in natural gas prices has profoundly influenced U.S. electricity markets, which underscores the importance of exploring the models' sensitivity to alternative natural gas prices.

The national average natural gas prices delivered to electric utilities are reported by the models for all scenarios are shown in Fig. 2. We discuss REF and HighNG natural gas prices in this section. Natural gas price trajectories from other scenarios are discussed in subsequent sections. REF gas prices are near the lower bound of historical record, so we modeled a high natural gas price sensitivity (HighNG) to better explore future possibilities if natural gas prices recover to historical levels. HighNG natural gas prices increase much faster than REF prices

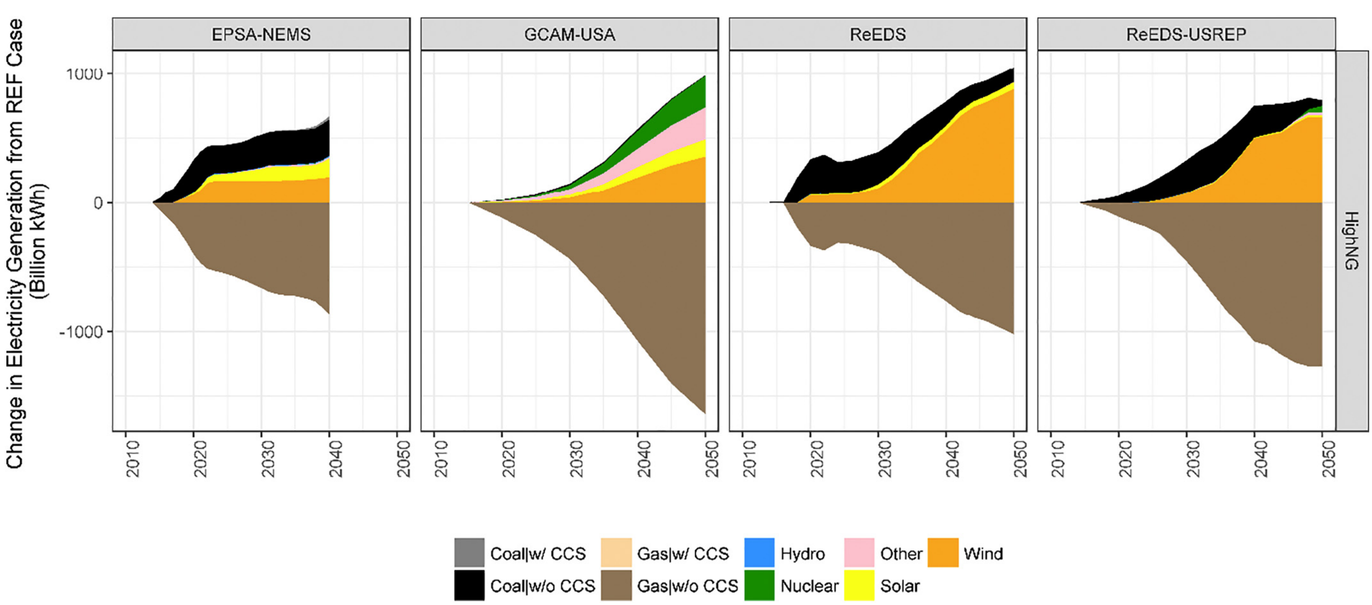

Fig. 3. Change in electricity generation for the HighNG case from the REF case. CCS = carbon capture, utilization, and storage; hydro = hydropower, other = geothermal power, biomass power, and oil-fired generation.

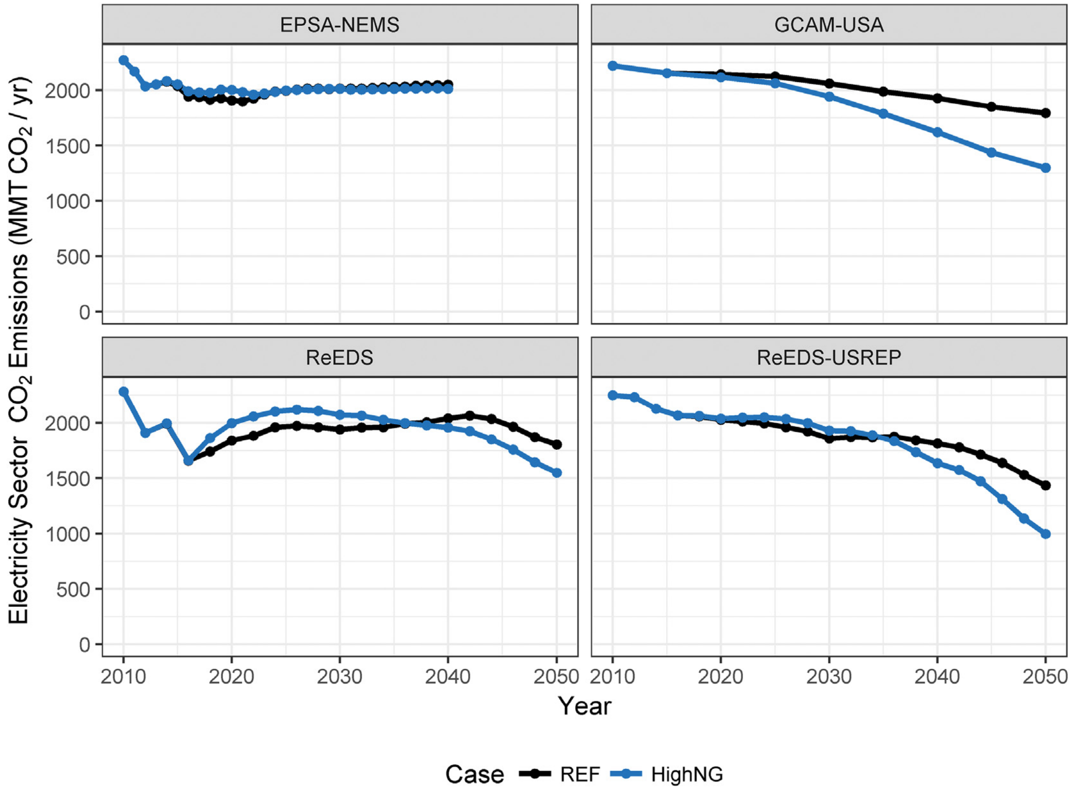

Fig. 4. Electricity sector CO_2 emissions for the HighNG and REF cases. Dots indicate model output years.

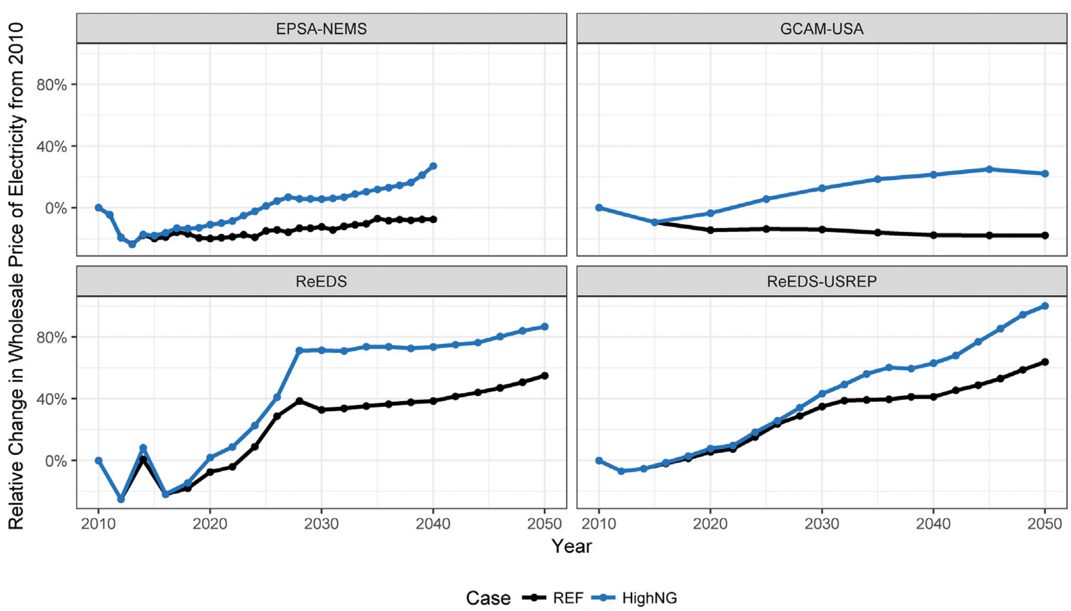

Fig. 5. Relative change in wholesale price of electricity from 2010 for the HighNG and REF cases. Dots indicate model output years.

by the final modeled year, reaching as high as \$12.50/GJ by 2050 in ReEDS-USREP.

3.1.2.2. Electricity generation. All models reduce natural gas-based generation when natural gas prices are high (Fig. 3). Fig. 3 shows the change in generation from REF. The magnitude of those changes (approximately ±1000 TWh), is on the order of approximately 15–25% of total generation at the end of the projection. In three models, existing coal-fired power plants are dispatched more often with higher natural gas prices. In addition, more renewable generating capacity, mostly onshore wind, is built (see Fig. 3).[12] Natural gas-fired generation competes primarily with existing coal-fired power and new renewable generation. GCAM-USA, does not permit increased coal generation by assumption for this analysis, which highlights the need for energy models to represent natural gas to coal fuel switching to capture transitions in generation due to fuel price volatility. Moreover, GCAM-USA,

[12] Note that the same exogenously specified electricity demand for ReEDS is assumed for both REF and HighNG, which is why it has a 1:1 switching from gas to other generating technologies versus a net electricity demand reduction as in other models.

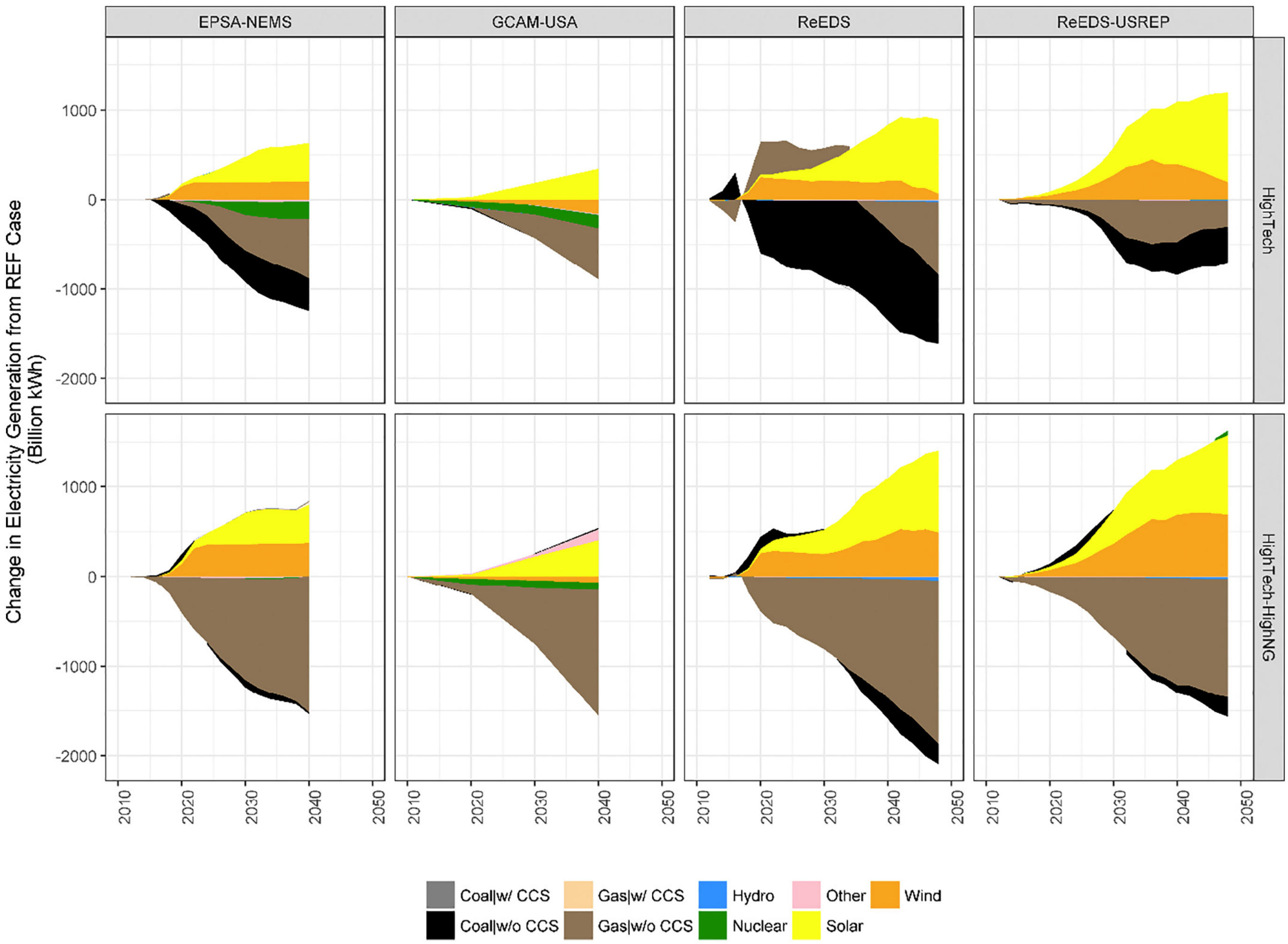

Fig. 6. Change in electricity generation for the HighTech and HighTech-HighNG cases from the REF case. CCS = carbon capture, utilization, and storage; hydro = hydropower, other = geothermal power, biomass power, and oil-fired generation.

which is designed to study average long-term trends rather than marginal changes to generating resources, builds more types of generating resources including nuclear.[13]

3.1.2.3. CO_2 emissions. Most of the models have slight increases in CO_2 emissions relative to the REF case under high gas prices relative to the REF case in the short term (Fig. 4). By mid to late projection, CO_2 emissions are either the same or lower than REF CO_2 emissions. Three models, EPSA-NEMS, ReEDS and ReEDS-USREP, initially displace the higher-priced natural gas-fired generation with coal-fired generation which increases short-term CO_2 emissions. Since GCAM-USA cannot increase coal generation, short-term CO_2 emissions decrease. Longer-term, the more natural gas prices increase, the more CO_2 emissions decrease by the end of the projection. Thus, EPSA-NEMS has almost no long-term change in CO_2 emissions compared to REF, and ReEDS-USREP has the highest long-term reduction in CO_2 emissions (approximately450 $MMTCO_2$ by 2050).

3.1.2.4. Wholesale electricity prices. Higher natural gas prices lead to higher wholesale electricity prices in HighNG compared to REF in all models throughout most of the projection (Fig. 5). Wholesale electricity prices increase by 25–40% in the final year of the respective model projections. For EPSA-NEMS and GCAM-USA, the projected increase in wholesale electricity prices largely follows projected natural gas price trends as expected. Natural gas is often the marginal generating resource. ReEDS and ReEDS-USREP HighNG wholesale electricity prices are also linked directly to natural gas price trends, but include an additional contribution to wholesale prices in the 2020s from the cost of capacity requirements. The capacity component of wholesale electricity prices is similar for HighNG and REF.

3.1.3. The high-technology goals cases (HighTech and HighTech-HighNG)

This section explores the impact of HighTech cases defined in Section 2.2.3 by comparing HighTech to the REF case and HighTech-HighNG to the HighNG case. The main findings include: achieving high-technology goals according to the technology cost projections used in this analysis mainly increases renewable generation and reduces new natural gas-fired and existing coal-fired generation (Fig. 6). Even though many different technology costs were considered and changed for HighTech and HighTech-HighNG, the two main generation technologies with additional market penetration by 2050 compared to reference conditions are solar photovoltaics and onshore wind.[14]

[13] Natural gas generation in GCAM-USA is replaced with a distribution of generating technologies, because it is designed to provide average long-term trends. The other three models choose one marginal generating resource for a given price and quantity.

[14] Note, as explained in Section 2.2.3, although all models implemented some subset of technology cost and performance changes, it varied by model for the HighTech and HighTech-HighNG cases (see Table 3). Thus, the differences between models for these two cases are partly due to differences in technology assumptions and partly due to model architecture, as explained in the text.

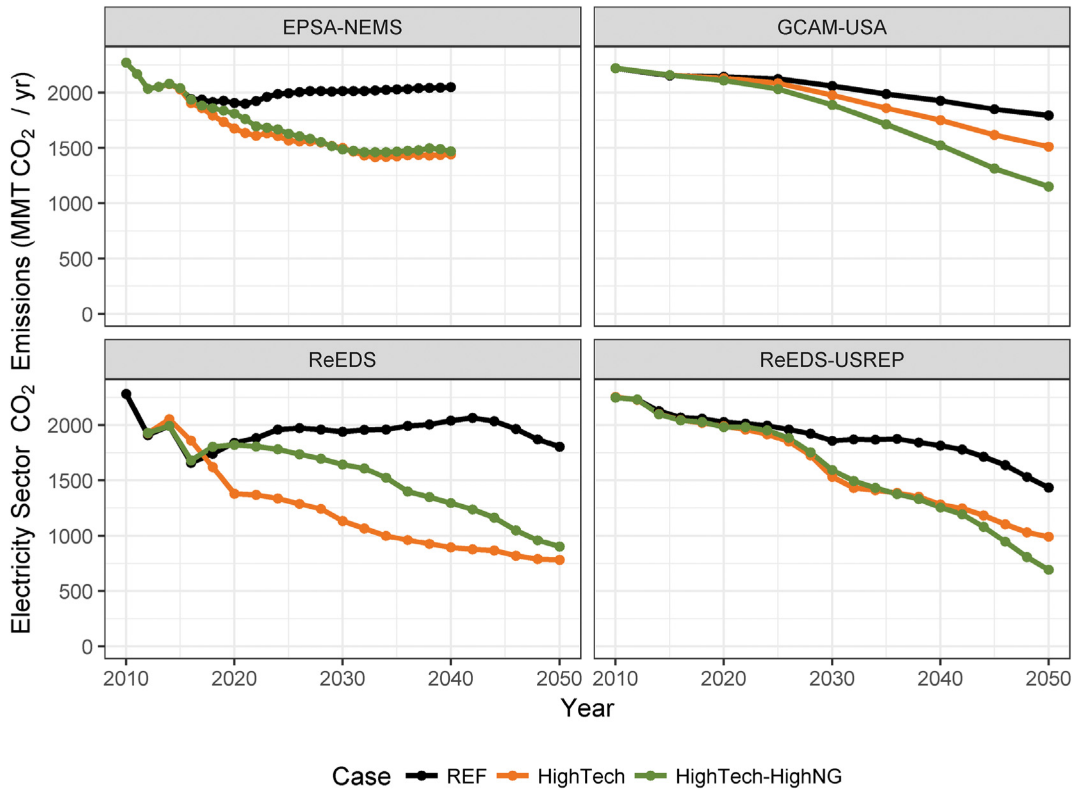

Fig. 7. Electricity Sector CO_2 emissions for the HighTech, HighTech-HighNG, and REF cases. Dots indicate model output years.

Achieving the high-technology goals decreases CO_2 emissions, regardless of the assumptions about natural gas prices, because low carbon generation becomes more cost competitive (Fig. 7). Furthermore, at reference natural gas prices, achieving the high-technology goals lowers wholesale prices. However, wholesale electricity cost savings decrease as the cost of natural gas generation increases (Fig. 8).

3.1.3.1. Electric power sector generation. The HighTech case increases combined solar and onshore wind generation by 100–640 billion kWh in 2030, 20–1080 billion kWh in 2040, and 390–700 billion kWh in 2050 (Fig. 6). These changes correspond to 9–24% of total generation in 2030, 14–35% in 2040, and 18–43% in 2050. Under the technology assumptions used for this analysis, wind is initially more cost-competitive than solar in EPSA-NEMS, ReEDS, and ReEDS-USREP until the 2030s when the cost of solar PV falls relative to other technologies (DOE, 2017b, Table C-1). ReEDS and ReEDS-USREP build the most additional solar PV in HighTech by the end of the projection. Solar PV deployment in these two models is more sensitive to changing technology costs due to higher resolution supply curves capturing low-cost resource and valuation of PV capacity during periods of high electricity demand. Note

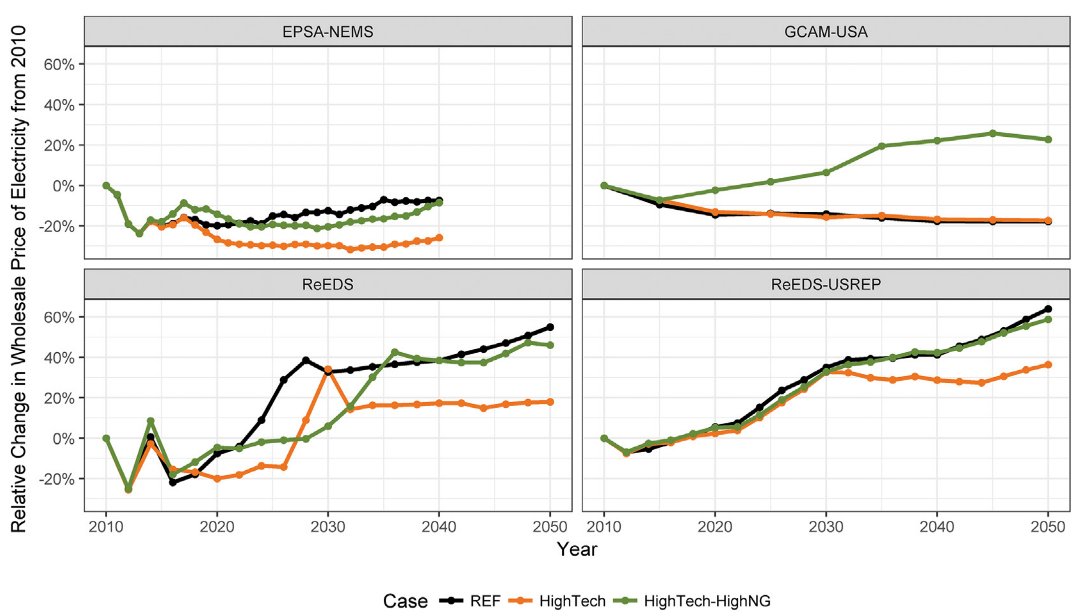

Fig. 8. Relative change in wholesale price of electricity for the REF, HighTech, and HighTech-HighNG cases. Dots indicate model output years.

that unlike the other three models, ReEDS-USREP does not incorporate DOE goals for demand technologies in HighTech, so low-cost generation allows a net increase in demand that is met by increased renewables deployment. The GCAM-USA response to renewables, especially wind, is somewhat unique in HighTech. As discussed more later, natural gas prices do not change in GCAM-USA between the reference technology conditions and HighTech, unlike for the other models. That, combined with the model's unequal weighting among generation technologies in favor of fossil-fuel fired generation, means that renewable generation in GCAM-USA's HighTech case is closer to reference conditions than the other models.

The HighTech case decreased coal and natural gas generation by 880–1960 billion kWh in 2030, 1960–2890 billion kWh in 2040, and 2190–3709 billion kWh in 2050 (Fig. 6). This is 47–67% in 2030, 40–66% in 2040, and 34–66% in 2050 of total generation. For all models that incorporate energy efficiency improvements (all but ReEDS-USREP, as defined in Table 3), there is a net reduction in total generation, which also contributes to a net reduction in natural gas- and coal-based generation. Without increased energy efficiency, low-cost electricity would facilitate greater consumption as happens in ReEDS-USREP. In the ReEDS HighTech case, coal generation decreases rapidly after a slight near-term increase because lower demand and competition from renewables reduce coal generation capacity factors, which below a given threshold triggers coal retirements. The ReEDS near-term increase in coal-fired generation is driven by slightly higher natural gas prices in those years (Fig. 2). As a point of comparison, EPSA-NEMS, which determines plant retirements based on the economic viability of each plant rather than on assumptions about plant utilization or lifetime, has a more gradual reduction in coal-fired generation over time. ReEDS-USREP, which includes the ReEDS electricity sector model, is not a useful comparison to ReEDS in this instance, because ReEDS-USREP slower coal retirements are tied to higher electricity demand. Another model-specific response, GCAM-USA has no additional coal retirements in HighTech compared to reference conditions. The GCAM-USA reference case includes more coal plant retirements than the other models due to plant lifetime assumptions. No additional economic-based coal retirements are triggered in HighTech.

The HighTech case reduces a small amount of nuclear generation in HighTech compared to REF in two models, EPSA-NEMS and GCAM-USA, due to higher operating costs than the new generation. The other two models, ReEDS and ReEDS-USREP, do not have economic-based nuclear retirements, and thus, neither model is useful for comparing how nuclear generation differs across the sensitivity cases.

Finally, the HighTech-HighNG case, with high-technology goals and high natural gas prices, mainly increases wind generation compared to HighTech with reference natural gas prices. Wind is preferred to solar because it has higher capacity factors and can supplant natural gas-based generation throughout the day, whereas solar cannot do the same without substantial storage investment. The incremental effect of high gas prices on gas-fired generation is similar with HighTech technology costs as with reference technology assumptions (i.e., HighTech-HighNG minus HighTech as compared to HighNG minus REF). Unlike HighNG with reference technology assumptions, coal generation does not increase beyond REF other than in limited quantities in the near term, but coal capacity retirements also do not significantly increase beyond REF. The additional plant retirements are almost exclusively natural-gas related.

3.1.3.2. CO_2 emissions. Achieving the high-technology goals decreases CO_2 emissions relative to REF regardless of natural gas price assumptions, because low carbon generation becomes more cost competitive (Fig. 7). HighTech annual CO_2 emissions ($MMTCO_2$) decrease by 250–1150 in 2030, 470–1390 in 2040, and 710–1500 2050 from 2010. This corresponds to a decrease of 11–50% in 2030, 21–61% in 2040, and 32–66% in 2050 from 2010.

One of the remarkable results in this analysis is how much CO_2 emission reductions varies across the models. The most important reason for the variation across models in the high technology cases is connected to variation in modeled natural gas prices (Fig. 2). Projected CO_2 emission reductions are directly related to the relative reduction in natural gas prices between the reference case and the HighTech case, because natural gas combined cycle power plants are often the marginal generating unit. For example, GCAM-USA models natural gas prices as a long-term global market price, which mutes the domestic natural gas price response considerably. The other three models include domestic natural gas markets. In addition, GCAM-USA HighTech includes some additional efficiency improvements relative to REF. Thus, GCAM-USA has the smallest reduction in CO_2 emissions in HighTech. On the other hand, ReEDS, which has the most CO_2 emission reductions in HighTech relative to REF, has both the greatest reduction in natural gas prices and the greatest increase in coal retirements. ReEDS-USREP has lower CO_2 emission reductions than ReEDS because the HighTech case does not include energy efficiency improvements that lower energy demand. EPSA-NEMS HighTech case has a more gradual decline in coal generation than ReEDS and has more demand reduction than GCAM and ReEDS-USREP and thus resulting CO_2 emissions are in the middle of the range of the four models.

Achieving high-technology goals at high natural gas prices (as in the HighTech-HighNG case), results in lower CO_2 emissions compared to reference technology and natural gas prices, but results in either higher or lower CO_2 emissions compared to achieving the high-technology goals at reference natural gas prices. EPSA-NEMS and ReEDS-USREP both allow for endogenous demand response when fuel and technology prices increase, which keeps CO_2 emissions more similar between the HighTech and HighTech-HighNG cases than for the other models. ReEDS HighTech-HighNG has higher CO_2 emissions compared to HighTech because ReEDS does not reduce electricity demand when natural gas prices increases. On the other hand, GCAM-USA does have demand response and thus the higher natural gas prices reduce natural gas generation and thus emissions.

3.1.3.3. Wholesale electricity prices. Fig. 8 plots wholesale electricity prices relative to a common 2010 baseline for REF, HighTech, and HighTech-HighNG. The difference in this measure between the HighTech and REF scenarios is in the range of −17% to 1% in 2030, −21% to 1% in 2040, and − 37% to −1% in 2050; electricity prices are typically lower in HighTech than the REF case. As for CO_2 emissions, wholesale electricity prices are directly related to natural gas prices. Natural gas prices do not change in GCAM-USA between the reference technology and high-technology cases and thus, wholesale electricity prices do not change. The other three models with domestic natural gas markets, decrease natural gas prices and, thus, decrease wholesale electricity prices as the fraction of variable renewable energy increases. As discussed previously, the big increase in the 2020s for ReEDS and ReEDS-USREP is due to the growing capacity market component of electricity prices, which stabilizes beyond 2030.

The difference in 2010–2050 price changes between HighTech-HighNG and REF are in the range of −20% to 27% in 2030, −40% to 1% in 2040, and −41% to 9% in 2050. All of the models have the same directional response. Higher natural gas prices increase wholesale electricity prices. For three of the models, the increase in wholesale electricity prices from higher natural gas prices roughly offsets the reduction from reaching the high-technology goals. For GCAM-USA, natural gas prices are not sensitive to changes in technology costs and thus, wholesale electricity prices for the high-technology goal case with high natural gas prices are the same as for the reference technology case with high natural gas prices.

3.1.4. Energy demand by sector in the reference scenarios

Demand for energy increases over time in the REF case for all models (Fig. 9). We note that the Annual Energy Outlook, which underpins the

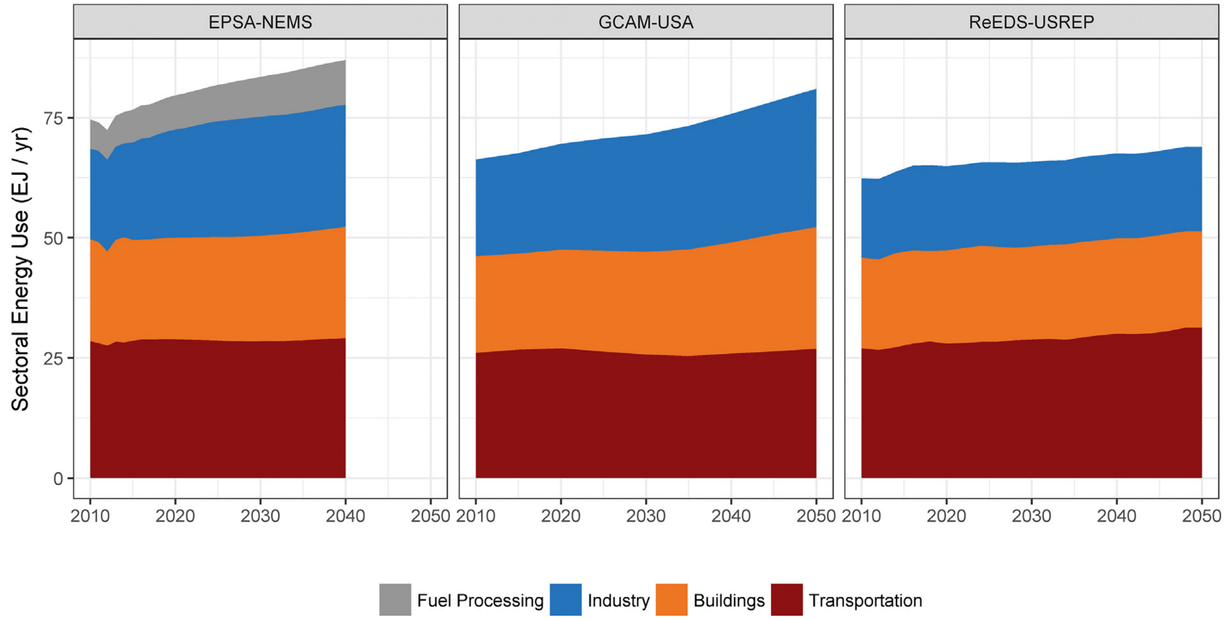

Fig. 9. Energy Demand by Sector for the REF case. Note that sectoral energy demand for ReEDS is not shown because ReEDS is an electricity sector only model. EPSA-NEMS industrial sector typically also includes fuel used to produce and process fuels for end-use consumption, such as for petroleum refining in its reporting. For comparison across the models, we break out fuel processing separately.

scenarios in this analysis, has overestimated the projected increase in demand for the last several years (EIA, 2017d). Thus, based on recent history, the demand projections used for this analysis may overestimate actual total demand in future years. However, the important comparison for this analysis is the relative differences of the various sensitivities compared to REF and what can be learned from those differences, not the absolute energy demand use for REF.

REF industrial sector energy use is comparable in EPSA-NEMS and GCAM-USA but differs for ReEDS-USREP. The differences stem from each model's definition of which subsectors are included in the industry sector. The industrial sector in EPSA-NEMS includes the energy used in all manufacturing and non-manufacturing industries, including fuel for feedstock. Although, GCAM-USA includes less sub-categorization in the industrial sector, the total industry energy demand is comparable to

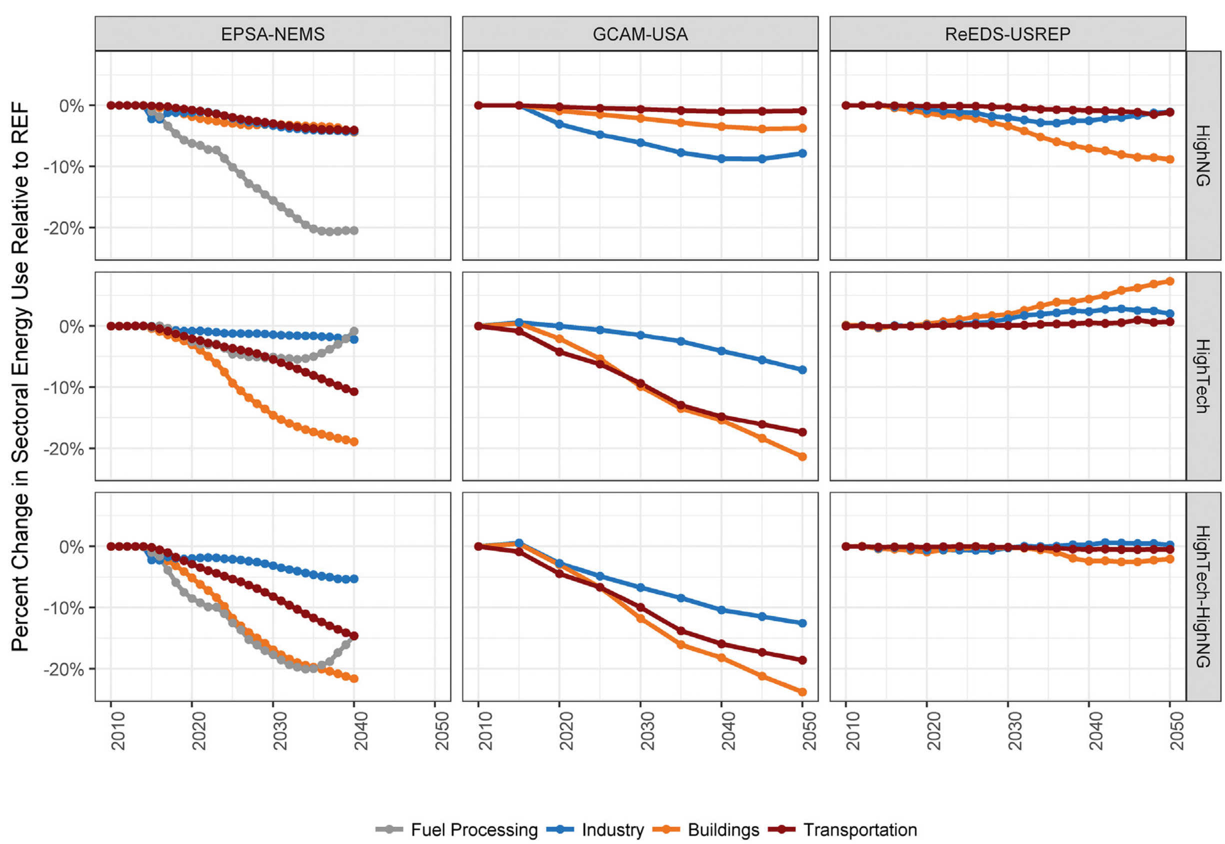

Fig. 10. Relative Change in Energy Demand by Sector for the HighNG, HighTech, and HighTech-HighNG cases from the REF case.

EPSA-NEMS. The ReEDS-USREP industrial sector includes manufacturing and energy-intensive services only, leaving out non-manufacturing categories such as agriculture, construction and mining.

Building and transportation sector REF energy use is more similar across the models. The building sector is defined similarly in each model and is the sum of the residential and commercial sectors' energy use. Although representation of the transportation sector varies across models, the modeled transportation subsectors included are similar, so the transportation sector's energy use does not vary greatly across models in the scenarios discussed in this analysis.

Changes to sectoral energy use depend on the models' representations of energy use and whether or not energy efficiency increases in the scenarios (Fig. 10). For example, in HighNG, natural gas usage in buildings and industry decreases for EPSA-NEMS and GCAM-USA, both sectors have significant natural gas use. Whereas in ReEDS-USREP, building energy use decreases in the HighNG scenario because the model finds natural gas less expensive to substitute in that sector than in other sectors. EPSA-NEMS HighNG has lower transportation energy consumption, mainly due to less pipeline fuel used to transport natural gas to all sectors, which is not represented in the other two models.

Energy demand varies even more across the HighTech cases. In EPSA-NEMS and GCAM-USA, the HighTech case includes lower cost end-use efficiency improvements, which lead to a decrease in energy demand in all sectors. The buildings sectors in both models has the largest reduction in energy demand due to the greater availability of cost-effective technologies to deploy and assumptions about increased adoption of efficient technologies. Increased fuel economy and availability of efficient transportation reduces demand in the transportation sector, which has the second highest reduction in demand in EPSA-NEMS and GCAM-USA for the HighTech case. Industry had the least options for reducing energy demand, including especially limited fuel-switching options in the models. ReEDS-USREP HighTech did not change demand sector cost and performance. Thus, when generating technologies become cheaper as in the HighTech case, wholesale electricity prices decrease and more energy is consumed.

The combination of the increased natural gas prices in HighNG and the efficiency gains from HighTech leads to a greater decrease of EPSA-NEMS and GCAM-USA estimated sectoral energy use in the HighTech-HighNG case than in any other case, with the buildings sector achieving the greatest reduction. For ReEDS-USREP, absent efficiency improvements, high gas prices and low technology costs counter each other, resulting in little change to energy usage in any sector.

3.2. CO_2 policy scenario

In this section, we further compare the effects of the high-technology goals on a representative national electricity sector CO_2 policy. The effect of the CO_2 policy differs considerably depending on the cost and availability of low and zero-emitting generating as well as efficient end-use technologies. For the cases with reference technologies, the CO_2 policy incentivizes additional generation from lower or zero-emitting sources, reduces generation from higher CO_2 emitting generation, and raises wholesale electricity prices. On the other hand, the CO_2 policy combined with the high-technology goals has little to no additional impact on generation, CO_2 emissions, and wholesale electricity prices beyond what is achieved by the high-technology goals with no CO_2 policy.

As noted in the previous section, emissions and prices are dependent on natural gas prices. For that reason, we use the three models with domestic natural gas markets for the following technology and policy comparison. These models are also the ones in this analysis which are designed to study near-term as well as long-term dynamics, which is an important additional attribute for this comparison.

3.2.1.1. CO_2 emissions and prices. CO_2 emissions with and without the representative national electricity sector CO_2 policy for all four cases are shown in Fig. 11. Although the CO_2 policy is the same for each modeled sensitivity case, the policy's effect on emissions varies. For the modeled cases with emissions in the no-policy (reference) scenarios that were already lower than the emissions cap assumed for the CO_2 policy scenarios, the CO_2 policy is non-binding. For those scenarios

Fig. 11. Electricity Sector CO_2 emissions by model and case. Note that EPSA-NEMS is reporting total power sector emissions for 50 states, which includes more geographic coverage and types of electric generating units than covered under the representative national CO_2 emissions cap.

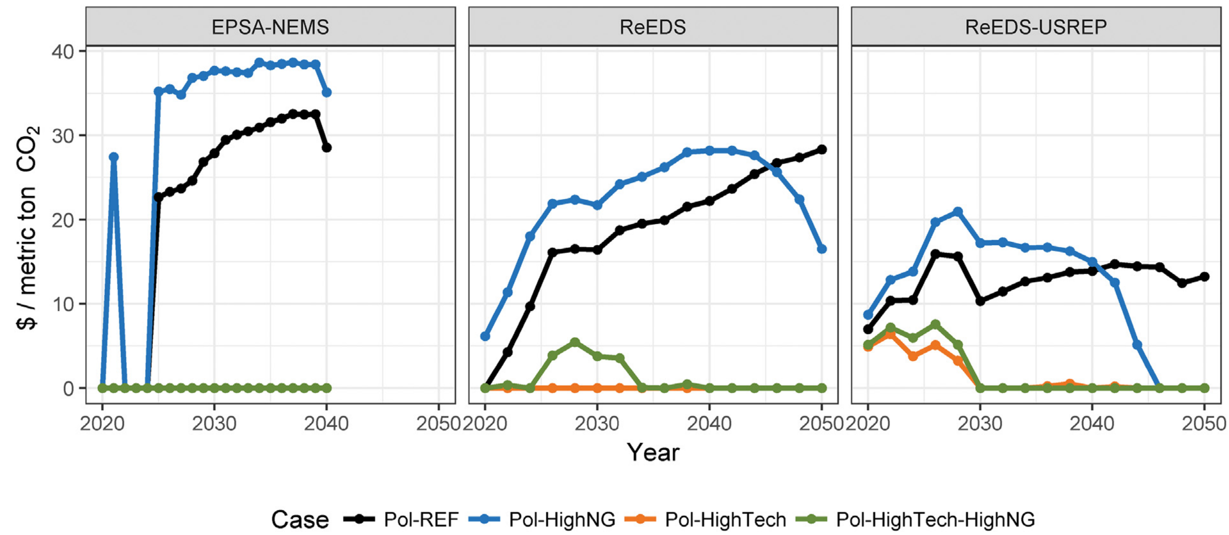

Fig. 12. CO_2 price in dollars per metric ton of CO_2. All monetary values are expressed in 2010 U.S. dollars.

with reference CO_2 emissions that are higher than the emissions cap, CO_2 emissions are reduced to the emissions limit.

The CO_2 policy has a major impact on the cases with reference technology costs, Pol-REF and Pol-HighNG. In these cases, the emissions cap is binding in all models for almost all years as soon as the CO_2 policy is implemented (top panel, Fig. 11). The CO_2 emission price in the CO_2 policy cases with reference technology costs is in the range of \$0–\$40/metric ton CO_2 depending on the model and case (Fig. 12). Only ReEDS-USREP has 2050 emissions below the cap for the Pol-HighNG scenario because high natural gas prices have sufficiently incentivized renewable technologies for the cap to become non-binding.

On the other hand, the CO_2 policy (Pol-HighTech and Pol-HighTech-HighNG) has little to no additional impact beyond what is achieved with the high-technology goals (HighTech and HighTech-HighNG, bottom panel, Fig. 11). The marginal cost of CO_2 abatement is below \$10/metric ton CO_2 across all models and years (Fig. 12). Both EPSA-NEMS and ReEDS emit below the CO_2 cap in all years with high-technology goals at reference natural gas prices (Pol-HighTech case), and EPSA-

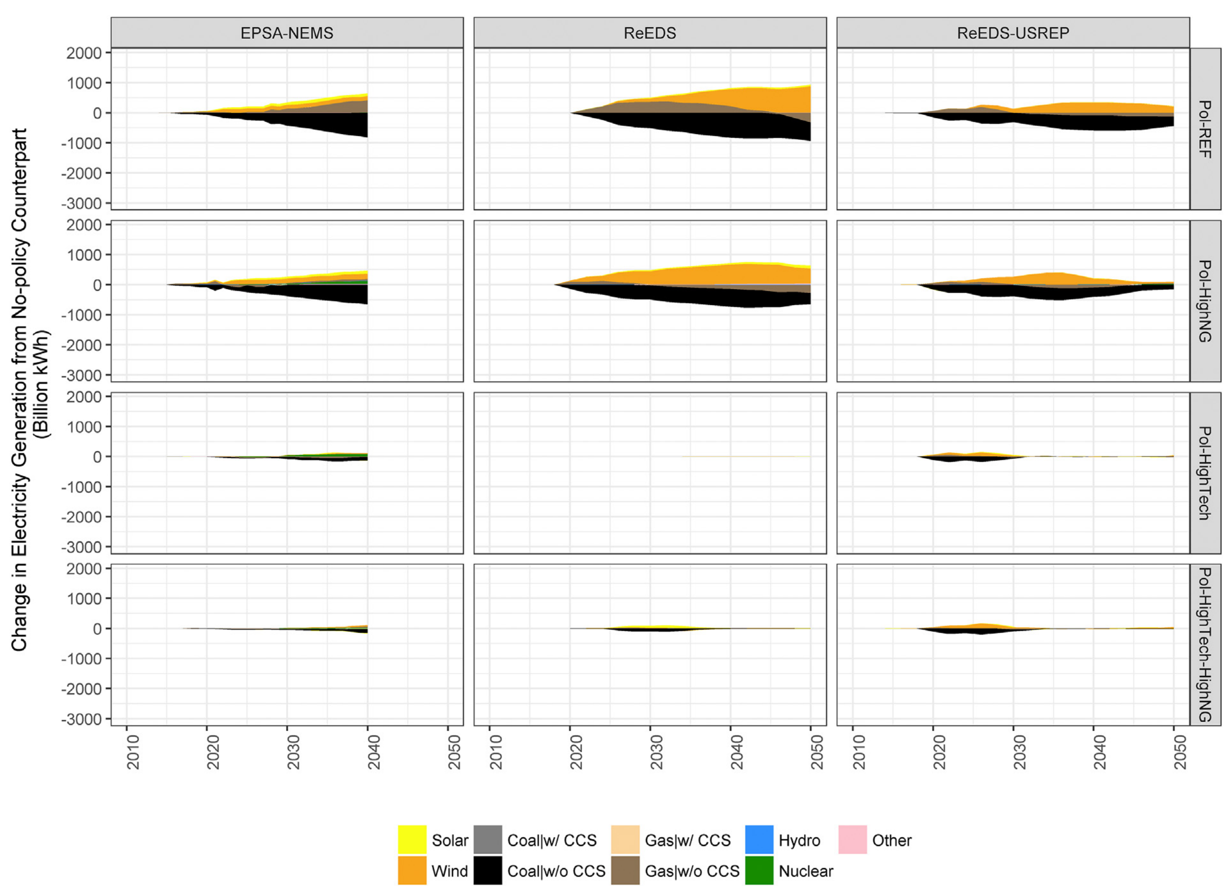

Fig. 13. Change in Electricity Generation from no-policy counterpart by model, case and generating technology type.

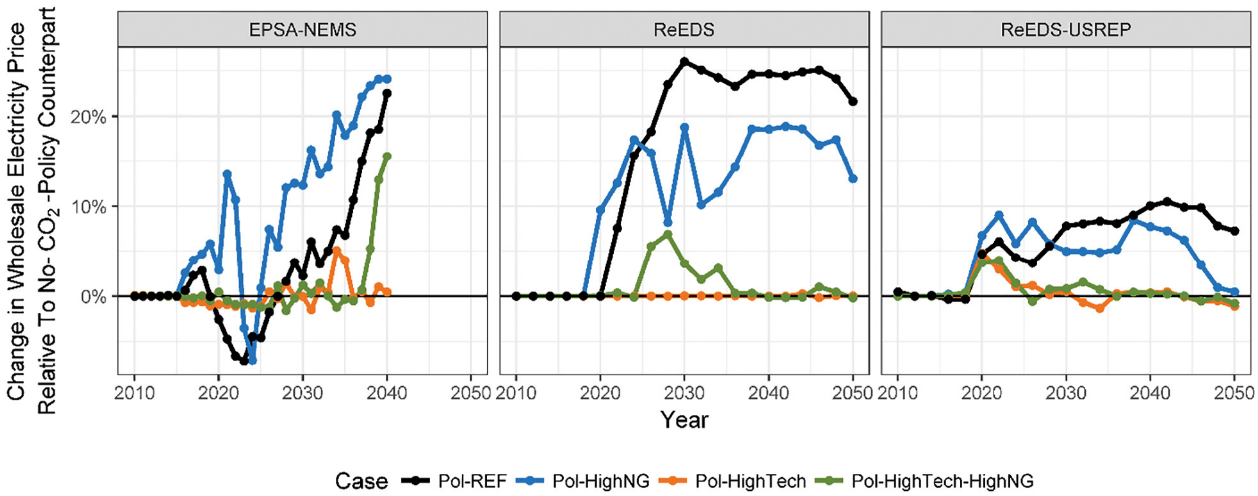

Fig. 14. Change in wholesale price of electricity relative to the reference no-policy counterpart for each case.

NEMS foresight into CO_2 policy evolution beyond the modeling horizon leads to additional emissions reductions with the policy. The ReEDS-USREP Pol-HighTech case does not represent lower-cost efficiency technologies, so low-cost electricity stimulates additional electricity demand and CO_2 emissions.

At higher natural gas prices (Pol-HighTech-HighNG case), ReEDS and ReEDS-USREP are both at the emissions cap. As discussed in the reference policy section, ReEDS does not include demand response as natural gas prices increase. Thus, emissions increase in the high-technology goal case with high natural gas prices compared to the reference natural gas price case with high-technology goals. In the later years, high natural gas prices sufficiently incentivize renewable technologies for the cap to become non-binding in ReEDS and ReEDS-USREP.

3.2.1.2. Electric power sector generation. Fig. 13 shows how the generation mix changes when applying a representative national electricity sector CO_2 policy to each of the four cases with no CO_2 policy. Especially for the cases with reference technology assumptions (Pol-REF and Pol-HighNG, upper panels of Fig. 13), the CO_2 policy incentivizes additional generation from lower or zero-emitting sources while reducing generation from higher CO_2 emitters such as coal. For the cases which achieve the high-technology goals (Pol-HighTech and Pol-HighTech-HighNG, lower panels of Fig. 13), CO_2 emissions are near or below limits imposed by the CO_2 policy, so there is very little change to the generation mix. Moreover, for all of the CO_2 policy cases there is almost no change in energy demand from the no-CO_2-policy counterpart, with the average relative change across sectors, models, and years at <0.1% (see Supplementary material).[15]

As an important caveat, CO_2 allowance banking is not modeled in this analysis. Allowance banking could possibly encourage greater near-term reductions that are relatively low cost (such as shifts in dispatch) while in the longer-term delay CO_2 mitigation to exploit future cost reductions in low-emitting technologies, particularly in the Pol-HighTech case. However, while the timing of investments and CO_2 emissions could change with allowance banking, we would expect similar long-term trends as shown here.

3.2.1.3. Wholesale electricity prices. In general, for the cases with reference technology costs (Pol-REF and Pol-HighNG), wholesale electricity prices increase when the CO_2 policy is implemented. This is true for all of the models shown in Fig. 14 past 2030. However, wholesale prices in EPSA-NEMS decline in the short term with a CO_2 policy and reference technology costs. This occurs because of the model's foresight which drives early investment in non-emitting renewable technology in anticipation of future CO_2 emission constraints, taking advantage of renewable tax credits that expire prior to 2024. This influx of new renewable generation drives down wholesale prices and CO_2 emissions and delays the policy's full impact as shown in the EPSA-NEMS CO_2 prices (Fig. 12) which are mostly zero prior to 2025.

For all the models there is a more modest or no increase in wholesale electricity prices for the cases which achieve the high-technology goals (Pol-HighTech and Pol-HighTech-HighNG). Conceptually this makes sense, since the cases which achieve the high-technology goals are already nearly achieving, meeting, or exceeding the CO_2 emissions pathway that is required under the CO_2 policy cases.

One difference between models is that EPSA-NEMS does, whereas ReEDS and ReEDS-USREP do not, capture learning-by-doing technological improvements which may be incentivized by a CO_2 policy under reference technology assumptions. In these cases, the difference in price impacts across the models could be partly due to these differences in technology cost reductions but is likely more related to differences in the models' technology retirement assumptions, model foresight, and whether the model includes a full or partial economy. On the other hand, the high-technology goal cases (Pol-HighTech and Pol-HighTech-HighNG) include exogenous technology parameterizations and thus do not include an interaction between the CO_2 policy and technology costs for any of the models. For these cases, we expect this limitation to have a small effect on the results given that CO_2 emissions for the HighTech and HighTech-HighNG cases nearly meet, meet, or exceed the representative CO_2 emissions cap.

4. Conclusions

This analysis uses four energy-economic models to examine the impact of natural gas prices, technology innovation, and CO_2 policy on projections of U.S. energy demand and electric sector development. Reference trends suggest: growth in natural gas, solar, and wind generation; reduced coal generation as older plants retire; and little change to other generation types (e.g., nuclear and hydropower). An increase in natural gas prices, achieving the representative high-technology goals modeled in this analysis, or the combination of the two, increase the amount of renewable generation that becomes cost-effective to build and operate. Higher natural gas prices lead to fewer coal capacity retirements, since these two types of fuels are the most substitutable for electricity generation.

[15] Sectoral emissions trends follow those of energy demand, but these results are not shown due to difficulties reconciling model differences in how sectoral emissions are characterized.

Absent a CO_2 policy, achieving the high-technology goals decreases CO_2 emissions, regardless of the assumptions about natural gas prices, because low carbon generation is more cost competitive, and energy efficiency improvements reduce demand. For the models that include domestic natural gas markets, achieving the high-technology goals lowers wholesale electricity prices. However, wholesale electricity prices decrease as the cost of natural gas generation increases.

For all models, wholesale electricity prices increase when natural gas prices increase, especially in the long term. Natural gas generation is often the marginal generating technology, making wholesale electricity prices trend with changes in natural gas prices. On the other hand, higher natural gas prices have a less definitive effect on CO_2 emissions throughout the projection, with annual emissions increasing or decreasing at different times throughout the horizon depending on the relative competitiveness of coal and renewables.

The effect of implementing a representative electricity sector CO_2 policy differs considerably depending on the cost and performance of generating and end-use technologies. The CO_2 policy influences the electricity sector demand and generation mix in all cases with reference technology assumptions, but the policy has little to no additional influence in the cases that achieve high-technology goals. Long-term, meeting the representative high-technology goals achieves a generation mix with similar CO_2 emissions to the representative CO_2 policy but with smaller increases to wholesale electricity prices. In the short-term, the relative effect on wholesale prices differs by model.

The four models used for this study differ in ways that are important for comparing results. Four main aspects that have a big impact on the quantitative results discussed in the analysis include:

1. how the models determine electricity generating capacity retirements, especially coal and nuclear capacity,
2. how the models value variable renewable energy,
3. the models' capability to include demand and price response, and
4. the models' assumptions about capacity requirements.

As changes are made to these and other energy system models in their respective analysis efforts, it is important to continue conducting comparative analyses using common model inputs and outputs while delving into detailed model outcomes and the structural differences that introduce variability among those outcomes. Doing so would improve our understanding of model results and enable us to provide the best information possible to decision-makers.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2018.03.027.

References

Bistline, John, et al., 2017. Electric sector policy, technological change, and U.S. emissions reductions goals: results from the EMF 32 model intercomparison project. Energy Econ. (Special Issue: EMF 32 Study – Power Sector).

Bosetti, Valentina, Carraro, Carlo, Duval, Romain, Tavoni, Massimo, 2011. What should we expect from innovation? A model-based assessment of the environmental and mitigation cost implications of climate-related R&. Energy Econ. 33, 1313–1320.

Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units, 40 C.F.R. § 60.

Cole, Wesley, Mai, Trieu, Logan, Jeffrey, Steinberg, Daniel, McCall, James, Richards, James, Sigrin, Benjamin, Porro, Gian, 2016. 2016 Standard Scenarios Report: A U.S. Electricity Sector Outlook. Technical Report NREL/TP-6A20–66939. National Renewable Energy Laboratory, Golden, CO http://www.nrel.gov/docs/fy17osti/66939.pdf, Accessed date: 5 November 2017.

Consolidated Appropriations Act of 2016, H.R. 2029, Sec. 301, 114th Cong.

Creason, Jared, Bistline, John E., Hodson, Elke L., Murray, Brian, Rossmann, Charles G., 2017. Technology and U.S. power sector emissions reductions goals: results from the EMF 32 model intercomparison project. Energy Econ. (Special Issue: EMF 32 Study – Power Sector).

Denholm, Paul, Clark, Kara, O'Connell, Matt, 2016. On the Path to SunShot: Emerging Issues and Challenges in Integrating High Levels of Solar into the Electrical Generation and Transmission System, NREL/TP-6A20-65800. National Renewable Energy Laboratory, Golden, CO (https://www.nrel.gov/docs/fy16osti/65800.pdf).

Eurek, Kelly, Cole, Wesley, Bielen, David A., Blair, Nate, Cohen, Stuart, Frew, Bethany, Ho, Jonathan, Krishnan, Venkat, Mai, Trieu, Steinberg, Daniel, 2016. Regional Energy Deployment System (ReEDS) Model Documentation: Version 2016. NREL/TP-6A20-67067. National Renewable Energy Laboratory, Golden, CO (http://www.nrel.gov/docs/fy17osti/67067.pdf).

Fawcett, Allen A., Clarke, Leon E., Weyant, John P., 2014. Introduction to EMF 24. Energy J. 35 (Special Issue 1) (Accessed November 5, 2017). https://doi.org/10.5547/01956574.34.SI1.

Fischer, Carolyn, Newell, Richard G., 2008. Environmental and technology policies for climate mitigation. J. Environ. Econ. Manag. 55, 142–162.

Fout, Tim, Zoelle, Alexander, Keairns, Dale, Turner, Marc, Woods, Mark, Kuehn, Norma, Shaw, Vasant, Chou, Vincent, Pinkerton, Lora, 2015. Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3. DOE/NETL-2015/1723. National Energy Technology Laboratory (NETL), Morgantown, WV https://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/Rev3Vol1aPC_NGCC_final.pdf, Accessed date: 5 November 2017.

IMPLAN, 2008. State-Level US Data for 2006. Minnesota IMPLAN Group. Minnesota IMPLAN Group, Stillwater, MN.

Iyer, Gokul, Clarke, Leon, Edmonds, Jae, Kyle, Page, Ledna, Catherine, McJeon, Haewon, Wise, Marshall, 2017. GCAM-USA Analysis of U.S. Electric Power Sector Transitions. PNNL Technical Report 26174. Pacific Northwest National Laboratory, Joint Global Change Research Center, College Park, MD http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-26174.pdf, Accessed date: 5 November 2017.

Kraucunas, Ian, Clarke, Leon E., et al., 2015. Investigating the nexus of climate, energy, water, and land at decision-relevant scales: the Platform for Regional Integrated Modeling and Analysis (PRIMA). Clim. Chang. 129, 573–588.

Matuszewski, Michael, Chou, Vincent H., 2013. Quality Guideline for Energy System Studies: Retrofit Difficulty Factors. National Energy Technology Laboratory (NETL), Morgantown, WV https://www.netl.doe.gov/energy-analyses/temp/QGESSRetrofitDifficultyFactors_083013.pdf, Accessed date: 5 November 2017.

Moawad, A., Kim, N., Shidore, N., Rousseau, A., 2016. Assessment of Vehicle Sizing, Energy Consumption, and Cost through Large-scale Simulation of Advanced Vehicle Technologies. Argonne National Laboratory, Argonne http://www.ipd.anl.gov/anlpubs/2016/04/126422.pdf, Accessed date: 5 November 2017.

Global Trade, Assistance, and Production: The GTAP 7 Data Base. In: Narayanan G., Badri, Walmsley, Terrie L. (Eds.), Center for Global Trade Analysis, Purdue University http://www.gtap.agecon.purdue.edu/databases/v7/v7_doco.asp, Accessed date: 5 November 2017.

National Renewable Energy Laboratory (NREL), 2016. 2016 Annual Technology Baseline and Standard Scenarios. NREL, Golden, CO https://www.nrel.gov/docs/fy16osti/66944.pdf, Accessed date: 5 November 2017.

National Renewable Energy Laboratory (NREL), 2017. 2017 Annual Technology Baseline and Standard Scenarios. NREL, Golden, CO http://www.nrel.gov/analysis/data_tech_baseline.html, Accessed date: 5 November 2017.

Pacific Northwest National Laboratory (PNNL), 2017. GCAM v4.2 Documentation: Table of Contents. Pacific Northwest National Laboratory, Joint Global Change Research Center http://jgcri.github.io/gcam-doc/v4.2/toc.html, Accessed date: 5 November 2017.

Rausch, S., Mowers, M., 2014. Distributional and efficiency impacts of clean and renewable energy standards for electricity. Resour. Energy Econ. 36 (2), 556–585.

Stephens, T.S., Taylor, C.H., Moore, J.S., Ward, J., 2016. Vehicle Technologies and Fuel Cell Technologies Program: Prospective Benefits Assessment Report for Fiscal Year 2016. Argonne National Laboratory https://anl.app.box.com/s/m4vfyxub1l4qnimc8xyduiuqekcj7vyw, Accessed date: 5 November 2017.

Turner, Marc J., Pinkerton, Lora L., 2013. Quality Guidelines for Energy System Studies: Capital Cost Scaling Methodology. DOE/NETL-341/013113. National Energy Technology Laboratory (NETL), Morgantown, WV https://www.netl.doe.gov/energy-analyses/temp/QGESSCapitalCostScalingMethodology_013113.pdf, Accessed date: 5 November 2017.

U.S. Census Bureau, 2010. Foreign Trade Statistics State Data Series: Origin of Movement and State of Destination Data Series. U.S. Census Bureau, Washington, DC http://www.census.gov/foreign-trade/aip/elom.htmlUS, Accessed date: 5 November 2017.

U.S. Department of Energy (DOE), 2014. Carbon Storage Technology Program Plan. DOE, Morgantown, WV and Washington, D.C. https://www.netl.doe.gov/research/coal/carbon-storage/publications.

U.S. Department of Energy (DOE), 2015a. Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Pulp and Paper Manufacturing. DOE, Washington, DC http://energy.gov/eere/amo/downloads/bandwidth-study-us-pulp-and-paper-manufacturing, Accessed date: 5 November 2017.

U.S. Department of Energy (DOE), 2015b. Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Iron and Steel Manufacturing. DOE, Washington, DC http://energy.gov/eere/amo/downloads/bandwidth-study-us-iron-and-steel-manufacturing, Accessed date: 5 November 2017.

U.S. Department of Energy (DOE), 2015c. Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Petroleum Refining. DOE, Washington, DC http://energy.gov/eere/amo/downloads/bandwidth-study-us-petroleum-refining, Accessed date: 5 November 2017.

U.S. Department of Energy (DOE), 2015d. Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Chemical Manufacturing. DOE, Washington, DC http://energy.gov/eere/amo/downloads/bandwidth-study-us-chemical-manufacturing, Accessed date: 5 November 2017.

U.S. Department of Energy (DOE), 2015e. Quadrennial Technology Review 2015. DOE, Washington, D.C. https://energy.gov/under-secretary-science-and-energy/quadrennial-technology-review-2015, Accessed date: 20 February 2018.

U.S. Department of Energy (DOE), 2016a. Hydropower Vision: A New Chapter for America's 1st Renewable Electricity Source. Technical Report, DOE/GO-102016-4869. DOE, Washington, D.C. http://energy.gov/eere/water/articles/hydropower-vision-new-chapter-america-s-1st-renewable-electricity-source, Accessed date: 5 November 2017.

U.S. Department of Energy (DOE), 2016b. On the Path to Sunshot. DOE, Washington, D.C.: p. 2016. https://energy.gov/eere/solar/path-sunshot, Accessed date: 20 February 2018.

U.S. Department of Energy (DOE), 2016c. Revolution…Now. DOE, Washington, D.C. https://www.energy.gov/sites/prod/files/2016/09/f33/Revolutiona%CC%82%E2%82%ACNow%202016%20Report_2.pdf.

U.S. Department of Energy (DOE), 2017a. Transforming the Nation's Electricity System: The Second Installment of the Quadrennial Energy Review. DOE, Washington, D.C. https://energy.gov/epsa/quadrennial-energy-review-second-installment, Accessed date: 5 November 2017.

U.S. Department of Energy (DOE), 2017b. Energy CO_2 Emissions Impacts of Clean Energy Technology Innovation and Policy. DOE, Washington, D.C. https://www.energy.gov/epsa/downloads/energy-co2-emissions-impacts-clean-energy-technology-innovation-and-policy, Accessed date: 5 November 2017.

U.S. Department of Energy (DOE), 2017c. Quadrennial Energy Review: Transforming the Nation's Electricity System: The Second Installment of the QER. DOE, Washington, D.C. https://www.energy.gov/sites/prod/files/2017/02/f34/Quadrennial%20Energy%20Review–Second%20Installment%20%28Full%20Report%29.pdf, Accessed date: 20 February 2018.

U.S. Department of Energy (DOE), 2018. Sunshot 2030. DOE, Washington, D.C. https://energy.gov/eere/solar/sunshot-2030, Accessed date: 20 February 2018.

U.S. Energy Information Administration (EIA), 2009. State Energy Data System. EIA, Washington, D.C.

U.S. Energy Information Administration (EIA), 2014. Annual Energy Outlook 2014. EIA, Washington, D.C. http://www.eia.gov/forecasts/archive/aeo14/, Accessed date: 5 November 2017.

U.S. Energy Information Administration (EIA), 2015. Assumptions to the Annual Energy Outlook 2015. EIA, Washington, DC https://www.eia.gov/outlooks/archive/aeo15/, Accessed date: 5 November 2017.

U.S. Energy Information Administration (EIA), 2016. Assumptions to the Annual Energy Outlook 2016. EIA, Washington, DC https://www.eia.gov/outlooks/archive/aeo16/, Accessed date: 5 November 2017.

U.S. Energy Information Administration (EIA), 2017a. Annual Energy Outlook 2017 with Projections to 2050. EIA, Washington, D.C. http://www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf, Accessed date: 5 November 2017.

U.S. Energy Information Administration (EIA), 2017b. NEMS Documentation. EIA, Washington, D.C. https://www.eia.gov/outlooks/aeo/nems/documentation/, Accessed date: 5 November 2017.

U.S. Energy Information Administration (EIA), 2017c. Henry Hub Natural Gas Spot Price. EIA, Washington, D.C. (Release Date: November 1, 2017, https://www.eia.gov/dnav/ng/hist/rngwhhdm.htm).

U.S. Energy Information Administration (EIA), 2017d. Annual Energy Outlook Retrospective Review: Evaluation of 2016 and Prior Reference Case Projections. EIA, Washington, D.C. https://www.eia.gov/outlooks/aeo/retrospective/pdf/retrospective.pdf, Accessed date: 5 November 2017.

U.S. Environmental Protection Agency (EPA), 2015. Regulatory Impact Analysis for the Clean Power Plan Final Rule, Table ES-2. EPA, Washington, D.C. https://www3.epa.gov/ttnecas1/docs/ria/utilities_ria_final-clean-power-plan-existing-units_2015-08.pdf, Accessed date: 5 November 2017.

U.S. Geological Survey (USGS), 2016. 2006–2015 U.S. Geological Survey Minerals Yearbooks. U.S. Department of the Interior, Washington, D.C. http://minerals.usgs.gov/minerals/pubs/commodity/aluminum/index.html#myb, Accessed date: 5 November 2017.

Zhou, Yuyu, Clarke, Leon E., et al., 2014. Modeling the effect of climate change on U.S. state-level buildings energy demands in an integrated assessment framework. Appl. Energy 113.