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## LETTER

# Assessing the costs and benefits of US renewable portfolio standards

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## Abstract

Renewable portfolio standards (RPS) exist in 29 US states and the District of Columbia. This article summarizes the first national-level, integrated assessment of the future costs and benefits of existing RPS policies; the same metrics are evaluated under a second scenario in which widespread expansion of these policies is assumed to occur. Depending on assumptions about renewable energy technology advancement and natural gas prices, existing RPS policies increase electric system costs by as much as \$31 billion, on a present-value basis over 2015–2050. The expanded renewable deployment scenario yields incremental costs that range from \$23 billion to \$194 billion, depending on the assumptions employed. The monetized value of improved air quality and reduced climate damages exceed these costs. Using central assumptions, existing RPS policies yield \$97 billion in air-pollution health benefits and \$161 billion in climate damage reductions. Under the expanded RPS case, health benefits total \$558 billion and climate benefits equal \$599 billion. These scenarios also yield benefits in the form of reduced water use. RPS programs are not likely to represent the *most* cost effective path towards achieving air quality and climate benefits. Nonetheless, the findings suggest that US RPS programs are, on a national basis, cost effective when considering externalities.

## 1. Introduction

Mandatory state renewable portfolio standards (RPS), which currently exist in 29 states and the District of Columbia, require that electric load-serving entities meet a minimum portion of their load with eligible forms of renewable electricity (RE). Along with federal tax incentives, state RPS programs have been identified as one of the key policy drivers for US RE growth (Barbose 2017). Moreover, in recent years, many states have proposed or enacted significant revisions to their RPS programs, in some cases increasing and extending the targets out further in time, while in other cases seeking to repeal or freeze existing RPS policies (Barbose 2017). In either context, questions about the potential costs, benefits, and other impacts of RPS programs are usually central to the decision-making process.

The present study represents the first national-level, integrated assessment of the prospective costs and

environmental benefits of state RPS policies. Focusing on the 2015–2050 timeframe, we evaluate current mandatory RPS policies, as well as a potential expansion of those policies, in terms of: (a) national electric system costs and national and regional retail electricity prices; and (b) environmental and health benefits associated with reduced greenhouse gas (GHG) and air pollution emissions and reduced water use. For each cost and benefit, we estimate effects in physical units. Where possible, we also present results in dollar-value terms and quantify elements of uncertainty.

We focus on the aggregate effects of RPS programs nationally and regionally, rather than on the impacts of each state RPS program, individually. Importantly, our analysis considers an important subset of—but not all—environmental effects; for example, we do not quantify heavy metal releases, radiological releases, waste products, and water quality impacts associated with power and upstream fuel production, as well as impacts related to wildlife, noise, and aesthetics. Our

analysis seeks to inform decision-makers about the merits and costs of state RPS programs as they consider revisions to existing policies and development of new policies.

## 2. Background

There is some disagreement in the literature about the effect of state RPS policies on renewable energy deployment relative to other drivers (Carley and Miller 2012, Shrimali *et al* 2015, Shrimali and Jenner 2013, Staid and Guikema 2013, Yin and Powers 2010). Nonetheless, it is clear that a substantial fraction of total renewable electricity supply is serving state RPS mandates (Barbose 2017).

Previous research has also sometimes sought to understand the costs and benefits of state RPS policies, mostly on a retrospective basis. This includes analyses of compliance cost data submitted to state regulatory agencies, which found total reported costs in 2015 equal to \$3.0 billion, equivalent to 1.6% of retail electricity bills in RPS states (Barbose 2017). Econometric analyses have also estimated the net effect of state RPS policies on average retail electricity prices at the state or utility level, with results ranging from a 3% to 7% increase (Morey and Kirsch 2013, Tra 2016, Wang 2015). Various researchers have applied statistical methods to try to isolate the historical effects of RPS programs on other policy-relevant criteria as well, such as greenhouse gas emissions (Eastin 2014, Yi 2015), air pollution (Eastin 2014, Werner 2014), and employment (Bowen *et al* 2013, Yi 2013). Additionally, a small number of states have commissioned analyses of broader environmental or other societal benefits of their individual RPS programs (Heeter *et al* 2014). Most recently, Barbose *et al* (2016) developed the first-ever national assessment of the benefits and impacts of state RPS programs, focusing on the year 2013. The study estimated \$7.4 billion in benefits from reduced air pollution and climate change damages, along with additional benefits from reduced water withdrawal and consumption.

Among those studies that have evaluated RPS policies on a prospective basis, many states estimated future RPS costs prior to initial enactment of their RPS, as summarized by Chen *et al* (2007). Prospective cost-effectiveness evaluations have also been conducted in concert with major revisions to individual RPS programs (e.g. Rouhani *et al* 2016). Prospective studies with a national scope have focused primarily on the potential effects of a national RPS or clean energy standard (EIA 2012, Goulder *et al* 2016, Mignone *et al* 2012, Paul *et al* 2014).

Notwithstanding the insights gained from these prior studies, two important gaps remain in terms of informing future policy development. The first is to provide a forward-looking perspective of all state RPS programs, considering currently scheduled increases in RPS targets as well as possible revisions to those targets.

The second is to estimate both costs and benefits in an integrated manner, to allow direct comparison. The present study addresses both of these gaps.

## 3. Scenario definitions

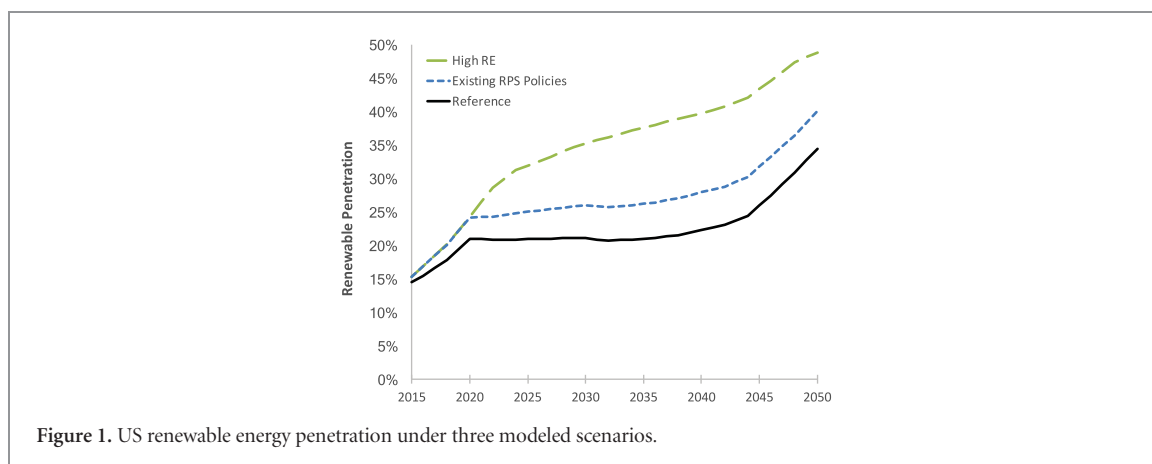
Our analysis assesses the costs and environmental and health benefits of (1) current mandatory RPS policies, as well as (2) a potential expansion of those policies beyond existing law. We contrast each of these two RE policy scenarios with a comparison scenario in which RPS purchase obligations are eliminated after 2014, allowing for an assessment of incremental effects from 2015 through 2050. Each of the three scenarios is described briefly below, with further details found in Mai *et al* (2016a).

The ‘Existing RPS Policies’ scenario is based on existing mandatory state RPS policies as they existed as of July 2016. It assesses the impacts of the RE purchase requirements in the 29 existing state RPS programs from 2015 through 2050<sup>4</sup>. The specific and diverse RPS designs of each state are reflected in our modeling assumptions, in as much as possible, with the renewable energy purchase standards increasing over time as established in current law and regulations. Assumptions about the eligibility of different types of RE generation for each state’s RPS and the ability of one state’s RPS standard to be met with RE purchased from other states are based on eligibility rules and historical practices (Holt 2016, Heeter *et al* 2015). RPS compliance obligations often have cost containment mechanisms of various designs—these too are reflected in our analysis, as are other state-specific RPS design details. Federal RE tax credits and state and regional carbon policies are modeled reflecting current law, with tax credits phased down over time on the schedule defined in the most-recent tax credit extension. RE deployment beyond state RPS policies is allowed, but only when found to be economically driven.

The ‘High RE’ scenario, meanwhile, represents a hypothetical future in which all states choose to adopt relatively aggressive RPS policies, well beyond current law, and is intended to help inform consideration of new or expanded RPS targets beyond those already implemented. RE targets under this scenario are based on the level of RE growth that would occur if states were to have met their entire Clean Power Plan compliance obligations solely with RE generation<sup>5</sup>. This scenario

<sup>4</sup> Several additional states and many municipalities have voluntary renewable energy goals. As these goals are voluntary—with no compliance mechanisms or penalties—we do not include them in our analysis.

<sup>5</sup> This scenario is modeled by applying mass-based CO<sub>2</sub> emissions targets from the Clean Power Plan for each state, restricting allowance trading, and restricting the ability to deploy other low-carbon generation options (e.g. nuclear and carbon capture and sequestration) or further increase coal-to-gas switching beyond what is estimated in the Existing RPS Policies scenario. Since the Clean Power Plan



does not represent economic or technical limits on or a forecast of RE, but instead reflects a simple means of generating a broadly defined scenario in which RE deployment is higher than under existing RPS policies. The much higher RE requirements inherent in this scenario are depicted in figure 1.

Finally, we apply a comparison scenario to enable an assessment of incremental impacts. The ‘Reference’ scenario serves that purpose, and assumes no further RPS purchase requirements beyond 2014; in effect, this scenario assumes that all existing RPS policies are eliminated as of the end of 2014. Renewable energy deployment is still allowed to grow beyond that year, but only based on economic considerations, not due to state RPS policies. Economic RE growth is capped at the same level as in the Existing RPS Policies scenario, so that the difference between the two scenarios solely reflects incremental RE serving existing RPS policies<sup>6</sup>.

Incremental impacts are then calculated by comparing the Existing RPS Policies and High RE scenarios with the Reference scenario, enabling an assessment of prospective costs and benefits from 2015 to 2050 under the two ‘policy’ scenarios relative to a counterfactual scenario.

#### 4. Methods and assumptions

Here we provide a broad overview of our methods, approach and assumptions, starting with our approach to electric sector modeling and cost estimation, and followed by a description of additional tools used to estimate environmental and health benefits. For specific methodological details, see Mai *et al* (2016a).

does not specify emissions targets after 2030, we apply the same 2030 target for all subsequent years. See Mai *et al* (2016a) for details.

<sup>6</sup> As noted briefly later in the conclusions to the paper, the scenario construct provides an upper bound on the impacts of the RPS policies themselves because greater ‘economic’ RE deployment exceeding the cap applied in our Reference scenario is possible in the absence of the policies.

#### 4.1. Electricity sector modeling and cost estimation

Our analysis relies on the National Renewable Energy Laboratory’s (NREL’s) Regional Energy Deployment System (ReEDS), an electric generation capacity-expansion model, to estimate changes to the US electric power sector through 2050, across various scenarios and sensitivity cases (Short *et al* 2011, Eurek *et al* 2016)<sup>7</sup>. ReEDS has been widely used in previous analyses of long-term renewable futures (e.g. Wiser *et al* 2016a, 2016b, DOE 2016, NREL 2012) and to simulate scenarios for analyses of a broad range of state and federal energy policies and regulations (e.g. Mai *et al* 2016b, Mignone *et al* 2012, Bird *et al* 2011).

To determine potential expansion of electricity generation, storage, and transmission systems throughout the contiguous United States over the next several decades, ReEDS chooses the cost-optimal mix of technologies that meet all regional electric power demand requirements, based on grid reliability requirements, technology resource constraints, and policy constraints. This cost-minimization routine is performed for two-year periods to 2050. Some of the major outputs of ReEDS include the amount of generator capacity and annual generation from each technology, storage capacity expansion, transmission capacity expansion, total electric sector costs, electricity prices, and various environmental metrics.

ReEDS is designed to address the unique characteristics of renewable electricity technologies, particularly the variability and uncertainty of solar and wind resources and the location-dependence of RE resources. The model accomplishes this through high spatial resolution and statistical parameterizations to estimate renewable capacity value, curtailment, and operating reserve requirements that inform model decisions. ReEDS considers transmission expansion, which is needed to compare, for example, the cost of remote high-quality renewable resources to lower-quality local resources.

<sup>7</sup> We use the 2016 Final Release version of ReEDS (see [www.nrel.gov/analysis/reeds/](http://www.nrel.gov/analysis/reeds/)). We also use the dSolar customer-adoption model to provide inputs to ReEDS for rooftop photovoltaic capacity additions (Sigrin *et al* 2016).

We use ReEDS to simulate three scenarios, as described previously, from 2015 through 2050. The central-case modeling assumptions used in our scenarios are consistent with those from NREL's 2016 *Standard Scenarios* report (Cole *et al* 2016, Eurek *et al* 2016). In particular, we rely on demand growth and fossil fuel prices from the *EIA Annual Energy Outlook 2016* Reference Case (EIA 2016) and renewable and non-renewable technology cost and performance assumptions based on the NREL Annual Technology Baseline 2016 'mid' projections<sup>8</sup>.

ReEDS estimates changes to the US electric power sector from 2015 through 2050. We also use ReEDS to estimate two cost metrics for each scenario, total electric-system costs and retail electricity prices, both of which reflect needed expenditures to build and operate the power system while maintaining reliability standards. Total system costs are calculated as the net present value, with a 3% real discount rate, of all electric system expenditures from 2015 through 2050. These costs include all fixed and operating costs, including capital costs for all renewable, non-renewable, and supporting (e.g. transmission and storage) electric sector infrastructure; fuel costs; and plant operations and maintenance costs. Retail electricity prices computed by ReEDS include the fixed costs of transmission and distribution, as well as the cost of electricity purchases. In the latter case, estimated costs are akin to the hourly locational marginal prices used by system operators for electricity market clearing, but the prices output by ReEDS are averages over all hours of the year and, as an equilibrium model, include recovery of capacity and ancillary service cost. Thus, they implicitly cover both the fixed and variable costs for all generators<sup>9</sup>.

In order to present a range of cost metrics, we model central-case assumptions described above, but also model four additional sets of sensitivities that include high and low assumptions for natural gas prices and renewable technology costs. The natural gas price scenarios are based on the *Annual Energy Outlook 2016* High and Low Oil and Gas Resource cases (EIA 2016), and reflect prices that are 44% above or 15% below central-case assumptions in 2050. The renewable technology sensitivities are based on the Annual Technology Baseline 2016 High and Low RE cost projections, and reflect a sizable range in possible future cost outcomes; for example, the high-cost wind energy case is one of virtually no additional cost reduction from 2014 values, whereas the low cost case reflects more than a 35% reduction by 2050 (for details, see Cole *et al* 2016).

#### 4.2. Environmental and health benefits

We evaluate benefits related to net reductions in air pollution, greenhouse gas emissions, and water use

within the power sector. We calculate these benefits using only central-case assumptions for fuel prices and RE technology costs and do not include sensitivity tests for the different cost input assumptions described in the previous section. Our approach to estimating air pollution and climate benefits build on or complement approaches used by other researchers (e.g. NRC 2010, Buonocore *et al* 2016, Johnson *et al* 2013, Siler-Evans *et al* 2013, Shindell 2015, Millstein *et al* 2017). Similarly, the approach used for estimating water use has been applied in multiple other studies (Clemmer *et al* 2013, Macknick *et al* 2012).

For air pollution, we generally use ReEDS to estimate combustion-related emissions of SO<sub>2</sub> and NO<sub>x</sub>. ReEDS was not able to estimate biomass power plant emissions or direct emissions of fine particulate matter (PM<sub>2.5</sub>); we therefore estimated these emissions separately (see Mai *et al* 2016a for details). ReEDS models the impacts of existing air pollution regulations, and we find that existing cap-and-trade programs are largely non-binding based on current regulatory requirements.

We then apply additional tools to translate physical emissions changes to health indicators and monetary benefits. We use multiple methods to do so in order to reflect some of the uncertainty in the marginal impacts of emissions on human health outcomes. More specifically, we quantify the health benefits (reduced mortality and morbidity) of emissions reductions using three methods: (a) the Air Pollution Emission Experiments and Policy analysis model (AP2, formerly APEEP; Muller *et al* 2011, Muller 2014), (b) EPA's marginal benefit methodology as used in recent regulatory impact assessments (EPA-RIA; described in EPA 2015a, EPA 2015b), and (c) the Estimating Air pollution Social Impacts Using Regression (EASIUR) model (Heo *et al* 2016). Each of these models addresses somewhat different health and environmental outcomes, but mortality estimates dominate monetary valuation estimates. To incorporate differences across epidemiological studies, EPA-RIA and EASIUR both include a low and high estimate. Finally, we report a 'central' value figure as the simple average of the five other monetary benefit estimates, but often emphasize the full range of results.

Our estimates of GHG emissions reductions are differentiated by generation type and derived from the combination of electric sector operational combustion-related CO<sub>2</sub> emissions, plus adjustments for life-cycle emissions based on the broader literature<sup>10</sup>. A full range of generation types are considered, including fossil (e.g. coal, CCGT, CT) and renewable energy (e.g. wind, PV) generation. These calculations occur within ReEDS.

We then estimate the monetary value of GHG reductions using the US Interagency Working Group

<sup>8</sup> [www.nrel.gov/analysis/data\\_tech\\_baseline.html](http://www.nrel.gov/analysis/data_tech_baseline.html).

<sup>9</sup> ReEDS is not a fully inter-temporally optimized model and therefore the limited foresight could prevent full revenue sufficiency from being achieved in some instances.

<sup>10</sup> Our life-cycle estimates derive from a comprehensive literature assessment conducted under the auspices of NREL's Life Cycle Assessment Harmonization project: [www.nrel.gov/harmonization](http://www.nrel.gov/harmonization).



(IWG) Social Cost of Carbon, SCC (IWG 2015). SCC estimates are particularly sensitive to the choice of discount rates, estimates of future climate change damage, and the potential for catastrophic climate tipping points, as well as the representation of abatement policies (Nordhaus 2014). To address uncertainties in the SCC, the IWG provides four different trajectories of the SCC to 2050, each associated with a different discount rate (2.5%, 3%, or 5%, real) and, in some cases, other assumptions. For 2010, the SCC values are \$11, \$33, \$53, and \$90, with the value of \$33 described as the central estimate. These estimates cover a similar range to those found in the analyses by Tol (2013), van den Bergh and Botzen (2014), and Havranek *et al* (2015).

Electric sector water use is estimated within ReEDS based on the cost, performance, and water-use characteristics of different generation types and cooling system technologies (Macknick *et al* 2015). We distinguish between water consumption (removal *without* return to source) and water withdrawals (removal *with* return to source). We focus exclusively on operational water-use requirements, because water withdrawals and consumption during plant operations are orders of magnitude greater than the demands from other life-cycle stages (Meldrum *et al* 2013). As such, we do not consider 'upstream' water demands for fuel supply. Nor do we consider water quality and temperature implications, beyond water use. We also do not attempt to monetize water-use benefits, as no standard valuation methods exist.

## 5. Results

### 5.1. Renewable energy deployment

In the Existing RPS Policies scenario, renewables reach 26% of total US electricity generation by 2030 and 40% by 2050, compared with 21% and 34% under the Reference scenario (see figure 1). Under the High RE scenario, renewables reach 35% by 2030 and 49% by 2050. The Existing RPS Policies and High RE scenarios march in lockstep until 2020, driven primarily by the availability of federal RE tax incentives. The higher RE requirements under the High RE scenario kick-in starting after 2020, whereas RE deployment slows during 2020–2040 under the Existing RPS Policies and Reference scenarios. This slowdown is due to the presumed phase-down of federal tax incentives, limited incremental RPS demand after the strong RE growth to 2020, and low natural gas prices. After 2040, significant RE growth is expected in all three scenarios given assumptions for continued RE cost reductions and a presumed increase in the price of natural gas.

Solar and wind constitute the majority of additional RE capacity and generation in the Existing RPS Policies and High RE scenarios. For example, the Existing RPS Policies scenario leads to 66 gigawatts (GW) of renewables above the Reference scenario by 2030, or an additional 218 terawatt-hours (TWh) of

renewable generation in 2030. ReEDS estimates that this 66 GW includes 42 GW of solar (both utility scale and distributed), 19 GW of wind, and the remaining 5 GW from biomass, geothermal, and hydropower. On a generation basis, of the 218 TWh of incremental RE in 2030, solar contributes 83 TWh, wind 74 TWh, and the combination of biomass, geothermal, and hydropower 61 TWh. The High RE scenario, meanwhile, results in 215 GW of RE above the Reference scenario by 2030, or 627 TWh of incremental RE. Wind and solar are the dominant technologies deployed in the High RE scenario. On a generation basis, the incremental wind and solar generation are of very similar magnitude (280 TWh wind, 273 TWh solar), while biomass, geothermal, and hydropower contribute an additional 73 TWh above the Reference scenario by 2030.

Air quality, GHG, and water benefits are sensitive to the amount of coal (and, to a lesser extent, natural gas) generation displaced within the RPS scenarios. Under the Existing RPS Policies scenario, more than half of cumulative displacements come from coal generation in the near term (through 2030), but coal falls to about one-third of displacements in the longer term (through 2050) as more natural gas generation from combined cycle units is displaced. The High RE scenario results in even greater levels of avoided coal generation than does the Existing RPS Policies scenario. In part, this is because states with RPS policies are typically not as coal-reliant as non-RPS states, resulting in relatively lower avoided coal generation in the Existing RPS Policies scenario. In contrast, the High RE scenario effectively applies to all states.

Also impacting the results that follow is the location of RE deployment. Figure 2 shows cumulative RE generation for the Existing RPS Policies and High RE scenarios relative to the Reference scenario, for each of the nine US census divisions (see also table 1 for a detailed summary of core model results by region). Under the Existing RPS Policies scenario, the Pacific region dominates in terms of incremental RE generation, whereas the distribution is more uniform in the High RE scenario. Though not presented here, the regional deployment of wind, solar, geothermal, biomass, and hydropower largely follows resource conditions (e.g. more wind in the interior 'wind belt' of the county), but is also impacted by policy design—some RPS policies, for example, have dedicated requirements for solar.

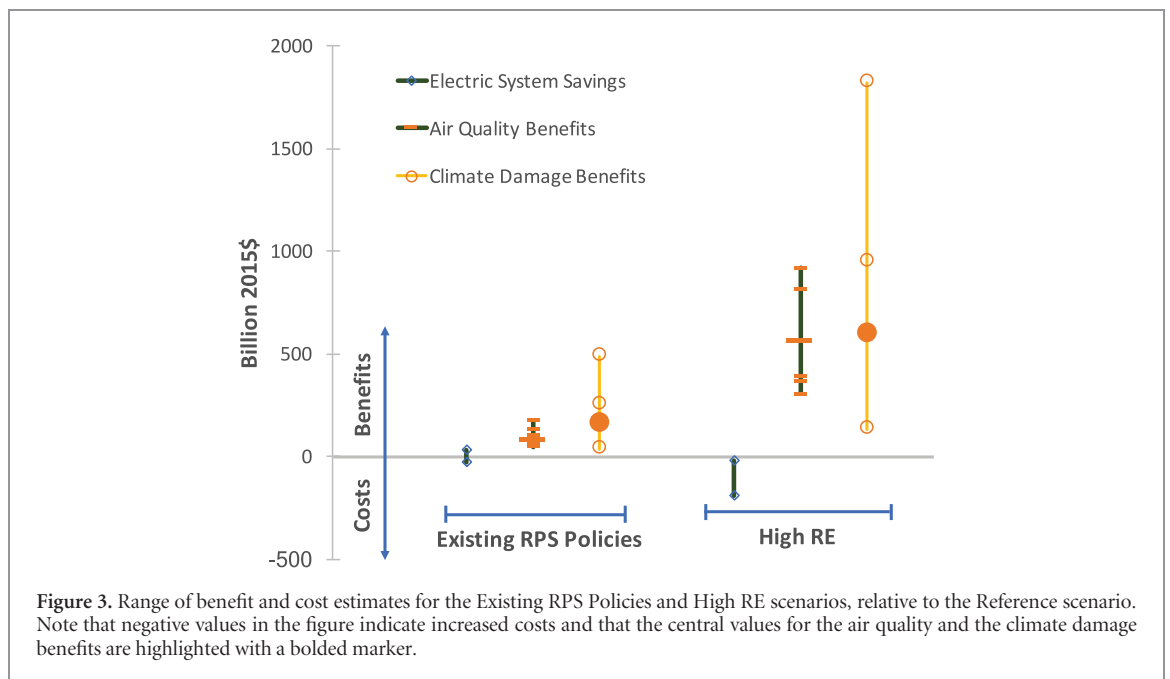
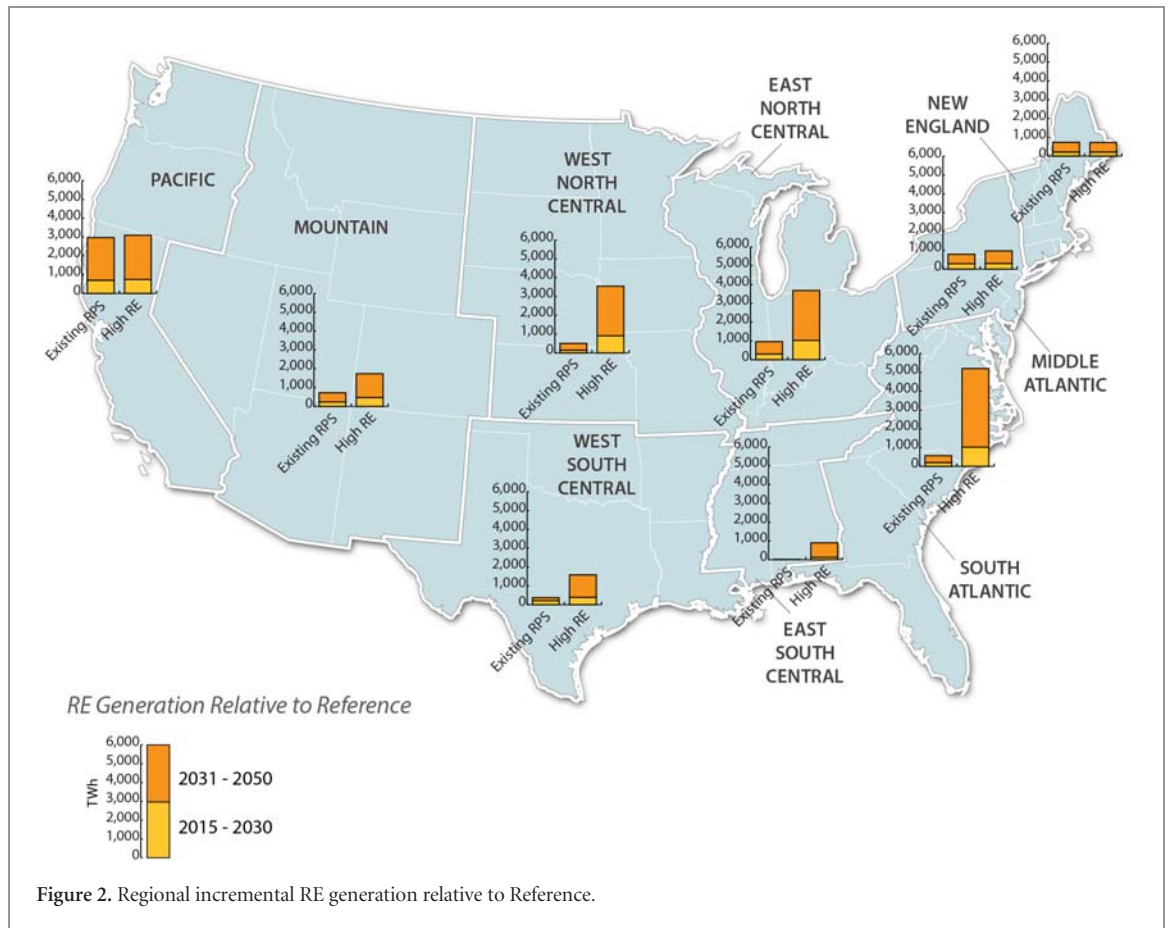
### 5.2. Electricity sector costs and prices

For the Existing RPS Policies scenario, the present value of incremental system costs (2015–2050) relative to the Reference case ranges from an additional cost of \$31 billion to a cost savings of \$31 billion (0.8% higher total system costs to 0.7% lower system costs, compared to the Reference scenario) across high and low sensitivity cases for natural gas prices and renewable technology costs. The fact that the low end of the cost range

**Table 1.** Summary of key physical results, by region (cumulative total spanning 2015–2050). ‘%ΔE’ and ‘%ΔH’ refer to the percentage change under the Existing RPS Policies scenario and the High RE scenario, respectively, in relation to the relevant Reference (Ref) scenario quantity. CO<sub>2</sub> reflects combustion-related emissions, and not other life-cycle stages for all regions except ‘Total’, which includes both combustion-related and full life-cycle emissions in parentheses. The sum of the regional values may not equal the total due to rounding.

	(TWh)						(thousand metric tons)						(million metric tons)						(trillion gallons water)					
	RE Generation			SO <sub>2</sub>			NO <sub>x</sub>			PM <sub>2.5</sub>			CO <sub>2</sub>			Withdrawal			Consumption					
	Ref	ΔE	% ΔH	Ref	ΔE	% ΔH	Ref	ΔE	% ΔH	Ref	ΔE	% ΔH	Ref	ΔE	% ΔH	Ref	ΔE	% ΔH	Ref	ΔE	% ΔH			
Pacific	8000	37	38	100	4	4	600	-8	-8	28	57	58	2800	-28	-27	33.8	1	0	1.8	-12	-15			
Mountain	5200	14	33	3400	-5	-18	7700	-4	-18	780	-4	-18	7700	-8	-20	13.3	-6	-12	5.4	-7	-17			
West North Central	5100	10	69	4800	-7	-23	5700	-9	-27	762	-8	-21	6700	-8	-22	146.6	-4	-20	3.4	-8	-18			
West South Central	9900	4	16	4300	-18	-20	4200	-18	-20	570	-17	-19	9300	-8	-12	57.8	-6	-9	6.4	-8	-10			
East North Central	1700	58	222	12 000	-2	-30	9800	-3	-35	1594	-2	-33	15 000	-4	-31	251	-2	-23	9.1	-3	-25			
East South Central	1100	2	81	3300	-4	-28	3500	-5	-28	603	-6	-29	6600	-5	-22	79.6	-7	-27	5.1	-3	-13			
New England	800	87	86	100	-9	-27	300	-11	-19	31	-2	-11	900	-25	-30	39.2	-1	-3	0.7	-16	-19			
Middle Atlantic	1800	45	55	3000	-11	-47	4200	-9	-43	418	-9	-48	6600	-8	-30	64.3	-8	-25	5.7	-5	-19			
South Atlantic	3400	17	155	7400	-1	-35	7800	0	-34	1532	0	-34	15 700	-1	-27	276.2	0	-13	11.5	0	-24			
Total	37 000	21	58	38 500	-5.5	-29	43 600	-5.7	-29	6317	-4.5	-29	71 300	-6.3	-24	962.1	-2.7	-18	49.1	-4.5	-18			
													(79 800)	(-5.9)	(-23)									





represents lower total system costs illustrates that, under certain conditions (namely, high natural gas prices or low renewable energy technology costs), RE used to meet existing RPS policies results can result in cost savings to the electric system. Conversely, when gas prices are relatively low or when renewable energy technology costs are high, RE used for existing RPS requirements results in a cost increase. In either

case, however, the effect is quite small as a share of overall system costs. In the High RE scenario, larger incremental system cost impacts are observed, ranging from \$23 billion (0.6%) to \$194 billion (4.5%) of additional costs. The upper bound of the range corresponds to the sensitivity with high RE technology costs. Figure 3 compares these cost impacts (shown with negative values when representing increased costs, and

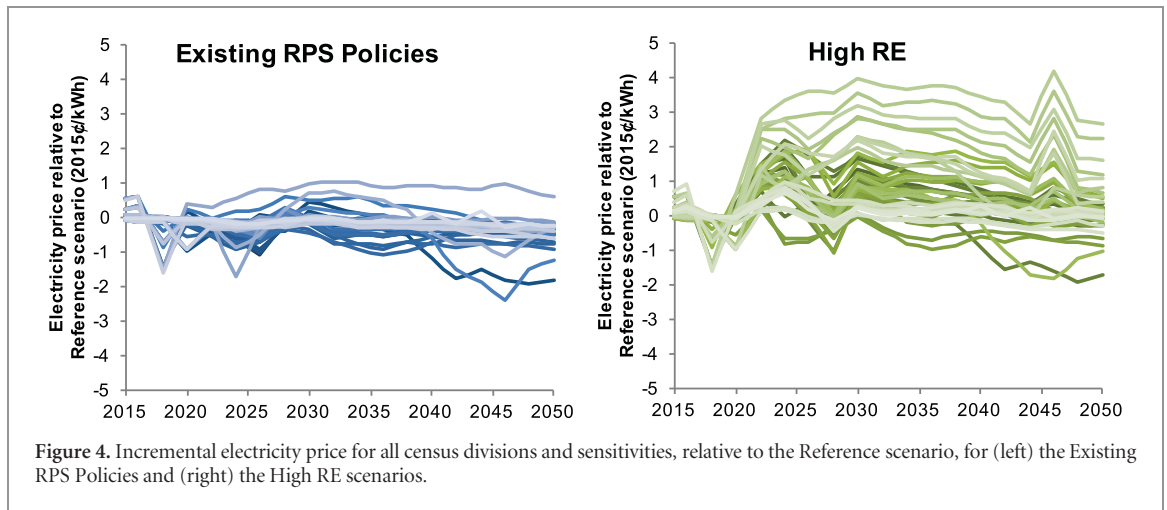


Figure 4. Incremental electricity price for all census divisions and sensitivities, relative to the Reference scenario, for (left) the Existing RPS Policies and (right) the High RE scenarios.

positive values when reflecting savings) to the estimated health and environmental benefits.

As detailed in Mai *et al* (2016a) and highlighted in figure 4, depending on the US census region, specific year and sensitivity case, retail electricity price impacts in the Existing RPS Policies scenario can be as much as roughly 1¢/kWh higher than in the Reference scenario<sup>11</sup>. However, estimated incremental prices vary significantly between regions and years and depend on future RE technology costs and fossil fuel prices. For some sensitivity cases and regions, electricity prices are projected to be lower in the Existing RPS Policies scenario than in the Reference scenario. The High RE case yields more-sizable impacts, with retail prices increasing in some years and regions by as much as 4.2¢/kWh, but declining in other cases<sup>12</sup>.

### 5.3. Air quality benefits

Cumulative (2015–2050) national emissions of SO<sub>2</sub>, NO<sub>x</sub>, and PM<sub>2.5</sub> decrease by 5.5%, 5.7%, and 4.5%, respectively, in the Existing RPS Policies scenario relative to the Reference scenario (see also table 1). The resultant health and environmental benefits are valued at \$48–\$175 billion on a discounted, present-value basis, primarily due to reductions to premature mortality associated with air pollution (figure 3). The simple

average of all five estimates is \$97 billion. Under the High RE scenario, we estimate cumulative emission reductions of 29% for each air pollutant (SO<sub>2</sub>, NO<sub>x</sub>, and PM<sub>2.5</sub>), corresponding to total benefits of \$303–\$917 billion on a present-value basis. The average estimate is \$558 billion.

Based on the EPA-RIA approach, the Existing RPS Policies scenario reduces premature mortalities by 12 000–28 000 from 2015 to 2050, compared to the Reference scenario, while the High RE scenario avoids 70 000–166 000 premature mortalities. These futures also result in numerous forms of avoided morbidity outcomes, as presented in Mai *et al* (2016a), though monetary estimates of the value of these outcomes is quite low in comparison to premature mortality.

Across both scenarios, most of the benefits stem from reduced SO<sub>2</sub> and subsequently reduced particulate sulfate concentrations. Particularly important is the avoided premature mortality primarily associated with reduced chronic exposure to ambient PM<sub>2.5</sub> (largely derived from the transformation of SO<sub>2</sub> to sulfate particles, but also from transformation of NO<sub>x</sub> to nitrate particles and direct PM<sub>2.5</sub> exposure). These benefits largely come from the displacement of coal generation and associated SO<sub>2</sub> emissions reductions in the central and eastern United States (see table 1 for regional estimates of emissions reductions).

### 5.4. Greenhouse gas emission reduction benefits

Cumulative (2015–2050) life-cycle GHG emissions are 6% lower (4.7 billion metric tons of CO<sub>2</sub>-equivalent) in the Existing RPS Policies scenario than in the Reference scenario. As shown in figure 3, this decrease is valued at \$161 billion in discounted global benefits based on a central value for the SCC (3% real discount rate). Across the full range of SCC estimates, total benefits span \$37 billion to \$487 billion. In the High RE scenario, cumulative life-cycle GHG emissions decrease by 23% (18.1 billion metric tons), resulting in \$599 billion of global benefits when using the central SCC value. Across the full range of SCC estimates, benefits span \$132 billion to \$1 821 billion.

<sup>11</sup> To provide some context for these price differences, wholesale average electricity prices (including energy, capacity, and modeled ancillary service prices) in 2050 under the Reference scenario are estimated to range from 6.2¢/kWh to 10.2¢/kWh across all census regions and all natural gas price and renewable cost sensitivities. Total retail electricity prices in 2050 under the Reference scenario also include distribution and transmission costs as well as other utility overhead expenditures, and range from 10.2¢/kWh to 20.6¢/kWh across all census regions and all sensitivities.

<sup>12</sup> Estimated electricity prices reflect the impact of RE tax credits, and so are lower than they would be absent the existence of those incentives. Reported total system costs, however, reflect total expenditures, and so include the effective cost of the available tax incentives to the US Treasury. The spike in incremental prices occurring during the mid-2040s on the right panel of figure 4 is a result of a confluence of our retirement assumptions, coincidentally leading to peak retirements occurring in 2046. These retirements lead to higher electricity prices, especially in the high renewable technology cost sensitivity.

Combustion-related CO<sub>2</sub> savings vary by region, timeframe, and scenario. Though GHGs are global pollutants, RPS programs are state creations, and so the regional allocation of emissions reductions may be important from a state policy perspective. As highlighted in table 1, under the Existing RPS Policies scenario, significant reductions accrue in most regions outside of the Southeast. Overall absolute reductions are substantially greater in the High RE scenario and are particularly sizable in the East North Central and South Atlantic regions. These results are driven by the relative amount and location of RE deployment in these scenarios and by the degree to which higher-carbon-emitting plants are displaced.

### 5.5. Water use reduction benefits

Cumulative (2015–2050) water consumption in the Existing RPS Policies scenario is 4.5% lower and water withdrawals are 2.7% lower compared to the Reference scenario. In the High RE scenario, water consumption and withdrawals are both 18% lower relative to consumption and withdrawal in the Reference scenario. To put these figures in context, the 2030 annual consumption savings are equal to the water demands of 420 000 US households in the Existing RPS Policies scenario, and 1.9 million households in the High RE scenario.

The water saved regionally is affected by the amount and type of incremental RE supply and the water use associated with displaced fossil generation units. The largest quantity of water savings are found to accrue in regions not generally considered water stressed, but which currently withdraw and consume larger quantities of water for power generation (see table 1). Although absolute water savings are lower in the water-stressed Southwest region of the United States, the percent savings there under the Existing RPS Policies scenario are more consistent with savings in other regions. Under the High RE scenario, absolute and percent water savings are much higher in regions other than the Southwest, and water savings are typically greater than those found in the Existing RPS Policies scenario.

## 6. Conclusion

Our analysis has several limitations that constrain what conclusions can be drawn. First, we focus solely on RPS programs, and do not compare our results to other policies that might achieve the same benefits more cost-effectively. Second, our analysis examines the costs and benefits of RE needed to meet RPS demand growth going forward, but we do not seek to *attribute* those effects solely to RPS policies. As a result, our estimates reflect an upper bound to the effects of *the policies themselves*, because other economic drivers might lead to some of this RE development even in the absence of RPS policies. Finally, as noted earlier, our analysis

considers an important subset of—but certainly not all—environmental and health benefits.

Despite these limitations, the analysis can inform decision-makers about the merits of state RPS programs as they consider revisions to existing policies and development of new policies. Specifically, the analysis suggests that, even under conservative assumptions, the benefits of RE used to meet RPS demand growth will exceed the costs (see figure 3). Under existing RPS policies, the net cost to the electric system over the 2015–2050 period is estimated to be no greater than \$31 billion, and could be negative in the case of higher-than-expected natural gas prices. By comparison, the *lower-bound* estimates of human health benefits associated with increased air quality total at least \$48 billion, plus an additional \$37 billion in benefits from reduced climate damages. Under the High RE scenario, the lower-bound estimates of air quality benefits (\$303 billion) and climate demand benefits (\$132 billion) again exceed the upper-bound cost estimate (\$194 billion). In both scenarios, additional benefits associated with reduced water usage, which are quantified in physical but not monetary units within our analysis, add further to the benefits tally and may be particularly salient in water-stressed regions.

Although this analysis indicates that RPS programs are, on a national scale, likely to be cost-effective when considering externalities, we do not claim that RPS programs represent the *most* cost-effective path towards achieving these air quality and climate benefits. Standard economic principles dictate that the most-efficient means of addressing environmental costs is typically through direct pricing or regulation of those emissions, not through renewable energy policies (Edenhofer *et al* 2013). Previous research focused on RPS policies has sometimes found that the desired benefits of RPS programs may not be fully achieved or achieved as cost effectively as desired (Carley 2011, Fischer and Newell 2008, Fell and Linn 2013, Rausch and Karplus 2014). Other research suggests that the pitfalls of such policies may be modest (Kalkuhl *et al* 2013), however, and direct and full pricing of emissions externalities has so-far proven elusive in the United States.

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