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Projected climate change impacts on Indiana's Energy demand and supply

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Abstract

This paper estimates changes in future energy demand and supply for Indiana due to projected climate change impacts. We first estimate demand changes under both the business-as-usual emissions scenario (RCP 8.5) and a scenario based on reduced emissions consistent with a 2-degree increase in global mean temperature (RCP 4.5), on both a statewide basis and for major urban areas. We then use our adjusted statewide energy demand projections as an input to a comprehensive model of Indiana's energy system, to project expected changes in the state's energy supply under both scenarios. Finally, we consider the potential impacts of two policy scenarios—a carbon pricing scheme and a renewable energy investment tax credit—on emissions and future energy supply choices. Our results suggest that climate change will have a relatively modest effect on energy demand and supply in Indiana, slightly increasing commercial demand and decreasing residential demand but having little effect on energy supply choices. In addition, our results suggest the potential for policy proposals currently being adopted in other states, such as a relatively small carbon price or investment credits for renewable energy sources, to have a larger impact on the state's future energy mix, increasing production from low or zero carbon energy sources and reducing emissions.

1 Introduction: Indiana's energy profile

How will climate change affect Indiana's energy system? This paper provides an initial answer to that question by estimating the impact of climate change on Indiana's future energy demand and supply. An assessment of expected climate impacts on the state's energy system is timely

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for several reasons. Although climate change is likely to have important effects on energy supply and demand, many state climate assessments do not try to model these effects on their energy systems (Wilbanks et al. 2013). In addition, Indiana's energy system is quite different from other more prominent and frequently studied states (such as California), making this assessment an important addition to our understanding of climate change's potential effects on different energy systems.

Indiana has a high reliance on fossil fuels, generating 75% of its electricity from coal and only 5% of its electricity from renewable sources (U.S. EIA 2017b; SUFG 2017). At the same time, the state is home to a growing wind energy sector (SUFG 2017), even as its reliance on coal is declining. This energy supply profile, combined with a climate and a manufacturing economy that creates significant needs for both space heating and cooling, makes Indiana the ninth most energy-intensive state on a per-capita basis and the eighth largest emitter of carbon dioxide nationally at just over 200 million metric tons per year (U.S. EIA 2017a). A better understanding of how climate change is likely to affect Indiana's energy supply and demand across sectors is therefore of interest to scholars studying potential climate change effects on energy systems in the Midwest, on states with a high dependence on fossil fuels but strong renewables potential, and on states with a relatively high level of energy intensity. In addition, the study is designed to be of interest to professionals and policymakers working on Indiana's energy system.

We begin our analysis by estimating the effects of future climate conditions on Indiana's energy demand. The state consumes approximately 46% of its energy in the industrial sector and 22% of its energy in transportation, with 19% of energy going to residential uses and 13% to the commercial sector (US EIA 2017b). Because industrial and transportation energy use has been shown in numerous studies (Mukherjee and Nateghi 2018a, 2017; Sailor 2001; Sailor and Muñoz 1997; Amato et al. 2005; Elkhafif 1996; Nateghi and Mukherjee 2017; Singh and Kennedy 2015) to be comparatively insensitive to climate variability, they are not expected to change significantly due to projected climate changes through 2080. For this reason, our demand analysis for the state focuses on the residential and commercial sectors.

The highest fraction of climate-sensitive energy demand in the residential sector is for space heating followed by water heating, with the lowest amount of energy used for space cooling. In the commercial sector, by contrast, consumption for space cooling ranks highest, followed by space heating and water heating (Nateghi and Mukherjee 2017; U.S. EIA 2016, 2017a, 2017c). These variations have important implications for differences in expected changes in energy demand in the residential and commercial sectors in the state.

The second part of our paper independently models the expected change in per-capita energy use in Indiana's 15 largest cities. Given that urban energy demand can vary significantly from suburban or rural demand (Norman et al. 2006), and the unique energy needs and systems for many Indiana urban areas (e.g., separate power companies and delivery systems in some urban areas), this analysis is also an important part of the effort to estimate energy demand changes due to changed future climate conditions.

Finally, the third part of our paper estimates expected changes in the state's energy supply using a version of the EPA Market Analysis (MARKAL) model (IEA-ETSAP 2011) tailored to Indiana's energy system (Lu 2015). Using this IN-MARKAL model, we can project which future trends in energy supply are more or less likely, and how expected changes in energy demand from climate change might influence those expected supply trends.

Finally, we consider the potential effect of two common state energy policies: a moderate carbon price of \$40/ton of CO_2 and a moderate investment tax credit for new renewable energy installations. Because state-level climate mitigation policies featuring a modest carbon price or an investment tax credit for renewables are already widely adopted, and likely to be considered in Indiana in the future, we find it important to estimate the impact of those two policy options on the state's energy supply and expected emissions.

2 Projected changes in residential and commercial energy demand

The projections of climate-driven changes in residential and commercial end-use energy demands are created by leveraging a three-step approach: (1) develop an ensemble tree-based Bayesian predictive model for the net energy demand[1] considering the influence of various climate factors, (2) project the net energy demand in both the residential and commercial sectors under climate change scenarios RCP 4.5 and 8.5, and (3) estimate the fractions of three major end-uses (space cooling, space heating, and water heating) for a representative user in the state of Indiana by generating sampling distributions: these fractions were multiplied with the net energy demand projections (obtained in step 2) to estimate the end-use demand projections under the climate change scenarios in the residential and commercial sectors of Indiana (for more information on these methods and the process, see Nateghi and Mukherjee 2017). We used the Bayesian based non-parametric statistical learning approach because it was found to best capture the complex energy demand–climate nexus in previous studies (Mukherjee and Nateghi 2017, 2018a, 2018b; Nateghi and Mukherjee 2017).

In step 1, we used time series data on historical net energy demand in the residential and commercial sectors[2] together with Indiana's historical monthly climate data[3] to develop the predictive models (based on Bayesian Additive Regression Trees—BART algorithm). We conducted a rigorous, randomized cross-validation technique (Hastie et al. 2008; James et al. 2013) to train, test, and validate the energy demand predictive model (for more information, see Electronic Supplemental Information (ESM)). In training our predictive models for each sector, we included the variable "year" to control for the non-climatic heterogeneities and secular trends,[4] in addition to considering the influence of climate on the net energy demand. Ideally, if the projected yearly values of the non-climatic factors (e.g., economic and population growth or technological advancement) existed for the state of Indiana, it would better capture these non-climatic heterogeneities. However, in the absence of reliable projected future values of the non-climatic factors affecting energy consumption, the variable "year" serves as a relevant non-climatic proxy variable.

In step 2, we ran multiple simulations to obtain the projected future net energy demand, using the Bayesian predictive model (developed in step 1) and the Indiana climate projections

[1] "Net energy demand" indicates total energy demand in the state of Indiana attributed toward all types of end-uses.

[2] We only used post-1980s data to exclude the shock associated with the energy crisis in the U.S. in the 1970s.

[3] Historical climate data used included maximum and minimum temperature (TMAX, TMIN), total precipitation (PRCP), and average wind speed (WDSP) during 1960–2013. To match the temporal resolution of the IN-MARKAL model used in our supply analysis, we aggregated the climate data over the three seasons: summer (June–September), winter (December–March), and intermediate (April, May, October, November).

[4] Secular trends refer to the non-seasonal/non-cyclical trends in the non-climatic factors such as economic or population growth and technological advancements.

data for RCP 4.5 and 8.5 (Hamlet et al. 2018). As an outcome of this step, we obtained scenario-based projections of the marginal effect of future climate conditions on net energy demand for both the residential and commercial sectors until the year 2080. Our models not only estimate the median effect of changes in future climate conditions on net energy demand but also provide probabilistic uncertainty assessments—in terms of Bayesian credible and prediction intervals.

In step 3, we obtained relative end-use demand proportions of space cooling, space heating, and water heating as a fraction of the net energy demand in the state of Indiana under the RCP 4.5 and 8.5 projected climatic conditions. We used U.S. EIA (2016; 2017c) data on residential and commercial energy consumption to generate sampling distributions of average end-use demand fractions for space cooling, space heating, and water heating for the respective sectors. To disaggregate estimates of state-level projected net energy demands into the “statistically representative” individual residential household/commercial building level, we multiplied the state-level median net energy demand projections—as well as the upper and lower bounds of the demand estimates (obtained in step 2)—by the generated sampling distributions representing the fractions of the end-use demands in the respective sectors.

Table 1 shows the top five predictors of energy demand in the residential sector, as measured by the inclusion proportion of the variables in the ensemble decision tree–based predictive model (for details, see Nateghi and Mukherjee 2017).

Our model shows that increased minimum winter temperature, which is associated with less energy use, is the most important predictor of residential energy use. Higher wind speeds in the intermediate season (spring/fall) are also important and are associated with increased residential energy demand due to the cooling effects of the stronger winds in Indiana during these periods (Nateghi and Mukherjee 2017). Non-climate factors captured by the “year” variable are also found to have a positive and significant effect on residential energy demand. For the commercial sector, our analysis shows that non-climatic factors are most important in shaping energy demand, followed by winter precipitation levels, wind speed during the winter, maximum temperature in the intermediate season, and minimum temperature in the winter (Table 1).

Table 1 Ranking of the top five energy demand predictors in the residential and commercial sectors (by inclusion proportion from Bayesian analysis)

Variables	Rank	Inclusion proportion	
		Mean	Standard deviation
Residential sector			
Minimum winter temperature	1	0.115	0.009
Year (non-climatic trends)	2	0.100	0.004
Maximum winter temperature	3	0.098	0.007
Wind speed in intermediate season	4	0.076	0.005
Maximum temperature in intermediate season	5	0.074	0.005
Commercial sector			
Year (non-climatic trends)	1	0.194	0.010
Winter precipitation levels	2	0.075	0.011
Wind speed during winter	3	0.074	0.008
Maximum temperature in intermediate season	4	0.074	0.009
Minimum temperature in winter	5	0.074	0.010

Our Bayesian predictive models indicate that the influence of future climate conditions on energy demand in Indiana is significant, but relatively small. Based on projected changes in maximum and minimum seasonal temperatures and precipitation under the RCP 4.5 and 8.5 scenarios (Hamlet et al. 2018), the net energy demand for an average residential household is projected to *decrease* by 2.8% and 3.0%, respectively, by 2050, and by 3.2% and 3.5%, respectively, by 2080, compared to a “no-climate change scenario” (Fig. 1). The marginal decrease is primarily due to a reduced heating requirement during warmer Indiana winters. On the other hand, net energy demand for an average commercial building is projected to *increase* by 5.0% and 5.5% by 2050 and 2080, respectively, under RCP 4.5, and by 5.4% and 5.2% by 2050 and 2080, respectively, under RCP 8.5 climate projections, compared to a “no-climate change scenario” (Fig. 1). This projected increase is due to the commercial sector’s greater use of cooling energy relative to the residential sector and higher projected future daytime temperatures.

Although the average impact of climate change on residential and commercial energy demands is relatively small, changes in demand may be greater for households or commercial enterprises located in the tails of the projected distributions, so these effects will vary across the state and across energy consumers. In addition, our modeling does not consider expected changes in several important climate variables that were not available from the initial modeling of future climate change impacts on Indiana (Hamlett et al. 2018). These omissions include climate-driven seasonal changes in wind speed, which was found to be in the top five factors for predicting both residential and commercial energy demand (Table 1), as well as changes in humidity and storm frequency and intensity that have been found to be important predictors of energy demand in previous studies (Mukherjee and Nateghi 2017, 2018b; Gotham et al. 2013). Projected changes in those climatic conditions would modify the results in Fig. 1: for example, higher humidity projections would generate a greater expected increase in residential and commercial cooling demand (Mukherjee and Nateghi 2017, 2018a), while increased wind speeds would be associated with an increase in residential energy demand and a decrease in commercial energy demand (Nateghi and Mukherjee 2017). In this respect, our analysis is a

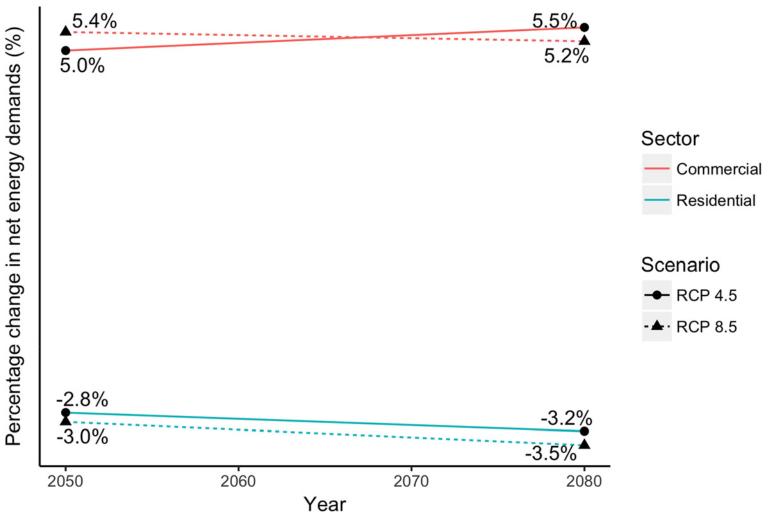

Fig. 1 Projected changes in state residential and commercial energy demand under RCP 4.5 and 8.5 in 2050 and 2080 over “no climate change” scenario

first pass at estimating the effects of future climate conditions on Indiana household and commercial energy demand, but future work is needed to extend our models to account for these additional climate factors.

3 Projected changes in urban energy demand

Because urban centers account for the majority of residential and commercial energy use (International Energy Agency 2016), and feature distinctive energy consumption patterns (Norman et al. 2006), we also performed a complementary city-level analysis of energy demand for the largest 15 Indiana cities (for complete list of cities studied, see ESM). These cities represent an estimated three quarters of Indiana's total population and GDP, making an understanding of the potentially unique influence of climate change on their residential and commercial energy use important. Fine-scale analysis for cities provides us the capability to inform stakeholders about the most relevant energy statistics for planning at small scale, as well as providing data that facilitates tailored policies in the places where they can have the most impact.

We model projected climate change impacts on residential and commercial heating and cooling demand in major cities using a statistical regression approach (for more detailed discussion of these methods, see Wachs and Singh under review). We use these models based on their proven track record for estimating the effects of climate conditions on urban energy demand (Singh and Kennedy 2015; Kennedy et al. 2015; McNeil et al. 2008; Isaac and Van Vuuren 2009) and due to a lack of data required to extend the Bayesian approach from Section 2 to specific urban areas. In addition, using an alternative method of estimating climate change impacts on energy demand provides an additional check by comparing the expected trends of energy consumption obtained from two independent modeling efforts: urban versus statewide.

We estimated potential climate change impacts on urban *heating* energy demand using an adapted version of the model developed by Singh and Kennedy (2015). This regression model was developed with World Bank data for global cities and tested predictor variables such as heating degree days (HDD), cooling degree days (CDD), GDP, and inverse urban density (land per capita), generating a model with HDD as the strongest predictive variable for per capital heating demand as shown in Eq. 1. Independent work by Kennedy et al. (2015) utilizing additional data for megacities also identified HDD as the most important predictor variable, improving our confidence in this model. The coefficient in Eq. 1 has been updated for this study by excluding heating energy portions for industrial use from total urban heating data (to capture the residential and commercial urban demand only) and running the regression model for urban heating energy against predictor variables again. We also performed additional statistical analysis for extrapolation to check for applicability of Eq. 1 for urban areas in Indiana, and found no hidden extrapolation for any of the heating projections in any of the scenarios and timeframes. This provided confidence in use of this model for projections of urban energy demand in Indiana as well (see Wachs and Singh under review for details).

$$H = 0.014725 \times HDD \tag{1}$$

Using this formula, we projected future per-capita heating demand for different Indiana cities using HDD based on projected average monthly temperature data for each urban area from the climate modeling output for scenarios RCP 4.5 and RCP 8.5 (Hamlet et al. 2018). HDD and

CDD are calculated around a base temperature of 18 °C using average monthly temperature projections (see Wachs and Singh under review and Singh and Kennedy 2015 for more details).

Per-capita urban cooling energy demand was estimated using another previously published model shown in Eq. 2 (McNeil et al. 2008; Isaac and Van Vuuren 2009). The model is derived based on a unitary method where the numerator gives the total energy consumption as product of number of households with cooling units ($= \frac{Population}{h} \times P$) where h = average people per household and P = penetration (percent of households with cooling units), and energy consumption per cooling unit (= UEC/EE), where UEC is the unit energy consumption for cooling to a certain temperature and EE is efficiency. UEC depends on cooling degree days (CDD) and household income (I) (see Eq. 3, taken directly from Isaac and Van Vuuren 2009). The UEC model was developed by running a linear regression on 37 data points to estimate the usage variable, unit energy consumption (UEC), against the explanatory variables of Income (I) and CDD (Isaac and Van Vuuren 2009). Since this model is developed using a causal relationship between energy consumption and driver variables (number of cooling units, cooling efficiency, UEC driven by CDD and Income), it is widely applicable. It also has been used globally for estimation of energy consumption due to climate change such as the TIMER model in IMAGE assessment (Stehfest et al. 2014), providing us confidence in use of this model for Indiana as well.

$$T = \frac{\frac{Population}{h} \times P \times \frac{UEC}{EE}}{Population} \tag{2}$$

$$UEC = CDD \times \{0.865 \times \ln(I) - 6.04\} \tag{3}$$

Using Eqs. 2 and 3, and projections on changes in CDD for RCP 4.5 and 8.5 (Hamlet et al. 2018), as well as projections for future income, population, and efficiency gains of cooling units, we projected the cooling energy demand changes for urban areas. Details on model development and methodology, underlying data and in-depth discussion on approach is given in Wachs and Singh (under review).

Our data suggest that per-capita heating demand should fall in Indiana's 15 largest cities by an average of 7.95% in 2050, and 13.04% in 2080 under the more moderate RCP 4.5 scenario, and by 13.3% in 2050 and 27.4% in 2080 using RCP 8.5, compared to estimated demand for 2015 (Fig. 2). The largest city in Indiana, Indianapolis, experiences very similar changes in expected heating demand compared to this average.

By contrast, climate changes are expected to increase average urban cooling demand per capita. This increase shows spatial variation, with higher cooling demand increases in cities to the north of Indianapolis. Assuming no efficiency gains (right panel Fig. 3) in air conditioning technology, average per-capita cooling demand increases in our 15 major cities by an average of 22.75% in 2050 and 31.68% in 2080 for RCP 4.5, and by 28.08% in 2050 and 39.77% in 2080 in RCP 8.5. Including projected efficiency gains in cooling technology significantly reduces this increase in energy for cooling to 16.75% over the 2015 benchmark for in 2050 for RCP 4.5, and to 21.30% for RCP 8.5. In addition, projected efficiency gains actually generate a small decline in per-capita cooling electricity demand from 2050 to 2080 under both climate scenarios (left panel, Fig. 3). In our analysis, Indianapolis cooling demand increases less than the statewide urban average due to its location (for more detailed information, see Wachs and Singh under review).

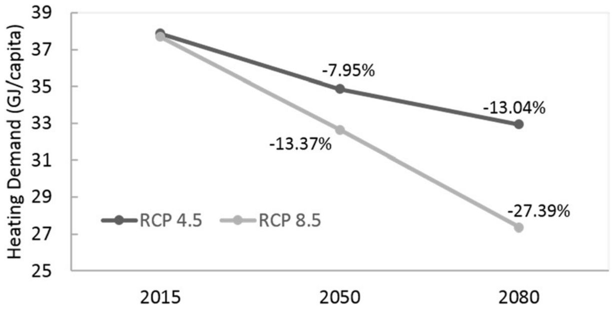

Fig. 2 Urban heating per-capita demand changes over climate scenarios (% changes are over the reference year of 2015 in each RCP category)

4 Projections of changes in Indiana's energy supply

In this section, we use the IN-MARKAL model to estimate potential changes in Indiana's energy supply portfolio based on climate-driven changes in energy demand, as well as the possible effects of two common climate mitigation policy options. IN-MARKAL minimizes the discounted sum of total system cost such that exogenously set end-use demands for energy services are satisfied by an optimal mix of technologies for extracting and converting energy into specific end-use demands over time, subject to technological, environmental, economic, and policy constraints. In addition, the model optimizes the mix of fuels used to produce electricity and traces emissions associated with the different fuels and energy conversion technologies selected. The model also incorporates an up-to-date representation of Indiana's current energy-producing sources, making the results reflect the state's specific energy mix.

IN-MARKAL has four primary end-use energy service demand sectors: residential, commercial, industrial, and transportation. Projected end-use demands for the years 2007–2043 in our analysis were taken from Lu (2015), which estimated future energy demand in Indiana across 42 different sectors using data from a variety of government and private sources (for more details, see ESM). The model's supply side energy technologies evolve over time as projected by the U.S. EPA (2013) through 2043. The model also considers alternative "demand-side conversion" technologies for serving a particular energy end-use demand, such as electric baseboard heating versus a natural gas furnace.

Fuels in the model include coal, natural gas, petroleum products, biomass, and renewable electricity generation technologies such as wind, solar, municipal solid waste, landfill gas, and hydropower. Fuel prices were initially parameterized through 2043 by Lu (2015) based on estimates of future energy price trends from the Energy Information Agency and other public

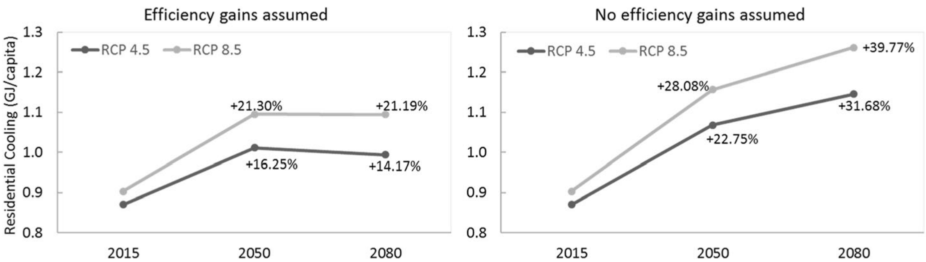

Fig. 3 Urban cooling per-capita demand changes with and without projected technology improvements. (% changes are over the reference year of 2015 in each RCP category)

and private sources, and extrapolated linearly for the present paper beyond 2043 in the absence of other published estimates. In sum, our analysis is based on projections of moderate future increases in coal prices and slow but steady increases in natural gas prices, which is broadly consistent with long-term predictions of future energy prices by other sources (see ESM for more details on fuel price sensitivity).

The electricity-generating sector is modeled with technologies parameterized with fuel usage levels, investment costs, known lifetimes, operating and maintenance costs, as well as generating capacity limits, generation efficiency levels, ability to serve peak demand, and emissions levels. Assumptions for changes to investment costs for electricity generation beyond the original horizon of 2043 were also made by linear extrapolation using the final five periods in the model by Lu (2015) (see ESM for more details on projected renewable energy costs).

Despite its detail, IN-MARKAL has limitations affecting its estimates of future energy supply. It does not estimate changes in energy service demands based on new energy prices—it finds the most cost-effective way to meet expected demand for heating and cooling, for example, but it does not adjust the demand for heating or cooling in the face of higher energy costs. In addition, IN-MARKAL does not incorporate certain distributed generation technologies, such as rooftop solar installations.

We estimate the effects of climate change on Indiana's energy supply by adjusting the exogenous, end-use demand for residential and commercial energy services in our IN-MARKAL model runs based on the analysis of relative demand changes under RCP 4.5 and RCP 8.5 in Section 2 above. In total, we ran the IN-MARKAL model under five different scenarios:

1. Climate scenario #1: "Baseline" demand under RCP 2.6, no policy
2. Climate scenario #2: Demand under RCP 4.5, no policy
3. Climate scenario #3: Demand under RCP 8.5, no policy
4. Policy scenario #1: Demand under RCP 8.5, carbon price
5. Policy scenario #2: Demand under RCP 8.5, renewable tax credit

To estimate the effects of climate change, we first ran scenario #1: a "baseline" run using the demand projections from Lu (2015) with the very small modifications expected under an RCP 2.6 scenario of very limited climate change. Then we modified the projected commercial and residential demand using the expected marginal impacts from climate change calculated in Section 2 under RCP 4.5 and 8.5 (scenarios #2 and #3), and estimated changes in supply by comparing those results with the energy mix under the baseline scenario. Finally, we ran policy scenarios 1 and 2 to consider the effects of two potential policies on the state's energy supply with demand as projected under RCP 8.5: a \$40/ton CO_2 economy-wide carbon price and a collection of investment tax credits on renewable generation technologies (SUFG 2016). In every scenario, we ran the model through 2092 in order to generate results for 2080 that recognized the need for future energy production beyond that date. Both policies are modeled as going into effect in 2022 and continuing through the end of the model horizon.

4.1 Climate change impacts on energy supply

In the baseline scenario using expected fuel price trajectories for coal, natural gas, wind, and solar outlined above and only minimal climate change impacts from RCP 2.6, the model projects a state energy mix for electricity generation of 64.6% coal, 34.9% natural gas, and less than 1% of all other fuels in 2050, and 51.3% natural gas, 48.3% wind, and less than 1% of all other fuels in 2080. A key feature of these results is that existing coal plants are projected to be retired in 2058 as they reach the end of their lifespans due to the price advantages of natural gas and renewables.

Projected climate-driven changes in energy demand have a minimal effect on the expected energy supply mix—the percentage of energy provided by natural gas, renewables, and coal remain virtually the same in 2050 and 2080 under both the climate-adjusted scenarios. For example, total 2050 energy output for electricity in the baseline scenario is 471.06 PJ from coal and 254.24 PJ from natural gas, with no output from wind. In the RCP 4.5 scenario, coal-fired electricity output is the same, and natural gas-fired output increases to 254.83 PJ, or less than 1% above the baseline scenarios. For RCP 8.5, coal-fired electricity production is the same in 2050 and natural gas production decreases slightly to 252.34 PJ, again a less than 1% change. Slightly larger changes in projected electricity production from natural gas and wind occur in 2080, especially under RCP 4.5, where electricity from natural gas declines from 527.44 PJ in the baseline scenario to 511.95 PJ (nearly 3%), while wind production increases from 497.06 to 511.79 PJ, an increase of nearly 3%. Although the pattern reverses for 2080 under RCP 8.5, with natural gas output increasing by 0.86% to 531.97 PJ and wind production decreasing slightly to 489.58 PJ, the overall changes due to adjusted energy demand from climate change remain extremely small even with the larger expected climate impacts from RCP 8.5 (see ESM for summary of these variations).

Figure 4 shows this evolution of the state's energy mix for producing electricity in greater detail under the RCP 8.5 scenario, illustrating the change over time toward natural gas and wind power instead of coal even under the strongest modeled climate changes for the state.

The projected shift to gas and wind is not only robust across all our climate scenarios but also to a wide range of possible fuel prices (see ESM for discussion of fuel price sensitivities). Even the extreme case of a future coal price of $0, for example, leads to less than 10% of post-2058 generation coming from coal. The mix between natural gas and wind power is much more sensitive to price projections for natural gas, however, with natural gas potentially replacing wind generation entirely if it were to remain at current prices throughout our model timeframe.

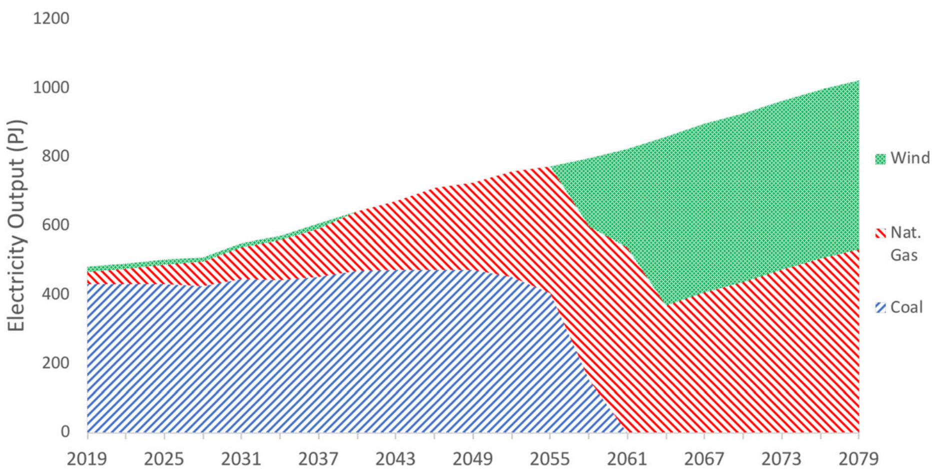

Fig. 4 Electricity generation by fuel type, RCP 8.5

As wind generation becomes a larger percentage of total electricity generation, installed wind capacity increases more than proportionately in order to meet seasonal and daily peak demand, leading to excess wind capacity in periods of low demand. Projected investment costs for solar (U.S. EPA 2013) keep it out of the model's energy mix, but in a scenario where solar capital costs fall by 50% and wind capital costs remain the same as the baseline, solar generation becomes nearly 80% of the electricity supply by 2080 under RCP 8.5 (see ESM Section 5 for detailed figures), so the mix between solar and wind is also sensitive to relative price changes in the capital costs of both technologies over time that are difficult to project through 2080.

4.2 Policy impacts on energy supply

Both of the policies we modeled have significant impacts on the state's electricity generation portfolio and total emissions even under the higher climate impacts scenario, RCP 8.5. Under the $40 carbon price, wind generation increases to 35% of electricity in 2050 and 73% in 2080, compared to 0% in 2050 and 48% in 2080 with no policy (bottom panel Fig. 5). Supply-side renewable investment credits generate a similar result, with investment in wind power slightly delayed but increasing more over time (bottom panel Fig. 5).

Both policies also have a substantial impact on expected CO_2 emissions. A carbon price yields the larger average annual reduction in carbon dioxide emissions from 2021 to 2080 (approximately 10%), followed by supply-side renewable generation investment subsidies at approximately 6% (top panel Fig. 5). Future emissions after 2065 are slightly lower under the renewable investment tax credits, however, than for the carbon price. It is also important to note that there are additional emissions reductions in the model from the carbon price due to changes in choices of different demand-side energy technologies driven by changes in relative fuel prices.

These results suggest the potential to achieve substantial changes in the state's use of renewables and CO_2 emissions using relatively modest policy changes. The $40/ton CO_2 price being modeled is well below the typical carbon price discussed in other long-term policy scenarios of $100/ton

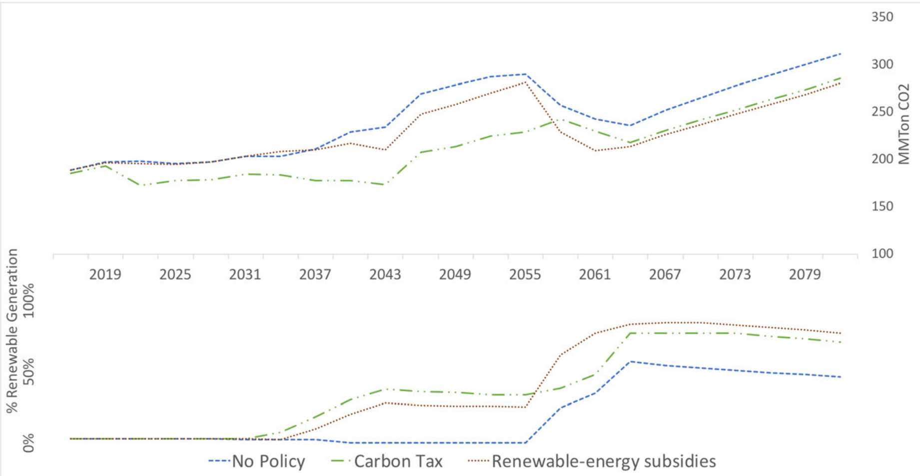

Fig. 5 Annual CO_2 emissions in million tons (top panel) and percentage generation from renewables for electricity sector (bottom panel), RCP 8.5, three policies

CO_2 or more (e.g., Stern and Stiglitz 2017), yet still has a substantial effect on emissions and the state's long-term energy mix. As of 2018, renewable investment tax credits have been implemented in many U.S. states, and 11 states have implemented some form of carbon pricing.

The results also suggest important trade-offs between objectives for different policy options. While a carbon price largely maintains the same level of electricity production, it leads suppliers to swap coal and natural gas for wind power earlier and sees a high percentage of electricity generated from wind in later years. Renewable energy tax credits actually increase electricity production compared to other energy sources, as investment credits to electricity generation decrease the capitalized cost of new investment, resulting in fuel substitution into electricity to satisfy end-use demand. For this reason, supply-side investment credits result in a smaller reduction in emissions because the increase in total demand for electricity somewhat offsets the reduction in emissions from this policy option. Of course, these two policies will also have different effects on energy prices and state economic development, which will be further impacted by how revenues from a carbon price are invested (Raymond 2016; Burtraw 2008) or how supply-side investment tax credits are funded. Unfortunately, those larger impacts of these policy scenarios are beyond the scope of the current analysis.

5 Discussion

Our analysis of projected climate change impacts on Indiana energy demand has several main conclusions. Bayesian prediction models of end-use demand as a function of climate variability indicate that decreased heating demand from expected higher winter temperatures will reduce net energy demand in the residential sector by around 3% by 2050 and 2080 under both climate change scenarios. At the same time, higher summer temperatures are expected to increase net energy demand in the commercial sector by about 5% by 2050 and 2080, due to greater demand for space cooling in the commercial than the residential sector. Differences in these projected energy demands between the two main climate scenarios (RCP 4.5 and 8.5) are modest. A different modeling approach projects parallel trends for Indiana's 15 major cities: an average decrease in per-capita heating demand between 13% and 27% by 2080, and an increase in per-capita cooling demand of 31% to 39% by the same date (not considering projected efficiency gains technology). Interestingly, the relative gap between expected urban demand changes under RCP 4.5 and 8.5 is much larger in the urban energy model than in our statewide analysis.

We find that the small projected changes in energy demand due to climate change are not expected to have a large effect on Indiana's future energy supply portfolio. Rather, the biggest factors shaping the state's future energy supply are expected trends in energy prices and the projected lifespan of currently operating coal-fired power plants. At the same time, our analysis of two possible policy scenarios indicates the potential for even a modest carbon price ($40/ton) or renewable energy investment tax credits to shift the state's energy mix toward low carbon energy sources more quickly.

Beyond these detailed estimates of changes in energy demand and supply, it is important to recognize many other impacts on the state's energy system from climate change that are not captured in our analysis. A detailed assessment of future changes in the state's generation and transmission infrastructure due to climate change is beyond the scope of our analysis except for IN-MARKAL's installation of extra capacity for wind power to meet peak demand as wind become a larger source of electricity. We also do not assess how possible climate-driven changes in storm frequency and intensity might affect the reliability of the state's energy supply, or how higher or lower water levels could also pose challenges to the state's existing electricity infrastructure, which is largely located along major waterways and vulnerable to flooding as well as low water levels threatening availability of cooling water. Nor can our analysis account for the possibility of a more dramatic improvement in energy efficiency technologies, or more widespread use of distributed generation of renewables and micro-grids, which have the potential to significantly reduce energy demand for the same levels of heating, cooling, and other services. Finally, our analysis does not consider potential climate-driven changes in non-climate factors that affect our statewide demand assessments, such as a greater-than-projected increase in population in Indiana from migrating residents of other states facing flooding from rising sea levels or severe summer temperatures and droughts.

In addition, changes in energy demand and supply have other important potential economic and health impacts that are not considered here. For example, U.S. job growth in renewables is higher than in fossil fuels, and on a total employment basis is already nearly on a par therewith (Energy Futures Initiative 2018). Currently, Indiana is behind many states for this growth, with under 2000 jobs in solar (SUFG 2017). In addition, research indicates that coal-fired power generation creates significant public health risks from "co-pollutants" not associated with climate change (Prehoda and Pearce 2017), and our paper does not estimate these public health impacts of different transition periods away from coal-fired electricity generation (for more on public health threats from climate change generally, see Filippelli et al. in review).

There are also common policy options that we could not evaluate in this effort. We could not assess the economic or technology cost impacts of dedicating carbon pricing revenue to consumer rebates or investment in research on renewable energy (Raymond 2016). In addition, it was not possible to model the supply effects of an important *demand management* policy like an Energy Efficiency Standard that requires and incentives statewide across the board percentage gains in energy efficiency.

6 Conclusion

The effects of climate change on Indiana's energy demand and supply are mixed. Our modeling is consistent with the intuitive finding that projected warmer winter temperatures will likely reduce heating demand, at least in the residential and commercial sectors, while increased summer temperatures and other factors will increase cooling demand. Because the state dedicates more energy to residential and commercial heating than to cooling, however, these changes end up reducing the state's total projected energy demand slightly under both climate change scenarios in 2050 and 2080. The impact of these modest demand changes on the state's energy supply is extremely small. At the same time, it is also notable that the state faces an energy supply future where coal is likely to be replaced by other lower-cost fuels or renewable technologies, and where common policies such as a low carbon price or an investment tax credit for renewable energy could shift the distribution of future energy supply even more heavily in favor of low or zero carbon energy options. Although this analysis lacks the space to fully address many other potential impacts from climate change on the state's energy system, including interruptions to supply, unexpected breakthroughs in low or zero-carbon energy technologies, or dramatic shifts in the state's population patterns due to climate change, these general trends are a first step in considering the future energy effects of climate change on the state.

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References

Amato AD, Ruth M, Kirshen P, Horwitz J (2005) Regional energy demand responses to climate change: methodology and application to the Commonwealth of Massachusetts. Clim Chang 71(1):175–201
Burtraw D (2008) Cap, auction, and trade: auctions and revenue recycling under carbon cap and trade. http://www.rff.org/focus_areas/features/Documents/CT-Burtraw-Testimony-08-01-23.pdf. Accessed 15 December 2017
Elkhafif MAT (1996) An iterative approach for weather-correcting energy consumption data. Energy Econ 18: 221–230
Energy Futures Initiative (2018) U.S. Energy and employment report. https://www.usenergyjobs.org. Accessed 3 July 2018
Filippelli G, Jay S, Gibson J, Wells E, Moreno-Madriñán MJ, Ogashawara I, Freeman J, Rosenthal F (in review). The current and future impacts of climate change on human health in Indiana. Clim Chang (under review)
Gotham, DJ, Angel JR, Pryor SC (2013) Vulnerability of the electricity and water sectors to climate change in the Midwest. In: Climate change in the Midwest: impacts, risks, vulnerability and adaptation, S.C. Pryor, ed., Indiana University Press, 158–177
Hamlet AF, Brun K, Robeson S, Widhalm M, Baldwin M (2018) Impacts of climate change on the state of Indiana: future projections based on statistical downscaling. Clim Change
Hastie T, Tibshirani R, Friedman JH (2008) The elements of statistical learning (second). Springer, New York
International Energy Agency (2016) Energy Technology Perspectives 2016. www.iea.org/etp2016. Accessed 3 January 2018
International Energy Agency—Energy Technology Systems Analysis Program (IEA-ETSAP) (2011) https://iea-etsap.org/index.php/etsap-tools/model-generators/markal. Accessed 26 November 2017
Isaac M, Van Vuuren D (2009) Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. Energy Policy 37(2):507–521
James G, Witten D, Hastie T, Tibshirani R (2013) An introduction to statistical learning—with applications in R. Springer-Verlag, New York
Kennedy CA, Stewart I, Facchini A, Cersosimo I, Mele R, Chen B, Uda M, Kansal A, Chiu A, Kim K, Dubeux C, LaRovere EL, Cunha B, Pincetl S, Keirstead J, Barles S, Pusaka S, Gunawa J, Adegbile M, Nazariha M, Hoque S, Marcotullio PJ, Otharan FG, Genena T, Ibrahim N, Farooqui R, Cervantes G, Sahin AD (2015) Energy and material flows of megacities. PNAS 112(19):5985–5990
Lu L (2015) An assessment of the efficacy and cost of alternative carbon mitigation policies for the state of Indiana. Dissertation, Purdue University
McNeil M, Letschert V, de la Rue du Can S (2008) Global potential of energy efficiency standards and labeling programs. Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley
Mukherjee S, Nateghi R (2017) Climate sensitivity of end-use electricity consumption in the built environment: an application to the state of Florida, United States. Energy 28
Mukherjee S, Nateghi R (2018a) A data-driven approach to assessing supply inadequacy risks due to climate-induced shifts in electricity demand. Risk Anal (under 3rd review)
Mukherjee S, Nateghi R (2018b) Estimating climate–demand nexus to support long-term adequacy planning in the energy sector. In: 2017 IEEE Power & Energy society general meeting. IEEE Xplore, pp 1–5
Nateghi R, Mukherjee S (2017) A multi-paradigm framework to assess the impacts of climate change on end-use energy demand. PLoS One 12(11):e0188033
Norman J, MacLean HL, Kennedy CA (2006) Comparing high and low residential density: life-cycle analysis of energy use and greenhouse gas emissions. J Urban Plan Dev 132(1):10–21

Prehoda EW, Pearce JM (2017) Potential lives saved by replacing coal with solar photovoltaic electricity production in the U.S. Renew Sust Energ Rev 80(Supplement C):710–715

Raymond L (2016) Reclaiming the atmospheric commons: the regional greenhouse gas initiative and a new model of emissions trading. MIT Press, Cambridge

Sailor DJ (2001) Relating residential and commercial sector electricity loads to climate—evaluating state level sensitivities and vulnerabilities. Energy 26:645–657

Sailor DJ, Muñoz JR (1997) Sensitivity of electricity and natural gas consumption to climate in the U.S.A.—methodology and results for eight states. Energy 22:987–998

Singh S, Kennedy C (2015) Estimating future energy use and CO_2 emissions of the world's cities. Environ Pollut 203:271–278

Stehfest E, van Vuuren D, Kram T, Bouwman L, Alkemade R, Bakkenes M, Biemans H, Bouwman A, den Elzen M, Janse J, Lucas P, van Minnen J, Müller C, Prins A (2014) Integrated assessment of global environmental change with IMAGE 30—model description and policy applications http://www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-IMAGE-3.0. Accessed 3 July 2018

(SUFG) State Utility Forecasting Group (2017) Indiana renewable energy resources study. http://www.purdue.edu/discoverypark/sufg/docs/publications/2017_RenewablesReport.pdf. Accessed 15 December 2017

(SUFG) State Utility Forecasting Group (2016) 2016 Indiana renewable energy Resources Study. http://dev.www.purdue.edu/discoverypark/sufg/docs/publications/2016%20Renewables%20Report.pdf. Accessed 26 November 2017

Stern N, Stiglitz JE (2017) Report of the high-level commission on carbon prices. World Bank, Washington D.C

U.S. Energy Information Agency (2016) State Energy Data System (SEDS) INDIANA: State Profile & Energy Estimates. http://www.eia.gov/state/seds/seds-data-complete.cfm?sid=IN. Accessed 15 December 2017

U.S. Energy Information Agency (2017a) Commercial Building Energy Consumption Survey (CBECS). https://www.eia.gov/consumption/commercial/maps.php. Accessed 10 May 2017

U.S. Energy Information Agency (2017b) Indiana State Energy Profile. https://www.eia.gov/state/print.php?sid=IN. Accessed 15 December 2017

U.S. Energy Information Agency (2017c) Residential Energy Consumption Survey (RECS). https://www.eia.gov/consumption/residential/data/2009/index.php?view=consumption. Accessed 15 December 2017

U.S. EPA (2013) Region Nine MARKAL database, database documentation. US Environmental Protection Agency, Cincinnati, OH, EPA/600/B-13/203

Wachs, E, Singh S (under review) Estimating spatial variations of urban energy demand in Indiana under future climate change scenarios. Clim Chang

Wilbanks T, Bilello D, Schmalzer D, Scott M et al (2013) Climate change and energy supply and use: technical report for the U.S. Department of Energy in support of the National Climate Assessment. Island Press, Washington, DC

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