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

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1 **Title:** Projected climate change impacts on Indiana’s Energy demand and supply

2

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19

20

21 **Abstract:** This paper estimates changes in future energy demand and supply for Indiana due to
22 projected climate change impacts. We first estimate demand changes under both the business-as-
23 usual emissions scenario (RCP 8.5) and a scenario based on reduced emissions consistent with a
24 2-degree increase in global mean temperature (RCP 4.5), on both a statewide basis and for major
25 urban areas. We then use our adjusted statewide energy demand projections as an input to a
26 comprehensive model of Indiana’s energy system, to project expected changes in the state’s
27 energy supply under both scenarios. Finally, we consider the potential impacts of two policy
28 scenarios—a carbon pricing scheme and a renewable energy investment tax credit—on
29 emissions and future energy supply choices. Our results suggest that climate change will have a
30 relatively modest effect on energy demand and supply in Indiana, slightly increasing commercial
31 demand and decreasing residential demand but having little effect on energy supply choices. In
32 addition, our results suggest the potential for policy proposals currently being adopted in other
33 states, such as a relatively small carbon price or investment credits for renewable energy sources,
34 to have a larger impact on the state’s future energy mix, increasing production from low or zero
35 carbon energy sources and reducing emissions.

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37

1. Introduction

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 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

83 areas), this analysis is also an important part of the effort to estimate energy demand changes due
84 to changed future climate conditions.

85
86 Finally, the third part of our paper estimates expected changes in the state’s energy supply using
87 a version of the EPA Market Analysis (MARKAL) model (IEA-ETSAP 2011) tailored to
88 Indiana’s energy system (Lu 2015). Using this IN-MARKAL model, we can project which future
89 trends in energy supply are more or less likely, and how expected changes in energy demand
90 from climate change might influence those expected supply trends.

91
92 Finally, we consider the potential effect of two common state energy policies: a moderate carbon
93 price of \$40/ton of CO₂ and a moderate investment tax credit for new renewable energy
94 installations. Because state-level climate mitigation policies featuring a modest carbon price or
95 an investment tax credit for renewables are already widely adopted, and likely to be considered
96 in Indiana in the future, we find it important to estimate the impact of those two policy options
97 on the state’s energy supply and expected emissions.

98

99 **2. Projected changes in residential and commercial energy demand**

100

101 The projections of climate-driven changes in residential and commercial end-use energy
102 demands are created by leveraging a three-step approach: (1) develop an ensemble treebased
103 Bayesian predictive model for the net energy demand¹ considering the influence of various
104 climate factors, (2) project the net energy demand in both the residential and commercial sectors
105 under climate change scenarios RCP 4.5 and 8.5, and (3) estimate the fractions of three major
106 end-uses (space cooling, space heating, and water heating) for a representative user in the state of
107 Indiana by generating sampling distributions: these fractions were multiplied with the net energy
108 demand projections (obtained in step 2) to estimate the end-use demand projections under the
109 climate change scenarios in the residential and commercial sectors of Indiana (for more
110 information on these methods and the process, see Nateghi and Mukherjee 2017). We used the
111 Bayesian based non-parametric statistical learning approach because it was found to best capture
112 the complex energy demand–climate nexus in previous studies (Mukherjee and Nateghi 2017,
113 2018a, 2018b; Nateghi and Mukherjee 2017).

114

115 In step 1, we used time series data on historical net energy demand in the residential and
116 commercial sectors² together with Indiana’s historical monthly climate data³ to develop the
117 predictive models (based on Bayesian Additive Regression Trees—BART algorithm). We
118 conducted a rigorous, randomized cross-validation technique (Hastie et al. 2008; James et al.
119 2013) to train, test, and validate the energy demand predictive model (for more information, see
120 Electronic Supplemental Information (ESM)). In training our predictive models for each sector,
121 we included the variable “year” to control for the non-climatic heterogeneities and secular
122 trends,⁴ in addition to considering the influence of climate on the net energy demand. Ideally, if
123 the projected yearly values of the non-climatic factors (e.g., economic and population growth or
124 technological advancement) existed for the state of Indiana, it would better capture these non-
125 climatic heterogeneities. However, in the absence of reliable projected future values of the non-
126 climatic factors affecting energy consumption, the variable “year” serves as a relevant non-
127 climatic proxy variable.

128

129 In step 2, we ran multiple simulations to obtain the projected future net energy demand, using the
130 Bayesian predictive model (developed in step 1) and the Indiana climate projections data for
131 RCP 4.5 and 8.5 (Hamlet et al. 2018). As an outcome of this step, we obtained scenario-based
132 projections of the marginal effect of future climate conditions on net energy demand for both the
133 residential and commercial sectors until the year 2080. Our models not only estimate the median
134 effect of changes in future climate conditions on net energy demand but also provide
135 probabilistic uncertainty assessments—in terms of Bayesian credible and prediction intervals.
136

137 In step 3, we obtained relative end-use demand proportions of space cooling, space heating, and
138 water heating as a fraction of the net energy demand in the state of Indiana under the RCP 4.5
139 and 8.5 projected climatic conditions. We used U.S. EIA (2016; 2017c) data on residential and
140 commercial energy consumption to generate sampling distributions of average end-use demand
141 fractions for space cooling, space heating, and water heating for the respective sectors. To
142 disaggregate estimates of state-level projected net energy demands into the “statistically
143 representative” individual residential household/commercial building level, we multiplied the
144 state-level median net energy demand projections—as well as the upper and lower bounds of the
145 demand estimates (obtained in step 2)—by the generated sampling distributions representing the
146 fractions of the end-use demands in the respective sectors.
147

148 Table 1 shows the top five predictors of energy demand in the residential sector, as measured by
149 the inclusion proportion of the variables in the ensemble decision tree–based predictive model
150 (for details, see Nateghi and Mukherjee 2017).
151

152 Our model shows that increased minimum winter temperature, which is associated with less
153 energy use, is the most important predictor of residential energy use. Higher wind speeds in the
154 intermediate season (spring/fall) are also important and are associated with increased residential
155 energy demand due to the cooling effects of the stronger winds in Indiana during these periods
156 (Nateghi and Mukherjee 2017). Non-climate factors captured by the “year” variable are also
157 found to have a positive and significant effect on residential energy demand. For the commercial
158 sector, our analysis shows that non-climatic factors are most important in shaping energy
159 demand, followed by winter precipitation levels, wind speed during the winter, maximum
160 temperature in the intermediate season, and minimum temperature in the winter (Table 1).
161

162 **Table 1.** Ranking of the top five energy demand predictors in the residential and commercial
163 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

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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 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.

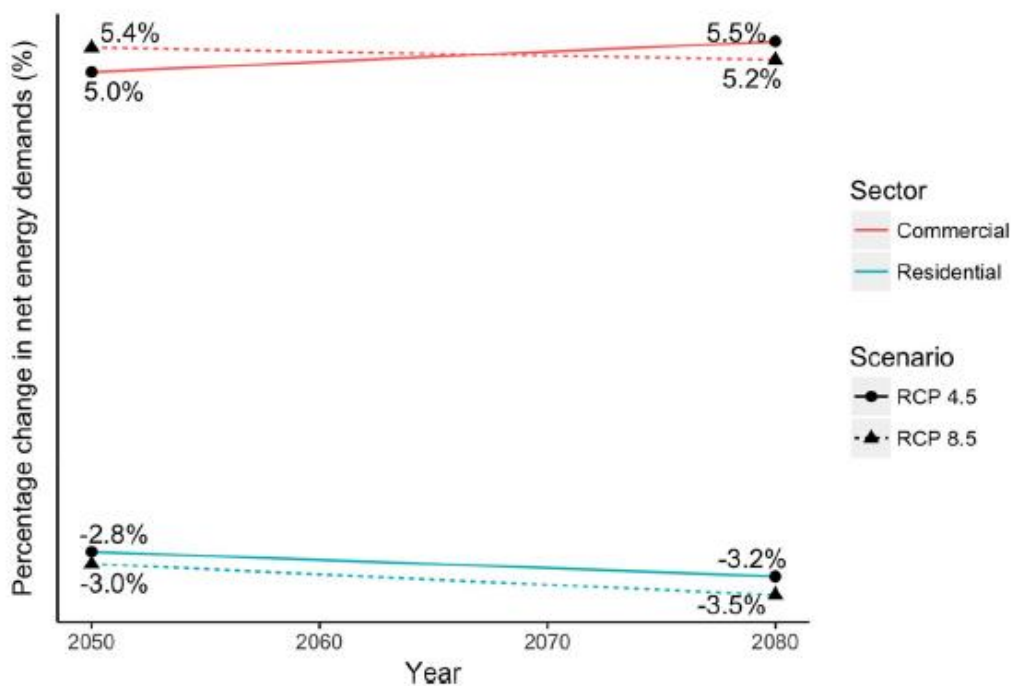


Fig. 1 Projected changes in state residential and commercial energy demand under RCP 4.5 and 8.5 in 2050 and 2080 over “no climate change” scenario

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.

223 We estimated potential climate change impacts on urban heating energy demand using an
224 adapted version of the model developed by Singh and Kennedy (2015). This regression model
225 was developed with World Bank data for global cities and tested predictor variables such as
226 heating degree days (HDD), cooling degree days (CDD), GDP, and inverse urban density (land
227 per capita), generating a model with HDD as the strongest predictive variable for per capital
228 heating demand as shown in Eq. 1. Independent work by Kennedy et al. (2015) utilizing
229 additional data for megacities also identified HDD as the most important predictor variable,
230 improving our confidence in this model. The coefficient in Eq. 1 has been updated for this study
231 by excluding heating energy portions for industrial use from total urban heating data (to capture
232 the residential and commercial urban demand only) and running the regression model for urban
233 heating energy against predictor variables again. We also performed additional statistical
234 analysis for extrapolation to check for applicability of Eq. 1 for urban areas in Indiana, and found
235 no hidden extrapolation for any of the heating projections in any of the scenarios and timeframes.
236 This provided confidence in use of this model for projections of urban energy demand in Indiana
237 as well (see Wachs and Singh under review for details).
238

$$H = 0.014725 \times HDD \quad (1)$$

239
240 Using this formula, we projected future per-capita heating demand for different Indiana cities
241 using HDD based on projected average monthly temperature data for each urban area from the
242 climate modeling output for scenarios RCP 4.5 and RCP 8.5 (Hamlet et al. 2018). HDD and
243 CDD are calculated around a base temperature of 18 °C using average monthly temperature
244 projections (see Wachs and Singh under review and Singh and Kennedy 2015 for more details).
245

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

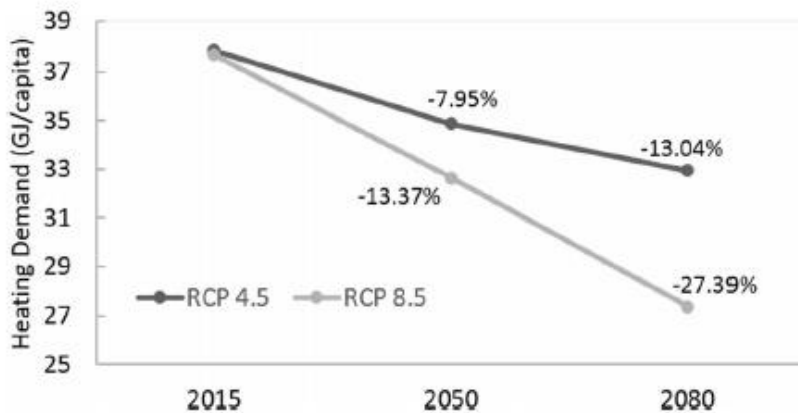
$$T = \frac{\frac{\text{Population}}{h} \times P \times \frac{UEC}{EE}}{\text{Population}} \quad (2)$$

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

261
 262 Using Eqs. 2 and 3, and projections on changes in CDD for RCP 4.5 and 8.5 (Hamlet et al.
 263 2018), as well as projections for future income, population, and efficiency gains of cooling units,
 264 we projected the cooling energy demand changes for urban areas. Details on model development
 265 and methodology, underlying data and in-depth discussion on approach is given in Wachs and
 266 Singh (under review).

267
 268 Our data suggest that per-capita heating demand should fall in Indiana’s 15 largest cities by an
 269 average of 7.95% in 2050, and 13.04% in 2080 under the more moderate RCP 4.5 scenario, and
 270 by 13.3% in 2050 and 27.4% in 2080 using RCP 8.5, compared to estimated demand for 2015
 271 (Fig. 2). The largest city in Indiana, Indianapolis, experiences very similar changes in expected
 272 heating demand compared to this average.

273
 274 By contrast, climate changes are expected to increase average urban cooling demand per capita.
 275 This increase shows spatial variation, with higher cooling demand increases in cities to the north
 276 of Indianapolis. Assuming no efficiency gains (right panel Fig. 3) in air conditioning technology,
 277 average per-capita cooling demand increases in our 15 major cities by an average of 22.75% in
 278 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.
 279 Including projected efficiency gains in cooling technology significantly reduces this increase in
 280 energy for cooling to 16.75% over the 2015 benchmark for in 2050 for RCP 4.5, and to 21.30%
 281 for RCP 8.5. In addition, projected efficiency gains actually generate a small decline in per-
 282 capita cooling electricity demand from 2050 to 2080 under both climate scenarios (left panel,
 283 Fig. 3). In our analysis, Indianapolis cooling demand increases less than the statewide urban
 284 average due to its location (for more detailed information, see Wachs and Singh under review).



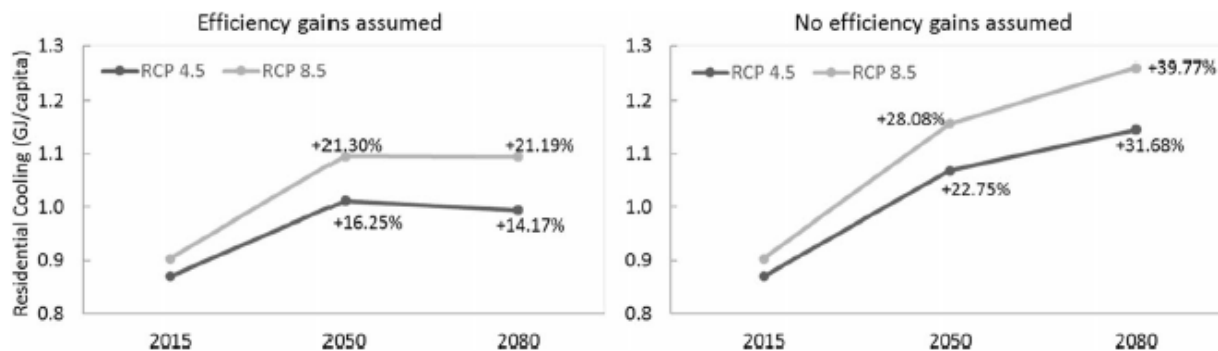
285
 286 **Fig 2.** Urban heating per-capita demand changes over climate scenarios (% changes are over the
 287 reference year of 2015 in each RCP category)
 288

289 4. Projections of changes in Indiana’s energy supply

290
291 In this section, we use the IN-MARKAL model to estimate potential changes in Indiana’s energy
292 supply portfolio based on climate-driven changes in energy demand, as well as the possible
293 effects of two common climate mitigation policy options. IN-MARKAL minimizes the
294 discounted sum of total system cost such that exogenously set end-use demands for energy
295 services are satisfied by an optimal mix of technologies for extracting and converting energy into
296 specific end-use demands over time, subject to technological, environmental, economic, and
297 policy constraints. In addition, the model optimizes the mix of fuels used to produce electricity
298 and traces emissions associated with the different fuels and energy conversion technologies
299 selected. The model also incorporates an up-to-date representation of Indiana’s current energy-
300 producing sources, making the results reflect the state’s specific energy mix.

301
302 IN-MARKAL has four primary end-use energy service demand sectors: residential, commercial,
303 industrial, and transportation. Projected end-use demands for the years 2007–2043 in our
304 analysis were taken from Lu (2015), which estimated future energy demand in Indiana across 42
305 different sectors using data from a variety of government and private sources (for more details,
306 see ESM). The model’s supply side energy technologies evolve over time as projected by the
307 U.S. EPA (2013) through 2043. The model also considers alternative “demand-side conversion”
308 technologies for serving a particular energy end-use demand, such as electric baseboard heating
309 versus a natural gas furnace.

310
311 Fuels in the model include coal, natural gas, petroleum products, biomass, and renewable
312 electricity generation technologies such as wind, solar, municipal solid waste, landfill gas, and
313 hydropower. Fuel prices were initially parameterized through 2043 by Lu (2015) based on
314 estimates of future energy price trends from the Energy Information Agency and other public and
315 private sources, and extrapolated linearly for the present paper beyond 2043 in the absence of
316 other published estimates. In sum, our analysis is based on projections of moderate future
317 increases in coal prices and slow but steady increases in natural gas prices, which is broadly
318 consistent with long-term predictions of future energy prices by other sources (see ESM for more
319 details on fuel price sensitivity).



320
321 **Fig. 3** Urban heating per-capita demand changes over climate scenarios (% changes are over the
322 reference year of 2015 in each RCP category)

323
324 The electricity-generating sector is modeled with technologies parameterized with fuel usage
325 levels, investment costs, known lifetimes, operating and maintenance costs, as well as generating

326 capacity limits, generation efficiency levels, ability to serve peak demand, and emissions levels.
327 Assumptions for changes to investment costs for electricity generation beyond the original
328 horizon of 2043 were also made by linear extrapolation using the final five periods in the model
329 by Lu (2015) (see ESM for more details on projected renewable energy costs).

330
331 Despite its detail, IN-MARKAL has limitations affecting its estimates of future energy supply. It
332 does not estimate changes in energy service demands based on new energy prices—it finds the
333 most cost-effective way to meet expected demand for heating and cooling, for example, but it
334 does not adjust the demand for heating or cooling in the face of higher energy costs. In addition,
335 IN-MARKAL does not incorporate certain distributed generation technologies, such as rooftop
336 solar installations.

337
338 We estimate the effects of climate change on Indiana’s energy supply by adjusting the
339 exogenous, end-use demand for residential and commercial energy services in our INMARKAL
340 model runs based on the analysis of relative demand changes under RCP 4.5 and RCP 8.5 in
341 Section 2 above. In total, we ran the IN-MARKAL model under five different scenarios:

- 342
343 1. Climate scenario #1: “Baseline” demand under RCP 2.6, no policy
344 2. Climate scenario #2: Demand under RCP 4.5, no policy
345 3. Climate scenario #3: Demand under RCP 8.5, no policy
346 4. Policy scenario #1: Demand under RCP 8.5, carbon price
347 5. Policy scenario #2: Demand under RCP 8.5, renewable tax credit

348
349 To estimate the effects of climate change, we first ran scenario #1: a “baseline” run using the
350 demand projections from Lu (2015) with the very small modifications expected under an RCP
351 2.6 scenario of very limited climate change. Then we modified the projected commercial and
352 residential demand using the expected marginal impacts from climate change calculated in
353 Section 2 under RCP 4.5 and 8.5 (scenarios #2 and #3), and estimated changes in supply by
354 comparing those results with the energy mix under the baseline scenario. Finally, we ran policy
355 scenarios 1 and 2 to consider the effects of two potential policies on the state’s energy supply
356 with demand as projected under RCP 8.5: a \$40/ton CO₂ economy-wide carbon price and a
357 collection of investment tax credits on renewable generation technologies (SUF₂ 2016). In every
358 scenario, we ran the model through 2092 in order to generate results for 2080 that recognized the
359 need for future energy production beyond that date. Both policies are modeled as going into
360 effect in 2022 and continuing through the end of the model horizon.

361 362 **4.1. Climate change impacts on energy supply**

363
364 In the baseline scenario using expected fuel price trajectories for coal, natural gas, wind, and
365 solar outlined above and only minimal climate change impacts from RCP 2.6, the model projects
366 a state energy mix for electricity generation of 64.6% coal, 34.9% natural gas, and less than 1%
367 of all other fuels in 2050, and 51.3% natural gas, 48.3% wind, and less than 1% of all other fuels
368 in 2080. A key feature of these results is that existing coal plants are projected to be retired in
369 2058 as they reach the end of their lifespans due to the price advantages of natural gas and
370 renewables.

371

372 Projected climate-driven changes in energy demand have a minimal effect on the expected
373 energy supply mix—the percentage of energy provided by natural gas, renewables, and coal
374 remain virtually the same in 2050 and 2080 under both the climate-adjusted scenarios. For
375 example, total 2050 energy output for electricity in the baseline scenario is 471.06 PJ from coal
376 and 254.24 PJ from natural gas, with no output from wind. In the RCP 4.5 scenario, coal-fired
377 electricity output is the same, and natural gas-fired output increases to 254.83 PJ, or less than 1%
378 above the baseline scenarios. For RCP 8.5, coal-fired electricity production is the same in 2050
379 and natural gas production decreases slightly to 252.34 PJ, again a less than 1% change. Slightly
380 larger changes in projected electricity production from natural gas and wind occur in 2080,
381 especially under RCP 4.5, where electricity from natural gas declines from 527.44 PJ in the
382 baseline scenario to 511.95 PJ (nearly 3%), while wind production increases from 497.06 to
383 511.79 PJ, an increase of nearly 3%. Although the pattern reverses for 2080 under RCP 8.5, with
384 natural gas output increasing by 0.86% to 531.97 PJ and wind production decreasing slightly to
385 489.58 PJ, the overall changes due to adjusted energy demand from climate change remain
386 extremely small even with the larger expected climate impacts from RCP 8.5 (see ESM for
387 summary of these variations).

388
389 Figure 4 shows this evolution of the state’s energy mix for producing electricity in greater detail
390 under the RCP 8.5 scenario, illustrating the change over time toward natural gas and wind power
391 instead of coal even under the strongest modeled climate changes for the state.

392
393 The projected shift to gas and wind is not only robust across all our climate scenarios but also to
394 a wide range of possible fuel prices (see ESM for discussion of fuel price sensitivities). Even the
395 extreme case of a future coal price of \$0, for example, leads to less than 10% of post-2058
396 generation coming from coal. The mix between natural gas and wind power is much more
397 sensitive to price projections for natural gas, however, with natural gas potentially replacing
398 wind generation entirely if it were to remain at current prices throughout our model timeframe.
399



400 **Fig 4.** Electricity generation by fuel type, RCP 8.5

401
402
403 As wind generation becomes a larger percentage of total electricity generation, installed wind
404 capacity increases more than proportionately in order to meet seasonal and daily peak demand,
405 leading to excess wind capacity in periods of low demand. Projected investment costs for solar
406 (U.S. EPA 2013) keep it out of the model’s energy mix, but in a scenario where solar capital
407 costs fall by 50% and wind capital costs remain the same as the baseline, solar generation
408 becomes nearly 80% of the electricity supply by 2080 under RCP 8.5 (see ESM Section 5 for
409 detailed figures), so the mix between solar and wind is also sensitive to relative price changes in
410 the capital costs of both technologies over time that are difficult to project through 2080.

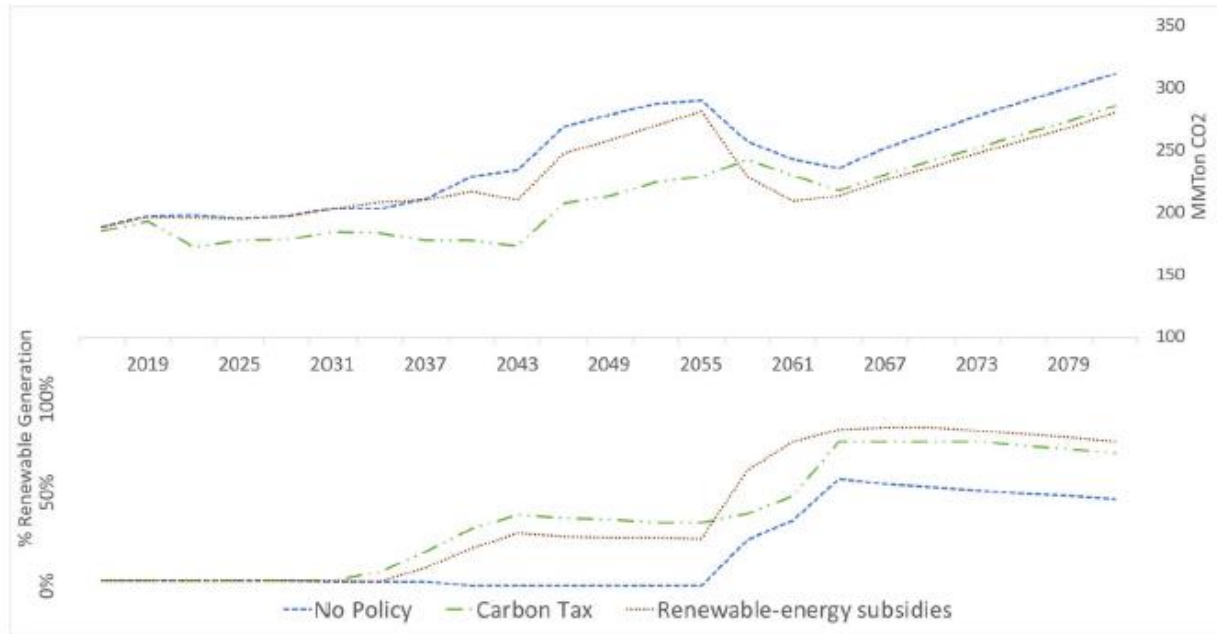
411 **4.2. Policy impacts on energy supply**

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413
414 Both of the policies we modeled have significant impacts on the state’s electricity generation
415 portfolio and total emissions even under the higher climate impacts scenario, RCP 8.5. Under the
416 \$40 carbon price, wind generation increases to 35% of electricity in 2050 and 73% in 2080,
417 compared to 0% in 2050 and 48% in 2080 with no policy (bottom panel Fig. 5). Supply-side
418 renewable investment credits generate a similar result, with investment in wind power slightly
419 delayed but increasing more over time (bottom panel Fig. 5).

420
421 Both policies also have a substantial impact on expected CO2 emissions. A carbon price yields
422 the larger average annual reduction in carbon dioxide emissions from 2021 to 2080
423 (approximately 10%), followed by supply-side renewable generation investment subsidies at
424 approximately 6% (top panel Fig. 5). Future emissions after 2065 are slightly lower under the
425 renewable investment tax credits, however, than for the carbon price. It is also important to note
426 that there are additional emissions reductions in the model from the carbon price due to changes
427 in choices of different demand-side energy technologies driven by changes in relative fuel prices.

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These results suggest the potential to achieve substantial changes in the state’s use of renewables and CO2 emissions using relatively modest policy changes. The \$40/ton CO2 price being modeled is well below the typical carbon price discussed in other long-term policy scenarios of \$100/ton CO2 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.



437
438 Fig 5. Annual CO2 emissions in million tons (top panel) and percentage generation from
439 renewables for electricity sector (bottom panel), RCP 8.5, three policies

440

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

454

455 5. Discussion

456

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

470

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

478

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

496

497 In addition, changes in energy demand and supply have other important potential economic and
498 health impacts that are not considered here. For example, U.S. job growth in renewables is
499 higher than in fossil fuels, and on a total employment basis is already nearly on a par therewith
500 (Energy Futures Initiative 2018). Currently, Indiana is behind many states for this growth, with
501 under 2000 jobs in solar (SUFG 2017). In addition, research indicates that coal-fired power
502 generation creates significant public health risks from “co-pollutants” not associated with climate

503 change (Prehoda and Pearce 2017), and our paper does not estimate these public health impacts
504 of different transition periods away from coal-fired electricity generation (for more on public
505 health threats from climate change generally, see Filippelli et al. [in review](#)).

506
507 There are also common policy options that we could not evaluate in this effort. We could not
508 assess the economic or technology cost impacts of dedicating carbon pricing revenue to
509 consumer rebates or investment in research on renewable energy (Raymond 2016). In addition, it
510 was not possible to model the supply effects of an important demand management policy like an
511 Energy Efficiency Standard that requires and incentives statewide across the board percentage
512 gains in energy efficiency.

513 514 **6. Conclusion**

515
516 The effects of climate change on Indiana’s energy demand and supply are mixed. Our modeling
517 is consistent with the intuitive finding that projected warmer winter temperatures will likely
518 reduce heating demand, at least in the residential and commercial sectors, while increased
519 summer temperatures and other factors will increase cooling demand. Because the state dedicates
520 more energy to residential and commercial heating than to cooling, however, these changes end
521 up reducing the state’s total projected energy demand slightly under both climate change
522 scenarios in 2050 and 2080. The impact of these modest demand changes on the state’s energy
523 supply is extremely small. At the same time, it is also notable that the state faces an energy
524 supply future where coal is likely to be replaced by other lower-cost fuels or renewable
525 technologies, and where common policies such as a low carbon price or an investment tax credit
526 for renewable energy could shift the distribution of future energy supply even more heavily in
527 favor of low or zero carbon energy options. Although this analysis lacks the space to fully
528 address many other potential impacts from climate change on the state’s energy system,
529 including interruptions to supply, unexpected breakthroughs in low or zero-carbon energy
530 technologies, or dramatic shifts in the state’s population patterns due to climate change, these
531 general trends are a first step in considering the future energy effects of climate change on the
532 state.

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535
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542 543 **References**

544
545 Amato AD, Ruth M, Kirshen P, Horwitz J (2005) Regional energy demand responses to climate
546 change: methodology and application to the Commonwealth of Massachusetts. *Clim Chang*
547 71(1):175–201

548

549 Burtraw D (2008) Cap, auction, and trade: auctions and revenue recycling under carbon cap and
550 trade. http://www.rff.org/focus_areas/features/Documents/CT-Burtraw-Testimony-08-01-23.pdf.
551 Accessed 15 December 2017
552

553 Elkhafif MAT (1996) An iterative approach for weather-correcting energy consumption data.
554 *Energy Econ* 18: 221–230
555

556 Energy Futures Initiative (2018) U.S. Energy and employment report.
557 <https://www.usenergyjobs.org>. Accessed 3 July 2018
558

559 Filippelli G, Jay S, Gibson J, Wells E, Moreno-Madriñán MJ, Ogashawara I, Freeman J,
560 Rosenthal F (in review). The current and future impacts of climate change on human health in
561 Indiana. *Clim Chang* (under review)
562

563 Gotham, DJ, Angel JR, Pryor SC (2013) Vulnerability of the electricity and water sectors to
564 climate change in the Midwest. In: *Climate change in the Midwest: impacts, risks, vulnerability*
565 *and adaptation*, S.C. Pryor, ed., Indiana University Press, 158–177
566

567 Hamlet AF, Brun K, Robeson S, Widhalm M, Baldwin M (2018) Impacts of climate change on
568 the state of Indiana: future projections based on statistical downscaling. *Clim Change*
569

570 Hastie T, Tibshirani R, Friedman JH (2008) *The elements of statistical learning* (second).
571 Springer, New York
572 International Energy Agency (2016) *Energy Technology Perspectives 2016*.
573 www.iea.org/etp2016. Accessed 3 January 2018
574

574 International Energy Agency—Energy Technology Systems Analysis Program (IEA-ETSAP)
575 (2011) <https://ieaetsap.org/index.php/etsap-tools/model-generators/markal>. Accessed 26
576 November 2017
577

578 Isaac M, Van Vuuren D (2009) Modeling global residential sector energy demand for heating
579 and air conditioning in the context of climate change. *Energy Policy* 37(2):507–521
580

581 James G, Witten D, Hastie T, Tibshirani R (2013) *An introduction to statistical learning—with*
582 *applications in R*. Springer-Verlag, New York
583

584 Kennedy CA, Stewart I, Facchini A, Cersosimo I, Mele R, Chen B, Uda M, Kansal A, Chiu A,
585 Kim K, Dubeux C, LaRovere EL, Cunha B, Pincetl S, Keirstead J, Barles S, Pusaka S, Gunawa
586 J, Adegbile M, Nazariha M, Hoque S, Marcotullio PJ, Otharan FG, Genena T, Ibrahim N,
587 Farooqui R, Cervantes G, Sahin AD (2015) Energy and material flows of megacities. *PNAS*
588 112(19):5985–5990
589

590 Lu L (2015) *An assessment of the efficacy and cost of alternative carbon mitigation policies for*
591 *the state of Indiana*. Dissertation, Purdue University
592

593 McNeil M, Letschert V, de la Rue du Can S (2008) Global potential of energy efficiency
594 standards and labeling programs. Ernest Orlando Lawrence Berkeley National Laboratory,
595 Berkeley
596

597 Mukherjee S, Nateghi R (2017) Climate sensitivity of end-use electricity consumption in the
598 built environment: an application to the state of Florida, United States. *Energy* 28
599

600 Mukherjee S, Nateghi R (2018a) A data-driven approach to assessing supply inadequacy risks
601 due to climate-induced shifts in electricity demand. *Risk Anal* (under 3rd review)
602

603 Mukherjee S, Nateghi R (2018b) Estimating climate–demand nexus to support long-term
604 adequacy planning in the energy sector. In: 2017 IEEE Power & Energy society general meeting.
605 IEEE Xplore, pp 1–5
606

607 Nateghi R, Mukherjee S (2017) A multi-paradigm framework to assess the impacts of climate
608 change on end-use energy demand. *PLoS One* 12(11):e0188033
609

610 Norman J, MacLean HL, Kennedy CA (2006) Comparing high and low residential density: life-
611 cycle analysis of energy use and greenhouse gas emissions. *J Urban Plan Dev* 132(1):10–21
612

613 Prehoda EW, Pearce JM (2017) Potential lives saved by replacing coal with solar photovoltaic
614 electricity production in the U.S. *Renew Sust Energ Rev* 80(Supplement C):710–715
615

616 Raymond L (2016) *Reclaiming the atmospheric commons: the regional greenhouse gas initiative
617 and a new model of emissions trading*. MIT Press, Cambridge
618

619 Sailor DJ (2001) Relating residential and commercial sector electricity loads to climate—
620 evaluating state level sensitivities and vulnerabilities. *Energy* 26:645–657
621

622 Sailor DJ, Muñoz JR (1997) Sensitivity of electricity and natural gas consumption to climate in
623 the U.S.A.— methodology and results for eight states. *Energy* 22:987–998
624

625 Singh S, Kennedy C (2015) Estimating future energy use and CO₂ emissions of the world’s
626 cities. *Environ Pollut* 203:271–278
627

628 Stehfest E, van Vuuren D, Kram T, Bouwman L, Alkemade R, Bakkenes M, Biemans H,
629 Bouwman A, den Elzen M, Janse J, Lucas P, van Minnen J, Müller C, Prins A (2014) Integrated
630 assessment of global environmental change with IMAGE 3.0—model description and policy
631 applications [http://www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-
632 change-with-IMAGE-3.0](http://www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-IMAGE-3.0). Accessed 3
633 July 2018
634

635 (SUFGR) State Utility Forecasting Group (2017) Indiana renewable energy resources study.
636 http://www.purdue.edu/discoverypark/sufgr/docs/publications/2017_RenewablesReport.pdf.
637 Accessed 15 December 2017
638

639 (SUFG) State Utility Forecasting Group (2016) 2016 Indiana renewable energy Resources Study.
640 [http://dev.www.purdue.edu/discoverypark/sufg/docs/publications/2016%20Renewables%20Rep](http://dev.www.purdue.edu/discoverypark/sufg/docs/publications/2016%20Renewables%20Report.pdf)
641 [ort.pdf](http://dev.www.purdue.edu/discoverypark/sufg/docs/publications/2016%20Renewables%20Report.pdf). Accessed 26 November 2017
642
643 Stern N, Stiglitz JE (2017) Report of the high-level commission on carbon prices. World
644 Bank, Washington D.C
645
646 U.S. Energy Information Agency (2016) State Energy Data System (SEDS) INDIANA: State
647 Profile & Energy Estimates. <http://www.eia.gov/state/seds/seds-data-complete.cfm?sid=IN>.
648 Accessed 15 December 2017
649
650 U.S. Energy Information Agency (2017a) Commercial Building Energy Consumption Survey
651 (CBECS).
652 <https://www.eia.gov/consumption/commercial/maps.php>. Accessed 10 May 2017
653
654 U.S. Energy Information Agency (2017b) Indiana State Energy Profile.
655 <https://www.eia.gov/state/print.php?sid=IN>. Accessed 15 December 2017
656
657 U.S. Energy Information Agency (2017c) Residential Energy Consumption Survey (RECS).
658 <https://www.eia.gov/consumption/residential/data/2009/index.php?view=consumption>. Accessed
659 15 December 2017
660
661 U.S. EPA (2013) Region Nine MARKAL database, database documentation. US Environmental
662 Protection Agency, Cincinnati, OH, EPA/600/B-13/203
663
664 Wachs, E, Singh S (under review) Estimating spatial variations of urban energy demand in
665 Indiana under future climate change scenarios. Clim Chang
666
667 Wilbanks T, Bilello D, Schmalzer D, Scott M et al (2013) Climate change and energy supply and
668 use: technical report for the U.S. Department of Energy in support of the National Climate
669 Assessment. Island Press, Washington, DC
670

671

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