ECONOMICS OF HOUSEHOLD SOLAR PANEL AND WIND TURBINE SYSTEMS

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Abstract: Small wind turbines and photovoltaic (PV) technologies are available for purchase and use to provide households with electricity. The objective of this research is to determine the economic consequences of installing microgeneration grid-tied wind turbine systems (6 kW; 10 kW) and solar panel systems (4 kW; 12 kW), given alternative pricing structures for households, at five locations with different wind speed and solar radiation resources. Twenty years of hourly wind speed, solar radiation, and temperature data, and hourly electricity use data for representative households, were obtained for each location. Weather data, electricity pricing rate schedules, and purchase prices and power output response functions for each wind turbine and solar panel system are used to address the objective. The estimated annual cost of $2,148 for the least costly household grid-tied 4 kW solar panel system with net metering is two-times greater than the annual cost of purchasing from the grid. If external consequences of electricity generation and distribution are ignored, given region specific rate structures and prices, household solar panel electricity generation systems are not economically competitive in the region studied. The economic consequences of grid-tied household wind turbine and solar panel systems differ substantially among locations.

Additionally, the consequences of a carbon tax, equal to an estimated social cost of carbon of $37.2/Mg, on household electricity cost is determined. Averaged across the five households, the carbon tax is expected to reduce annual consumption by 4.4% for traditional meter households and by 4.9% for households charged smart meter rates. The carbon tax increases electricity cost by 19%. For a household cost of $202/year the carbon tax is expected to reduce social costs by $11. Annual carbon tax collections of $234/household are expected. Adding the carbon tax was found to be insufficient to incentivize households to install either a solar panel or wind turbine system. Installation of a 4 kW solar system would increase the annual cost by $1,546 and decrease CO_2 emissions by 38% valued at $94/household. The consequence of a carbon tax would depend largely on how the proceeds of the tax are used.

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CHAPTER I

ECONOMICS OF HOUSEHOLD WIND TURBINE GRID-TIED SYSTEMS FOR FIVE WIND RESOURCE LEVELS AND ALTERNATIVE GRID PRICING RATES[*]

Abstract

Households in the USA state of Oklahoma serviced by investor owned electric utilities that have smart meters may select to be charged based on either a traditional meter rate schedule, a smart meter schedule, or they may install a household grid-tied wind turbine and be subject to a different rate schedule. The objective of the research was to determine the economic consequences of installing microgeneration grid-tied wind turbine systems (6 kW; 10 kW) given alternative pricing structures for households at five unique locations with different wind resources. Twenty years of hourly wind speed data, and hourly electricity use data for representative households, were obtained for each location. The annual household electricity cost among the five locations ranged from $894 to $1,199 for the smart meter rates and $870-$1,191 for the traditional meter rates. The estimated annual cost of $5,389 for the least costly household grid-tied 6 kW wind turbine system, is five times greater than the annual cost of purchasing from the grid. If external consequences of electricity generation and distribution are ignored, given current and proposed rate structures and prices, household wind turbine electricity generation systems are not economically competitive in the region.

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Key words: cost, grid-tied, renewable distributed generation, smart meter, wind energy, wind turbine

Introduction

Prior to the introduction of rural electrification, windmills used to pump water were common in rural areas of the USA Great Plains. Windmills are still common in remote areas that do not have access to the grid. Wind turbines for electricity microgeneration are manufactured by private companies, and advertised for sale to rural on-grid households in the region. The economics of grid-tied household wind turbine electricity generation systems for the region have not been fully explored. Economics depends on a number of factors for which data are readily available such as investment cost, price of grid electricity, and type of metering system. However, a comprehensive economic analysis also requires information that is more difficult to obtain, such as hourly information regarding site-specific wind speed.

The USA state of Oklahoma is located in the southern Great Plains. The unique Oklahoma Mesonet weather system has recorded 20 years of hourly wind data for more than 100 sites across the state. The geography and climate of the state is quite diverse ranging from an elevation of 110 m, 132 cm of annual rainfall, and average wind speed of 2.8 m/s at Idabel in the southeast, to an elevation of 1,267 m, 46 cm of annual rainfall, and average wind speed of 5.5 m/s at Boise City in the northwest [1]. The western half of Oklahoma is located in America's wind corridor [2]. The prevalence of wind inspired the line "…where the wind comes sweeping down the plain..." in the musical play named after the state [3]. Seventeen percent of the electricity generated in the state is produced by large commercial wind turbines [4]. Development of the commercial wind turbine sector has been aided by a state subsidy of $0.005 per kWh produced by systems with rated production capacity of one megawatt or greater [5] and by a federal investment tax credit of 30% [5].

Household wind systems are not common in the state. A 2009 census survey found that 20 Oklahoma farms reported an installed wind turbine for on-farm use [6]. There are about 80,000 farms in Oklahoma [7]. Thus, these data suggest that 0.025% of Oklahoma farms have a farm-based wind turbine system. Some Oklahoma farms purchase electricity from rural electric cooperatives. However, much of rural Oklahoma is serviced by investor-owned electric utilities that are natural monopolies. In the USA, rates charged by investor-owned public utilities are regulated by state authorities. The Constitution of the State of Oklahoma provides the Oklahoma Corporation Commission (OCC) with the authority and responsibility to supervise, regulate, and control Oklahoma investor-owned electric utilities [8]. The OCC is charged with the responsibility of insuring adequate service, preventing unfair charges to the public, protecting the utilities from unreasonable demands, and enabling a fair return to investors [9].

Electric meters measure the quantity of electricity removed from the electrical grid at the metered site. Traditional (accumulation) meters measure total consumption and do not provide information of when the energy was used during the time period of interest [10]. Historically, rates approved by the OCC followed from the technical constraint imposed by traditional meters and billing systems. OCC rates approved for one utility to apply to farms and households with traditional meters are shown as alternative I in Appendix A [11]. A fixed price per kilowatt-hour (kWh) is charged independent of the time of day the electricity is consumed. The regulated prices are assumed to be greater than the marginal cost at off-peak load times, and lower than the marginal cost at peak load times.

Introduction of alternative pricing systems to more nearly align prices with marginal costs has been limited by the prevalence of traditional meters [12,13,14]. Smart meters provide a way of measuring site-specific information, allowing regulators to permit utility companies to charge different rates based on time of use. Different rates for different hours of the day may be used to incentivize reductions in use during traditional peak time periods. Theoretically, smart meters that enable two-way communications between the utility and their customers, facilitate real-time monitoring of electricity flows, and enhance both the technical and allocative efficiency of electricity markets. Smart meters enable the utility to charge different rates for different times of the day. Alternative II rates as shown in Appendix A have been approved for one utility by the OCC [11] for Oklahoma users that have smart meters [15]. Customers that have smart meters may select either the alternative I or alternative II pricing system subject to 12 month contracts that may be renewed each year.

Figure 1 illustrates marginal costs for hypothetical base load and peak load situations. Base load is assumed to be generated by the lowest cost fuel source, which, in Oklahoma, if externalities including the consequences of carbon released into the atmosphere are ignored, is coal. During hot summer afternoons, for example between 2 p.m. and 7 p.m., when electric powered air conditioners are operating near capacity, electricity use peaks [11]. During the peak-load period, use may exceed base load plant capacity. In Oklahoma, most requirements in excess of base load are generated by natural gas powered plants. If the external consequences are ignored, the marginal cost of using natural gas is greater than the marginal cost of using coal (Figure 1). For example, in October 2015 the cost of producing one kWh from coal was 61% as much as the cost of producing one kWh from natural gas [16].

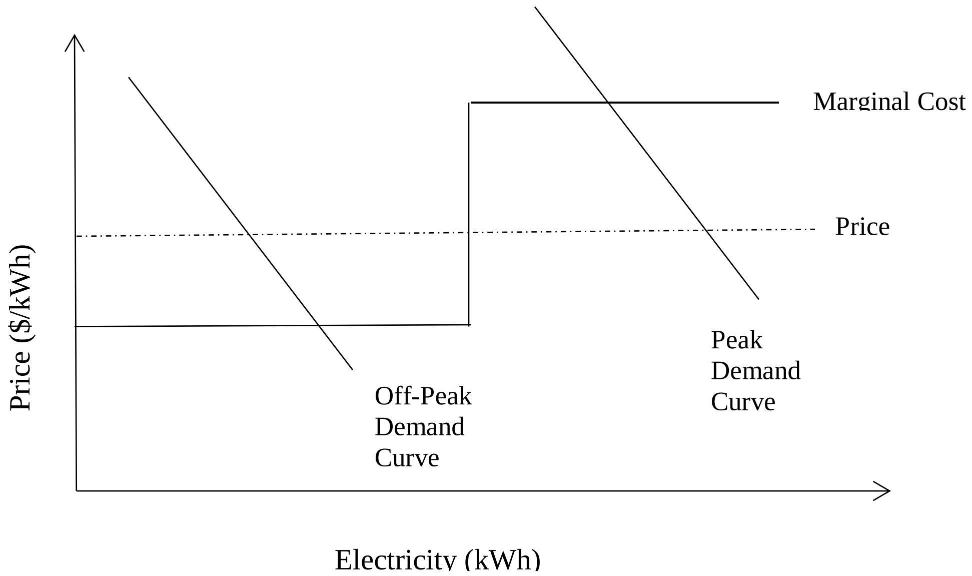

Figure I-1: Household Electricity Marginal Cost, Peak Demand, and Off-Peak Demand

The economics of a grid-tied household wind turbine microgeneration system depends in part on the grid electricity pricing structure in effect for the household. Prior to 2014 the OCC required Oklahoma utilities to make net metering available to all customer classes [17]. For net metering scenarios, each rate block during a billing period (assumed to be one month) is treated separately. The consumer is charged for the difference between the total electricity removed from the grid during the block and the total electricity provided to the grid during that block for the month. However, the consumer is not compensated if household production during a block exceeds household use during the same block. The household is charged for the net electricity withdrawn from the grid, that is, the total removed minus the total provided to the grid during the billing period. However, to participate in net metering, the household could be required to provide net excess generation to the grid at no charge [18]. Smart meter (Time of Use (TOU)) net-metering charges to the household are determined by each block (on-peak and off-peak) for each billing period (monthly).

There are several issues associated with net metering that influence aggregate economic efficiency. If households are reimbursed at the full retail rate, the net effect is that on average the utility will pay more for electricity from net metering households than for electricity from power plants. Net metering requires that additional investments be made by the utility in equipment required to safely manage the reliability of the grid when electricity produced by an individual household is sent to the grid [19]. In addition, since wind turbines depend on the quantity of wind, they cannot be relied on to be available during peak load periods. For these reasons, representatives of electric utility companies contend that with net metering, households that have microgeneration grid-tied systems would be subsidized by households that do not. In response to these issues, in 2014, the Oklahoma legislature passed and the Governor signed a bill enabling substantial changes in the way grid-tied household microgeneration systems in Oklahoma are charged for electricity purchased from the grid [20].

The 2014 legislation enables Oklahoma utilities regulated by the OCC to submit unique rate structures for households that have a microgeneration grid-tied system. One major utility has proposed the alternative III rates as shown in Appendix A that would be applicable for households with Renewable Distributed Generation (RDG) grid-tied (microgeneration) systems. RDG customers would be assessed a greater monthly base charge ($18 rather than $13) than traditional and smart meter customers, plus a charge based on peak withdrawal from the grid. This peak (maximum demand) charge would be determined based on the maximum 15-minute period withdrawal from the grid during the billing period (assumed to be one month). For example, for a month with 30 days, the utility would determine the quarter hour from among the 2,880 15-minute periods during the month with the maximum usage. The quantity of electricity (kWh) withdrawn from the grid during that quarter hour would then be multiplied by the $2.68 proposed rate [11, 21]. In addition, for weekday usage between 2 p.m. and 7 p.m. during the months of June through October, RDG customers would be charged $0.173/kWh. This is 23.6% greater than the smart meter rate for this time segment.

Some research has been conducted to evaluate household microgeneration systems [22-29]. For example, Elhadidy [22] evaluated the performance of hybrid wind-solar plus battery storage systems with Diesel back-up to satisfy a specific level of annual electricity requirements. Elkinton et al. [23] sized hybrid wind-solar grid-tied systems required for residential housing developments in five different locations to fully compensate the grid for electricity withdrawn during a year. Darbali-Zamora et al. [24] and Li et al. [25] also estimated the feasibility of hybrid wind-solar systems. Iqbal [26], Grieser et al. [27], Mostafaeipour et al. [28], and Dalabeeh [29] have studied the technical and economic feasibility of wind turbine systems.

Since public utilities may charge different rates for electricity withdrawn from the grid depending on hour of use and month of year, a comprehensive economic analysis of grid-tied household wind systems requires detailed wind speed data. One limitation of the prior studies [22-29] is that hourly wind speed data for a number of years was not available for the location under study. Thus, the analysis was limited to either expected annual, monthly, or daily wind speeds. This limitation reduced the ability of the models to capture fully the variability in electricity production. A second limitation is that household consumption also varies depending on hour of use and month of year. Prior studies have used accumulated profile load estimates and have only matched crudely time of production with time of use. A third limitation of prior research is that an average monthly price was assumed for electricity purchased from the grid. This shortcoming fails to account for the economic consequences of peak load pricing schemes.

This research builds on prior research [22-29] and extends it in several important aspects. First, the Mesonet system provides 20 years of hourly wind speed data for each of the five locations. This enables the production of estimates of the electricity generated by each system at each of the five locations for each hour of each month. This is important because electricity rates charged by public utilities differ depending on month and hour. Second, in addition to differences in wind speed among hours and months, the modeling system accounts for differences in air density when estimating the productivity of each turbine, at each of the five locations. Third, representative households as defined from census data for structure size and characteristics and number of occupants were defined for each of the five locations. Estimates of household electricity consumption by these representative households for each hour for each month for each location were obtained from simulations by the USA Department of Energy. These simulations find that each location has a unique average load profile resulting from differences in climate and household characteristics. Fourth, cost estimates are produced for three different types of rate structures including a smart meter rate schedule that has seven different rates depending on hour of the day, month of the year, and quantity of household use.

The overall objective of the research is to determine the economic consequences of installing microgeneration grid-tied wind turbine systems (6 kW; 10 kW) given alternative pricing structures (traditional accumulation meter; smart meter; proposed RDG; each with and without net metering) for households at five unique locations in Oklahoma (Boise City; Miami; Shawnee; Hollis; Idabel) that have substantially different wind resources. The specific objectives are to determine the annual cost of electricity for the five case study households based on:

a) traditional meter rates for grid-only electricity;

b) smart meter rates for grid-only electricity;

c) proposed RDG rates for a 6 kW wind turbine grid-tied system;

d) proposed RDG rates for a 10 kW wind turbine grid-tied system;

e) traditional meter rates for a 6 kW wind turbine grid-tied system with net metering;

f) traditional meter rates for a 10 kW wind turbine grid-tied system with net metering;

g) smart meter rates for a 6 kW wind turbine grid-tied system with net metering;

h) smart meter rates for a 10 kW wind turbine grid-tied system with net metering;

i) proposed RDG rates for a 6 kW wind turbine grid-tied system with net metering;

j) proposed RDG rates for a 10 kW wind turbine grid-tied system with net metering;

In addition, the purchase price at which each of the wind turbine systems breaks even with the grid-only system will be determined. The findings will enable a determination of the economic value of the microgeneration systems for each of the locations.

Since wind resources differ substantially across the state, five sites were chosen: Boise City in the Northwest, Miami in the Northeast, Shawnee in the Central, Hollis in the Southwest, and Idabel in the Southeast, as shown in Figure 2.

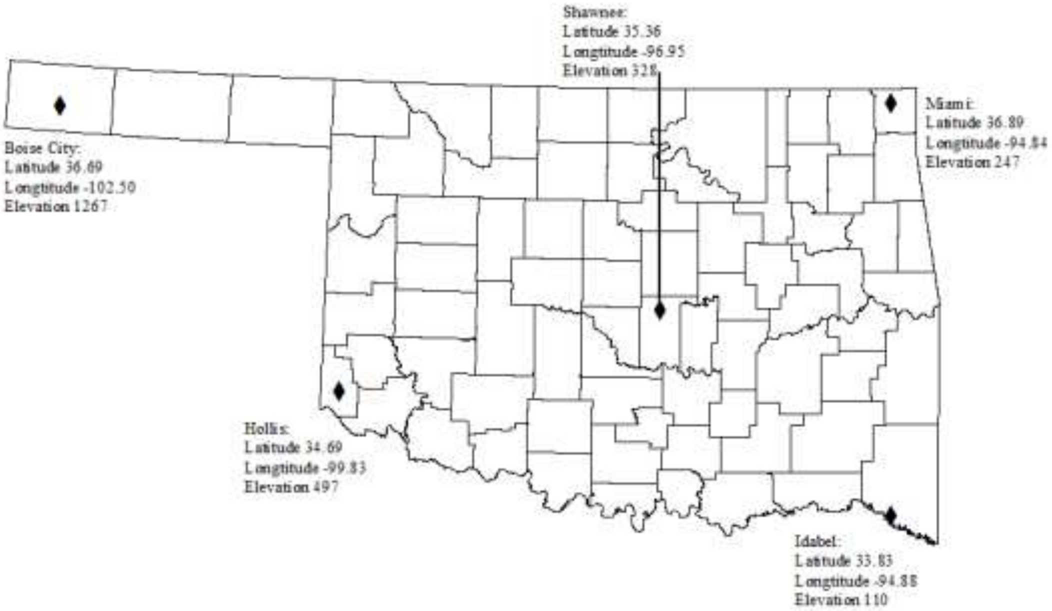

Figure I-2: Location of the Oklahoma Selected Sites for the Study

Conceptual Framework

The economics of a household grid-tied wind turbine system depends on the cost of owning and operating the system, the amount and timing of electricity produced by the system, the quantity and timing of electricity required by the household, and the cost of purchasing electricity from the grid.

Estimation of Wind Turbine Power Output

Theoretically, the power output produced by wind turbines depends on the rotor sweep area, air density, mechanical efficiency (proportion of wind power transferred into electricity), and wind speed [30]. At a certain level of wind speed, the cut-in wind speed, the wind turbine starts to produce electricity. Electricity output is effectively zero for wind speeds less than cut-in. Over a range of wind speeds, electricity output increases at an increasing rate and may be described by a cubic function [30]. To prevent damage from high wind speeds, wind turbines are equipped with an automatic furling system. Over a range of wind speeds, electricity production continues to increase but at a decreasing rate to a level at which power output plateaus. This range may be described by a quadratic function. Conceptual representation of the entire power curve can be accomplished by splicing a cubic function [29] to a quadratic function to a plateau as described in equation 1.

The electricity output (kWh) from a wind turbine can be described as:

$$P = \begin{cases} 0 & V_i < V_{Cut-in}, V > V_0 \\ K\, C_p\, \frac{1}{2}\, \rho\, A\, V^3 & V_{Cut-in} \leq V \leq V_r \\ \alpha_0 + \alpha_1 V + \alpha_2 V^2 & V_r < V < V_p \\ P_r & V_p \leq V \leq V_0 \end{cases} \tag{1}$$

where, P is the power output (kW), P_r is the plateau output level (kW), K is equal to 0.001, which is a constant to transfer the power output from W to kW, C_p is the mechanical efficiency coefficient, ρ is the air density (kg/m^3), A is the rotor sweep area (m^2), V is wind speed (m/s), V_{Cut-in} is the minimal wind speed required to initiate production, V_r is the wind speed at which production begins to increase at a decreasing rate, V_p is the wind speed at which production is at a plateau level, V_0 is the wind speed at which production is assumed to be zero (high wind speeds at which the turbine is braked to prevent damage), α_0 is the constant of the quadratic function, α_1 is the coefficient for the linear term, and α_2 is the coefficient for the quadratic term.

Estimation of the Annual Electricity Cost for Each Alternative

For a household serviced by a traditional meter, the annual cost of electricity is calculated as:

$$ECTM = \sum_{j=1}^{12} BC_j + \sum_{j=1}^{12} D_j \, ERTM_j \left(\sum_{i=1}^{24} G_{ij}\right) \tag{2}$$

where, $ECTM$ is the annual electricity cost for the household using the traditional meter, $ERTM_j$ is the OCC rate for the traditional meter rate during the j^{th} month, G_{ij} is the electricity used (kWh) in the i^{th} hour, during the j^{th} month where $i = 1, 2, \ldots, 24$, D_j is the number days of the j^{th} month, if j = 1, 3, 5, 7, 8, 10, or 12 then D_j = 31, if j = 4, 6, 9, or 11 then D_j = 30, and if j = 2 then D_j = 28, and BC_j is a fixed base charge per month independent of electricity use.

For a household serviced by a smart meter, the annual cost of electricity is calculated as:

$$ECSM = \sum_{j=1}^{12} BC_j + \sum_{j=1}^{12} D_j \left(\sum_{i=1}^{24} ERSM_{ij} G_{ij}\right) \tag{3}$$

where, $ECSM$ is the annual electricity cost for the household using the smart meter rate, $ERSM_{ij}$ is the OCC rate for the smart meter rate in the i^{th} hour during the j^{th} month.

The annual charge for electricity withdrawn from the grid and for the opportunity of having a grid tied wind turbine based on the proposed rate schedule would be:

$$ECGT = \sum_{j=1}^{12} BCGT_j + \sum_{j=1}^{12} \left(\frac{H_j}{4}\right) 2.68 + \sum_{j=1}^{12} D_j \left(\sum_{i=1}^{24} ERGT_{ij} NG_{ij}\right) \tag{4}$$

where, $ECGT$ is the annual electricity cost for the household with the grid-tied RDG rate, $BCGT_j$ is the base charge for a grid tied system, H_j is the quantity (kWh) withdrawn from the grid during the highest consumption hour of electricity withdrawn in the j^{th} month, $ERGT_{ij}$ is the proposed RDG rate for the i^{th} hour during the j^{th} month, NG_{ij} (kWh) is the net electricity used by households after using the power output produced by the wind turbine, where $NG_{ij} \geq 0$.

The annual charge for electricity withdrawn from the grid and for the opportunity of having a grid-tied wind turbine based on the traditional meter rate schedule with net metering would be:

$$ECTMN = \sum_{j=1}^{12} BC_j + \sum_{j=1}^{12} D_j \, ERTM_j (\sum_{i=1}^{24} G_{ij}) - \sum_{j=1}^{12} D_j \, ERTM_j (\sum_{i=1}^{24} P_{ij}) \tag{5}$$

where, $ECTMN$ is the annual electricity cost for the household with the grid-tied RDG system using the traditional meter rates with the opportunity of net metering, and P_{ij} (kWh) is the excess power output produced by the wind turbine in the *i*th hour, during the *j*th month.

The annual charge for electricity withdrawn from the grid and for the opportunity of having a grid tied wind turbine based on the smart meter rate schedule with net metering would be:

$$ECSMN = \sum_{j=1}^{12} BC_j + \sum_{j=1}^{12} D_j \, (\sum_{i=1}^{24} ERSM_{ij} G_{ij}) - \sum_{j=1}^{12} D_j \, (\sum_{i=1}^{24} ERSM_{ij} P_{ij}) \tag{6}$$

where, $ECSMN$ is the annual electricity cost for the household with the grid tied RDG system using the smart meter rates with the opportunity of net metering.

The annual charge for electricity withdrawn from the grid and for the opportunity of having a grid tied wind turbine based on the proposed rate schedule with net metering would be:

$$ECGTN = \sum_{j=1}^{12} BCGT_j + \sum_{j=1}^{12}(\frac{H_j}{4})\ 2.68 \ + \sum_{j=1}^{12} D_j \ (\sum_{i=1}^{24} ERGT_{ij}G_{ij}) - \sum_{j=1}^{12} D_j \ (\sum_{i=1}^{24} ERGT_{ij}P_{ij}) \quad (7)$$

where, $ECGTN$ is the annual electricity cost for the household with the grid tied RDG system using the proposed rates with the opportunity of net metering.

Estimation of Wind Turbine Breakeven Price

To determine the purchase price at which an investment in a wind turbine system would break even with grid only electricity, the difference between the present value of the cost before and after adopting the wind turbines is determined.

For the households paying traditional meter rates, the breakeven price is:

$$BETM = \frac{\sum_{t=1}^{20} ECTM_t}{(1+r)^t} - \frac{\sum_{t=1}^{20} ECGTN_t + \sum_{t=1}^{20} VC_t}{(1+r)^t} \quad (8)$$

where, $BETM$is the wind turbine breakeven price for traditional meter rate households, and VC_t is the variable cost of the wind turbines at the t^{th} years, $t = 1, 2, \ldots, 20$.

For the households who are charged smart meter rates, the breakeven price is:

$$BESM = \frac{\sum_{t=1}^{20} ECSM_t}{(1+r)^t} - \frac{\sum_{t=1}^{20} ECGTN_t + \sum_{t=1}^{20} VC_t)}{(1+r)^t} \quad (9)$$

where, $BESM$ is the wind turbine breakeven price for smart meter rate households.

Estimation of the Annual Cost of the Wind Turbine

The following equations were used to estimate the annual cost of the RDG systems [31]

$$\text{Depreciation } (\frac{\$}{\text{year}}) = \frac{(\text{Purchase Price} - \text{Salvage Value})}{\text{Years of Life}}, \quad (10)$$

$$\text{Interest } (\frac{\$}{\text{year}}) = \frac{\text{Purchase Price} + \text{Salvage Value}}{2} * \text{Real Interest Rate}, \quad (11)$$

$$\text{Insurance } (\frac{\$}{\text{year}}) = \frac{\text{Purchase Price} + \text{Salvage Value}}{2} * \text{Insurance Rate, and} \quad (12)$$

$$\text{Property Tax}\left(\frac{\$}{\text{year}}\right) = \text{Average System Price} * \text{Assessed Rate} * 0.086. \qquad (13)$$

Data and Method

Hourly Weather Data

Hourly weather data were obtained from the Oklahoma Mesonet. The Mesonet consists of 120 automated weather stations. Many of these stations have been collecting precise weather data since 1994. Data collected includes wind speed (m/s), air pressure (inches of mercury), air temperature (F^o), relative humidity (%), and solar radiation ($watt/m^2$). For the present study, average values of power output for each of 24 hours for each of 12 months were obtained, as the wind turbine power output is a function of wind speed. For example, the power output estimate for hour one for January is the mean of 620 observed values; 31 days of hour one observations for each of 20 years. These data may be used to estimate the expected power output from wind turbine systems at a specific site for each hour of the day for each month.

Residential hourly electricity data

The residential hourly electricity profiles for Boise City, Hollis, Shawnee, Miami, and Idabel, Oklahoma households were obtained from the U.S. Department of Energy [32]. Simulated load profiles are averages over many households. The characteristics of the house and household to be modeled are reported in Table 1.

Table I-1: Characteristics of the House and Household being Modeled

Characteristics	Description/Unit	
	Mixed Humid†	**Mixed Dry**
Building Fuel Types		
Space Heating	Natural Gas	Natural Gas
Air Conditioning	Yes	Yes
Water Heating	Natural Gas	Natural Gas
Building Structure Types		
Total Size	236.5 (m^2)	185.8 (m^2)
Number of Stories/Level	1 Story	1 Story
Bedrooms	3	3
Bathrooms	1	2
Basement	No	No
Type of Glass in Windows	Double-pane Glass	Single-pane Glass

Source: National Renewable Energy Laboratory

† Hollis, Shawnee, Miami, and Idabel are included in the mixed humid region. Boise City is included in the mixed dry region.

Wind Turbines

The American Wind Energy Association (AWEA) has adopted a set of household scale wind turbine performance standards [33]. They have established a common system for testing and reporting wind turbine energy performance. The Small Wind Certification Council (SWCC) is an independent certification agency that verifies and certifies test results relative to the AWEA standard [34]. SWCC has certified seven wind turbines. Information for each of these seven systems is reported in Table 2. The SWCC certified systems range from 1.5 to 10.4 kW rated at 11 m/s. The total cost divided by the rated annual energy output is approximately $5/kW for the four larger machines that range from 5.2 to 10.4 kW. The cost per kW is substantially greater for the smaller (1.5 to 2.5 kW) systems. Given the higher cost per kW for the smaller systems and given that the

AWAE recommends a minimum size of 5 kW for a USA household, the three smaller systems were not considered. Since both the Excel 6 and Excel 10 are marketed in the region of the study, they were selected for modeling.

Table I-2: List of available wind turbines in USA and their cost

Applicant	Turbine	SWCC Certification Type	AWEA Rated Annual Energy (kWh)	AWEA Rated Power at 11 m/s (kW)	Peak Power	Total Cost $	Annual Average Cost $/kWh †
Bergey Windpower Co.	Excel 10	AWEA 9.1-2009	13,800 kWh	8.9	12.6 kW @ 16.5 m/s	65,000*	4.7
Xzeres Wind Corporation	442SR	AWEA 9.1-2009	16,700 kWh	10.4	11.3 kW @ 12.0 m/s	83,000**	5.0
Kingspan Environmental	KW6	AWEA 9.1-2009	8,950 kWh	5.2	6.1 kW @ 17.0 m/s	45,000*	5.0
Bergey Windpower Co.	Excel 6	AWEA 9.1-2009	9,920 kWh	5.5	6.7 kW @ 16.0 m/s	55,000**	5.5
Xzeres Wind Corporation	Skystream 3.7	AWEA 9.1-2009	3,420 kWh	2.1	2.4 kW @ 14.0 m/s	23,800**	7.0
Pika Energy	T701	AWEA 9.1-2009	2,420 kWh	1.5	1.7 kW @ 13.5 m/s	22,350**	9.2
Eveready Diversified Products (Pty) Ltd.	Kestrel e400nb	AWEA 9.1-2009	3,930 kWh	2.5	3.0 kW @ 19.5 m/s	-	

* Source: personal contact with Bergey Windpower Co.

** Source: [35]

† Annual Average Cost = Total Cost / AWEA Rated Annual Energy

The modeled wind turbine systems are Excel 10 (10 kW) and Excel 6 (6 kW), with 7 m and 6.2 m rotor diameter, respectively. The installed cost of the 10 kW machine is estimated to be $65,000 ($32,000 for the turbine; $15,000 for the 30.5 m tower; $15,000 for installation and foundation preparation; $3,000 for permits). The installed cost for the 6 kW system is estimated to be $55,000 ($22,000 for the turbine with other costs the same as for the 10 kW).

The Bergey Windpower Company [36] that manufactures both modeled turbines recommends that purchasers expect a useful life of no more than 20 years. Several studies have cautioned against extending the expected life of household wind turbines beyond 20 years. For example, Staffell and Green [37] found that expected power output declines with wear, and over a 20-year period, users could expect a 12% reduction. Rademakers et al. [38] report that after 20 years a user could expect to incur repair costs in excess of 60% of the original investment costs. Hence, the useful life of the turbines is assumed to be 20 years, with no maintenance cost the first five years and maintenance cost in years 6-10 of $250 annually; years 11-15 of $500 annually; and years 16-20 of $1000 annually. Both systems are equipped with automatic furling systems that enable power output over a range of wind speeds while protecting the integrity of the equipment [36].

The SWCC test report includes the power curve; the power (kW) output response as a function of wind speed, as shown in Figure 3. The power curve is reported over the range of wind speeds from 0.5 to 20.5 m/s for the Excel 10 [39] and from 0.5 to 18.5 m/s for the Excel 6 [40]. For the case study locations, the maximum wind speed across all hour-month combinations was 23 m/s. Power output from the Excel 10 tracks the theoretical cubic power output curve from 0.5 to 11 m/s. Output continues to increase at a decreasing rate from 11 to 15 m/s for Excel 10 and from 9 to 14 m/s for Excel 6 after which output plateaus. For Excel 10 and Excel 6 after 20.5 m/s and 18.5 m/s wind speed, respectively, the wind turbine will shut down to prevent damage.

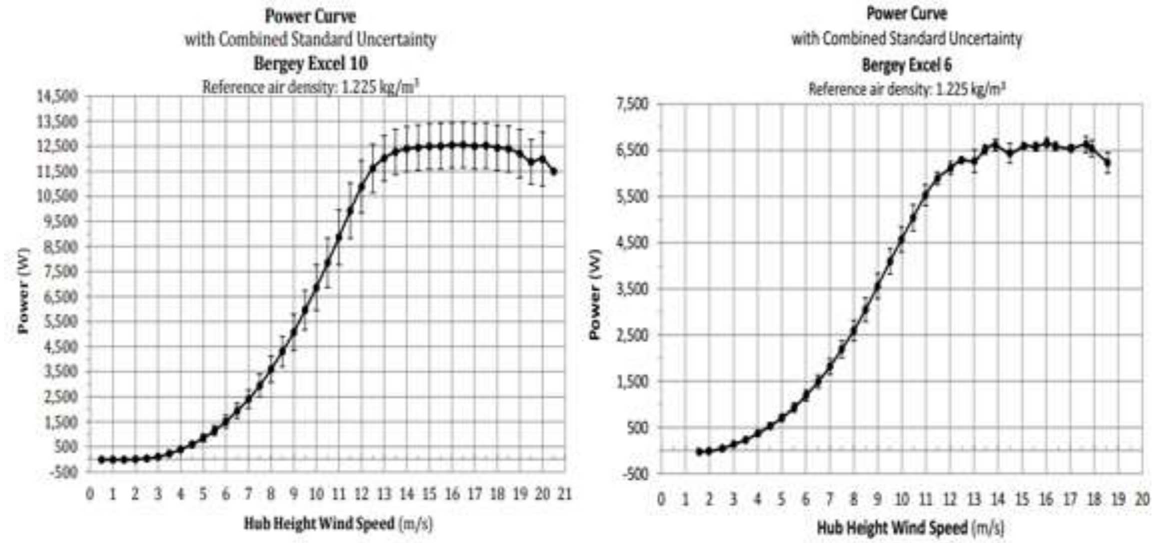

Figure I-3: Bergey Excel 10 and 6 SWCC report power curves

Source: The Small Wind Certification Council (SWCC)

Wind Turbine Power Output Calibration

Given the data and the SWCC power curves, values for the parameters defined in equation 1 may be determined. For a given turbine, wind speed (*V* in equation 1) is available from the chart; rotor sweep area (*A* in equation 1) is 30.7 m^2 for the 6 kW and 38.6 m^2 for the 10 kW. For calibration, the air density (ρ in equation 1) is set at a base sea level value of 1.225 kg/m^3. The power coefficient (C_p in equation 1) for each turbine was estimated by solving for the value at which the absolute difference from the tested power output and the predicted power output was minimized. By this measure, C_p values of 0.285 and 0.258 were obtained for the 10 kW and 6 kW turbines, respectively.

Average air densities for the five locations are 0.91, 1.08, 1.13, 1.15, and 1.18 kg/m^3 for Boise City, Hollis, Shawnee, Miami, and Idabel, respectively. These values are entered for ρ in equation 1 to obtain power output levels for the calibrated values of C_p.

For wind velocity levels less than V_r, these less than sea level air densities result in estimated power levels of 74%, 88%, 92%, 94%, and 97% of the base level for Boise City, Hollis, Shawnee, Miami, and Idabel, respectively.

For velocity levels between V_r and V_p an ordinary least square regression was estimated to obtain parameter values for α_0, α_1, and α_2 for each location. Estimated coefficients are reported in Table 3.

Table I-3: Regression coefficients results for the power output quadratic function for the two turbine modules and five locations

Location	System	10 kW Wind Turbine	6 kW Wind Turbine
Boise City	Constant (α_0)	-41.78	-12.84
	Wind Speed Linear Term (α_1)	7.16	2.54
	Wind Speed Quadratic Term (α_2)	-0.25	-0.09
Hollis	Constant (α_0)	-49.60	-15.24
	Wind Speed Linear Term (α_1)	8.50	3.01
	Wind Speed Quadratic Term (α_2)	-0.30	-0.11
Shawnee	Constant (α_0)	-51.81	-15.92
	Wind Speed Linear Term (α_1)	8.88	3.14
	Wind Speed Quadratic Term (α_2)	-0.31	-0.11
Miami	Constant (α_0)	-53.13	-16.33
	Wind Speed Linear Term (α_1)	9.11	3.22
	Wind Speed Quadratic Term (α_2)	-0.32	-0.12
Idabel	Constant (α_0)	-54.39	-16.72
	Wind Speed Linear Term (α_1)	9.32	3.30
	Wind Speed Quadratic Term (α_2)	-0.33	-0.12

All parameters are significant at 99% confident level.

Assumptions for Estimating the Annual Cost of the Wind Turbines

The wind turbine systems are assumed to be installed and used for their estimated life of 20 years. The salvage value is assumed to be zero. A 5% interest rate and discount factor are assumed. The insurance rate is assumed to be 0.6%. The assessed proportion for property tax is assumed to be 12% [41]. Estimates of costs for both machines are reported in Table 4.

Table I-4: Purchase price and annual cost for two wind turbine

Description	Unit	10 kW Wind Turbine	6 kW Wind Turbine
Purchase Price	$	65,000	55,000
Life	years	20	
Depreciation	$/year	3,250	2,750
Interest on Average Investment	$/year	1,625	1,375
Insurance	$/year	195	165
Property Tax	$/year	352	298
Repairs	$/year	437	437
Total Annual Cost	$/year	5,860	5,025

Source: Bergey Company provided purchase price and repair cost estimates for the wind turbines. Salvage value is assumed to be zero at the end of life for each of the systems.

Results and Discussion

Figures 4, 5, and 6 show the electricity consumption and power output for each wind turbine system for the five case study locations for the months of January, April, and July. Estimated electricity production is greatest in Boise City where most of the electricity consumption in winter (January) and all the consumption in spring (April) is produced by the wind turbine. Peak load summer (July) requirements exceed expected turbine output. For the other four locations, wind speeds are lower, and the power output is not sufficient to cover the electricity consumption. Average wind velocity is relatively low at Idabel, in southeast Oklahoma, and the expected electricity production from the modeled turbines is low. As the charts illustrate, location and time of year matters.

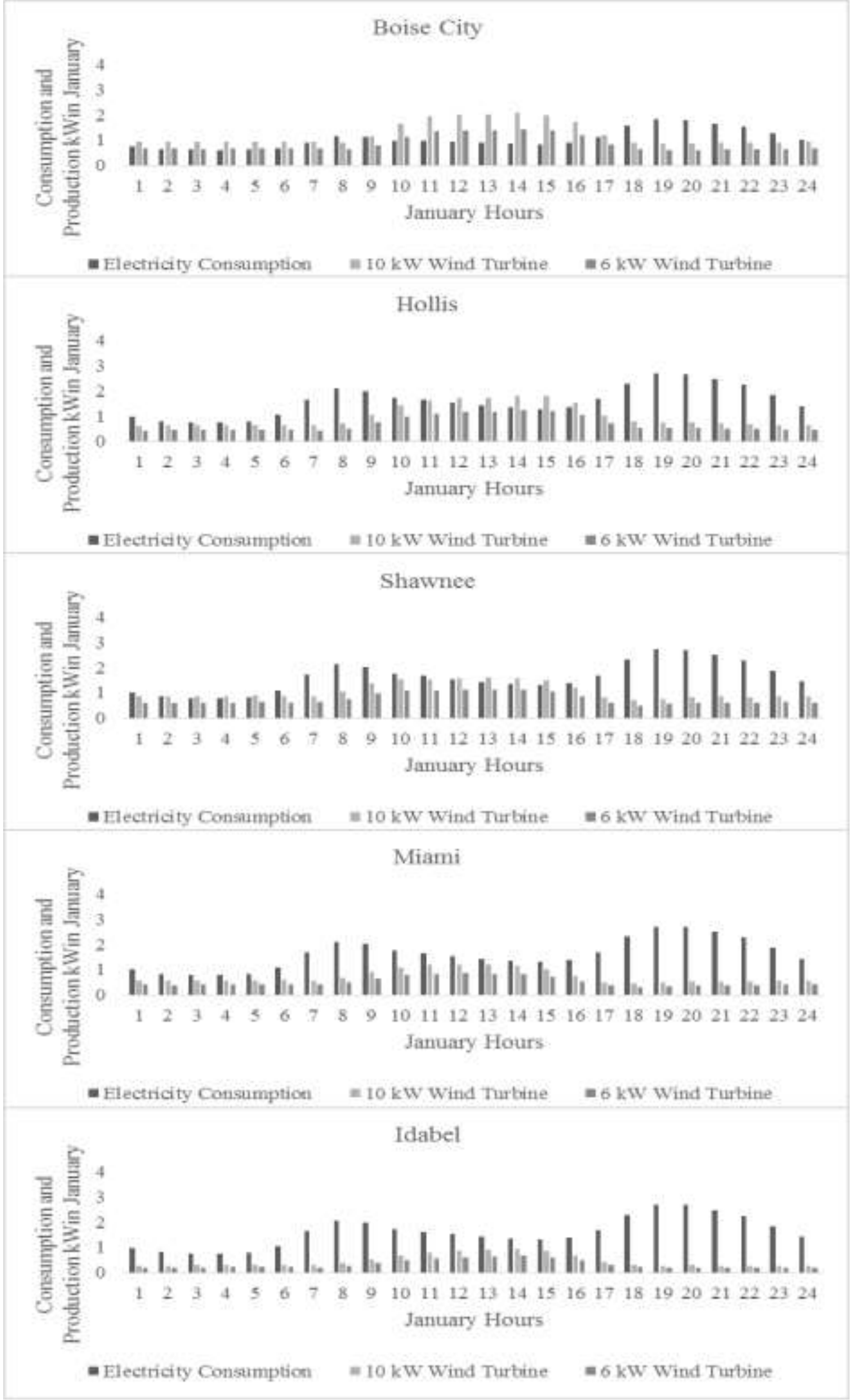

Figure I-4: Estimates of electricity consumption and power output for two wind turbine systems for the five locations, Oklahoma representative household in January

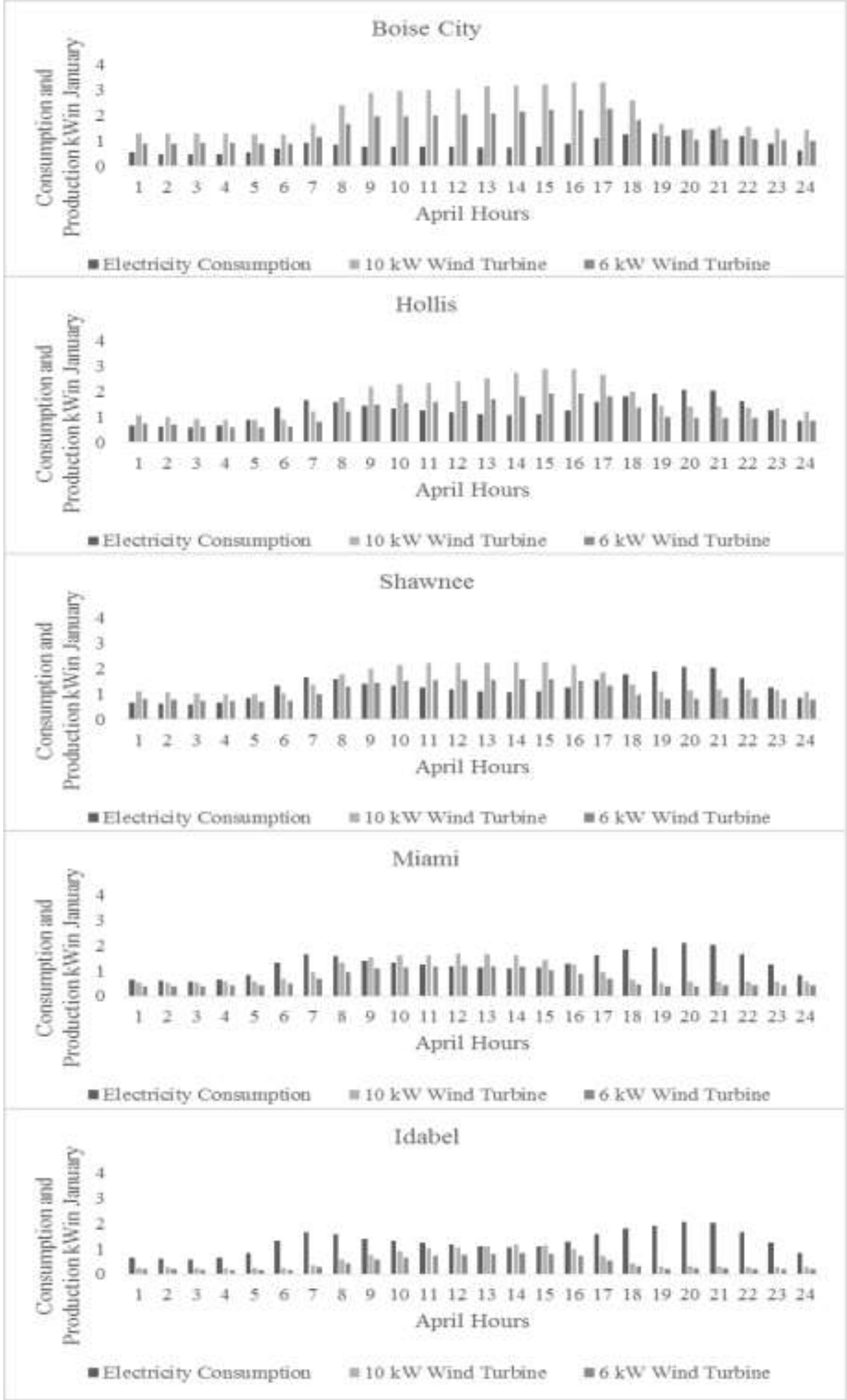

Figure I-5: Estimates of electricity consumption and power output for two wind turbine systems for the five locations, Oklahoma representative household in April

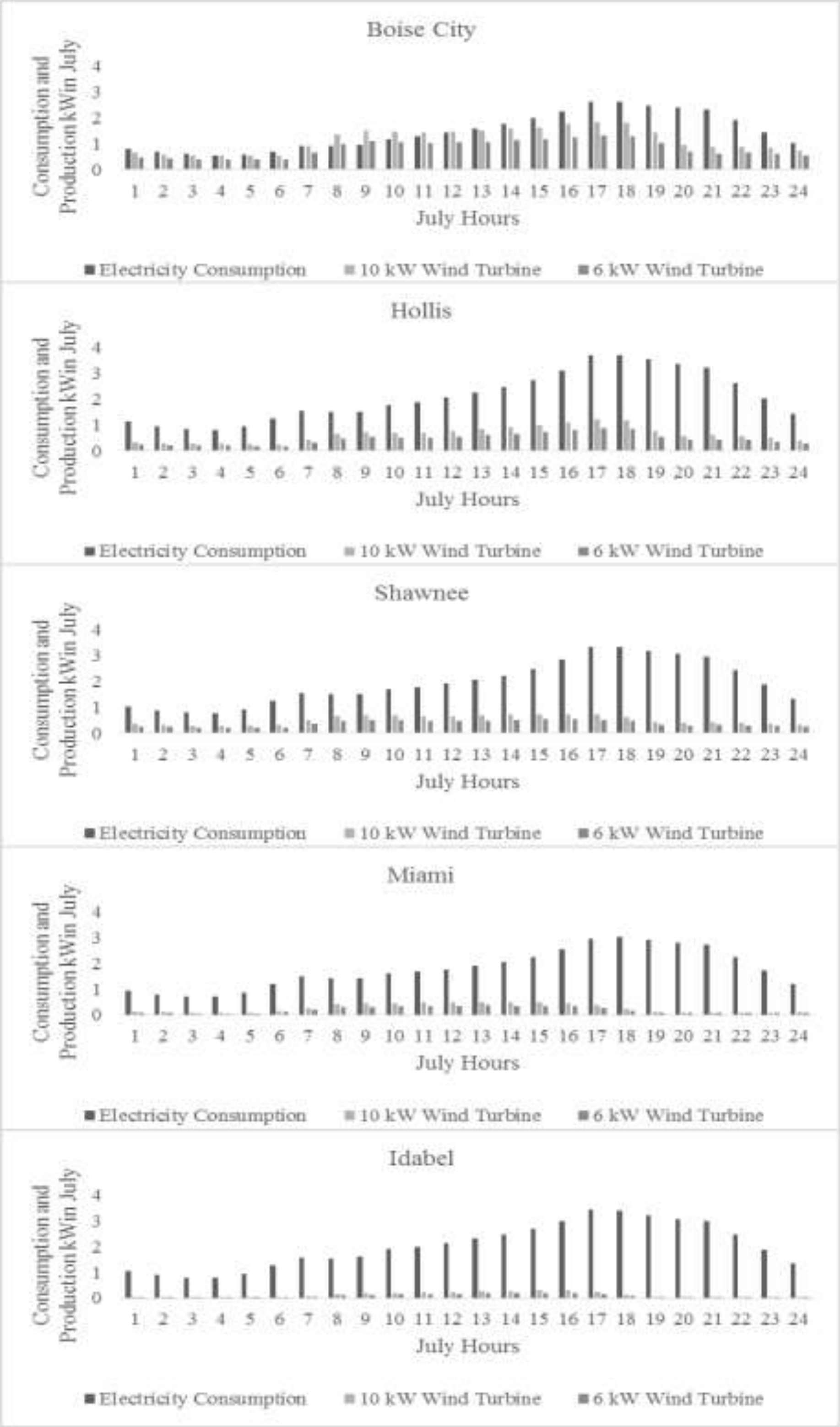

Figure I-6: Estimates of electricity consumption and power output for two wind turbine systems for the five locations, Oklahoma representative household in July

Table 5 shows the percentage of electricity production used by the household for each location and wind turbine size. Boise City has the lowest electricity consumption and the highest power output production. Expected electricity production from 10 kW and 6 kW wind turbines located at Boise City are expected to produce 85% and 73%, respectively, of annual household requirements. Whereas, turbines located at Idabel are expected to produce only 15%-21% of annual household requirements.

Table I-5: Annual electricity consumed, produced, used, and the percentage of the representative household consumption produced by each of the two RDG systems in each location

Location	System	Electricity Consumption (kWh/yr)	Power Production (kWh/yr)	Power Production Used (kWh/yr)	Power Production Used (%)	Percentage of Household Consumption Produced by Wind Turbine (%)
Boise City		9,206				
	10 kW Turbine		12,445	7,785	63%	85%
	6 kW Turbine		8,704	6,709	77%	73%
Hollis		14,289				
	10 kW Turbine		9,254	8,125	88%	57%
	6 kW Turbine		6,415	6,214	97%	43%
Shawnee		13,502				
	10 kW Turbine		8,327	7,522	90%	56%
	6 kW Turbine		5,929	5,797	98%	43%
Miami		12,847				
	10 kW Turbine		5,087	4,965	98%	39%
	6 kW Turbine		3,642	3,637	100%	28%
Idabel		13,538				
	10 kW Turbine		2,906	2,902	100%	21%
	6 kW Turbine		2,084	2,084	100%	15%

Electricity consumption and production for each block for each billing period (month) for Boise City and Idabel are shown in Appendix B and C, respectively. These locations represent the extremes in expected electricity production among the five locations. Blocks F and J for the smart meter and proposed RDG rates, respectively, are the peak load pricing blocks. A 10 kW machine at Boise City is expected to produce sufficient electricity to meet household requirements during the months of June and October. Production from a 6 kW turbine is expected to be sufficient for October. The household is not expected to be compensated for excess electricity sent to the grid during a block. For net metering systems, zero net electricity from the grid results if total production during a block exceeds total household requirement during the same block. Electricity production from either system at Idabel would be insufficient to cover household requirements during any block (Appendix C).

The annual cost for installing and maintaining each of the wind turbine systems is reported in Table 4. Payments to the utility and annual cost of electricity for the case study household for each location and each of the ten alternatives, (a) traditional meter, (b) smart meter, (c) RDG rates 6 kW wind turbine, (d) RDG rates 10 kW wind turbine, (e) traditional meter with 6 kW wind turbine with net metering, (f) traditional meter with 10 kW wind turbine with net metering, (g) smart meter with 6 kW wind turbine with net metering, (h) smart meter with 10 kW wind turbine with net metering, (i) proposed RDG rates for a 6 kW wind turbine grid-tied system with net metering, and (j) proposed RDG rates for a 10 kW wind turbine grid-tied system with net metering are reported in Table 6.

Table I-6: Annual cost of electricity for a representative five locations, Oklahoma household, for three alternative rate structures

Location	System	Unit	Alternative I: Traditional Meter			Alternative II: Smart Meter			Proposed Alternative III: Smart plus RDG			
			Payment to Utility	Payment to Utility with Net Metering	Total Cost	Payment to Utility	Payment to Utility with Net Metering	Total Cost	Payment to Utility without Net Metering	Payment to Utility with Net Metering	Total Cost without Net Metering	Total Cost with Net Metering
Boise City	Grid-Only	$/yr	870			894						
	10 kW Wind Turbine	$/yr		198	6,058		213	6,073	309	286	6,169	6,146
	6 kW Wind Turbine	$/yr		274	5,299		289	5,314	374	364	5,399	5,389
Hollis	Grid-Only	$/yr	1,191			1,199						
	10 kW Wind Turbine	$/yr		597	6,457		617	6,477	654	629	6,514	6,489
	6 kW Wind Turbine	$/yr		784	5,809		807	5,832	764	757	5,789	5,782
Shawnee	Grid-Only	$/yr	1,122			1,137						
	10 kW Wind Turbine	$/yr		592	6,452		626	6,486	658	633	6,518	6,493
	6 kW Wind Turbine	$/yr		763	5,788		893	5,918	749	738	5,774	5,763
Miami	Grid-Only	$/yr	1,066			1,072						
	10 kW Wind Turbine	$/yr		773	6,633		796	6,656	725	721	6,585	6,581
	6 kW Wind Turbine	$/yr		871	5,896		622	5,647	789	789	5,814	5,814
Idabel	Grid-Only	$/yr	1,128			1,145						
	10 kW Wind Turbine	$/yr		981	6,841		1,005	6,865	900	900	6,760	6,760
	6 kW Wind Turbine	$/yr		1,026	6,051		1,048	6,073	939	939	5,964	5,964

The annual cost range among the five locations is estimated to be $894-$1,199 for the smart meter system and $870-$1,191 for the traditional meter system. The pricing structure provides a small incentive for the modeled household to select the traditional meter rate structure. These findings are based on the assumption that switching from the traditional to smart meter rate structure does not alter household behavior. If the household adjusted time of electricity use to reduce consumption during the June through October (block F) weekday afternoon (2 p.m. to 7 p.m.) high rate time period, savings to the household from adopting the smart meter rate structure would be greater than those estimated. Presumably, the utility could also benefit from the reduction in use during the high cost peak load time period.

The results as reported in Table 6 also show that none of the two household wind turbine systems are economically competitive with grid provided electricity. The estimated annual cost of $5,389 for the least costly 6 kW wind turbine system, is more than five times greater than the annual cost of purchasing from the grid via a smart meter system in Boise City. Given the budgeted price structure, and the wind resources, household wind turbines are not economically viable alternatives for the region. The proposed RDG rates relative to the traditional and smart meter rates would increase the cost of electricity for Boise City, Hollis, and Shawnee households that install a 10 kW turbine.

Table 7 shows the breakeven installation costs for the two selected wind turbine systems for each location. These breakeven prices can be compared to the estimated installation costs of $65,000 for the 10 kW system and $55,000 for the 6 kW system. Among the 20 situations evaluated, the highest breakeven installation cost of $3,275 is for the 10 kW wind turbine located at Boise City for a household on a smart meter rate system. In other words, to break even with grid-only electricity the installed cost of the system would have to decrease by $61,725. Breakeven values less than zero as reported for the 6 kW systems for Miami and Idabel imply that households at these locations would have to be paid to install this wind turbine system.

Table I-7: Breakeven prices of the two wind turbines for the for the Oklahoma five locations ($)

Location	System	Household using Alternative I: Traditional Meter	Household using Alternative II: Smart Meter
Boise City	10 kW Turbine	3,018†	3,275
	6 kW Turbine	2,043†	2,301
Hollis	10 kW Turbine	2,747	2,837
	6 kW Turbine	1,155	1,245
Shawnee	10 kW Turbine	1,834	2,028
	6 kW Turbine	518	711
Miami	10 kW Turbine	43	116
	6 kW Turbine	< 0	< 0
Idabel	10 kW Turbine	< 0	< 0
	6 kW Turbine	< 0	< 0

† These breakeven prices can be compared to the estimated installation costs of $65,000 for the 10 kW system and $55,000 for the 6 kW system.

Conclusion

The study was conducted to determine the annual cost of electricity for representative households at five case study locations and to determine the economics of grid-tied wind turbines. Annual electricity consumption for the representative households ranged from 9,206 kWh to 14,289 kWh. Annual electricity production for the $55,000 6 kW system ranged from 2,084 kWh at Idabel to 8,704 kWh at Boise City. The 6 kW system produced 73% of household requirements at Boise City but only 15% at Idabel. Production for the $65,000 10 kW system ranged from 2,906 kWh at Idabel to 12,445 kWh at Boise City. Among locations, the 6 kW system is expected to produce 70% as much electricity as the 10 kW system. The 10 kW system produced 85% of household requirements at Boise City but only 21% at Idabel. Wind resources vary greatly across the modeled locations.

For the modeled households among the five locations, annual electricity cost was estimated to be $894-1,199 for the smart meter system and $870-1,191 for the traditional meter system. The estimated annual cost of $5,389 for the least costly household grid tied production system, a 6 kW wind system, is five times greater than the annual cost of purchasing from the grid via a smart meter system. If external consequences of electricity generation and distribution are ignored, given current and proposed rate structures and prices, the grid-tied wind systems are not economically competitive for households in the region.

Grid-only electricity under the traditional meter rates is the least-cost alternative for each of the five locations. Consequently, for a given and fixed household consumption pattern, the utility would collect more under the smart meter rates. Of course, household consumption patterns may change under the incentives provided by the smart meter rates relative to the traditional accumulation meter rates.

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Appendices

Appendix A. Oklahoma Gas and Electric Company Electricity Pricing Rates

Time and quantity of electricity used	Block	Price ($ per month)	Price (¢ per kWh)	Fuel Cost Adjustment† (¢ per kWh)
		Alternative I: Traditional Meter		
Base Charge		3.00		
June through September				2.38
0 ≤ kWh per month ≤ 1,400	**A**		5.73	
kWh per month > 1,400	**B**		6.68	
November through April				2.22
0 ≤ kWh per month ≤ 600	**C**		5.73	
kWh per month > 600	**D**		1.37	
May and October	**E**		5.73	
		Alternative II: Smart Meter		
Base Charge		13.00		
June through October				
2 p.m. through 7 p.m. weekdays	**F**		14.00	4.26
7:01 p.m. through 1:59 p.m., and weekends	**G**		2.70	2.11
November through May				2.22
First 600 kWh per month	**H**		5.73	
Additional kWh	**I**		1.37	
		Proposed Alternative III: Smart plus RDG		
Base Charge		18.00		
Maximum 15-minute Period Monthly Charge		‡		
June through October				
2 p.m. through 7 p.m. weekdays	**J**		17.30	4.26
7:01 p.m. through 1:59 p.m., and weekends	**K**		1.37	2.11
November through May	**L**		1.37	2.22

Source: Oklahoma Corporation Commission

† Fuel adjustment charge is a surcharge added to compensate for increases, usually unanticipated, in the price of energy (coal and natural gas).

‡ The "maximum demand" charge is determined by multiplying use (kWh) during the 15-minute period during the month for which withdrawal from the grid was greatest by $2.68 (Oklahoma Gas & Electric, 2012; Champion, 2016). Thus, this charge varies with each month and each system. For the representative household it ranged from $1.38 for the month of April to $2.24 for the month of August. Since 15-minute period data were not available, withdrawal from the grid for the hour of the month with the greatest withdrawal was divided by four.

Appendix B. Electricity Consumption and Production for each Block in Boise City

Month	Block	Total Use	6 kW			10 kW		
			Production	Net Used from Grid	Excess Sent to Grid	Production	Net Used from Grid	Excess Sent to Grid
		kWh/block/year		kWh/block/year			kWh/block/year	
				Traditional Meter				
June	A	888	818	69	0	1158	0	271
	B	0	0	0	0	0	0	0
July	A	1080	607	472	0	848	232	0
	B	0	0	0	0	0	0	0
August	A	983	496	487	0	691	291	0
	B	0	0	0	0	0	0	0
September	A	799	599	199	0	842	0	44
	B	0	0	0	0	0	0	0
November	C	600	600	0	0	600	0	0
	D	71	80	0	9	373	0	302
December	C	600	600	0	0	600	0	0
	D	168	75	93	0	370	0	202
January	C	600	600	0	0	600	0	0
	D	181	38	143	0	314	0	132
February	C	600	600	0	0	600	0	0
	D	82	91	0	9	398	0	317
March	C	600	600	0	0	600	0	0
	D	78	273	0	195	663	0	585
April	C	600	600	0	0	600	0	0
	D	6	453	0	446	941	0	935
May	E	604	878	0	274	1252	0	647
October	E	667	697	0	30	994	0	327
				Smart Meter				
June	F	247	212	35	0	303	0	56
	G	640	606	34	0	855	0	215
July	F	316	165	150	0	231	85	0
	G	764	442	322	0	617	147	0
August	F	284	126	158	0	175	108	0
	G	699	370	329	0	516	183	0
September	F	227	137	90	0	192	34	0
	G	572	462	109	0	650	0	78
October	F	164	150	14	0	216	0	51
	G	503	547	0	44	778	0	275
November	H	600	600	0	0	600	0	0
	I	71	80	0	9	373	0	302
December	H	600	600	0	0	600	0	0
	I	168	75	93	0	370	0	202
January	H	600	600	0	0	600	0	0
	I	181	38	143	0	314	0	132
February	H	600	600	0	0	600	0	0
	I	82	91	0	9	398	0	317
March	H	600	600	0	0	600	0	0
	I	78	273	0	195	663	0	585
April	H	600	600	0	0	600	0	0
	I	6	453	0	446	941	0	935
May	H	600	600	0	0	600	0	0
	I	4	278	0	274	652	0	647
				Proposed RDG				
June	J	247	212	35	0	303	0	56
	K	640	606	34	0	855	0	215
July	J	316	165	150	0	231	85	0
	K	764	442	322	0	617	147	0
August	J	284	126	158	0	175	108	0
	K	699	370	329	0	516	183	0
September	J	227	137	90	0	192	34	0
	K	572	462	109	0	650	0	78
October	J	164	150	14	0	216	0	51
	K	503	547	0	44	778	0	275
November	L	671	680	0	9	973	0	302
December	L	768	675	93	0	970	0	202
January	L	781	638	143	0	914	0	132
February	L	682	691	0	9	998	0	317
March	L	678	873	0	195	1263	0	585
April	L	606	1053	0	446	1541	0	935
May	L	604	878	0	274	1252	0	647

Appendix C. Electricity Consumption and Production for each Block in Idabel

Month	Block	Total Use	6 kW			10 kW		
			Production	Net Used from Grid	Excess Sent to Grid	Production	Net Used from Grid	Excess Sent to Grid
		kWh/block/year	kWh/block/year			kWh/block/year		
			Traditional Meter					
June	A	1284	116	1168	0	161	1122	0
	B	0	0	0	0	0	0	0
July	A	1400	67	1333	0	93	1307	0
	B	113	0	113	0	0	113	0
August	A	1314	61	1252	0	85	1228	0
	B	0	0	0	0	0	0	0
September	A	1239	86	1153	0	120	1119	0
	B	0	0	0	0	0	0	0
November	C	600	179	421	0	249	351	0
	D	370	0	370	0	0	370	0
December	C	600	218	382	0	304	296	0
	D	507	0	507	0	0	507	0
January	C	600	241	359	0	336	264	0
	D	589	0	589	0	0	589	0
February	C	600	236	364	0	329	271	0
	D	429	0	429	0	0	429	0
March	C	600	310	290	0	433	167	0
	D	431	0	431	0	0	431	0
April	C	600	287	313	0	401	199	0
	D	318	0	318	0	0	318	0
May	E	936	167	769	0	232	704	0
October	E	1008	116	892	0	161	847	0
			Smart Meter					
June	F	349	33	317	0	45	304	0
	G	934	83	851	0	116	818	0
July	F	419	21	398	0	29	390	0
	G	1094	46	1048	0	63	1031	0
August	F	366	20	346	0	28	338	0
	G	948	41	907	0	57	891	0
September	F	337	21	316	0	29	308	0
	G	901	65	836	0	90	811	0
October	F	237	28	209	0	39	198	0
	G	772	88	684	0	122	649	0
November	H	600	179	421	0	249	351	0
	I	370	0	370	0	0	370	0
December	H	600	218	382	0	304	296	0
	I	507	0	507	0	0	507	0
January	H	600	241	359	0	336	264	0
	I	589	0	589	0	0	589	0
February	H	600	236	364	0	329	271	0
	I	429	0	429	0	0	429	0
March	H	600	310	290	0	433	167	0
	I	431	0	431	0	0	431	0
April	H	600	287	313	0	401	199	0
	I	318	0	318	0	0	318	0
May	H	600	167	433	0	232	368	0
	I	336	0	336	0	0	336	0
			Proposed RDG					
June	J	349	33	317	0	45	304	0
	K	934	83	851	0	116	818	0
July	J	419	21	398	0	29	390	0
	K	1094	46	1048	0	63	1031	0
August	J	366	20	346	0	28	338	0
	K	948	41	907	0	57	891	0
September	J	337	21	316	0	29	308	0
	K	901	65	836	0	90	811	0
October	J	237	28	209	0	39	198	0
	K	772	88	684	0	122	649	0
November	L	970	179	791	0	249	721	0
December	L	1107	218	889	0	304	803	0
January	L	1189	241	948	0	336	853	0
February	L	1029	236	793	0	329	700	0
March	L	1031	310	721	0	433	598	0
April	L	918	287	631	0	401	518	0
May	L	936	167	769	0	232	704	0

CHAPTER II

ECONOMICS OF GRID-TIED HOUSEHOLD SOLAR PANEL SYSTEMS VERSUS GRID-ONLY ELECTRICITY[*]

Abstract

Photovoltaic (PV) technology is available for purchase and use to provide households with electricity. The objective of this research is to determine the economic consequences of installing microgeneration grid-tied solar panel systems (4 kW; 12 kW), given alternative pricing structures for households, at five locations with different solar radiation resources. Twenty years of hourly solar radiation and temperature data, and hourly electricity use data for representative households, were obtained for each location. These data, electricity pricing rate schedules, and purchase prices and power output response functions for each solar panel system are used to address the objective. The annual household electricity cost among the five locations ranges from $845 to $1,128 for smart meter rates and from $870 to $1,191 for traditional accumulation meter rates. The estimated annual cost of $2,148 for the least costly household grid-tied 4 kW solar panel system with net metering is two-times greater than the annual cost of purchasing from the grid. If external consequences of electricity generation and distribution are ignored, given

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region specific rate structures and prices, household solar panel electricity generation systems are not economically competitive in the region studied. A major finding is that the economic consequences of grid-tied household solar systems differ substantially among locations that are relatively close in proximity.

Key words: cost, grid-tied, net metering, smart meter, solar panel

Introduction

Photovoltaic (PV) technology was developed in the 1950s, and work has continued to improve its efficiency [1]. PV solar panels for electricity microgeneration are manufactured by private companies, and advertised for sale to on-grid households. The economics of grid-tied household solar panel electricity generation systems have not been fully explored. Economics depends on a number of factors such as investment cost, the price of grid electricity, and the type of metering system. A comprehensive economic analysis also requires information that is more difficult to obtain, such as hourly information regarding site-specific solar radiation and temperature.

The USA state of Oklahoma has installed a unique Mesonet weather system that has recorded 20 years of hourly solar radiation and temperature data for more than 100 sites across the state [2]. The geography and climate of the state is quite diverse ranging from an elevation of 110 m with 132 cm of annual rainfall, and average solar radiation of 189 watt/m^2 at Idabel (33° 49' 48" N 94° 52' 49" W) in the southeast, to an elevation of 1,267 m with 46 cm of annual rainfall, and average solar radiation of 220 watt/m^2 at Boise City (36° 41' 33" N 102° 29' 49" W) in the northwest [2].

Some Oklahoma households purchase electricity from investor-owned electric utilities, and others are serviced by rural electric cooperatives. The investor-owned electric utilities are natural monopolies. In the USA, rates charged by investor-owned public utilities are regulated by state authorities. The Constitution of the State of Oklahoma provides the Oklahoma Corporation Commission (OCC) with the authority and responsibility to supervise, regulate, and control Oklahoma investor-owned electric utilities [3]. The OCC is charged with the responsibility of ensuring adequate service, preventing unfair charges to the public, protecting the utilities from unreasonable demands, and enabling a fair return to investors [4].

The OCC has approved two pricing rates currently offered to farms and households-alternative I and alternative II-as shown in Appendix A [5]. Alternative I is based on the traditional (accumulation) meter, where fixed prices per kilowatt-hour (kWh) are charged independent of the time of day the electricity is consumed. Traditional meters measure total consumption, but do not provide information on when the energy is used during the time period of interest [6]. Households are charged based on the total electricity consumed in the billing period (assumed to be one month).

Some households in the region are equipped with smart meters that enable two-way communication between the electric company and their customers. They facilitate real-time monitoring of electricity flows and are designed to enhance both the technical and allocative efficiency of electricity markets. Smart meters enable the utility to charge different rates during different times of the day. Different rates for different hours of the day may be used to incentivize reductions in electricity use during traditional peak time periods (for example, between 2 p.m. and 8 p.m. on hot summer days when electricity is used to power air conditioners). The OCC approved alternative II, as shown in Appendix A, in conjunction with the introduction and application of smart meters [7].

This study builds on prior research and extends it in several important aspects [8-12]. First, 20 years of hourly solar radiation data as recorded by the Mesonet weather monitoring system enables empirical estimates of solar panel electricity production for each hour of each month for each of the five unique locations [2]. Second, the modeling system also accounts for differences in temperature when estimating electricity production. Third, representative households as defined from census data for structure size and characteristics and number of occupants were defined for each of the five locations. Estimates of household electricity consumption by these representative households for each hour for each month for each location were obtained from simulations by the USA Department of Energy [13]. These simulations find that each location has a unique average load profile resulting from differences in climate and household characteristics. Fourth, the representative household use estimates are based on expected response to traditional accumulation meter prices. Smart meter systems use different prices for different times of the day to incentivize households to shift some consumption from peak to off peak times. An electricity demand price elasticity estimate is used to estimate household use response to price changes associated with a switch from a traditional meter to a smart meter. Fifth, cost estimates are produced for both traditional accumulation meter and smart meter rate structures. In the case study region, households with smart meters encounter four different rates depending on hour of the day, month of the year, and quantity of household use during the billing period. The major unique contribution of the study is that the 20 years of site specific hourly data enables a rather precise determination of the extent to which the economics of grid-tied solar systems differ among locations that are geographically in close proximity.

Several studies have been conducted to determine the economics of off-grid stand-alone systems that include either a diesel generator, or battery, or fuel cell to be used in combination with solar panels [14-21]. The present study is limited to grid-tied systems. The objective of this research is to determine the economic consequences of installing microgeneration grid-tied solar panel systems (4 kW; 12 kW) given alternative pricing structures (traditional accumulation meter; smart meter), with and without net metering, for households at five Oklahoma locations. Solar radiation resources differ substantially across the state. The five sites were chosen to encompass the range of variability in the state’s solar radiation resources; Boise City in the Northwest (36° 41' 33" N 102° 29' 49" W), Miami in the Northeast (36° 53' 17" N 94° 50' 39" W), Shawnee in the center (35° 21' 53" N 96° 56' 53" W), Hollis in the Southwest (34° 41' 7" N 99° 49' 59" W), and Idabel in the Southeast (33° 49' 48" N 94° 52' 49" W)). The purchase price at which each of the solar panel systems breaks even with the grid-only system will be determined. In addition, the percentage change in grid prices required for the household solar systems to break even with grid-only purchased electricity will be determined for both traditional and smart meters. The findings will enable a determination of the economic consequences of household solar microgeneration systems for each location. Thus, the precise price data, in combination with the precise weather data, enable precise site-specific estimates of the economic consequences and economic potential of grid-tied household solar systems.

Conceptual Framework

The economics of a household grid-tied solar panel system depend on the cost of owning and operating the system, the amount and timing of electricity produced by the system, the quantity and timing of electricity required by the household, the net cost of electricity from the grid, the grid pricing structure, and the absence or presence of net metering.

Estimation of solar panel power output

Theoretically, the power output produced by a solar panel is a function of the panel's area, mechanical efficiency (proportion of energy in the solar radiation transferred into electricity), solar radiation, and temperature [22]. The electricity output (kW) from a solar panel can be described as:

(1) $P = 0.001(I\ A\ \eta_{PV}\varphi)$,

where P is the power output (kW); I is the solar radiation (W/m^2); A is the area of the PV in m^2; and η_{PV} is the mechanical efficiency (overall efficiency of the PV panels) in percentage; and φ is included to account for efficiency losses.

Estimation of the annual electricity cost for each alternative

For a household serviced by a traditional meter, the annual cost of electricity is calculated as:

(2) $ECTM = \sum_{j=1}^{12} BC_j + \sum_{j=1}^{12} D_j\ ERTM_{jr}\ G_{jr}$,

where $ECTM$ is the annual electricity cost for a household using a traditional meter; BC_j is a fixed base charge per month independent of electricity use; $ERTM_{jr}$ is the OCC traditional meter rate for the j^{th} month and r^{th} block ($/kWh); and G_{jr} is the net quantity of electricity used (kWh) in r^{th} block and j^{th} month, and D_j is the number days in the j^{th} month, if j = 1, 3, 5, 7, 8, 10, or 12 then D_j = 31, if j = 4, 6, 9, or 11 then D_j = 30, and if j = 2 then D_j = 28.

For a household serviced by a smart meter, the annual cost of electricity is calculated as:

$$(3)\ ECSM = \sum_{j=1}^{12} BC_j + \sum_{j=1}^{12} D_j \sum_{i=1}^{24} ERSM_{ijr}(G_{ijr}\, \varepsilon\, PC_{ijr}),$$

where $ECSM$ is the annual electricity cost for the household using the smart meter rate, and $ERSM_{ijr}$ is the OCC smart meter rate ($/kWh); ε is the demand price electricity elasticity; and PC_{ijr} is the percent change in electricity prices from traditional meter to smart meter rates for the i^{th} hour and r^{th} block during the j^{th} month, where $i = 1, 2, 3, \ldots, 24$.

The annual charge for net electricity withdrawn from the grid for a household with a grid-tied solar panel based on the traditional meter rate schedule with net metering would be:

$$(4)\ ECTMN = \sum_{j=1}^{12} BC_j + \sum_{j=1}^{12} D_j\, ERTM_{jr}\, (G_{jr} - P_{jr}),$$

where $ECTMN$ is the annual electricity cost for the household, and P_{jr} (kWh) is the electricity produced by the solar panel in r^{th} block, during the j^{th} month, where $(G_{jr} - P_{jr}) \geq 0$.

The annual charge for net electricity withdrawn from the grid for a household with a grid-tied solar panel based on the smart meter rate schedule with net metering would be:

$$(5)\ ECSMN = \sum_{j=1}^{12} BC_j + \sum_{j=1}^{12} D_j \sum_{i=1}^{24} ERSM_{ijr}((G_{ijr}\, \varepsilon\, PC_{ijr}) - P_{ijr}),$$

where $ECSMN$ is the annual electricity cost for the household with the grid-tied solar system using the smart meter rates with the opportunity of net metering, where $((G_{ijr}\, \varepsilon\, PC_{ijr}) - P_{ijr}) \geq 0$.

Estimation of breakeven price of the solar panel

To determine the purchase price at which an investment in a solar panel system would break even with grid only electricity, the difference between the present value of the cost before and after adopting the solar panel is determined.

For the households paying traditional meter rates, the breakeven price is:

(6) $BETM = \frac{\sum_{t=1}^{T} ECTM_t}{(1+r)^t} - \frac{\sum_{t=1}^{T} ECTMN_t}{(1+r)^t}$,

where $BETM$is the solar panel breakeven price for traditional meter rate households; t is the years, where $t = 1, 2, \ldots, T$; and r is the discount factor rate.

For the households that are charged smart meter rates, the breakeven price is:

(7) $BESM = \frac{\sum_{t=1}^{T} ECSM_t}{(1+r)^t} - \frac{\sum_{t=1}^{T} ECSMN_t}{(1+r)^t}$,

where $BESM$ is the solar panel breakeven price for smart meter rate households.

Estimation of percentage change of the electricity price rates to break even with the solar panels

For the prevailing prices for grid electricity as reported in Appendix A, grid-tied solar panel systems are more costly to the households than grid-only electricity. A mathematical programming model may be formulated to determine the percentage increase in the prices reported in Appendix A at which the cost of the grid-tied solar panel system is equal to the cost of grid-only electricity. Consider the model that follows (equations 8, 9, and 10) for households paying traditional meter rates.

(8) $\underset{PR}{\text{Min}}\, Z = |ECTM - ASPCT|$ subject to

(9) $ECTM = \sum_{j=1}^{12} BC_j + \sum_{j=1}^{12} D_j\, (ERTM_{jr} * PR)(\sum_{i=1}^{24} G_{ijr})$

(10) $ECTM = ASPCT$,

where equation 10 is set to equate the annual electricity cost for a household using grid-only electricity (*ECTM*) with the annual cost of the solar panel system (*ASPCT*). Equation 8, the objective function, is set up to minimize the absolute value of the difference between *ECTM* and *ASPCT* which will optimally be zero when the two are equal. In equation 9, the model solves for the level of *PR*, the choice variable that represents the percentage change in the prices, at which the two costs will be equal. Other variables are as previously defined.

For the households paying smart net metering rates, equations 11, 12, and 13 may be solved to determine the percentage change in rates (*PR*) required for the solar panel system to break even with grid-only electricity.

(11) $\underset{PR}{\text{Min}}\, Z = |\, ECSM - \; ASPCS|$ subject to

(12) $ECSM = \; \sum_{j=1}^{12} BC_j + \; \sum_{j=1}^{12} \; D_j \; (\sum_{i=1}^{24}(ERSM_{ijr} * PR) G_{ijr} \,)$

(13) $ECSM = \; ASPCS,$

where $ASPCS$ is the annual cost of the solar panel using smart net metering rates.

Estimation of the annual cost of the solar panel.

Households that invest in a solar panel system in the case study region will incur ownership costs. These costs may be categorized as depreciation, interest, insurance, and property tax [23]. Depreciation is the cost resulting from the reduction in the value of an asset with the passage of time. Interest is the cost incurred because the money invested in the solar panel is not available for investing elsewhere, or alternatively it is the cost of the money borrowed to finance the asset. Insurance against loss to catastrophes such as fire and tornadoes also is costly. Finally, in the case study region, property taxes are assessed based on value. An addition of solar panels would result in a greater assessed value and added annual property tax.

The following equations were used to estimate the annual cost of the solar systems [24]

$$(14)\qquad \text{Depreciation}\ (\frac{\$}{\text{year}}) = \frac{(\text{Purchase Price} - \text{Salvage Value})}{\text{Years of Life}},$$

where purchase price is the cost of the system ($), salvage value is the estimated resale value of the system at the end of its useful life ($), and years of life is the estimated useful life of the system.

$$(15)\qquad \text{Interest}\ (\frac{\$}{\text{year}}) = \frac{\text{Purchase Price} + \text{Salvage Value}}{2} * \text{Interest Rate},$$

where interest rate is the opportunity cost of capital.

$$(16)\qquad \text{Insurance}\ (\frac{\$}{\text{year}}) = \frac{\text{Purchase Price} + \text{Salvage Value}}{2} * \text{Insurance Rate},$$

where insurance rate is the market rate for household insurance.

$$(17)\qquad \text{Property Tax}\ (\frac{\$}{\text{year}}) = \text{Average Assessed Value} * \text{Tax Rate},$$

where average assessed value of the system in dollars is taxed at a rate per dollar of value.

Data and Method

Hourly weather data

Hourly weather data were obtained for each location from the Oklahoma Mesonet. The solar radiation and temperature values were used in combination with equation (1) to produce an estimate of power output for each of 24 hours for each of 12 months. For example, the power output estimate for hour one for January is the mean of 620 observed values; 31 days of hour one observations for each of 20 years. These data may be used to estimate the expected power output from solar panel systems at a specific site for each hour of the day for each month.

Residential hourly electricity data

Residential hourly electricity simulated load profiles for each of the five households were obtained from the U.S. Department of Energy [13]. The characteristics of the house and household to be modeled are reported in Table 1. These load profiles produced point estimates of electricity use for a representative average household for each hour for each month for each location. These point estimates are assumed to be appropriate for households subject to traditional meter rates and do not reflect household response to changes in electricity prices depending on time of use.

Table II-1: Characteristics of the House and Household being Modeled

Characteristics	**Description/Unit**	
	Mixed Humid†	**Mixed Dry**
Building Fuel Types		
Space Heating	Natural Gas	Natural Gas
Air Conditioning	Yes	Yes
Water Heating	Natural Gas	Natural Gas
Building Structure Types		
Total Size	236.5 (m^2)	185.8 (m^2)
Number of Stories/Level	1 Story	1 Story
Bedrooms	3	3
Bathrooms	1	2
Basement	No	No
Type of Glass in Windows	Double-pane Glass	Single-pane Glass

Source: National Renewable Energy Laboratory

† Hollis, Shawnee, Miami, and Idabel are included in the mixed humid region. Boise City is included in the mixed dry region.

Traditional and smart meter rates residential electricity demand

Alternative II smart meter systems and block rates are intended to incentivize shifts in electricity use from peak to off-peak time periods (Appendix A). These systems are intended to reduce the utility’s total peak electricity production requirement and thereby reduce expensive peak load production. The substantially higher prices for block E are expected to encourage households to shift some electricity use such as that used for laundry, dishwashing, and baking from block E to block F. Households have less flexibility for shifting use for heating and cooling. However, a higher price for electricity used to power air conditioners provides an incentive to adjust household thermostats.

Household electricity demand price elasticity is a measure of household response to electricity price changes. An elasticity estimate in combination with information regarding the percentage change in price may be used to estimate the expected change in electricity consumption during a block when a household shifts from traditional (Alternative I) to smart meter (Alternative II) pricing. Bernstein and Griffin [25] estimate a household electricity demand price elasticity of -0.174. By this measure, households would be expected to respond to a 1.0% increase in the electricity price by decreasing use by 0.174%. Thus, for the block E price change of 125% (from $0.0811 to $0.1826 /kWh) and the elasticity estimate of -0.174, the household is expected to reduce electricity use by 21.75%. For block F for which the price is reduced by 39% (from $0.0795 to $0.0481/kWh) and the elasticity estimate of -0.174, the household is expected to reduce electricity use by 6.8%.

Net Metering System

Some households with installed grid-tied PV solar panels may engage in contractual arrangements with their local utilities that permit net metering. Under net metering, households are charged for the difference between the total electricity removed from the grid (during the billing period) and the total electricity provided to the grid (during the billing period) by the household's solar panels. During nights and cloudy days when the PV panels do not produce electricity, the household will use electricity from the grid. When sunshine is available and the household's solar panels are producing more electricity than household use, the excess can be sent to the grid for use by others. Households with net metering are charged for the quantity of electricity removed from the grid minus the quantity of electricity provided to the grid during the billing period. By OCC policy, households are not compensated for production in excess of use during a billing period [26]. However by OCC policy, if a household system is tied to the grid, any excess electricity produced must be made available to the grid. If net metering is not in effect, the household would be required to pay for each kWh removed from the grid and receive zero compensation for all production in excess of household use.

Households that have smart meters may opt to enroll in the alternative I or alternative II pricing systems subject to 12 month contracts that may be renewed each year. Smart meter net-metering charges to a household are determined by use during each block (on-peak and off-peak) for each billing period (monthly), as shown in Appendix A [5]. For example, when totaled over a typical 30 day billing period, production in excess of household use during block E cannot be used to offset use during block F. And, as noted, if total production during block E for the billing period exceeds total household use during the same period, the net excess is provided to the grid. For example, suppose that during the first 15 days of a billing period during block E the solar panels produced zero electricity but the household used 500 kWh. Further, suppose during days 16 through 30 the household used another 500 kWh and the solar panels produced 1,200 kWh. Without net metering, the household would be charged for 500 kWh ($13 base charge plus $0.1826/kWh * 500 kWh = $104.30 for the billing period). With net metering, the household would be charged only the $13 base charge. In effect, with net metering the utility purchases 500 kWh from the household at the retail price of $0.1826/kWh and receives an additional 200 kWh for a price of $0.00/kWh. Without net metering the utility (the grid) would receive 700 kWh for no charge.

PV solar panel modules

Total annual estimated electricity consumption for the case study households ranged from approximately 9,000 kWh for the representative Boise City household to 14,000 kWh for the Hollis household. Given the average daily use, average number of solar hours per day, and the expected DC to AC transfer efficiency, a 4 kW solar panel system would be recommended for these households [27]. Vendors contacted to obtain price information for a 4 kW system, requested that economics also be determined for a 12 kW system. Installed cost information was obtained for both a 4 kW and a 12 kW system with 17% panel efficiency. These 4 kW and 12 kW systems would require 27.9 m^2 and 92.9 m^2 of roof area, respectively. The installed costs including all required components and wiring are estimated to be $32,000 for the 4 kW system and $65,000 for the 12 kW system [28].

PV solar panel efficiency loss

As noted, φ is included in equation (1) to account for efficiency losses that result between the electricity produced by the PV panels and the electricity available for use by the household [29, 30]. First, inverter losses result when the power output is transformed from direct current (DC) to alternating current (AC). The default loss due to the inverter is assumed to be 8%. Second, mismatch losses occur when the level of production differs across the solar cells included in the panels. For example, when one solar cell is not performing at full capacity while the other cells in the module are, the power generated by the "good" solar cells can be affected by the lower performance cell. The overall default loss of the PV solar panel due to mismatch is assumed to be 2%.

Third, loss occurs at connecting points and at diodes that are required to restrict the flow of electricity to one direction. Resistive loss is assumed to be 0.5%. Fourth, some power output is lost due to the cables and wires used throughout the system. DC cables result in losses between the PV module and the inverter. AC cables account for losses between the inverter and household use. DC and AC cable losses are assumed to be 2% and 1%, respectively. Fifth, dust, dirt, snow, or other foreign matter on the surface of the PV module will reduce the amount of solar radiation that the PV module can absorb. These soiling losses are assumed to be 5%.

Sixth and seventh are sun-tracking and shading losses, respectively. The losses from both factors are assumed to be zero. It is assumed that the system will be installed at the optimum orientation for sun-tracking and that the system will be installed in an area that is opened to sunshine and not subject to shading by either buildings or trees. The eighth factor that influences solar panel efficiency is ambient temperature. PV module efficiency is a function of temperature. For each degree higher than 25^{o}C the efficiency of the PV module will decrease by 0.5% [30, 31].

Assumptions for estimating the annual cost of the solar panels

The solar panel systems are assumed to be installed and used for their estimated life of 40 years. The salvage value is assumed to be zero. A 5% interest rate and discount factor are assumed. The insurance rate is assumed to be 0.6%. The property tax rate was obtained from Addcox et al. [32]. Estimates of costs for both systems are reported in Table 2.

Table II-2: Purchase price and annual cost for two solar panel systems

Description	Unit	12 kW Solar Panel	4 kW Solar Panel
Purchase Price	$	65,000	32,000
Life	years	40	
Depreciation	$/year	1,625	800
Interest on Average Investment	$/year	1,625	800
Insurance	$/year	195	96
Property Tax	$/year	335	165
Repairs	$/year	-	-
Total Annual Cost	$/year	3,780	1,861

Source: Green Wind and Solar Company provided the purchase price for the solar panels. Salvage value is assumed to be zero at the end of life for each of the systems.

Results and Discussion

The electricity use estimates produced by the U.S. Department of Energy [16] are assumed to be quantities demanded in response to the traditional meter price structure as reported in appendix A. Table 3 includes expected electricity use estimates for each August 15th hour for Boise City and Hollis. The U.S. Department of Energy [16] estimates are reported in the traditional meter columns. Values in the smart meter columns reflect use adjustments expected if the household transitions from traditional to smart meter prices. These smart meter use levels are based on the elasticity estimate of -0.174 and the price changes reported in appendix A. Less use is expected for hours 14 through 19 in response to the 125% increase in price. More use is expected for hours 20 through 13 in response to the 39% decline in price. By this measure, a switch from traditional to smart meter rates is expected to decrease total expected August 15th electricity use by 3.8% at Boise City and by 3.9% at Hollis.

Table II-3: August 15 expected electricity consumption for Boise City and Hollis households using traditional meter rates and smart meter rates

Hour	Boise City Traditional Meter Expected Consumption (kWh)	Boise City Smart Meter Expected Consumption (kWh)	Hollis Traditional Meter Expected Consumption (kWh)	Hollis Smart Meter Expected Consumption (kWh)
1	0.878	0.938	0.688	0.735
2	0.736	0.786	0.592	0.633
3	0.615	0.657	0.545	0.583
4	0.555	0.593	0.524	0.560
5	0.554	0.592	0.572	0.611
6	0.579	0.619	0.707	0.756
7	0.820	0.876	0.853	0.911
8	0.760	0.812	0.749	0.801
9	0.722	0.772	0.615	0.658
10	0.980	1.047	0.640	0.684
11	1.093	1.168	0.728	0.778
12	1.273	1.360	0.860	0.919
13	1.454	1.554	0.986	1.054
14	1.600	1.252	1.173	0.918
15	1.779	1.392	1.414	1.106
16	1.991	1.558	1.581	1.237
17	1.865	1.459	1.921	1.503
18	1.824	1.427	1.903	1.488
19	1.751	1.370	1.873	1.465
20	1.832	1.958	1.920	2.052
21	1.842	1.969	1.944	2.078
22	1.487	1.589	1.520	1.625
23	1.161	1.240	1.176	1.256
24	0.831	0.887	0.786	0.839

With the transition from traditional meter (block A) to smart meter (block E) rates (14 through 19), the expected electricity consumption for households using smart meter rates is decreased due to the respond of the household to the demand elasticity estimate of -0.174 and 125% increase in the price rates

With the transition from traditional meter (block A) to smart meter (block F) rates (20 through 13), the expected electricity consumption for households using smart meter rates is increased due to the respond of the household to the demand elasticity estimate of -0.174 and 39% decrease in the price rates

Estimates of monthly (assumed to be the billing period) and total annual electricity consumption for each of the five households for both traditional and smart meter rates are shown in appendices B through F. Implementation of the smart meter rates is expected to reduce total annual use by 1.4% at Miami and by 2.0% at Hollis. Annual use at Boise City, the lowest use household, is expected to be 36% less than that of the greatest use household at Hollis. Appendices B through F also contain estimates of total electricity use; expected production from the solar systems; quantity withdrawn from the grid; quantity produced by the solar systems that is used by the household; quantity produced by the solar system that is made available to the grid; and quantity made available to the grid that is in excess of use for the billing period.

Total June electricity use for the Boise City household using a traditional meter is estimated to be 888 kWh (Appendix B). Total June production from the 4 kW system is estimated to be 867 kWh. However, since nothing is produced at night and since some days are cloudy, 427 kWh are used from the grid, and only 460 kWh (53%) of the 867 kWh produced by the 4 kW system are used by the household. An estimated 407 kWh are returned to the grid. If net metering is in effect, these 407 kWh may be used to offset 407 kWh withdrawn from the grid, and the household will be charged for only 20 kWh. If net metering is not in effect, the household would be charged for 427 kWh.

Total June electricity use for households using a smart meter and alternative II rates is estimated to be 852 kWh; 194 kWh during block E and 658 kWh during block F (Appendix B). Total household use is 36 kWh less than with the traditional meter since households are expected to respond to the price changes included in alternative II rates. During block E (hours 14 through 19), the 4 kW system is expected to produce 293 kWh.

The household is expected to use 30 kWh from the grid and 163 kWh from the 4 kW system and to return 130 kWh to the grid. If net metering is in effect, these 130 kWh may be used to offset 30 kWh removed from the grid, and the additional 100 kWh would be provided to the grid for no compensation. If net metering is not in effect, the household would be charged for 30 kWh. During June block F hours (hours 20 through 13), the 4 kW system for the Boise City household is expected to use 658 kWh and produce 574 kWh. However, the household is expected to use 389 kWh from the grid, since timing of solar production does not mesh with household use. If net metering is in effect, 305 kWh would be used to offset kWh withdrawn from the grid, and the household will be charged for 84 kWh. If net metering is not in effect, the household would be charged for 389 kWh.

Total estimated use for the Boise City smart meter alternative II rates household is 9,029 kWh. The 4 kW system is expected to produce 7,458 kWh (83% of use). However, production timing is such that only 3,735 kWh are produced at times that they can be used by the household. By this measure, the 4 kW system produces only 41% of the electricity used by the household. If net metering is not in effect, the household would be required to purchase 5,295 kWh from the grid, 59% of its total annual use. However, if net metering is in effect, the household would be able to sell 3,035 kWh to the grid to offset use and purchase a net of 2,259 kWh. Without net metering, the utility would charge the household for 59% of total annual kWh used. Net metering reduces that to 25%.

Total annual electricity production from a 4 kW system at Hollis is expected to be equal to 51% of the annual use. However, only 75% of the expected production is available at times during which it can be used by the household. If net metering is not in effect, the Hollis household would purchase 62% of total annual use from the grid. If net metering is in effect, the net purchase would be reduced to 49%. A 4kW system at Miami is expected to produce 50% of the annual quantity used. However, if net metering is not in effect, the Miami household would purchase 64% of annual use. If net metering is in effect, net purchase would be reduced to 50% of annual use.

Figures 1, 2, and 3 show the electricity consumption for the traditional and smart meters and power output for each solar panel system for the five case study locations for the months of January, April, and July. In winter (January) and in spring (April), the electricity consumption is the same for the traditional and smart meter as the price rates are the same. As the charts illustrate, location and time of year matters, as production and consumption of electricity differ among locations.

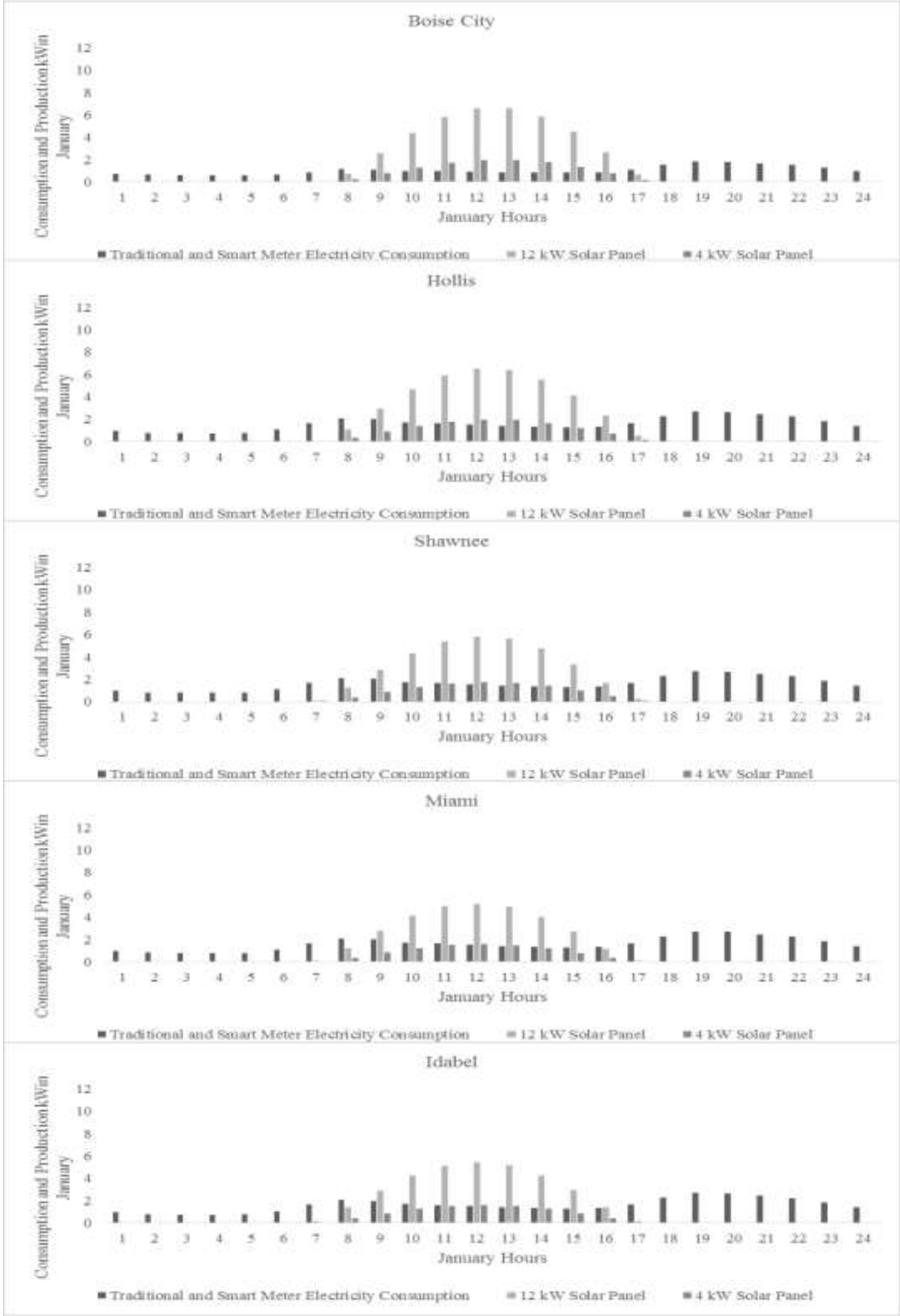

Figure II-1: Estimates of electricity consumption and power output for two solar panel systems for the five locations, Oklahoma representative household in January

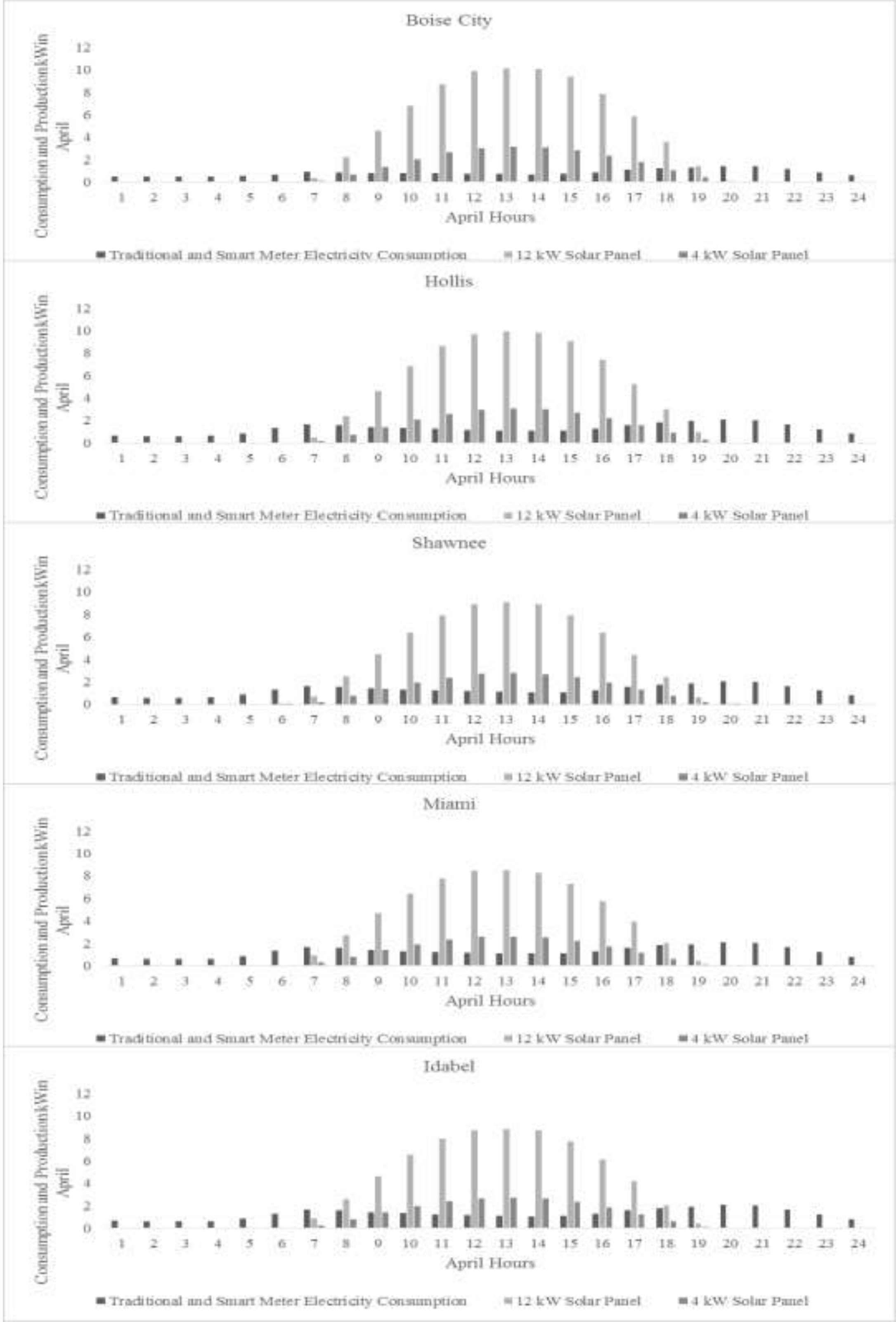

Figure II-2: Estimates of electricity consumption and power output for two solar panel systems for the five locations, Oklahoma representative household in April

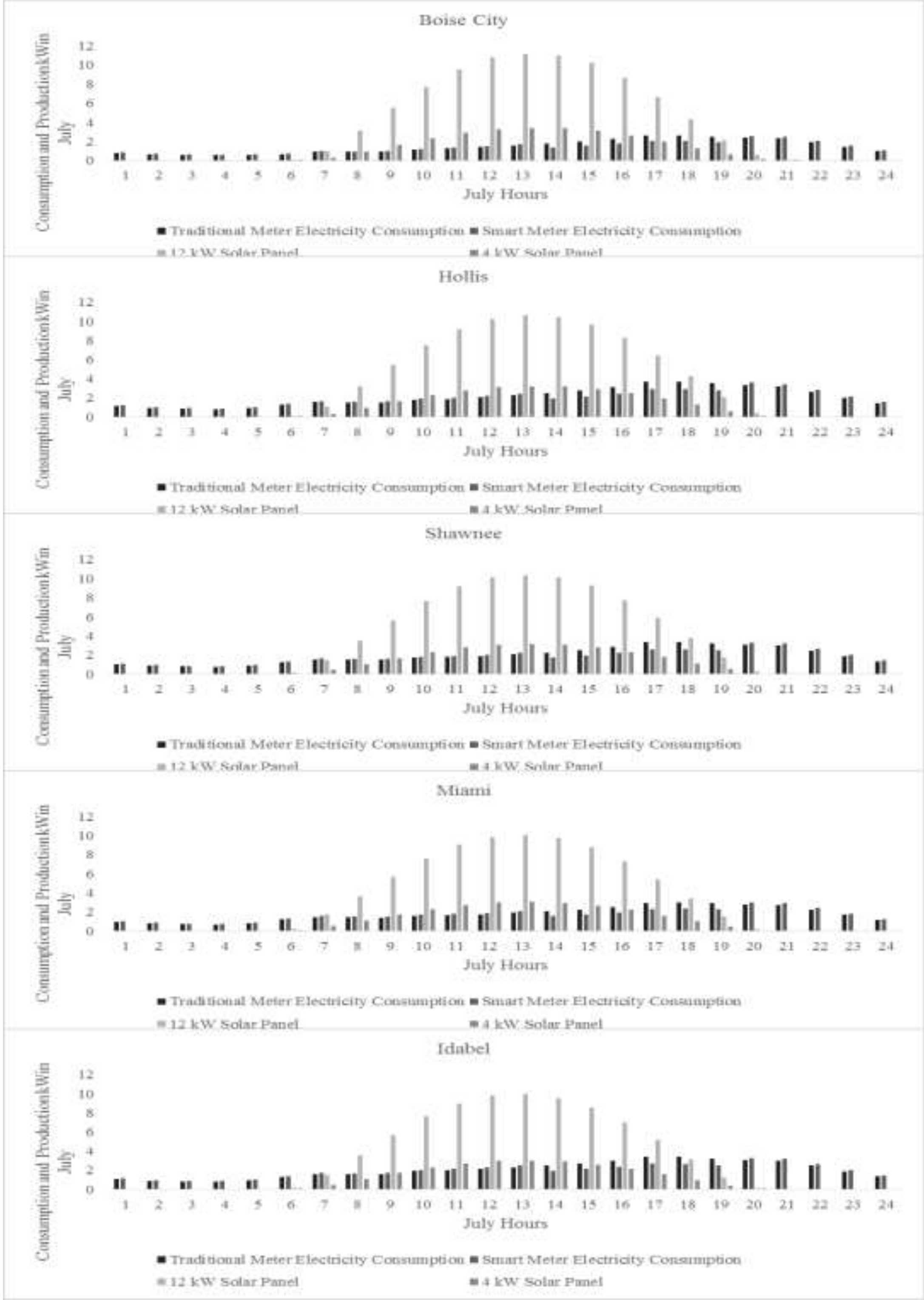

Figure II-3: Estimates of electricity consumption and power output for two solar panel systems for the five locations, Oklahoma representative household in July

The annual cost of installing and maintaining each of the solar panel systems is reported in Table 2. Payments to the utility and annual cost of electricity for the case study household for each location and each of ten alternatives are reported in Table 4. The ten alternatives are: (1) traditional meter, (2) smart meter, (3) traditional meter with 4 kW solar panel with net metering, (4) traditional meter with 12 kW solar panel with net metering, (5) smart meter with 4 kW solar panel with net metering, (6) smart meter with 12 kW solar panel with net metering, (7) traditional meter with 4 kW solar panel without net metering, (8) traditional meter with 12 kW solar panel without net metering, (9) smart meter with 4 kW solar panel without net metering, and (10) smart meter with 12 kW solar panel without net metering.

Given prices and use assumptions, neither of the solar panels is economically competitive at any of the five locations, for either rate structure or metering system. Average annual payment to the utility across the five households that do not have solar panels is $1,075 for the traditional meter and $1,024 for the smart meter. The annual cost range among the five locations is estimated to be $845-$1,128 for the smart meter system and $870-$1,191 for the traditional meter system. Based on the assumed price elasticity estimate of -0.174, the pricing structure provides a small incentive for the modeled household to select the smart meter rate structure.

Table 4 shows the estimated annual payment to the utility with and without net metering for both solar panel systems for each of the five locations. The annual payment range among the five locations is estimated to be $425-$563 for the smart meter system without net metering and $156-$181for the smart meter system with net metering for the 12 kW system. The annual payment for traditional metering without and with net metering for the 12 kW system among the five locations is estimated to be $525-$718 and $156-$181, respectively.

For Boise City traditional meter households, the annual cost of electricity from the grid is $870 per year. For an annual cost of $3,780 for a 12 kW system, the household could reduce annual payments to the utility by $345. Clearly, a choice to pay $3,780 to save $345 (or $714 with net metering) would not be preferred by most households. Alternatively, for an annual cost of $1,861 the household could install a 4 kW system and reduce annual payments to the utility by $284 (or $542 with net metering). The choice to pay $1,861 to save $542 would be declined by most households. The estimated annual cost of $2,148 for the least costly 4 kW solar panel system for the Boise City household is more than two times greater than the annual cost of purchasing from the grid via a smart meter system. Given the budgeted price structure and the solar radiation resources, household solar panels are not economically viable alternatives for the region studied.

Utility company revenue would be impacted substantially if a number of their customers installed household solar systems. For example, annual revenue from the average household with an installed 12 kW system and a traditional meter would decrease by $412 from $1,075 to $663 (Table 4). If net metering was in effect, the average annual revenue received from the household would decrease by $910 to $165. Some of these loses might be offset by the value of the electricity provided to the grid. However, utility companies clearly have an interest in the consequences of the development of household solar systems and in public policy regarding net metering.

Table II-4: Annual cost of electricity for a representative five locations, Oklahoma household, for two alternative rate structures

Location	System	Unit	Alternative I: Traditional Meter					Alternative II: Smart Meter				
			Payment to Utility	Without Net Metering	With Net Metering	Total Cost without Net Metering	Total Cost with Net Metering	Payment to Utility	Without Net Metering	With Net Metering	Total Cost without Net Metering	Total Cost with Net Metering
Boise City	Grid-Only	$/yr	870					845				
	12 kW Solar Panel	$/yr		525	156†	4,305	3,936		425	156	4,205	3,936
	4 kW Solar Panel	$/yr		586	328	2,447	2,189		482	287	2,343	2,148
Hollis	Grid-Only	$/yr	1,191					1,128				
	12 kW Solar Panel	$/yr		718	156	4,498	3,936		558	156	4,338	3,936
	4 kW Solar Panel	$/yr		836	700	2,697	2,561		680	566	2,541	2,427
Shawnee	Grid-Only	$/yr	1,122					1,066				
	12 kW Solar Panel	$/yr		697	166‡	4,477	3,946		561	166	4,341	3,946
	4 kW Solar Panel	$/yr		800	674	2,661	2,535		658	537	2,519	2,398
Miami	Grid-Only	$/yr	1,066					1,010				
	12 kW Solar Panel	$/yr		675	181	4,455	3,961		522	181	4,302	3,961
	4 kW Solar Panel	$/yr		769	639	2,630	2,500		644	555	2,505	2,416
Idabel	Grid-Only	$/yr	1,128					1,072				
	12 kW Solar Panel	$/yr		701	169	4,481	3,949		563	169	4,343	3,949
	4 kW Solar Panel	$/yr		809	696	2,670	2,557		669	563	2,530	2,424

The base charge = 12 * 13 = $156 per yr. Any value above $156 per yr will be considered as the payment for the kWh in the billing period

† Boise City household has to pay $ 156 per yr for base charge only

‡ Shawnee household has to pay $ 156 per yr for base charge, in addition $ 10 per kWh per yr used from the grid

Table 5 shows the breakeven installation costs for both solar panel systems for each location, for both traditional meter and smart meter rates, with and without net metering. These breakeven prices can be compared to the estimated installation costs of $65,000 for the 12 kW system and $32,000 for the 4 kW system. Among the 10 12 kW situations evaluated, the greatest breakeven installation cost of $17,758 is for the Hollis household on a traditional meter rate system with net metering. In other words, to break even with grid-only electricity, the installed cost of the system would have to decrease by $47,242 (73%). If net metering is not in effect, then the installed cost of the 12 kW system on a traditional meter rates in Hollis would have to decrease from $65,000 by 87.5% to $8,123 for the cost of the 12 kW system to break even with purchasing electricity from the grid.

Equations 8, 9, and 10 are solved to determine the percentage change in electricity price rates at which grid-only electricity would break even with a household solar panel system for households paying traditional meter rates. For net metering at the Hollis household, the 12 kW system on a traditional meter rate would break even with grid-only electricity at a rate increase of 366%, from $0.0811 and $0.0918, $0.0795, $0.0359, $0.0795, and $0.0811 for Blocks A1, A2, B1, B2, C, and D respectively to $0.2969, $0.3361, $0.2909, $0.1314, $0. 2909, and $0. 2969 for Blocks A1, A2, B1, B2, C, and D respectively. For the 4kW system, the breakeven rate increase is 233%, from $0.0811 and $0.0918, $0.0795, $0.0359, $0.0795, and $0.0811 for Blocks A1, A2, B1, B2, C, and D respectively to $0.189, $0.2139, $0.1852, $0.0836, $0. 1852, and $0. 189 for Blocks A1, A2, B1, B2, C, and D respectively.

Table II-5: Breakeven prices of the two solar panel systems for the Oklahoma five locations ($), and the percentage increase in price rates to breakeven with the solar systems.

Location	**System**	**Solar systems breakeven prices for household using Alternative I: Traditional Meter ($)**	**Solar systems breakeven prices for household using Alternative I: Traditional Meter without Net Metering ($)**	**Solar systems breakeven prices for household using Alternative II: Smart Meter ($)**	***Solar systems breakeven prices for household using Alternative II: Smart Meter without Net Metering ($)***	**Percentage increase in price rates to breakeven with the solar systems for household using Alternative I: Traditional Meter**	**Percentage increase in price rates to breakeven with the solar systems for household using Alternative I: Traditional Meter without Net Metering**	**Percentage increase in price rates to breakeven with the solar systems for household using Alternative II: Smart Meter**	**Percentage increase in price rates to breakeven with the solar systems for household using Alternative II: Smart Meter without Net Metering**
Boise City	12 kW PV Panel	12,243†	5,911	11,829	*7,214*	531%‡	583%	550%	589%
	4 kW PV Panel	9,294†	4,865	9,582	*6,236*	285%	322%	290%	318%
Hollis	12 kW PV Panel	17,758	8,123	16,677	*9,784*	366%	420%	390%	431%
	4 kW PV Panel	8,431	6,098	9,647	*7,691*	233%	246%	234%	246%
Shawnee	12 kW PV Panel	16,401	7,290	15,435	*8,657*	393%	448%	418%	461%
	4 kW PV Panel	7,684	5,522	9,069	*6,993*	247%	260%	247%	260%
Miami	12 kW PV Panel	15,187	6,710	14,230	*8,379*	419%	473%	446%	486%
	4 kW PV Panel	7,328	5,097	7,813	*6,286*	258%	272%	265%	275%
Idabel	12 kW PV Panel	16,464	7,335	15,492	*8,731*	391%	446%	415%	458%
	4 kW PV Panel	7,421	5,482	8,731	*6,912*	247%	259%	248%	260%

† These breakeven prices can be compared to the estimated installation costs of $65,000 for the 12 kW system and $32,000 for the 4 kW system.

‡ The electricity rates could increase by 531%, for example from $0.0811 and $0.0918, $0.0795, $0.0359, $0.0795, and $0.0811 for Blocks A_1, A_2, B_1, B_2, C, and D respectively to $0.4308, $0.4876, $0.4221, $0.1906, $0.4221, and $0.4308 for Blocks A_1, A_2, B_1, B_2, C, and D respectively, at which level the cost of installing the 12 kW system at Boise City would breakeven with the grid.

Conclusion

This study was conducted to determine the annual cost of electricity for representative households at five locations in the case study region and to determine the economics of grid-tied solar panels. The average annual cost for grid-only electricity is estimated to be $1,075 for the traditional meter and $1,024 for the smart meter among the five households. Given prices and use assumptions, neither of the solar panels is economically competitive at any of the five locations, for either rate structure or metering system.

On average, for the $65,000 12 kW system to be economically competitive with grid provided electricity, grid prices would have to increase by 420% and 444% for the traditional meter and smart meter rates, respectively. Grid price increases of 254% and 257% for the traditional meter and smart meter rates, respectively, would be required for the $32,000 4 kW system to be competitive with grid provided electricity. In the absence of substantial rate increases, rather sizeable reductions in the cost of the solar systems would be required for solar systems to be competitive. Averaged across the five locations, the installed cost of the 12 kW system on a traditional meter rate would have to decrease from $65,000 to $15, 611 ($7,074 without net metering) for it to be economically competitive. The installed cost of the 4 kW system would have to decrease from $32,000 to $8,032 ($5,413 without net metering).

The study also enables a determination of the extent to which location matters. A major finding is that the economic consequences of grid-tied household solar systems differ substantially among locations that are relatively close in proximity. Annual use estimates for households with similar characteristics may differ substantially. For example, the representative Hollis household is expected to consume 55% more electricity per year than the Boise City household even though they are separated by only 350 km.

Location also matters in production. Total annual production from an identical 4 kW system is estimated to be 18% greater at Boise City than at Miami. The proportion of electricity produced by the 4 kW system that is produced at a time when it can be used by the household ranges from 78% at Idabel to 52% at Boise City. A grid-tied 4 kW system at Boise City would provide 3,616 kWh annually to the grid, but an identical system at Idabel would provide only 1,412 kWh annually to the grid. The 4 kW system provides for 42% of total annual household use at Boise City but only 36% of total annual household use at Miami.

Economic consequences also differ among locations. Annual cost for electricity for the representative households, given the same price structure, is estimated to be 29% greater at Shawnee than at Boise City if on a traditional meter and 26% greater at Shawnee if using the smart meter rates. Based on the price structure approved for use in the region switching from traditional to smart meters is expected to reduce aggregate annual consumption by less than 2%.

The utility providing grid electricity to the households with operating 4 kW solar systems without net metering could expect to receive from $284 to $355 per household annual less gross revenue. The consequences of net metering on gross revenue collected by the utility providing electricity to the grid are also location specific. The gross revenue loss to the utility of providing net metering ranges from $89/household/year for smart meter households at Miami to $258/household/year for traditional meter households at Boise City (290% more).

Based on prevailing prices, and consumption and production estimates, the 4 kW system would increase annual household cost by $1,300 to $1,550 depending on location and grid pricing system. If external consequences of electricity generation and distribution are ignored, given current rate structures and the cost of installing solar systems, the grid-tied solar panel systems are not economically competitive for households in the region studied. Further research would be required to determine differences in environmental consequences between household solar and grid provided electricity and the economics of these differences.

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Appendices

Appendix A. Oklahoma Gas and Electric Company Electricity Pricing Rates

Time and quantity of electricity used	Block	Price		Fuel Cost Adjustment†
		($ per month)	(¢ per kWh)	(¢ per kWh)
	Alternative I: Traditional Meter			
Base Charge		13		
June through September	**A**			2.38
0 ≤ kWh per month ≤ 1,400	A_1		5.73	
kWh per month > 1,400	A_2		6.80	
November through April	**B**			2.22
0 ≤ kWh per month ≤ 600	B_1		5.73	
kWh per month > 600	B_2		1.37	
May	**C**		5.73	2.22
October	**D**		5.73	2.38
	Alternative II: Smart Meter			
Base Charge		13		
June through October				
2 p.m. to 7:59 p.m. weekdays	**E**		14	4.26
8:00 p.m. through 1:59 p.m., and weekends	**F**		2.7	2.11
November through May	**G**			2.22
First 600 kWh per month	G_1		5.73	
Additional kWh	G_2		1.37	

Source: Oklahoma Corporation Commission

† Fuel adjustment charge is a surcharge added to compensate for increases, usually unanticipated, in the price of energy (coal and natural gas).

Appendix B. Electricity Consumption and Production for each Block in Boise City

Month	**Block**	**Total Use (a)**	**4 kW**					**12 kW**				
			Production (b)	**Used from Grid (c)**	**Power Output produced Used (d)**	**Sent to the Grid compensated (e)**	**Excess Sent to Grid Not Compensated (f)**	**Production**	**Used from Grid**	**Power Output produced Used**	**Sent to the Grid compensated**	**Excess Sent to Grid Not Compensated**
		kWh/block/year	**kWh/block/year**					**kWh/block/year**				
						Traditional Meter						
June	A	888	867	427	460	407	0	2847	323	565	323	1960
July	A	1080	866	532	548	317	0	2864	393	687	393	1784
August	A	983	776	511	471	305	0	2575	403	580	403	1592
September	A	799	655	436	362	293	0	2175	361	438	361	1376
November	B	671	386	461	210	176	0	1281	431	240	431	610
December	B	768	331	555	213	119	0	1100	512	256	512	333
January	B	781	377	551	230	147	0	1253	506	275	506	472
February	B	682	432	454	228	204	0	1435	414	267	414	753
March	B	678	634	412	266	368	0	2104	376	302	376	1426
April	B	606	737	320	286	320	131	2425	274	332	274	1819
May	C	604	872	290	314	290	268	2851	246	358	246	2246
October	D	667	525	414	253	272	0	1744	360	307	360	1076
Total		9206	7458	5364	3842	3217	399	24655	4599	4607	4599	15449
						Smart Meter						
June	E	194	293	30	163	30	99	963	0	194	0	769
	F	658	574	389	269	305	0	1884	347	312	347	1226
July	E	247	299	48	199	48	52	989	0	247	0	742
	F	785	567	462	324	243	0	1875	410	375	410	1090
August	E	222	271	49	173	49	49	898	6	216	6	676
	F	719	505	445	274	232	0	1677	409	309	409	958
September	E	177	223	48	129	48	46	740	21	156	21	563
	F	588	432	373	214	218	0	1435	349	239	349	847
October	E	129	172	49	80	49	43	571	28	100	28	442
	F	521	353	358	163	190	0	1173	333	188	333	652
November	G	671	386	461	210	176	0	1281	431	240	431	610
December	G	768	331	555	213	119	0	1100	512	256	512	333
January	G	781	377	551	230	147	0	1253	506	275	506	472
February	G	682	432	454	228	204	0	1435	414	267	414	753
March	G	678	634	412	266	368	0	2104	376	302	376	1426
April	G	606	737	320	286	320	131	2425	274	332	274	1819
May	G	604	872	290	314	290	268	2851	246	358	246	2246
Total		9029	7458	5295	3735	3035	687	24655	4663	4366	4663	15626

a = c + d
b = d + e + f
With net metering, the kWh purchased from the grid = c – e, where (c – e) > 0
Without net metering, the kWh purchased from the grid = c

Appendix C. Electricity Consumption and Production for each Block in Hollis

Month	**Block**	**Total Use (a)**	**4 kW**					**12 kW**				
			Production (b)	**Used from Grid (c)**	**Power Output produced Used (d)**	**Sent to the Grid compensated (e)**	**Excess Sent to Grid Not Compensated (f)**	**Production**	**Used from Grid**	**Power Output produced Used**	**Sent to the Grid compensated**	**Excess Sent to Grid Not Compensated**
		kWh/block/year			**kWh/block/year**					**kWh/block/year**		
					Traditional Meter							
June	A	1629	803	909	720	83	0	2658	621	1008	621	1029
July	A	1568	832	871	697	135	0	2760	625	943	625	1192
August	A	1525	755	884	641	114	0	2507	655	870	655	982
September	A	1221	625	736	485	140	0	2075	587	634	587	854
November	B	985	378	686	299	80	0	1256	608	377	608	271
December	B	1110	332	807	302	30	0	1104	702	408	697	0
January	B	1192	375	862	331	44	0	1245	758	434	758	53
February	B	1042	423	711	331	92	0	1404	613	429	613	362
March	B	1040	598	649	390	208	0	1986	566	474	566	946
April	B	925	711	525	400	311	0	2344	440	485	440	1418
May	C	1052	792	565	487	304	0	2606	432	620	432	1554
October	D	1000	498	655	346	153	0	1655	558	442	558	654
Total		14289	7122	8860	5428	1693	0	23598	7165	7124	7160	9315
					Smart Meter							
June	E	368	271	130	238	33	0	897	21	347	21	528
	F	1189	533	721	467	66	0	1761	618	571	618	573
July	E	347	285	109	238	47	0	947	16	331	16	600
	F	1157	546	714	442	104	0	1812	628	529	628	655
August	E	346	255	128	218	37	0	846	32	314	32	501
	F	1113	500	705	408	92	0	1660	633	481	633	547
September	E	265	201	107	158	43	0	667	48	217	48	403
	F	908	424	596	312	111	0	1407	534	374	534	499
October	E	195	155	94	101	54	0	515	64	131	64	320
	F	778	343	546	232	112	0	1140	496	282	496	362
November	G	985	378	686	299	80	0	1256	608	377	608	271
December	G	1108	332	816	292	41	0	1104	719	389	715	0
January	G	1192	375	862	331	44	0	1245	758	434	758	53
February	G	1042	423	711	331	92	0	1404	613	429	613	362
March	G	1040	598	649	390	208	0	1986	566	474	566	946
April	G	925	711	525	400	311	0	2344	440	485	440	1418
May	G	1052	792	565	487	304	0	2606	432	620	432	1554
Total		14009	7122	8665	5344	1778	0	23598	7226	6784	7222	9592

$a = c + d$
$b = d + e + f$
With net metering, the kWh purchased from the grid = $c – e$, where $(c – e) > 0$
Without net metering, the kWh purchased from the grid = c

Appendix D. Electricity Consumption and Production for each Block in Shawnee

Month	Block	Total Use (a)	4 kW					12 kW				
			Production (b)	Used from Grid (c)	Power Output produced Used (d)	Sent to the Grid compensated (e)	Excess Sent to Grid Not Compensated (f)	Production	Used from Grid	Power Output produced Used	Sent to the Grid compensated	Excess Sent to Grid Not Compensated
		kWh/block/year	kWh/block/year					kWh/block/year				
					Traditional Meter							
June	A	1150	763	603	548	215	0	2526	447	704	447	1376
July	A	1444	810	794	650	160	0	2687	572	872	572	1243
August	A	1439	733	827	612	121	0	2434	625	814	625	995
September	A	1152	595	695	456	139	0	1977	567	585	567	826
November	B	991	342	701	290	52	0	1135	610	381	610	144
December	B	1119	291	841	278	13	0	968	733	386	582	0
January	B	1215	331	901	314	17	0	1100	779	436	663	0
February	B	1041	375	725	316	59	0	1246	624	417	624	205
March	B	1039	523	662	377	146	0	1738	567	472	567	699
April	B	915	642	530	385	257	0	2123	438	477	438	1208
May	C	949	724	517	432	292	0	2389	404	545	404	1439
October	D	1049	467	688	360	106	0	1550	579	469	579	501
Total		13502	6596	8483	5018	1577	0	21870	6944	6558	6677	8636
					Smart Meter							
June	E	239	248	64	175	64	8	822	9	230	9	583
	F	871	515	521	349	166	0	1704	450	421	450	833
July	E	313	266	99	214	52	0	883	18	295	18	571
	F	1076	544	657	419	124	0	1803	573	503	573	727
August	E	317	238	117	200	38	0	789	35	282	35	472
	F	1064	495	666	398	97	0	1645	596	468	596	580
September	E	239	182	99	140	42	0	604	51	187	51	366
	F	873	413	570	303	110	0	1373	513	360	513	500
October	E	201	135	102	99	36	0	447	72	129	72	246
	F	821	332	567	254	78	0	1102	510	311	510	282
November	G	991	342	701	290	52	0	1135	610	381	610	144
December	G	1119	291	841	278	13	0	968	733	386	582	0
January	G	1215	331	901	314	17	0	1100	779	436	663	0
February	G	1041	375	725	316	59	0	1246	624	417	624	205
March	G	1039	523	662	377	146	0	1738	567	472	567	699
April	G	915	642	530	385	257	0	2123	438	477	438	1208
May	G	949	724	517	432	292	0	2389	404	545	404	1439
Total		13281	6596	8337	4944	1644	8	21870	6981	6300	6714	8856

a = c + d

b = d + e + f

With net metering, the kWh purchased from the grid = c – e, where (c – e) > 0

Without net metering, the kWh purchased from the grid = c

Appendix E. Electricity Consumption and Production for each Block in Miami

Month	Block	Total Use (a)	4 kW					12 kW				
			Production (b)	Used from Grid (c)	Power Output produced Used (d)	Sent to the Grid compensated (e)	Excess Sent to Grid Not Compensated (f)	Production	Used from Grid	Power Output produced Used	Sent to the Grid compensated	Excess Sent to Grid Not Compensated
		kWh/block/year	kWh/block/year					kWh/block/year				
						Traditional Meter						
June	A	1121	749	581	540	210	0	2481	424	696	424	1361
July	A	1334	789	721	613	176	0	2616	525	809	525	1283
August	A	1112	721	622	490	231	0	2395	483	629	483	1283
September	A	990	579	592	398	182	0	1925	494	496	494	935
November	B	1004	311	722	282	29	0	1034	631	372	631	30
December	B	1132	259	874	258	1	0	860	755	376	483	0
January	B	1202	292	913	290	3	0	971	780	423	549	0
February	B	1046	340	743	303	37	0	1130	637	409	637	84
March	B	1051	495	678	373	122	0	1644	574	477	574	593
April	B	921	609	539	383	226	0	2013	438	484	438	1092
May	C	972	711	531	442	269	0	2349	409	563	409	1377
October	D	962	445	643	318	127	0	1479	544	418	544	935
Total		12847	6302	8158	4689	1613	0	20898	6694	6153	6190	8972
						Smart Meter						
June	E	238	233	69	169	64	0	774	12	227	12	535
	F	840	516	491	350	167	0	1708	424	416	424	868
July	E	284	251	89	195	56	0	833	18	265	18	550
	F	1002	538	601	400	137	0	1783	521	481	521	781
August	E	233	225	77	156	69	0	748	26	207	26	515
	F	840	496	529	312	185	0	1647	472	368	472	807
September	E	194	169	81	112	57	0	562	45	148	45	368
	F	768	410	496	271	139	0	1363	447	320	447	595
October	E	174	120	92	81	39	0	400	69	105	69	226
	F	768	325	537	231	94	0	1080	464	289	464	326
November	G	1004	311	722	282	29	0	1034	631	372	631	30
December	G	1132	259	874	258	1	0	860	755	376	483	0
January	G	1202	292	913	290	3	0	971	780	423	549	0
February	G	1046	340	743	303	37	0	1130	637	409	637	84
March	G	1051	495	678	373	122	0	1644	574	477	574	593
April	G	921	609	539	383	226	0	2013	438	484	438	1092
May	G	972	711	531	442	269	0	2349	409	563	409	1377
Total		12669	6302	8061	4608	1694	0	20898	6723	5931	6220	8747

a = c + d

b = d + e + f

With net metering, the kWh purchased from the grid = c – e, where (c – e) > 0

Without net metering, the kWh purchased from the grid = c

Appendix F. Electricity Consumption and Production for each Block in Idabel

Month	Block	Total Use (a)	4 kW					12 kW				
			Production (b)	**Used from Grid (c)**	**Power Output produced Used (d)**	**Sent to the Grid compensated (e)**	**Excess Sent to Grid Not Compensated (f)**	**Production**	**Used from Grid**	**Power Output produced Used**	**Sent to the Grid compensated**	**Excess Sent to Grid Not Compensated**
		kWh/block/year	**kWh/block/year**					**kWh/block/year**				
						Traditional Meter						
June	A	1284	739	702	582	157	0	2450	504	779	504	1166
July	A	1513	767	844	670	97	0	2545	604	909	604	1032
August	A	1314	720	760	554	166	0	2391	585	729	585	1077
September	A	1239	584	760	479	105	0	1938	610	628	610	700
November	B	970	328	687	282	46	0	1089	599	371	599	119
December	B	1107	284	834	274	11	0	945	723	385	560	0
January	B	1189	310	887	302	8	0	1030	755	434	596	0
February	B	1029	344	723	306	38	0	1141	617	412	617	112
March	B	1031	502	661	370	132	0	1666	559	472	559	635
April	B	918	629	536	382	247	0	2080	441	477	441	1162
May	C	936	701	520	416	285	0	2316	406	530	406	1380
October	D	1008	467	662	346	120	0	1550	557	451	557	541
Total		13538	6373	8577	4961	1412	0	21140	6961	6577	6639	7924
						Smart Meter						
June	E	273	228	92	181	46	0	756	22	251	22	483
	F	962	511	574	388	123	0	1693	495	467	495	732
July	E	328	240	120	208	33	0	799	29	299	29	471
	F	1127	526	676	451	75	0	1746	586	542	586	619
August	E	286	220	109	177	42	0	730	36	250	36	444
	F	977	500	613	364	137	0	1661	548	428	548	684
September	E	264	169	123	140	28	0	561	68	196	68	297
	F	928	415	601	327	88	0	1378	539	389	539	450
October	E	185	129	96	89	40	0	428	71	114	71	243
	F	801	338	551	250	87	0	1122	490	311	490	321
November	G	970	328	687	282	46	0	1089	599	371	599	119
December	G	1107	284	834	274	11	0	945	723	385	560	0
January	G	1189	310	887	302	8	0	1030	755	434	596	0
February	G	1029	344	723	306	38	0	1141	617	412	617	112
March	G	1031	502	661	370	132	0	1666	559	472	559	635
April	G	918	629	536	382	247	0	2080	441	477	441	1162
May	G	936	701	520	416	285	0	2316	406	530	406	1380
Total		13312	6373	8404	4907	1466	0	21140	6985	6327	6663	8150

a = c + d
b = d + e + f
With net metering, the kWh purchased from the grid = c – e, where (c – e) > 0
Without net metering, the kWh purchased from the grid = c

CHAPTER III

CONSEQUENCES OF A CARBON TAX ON HOUSEHOLD ELECTRICITY USE AND COST, CARBON EMISSIONS, AND ECONOMICS OF HOUSEHOLD SOLAR AND WIND[*]

Abstract

The study was conducted to determine the consequences of a carbon tax, equal to an estimated social cost of carbon of $37.2/Mg, on household electricity cost, and to determine if a carbon tax would be sufficient to incentivize households to install either a grid-tied solar or wind system. U.S. Department of Energy hourly residential profiles for five locations, 20 years of hourly weather data, prevailing electricity pricing rate schedules, and purchase prices and solar panel and wind turbine power output response functions, were used to address the objectives. Two commercially available household solar panels (4 kW, 12 kW), two wind turbines (6 kW, 12 kW), and two price rate structures (traditional meter, smart meter) were considered. Averaged across the five households, the carbon tax is expected to reduce annual consumption by 4.4% (552 kWh/year) for traditional meter households and by 4.9% (611 kWh/year) for households charged smart meter rates. The carbon tax increases electricity cost by 19% ($202/year). For a household cost of $202/year the carbon tax is expected to reduce social costs by $11. Annual carbon tax collections of $237/household are expected. Adding the carbon

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[*] This paper has been formatted to fit requirements for a targeted journal.

tax was found to be insufficient to incentivize households to install either a solar panel or wind turbine system. Installation of a 4 kW solar system would increase the annual cost by $1,546 (247%) and decrease CO_2 emissions by 38% (2,526 kg) valued at $94/ household. The consequence of a carbon tax would depend largely on how the proceeds of the tax are used.

Key words: Carbon tax, economics, social cost of CO_2, smart meter, solar panel, wind turbine

Introduction

Global atmospheric concentration of CO_2 increased from 312 ppm in 1950 to 401 ppm in 2015 (1). A number of environmental factors, including temperature, sea level, rainfall patterns, storm intensity, plant productivity, ocean chemistry, and marine life are influenced by the level of atmospheric carbon (2). On balance, the increase in atmospheric concentration of CO_2 imposes a cost on society. Estimates of the level of the cost vary and depend critically on the assumed discount rate. Nordhaus estimated the social cost of CO_2 (SC-CO_2) emissions to be $34 per Mg in 2010 dollars (3). For a 3% discount rate, the 2016 SC-CO_2 was estimated to be $37.2 per Mg by the Interagency Working Group on the Social Cost of Carbon (4).

Electricity generation by fossil fuel combustion is a major source of CO_2 emissions (5). The conventional textbook solution for improving the efficiency of a production activity that produces external costs is to internalize the externality (6-13). Internalization of the SC-CO_2 resulting from electricity generation by imposing a specific carbon tax per kWh would result in an increase in the price of electricity sold to households. Implementation of a carbon tax on electricity purchased from the grid would have a number of consequences. A number of studies have evaluated the aggregate consequences and welfare implications of imposition of a carbon tax (6-13).

The purpose of this paper is to use hourly weather data collected at specific Oklahoma Mesonet sites since 1994 to estimate consequences of a carbon tax on electricity purchased by households from the grid and to determine if a carbon tax would incentivize households to install either a grid-tied solar or grid-tied wind turbine microgeneration system. The USA state of Oklahoma includes multiple climate zones and has a wide range of wind and solar resources (14-16). The 20 years of site-specific hourly weather data enable estimates of the expected productivity of household microgeneration wind and solar systems and provide an opportunity for case studies to inform citizens and policy makers of the consequences of a carbon tax on household electricity use and on the potential value of subsidizing household wind and solar systems.

The objective is to address the following research questions:

(a) What level of carbon tax would be required to account for the SC-CO_2 emissions?

(b) What are the expected consequences of a carbon tax on household electricity use?

(c) What would a carbon tax on electricity cost a representative household?

(d) What are the expected consequences of an electricity carbon tax on CO_2 emissions?

(e) Would it matter if the household was on a smart rather than a traditional accumulation meter?

(f) How would the consequences differ among different geographical locations?

(i) Would a carbon tax equivalent to the SC-CO_2 be sufficient to incentivize households to install a household microgeneration grid-tied solar panel system?

(j) Would a carbon tax equivalent to the SC-CO_2 be sufficient to incentivize households to install a household microgeneration grid-tied wind turbine system?

(k) At what level of carbon tax would the cost to the household of a grid-tied microgeneration solar system be equal to that of a grid-only system?

(l) At what level of carbon tax would the cost to the household of a grid-tied household wind turbine system be equal to that of a grid-only system?

Household electricity use, solar and wind resources, and the costs and benefits of their use are time and location specific. Twenty years of hourly solar radiation, temperature, and wind speed data, and hourly electricity use data for representative households, were obtained for each of five diverse Oklahoma locations: Boise City in the Northwest (36° 41' 33" N 102° 29' 49" W), Miami in the Northeast (36° 53' 17" N 94° 50' 39" W), Shawnee in the center (35° 21' 53" N 96° 56' 53" W), Hollis in the Southwest (34° 41' 7" N 99° 49' 59" W), and Idabel in the Southeast (33° 49' 48" N 94° 52' 49" W). These data, U.S. Department of Energy hourly residential profiles, prevailing electricity pricing rate schedules, and purchase prices and power output response functions for each solar panel and wind turbine system are used to address the objectives for each of the five locations, two commercially available household solar panels (4 kW, 12 kW), two commercially available wind turbines (6 kW, 12 kW), and two price rate structures (traditional meter, smart meter).

Results

Level of carbon tax required to compensate for the SC-CO_2 emissions

The estimate of CO_2 emissions is based on the 2015-2016 portfolio of grid electricity generating sources in the case study region (*SI Appendix*, Table S1) (17-28).

The quantity of CO_2 emitted when natural gas and coal are used to produce electricity for the grid is estimated to be 0.55 kg/kWh and 0.96 kg/kWh, respectively (29). Based on the portfolio of fuels used to generate grid electricity and consumed by households in the region (28% coal; 46% natural gas; 22% commercial wind; 4% hydro), a carbon tax of \$0.0195 per kWh would be required to account for the estimated SC-CO_2 of \$37.2 per metric ton of emitted CO_2. For the entire USA the portfolio of fuels is; 33% coal, 33% natural gas, 20% nuclear, 7% renewables, 6% hydro, 1% petroleum (30), and the equivalent carbon tax would be \$0.0185 per kWh.

Expected consequences of a carbon tax on household electricity use

Since utility companies are regulated monopolies (31) assumed to be producing over a range with a nearly perfectly elastic marginal cost, governing price regulators could be expected to facilitate full incidence of a carbon tax to the household. Thus, the level of the tax is assumed to be added to prevailing prices. Reduction in household electricity consumption in response to the increase in price resulting from imposition of a carbon tax, is estimated based on the Bernstein and Griffin (32) electricity demand price elasticity estimate for Oklahoma households of -0.174. Other studies have produced similar estimates of household electricity price elasticities (33-37). By this measure, households are expected to respond to a 100% price increase in a block by decreasing consumption 17.4% within the block. For the analysis, use reductions in response to price increases greater than 115% was assumed to be 20%. Studies of household behavior find little to no evidence of use reductions in excess of 20% in response to price increases when electricity is available on a continuous basis from the grid (38-40).

Estimates of the annual quantity of electricity consumed for both traditional and smart meter price schedules with and without a carbon tax for each of the five representative households are reported in Table 1. Smart meter rates (*SI Appendix,* Table S2) (41) in the case study region are structured to incentivize households to shift consumption from on-peak to off-peak load times. For example, the smart meter rate schedule imposes 125% higher prices than the traditional meter rate schedule from 2 pm through 7 pm during the air conditioning season (June to October). Smart meter rates are set lower than those in effect for traditional meters during traditionally low use periods. Averaged across the five households, the carbon tax is expected to reduce annual consumption by 4.4% (552 kWh/year) for traditional meter households and by 4.9% (611 kWh/year) for households charged smart meter rates (Table 1).

Expected cost to household of a carbon tax on electricity

Averaged across the five households, the carbon tax is expected to increase annual electricity cost by 18.9% ($203/year) for traditional meter households and by 19.7% ($202/year) for households billed via smart meters (Table 1). Annual carbon tax collected averaged across the five households for both metering systems is expected to be $237. However, the estimated annual household tax ranges from $168 for the smart-metered Boise City household to $267 for the traditional-metered Hollis household.

Expected consequences of a household electricity carbon tax on CO_2 emissions

Estimated annual reduction in CO_2 emissions as a consequence of the carbon tax range from 205 kg for traditional-metered Boise City household to 362 kg for the smart-metered Hollis household (Table 1). Averaged across the five households, the carbon tax is expected to reduce annual CO_2 emissions by 290 kg (4.4%) for the traditional meter households and by 5.0% (325 kg/year) for households charged smart meter rates. For a SC-CO_2 of $37.2 per Mg, the social value of these savings range from $8 to $13 per year.

Expected differences between traditional and smart meters

Averaged across the five locations, when the carbon tax is imposed on traditional meter households they are expected to respond by reducing annual use by 552 kWh. However, the tax results in an expected 611 kWh reduction in annual use for the households billed via the smart meter rates. Consequently, the carbon tax is expected to increase annual household expenditure for electricity by $202 for the smart meter households and by $203 for the traditional meter households (Table 1).

Differences among geographical locations

The USA Department of Energy estimates that a representative household at Hollis will, on average, consume 55% more electricity per year than a similar sized household at Boise City even though they are less than 327 km apart (42). Based on the rate schedule (*SI Appendix*, Table S2) the annual cost of electricity prior to implementation of the carbon tax for the representative traditional-metered Hollis household is estimated to be 37% greater (33% greater for smart meter) than for the Boise City household. Implementation of the $0.0195/kWh tax would cost the traditional-metered Boise City household $148/year and the Hollis household $228/year ($145 and $228/year if using smart meter rates). Estimated annual carbon tax collections are $172 and $267 for the Boise City and Hollis households, respectively. Since total annual consumption for a given household is similar for traditional and smart meter rates, annual tax collection is also expected to be similar.

Carbon tax and household microgeneration grid-tied solar panel system

Table 2 includes estimates of the annual household expenditure for electricity after installation of a 4 kW solar panel system. It includes the cost of electricity purchased from the grid to provide for household needs during times when the solar panel is not producing and the annual ownership and operating cost of the solar panel. The procedure used to estimate solar panel costs is described in the *SI Appendix* (Conceptual Framework). Values used to estimate annual cost of owning and operating the solar panel are reported in the *SI Appendix*, Table S3. Estimates are provided for each of the five case study locations. (Findings for a 12 kW solar panel system are reported in *SI Appendix*, Table S4). Household electricity cost is location specific. It depends on the quantity of electricity consumed that differs among locations and also on the power output produced from the solar panel that depends in part on solar radiation and temperature.

Averaged across the five locations and two metering systems, installation of a 4 kW solar system would increase the annual cost of household electricity by 247% from \$1,050 to \$2,596. Annual CO_2 emissions would decrease by 38% from 6,602 kg to 4,076 kg (Tables 1 and 2). Based on a SC-CO_2 of \$37.2 per metric ton the social value of these savings would average \$94 per household. In other words, for a cost of \$1,546 the household could reduce annual CO_2 emissions by 2,526 kg that are valued at \$94. Adding a carbon tax would increase annual household expenditure for electricity by \$119 and reduce emissions by an additional 230 kg.

Carbon tax and household microgeneration grid-tied wind turbine system

Table 3 includes estimates of the annual household expenditure for electricity after installation of a 6 kW grid-tied wind turbine system. It includes the cost of electricity purchased from the grid to provide for household needs during times when the wind turbine is not producing sufficient electricity to fulfill household use, and the annual ownership and operating cost of the wind turbine. The procedure used to estimate wind turbine power output and costs is described in the *SI Appendix* (Conceptual Framework). Values used to estimate annual cost of owning and operating the wind turbine are reported in the *SI Appendix* (Table S3). Estimates are provided for each of the five case study locations. (Findings for a 10 kW wind turbine system are reported in *SI Appendix*, Table S5).

Averaged across the five locations and two metering systems, installation of a 6 kW wind turbine system would increase the annual cost of household electricity by 550% from \$1,050 to \$5,771. Annual CO_2 emissions would decrease by 38% from 6,602 kg to 4,124 kg. Based on a SC-CO_2 of \$37.2 per metric ton the social value of these savings would average \$92 per household. In other words, for a cost of \$4,721 the household could reduce annual CO_2 emissions by 2,478 kg that are valued at \$94. Adding a carbon tax would further increase annual household expenditure for electricity by \$106 and reduce emissions by an additional 283 kg.

Level of carbon tax required to incentivize household to install grid-tied solar system

Table 4 shows the level of carbon tax (\$/kWh) at which the household cost of grid-only electricity would be equal to that of a grid-tied solar or wind system. The carbon tax level for a household grid-tied 4 kW solar panel ranges from \$0.33/kWh in Hollis to \$0.50/kWh in Boise City. For the grid-tied 12 kW solar panel the carbon tax ranges from \$0.58/kWh in Hollis to \$0.95/kWh in Boise City. In another words, if a smart-metered Hollis household faced a carbon tax of \$0.33/kWh, expected total annual expenditure for electricity from a grid-tied 4 kW solar panel system would be equal to the cost of grid-only electricity. Averaged across the five locations and both metering systems, the breakeven carbon tax level is \$0.39/kWh for the 4 kW system and \$0.70/kWh for the 12 kW solar panel grid-tied system.

Level of carbon tax required to incentivize household to install grid-tied wind turbine system

The carbon tax level at which the household cost of grid-only electricity would be equal to that of a grid-tied 6 kW solar panel ranges from \$0.76/kWh in Boise City to \$2.36/kWh in Idabel. For the grid-tied 10 kW wind turbine the breakeven tax ranges from \$0.70/kWh in Hollis to \$1.99/kWh in Idabel. Averaged across the five locations and both metering systems, the breakeven carbon tax level is \$1.22/kWh for the 6 kW system and \$1.09/kWh for the 10 kW wind turbine grid-tied system.

Discussion

Averaged across the five households and two metering methods the average case study household is estimated to use 12,571 kWh of electricity annually for a cost of \$1,050 per year. These values are consistent with USA Energy Information Agency estimates that in 2015 the average Oklahoma household used 13,119 kWh and was charged \$1,330 (43). Based on the estimates presented, averaged across the five households and two metering methods approximately 6,602 kg of CO_2 are emitted annually for the production of electricity for the case study households. If the five case study households are representative of the 126 million (44) USA households, electricity produced for their use would be responsible for the emission of 832 million metric tons of CO_2. The USA Energy Information Agency estimates that an annual total of 737 million metric tons of CO_2 are emitted to produce electricity for USA households (29, 30, 45). As noted the national average portfolio of fuels emits 0.5 kg/kWh, slightly less than the portfolio in the case study region 0.53 kg/kWh. Hence, electricity use and emissions to produce that electricity for the case study households is assumed to be representative of USA households.

For a carbon tax of $0.0195/kWh based on an estimated SC-CO_2 of $37.20/Mg across the five case study households and two metering systems, the average annual tax would be approximately $234/household, more than $29 billion annually if charged across all USA households. The average tax collected across the five households and two metering systems would be $234. However, since residents are expected to adjust electricity use in response to the tax, the annual cost of the tax averaged across the five households and two price rates (traditional and smart meters) is estimated to be $202. However, if annual household expenditures for electricity increased by $202, spending on other goods and services would be reduced. Additional research would be required to determine consequences of the tax on purchases of other goods and services.

The estimated reduction in CO_2 emissions is 290 kg/year for the five traditional meter households and 325 kg/year for the five smart meter households. The carbon tax that is expected to cost the average case study household $202/year is expected to reduce social costs by approximately $11/year. In the short run, implementation of the tax would not result in major reductions in CO_2 emissions.

None of the four household microgeneration systems evaluated (4 kW and 12 kW solar panels; 6 kW and 12 kW wind turbines) are economically competitive producers of electricity for households tied to the grid. The least inefficient system, a 4 kW solar panel, would add an annual cost to the average household relative to grid-only of $1,463. Installing a 4 kW solar panel system, on average, would decrease CO_2 emissions by 38% (2,449 kg/year/household). In other words, the cost to reduce one kg of CO_2 emissions by installing a 4 kW solar panel would be $0.60/kg. Averaged across the five households, a carbon tax of $0.39/kWh would be required for the cost of a grid-tied 4 kW solar panel to breakeven with grid-only electricity. This would be equivalent to a SC-CO_2 of $744 per Mg, 20 times more than the 2016 SC-CO_2 estimate of $37.2 per Mg by the Interagency Working Group on the Social Cost of Carbon (4). The household microgeneration systems evaluated in this study are not economically competitive producers of electricity for households tied to the grid and would not be economical means of reducing CO_2 emissions.

The ultimate consequence of a carbon tax will depend to a great extent on how the proceeds of the tax are used. A number of alternatives for uses of carbon tax revenue have been proposed (46-51). Examples include funding additional research and development of alternative low and zero carbon emission energy systems, and funding of subsidies for renewable energy technologies. Based on the findings of this study, use of the tax to incentivize household microgeneration wind and solar systems would not be warranted.

Methods

The conceptual framework for the analysis is presented in the *SI Appendix* (Conceptual Framework).

Hourly weather data

Hourly weather data were obtained from the Oklahoma Mesonet. The Mesonet consists of 120 automated weather stations. Many of these stations have been collecting precise weather data since 1994. Data required for equation (1) and (2) (*SI Appendix*, Conceptual Framework) includes wind speed (m/s), air pressure, air temperature (F^o), relative humidity (%), and solar radiation (watt/m^2). For the present study, average values of power output for each of 24 hours for each of 12 months were obtained, as the power output from wind turbines and solar panels is a function of weather variables that differ across time and space. For example, the power output estimate for hour one for January is the mean of 620 observed values; 31 days of hour one observations for each of 20 years. These data may be used to estimate the expected power output from wind turbine systems and solar panels at a specific site for each hour of the day for each month.

Residential hourly electricity data

Hourly residential electricity profiles for Boise City, Hollis, Shawnee, Miami, and Idabel, Oklahoma households were obtained from the U.S. Department of Energy (42). These simulated load profiles are designed to be representative of average electricity consumption for households in the region. The characteristics of the household to be modeled are reported in the *SI Appendix* (Table S6). These load profiles produced point estimates of electricity use for a representative average household for each hour for each month for each location. These point estimates are assumed to be appropriate for households subject to traditional meter rates.

Traditional and smart meter rates

Smart meter rates differ depending on month and time of day. Rates are greater for the months of June to October for the on-peak period (2 p.m. to 8 p.m.). Households are expected to respond to higher prices by changing the time and quantity of electricity use. The electricity demand price elasticity estimate of -0.174 produced by Bernstein and Griffin (32) is used to adjust quantity demanded to price changes.

Smart meter prices are 125% greater for the on-peak period than traditional meter prices and 39% lower during the off-peak period. Based on the elasticity estimate of -0.174, the decrease in use during the on-peak period will be greater than the increase in use during the off-peak period.

Wind turbines

The modeled wind turbine systems are 10 kW and 6 kW, with 7 m and 6.2 m rotor diameter, respectively. The installed cost of the 10 kW machine is estimated to be $65,000 ($32,000 for the turbine; $15,000 for the 30.5 m tower; $15,000 for installation and foundation preparation; $3,000 for permits). The installed cost for the 6 kW system is estimated to be $55,000 ($22,000 for the turbine with other costs the same as for the 10 kW). The useful life of the turbines is assumed to be 20 years, with no maintenance cost the first five years and maintenance cost in years 6-10 of $250 annually; years 11-15 of $500 annually; and years 16-20 of $1000 annually. Both systems are equipped with automatic furling systems that enable power output over a range of wind speeds while protecting the integrity of the equipment (52).

Solar panels

The modeled solar panel systems have capacity ratings of 4 kW and 12 kW with a 17% PV panel efficiency. These 4 kW and 12 kW systems would require 27.9 m^2 and 92.9 m^2 of roof area, respectively. The installed costs including all required components and wiring are estimated to be \$32,000 for the 4 kW system and \$65,000 for the 12 kW system. The useful life of both systems is estimated to be 40 years (53).

Annual cost of solar panels and wind turbines

The solar panel and wind turbine systems are assumed to be installed and used for their estimated life of 40 and 20 years, respectively. The salvage value is assumed to be zero. The insurance rate is assumed to be 0.6%. The assessed proportion for property tax is assumed to be 12% (54). Estimates of costs for both systems are reported in the *SI Appendix* (Table S3).

Electricity consumption and electricity production from microgeneration systems

SI Appendix (Tables S7-S16) includes detailed estimates for each location and each system including electricity consumption for each household location and estimated power output for each system at each location in each block.

Quantity and estimated social cost of emitted CO_2

The quantity of CO_2 emitted when natural gas and coal are used to produce electricity for the grid is estimated to be 0.55 kg/kWh and 0.96 kg/kWh, respectively (29). The proportion of case study region electricity generated by each source was based on production during 2015 and 2016 (17-28). For example, the estimate of CO_2 emitted by natural gas and coal to produce grid electricity for consumption by a Boise City household using a traditional meter in June (block A) was obtained by multiplying the quantity of June electricity consumption (block A) (888 kWh) by the proportion of June electricity generated by natural gas (43%) and coal (35%) by the quantity of CO_2 emitted to produce one kWh by natural gas (0.55 kg/kWh) and coal (0.96 kg/kWh). The result is

210 kg and 298 kg of CO_2 emitted from combustion of natural gas and coal, respectively, in June for a Boise City household using traditional meter rates.

Carbon tax and estimated demand response

Adding a \$0.0195 per kWh imputed cost of CO_2 to existing prices would be expected to change household electricity consumption (*SI Appendix*, Table S2). The percentage change in price can be multiplied by the electricity demand price elasticity estimate of -0.174 to produce an estimate of the expected change in household electricity use. However, for the present study it was assumed that the reduction in household use during a pricing block was limited to 20%. Studies of household behavior find little to no evidence of use reductions in excess of 20% in response to price increases when electricity is available on a continuous basis from the grid (38-40). Given the elasticity estimate of -0.174, a price increase of 115% would decrease use by 20%. Reduction in use is expected to reduce the quantity of natural gas and coal combustion and thereby reduce CO_2 emissions.

Household cost of carbon tax and value of reduction in CO_2 emissions

The annual cost of the carbon tax is estimated by taking the difference between the total cost of the grid-only electricity before and after imposing the carbon tax. The annual carbon tax collected from each household is estimated by multiplying the total CO_2 emitted from the household electricity consumption after imposing the carbon tax by the value of the carbon tax (\$0.0195 per kWh).

The annual value of reduction in CO_2 emissions is estimated by taking the difference between the total CO_2 emissions before and after imposing the carbon tax multiplying the difference by the estimated social cost of carbon (\$0.0372/kg).

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Table III-1. Annual quantity of electricity consumed, cost, CO_2 emission consequences, for both traditional and smart meter price schedules without and with a CO_2 emissions carbon tax for five representative households in the Oklahoma case study region

Representative household in Oklahoma case study region	Annual quantity of electricity consumed (kWh)[*]	Annual cost of electricity ($)	Annual quantity of CO_2 emitted to produce the electricity (kg)[†]	Annual quantity of electricity consumed if $0.0195/kWh carbon tax imposed (kWh)[‡]	Annual cost of electricity if carbon tax imposed ($)	Annual quantity of CO_2 emitted to produce the electricity if carbon tax imposed (kg)	Annual cost of carbon tax ($)[§]	Estimated annual value of reduction in CO_2 emissions ($)[¶]	Annual carbon tax collected from each household ($)[#]
Traditional meter price schedule (per household)[‖]									
Boise City	9,206	870	4,855	8,816	1,017	4,649	148	8	172
Hollis	14,289	1,191	7,549	13,682	1,419	7,228	228	12	267
Shawnee	13,533	1,124	7,113	12,930	1,339	6,796	215	12	252
Miami	12,847	1,066	6,701	12,260	1,272	6,396	206	11	239
Idabel	13,538	1,128	7,121	12,965	1,347	6,819	218	11	253
Smart meter price schedule (per household)									
Boise City	9,029	845	4,751	8,593	990	4,518	145	9	168
Hollis	14,009	1,128	7,385	13,331	1,356	7,023	228	13	260
Shawnee	13,281	1,066	6,967	12,637	1,281	6,624	215	13	246
Miami	12,669	1,010	6,596	12,015	1,215	6,252	205	13	234
Idabel	13,312	1,072	6,988	12,666	1,288	6,644	216	13	247

[*] Residential electricity profiles for Boise City, Hollis, Shawnee, Miami, and Idabel, Oklahoma households were obtained from the U.S. Department of Energy (42) and used as quantities for the traditional meter price schedule. Quantities for the smart meter price schedule were adjusted based on an electricity price elasticity estimate of -0.174.

[†] The quantity of CO_2 emitted when natural gas and coal are used to produce electricity for the grid is estimated to be 0.55 kg/kWh and 0.96 kg/kWh, respectively (29).

[‡] Based on the current portfolio of fuels used to generate electricity sold to households in the case study region of Oklahoma, a charge of $0.0195 per kWh would be required to account for the EPA estimated social cost of $37.2 per metric ton of emitted CO_2. Reduction in use in response to the increase in price is estimated based on the Bernstein and Griffin (32) electricity price estimate for Oklahoma households of -0.174, with use reduction capped at 20%.

[§] The annual cost of carbon tax is estimated by taking the difference between annual cost of electricity before the carbon tax is imposed and the annual cost of electricity after the carbon tax is imposed.

[¶] The annual value of reduction in CO_2 emissions is estimated by multiplying the difference between the annual quantity of CO_2 emissions before and after imposing the carbon tax by the social cost of $0.0372 per kg.

[#] The annual carbon tax collected from each household is estimated by multiplying the annual quantity of electricity consumed after imposing the carbon tax by the carbon tax value of $0.0195/kWh.

[‖] Traditional and smart meter prices as approved by the Oklahoma Corporation Commission for Oklahoma residential consumers.

Table III-2. Comparison of the annual cost of electricity between grid-only and grid-tied 4 kW solar system for both traditional and smart meter price schedules for five representative households in the Oklahoma case study region, and differences in CO_2 emissions, after imposing the carbon tax

	4 kW Solar Panel								
Representative household in Oklahoma case study region	Cost of purchased and produced electricity ($)*	Annual quantity of CO_2 emitted to produce the electricity (kg) †	Annual added cost of system relative to grid-only ($)‡	Annual reduction of CO_2 emissions (kg) §	Annual value to society of emissions reduction ($)¶	Annual cost of tax ($)#	Added annual reduction of CO_2 emissions attributable to tax (kg) ‖	Annual value to society of added emissions reduction due to tax ($) **	Total Annual value to society of added emissions reduction($) ††
Before imposing the carbon charge									
Traditional meter price schedule (per household) ‡‡									
Boise City	2,451	2,800	1,581	2,055	76	NA	NA	NA	76
Hollis	2,701	4,653	1,510	2,896	108	NA	NA	NA	108
Shawnee	2,667	4,442	1,543	2,671	99	NA	NA	NA	99
Miami	2,634	4,217	1,568	2,484	92	NA	NA	NA	92
Idabel	2,674	4,478	1,546	2,643	98	NA	NA	NA	98
Smart meter price schedule (per household)									
Boise City	2,401	2,759	1,556	1,992	74	NA	NA	NA	74
Hollis	2,634	4,537	1,506	2,848	106	NA	NA	NA	106
Shawnee	2,604	4,339	1,538	2,628	98	NA	NA	NA	98
Miami	2,580	4,160	1,570	2,436	91	NA	NA	NA	91
Idabel	2,616	4,377	1,544	2,611	97	NA	NA	NA	97
After imposing the carbon charge									
Traditional meter price schedule (per household)									
Boise City	2,529	2,661	1,512	1,988	74	78	139	5	79
Hollis	2,837	4,416	1,417	2,812	105	136	237	9	113
Shawnee	2,796	4,198	1,457	2,598	97	129	244	9	106
Miami	2,757	3,974	1,485	2,422	90	123	243	9	99
Idabel	2,806	4,246	1,459	2,573	96	132	232	9	104
Smart meter price schedule (per household)									
Boise City	2,479	2,599	1,488	1,920	71	78	160	6	77
Hollis	2,767	4,270	1,411	2,753	102	133	267	10	112
Shawnee	2,732	4,083	1,452	2,542	95	128	256	10	104
Miami	2,702	3,891	1,488	2,361	88	122	269	10	98
Idabel	2,745	4,119	1,457	2,525	94	129	258	10	104

*Cost includes the net annual cost of electricity purchased from the grid plus the annual ownership and operating cost of a 4 kW grid-tied 17% efficient solar system with an installed cost of $32,000.

†The quantity of CO_2 emitted in the production and installation of the solar system is not included.

‡The annual added cost of system relative to grid-only is estimated by taking the difference between the annual cost of electricity purchased and produced by 4 kW solar panel system and the annual cost of the electricity from the grid-only.

§The annual reduction of CO_2 emissions is estimated by taking the difference between the annual CO_2 emitted by consuming electricity just from the grid-only and the annual CO_2 emitted by consuming electricity produced by 4 kW solar panel and purchased electricity from the grid.

¶The annual value to society of emissions reduction is estimated by multiplying the annual reduction of CO_2 emissions by the SC-CO_2 ($0.0372/kg).

The annual cost of tax is estimated by taking the difference between the cost of purchased and produced electricity by 4 kW solar panel before and after imposing the carbon tax of $0.0195/kWh.

‖ The added annual reduction of CO_2 emissions attributable to tax is estimated by taking the difference between the annual quantity of CO_2 emitted to produce the electricity with 4 kW solar panel before and after imposing the carbon tax of $0.0195/kWh.

** The annual value to society of added emissions reduction due to tax is estimated by multiplying the added annual reduction of CO2 emissions attributable to tax by the SC-CO2 ($0.0372/kg).

†† The total annual value to society of added emissions reduction is estimated by summing the annual value to society of emission reduction and annual value to society of added emissions reduction due to tax.

‡‡ Estimates based on traditional and smart meter prices as approved by the Oklahoma Corporation Commission for Oklahoma residential consumers.

Table III-3. Comparison of the annual cost of electricity between grid-only and grid-tied 6 kW wind turbine for both traditional and smart meter price schedules for five representative households in the Oklahoma case study region, and differences in CO_2 emissions, after imposing the carbon tax

	6 kW Wind Turbine								
Representative household in Oklahoma case study region	Cost of purchased and produced electricity ($)*	Annual quantity of CO_2 emitted to produce the electricity (kg) †	Annual added cost of system relative to grid-only ($)‡	Annual reduction of CO_2 emissions (kg) §	Annual value to society of emissions reduction ($)¶	Annual cost of tax ($)#	Added annual reduction of CO_2 emissions attributable to tax (kg) ‖	Annual value to society of added emissions reduction due to tax ($) **	Total Annual value to society of added emissions reduction($) ††
Before imposing the carbon charge									
	Traditional meter price schedule (per household) ‡‡								
Boise City	5,382	1,363	4,512	3,492	130	NA	NA	NA	130
Hollis	5,825	4,389	4,634	3,159	118	NA	NA	NA	118
Shawnee	5,800	4,201	4,677	2,913	108	NA	NA	NA	108
Miami	5,896	4,891	4,830	1,810	67	NA	NA	NA	67
Idabel	6,051	6,097	4,922	1,024	38	NA	NA	NA	38
	Smart meter price schedule (per household)								
Boise City	5,359	1,264	4,514	3,487	130	NA	NA	NA	130
Hollis	5,779	4,231	4,651	3,153	117	NA	NA	NA	117
Shawnee	5,763	4,054	4,698	2,913	108	NA	NA	NA	108
Miami	5,856	4,787	4,845	1,810	67	NA	NA	NA	67
Idabel	6,000	5,964	4,928	1,024	38	NA	NA	NA	38
After imposing the carbon charge									
	Traditional meter price schedule (per household)								
Boise City	5,407	1,233	4,390	3,416	127	25	130	5	132
Hollis	5,930	4,086	4,511	3,143	117	105	303	11	128
Shawnee	5,897	3,896	4,558	2,900	108	97	304	11	119
Miami	6,029	4,595	4,757	1,801	67	132	296	11	78
Idabel	6,228	5,795	4,881	1,024	38	177	301	11	49
	Smart meter price schedule (per household)								
Boise City	5,382	1,119	4,391	3,400	126	22	145	5	132
Hollis	5,880	3,887	4,525	3,136	117	101	344	13	129
Shawnee	5,858	3,725	4,577	2,900	108	95	329	12	120
Miami	5,987	4,451	4,772	1,801	67	131	336	12	80
Idabel	6,175	5,620	4,887	1,024	38	175	344	13	51

* Cost includes the net annual cost of electricity purchased from the grid plus the annual ownership and operating cost of a 6 kW grid-tied wind system with an installed cost of $55,000.

†The quantity of CO_2 emitted in the production and installation of the solar system is not included.

‡The annual added cost of system relative to grid-only is estimated by taking the difference between the annual cost of electricity purchased and produced by 6 kW wind turbine system and the annual cost of the electricity from the grid-only.

§The annual reduction of CO_2 emissions is estimated by taking the difference between the annual CO_2 emitted by consuming electricity just from the grid-only and the annual CO_2 emitted by consuming electricity produced by 6 kW wind turbine and purchased electricity from the grid.

¶The annual value to society of emissions reduction is estimated by multiplying the annual reduction of CO_2 emissions by the SC-CO_2 ($0.0372/kg).

The annual cost of tax is estimated by taking the difference between the cost of purchased and produced electricity by 6 kW wind turbine system before and after imposing the carbon tax of $0.0195/kWh.

‖ The added annual reduction of CO_2 emissions attributable to tax is estimated by taking the difference between the annual quantity of CO_2 emitted to produce the electricity with 6 kW wind turbine system before and after imposing the carbon tax of $0.0195/kWh.

** The annual value to society of added emissions reduction due to tax is estimated by multiplying the added annual reduction of CO2 emissions attributable to tax by the SC-CO2 ($0.0372/kg).

†† The total annual value to society of added emissions reduction is estimated by summing the annual value to society of emission reduction and annual value to society of added emissions reduction due to tax.

‡‡ Estimates based on traditional and smart meter prices as approved by the Oklahoma Corporation Commission for Oklahoma residential consumers.

Table III-4. The level of carbon tax would be required to increase the cost of grid electricity to a level equivalent to that of a grid-tied solar or wind turbine systems

Location	**Meter Price Rate**		**Solar Panels**		**Wind Turbines**	
			4 kW	**12 kW**	**6 kW**	**10 kW**
Boise City	Traditional Meter	$/kWh	0.50	0.93	0.77	0.79
	Smart Meter	$/kWh	0.50	0.95	0.76	0.79
Hollis	Traditional Meter	$/kWh	0.33	0.58	0.78	0.71
	Smart Meter	$/kWh	0.33	0.59	0.78	0.70
Shawnee	Traditional Meter	$/kWh	0.36	0.63	0.83	0.78
	Smart Meter	$/kWh	0.36	0.64	0.83	0.77
Miami	Traditional Meter	$/kWh	0.40	0.68	1.34	1.16
	Smart Meter	$/kWh	0.39	0.69	1.34	1.16
Idabel	Traditional Meter	$/kWh	0.37	0.63	2.36	1.99
	Smart Meter	$/kWh	0.37	0.64	2.36	1.99

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Supplementary Information Appendix

Section S1. Conceptual Framework

Estimation of solar panel power output

Theoretically, the power output produced by a solar panel is a function of the panel's area, mechanical efficiency (proportion of energy in the solar radiation transferred into electricity), solar radiation, and temperature (S1). Electricity output (kW) from a solar panel can be estimated by:

$$P = 0.001(I\ A\ \eta_{PV}\varphi) \qquad (1)$$

where P is the power output (kW); I is the solar radiation (W/m^2); A is the area of the photovoltaic (PV) panel in m^2; and η_{PV} is the mechanical efficiency (overall efficiency of the PV panels) in percentage; and φ is included to account for efficiency losses.

Estimation of wind turbine power output

Theoretically, the power output produced by wind turbines depends on the rotor sweep area, air density, mechanical efficiency (proportion of wind power transferred into electricity), and wind speed (S2). At a certain level of wind speed, the cut-in wind speed, the wind turbine starts to produce electricity. Electricity output is effectively zero for wind speeds less than cut-in. Over a range of wind speeds, electricity output increases at an increasing rate and may be described by a cubic function (S2). To prevent damage from high wind speeds, wind turbines are equipped with an automatic furling system. Over a range of wind speeds, electricity production continues to increase but at a decreasing rate to a level at which power output plateaus. This range may be described by a quadratic function. Electricity output (kWh) from a wind turbine can be estimated by:

$$P = \begin{cases} 0 & V_i < V_{Cut-in}, V > V_0 \\ 0.001\, C_p\, \frac{1}{2}\, \rho\, A\, V^3 & V_{Cut-in} \leq V \leq V_r \\ \alpha_0 + \alpha_1 V + \alpha_2 V^2 & V_r < V < V_p \\ P_r & V_p \leq V \leq V_0 \end{cases} \quad (2)$$

where, P is the power output (kW), P_r is the plateau output level (kW), C_p is the mechanical efficiency coefficient, ρ is the air density (kg/m^3), A is the rotor sweep area (m^2), V is wind speed (m/s), V_{Cut-in} is the minimal wind speed required to initiate production, V_r is the wind speed at which production begins to increase at a decreasing rate, V_p is the wind speed at which production is at a plateau level, V_0 is the wind speed at which production is assumed to be zero (high wind speeds at which the turbine is braked to prevent damage), α_0 is the constant of the quadratic function, α_1 is the coefficient for the linear term, and α_2 is the coefficient for the quadratic term.

Estimation of the annual cost of the solar panel and wind turbine

The following equations may be used to estimate the annual cost of a household electricity production system (S3)

$$\text{Depreciation } \left(\frac{\$}{\text{year}}\right) = \frac{(\text{Purchase Price} - \text{Salvage Value})}{\text{Years of Life}}, \quad (3)$$

where purchase price is the cost of the system ($), salvage value is the estimated resale value of the system at the end of its useful life ($), and years of life is the estimated useful life of the system.

$$\text{Interest } \left(\frac{\$}{\text{year}}\right) = \frac{\text{Purchase Price} + \text{Salvage Value}}{2} * \text{Real Interest Rate}, \quad (4)$$

where interest rate is the opportunity cost of capital.

$$\text{Insurance } \left(\frac{\$}{\text{year}}\right) = \frac{\text{Purchase Price} + \text{Salvage Value}}{2} * \text{Insurance Rate, and} \quad (5)$$

where insurance rate is the market rate for household insurance.

$$\text{Property Tax}\left(\frac{\$}{\text{year}}\right) = \text{Average System Price} * \text{Tax Rate}, \quad (6)$$

where average assessed value of the system in dollars is taxed at a rate per dollar of value.

Estimation of the annual electricity cost for each alternative

For a household serviced by a traditional meter, the annual cost of electricity is calculated as:

$$ECTM = \sum_{j=1}^{12} BC_j + \sum_{j=1}^{12} D_j \, ERTM_{jr} \, G_{jr}\,, \quad (7)$$

where $ECTM$ is the annual electricity cost for a household using a traditional meter; BC_j is a fixed base charge per month independent of electricity use; $ERTM_{jr}$ is the OCC traditional meter rate for the j^{th} month and r^{th} block ($/kWh); and G_{jr} is the net quantity of electricity used (kWh) in r^{th} block and j^{th} month, and D_j is the number days in the j^{th} month, if j = 1, 3, 5, 7, 8, 10, or 12 then D_j = 31, if j = 4, 6, 9, or 11 then D_j = 30, and if j = 2 then D_j = 28.

For a household serviced by a smart meter, the annual cost of electricity is calculated as:

$$ECSM = \sum_{j=1}^{12} BC_j + \sum_{j=1}^{12} D_j \sum_{i=1}^{24} ERSM_{ijr}(G_{ijr}\, \varepsilon \, PC_{ijr}), \quad (8)$$

where $ECSM$ is the annual electricity cost for the household using the smart meter rate, and $ERSM_{ijr}$ is the OCC smart meter rate ($/kWh); ε is the electricity demand price elasticity; and PC_{ijr} is the percent change in electricity prices from traditional meter to smart meter rates for the i^{th} hour and r^{th} block during the j^{th} month, where i = 1, 2, 3, …, 24.

The annual charge for net electricity withdrawn from the grid for a household with a grid-tied solar panel or wind turbine based on the traditional meter rate schedule is:

$$ECTMN = \sum_{j=1}^{12} BC_j + \sum_{j=1}^{12} D_j\, ERTM_{jr}\,(G_{jr} - P_{jr}), \tag{9}$$

where $ECTMN$ is the annual electricity cost for the household, and P_{jr} (kWh) is the electricity produced by the solar panel or wind turbine in r^{th} block, during the j^{th} month, where $(G_{jr} - P_{jr}) \geq 0$.

The annual charge for net electricity withdrawn from the grid for a household with a grid-tied solar panel or wind turbine based on the smart meter rate schedule is:

$$ECSMN = \sum_{j=1}^{12} BC_j + \sum_{j=1}^{12} D_j \sum_{i=1}^{24} ERSM_{ijr}((G_{ijr}\,\varepsilon\, PC_{ijr}) - P_{ijr}), \tag{10}$$

where $ECSMN$ is the annual electricity cost for the household with the grid-tied solar system using the smart meter rates, where $((G_{ijr}\,\varepsilon\, PC_{ijr}) - P_{ijr}) \geq 0$.

Estimation of the annual cost of CO_2 emission

The household cost of carbon emitted to generate electricity for the grid is estimated as:

$$C_{CO_2} = \left(\sum_{j=1}^{12} PNG_j G_{jr}\gamma + \sum_{j=1}^{12} PC_j G_{jr}\delta\right) EPAP \tag{11}$$

where C_{CO_2} is the annual household cost of carbon, PNG_j is the percentage of electricity generated by natural gas, γ is the quantity of CO_2 emitted by natural gas, PC_j is the percentage of electricity generated by coal, δ is the quantity of CO_2 emitted by coal, and $EPAP$ is the estimated social cost of carbon.

The cost of carbon for a household that uses either a solar panel or a wind turbine system is:

$$C_{CO_2} = \left(\sum_{j=1}^{12} PNG_j\,(G_{jr} - P_{jr})\,\gamma + \sum_{j=1}^{12} PC_j\,(G_{jr} - P_{jr})\,\delta\right) EPAP \tag{12}$$

where $(G_{jr} - P_{jr}) \geq 0$.

Estimation of level of carbon tax would be required to increase the cost of grid electricity to a level equivalent to that of a grid-tied solar or wind turbine system

A mathematical programming model may be formulated and solved to determine the level of carbon tax and quantity demanded for electricity at which grid-only electricity would breakeven with a household system. Consider the model that follows (equations 13 through 20) for households paying traditional meter rates.

$$\min_{CT, QPR_{jr}} Z = |ECTM - ACT| \text{ subject to} \tag{13}$$

$$ECTM = \sum_{j=1}^{12} BC_j + \sum_{j=1}^{12} D_j \left(ERTM_{jr} + CT\right)\left(GT_{jr}(1 + QPR_{jr})\right) \tag{14}$$

$$ACT = AC + \sum_{j=1}^{12} BC_j + \sum_{j=1}^{12} D_j \left(ERTM_{jr} + CT\right)\left(GT_{jr}(1 + QPR_{jr}) - P_{jr}\right) \tag{15}$$

$$QPR_{jr} = \frac{\left(ERTM_{jr} + CT\right) - \left(ERTM_{jr}\right)}{ERTM_{jr}} \epsilon \tag{16}$$

$$ECTM = ACT \tag{17}$$

$$GT_{jr}\left(1 + \left(QPR_{jr}\epsilon\right)\right) \geq GT_{jr}(1 + LBP) \tag{18}$$

$$GT_{jr}\left(1 + \left(QPR_{jr}\epsilon\right)\right) - P_{jr} \geq 0 \tag{19}$$

$$QPR_{jr}, CT \geq 0\,, \tag{20}$$

where $ECTM$ is the annual electricity cost for a household using a traditional meter; BC_j is a fixed base charge per month independent of electricity use; $ERTM_{jr}$ is the OCC traditional meter rate for the j^{th} month and r^{th} block ($/kWh); CT is the choice variable which represents the carbon charge ($/kWh); QPR_{jr} is the choice variable which represent the percentage change in the quantity of electricity demanded in r^{th} block, during the j^{th} month; GT_{jr} is the net quantity of electricity used for households on traditional meter rates (kWh) in r^{th} block and j^{th} month; ACT is the annual electricity cost after installing a household system for a household using a traditional meter; AC is the annual cost of a household system; P_{jr} (kWh) is the electricity produced by the household system in r^{th} block, during the j^{th} month; LBP is the percentage lower bound that the electricity used by household would reach; and D_j is the number days in the j^{th} month, if j = 1, 3, 5, 7, 8, 10, or 12 then D_j = 31, if j = 4, 6, 9, or 11 then D_j = 30, and if j = 2 then D_j = 28.

As for households on smart meter rates, consider the model that follows (equations 21 through 28) for households paying smart meter rates.

$$\min_{CT,QPR_{jr}} Z = |ECSM - ACM| \text{ subject to} \tag{21}$$

$$ECSM = \sum_{j=1}^{12} BC_j + \sum_{j=1}^{12} D_j \left(ERSM_{jr} + CT\right)(GM_{jr}(1 + QPR_{jr})) \tag{22}$$

$$ACM = AC + \sum_{j=1}^{12} BC_j + \sum_{j=1}^{12} D_j \left(ERSM_{jr} + CT\right)(GM_{jr}(1 + QPR_{jr}) - P_{jr}) \tag{23}$$

$$QPR_{jr} = \frac{(ERSM_{jr}+CT)-(ERSM_{jr})}{ERSM_{jr}} \epsilon \tag{24}$$

$$ECTM = ACT \tag{25}$$

$$GM_{jr}\left(1 + \left(QPR_{jr}\epsilon\right)\right) \geq GM_{jr}(1 + LBP) \tag{26}$$

$$GM_{jr}\left(1 + \left(QPR_{jr}\epsilon\right)\right) - P_{jr} \geq 0 \tag{27}$$

$$QPR_{jr}, CT \geq 0 , \tag{28}$$

where $ECSM$ is the annual electricity cost for a household using a smart meter; $ERSM_{jr}$ is the OCC smart meter rate for the j^{th} month and r^{th} block (\$/kWh); GM_{jr} is the net quantity of electricity used for households on smart meter rates (kWh) in r^{th} block and j^{th}

month; and ACM is the annual electricity cost after installing a solar panel or wind turbine system for a household using a smart meter.

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Section S2. Supplementary Tables

Table S1. Fuel sources used to generate electricity for the Oklahoma grid (percent by month)

Month	Source of electricity generation from each month in Oklahoma (%)				
	Natural Gas	**Coal**	**Hydro**	**Wind**	**Biomass**
January	46	25	7	22	0.4
February	41	23	3	32	0.5
March	44	19	4	33	0.5
April	54	14	3	29	0.5
May	42	31	5	20	0.4
June	43	35	6	16	0.4
July	48	33	4	14	0.3
August	49	35	3	13	0.3
September	43	35	1	21	0.4
October	40	39	1	19	0.5
November	47	24	3	26	0.4
December	50	21	6	23	0.4

Source: U.S. Energy Information Administration

Table S2. Oklahoma Gas and Electric Company Electricity Pricing Rates and the Carbon Tax of CO_2 Emissions

Time and quantity of electricity used	**Block**	**Price**		**Fuel Cost Adjustment***	**Total Price (no carbon tax)**	**Total Price plus $0.0195/kWh carbon tax**	**Percentage Increase in Prices from adding carbon tax**
		($ per month)	**(¢ per kWh)**	**(¢ per kWh)**	**(¢ per kWh)**	**(¢ per kWh)**	**(%)**
Alternative I: Traditional Meter							
Base Charge		13					
Carbon Tax†			1.95				
June through September	**A**			2.38			
0 ≤ kWh per month ≤ 1,400			5.73		8.11	10.06	24%
kWh per month > 1,400			6.80		9.18	11.13	
November through April	**B**			2.22			
0 ≤ kWh per month ≤ 600			5.73		7.95	9.90	25%
kWh per month > 600			1.37		3.59	5.54	
May	**C**		5.73	2.22	7.95	9.90	25%
October	**D**		5.73	2.38	8.11	10.06	24%
Alternative II: Smart Meter							
Base Charge		13					
Carbon Tax			1.95				
June through October							
2 p.m. to 7:59 p.m. weekdays	**E**		14.00	4.26	18.26	20.21	11%
8:00 p.m. through 1:59 p.m., and weekends	**F**		2.70	2.11	4.81	6.76	41%
November through May	**G**			2.22			
First 600 kWh per month			5.73		7.95	9.90	25%
Additional kWh			1.37		3.59	5.54	

Source: Oklahoma Corporation Commission

*Fuel adjustment charge is a surcharge added to compensate for increases, usually unanticipated, in the price of energy (natural gas and coal)

† The $0.0195/kWh charge is based on the EPA social cost of carbon estimate of $37.2 per metric ton and the portfolio of fuels combusted to produce electricity for the Oklahoma electricity grid.

Table S3. Purchase price and annual cost for two solar panel systems and two wind turbine systems

Description	Unit	12 kW Solar Panel	4 kW Solar Panel	10 kW Wind Turbine	6 kW Wind Turbine
Purchase Price	$	65,000	32,000	65,000	55,000
Life	years	40		20	
Depreciation	$/year	1,625	800	3,250	2,750
Interest on Average Investment	$/year	1,625	800	1,625	1,375
Insurance	$/year	195	96	195	165
Property Tax	$/year	344	169	352	298
Repairs	$/year	-	-	437	437
Total Annual Cost	$/year	3,789	1,865	5,860	5,025

Source: Green Wind and Solar Company provided the purchase price for the solar panels. Bergey Company provided purchase price and repair cost estimates for the wind turbines. Salvage value is assumed to be zero at the end of life for each of the systems

Table S4. Comparison of the annual cost of electricity between grid-only and grid-tied 12 kW solar system for both traditional and smart meter price schedules for five representative households in the Oklahoma case study region, and differences in CO_2 emissions, after imposing the carbon tax

Representative household in Oklahoma case study region	12 kW Solar Panel								
	Cost of purchased and produced electricity ($)*	Annual quantity of CO_2 emitted to produce the electricity (kg) †	Annual added cost of system relative to grid-only ($)‡	Annual reduction of CO_2 emissions (kg) §	Annual value to society of emissions reduction ($)¶	Annual cost of tax ($)#	Added annual reduction of CO_2 emissions attributable to tax (kg) ‖	Annual value to society of added emissions reduction due to tax ($) **	Total Annual value to society of added emissions reduction($) ††
Before imposing the carbon charge									
Traditional meter price schedule (per household) ‡‡									
Boise City	4,314	2,384	3,444	2,471	92	NA	NA	NA	92
Hollis	4,507	3,735	3,316	3,814	142	NA	NA	NA	142
Shawnee	4,489	3,619	3,365	3,494	130	NA	NA	NA	130
Miami	4,464	3,445	3,398	3,256	121	NA	NA	NA	121
Idabel	4,490	3,615	3,362	3,506	130	NA	NA	NA	130
Smart meter price schedule (per household)									
Boise City	4,263	2,421	3,418	2,330	87	NA	NA	NA	87
Hollis	4,434	3,768	3,306	3,617	135	NA	NA	NA	135
Shawnee	4,421	3,623	3,355	3,344	124	NA	NA	NA	124
Miami	4,407	3,471	3,397	3,125	116	NA	NA	NA	116
Idabel	4,427	3,629	3,355	3,359	125	NA	NA	NA	125
After imposing the carbon charge									
Traditional meter price schedule (per household)									
Boise City	4,382	2,273	3,365	2,376	88	68	111	4	93
Hollis	4,618	3,563	3,198	3,665	136	111	172	6	143
Shawnee	4,594	3,430	3,254	3,366	125	105	189	7	132
Miami	4,565	3,256	3,293	3,140	117	101	189	7	124
Idabel	4,597	3,443	3,250	3,377	126	107	172	6	132
Smart meter price schedule (per household)									
Boise City	4,332	2,281	3,342	2,238	83	69	140	5	88
Hollis	4,544	3,546	3,188	3,476	129	110	222	8	138
Shawnee	4,528	3,413	3,247	3,211	119	107	210	8	127
Miami	4,508	3,245	3,294	3,007	112	101	226	8	120
Idabel	4,534	3,419	3,246	3,225	120	107	210	8	128

*Cost includes the net annual cost of electricity purchased from the grid plus the annual ownership and operating cost of a 12 kW grid-tied 17% efficient solar system with an installed cost of $65,000.

†The quantity of CO_2 emitted in the production and installation of the solar system is not included.

‡The annual added cost of system relative to grid-only is estimated by taking the difference between the annual cost of electricity purchased and produced by 12 kW solar panel system and the annual cost of the electricity from the grid-only.

§The annual reduction of CO_2 emissions is estimated by taking the difference between the annual CO_2 emitted by consuming electricity just from the grid-only and the annual CO_2 emitted by consuming electricity produced by 12 kW solar panel and purchased electricity from the grid.

¶The annual value to society of emissions reduction is estimated by multiplying the annual reduction of CO_2 emissions by the SC-CO_2 ($0.0372/kg).

The annual cost of tax is estimated by taking the difference between the cost of purchased and produced electricity by 12 kW solar panel before and after imposing the carbon tax of $0.0195/kWh.

‖ The added annual reduction of CO_2 emissions attributable to tax is estimated by taking the difference between the annual quantity of CO_2 emitted to produce the electricity with 12 kW solar panel before and after imposing the carbon tax of $0.0195/kWh.

** The annual value to society of added emissions reduction due to tax is estimated by multiplying the added annual reduction of CO2 emissions attributable to tax by the SC-CO2 ($0.0372/kg).

†† The total annual value to society of added emissions reduction is estimated by summing the annual value to society of emission reduction and annual value to society of added emissions reduction due to tax.

‡‡ Estimates based on traditional and smart meter prices as approved by the Oklahoma Corporation Commission for Oklahoma residential consumers.

Table S5. Comparison of the annual cost of electricity between grid-only and grid-tied 10 kW wind turbine for both traditional and smart meter price schedules for five representative households in the Oklahoma case study region, and differences in CO_2 emissions, after imposing the carbon tax

	10 kW Wind Turbine								
Representative household in Oklahoma case study region	Cost of purchased and produced electricity ($)*	Annual quantity of CO_2 emitted to produce the electricity (kg) †	Annual added cost of system relative to grid-only ($)‡	Annual reduction of CO_2 emissions (kg) §	Annual value to society of emissions reduction ($)¶	Annual cost of tax ($)#	Added annual reduction of CO_2 emissions attributable to tax (kg) ‖	Annual value to society of added emissions reduction due to tax ($) **	Total Annual value to society of added emissions reduction($) ††
	Before imposing the carbon charge								
	Traditional meter price schedule (per household) ‡‡								
Boise City	6,130	783	5,261	4,072	151	NA	NA	NA	151
Hollis	6,513	3,394	5,321	4,154	155	NA	NA	NA	155
Shawnee	6,500	3,308	5,376	3,805	142	NA	NA	NA	142
Miami	6,643	4,224	5,577	2,477	92	NA	NA	NA	92
Idabel	6,842	5,695	5,713	1,426	53	NA	NA	NA	53
	Smart meter price schedule (per household)								
Boise City	6,110	709	5,264	4,042	150	NA	NA	NA	150
Hollis	6,466	3,245	5,338	4,139	154	NA	NA	NA	154
Shawnee	6,466	3,167	5,400	3,800	141	NA	NA	NA	141
Miami	6,607	4,120	5,596	2,477	92	NA	NA	NA	92
Idabel	6,793	5,562	5,722	1,426	53	NA	NA	NA	53
	After imposing the carbon charge								
	Traditional meter price schedule (per household)								
Boise City	6,140	686	5,123	3,963	147	10	97	4	151
Hollis	6,586	3,139	5,166	4,090	152	73	256	10	162
Shawnee	6,569	3,045	5,230	3,751	140	69	263	10	149
Miami	6,748	3,939	5,476	2,457	91	105	284	11	102
Idabel	7,000	5,395	5,654	1,424	53	159	299	11	64
	Smart meter price schedule (per household)								
Boise City	6,118	600	5,128	3,919	146	8	110	4	150
Hollis	6,534	2,945	5,179	4,078	152	68	300	11	163
Shawnee	6,533	2,878	5,252	3,746	139	67	289	11	150
Miami	6,708	3,796	5,493	2,456	91	102	323	12	103
Idabel	6,950	5,220	5,662	1,424	53	157	342	13	66

*Cost includes the net annual cost of electricity purchased from the grid plus the annual ownership and operating cost of a 10 kW grid-tied wind system with an installed cost of $65,000.

†The quantity of CO_2 emitted in the production and installation of the solar system is not included.

‡The annual added cost of system relative to grid-only is estimated by taking the difference between the annual cost of electricity purchased and produced by 10 kW wind turbine system and the annual cost of the electricity from the grid-only.

§The annual reduction of CO_2 emissions is estimated by taking the difference between the annual CO_2 emitted by consuming electricity just from the grid-only and the annual CO_2 emitted by consuming electricity produced by 10 kW wind turbine system and purchased electricity from the grid.

¶The annual value to society of emissions reduction is estimated by multiplying the annual reduction of CO_2 emissions by the SC-CO_2 ($0.0372/kg).

The annual cost of tax is estimated by taking the difference between the cost of purchased and produced electricity by 10 kW wind turbine system before and after imposing the carbon tax of $0.0195/kWh.

‖ The added annual reduction of CO_2 emissions attributable to tax is estimated by taking the difference between the annual quantity of CO_2 emitted to produce the electricity with 10 kW wind turbine system before and after imposing the carbon tax of $0.0195/kWh.

** The annual value to society of added emissions reduction due to tax is estimated by multiplying the added annual reduction of CO2 emissions attributable to tax by the SC-CO2 ($0.0372/kg).

†† The total annual value to society of added emissions reduction is estimated by summing the annual value to society of emission reduction and annual value to society of added emissions reduction due to tax.

‡‡ Estimates based on traditional and smart meter prices as approved by the Oklahoma Corporation Commission for Oklahoma residential consumers

Table S6. Characteristics of the Oklahoma house and household being modeled

Characteristics	**Description/Unit**	
	Mixed Humid[*]	**Mixed Dry**
Building Fuel Types		
Space Heating	Natural Gas	Natural Gas
Air Conditioning	Yes	Yes
Water Heating	Natural Gas	Natural Gas
Building Structure Types		
Total Size	236.5 (m^2)	185.8 (m^2)
Number of Stories/Level	1 Story	1 Story
Bedrooms	3	3
Bathrooms	1	2
Basement	No	No
Type of Glass in Windows	Double-pane	Single-pane

Source: National Renewable Energy Laboratory

[*] Hollis, Shawnee, Miami, and Idabel are included in the mixed humid region. Boise City is included in the mixed dry region.

Table S7. Electricity Consumption and Production for each Block in Boise City for Two selected Solar Panel Systems

Month	**Block**	**Total Use**	**4 kW**				**12 kW**			
			Production	**Electricity Used from Grid**[*]	**Power Output produced Used †**	**Provided to Grid ‡**	**Production**	**Electricity Used from Grid**	**Power Output produced Used**	**Provided to Grid**
		kWh/block/year	**kWh/block/year**				**kWh/block/year**			
					Traditional Meter					
June	A	888	867	427	460	407	2847	323	565	2283
July	A	1080	866	532	548	317	2864	393	687	2177
August	A	983	776	511	471	305	2575	403	580	1995
September	A	799	655	436	362	293	2175	361	438	1737
November	B	671	386	461	210	176	1281	431	240	1041
December	B	768	331	555	213	119	1100	512	256	844
January	B	781	377	551	230	147	1253	506	275	978
February	B	682	432	454	228	204	1435	414	267	1168
March	B	678	634	412	266	368	2104	376	302	1803
April	B	606	737	320	286	451	2425	274	332	2093
May	C	604	872	290	314	558	2851	246	358	2493
October	D	667	525	414	253	272	1744	360	307	1437
Total		9206	7458	5364	3842	3616	24655	4599	4607	20048
					Smart Meter					
June	E	194	293	30	163	129	963	0	194	769
	F	658	574	389	269	305	1884	347	312	1573
July	E	247	299	48	199	100	989	0	247	742
	F	785	567	462	324	243	1875	410	375	1500
August	E	222	271	49	173	98	898	6	216	682
	F	719	505	445	274	232	1677	409	309	1368
September	E	177	223	48	129	94	740	21	156	584
	F	588	432	373	214	218	1435	349	239	1196
October	E	129	172	49	80	92	571	28	100	471
	F	521	353	358	163	190	1173	333	188	985
November	G	671	386	461	210	176	1281	431	240	1041
December	G	768	331	555	213	119	1100	512	256	844
January	G	781	377	551	230	147	1253	506	275	978
February	G	682	432	454	228	204	1435	414	267	1168
March	G	678	634	412	266	368	2104	376	302	1803
April	G	606	737	320	286	451	2425	274	332	2093
May	G	604	872	290	314	558	2851	246	358	2493
Total		9029	7458	5295	3735	3723	24655	4663	4366	20289

[*] The electricity used from the grid, is when the solar panel system doesn’t produce sufficient power output at a specific hour in a specific month for a specific block to meet the electricity needs of the household, the household will use the grid to provide them with the electricity needed

† The power output produced by the solar panel system used, is when the system produces a sufficient power output to meet the electricity needs of the household at a specific hour in a specific month for a specific block

‡ Power output provided to the grid, is when the solar panel system produces power output that meet the household’s electricity needs at a specific hour in a specific month for a specific block, and produces an excess of the household’s need, then the excess power output will be provided back to the grid

Table S8. Electricity Consumption and Production for each Block in Hollis for Two selected Solar Panel Systems

Month	Block	Total Use	4 kW				12 kW			
			Production	Electricity Used from Grid*	Power Output produced Used †	Provided to Grid ‡	Production	Electricity Used from Grid	Power Output produced Used	Provided to Grid
		kWh/block/year	kWh/block/year				kWh/block/year			
			Traditional Meter							
June	A	1629	803	909	720	83	2658	621	1008	1650
July	A	1568	832	871	697	135	2760	625	943	1817
August	A	1525	755	884	641	114	2507	655	870	1636
September	A	1221	625	736	485	140	2075	587	634	1440
November	B	985	378	686	299	80	1256	608	377	879
December	B	1110	332	807	302	30	1104	702	408	697
January	B	1192	375	862	331	44	1245	758	434	811
February	B	1042	423	711	331	92	1404	613	429	975
March	B	1040	598	649	390	208	1986	566	474	1512
April	B	925	711	525	400	311	2344	440	485	1858
May	C	1052	792	565	487	304	2606	432	620	1986
October	D	1000	498	655	346	153	1655	558	442	1212
Total		14289	7122	8860	5428	1693	23598	7165	7124	16474
			Smart Meter							
June	E	368	271	130	238	33	897	21	347	549
	F	1189	533	721	467	66	1761	618	571	1191
July	E	347	285	109	238	47	947	16	331	617
	F	1157	546	714	442	104	1812	628	529	1283
August	E	346	255	128	218	37	846	32	314	532
	F	1113	500	705	408	92	1660	633	481	1180
September	E	265	201	107	158	43	667	48	217	450
	F	908	424	596	312	111	1407	534	374	1034
October	E	195	155	94	101	54	515	64	131	383
	F	778	343	546	232	112	1140	496	282	858
November	G	985	378	686	299	80	1256	608	377	879
December	G	1108	332	816	292	41	1104	719	389	715
January	G	1192	375	862	331	44	1245	758	434	811
February	G	1042	423	711	331	92	1404	613	429	975
March	G	1040	598	649	390	208	1986	566	474	1512
April	G	925	711	525	400	311	2344	440	485	1858
May	G	1052	792	565	487	304	2606	432	620	1986
Total		14009	7122	8665	5344	1778	23598	7226	6784	16815

*The electricity used from the grid, is when the solar panel system doesn't produce sufficient power output at a specific hour in a specific month for a specific block to meet the electricity needs of the household, the household will use the grid to provide them with the electricity needed

† The power output produced by the solar panel system used, is when the system produces a sufficient power output to meet the electricity needs of the household at a specific hour in a specific month for a specific block

‡ Power output provided to the grid, is when the solar panel system produces power output that meet the household's electricity needs at a specific hour in a specific month for a specific block, and produces an excess of the household's need, then the excess power output will be provided back to the grid

Table S9. Electricity Consumption and Production for each Block in Shawnee for Two selected Solar Panel Systems

Month	Block	Total Use	4 kW				12 kW			
			Production	Electricity Used from Grid*	Power Output produced Used †	Provided to Grid ‡	Production	Electricity Used from Grid	Power Output produced Used	Provided to Grid
		kWh/block/year	kWh/block/year				kWh/block/year			
Traditional Meter										
June	A	1150	763	603	548	215	2526	447	704	1822
July	A	1444	810	794	650	160	2687	572	872	1815
August	A	1439	733	827	612	121	2434	625	814	1620
September	A	1152	595	695	456	139	1977	567	585	1393
November	B	991	342	701	290	52	1135	610	381	754
December	B	1119	291	841	278	13	968	733	386	582
January	B	1215	331	901	314	17	1100	779	436	663
February	B	1041	375	725	316	59	1246	624	417	829
March	B	1039	523	662	377	146	1738	567	472	1266
April	B	915	642	530	385	257	2123	438	477	1646
May	C	949	724	517	432	292	2389	404	545	1844
October	D	1049	467	688	360	106	1550	579	469	1080
Total		13502	6596	8483	5018	1577	21870	6944	6558	15313
Smart Meter										
June	E	239	248	64	175	73	822	9	230	592
	F	871	515	521	349	166	1704	450	421	1283
July	E	313	266	99	214	52	883	18	295	589
	F	1076	544	657	419	124	1803	573	503	1300
August	E	317	238	117	200	38	789	35	282	507
	F	1064	495	666	398	97	1645	596	468	1177
September	E	239	182	99	140	42	604	51	187	417
	F	873	413	570	303	110	1373	513	360	1013
October	E	201	135	102	99	36	447	72	129	319
	F	821	332	567	254	78	1102	510	311	791
November	G	991	342	701	290	52	1135	610	381	754
December	G	1119	291	841	278	13	968	733	386	582
January	G	1215	331	901	314	17	1100	779	436	663
February	G	1041	375	725	316	59	1246	624	417	829
March	G	1039	523	662	377	146	1738	567	472	1266
April	G	915	642	530	385	257	2123	438	477	1646
May	G	949	724	517	432	292	2389	404	545	1844
Total		13281	6596	8337	4944	1652	21870	6981	6300	15570

*The electricity used from the grid, is when the solar panel system doesn't produce sufficient power output at a specific hour in a specific month for a specific block to meet the electricity needs of the household, the household will use the grid to provide them with the electricity needed

† The power output produced by the solar panel system used, is when the system produces a sufficient power output to meet the electricity needs of the household at a specific hour in a specific month for a specific block

‡ Power output provided to the grid, is when the solar panel system produces power output that meet the household's electricity needs at a specific hour in a specific month for a specific block, and produces an excess of the household's need, then the excess power output will be provided back to the grid

Table S10. Electricity Consumption and Production for each Block in Miami for Two selected Solar Panel Systems

Month	Block	Total Use	4 kW				12 kW			
			Production	Electricity Used from Grid*	Power Output produced Used †	Provided to Grid ‡	Production	Electricity Used from Grid	Power Output produced Used	Provided to Grid
		kWh/block/year	kWh/block/year				kWh/block/year			
Traditional Meter										
June	A	1121	749	581	540	210	2481	424	696	1785
July	A	1334	789	721	613	176	2616	525	809	1808
August	A	1112	721	622	490	231	2395	483	629	1766
September	A	990	579	592	398	182	1925	494	496	1428
November	B	1004	311	722	282	29	1034	631	372	661
December	B	1132	259	874	258	1	860	755	376	483
January	B	1202	292	913	290	3	971	780	423	549
February	B	1046	340	743	303	37	1130	637	409	721
March	B	1051	495	678	373	122	1644	574	477	1167
April	B	921	609	539	383	226	2013	438	484	1530
May	C	972	711	531	442	269	2349	409	563	1786
October	D	962	445	643	318	127	1479	544	418	1061
Total		12847	6302	8158	4689	1613	20898	6694	6153	14745
Smart Meter										
June	E	238	233	69	169	64	774	12	227	547
	F	840	516	491	350	167	1708	424	416	1292
July	E	284	251	89	195	56	833	18	265	568
	F	1002	538	601	400	137	1783	521	481	1302
August	E	233	225	77	156	69	748	26	207	541
	F	840	496	529	312	185	1647	472	368	1279
September	E	194	169	81	112	57	562	45	148	414
	F	768	410	496	271	139	1363	447	320	1043
October	E	174	120	92	81	39	400	69	105	295
	F	768	325	537	231	94	1080	464	289	791
November	G	1004	311	722	282	29	1034	631	372	661
December	G	1132	259	874	258	1	860	755	376	483
January	G	1202	292	913	290	3	971	780	423	549
February	G	1046	340	743	303	37	1130	637	409	721
March	G	1051	495	678	373	122	1644	574	477	1167
April	G	921	609	539	383	226	2013	438	484	1530
May	G	972	711	531	442	269	2349	409	563	1786
Total		12669	6302	8061	4608	1694	20898	6723	5931	14967

*The electricity used from the grid, is when the solar panel system doesn't produce sufficient power output at a specific hour in a specific month for a specific block to meet the electricity needs of the household, the household will use the grid to provide them with the electricity needed

† The power output produced by the solar panel system used, is when the system produces a sufficient power output to meet the electricity needs of the household at a specific hour in a specific month for a specific block

‡ Power output provided to the grid, is when the solar panel system produces power output that meet the household's electricity needs at a specific hour in a specific month for a specific block, and produces an excess of the household's need, then the excess power output will be provided back to the grid

Table S11. Electricity Consumption and Production for each Block in Idabel for Two selected Solar Panel Systems

Month	Block	Total Use	4 kW				12 kW			
			Production	Electricity Used from Grid[*]	Power Output produced Used †	Provided to Grid ‡	Production	Electricity Used from Grid	Power Output produced Used	Provided to Grid
		kWh/block/year	kWh/block/year				kWh/block/year			
					Traditional Meter					
June	A	1284	739	702	582	157	2450	504	779	1670
July	A	1513	767	844	670	97	2545	604	909	1636
August	A	1314	720	760	554	166	2391	585	729	1662
September	A	1239	584	760	479	105	1938	610	628	1310
November	B	970	328	687	282	46	1089	599	371	718
December	B	1107	284	834	274	11	945	723	385	560
January	B	1189	310	887	302	8	1030	755	434	596
February	B	1029	344	723	306	38	1141	617	412	729
March	B	1031	502	661	370	132	1666	559	472	1194
April	B	918	629	536	382	247	2080	441	477	1604
May	C	936	701	520	416	285	2316	406	530	1786
October	D	1008	467	662	346	120	1550	557	451	1099
Total		13538	6373	8577	4961	1412	21140	6961	6577	14563
					Smart Meter					
June	E	273	228	92	181	46	756	22	251	505
	F	962	511	574	388	123	1693	495	467	1226
July	E	328	240	120	208	33	799	29	299	500
	F	1127	526	676	451	75	1746	586	542	1205
August	E	286	220	109	177	42	730	36	250	480
	F	977	500	613	364	137	1661	548	428	1233
September	E	264	169	123	140	28	561	68	196	365
	F	928	415	601	327	88	1378	539	389	988
October	E	185	129	96	89	40	428	71	114	314
	F	801	338	551	250	87	1122	490	311	810
November	G	970	328	687	282	46	1089	599	371	718
December	G	1107	284	834	274	11	945	723	385	560
January	G	1189	310	887	302	8	1030	755	434	596
February	G	1029	344	723	306	38	1141	617	412	729
March	G	1031	502	661	370	132	1666	559	472	1194
April	G	918	629	536	382	247	2080	441	477	1604
May	G	936	701	520	416	285	2316	406	530	1786
Total		13312	6373	8404	4907	1466	21140	6985	6327	14813

[*] The electricity used from the grid, is when the solar panel system doesn’t produce sufficient power output at a specific hour in a specific month for a specific block to meet the electricity needs of the household, the household will use the grid to provide them with the electricity needed

† The power output produced by the solar panel system used, is when the system produces a sufficient power output to meet the electricity needs of the household at a specific hour in a specific month for a specific block

‡ Power output provided to the grid, is when the solar panel system produces power output that meet the household’s electricity needs at a specific hour in a specific month for a specific block, and produces an excess of the household’s need, then the excess power output will be provided back to the grid

Table S12. Electricity Consumption and Production for each Block in Boise City for Two selected Wind Turbine Systems

Month	**Block**	**Total Use**	**6 kW**				**10 kW**			
			Production	**Electricity Used from Grid***	**Power Output produced Used †**	**Provided to Grid ‡**	**Production**	**Electricity Used from Grid**	**Power Output produced Used**	**Provided to Grid**
		kWh/block/year	**kWh/block/year**				**kWh/block/year**			
					Traditional Meter					
June	A	888	818	156	732	87	1158	57	830	328
July	A	1080	607	480	600	7	848	280	800	48
August	A	983	496	490	493	3	691	326	657	35
September	A	799	599	255	543	56	842	166	633	209
November	B	671	680	173	498	182	973	98	573	400
December	B	768	675	210	557	117	970	122	646	324
January	B	781	638	237	544	94	914	145	636	278
February	B	682	691	163	519	172	998	88	594	405
March	B	678	873	100	578	295	1263	40	638	625
April	B	606	1053	29	577	476	1541	0	606	935
May	C	604	878	49	556	322	1252	9	595	656
October	D	667	697	154	513	184	994	90	577	416
Total		9206	8704	2497	6709	1995	12445	1421	7785	4660
					Smart Meter					
June	E	194	212	11	182	30	303	0	194	109
	F	658	606	123	536	70	855	62	597	259
July	E	247	165	82	165	0	231	22	225	6
	F	785	442	346	439	3	617	209	577	41
August	E	222	126	96	126	0	175	49	173	2
	F	719	370	350	369	1	516	229	490	27
September	E	177	137	49	128	8	192	29	149	44
	F	588	462	170	418	44	650	116	471	179
October	E	129	150	29	100	50	216	17	112	104
	F	521	547	112	409	138	778	63	458	320
November	G	671	680	173	498	182	973	98	573	400
December	G	768	675	210	557	117	970	122	646	324
January	G	781	638	237	544	94	914	145	636	278
February	G	682	691	163	519	172	998	88	594	405
March	G	678	873	100	578	295	1263	40	638	625
April	G	606	1053	29	577	476	1541	0	606	935
May	G	604	878	49	556	322	1252	9	595	656
Total		9029	8704	2328	6701	2003	12445	1297	7732	4713

*The electricity used from the grid, is when the wind turbine system doesn't produce sufficient power output at a specific hour in a specific month for a specific block to meet the electricity needs of the household, the household will use the grid to provide them with the electricity needed

† The power output produced by the wind turbine system used, is when the system produces a sufficient power output to meet the electricity needs of the household at a specific hour in a specific month for a specific block

‡ Power output provided to the grid, is when the wind turbine system produces power output that meet the household's electricity needs at a specific hour in a specific month for a specific block, and produces an excess of the household's need, then the excess power output will be provided back to the grid

Table S13. Electricity Consumption and Production for each Block in Hollis for Two selected Wind Turbine Systems

Month	Block	Total Use	6 kW				10 kW			
			Production	Electricity Used from Grid*	Power Output produced Used †	Provided to Grid ‡	Production	Electricity Used from Grid	Power Output produced Used	Provided to Grid
		kWh/block/year	kWh/block/year				kWh/block/year			
Traditional Meter										
June	A	1629	598	1031	598	0	847	782	847	0
July	A	1568	340	1228	340	0	475	1093	475	0
August	A	1525	300	1225	300	0	419	1106	419	0
September	A	1221	359	862	359	0	503	718	503	0
November	B	985	475	514	471	4	690	369	616	74
December	B	1110	464	646	464	0	675	469	641	34
January	B	1192	511	681	511	0	742	502	690	51
February	B	1042	569	480	562	7	834	317	725	109
March	B	1040	784	316	724	61	1154	162	877	277
April	B	925	847	207	718	129	1248	92	833	415
May	C	1052	682	371	682	0	974	190	863	111
October	D	1000	486	514	486	0	694	365	635	58
Total		14289	6415	8075	6214	201	9254	6164	8125	1130
Smart Meter										
June	E	368	170	199	170	0	242	127	242	0
	F	1189	429	760	429	0	605	583	605	0
July	E	347	102	245	102	0	142	205	142	0
	F	1157	238	919	238	0	333	824	333	0
August	E	346	91	254	91	0	127	218	127	0
	F	1113	209	905	209	0	292	822	292	0
September	E	265	96	169	96	0	134	130	134	0
	F	908	263	645	263	0	369	539	369	0
October	E	195	122	80	115	8	174	59	136	39
	F	778	364	417	361	3	519	296	482	37
November	G	985	475	514	471	4	690	369	616	74
December	G	1108	464	644	464	0	675	476	631	43
January	G	1192	511	681	511	0	742	502	690	51
February	G	1042	569	480	562	7	834	317	725	109
March	G	1040	784	316	724	61	1154	162	877	277
April	G	925	847	207	718	129	1248	92	833	415
May	G	1052	682	371	682	0	974	190	863	111
Total		14009	6415	7805	6204	211	9254	5912	8097	1157

*The electricity used from the grid, is when the wind turbine system doesn't produce sufficient power output at a specific hour in a specific month for a specific block to meet the electricity needs of the household, the household will use the grid to provide them with the electricity needed

† The power output produced by the wind turbine system used, is when the system produces a sufficient power output to meet the electricity needs of the household at a specific hour in a specific month for a specific block

‡ Power output provided to the grid, is when the wind turbine system produces power output that meet the household's electricity needs at a specific hour in a specific month for a specific block, and produces an excess of the household's need, then the excess power output will be provided back to the grid

Table S14. Electricity Consumption and Production for each Block in Shawnee for Two selected Wind Turbine Systems

Month	Block	Total Use	6 kW				10 kW			
			Production	Electricity Used from Grid*	Power Output produced Used †	Provided to Grid ‡	Production	Electricity Used from Grid	Power Output produced Used	Provided to Grid
		kWh/block/year	kWh/block/year				kWh/block/year			
					Traditional Meter					
June	A	1150	432	718	432	0	603	548	603	0
July	A	1444	270	1174	270	0	376	1068	376	0
August	A	1439	243	1196	243	0	338	1101	338	0
September	A	1152	281	870	281	0	392	760	392	0
November	B	991	531	460	531	0	745	319	671	73
December	B	1119	513	607	513	0	720	424	696	25
January	B	1215	565	650	565	0	794	446	769	25
February	B	1041	554	487	554	0	782	326	715	67
March	B	1039	768	311	728	41	1087	185	854	233
April	B	915	778	228	687	91	1101	124	791	310
May	C	949	556	393	556	0	777	241	708	70
October	D	1049	439	610	439	0	612	438	611	2
Total		13502	5929	7704	5797	132	8327	5980	7522	805
					Smart Meter					
June	E	239	98	141	98	0	137	102	137	0
	F	871	334	537	334	0	466	405	466	0
July	E	313	65	248	65	0	90	222	90	0
	F	1076	205	871	205	0	286	790	286	0
August	E	317	57	259	57	0	80	237	80	0
	F	1064	185	879	185	0	258	807	258	0
September	E	239	62	177	62	0	86	152	86	0
	F	873	219	653	219	0	305	567	305	0
October	E	201	89	112	89	0	124	85	116	8
	F	821	350	470	350	0	489	335	486	3
November	G	991	531	460	531	0	745	319	671	73
December	G	1119	513	607	513	0	720	424	696	25
January	G	1215	565	650	565	0	794	446	769	25
February	G	1041	554	487	554	0	782	326	715	67
March	G	1039	768	311	728	41	1087	185	854	233
April	G	915	778	228	687	91	1101	124	791	310
May	G	949	556	393	556	0	777	241	708	70
Total		13281	5929	7484	5797	132	8327	5768	7513	814

*The electricity used from the grid, is when the wind turbine system doesn’t produce sufficient power output at a specific hour in a specific month for a specific block to meet the electricity needs of the household, the household will use the grid to provide them with the electricity needed

† The power output produced by the wind turbine system used, is when the system produces a sufficient power output to meet the electricity needs of the household at a specific hour in a specific month for a specific block

‡ Power output provided to the grid, is when the wind turbine system produces power output that meet the household’s electricity needs at a specific hour in a specific month for a specific block, and produces an excess of the household’s need, then the excess power output will be provided back to the grid

Table S15. Electricity Consumption and Production for each Block in Miami for Two selected Wind Turbine Systems

Month	Block	Total Use	6 kW				10 kW			
			Production	Electricity Used from Grid[*]	Power Output produced Used †	Provided to Grid ‡	Production	Electricity Used from Grid	Power Output produced Used	Provided to Grid
		kWh/block/year	kWh/block/year				kWh/block/year			
Traditional Meter										
June	A	1121	234	887	234	0	326	794	326	0
July	A	1334	144	1190	144	0	200	1134	200	0
August	A	1112	137	975	137	0	190	922	190	0
September	A	990	167	823	167	0	232	758	232	0
November	B	1004	352	652	352	0	492	514	489	2
December	B	1132	329	803	329	0	460	672	460	0
January	B	1202	380	822	380	0	531	671	531	0
February	B	1046	366	680	366	0	512	534	512	0
March	B	1051	488	563	488	0	682	407	644	38
April	B	921	491	435	486	4	688	314	607	81
May	C	972	298	674	298	0	414	558	414	0
October	D	962	258	704	258	0	359	603	359	0
Total		12847	3642	9209	3637	4	5087	7881	4965	122
Smart Meter										
June	E	238	53	185	53	0	75	164	75	0
	F	840	181	659	181	0	252	588	252	0
July	E	284	37	247	37	0	51	233	51	0
	F	1002	107	895	107	0	149	853	149	0
August	E	233	35	198	35	0	49	185	49	0
	F	840	102	738	102	0	142	698	142	0
September	E	194	37	157	37	0	51	143	51	0
	F	768	130	637	130	0	181	587	181	0
October	E	174	53	121	53	0	74	100	73	1
	F	768	204	563	204	0	285	469	284	0
November	G	1004	352	652	352	0	492	514	489	2
December	G	1132	329	803	329	0	460	672	460	0
January	G	1202	380	822	380	0	531	671	531	0
February	G	1046	366	680	366	0	512	534	512	0
March	G	1051	488	563	488	0	682	407	644	38
April	G	921	491	435	486	4	688	314	607	81
May	G	972	298	674	298	0	414	558	414	0
Total		12669	3642	9031	3637	4	5087	7690	4965	123

[*] The electricity used from the grid, is when the wind turbine system doesn't produce sufficient power output at a specific hour in a specific month for a specific block to meet the electricity needs of the household, the household will use the grid to provide them with the electricity needed

† The power output produced by the wind turbine system used, is when the system produces a sufficient power output to meet the electricity needs of the household at a specific hour in a specific month for a specific block

‡ Power output provided to the grid, is when the wind turbine system produces power output that meet the household's electricity needs at a specific hour in a specific month for a specific block, and produces an excess of the household's need, then the excess power output will be provided back to the grid

Table S16. Electricity Consumption and Production for each Block in Idabel for Two selected Wind Turbine Systems

Month	Block	Total Use	6 kW				10 kW			
			Production	Electricity Used from Grid*	Power Output produced Used †	Provided to Grid ‡	Production	Electricity Used from Grid	Power Output produced Used	Provided to Grid
		kWh/block/year	kWh/block/year				kWh/block/year			
Traditional Meter										
June	A	1284	116	1168	116	0	161	1122	161	0
July	A	1513	67	1446	67	0	93	1420	93	0
August	A	1314	61	1252	61	0	85	1228	85	0
September	A	1239	86	1153	86	0	120	1119	120	0
November	B	970	179	791	179	0	249	721	249	0
December	B	1107	218	889	218	0	304	803	304	0
January	B	1189	241	948	241	0	336	853	336	0
February	B	1029	236	793	236	0	329	700	329	0
March	B	1031	310	721	310	0	433	598	433	0
April	B	918	287	631	287	0	401	521	397	4
May	C	936	167	769	167	0	232	704	232	0
October	D	1008	116	892	116	0	161	847	161	0
Total		13538	2084	11454	2084	0	2906	10636	2902	4
Smart Meter										
June	E	273	33	241	33	0	45	228	45	0
	F	962	83	878	83	0	116	846	116	0
July	E	328	21	307	21	0	29	299	29	0
	F	1127	46	1082	46	0	63	1064	63	0
August	E	286	20	266	20	0	28	258	28	0
	F	977	41	936	41	0	57	919	57	0
September	E	264	21	243	21	0	29	234	29	0
	F	928	65	863	65	0	90	838	90	0
October	E	185	28	157	28	0	39	146	39	0
	F	801	88	713	88	0	122	679	122	0
November	G	970	179	791	179	0	249	721	249	0
December	G	1107	218	889	218	0	304	803	304	0
January	G	1189	241	948	241	0	336	853	336	0
February	G	1029	236	793	236	0	329	700	329	0
March	G	1031	310	721	310	0	433	598	433	0
April	G	918	287	631	287	0	401	521	397	4
May	G	936	167	769	167	0	232	704	232	0
Total		13312	2084	11227	2084	0	2906	10409	2902	4

*The electricity used from the grid, is when the wind turbine system doesn't produce sufficient power output at a specific hour in a specific month for a specific block to meet the electricity needs of the household, the household will use the grid to provide them with the electricity needed

† The power output produced by the wind turbine system used, is when the system produces a sufficient power output to meet the electricity needs of the household at a specific hour in a specific month for a specific block

‡ Power output provided to the grid, is when the wind turbine system produces power output that meet the household's electricity needs at a specific hour in a specific month for a specific block, and produces an excess of the household's need, then the excess power output will be provided back to the grid

CHAPTER IV

EPILOGUE

The primary purpose of this dissertation research was to determine the economic consequences of grid-tied electricity microgeneration systems for Oklahoma households. Two commercially available household solar panel systems (4 kW and 12 kW) and two wind turbine (6 kW and 10 kW) systems were evaluated for each of five households and two pricing rate systems (traditional meter and smart meter). Twenty years of hourly weather data for the five unique household locations were available from the Oklahoma Mesonet system. These data in combination with the power production functions for each of the four devices was used to estimate the power output for each hour for each month for each location for each device. Household electricity use estimates were obtained from simulations of representative households for each location. Retail prices of grid-purchased electricity were based on Oklahoma Corporation Commission approved traditional and smart meter rates. Standard budgeting methods were used to produce estimates of annual cost for each of the four microgeneration systems.

It was determined that none of the four grid-tied systems is economically competitive with grid-only electricity for any of the five household locations. The estimated annual cost for the least costly microgeneration system, the grid-tied 4 kW solar panel system with net metering, is more than two times greater than the cost of grid-only electricity.

The consequences of federal tax credits were not directly evaluated. The net effect of an income tax credit for a household with sufficient income to take advantage of the credit is to reduce the effective purchase price of the microgeneration system [1]. For example, the budgeted purchase and installation prices were $32,000, $65,000, $55,000, and $65,000 for the 4 kW and 12 kW solar panel systems and 6 kW and 10 kW wind turbine systems, respectively. The net effect of a 30% income tax credit for a household with sufficient income to use the full credit, would reduce the effective installation costs to $22,400, $45,500, $38,500, and $45,500. However, the most favored location, across the five households for a grid-tied wind turbine to compete with grid-only electricity, is Boise City. The price of a 6 kW wind turbine would have to decline from $55,000 to $2,301 for it to breakeven with grid-only electricity for a smart-metered Boise City household. Similarly, installation costs of a grid-tied 4 kW solar panel for the most favorable Hollis location would have to decrease from $32,000 to $8,431 for it to breakeven with grid-only assuming traditional meter rates with net metering. By these measures, a 30% income tax credit would not be sufficient to incentivize any of the five households to install a solar or wind microgeneration system even with net metering.

In the USA the 30% federal income tax credit for installed small wind turbines expired at the end of 2016 [1]. By current policy, the 30% credit for solar panels remains in effect through 2019. For 2020 and 2021 the credit is scheduled to be reduced to 26%. A credit of 22% is scheduled to be available for 2021 and 2022 with zero credits after that time [1].

Carbon tax

An additional objective of the research was to determine the consequences of a carbon tax on household electricity cost and to determine the level of carbon tax required to incentivize households to install microgeneration systems. An estimate of the appropriate carbon tax to be imposed on household electricity requires an estimate of the social cost of carbon emissions. There is no universally accepted estimate of the cost to society of emissions. Estimates are sensitive to forecasts of future consequences and to the discount rate.

For the purpose of this research, the social cost of CO_2 (SC-CO_2) estimate, derived with a 3% discount rate, by the USA government's Interagency Working Group on the Social Cost of Carbon of \$37.2 per Mg [2] was used. The Interagency Working Group is a committee composed of representatives from a number of USA government agencies including: Council of Economic Advisers; Council on Environmental Quality; Department of Agriculture; Department of Commerce; Department of Energy; Department of Transportation; Environmental Protection Agency; National Economic Council; Office of Management and Budget; Office of Science and Technology Policy; Department of the Treasury. The SC-CO_2 is intended to be a comprehensive estimate of damages resulting from changes in increased levels of CO_2 in the atmosphere on net agricultural productivity, human health, flood risk, reduced costs for heating, and increased costs for air conditioning.

Based on the portfolio of fuels used to generate electricity sold to households in the case study region of Oklahoma, a charge of \$0.0195 per kWh would be required to account for the SC-CO_2 of $37.2 per metric ton of emitted CO_2. Reduction in household electricity use in response to the price increase was estimated based on an electricity price elasticity estimate for Oklahoma households of -0.174 [3], with use reduction capped at 20%. Adding the carbon tax to the retail price of electricity was found to be insufficient to incentivize households to install either a solar panel or wind turbine system. For the systems to breakeven with grid-only electricity, rather than $0.0195 per kWh, a carbon tax of $0.39, $0.70, $1.22, and $1.08 per kWh for the 4 kW and 12 kW solar panel systems and 6 kW and 10 kW wind turbine systems, respectively, would be required.

Welfare implication of carbon tax

The national average portfolio of fuels used to generate grid electricity emits 0.50 kg CO_2 per kWh, similar to the portfolio in the case study region (0.53 kg CO_2 per kWh) [4, 5, 6]. Hence, electricity use and emissions to produce grid electricity for the case study households is assumed to be representative of USA households. Figure IV-1 shows the welfare implication of adding the carbon tax ($0.0195/kWh) as described in Chapter III (Table III-1).

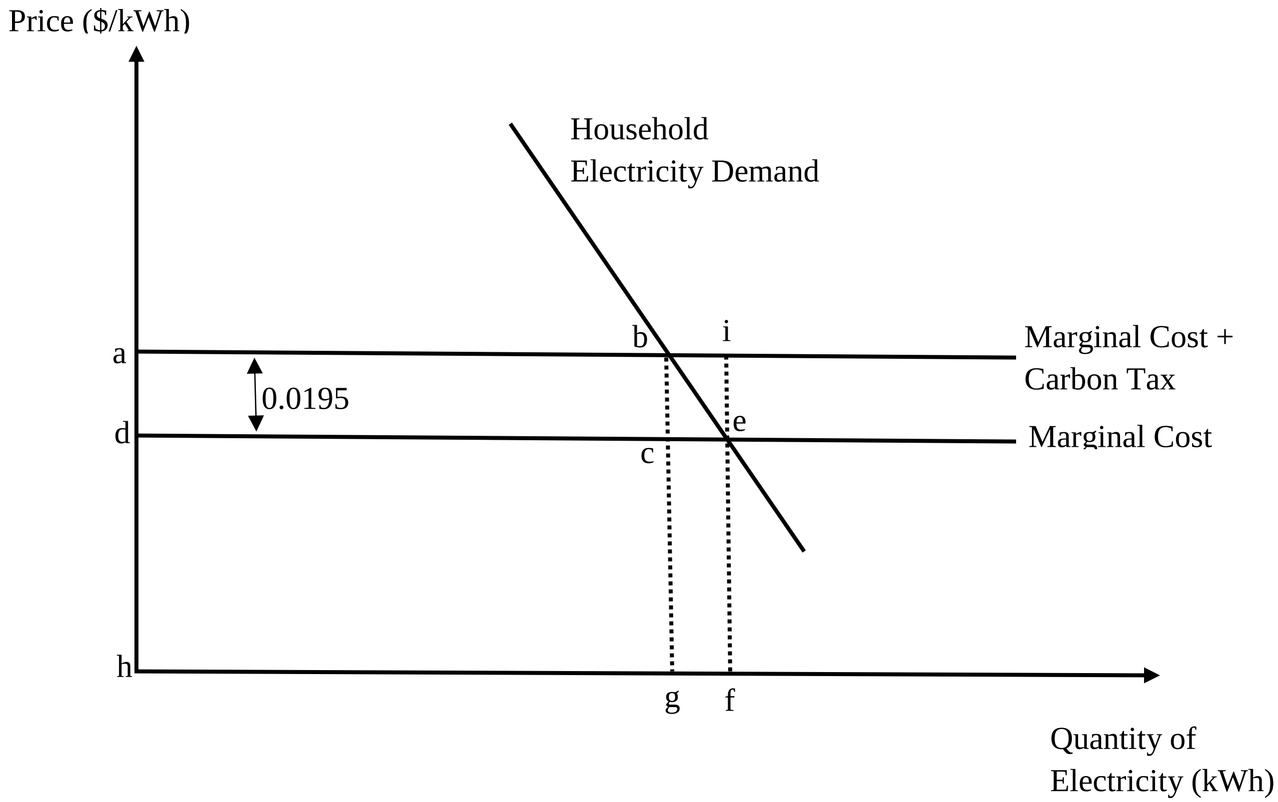

Figure IV-1: Welfare implication of carbon tax

It was assumed that the case study households are representative of the 126 million USA households [7]. Before adding the carbon tax, the average annual electricity consumption was 12,571 kWh per household (point f). The annual cost of electricity is represented by the area enclosed by d-e-f-h, which was estimated to be $1,050 per household (Figure IV-1, Table III-1). Adding a carbon tax of $0.0195 per kWh to the retail price (the distance between points a and d) is expected to incentivize households to decrease the annual electricity consumption to 11,989 kWh (point g). This follows from the estimated -0.174 electricity demand price elasticity [3]. The annual cost of electricity after adding the carbon tax ($1,252) is represented by the area enclosed by a-b-g-h in Figure IV-1.

The area enclosed by a-b-c-d is the annual tax collected from the household. It was estimated to be $233.8[1] per household (Table III-1). Assuming that households in the case study region are representative of the 126 million USA households, the total annual tax collected would be more than $29 billion. The area enclosed by c-e-f-g represents the annual reduction in payments to the grid-electricity provider due to the decrease in household electricity consumption in response to the carbon tax of $0.0195 per kWh. The annual reduction in payments to the grid-electricity provider was estimated to be $31.4[2] per household ($3.9 billion for the USA).

The area enclosed by a-i-d-e is an estimate of the social cost of the emitted CO_2 prior to imposition of the tax when emissions are valued at $37.2 per metric ton of emitted CO_2. This is estimated to be $245 per household. In the absence of a carbon tax, this is an estimate of the cost that the current household is imposing on future generations. Imposing a carbon tax of $0.0195 per kWh would reduce this cost on future generations by the area enclosed by b-i-e-c, which is $11.3 per household per year. This $11.3 is 4.6% of the total social cost of the emitted CO_2 prior to imposition of the tax.

Several studies have suggested alternatives for using the revenue from the carbon tax [8-12]. One of the alternatives is to offset the burden created by the carbon tax (neutral distribution of the revenue). According to Table III-1, the annual tax cost is estimated to be $203 per household. Theoretically, the household cost of the carbon tax

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[1, 2] The estimated annual cost averaged among the five households is a simple average (unweighted). The price rates (traditional meter and smart meter rates) differ in each block. Therefore, when averaged across the five households and two pricing systems, the overall average price charged before and after imposing the carbon tax is $0.084/kWh and $0.104/kWh, respectively. The average difference between the two prices is $0.0209/kWh. When estimating the area enclosed by a-b-c-d with the average difference, the estimated area (annual tax collected) is computed to be $251 (rather than $234). By these measures the area enclosed by c-e-f-g (annual reduction in payment for grid-electricity) is estimated to be $49 (rather than $31).

could be returned to the household as a lump sum via other means, such as a reduction in federal income tax. Note that the annual tax collected, estimated to be $234, exceeds the annual increase in household expenditure of $203 by $31 per household. Assuming zero transactions costs of implementing, policing, and collecting the tax, if imposed across all USA households, an estimated $3.9 billion (net social dividend) would be available for other uses after compensating households for the cost of the tax. These calculations ignore the change in household utility and substitutions in consumption resulting from the carbon tax implementation.

Recommendations for additional research

The analysis conducted can be characterized as partial equilibrium. It does not consider household changes in consumption of other goods and services in response to a carbon tax. Also, it does not consider changes made by providers of grid electricity in response to the tax. Additional research in a more general equilibrium framework would be required to more fully analyze expected consequences of a carbon tax on household behavior.

Additional research to determine the most efficient means for implementing and managing a carbon tax is warranted. Some collected funds could be used to support and fund additional research and development of alternative low and zero carbon emission energy systems. Funds could be used to subsidize renewable energy technologies and zero carbon emissions technologies [8-12]. Additional research is also warranted to determine the consequences of installing household grid-tied solar panel and wind turbine systems on electricity utility companies.

A report from the National Surveys on Energy and Environment [13] found that 56% of Americans support a revenue-neutral carbon tax. Sixty percent support the use of carbon tax revenue to fund research and development for renewable energy programs. Based on the findings of this study, use of the tax to incentivize household microgeneration wind and solar systems would not be warranted.

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