Consequences of a carbon tax on household electricity use and cost, carbon emissions, and economics of household solar and wind

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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 $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 $1546 (247%) and decrease CO_2 emissions by 38% (2526 kg) 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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1. Introduction

Global atmospheric concentration of CO_2 increased from 312 ppm in 1950 to 401 ppm in 2015 (EPA, 2016b). 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 (Marron et al., 2015). 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/Mg in 2010 dollars (Nordhaus, 2017). For a 3% discount rate, the 2016 SC-CO_2 was estimated to be $37.2/Mg by the USA government's Interagency Working Group on the Social Cost of Carbon (Interagency Working Group, 2016).

Electricity generation by fossil fuel combustion is a major source of CO_2 emissions (EPA, 2016a). The conventional textbook solution for improving the efficiency of a production activity that produces external costs is to internalize the externality (Schneider, 1989; Nordhaus,

1991; Poterba, 1991; Ulph and Ulph, 1994; Sumner et al., 2011; Heal and Millner, 2014; Dennig et al., 2015). 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.

Most prior research has focused on the expected aggregate consequences of carbon taxation (Schneider, 1989; Nordhaus, 1991; Poterba, 1991; Ulph and Ulph, 1994; Palmer and Burtraw, 2005; Sumner et al., 2011; Lim and Kim, 2012; Orlov et al., 2013; Heal and Millner, 2014; Dennig et al., 2015). Consequences are assumed to be similar across households. However, households are not homogeneous and the economic consequences of implementation of a carbon tax on household electricity may differ substantially among households. Electricity use, especially for cooling and heating, differ across similarly sized households in response to external climate. In addition, the economic potential for households to respond to a carbon tax by installing a microgeneration solar or wind system also depends on local conditions such as wind speed and solar radiation. Information regarding the extent to which potential economic consequences differ across households would be useful for policy makers as they design and implement public policies to address the carbon emissions issue. Information regarding the expected net consequences of a carbon tax and household

microgeneration systems would also be of value to citizens who will respond to implementation of a carbon tax.

The purpose of this paper is 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. A comprehensive evaluation of electricity production from microgeneration systems requires relatively precise estimates of weather data for the location under study. The USA state of Oklahoma has a unique mesonet weather system that has recorded 20 years of hourly solar radiation, temperature, and wind speed data for >100 sites across the state (Oklahoma Mesonet, 2016). The geography and climate of the state is quite diverse (EIA, 2003; NREL, 2009; WRI, 2009). For example, Idabel (33° 49′ 48″ N 94° 52′ 49″ W) in the southeast has an elevation of 110 m with 132 cm of annual rainfall, average solar radiation of 189 W/m^2, and average wind speed of 2.8 m/s. Boise City (36° 41′ 33″ N 102° 29′ 49″ W) in the northwest, is at an elevation of 1267 m with 46 cm of annual rainfall, average solar radiation of 220 W/m^2, and average wind speed of 5.5 m/s (Oklahoma Mesonet, 2016).

An additional factor relative to household electricity markets is that investor-owned electric utilities are natural monopolies. In the USA, rates charged by investor-owned public utilities are regulated by state authorities. Two pricing systems exist in Oklahoma; traditional and smart meter. Traditional accumulation meters measure total consumption. They do not provide information on when the energy is used during the time of interest. Households are charged based on the total electricity consumed in the billing period (usually one month). Smart meters enable two-way communication between the electric company and the household. 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). 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.

This study is unique in several important aspects. First, it uses household scale information for five precise locations. Second, 20 years of hourly solar radiation and wind speed data as recorded by the mesonet weather monitoring system enables empirical estimates of solar panel and wind turbine electricity production for each hour of each month for each of the five unique locations. Third, the modeling system also accounts for differences in temperature when estimating electricity production. Fourth, 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 (Wilson et al., 2014). These simulations find that each location has a unique average load profile resulting from differences in climate and household characteristics. Fifth, 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 and in response to implementation of a carbon tax. Sixth, 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. A 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 a carbon tax on household electricity use differ among similarly sized households located geographically in close proximity but subject to different climate conditions.

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).

Household microgeneration systems are rare in the state. According to the Solar Energy Industries Association (2017), 0.02% (336) of Oklahoma residences had solar panel systems. Oklahoma ranked 47th among the 50 USA states in terms of household solar. Household wind turbine systems were also not common. Data for urban areas are not available. However, a 2009 census survey found that only 20 of Oklahoma's 80,000 farms reported an installed wind turbine for on-farm use (Vilsack and Clark, 2011).

2. Conceptual framework

2.1. 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 (Maleki and Askarzadeh, 2014; Ghaith et al., 2017a). Electricity output (kW) from a solar panel can be estimated by:

$$P = 0.001(IA\eta_{PV}\varphi) \tag{1}$$