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Modeling energy consumption and CO_2 emissions at the urban scale: Methodological challenges and insights from the United States

Lily Parshall [a,*], Kevin Gurney [b], Stephen A. Hammer [a], Daniel Mendoza [b], Yuyu Zhou [b], Sarath Geethakumar [b]

[a] Center for Energy, Marine Transportation and Public Policy, Columbia University, 514 West 113th Street, New York, NY 10025, United States
[b] Department of Atmospheric Sciences, 550 West Stadium Mall Drive, Purdue University, West Lafayette, IN 77907, United States

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ABSTRACT

Local policy makers could benefit from a national, high-resolution inventory of energy consumption and related carbon dioxide (CO_2) emissions based on the Vulcan data product, which plots emissions on a 100 km^2 grid. We evaluate the ability of Vulcan to measure energy consumption in urban areas, a scale of analysis required to support goals established as part of local energy, climate or sustainability initiatives. We highlight the methodological challenges of this type of analytical exercise and review alternative approaches. We find that between 37% and 86% of direct fuel consumption in buildings and industry and between 37% and 77% of on-road gasoline and diesel consumption occurs in urban areas, depending on how these areas are defined. We suggest that a county-based definition of urban is preferable to other common definitions since counties are the smallest political unit for which energy data are collected. Urban counties, account for 37% of direct energy consumption, or 50% if mixed urban counties are included. A county-based definition can also improve estimates of per-capita consumption.

1. Introduction

While federal and state governments dictate much of US energy policy, increasingly municipal authorities are engaging on energy issues, often within the context of local climate or sustainability initiatives. Because of their density of demand, cities can take advantage of a wide array of technology and policy options to increase energy efficiency and reduce per-capita consumption of fossil fuels. But local planners also face several challenges, including inadequate data, decentralized energy planning, and the difficulty of formulating local policy to address national and international problems.

In this paper we suggest that local policy makers could benefit from a national, high-resolution inventory of energy consumption and related carbon dioxide (CO_2) emissions. A national inventory, completed at regular intervals, would allow local authorities to establish baseline energy consumption and monitor changes over time, compare themselves to other similar localities, set appropriate energy- and emissions-reduction targets, and support local participation in carbon markets. Such an inventory also could provide the type of consistent data needed to analyze how different aspects of the urban environment interact with socio-demographic factors to shape patterns of energy use, informing debates on smart growth and urban sprawl.

The Vulcan data product is promising as the basis of an inventory because it consolidates data from a wide variety of point, non-point, and mobile sources and quantifies these data in their "native" resolution (geocoded points, roads, counties) and on a regular 100 km^2 (10 km × 10 km) grid over the conterminous United States every hour of the year (Gurney et al., 2008, 2009). Vulcan draws on point source and county-scale non-point source data, the highest resolution at which these data are available. Vulcan was originally conceived of as an inventory of fossil-based sources of carbon with scientific applications in carbon cycle modeling, so the results do not cover renewable energy or nuclear power, which together comprise approximately 28% of electricity supply. With these exceptions, Vulcan offers complete and systematic coverage of energy-related CO_2 emissions in the residential, commercial, industrial, transportation, and electricity sectors.[1] Since Vulcan categorizes emissions into 50 different sub-fuels, it is relatively straightforward to convert between metric tons of CO_2 and gigajoules (GJ) of energy.[2] The ability to

* Corresponding author. Tel.: +1 212 854 0615; fax: +1 212 854 0603.
E-mail address: llp15@columbia.edu (L. Parshall).

[1] Vulcan also covers carbon emissions associated with agriculture and cement production.

[2] For clarity, we refer to the detailed fuel breakdown, which distinguishes between different types of coal (e.g. bituminous vs. subbituminous), natural gas (e.g. gas vs. LPG), and fuel oil (e.g. distillate vs. residual), as "sub-fuel" data.

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distinguish between the energy and carbon intensity of different sectors can help local authorities analyze trade-offs between policies to reduce energy consumption and policies to reduce the carbon intensity of fuel use.

Much of the literature on local energy consumption and emissions inventories focuses on urban areas. Interest in urban energy consumption stems from the central role that cities play in shaping global energy demand as well as growing urban leadership on climate change mitigation. Our research began as part of an effort by the International Energy Agency (IEA) to quantify urban energy consumption for the 2008 World Energy Outlook (WEO) (IEA, 2008). The IEA study found that globally, urban areas account for 67% of energy consumption and 71% of CO_2 emissions worldwide, figures that are expected to rise in the coming decades given global demographic trends (IEA, 2008).

We used Vulcan to estimate US urban energy consumption for the IEA study since Vulcan is the only national dataset with sufficient spatial resolution to isolate urban and rural areas. We found that 80% of the United States' energy consumption occurs in urban areas, which have slightly lower per-capita consumption than the nation as a whole (IEA, 2008).[3] We used the United Nations' (UN) definition of urban for the United States to maintain consistency with estimates for other regions covered by the IEA analysis (UN, 2009). However, as we show in this paper, the share of energy consumption attributed to urban areas varies widely depending on how urban areas are defined and bounded in space. We suggest that efforts to create local inventories should be mindful of how different spatial scales and urban thresholds affect perceived patterns of urban and rural energy consumption. Inventories that can properly distinguish between localities of different character are needed to make meaningful comparisons of per-capita energy consumption and the energy intensity of different local economies and lifestyles.

A national inventory of local-scale energy use requires the type of data provided by Vulcan at a spatial resolution appropriate for local energy governance. Through our analysis of US urban energy consumption, we combine an exploration of different urban/rural classification systems with an evaluation of Vulcan's current ability to measure local energy use. We highlight methodological challenges inherent in this type of analytical exercise and review alternative approaches. We conclude by recommending improvements in future energy and CO_2 emissions inventories, which will help policy makers at multiple scales make informed decisions regarding energy supply and demand, fossil fuel consumption, and climate change mitigation.

2. Estimating energy consumption and CO_2 emissions at small spatial scales

Currently, there is no centralized reporting of local energy consumption, or related CO_2 emissions, in the United States.[4] A growing number of studies are developing their own estimates at small spatial scales. These studies fall into two broad categories: (1) those that inventory local emissions to directly support local policy objectives and (2) those that analyze a cross-section of localities to derive general relationships between energy use and patterns of urban development. Both types of studies address the dearth of local energy statistics by culling data from multiple sources. They use a combination of downscaling, aggregation, and weighting to estimate consumption at the scale of interest (e.g. metropolitan areas, urban areas, cities, towns, or counties).

ICLEI–Local Governments for Sustainability was one of the first organizations to help local governments conduct GHG emissions inventories.[5] Local authorities prepare two types of inventories: (1) a "corporate" inventory of emissions associated with government buildings, streetlights, traffic signals, and the city-operated vehicle fleet ("organizational boundary")[6]; and (2) a city-wide "community" inventory that covers the residential, commercial, industrial, transportation, and waste sectors ("geopolitical boundary").[7] For energy-related CO_2 emissions, ICLEI has historically focused on accounting for all emissions associated with total final consumption (direct fuel consumption and electricity demand) within a geopolitical boundary. ICLEI has standardized the inventory process by commissioning a proprietary software package and developing the "International Local Government GHG Emissions Analysis Protocol" (ICLEI, 2008b), but cities complete the inventories themselves; have some latitude in their choice of data, baseline year, and level of detail; and are free to decide whether and how to disseminate inventory data and results.[8]

Whereas ICLEI's main objective is to support the emissions reduction efforts of local governments, cross-sectional studies seek to provide an analytical underpinning for sustainable development goals such as reducing urban sprawl and promoting public transportation. The majority of cross-sectional studies develop regression models that relate energy consumption to physical, economic, and social aspects of the urban environment. The dependent variable in these models is typically an energy or emissions indicator such as total or per-capita consumption for a particular fuel or sector. Independent variables to be tested or controlled for might include climate, population density, housing characteristics, energy prices, commuting distance, various indicators of sprawl, and various economic indicators such as GDP, industry mix, or per-capita income. These exercises often use household surveys or other types of sample data rather than community-wide inventories. Examples of residential-sector studies include Moyers et al. (2005) and Ewing and Rong (2008)[9]; examples of transportation-sector studies include Naess et al. (1996) and Holden and Norland (2005).[10] Some of these

[3] The IEA methodology for computing US urban energy consumption is available on the WEO website. The Vulcan data product was used in the US analysis, but the methodology was somewhat different from the methodology described in this paper (IEA, 2008).

[4] We focus on energy-related CO_2 emissions, rather than total GHG emissions. Most urban GHG emissions are associated with the combustion of fossil fuels. In the United States, energy-related CO_2 emissions account for 82% of total GHG emissions (US DOE, 2008a).

[5] Local authorities, with technical assistance from ICLEI's Cities for Climate Change Program (CCP), complete an inventory as part of a program that includes setting emissions reduction targets, identifying policy measures, and evaluating progress. More than 800 local governments worldwide have participated in CCP, many of which have completed GHG emissions inventories (ICLEI, 2008a).

[6] CCP corporate inventories, which typically involve analysis of individual utility bills and fuel purchases, provide a detailed accounting, often at the scale of individual buildings or government departments.

[7] Community inventories incorporate local data on electricity and fuel consumption when available, but can also be constructed by combining local Census data with state and regional electricity and fuel consumption indicators available from the Energy Information Administration (EIA). In the waste sector, the primary source of GHG emissions is methane from landfills.

[8] ICLEI (2008b) contains protocols for conducting local inventories, with the intention of providing an internationally recognized set of standards comparable to standards for national inventories developed by the International Panel on Climate Change (IPCC) (ICLEI, 2008b). The document offers a careful treatment of boundary issues and energy accounting for local-scale inventories.

[9] Ewing and Rong used data from the EIA's Residential Energy Consumption Survey (RECS). See US DOE (2005). Critiques of Ewing and Rong (2008) can be found in Staley (2008) and Randolph (2008).

[10] Schipper (1995) reviews the literature on automobile use and energy consumption in OECD countries.