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Modeling energy consumption and CO_2 emissions at the urban scale: Methodological challenges and insights from the 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 $\times$ 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

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[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.

studies offer nuanced findings. For example, Moyers et al. (2005) found that high-rise buildings in Sydney have higher per-capita CO_2 emissions compared with detached dwellings due to smaller household size. Bento et al. (2005), who found that household characteristics have a stronger influence on commute-mode choice than urban-scale characteristics, do not directly analyze energy consumption, but their study is a good example of a careful statistical analysis.

Several recent studies have combined elements of both approaches to develop cross-sectional local inventories. These studies first derive a set of energy indicators and then scale up to the geographic extent of interest. Although such studies are philosophically rooted in the cross-sectional approach, their methods are similar to the ICLEI community inventories. One example is a recent Brookings study on energy consumption and CO_2 emissions in the 100 largest metropolitan areas in the United States (Brown et al., 2008). The authors compiled residential and highway transportation data for each metropolitan area for 2000 and 2005, constructing a panel that could be used to analyze variation in time and space.[11] Their methodology and data were consistent across all metropolitan areas, allowing them to rank and compare the areas and identify broad patterns of final energy consumption and associated emissions across the most heavily populated parts of the country.

The choice of metropolitan areas as a scale of analysis has several implications. An advantage is the availability of detailed GDP data for each metropolitan area, which can be used to benchmark the energy and carbon intensity of local economies.[12] A disadvantage is that metropolitan areas do not explicitly separate urban and rural areas. In fact, the majority of the US rural population lives within metropolitan areas (Isserman, 2005). One study addressed this problem by dividing each metropolitan area into a central city and suburban regions to examine the relationship between urban form and CO_2 emissions within, as well as across, metropolitan areas (Glaeser and Kahn, 2008).[13] Like the Brookings study, Glaeser and Kahn (2008) developed their own estimates of residential and personal transportation CO_2 emissions for a subset of metropolitan areas, but they used different datasets: the 2001 National Household Travel Survey (NHTS) instead of the Highway Performance Monitoring System (HPMS) for transportation and the 2000 Individual Public Use Microsample (IPUM) instead of US Department of Energy (DOE) data for the residential sector.[14] The lack of standardized datasets is one of many challenges involved in creating inventories that can meet the needs of those interested in cross-sectional analysis. Often, dependent variables are constructed from multiple data sources and incorporate factors, such as housing characteristics, that intuitively belong as independent factors in statistical models. Metropolitan-scale data also may bear little relevance to energy use targeted by local energy policy planning, as the policy control powers of local authorities tend to end at their political boundaries, representing a fraction of the geographic area encompassed by the metropolitan area designation.

2.1. *Local energy accounting*

Local inventories make implicit assumptions about the boundaries of the local energy sector. In local energy accounting a number of different types of inventories have been recognized: (1) corporate energy use by municipal governments or other organizations (e.g. ICLEI corporate inventory); (2) direct final consumption within the local territory, where direct fuel consumption is included, but the power sector is not[15]; (3) total final consumption within the local territory, including imported energy such as heat and electricity generated outside an urban area but excluding energy lost during generation, transmission, and distribution; (4) total primary energy supply to meet demand in the local territory including total fuel consumption associated with electricity generation; and (5) energy embodied in infrastructure as well as material goods and services. The last category encompasses a continuum that spans from life-cycle analysis of local infrastructure to a complete footprint of all goods and services entering and leaving the local territory.

Most local inventories are situated in the third category, suggesting that energy-related CO_2 emissions should be attributed to the point of demand rather than to the point of production. This approach is consistent with national energy inventories, which usually cover total final consumption and primary energy supply. But, national CO_2 emissions inventories use production-based accounting so power-sector emissions, for example, are attributed to the location where they are emitted. From an energy sector perspective, this means that the portion of CO_2 emissions accounts that cover direct final consumption are generally consistent with energy accounts, but other portions are not.

Satterthwaite (2008) discusses the implications of allocating responsibility for local sources of CO_2 emissions under different accounting frameworks. Along with power generation, production-driven accounts may be inflated by industrial emissions associated with products exported from the urban area and transport emissions associated with through-travel. Satterthwaite suggests that demand-driven accounting best captures the role of middle- and upper-income groups in driving consumption patterns, particularly when the embodied energy of goods and services is included (Satterthwaite, 2008). Local accounts that include embodied energy fall within the general framework of ecological footprint analysis, which looks at the impact of a locality's demand on global environmental resources. Estimating embodied energy demand for a local territory in this way is a time- and data-intensive endeavor, but can help cities and consumers understand their role in global supply and demand networks and associated implications for sustainable development.[16] Quantifying embodied emissions is difficult, particularly

[11] The Brookings study chose to focus on these sectors due to data shortcomings (Brown et al., 2008). To estimate residential fuel consumption, Brookings used a similar approach to ICLEI, but relied solely on the Energy Information Administration's (EIA) state data to derive energy indicators for different types of housing stock in different locations rather than incorporate available local data. Brown et al. (2008) provides a brief summary of the study's methodology, data sources, and data gaps. To estimate highway consumption, Brookings used highway traffic count data from the Highway Performance Monitoring System (HPMS) to estimate VMT and associated fuel consumption (Brown et al., 2008). Brown and Logan (2008) and Southworth et al. (2008) describe the residential and transportation sector methodologies in more detail.

[12] GDP data for metropolitan areas are available through the Bureau of Economic Analysis (US BEA, 2008). This is the smallest spatial scale for which GDP data are available in the United States.

[13] This study builds on Kahn's earlier work studying the impact of suburbanization on energy and land consumption (Kahn, 2000).

[14] More information on the NHTS can be found at US DOT (2009). The IPUM dataset, available from the US Census, is a sample of the US population that includes household spending on electricity, fuel oil, and natural gas, which the authors converted to energy consumption using state price indices. The authors first derived average per-capita consumption for each metropolitan area, and then used housing stock characteristics to downscale these estimates to Census tracts. They acknowledge the "coarser procedure" associated with this process, but it does allow them to make a basic comparison between the urban center and suburbs (Glaeser and Kahn, 2008).

[15] In EIA terminology, this is equivalent to delivered energy in the four end-use sectors (residential, commercial, industrial, and transportation).

[16] An example of a local-scale GHG emissions inventory that includes embodied energy demand can be found in the Paris Bilan Carbone (City of Paris, 2008).

given the globalized nature of the economy; examples of recent studies include Lenzen et al. (2004) and Weber and Matthews (2007).

Currently, few local inventories attempt to include embodied energy, but many include electricity demand. Creating accounts of final consumption in the electricity sector that are consistent across energy and CO_2 emissions presents two challenges: (1) estimation of total electricity consumption in a locality and (2) estimation of the fuel mix serving the locality. The Brookings study's authors solved the first problem by obtaining proprietary data on total demand and customers within each utility service area (Brown and Logan, 2008). From this dataset, they derived average electricity consumption per residential customer for each utility serving each metropolitan area, multiplied this figure by the number of households the utility serves in the metropolitan area (with some adjustments to avoid over-counting landlord electricity payments), and extrapolated across utilities to entire metropolitan areas (Brown and Logan, 2008). This multi-step procedure was required since utility service areas tend not to match other types of local boundaries.

Addressing the second problem requires defining which power plants are serving a particular locality, and in what proportion.[17] Since a large number of different power plants generate electricity, which may then be transmitted over long distances before being distributed to households, and since several different distribution network operators may serve a locality, determining the local fuel mix is not an easy task. Brookings applied the statewide average fuel mix to derive emissions, although work on New York City has shown that the urban fuel mix can differ substantially from the state fuel mix (NYC OLTPS, 2008). Approximately 57% of the city's electricity demand is met by in-city power plants, nearly all of which is natural gas, with the remainder imported from fossil, nuclear, and hydro plants in upstate New York, New Jersey, Pennsylvania, and New England (NYC OLTPS, 2008). Using statewide averages obscures differences in local carbon intensity that might result from municipal efforts to purchase cleaner sources of power or to support local generation. Future inventories could be improved by developing methodologies to systematically derive local-scale fuel mix factors.

2.2. Local boundaries and urban/rural classification schemes

Local energy and emissions inventories have been completed at many different spatial scales, and, as Satterthwaite (2008) discusses, comparisons across localities can be very sensitive to these differing scales. The IEA's recent estimate of global urban energy used the UN definition of urban. The UN publishes statistics on urban and rural population for each country, but these numbers do not reflect a standard, international definition of urban. Rather, countries are asked to establish their own definitions "in accordance with their own needs" (UN, 2009).[18] The UN's primary interest is in identification of urban and rural population size, rather than in defining the geographic boundaries of different urban areas. The only international, spatial dataset with urban boundaries is the Global Rural-Urban Mapping Project's (GRUMP) "urban extents," but the spatial boundaries of these extents do not match any of the various definitions of "urban" in the United States (CIESIN, 2004).[19]

Even within the United States, a number of different systems for classifying settlements as "urban" or "rural" have been proposed (Table 1).[20] The authoritative urban/rural classification is the Census Bureau's urban areas, which are divided between "urbanized areas" and smaller, less dense "urban clusters" (US Census, 2000).[21] Urban areas, which are constructed from Census blocks, are the most accurate representation of where urban populations live, but, like GRUMP urban extents, their spatial boundaries are not necessarily aligned with the jurisdictional boundaries of "populated places" such as cities, towns, or counties.[22] Creating an energy inventory at this scale would require data collection for each Census block.

A widely accepted alternative is the Office of Management and Budget's Metropolitan and Micropolitan Statistical Areas, which are also available through the Census (US Census, 2000). Each of these areas is constructed around an urban core and includes adjacent counties that have a high degree of economic integration with the core.[23] Metropolitan areas, which sometimes span several states, may play an informal role in governance but are not recognized as a formal branch of local government, thus reducing the value of metropolitan-scale data to local policy makers. In some cases, such as New York City, the metropolitan area may cross multiple state boundaries, further exacerbating governance issues. Also, metropolitan areas are not irreducible units: they are composed of counties, the highest resolution at which much of the nation's raw energy data are available (Gurney et al., 2008).

The OMB's primary indicator for "level of integration" is commuting patterns between adjacent counties and the urban core. Morrill et al. (1999) argue that metropolitan areas are too large to capture patterns of human settlement and interdependencies revealed by commuting patterns. The authors assign "commuting codes" to Census tracts by analyzing journey to work data and find significant differences between metropolitan areas and interdependent groups of tracts.

In the continental United States, there are approximately 65,000 Census tracts, 3100 counties, and 360 metropolitan areas. Since metropolitan areas do not separate urban and rural areas, but Census tracts are smaller than the highest resolution of available energy data, the county scale holds promise as an intermediate resolution for local inventories.

Inventories that use the Census urban boundaries or the OMB metropolitan area boundaries implicitly group the rural or non-metropolitan parts of the country into a single geographic entity, whereas a county-based classification system can provide coverage of the entire United States at a relatively small spatial

[17] Data on individual power plants, including plant capacity, total production, and CO_2 emissions, are available from a number of sources including US EPA (2008), CARMA (2008), and US DOE (2008b). However, information on where power generated at these facilities is ultimately consumed is not available. Petron et al. (2008) develop an emissions inventory for the US power sector.

[18] National definitions may be based on population size and/or density, or on socioeconomic structure (UN, 2009).

[19] CIESIN analyzed night-time light imagery from remote sensing data sources, built-up land area from the Digital Chart of the World (DCW), and other sources to create spatial boundaries for each urban extent (CIESIN, 2004). It has been suggested that Internet router density may be a better indicator of urbanization than night lights. See Lakhina et al. (2003).

[20] In the United States, cities are defined on the basis of size. Populated places with more than 10,000 people are considered cities. In this paper, we focus on urban/rural classification systems, rather than on cities vs. other settlements.

[21] UN statistics on urban and rural population in the United States reflect this classification scheme.

[22] Isserman (2005) succinctly describes the Census algorithm for constructing urban areas.

[23] For Metropolitan Statistical Areas, the urban core is an urbanized area; for a Micropolitan Statistical area, the urban core is an urban cluster. In New England, metropolitan areas may be composed of cities and towns rather than whole counties. Groups of metropolitan areas with a high degree of economic integration are designated Combined Statistical areas. In this paper, we analyze only Metropolitan areas. We do not analyze Micropolitan areas or Combined Statistical areas.

Table 1
Selected urban–rural classification systems.

United States	Definition	Spatial units used to construct boundaries	Spatial data source	Advantages and disadvantages of classification system
[a]Urban area (Census) *Urbanized area* *Urban cluster*	Urban cluster or urbanized area *>50,000 people, 1000/mi² (386/km²)* *>2,500 people, 500/mi² (193/km²)*	Census block	Census (2000)	Most accurate representation of where people live, but spatial boundaries are not aligned with administrative boundaries. Non-urban settlements are not separated from one another.
[a]Metropolitan area	Core urban center plus adjacent counties as defined OMB	County	Tele Atlas (2005)	Only scale at which GDP data are available, but metropolitan areas include the majority of the rural population and are not irreducible units since they are composed of counties.
[a]Rural–urban continuum	Based on metro/non-metro, adjacent to metro, and population	County	USDA (2003a)	Improves on metro/non-metro classification of counties, but does not explicitly separate urban and rural population.
[a]Rural–urban density code (character)	Based on urban–rural density mix and urban agglomeration	County	Isserman (2005)	Classifies counties as urban or rural using density and agglomeration thresholds for Census urban areas as a starting point, so has the advantage of separating urban and rural areas at an administrative level, but counties may include multiple cities or towns.
[a]Commuting area	Based on commuting flow and classification of destination	Census tract	Morrill et al. (1999)	More accurate than metropolitan areas at separating integrated urban regions, but defined at the Census tract level, which is higher resolution than available energy/emissions data.
Urban influence code	Based on metro/micro, core/non-core, existence of town, and population	County	USDA (2003b)	Improves on urban/rural continuum, but is a somewhat cumbersome classification system and still does not explicitly separate urban and rural counties.
Populated place	Political boundaries for cities, towns, and other incorporated places based on Census (2000)	Census block	Tele Atlas (2006)	Smallest unit for local jurisdictions and appealing from a local governance standpoint, but does not reflect a consistent definition of cities and has a higher resolution than available energy/emissions data.
Urban land cover	Areas of built-up land where large populations exist based on the urban layer of the DCW	None	National Atlas (2006)	Based on land use, but spatial boundaries are not aligned with administrative boundaries. Data on population, income, etc. do not match spatial boundaries.
International (selected)				
United Nations	Accepts urban definition of each country	Non-spatial	UN (2009)	Authoritative international source for urban and rural population counts, but does not reflect a standardized, international definition of urban.
GRUMP urban	Urban extents identified from night lights, DCW data, and other sources	Urban extents defined by analysis	CIESIN (2004)	Only international, spatial dataset with urban boundaries, but urban extents do not match other types of urban boundaries in the US.

[a] These classification systems are included in the analysis shown in Fig. 5.

resolution. Most county classification systems attempt to improve on the metro/non-metro division by incorporating additional attributes such as population size, whether metropolitan counties are part of the urban core, and whether non-metropolitan counties are adjacent to a metropolitan area (USDA, 2003a, b). However, these systems do not incorporate a key element of the Census definition of urban: a population density threshold. Isserman (2005) uses the Census definition of urban areas (population density >500 people per square mile, population in urbanized areas >50,000) as a starting point to classify counties into urban, mixed urban, mixed rural, and rural.[24] Among the county-scale definitions, Isserman's system provides the clearest division between urban and rural areas by requiring that at least 50,000 people or more than 90% of the population must live within an urbanized area in the county to receive a designation of urban. Isserman's definition picks up the core portions of major urban centers in the United States, but excludes smaller cities and suburban regions. For example, in California only the urban cores of San Francisco and Los Angeles are classified as urban, although the majority of California's counties are in metropolitan areas. Fig. 1 compares the spatial extent of urban areas based on Isserman's classification system with Census urban areas, GRUMP urban extents, and OMB metropolitan areas Fig. 2 illustrates various boundaries for the urban area around New York City.

[24] Isserman (2005) describes the classification system. *Urban county:* The county's population density is as least 500 people per square mile; 90% of the county population lives in urban areas; the county's population in urbanized areas is at least 50,000 or 90% of the county population. *Rural county*: The county's population density is less than 500 people per square mile; 90% of the county population is in rural areas or the county has no urban area with a population of 10,000 or more. *Mixed urban county*: The county meets neither the urban nor the rural county criteria; its population density is at least 320 people per square mile. *Mixed rural county*: The county meets neither the urban nor the rural county criteria; its population density is less than 320 people per square mile.

3. Estimating urban energy consumption and CO_2 emissions using Vulcan

We estimate the percentage of direct fuel consumption that occurs in urban areas by using a geographic information system (GIS) to overlay urban boundaries on Vulcan data.[25] Our analysis has three objectives: (1) to illustrate the benefits of a national, high-resolution energy and emissions inventory, (2) to revisit the question of US urban energy consumption, and (3) to uncover

[25] An earlier version of this work appeared in Chapter 8 of the 2008 World Energy Outlook (IEA, 2008).

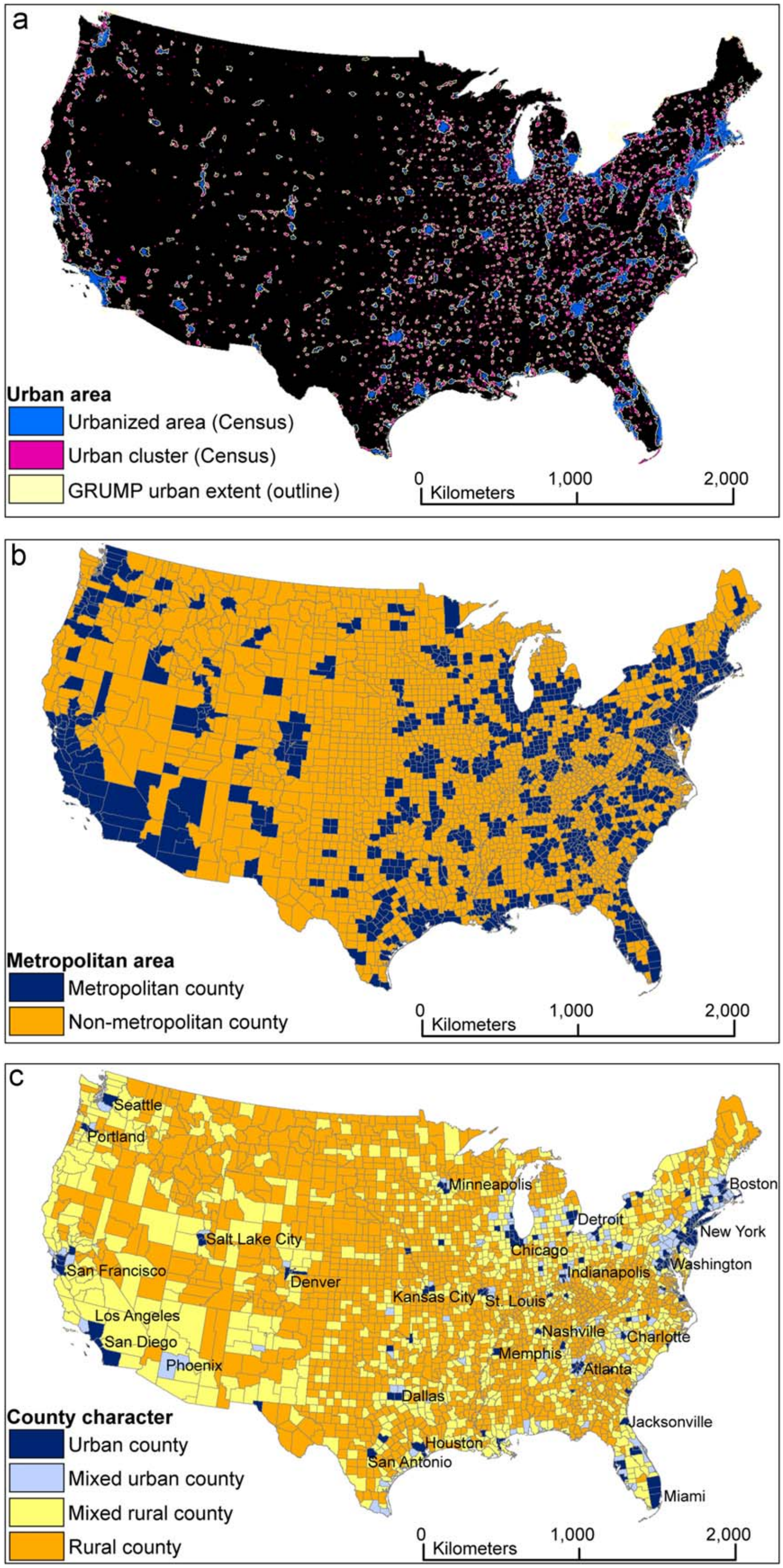

Fig. 1. Spatial extent of selected urban/rural classification systems in the United States. (a) Urban areas defined by the Census and GRUMP. (b) Metropolitan areas defined by the OMB. (c) Urban and rural counties defined by Isserman (2005). Refer to Table 1 for more information about these classification systems.

limitations in the current iteration of the Vulcan data product that could be addressed as part of future efforts to improve its utility for policy applications.

The Vulcan United States fossil fuel CO_2 emissions inventory covers the continental United States and contains hourly data for 2002, although we use aggregate annual data in this

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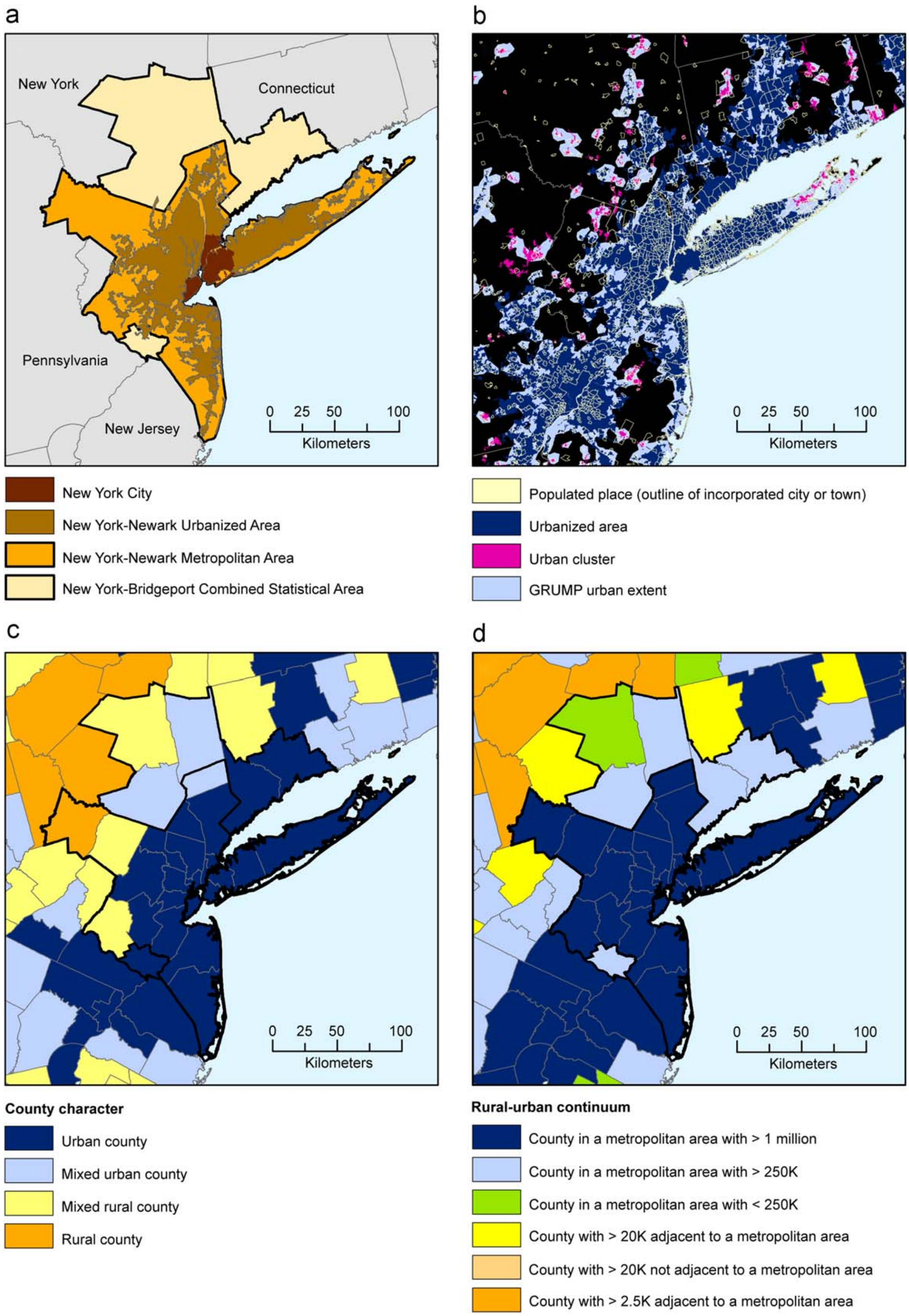

Fig. 2. Spatial boundaries in and around the New York Metropolitan Region. (a) New York City is the core of the New York urbanized area, which is the core of the New York Metropolitan Area. Additional counties within commuting distance of New York City are part of the New York Combined Statistical Area. (b) Urban areas and GRUMP urban extents may be composed of multiple cities and towns. (c) County character. (d) Rural-urban continuum. Refer to Table 1 for more information about these classification systems.

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Table 2
Key data sources for energy-sector CO_2 emissions in Vulcan.

Data source	Direct fuel consumption in buildings and industry National emissions inventory (NEI)		Direct fuel consumption for transportation NEI	 NMIM NCD[c]	Electricity[a] ETS/CEM[d]
Data type	Point	Non-point	Non-road[b]	On road	Power production
Pollutant utilized	CO	CO	Activity and population	VMT & population	CO_2
Incoming spatial resolution	Lat/Lon	County	County	County	Lat/Lon
Incoming temporal resolution	Annual	Annual	Monthly	Monthly	Hourly
Sectors	Commercial Residential Industrial Electric	Commercial Residential Industrial Electric	Transportation	Transportation	Electric

[a] Electricity sector data from Vulcan were not incorporated into our analysis.
[b] Non-road data were not included in the version of Vulcan used in this analysis. Version 1.1 of Vulcan includes airport emissions based on NEI data and aircraft emissions based on Aero 2k data.
[c] NMIM NCD = National Mobile Inventory Model County Database.
[d] ETS/CEM = Emissions Tracking System/Continuous Emissions.

Table 3
Sectors and fuels covered by our analysis of direct final consumption as a percentage of total national primary energy demand.

	Transportation (%)	Industrial (%)	Residential and commercial (%)	Electric power (%)	Total (%)
Petroleum	**27**	**9**	**2**	1	39
Natural gas	**1**	**8**	**8**	7	24
Coal	**n/a**	**1**	$<$**1**	20	22
Renewable energy	1	2	1	3	7
Nuclear electric power	n/a	n/a	n/a	8	8
Total covered	**28**	**18**	$\sim$**10**	0	**56**
Total not covered	1	2	1	40	44

The percentages in this table are estimates based on the total national primary energy demand in 2007 (US DOE, 2008a). Bold sector-fuel combinations were covered by our analysis.

analysis.[26] Vulcan relies on publicly reported emissions inventory and stack monitoring data from facilities statutorily required to report CO_2 or criteria pollutant (CO, O_3, NO_x, So_x, particulates, Pb) emissions to local, state, and federal authorities. Differing methodologies may be employed by the reporting facilities and agencies. The Vulcan effort, with few exceptions, incorporates all data at face value. Criteria pollutant data are used to estimate CO_2 emissions in cases where CO_2 data are not directly available. Table 2 summarizes key sources of emissions data. Vulcan includes emissions defined at geocoded points for electricity production and the majority of industrial emissions. Vulcan downscales area-based emissions (mostly residential and commercial) to the 100 km^2 resolution using building square footage estimates from Census tract data. On-road transportation is downscaled from county-level data via a GIS Road Atlas.[27] The complete Vulcan methodology and data sources are described in Gurney et al. (2009).

Since Vulcan allocates emissions to the point of combustion, the model can be used to estimate direct sources of emissions within a local territory but not emissions associated with imported energy such as electricity. To avoid misallocating power sector emissions, we confined our use of Vulcan to direct fuel consumption by buildings and the transportation sector. This approach is consistent with the accounting approach of direct final consumption, although the exclusion of electricity understates total urban demand.

We include direct consumption of coal, natural gas, and fuel oil in residential, commercial, and industrial buildings. These fuels are used primarily for heating and hot water, though natural gas also is used for cooking. In industrial buildings, fuel is also consumed in industrial production, processing, and assembly of goods.

In the transportation sector, we include gasoline and diesel consumption associated with vehicle miles traveled (VMT) within the local territory.[28] Aviation and marine fuel consumption are excluded because of the difficulty of allocating it to any particular locality and because regional and international factors play such a strong role in these sub-sectors. Since Vulcan covers only fossil fuels, direct consumption of renewable sources of energy are not covered.[29] Table 3 summarizes the sectors and fuels that were included in our analysis of urban energy consumption.[30] Overall, direct consumption of fossil fuels accounts for approximately 95%

[26] Vulcan collects data for Alaska and Hawaii, but these data have not been plotted on the 100 km^2 grid, so we exclude these states from our analysis.

[27] County-level data on VMT are available through the National Mobile Inventory Model (NMIM) County Database (NCD), which quantifies VMT in a county by month, specific to vehicle class and road type. For additional details on Vulcan data sources and methods, see Gurney et al. (2009).

[28] In the transportation sector, the portion of a trip that takes place within the territorial boundaries of a particular locality is attributed to that locality, regardless of where the trip originated or ended. This approach was used for both personal transportation and freight. Although the transportation sector consumes a small amount of natural gas, we exclude this from the analysis due to data constraints.

[29] Vulcan data for the electricity sector do not cover nuclear power or renewables. Our analysis does not cover the electricity sector.

[30] From a greenhouse gas emissions accounting perspective, we cover IPCC Scope 1 emissions associated with stationary combustion in the energy sector, but exclude utility-consumed fuel for electricity and heat generation. This approach is consistent with ICLEI's community-scale Scope 1, which covers "all direct emissions sources located within the geopolitical boundary of the local government" (ICLEI, 2008).

of total direct fuel consumption and 56% of total primary energy demand in the United States.[31]

To convert from metric tons of carbon to GJ of energy, we used emissions coefficients that can be found in Gurney et al. (2008). The availability of sub-fuel data allowed for reasonably accurate conversion to energy units, but some error may have been introduced at this step as a result of varying combustion processes and fuel quality. We next aggregated from sub-fuels to the following major fuel groups: (1) coal, (2) natural gas and LPG, (3) fuel oil and diesel, and (4) gasoline.[32] We grouped fuel oil and diesel because there is no difference between distillate fuel oil used to heat buildings and diesel fuel used in the transportation sector. The result was a 10 km × 10 km grid of energy consumption categorized by fuel type. We also used raw county-level data to create an analogous non-gridded file for our analyses of urban/rural classification systems that have a county spatial resolution.

Emissions from Vulcan can be reported by sectoral (residential, commercial, industrial, transportation) and/or fuel divisions (coal, oil, and natural gas). Rather than employ a dataset with sectoral categories, we used a dataset where emissions were disaggregated by sub-fuel but not by sector. Sub-fuel data were required to convert from emissions to energy units, but sub-fuel data disaggregated by sector were not available at the time of our analysis. We were able to broadly group sub-fuel data into "on-road transportation" and "buildings and industry" by assigning motor gasoline and diesel fuel to "on-road transportation" and all other data to "buildings and industry." Further research is required to develop a more complete sector breakdown, which is needed to separate the energy and carbon intensity of personal consumption from local economic activity. Separating economic activity from household consumption is important since different sets of policy levers may apply to these different sectors.

3.1. Evaluation of Vulcan fuel consumption estimates

We evaluated our fuel consumption estimates by comparing them with US Department of Energy data (DOE) available at the state and national resolution since independent sources of data were not available for a county-scale evaluation.[33] DOE data were obtained from the Energy Information Administration's (EIA) State Energy Data System (SEDS) (US DOE, 2008c). The goal of the evaluation was to compare the estimates of US final consumption obtained by converting Vulcan emissions data to EIA statistics, and to identify any differences between Vulcan and the EIA that might affect our analysis of urban energy consumption.

Table 4
Comparison of Vulcan and EIA totals for direct final consumption in 2002.

	Vulcan (EJ[a])	EIA (EJ)	Difference (EJ)	Difference (%)
Fuel				
Coal	2.16	2.23	−0.07	−3
Natural gas and LPG	21.57	20.84	0.73	4
Oil–diesel, distillate, residual	10.13	9.23	0.90	10
Oil–gasoline	18.94	17.28	1.66	10
Sector				
Buildings and industry[b]	28.90	26.66	2.24	8
On-road transportation[c]	23.90	22.92	0.98	4
National total	**52.80**	**49.58**	**3.22**	**6**

[a] EJ = Exajoule = 10^{18} Joules.
[b] The total for the EIA buildings and industry category includes the following sectors and fuels: residential coal, commercial coal, industrial coal, residential natural gas, commercial natural gas, industrial natural gas, residential LPG, commercial LPG, industrial LPG, residential distillate, commercial distillate, industrial distillate, commercial residual, industrial residual, and transportation residual. The total for the Vulcan buildings and industry category includes coal, natural gas, LPG, distillate, and residual fuel oil.
[c] The total for EIA on-road transportation includes transportation motor gasoline and transportation distillate. The total for Vulcan on-road transportation includes motor gasoline and diesel.

Table 4 summarizes the results of the national evaluation. Overall, the Vulcan total was 6% higher than the EIA total after averaging over all fuel groups. Differences for individual fuels were all less than 10%. Gasoline consumption accounts for over a third of direct final consumption, and the Vulcan estimate for gasoline consumption is 10% higher than the EIA estimate. Vulcan used the EPA's MOBILE6.2 model to directly convert VMT into CO_2 emissions and the national average fleet when characterizing vehicle efficiency. Differences between actual fuel efficiency and the national average explain the bulk of the discrepancy between the EIA and Vulcan gasoline estimates.

Other sources of national differences may be a result of the imperfect process of converting from emissions to energy and/or the imperfect correspondence between the sectors as Vulcan currently covers them versus the definitions used by the EIA. Overall, we believe that the national differences are reasonable given the variety of different data sources used by Vulcan and the EIA.

At the state level, differences were larger, although the two fuels that account for the majority of total consumption (natural gas and gasoline) had the highest correlations (Fig. 3).[34] EIA state estimates are based on sales to large suppliers, who often sell the fuel in other locations. It is not uncommon for fuel sold in one state to be consumed in another. Since the Vulcan project spatially allocates emissions based on the point of combustion, fuel consumption is likely to be allocated to different locations by Vulcan than by the EIA. The Vulcan approach to spatial allocation is better aligned with the goals of local inventories, although methods of data assimilation and downscaling are being improved.

3.2. Spatial overlays

We divided direct energy consumption between urban and rural areas for the following urban/rural classification systems:

[31] These estimates are based on analysis of total primary energy demand in the United States and have not been adjusted to account for the exclusion of Alaska and Hawaii.

[32] We incorporated the following Vulcan sub-fuels into each of these categories: (1) coal–anthracite, bituminous, bituminoussubbituminous, coal, lignite, subbituminous; (2) natural gas and lpg–gas, lpg, naturalgas, processgas, butane, propane, propanebutane; (3) fuel oil consists of both distillate and residual oil–distillateoil, distillateoildiesel, distillateoilno1and2, distillateoilno2, distillateoilno4, oil, wasteoil, dieselkerosene, residualoil, residualoilno5, residualoilno6, crudoil, residualoil, diesel; (4) gasoline–gasoline. The following Vulcan sub-fuels were not included in the analysis because all values were 0: anthraciteculm, distillate, distillateilno1, ethane, heat, lubeoil, rawcoke, refinedoil, refinerygas, sourgas. The following Vulcan sub-fuels were not included because they were considered outside the local energy sector: coke, cokeovengas, cokeovenorblasfurnacegas, crudeoil, jetafuel, jetfuel, jetkerosene, jetnaphtha, kerosene. The following Vulcan sub-fuels were not included because emissions are not associated with fossil fuel combustion: cement, clinker, concrete.

[33] For the evaluation, we used the raw county data, which we then aggregated to states.

[34] A small amount of coal is consumed directly (versus used to produce grid electricity) in the United States. The poor correlation between Vulcan and EIA coal data is likely related to the difficulty of separating direct coal consumption from electricity production.

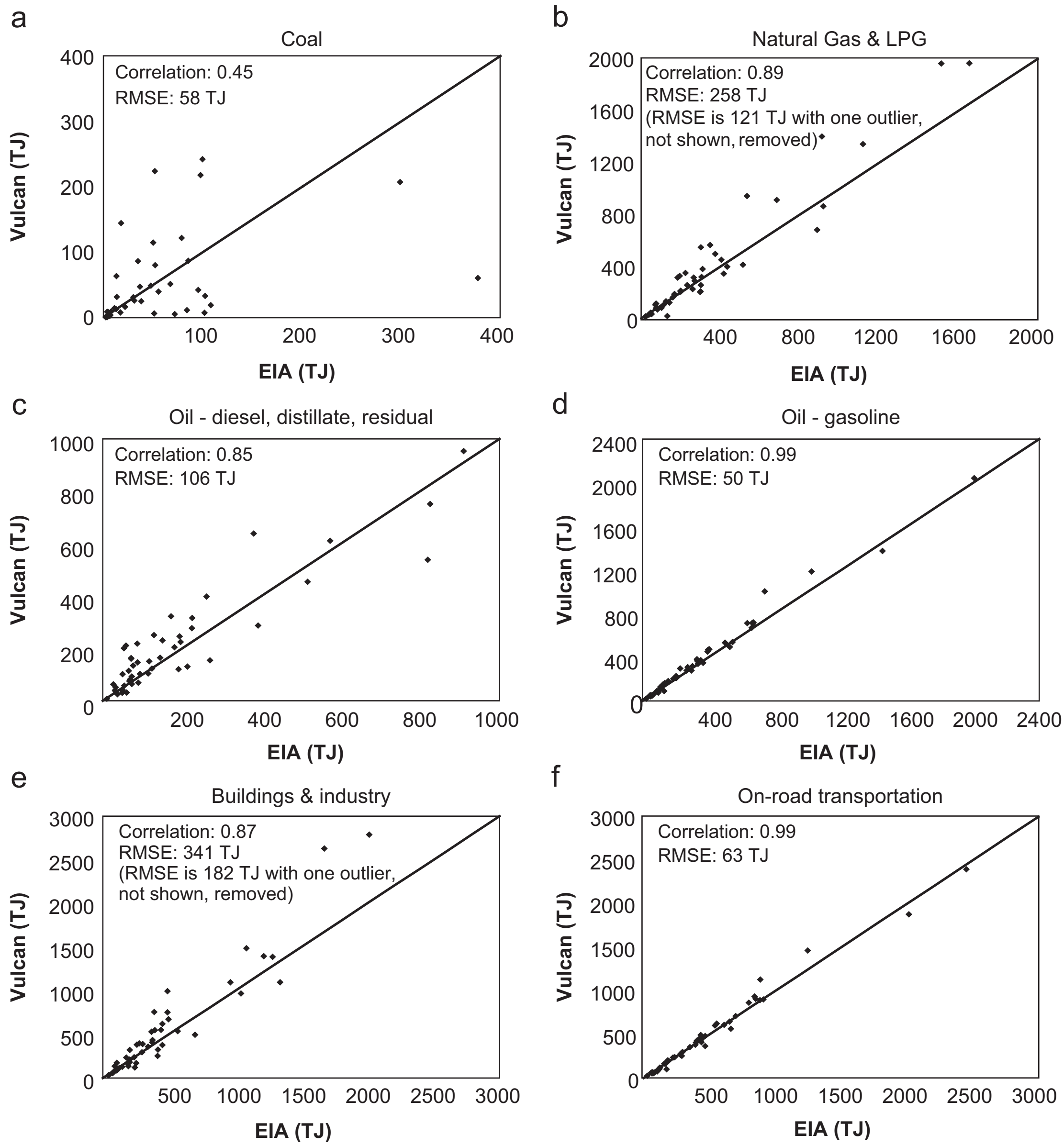

Fig. 3. Comparison between Vulcan fuel consumption and EIA fuel consumption in each state in 2002. (a) Coal. (b) Natural gas and LPG. (c) Oil–diesel, distillate, and residual. (d) Oil–gasoline. (e) Buildings and industry (coal, natural gas, LPG, distillate fuel oil, residual fuel oil). (f) On-road transportation (gasoline, diesel).

Census urban areas, GRUMP urban extents, metropolitan areas, the rural–urban continuum, rural–urban density codes, and commuting areas (see Table 1). For the three classification systems based on counties – metropolitan areas, the rural–urban continuum, and rural–urban density codes – we used Vulcan county-scale data. For other classification systems, we overlaid urban boundaries on the Vulcan 100 km^2 grid.

Census urban areas and GRUMP urban extents are not continuous in space. In other words, they define the extent of each urban area, but blank space in-between is simply "non-urban." To estimate urban energy consumption, we classified all Vulcan grid cells that intersected an urban area as "urban." In the case of the Census classification system, this included both urbanized areas and urban clusters. Fig. 4 illustrates the imperfect match between the Vulcan grid and the Census boundaries, which is particularly pronounced when small, urban clusters are included. We considered weighting Vulcan data based on the percent of the cell inside an urban boundary to avoid overestimating urban energy consumption, but ultimately decided against this since it is unlikely that the "urban" and "rural" portion of these cells have the same energy consumption per unit area. We also considered excluding cells that were below an overlap threshold—for example, cells that were less than 1%, 5%, or 10% urban. We conducted some simple *t*-tests to determine whether these border cells were significantly different from rural and/or non-border urban cells. Since border cells that were just 1% urban were significantly different from rural cells, we chose to include all cells regardless of the extent of overlap.

We did not calculate energy consumption or CO_2 emissions for individual urban areas (as defined by the Census) because of the limitations of the overlay methodology, which not only introduced positive bias, but also raised questions about how to allocate data in Vulcan cells that intersected more than one urban area. These challenges reinforce the limitations of the Census urban boundaries as an appropriate spatial unit for local inventories as well as the difficulty of working with the gridded version of the Vulcan data product when dealing with political boundaries.

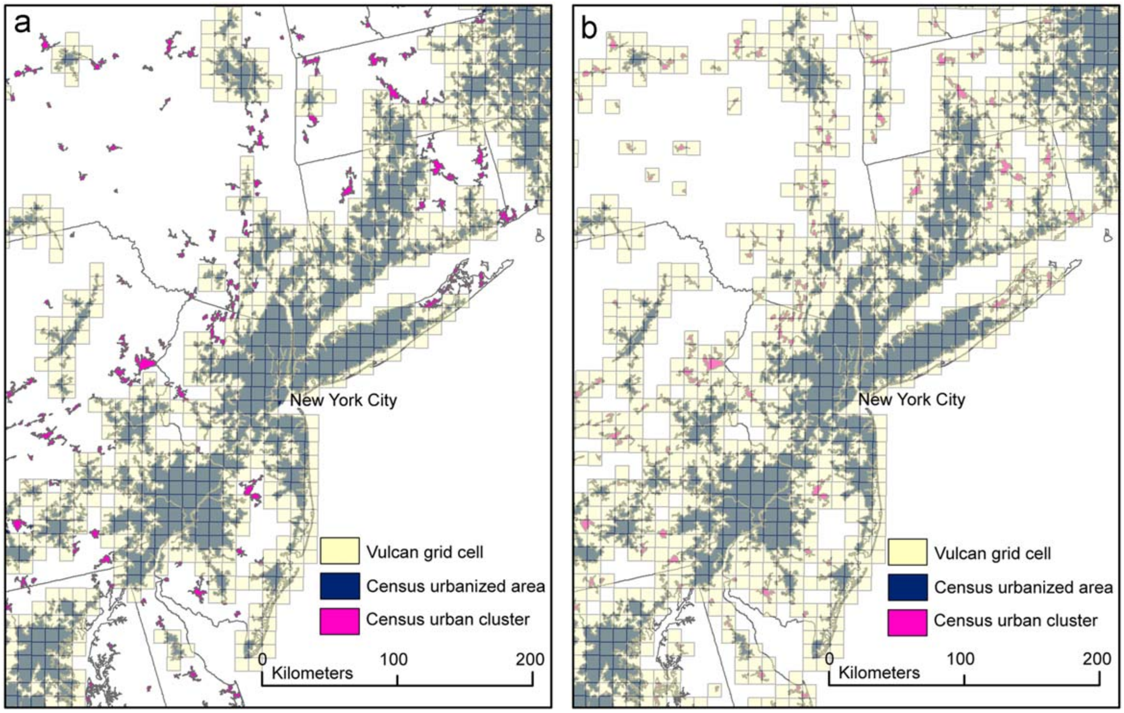

Fig. 4. Spatial overlays of the Vulcan grid on Census urban areas. (a) Vulcan cells that intersect urbanized areas. (b) Vulcan cells that intersect urban areas, including urbanized areas and urban clusters.

Table 5
Summary statistics for selected urban-rural classification schemes based on data for the continental United States.

	Number of urban areas or counties	Population[a] (% of total)	Land area[b] (% of total)	Mean population density (sdev) (people/km^2)	Mean per-capita income[c] (sdev)
Census					
Urbanized area	448	68	2.0	832 (338)	–
Urban cluster	3121	10	0.5	681 (1078)	–
Urban (urbanized areas+clusters)	3569	78	2.5	700 (1016)	–
Not urban	–	22	97.5	–	–
Metropolitan					
Metropolitan (all metropolitan counties)	1069	83	29	219 (979)	$26,447 ($6897)
Metropolitan county >1 mil	405	53	9	460 (1558)	$29,710 ($8493)
Metropolitan county >250 K	320	19	10	94 (104)	$25,428 ($5315)
Metropolitan county <250 K	344	10	11	52 (56)	$23,554 ($3884)
Adjacent to metropolitan >20 K	215	5	8	22 (2)	$22,975 ($3785)
Not adjacent to metropolitan >20 K	101	2	5	24 (17)	$22,930 ($3785)
Adjacent to metropolitan >2.5 K	602	5	18	16 (10)	$20,820 ($3211)
Not adjacent to metropolitan >2.5 K	439	3	19	12 (11)	$21,522 ($4852)
Adjacent to metropolitan <2.5 K	232	<1	7	8 (7)	$20,352 ($3448)
Not adjacent to metropolitan <2.5 K	424	<1	14	5 (6)	$20,966 ($4954)
County character					
Urban county	157	45	3	1125 (2360)	$34,401 ($9451)
Mixed urban county	145	15	3	173 (51)	$29,682 ($6238)
Mixed rural county	1013	31	38	42 (29)	$23866 ($4536)
Rural county	1767	10	56	10 (9)	$21,094 ($4195)

[a] Population data are from Census (2000).
[b] See Table 1 for spatial data sources for land area boundaries. Area estimates were obtained using a Lambert conformal conic projection for the continental United States.
[c] Per-capita income is from BEA (2008).

The final classification system tested was commuting areas, which have a spatial resolution of Census tracts and range in value from 1 (for an independent, urbanized core) to 10 (for a rural area).[35] Unlike urban areas, but similar to counties, Census tracts are continuous in space. Since Census tracts are typically smaller than the Vulcan resolution of 100 km^2, most Vulcan cells intersected multiple tracts. We assigned the data in each Vulcan cell to the lowest (most urban) code it intersected. This was equivalent to classifying all cells that intersected an urban area as urban, the procedure chosen for Census urban areas and GRUMP urban extents.

[35] We used Morrill et al. (1999) primary commuting codes, which have 10 gradations, rather than the more complex secondary commuting codes.

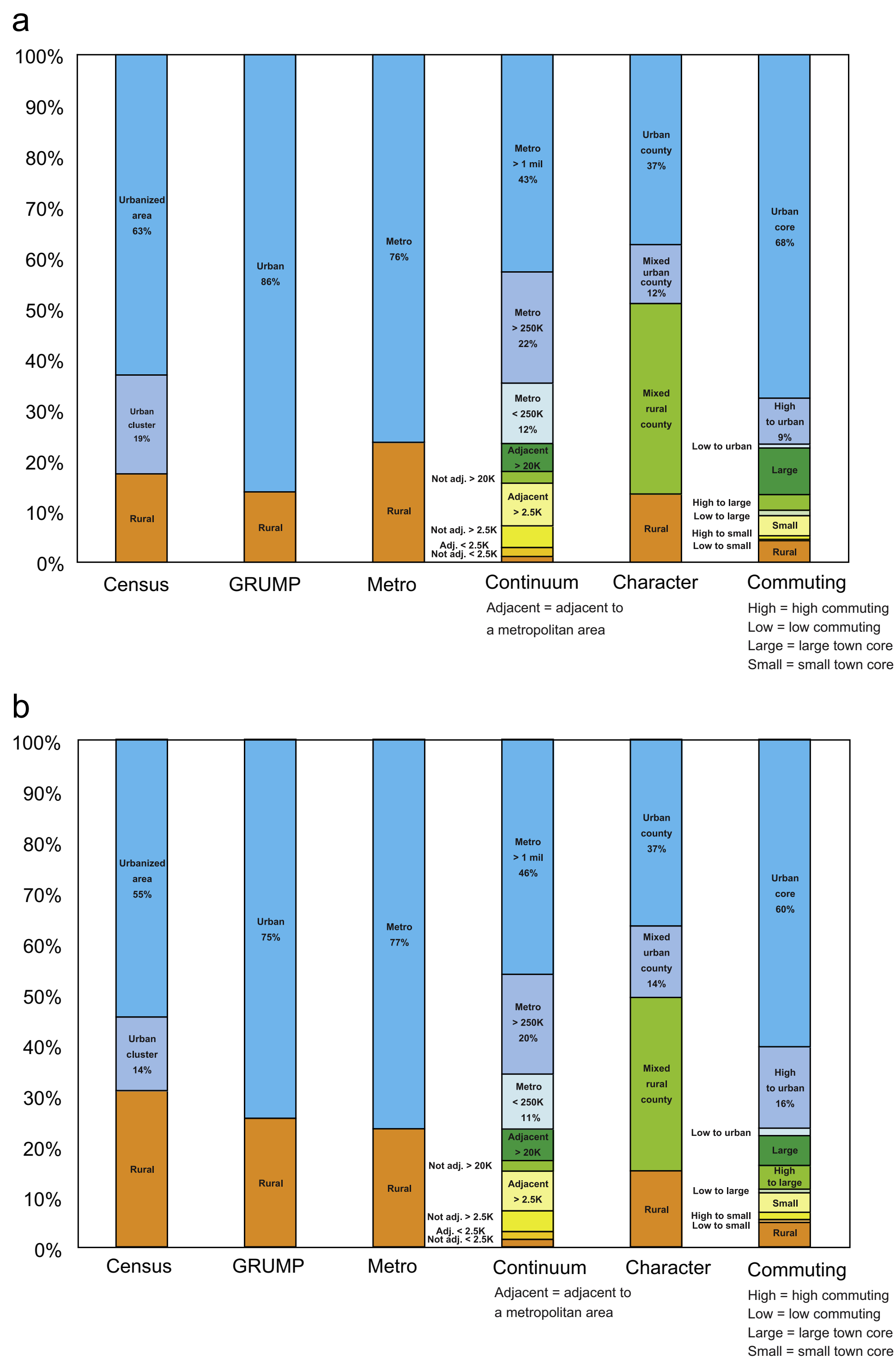

Fig. 5. Percent of direct fuel consumption that occurs in urban areas based on a range of different urban/rural classification systems. (a) Buildings and industry consumption of coal, natural gas, LPG, distillate fuel oil, and residual fuel oil. (b) Gasoline and diesel consumption on roadways. Refer to Table 1 for more information about urban/rural classification systems.

3.3. Comparing localities on the basis of per-capita consumption

A straightforward way to compare localities is on the basis of per-capita consumption. Population data for each set of spatial boundaries were obtained from the US Census (2000).[36]

[36] Although Vulcan data are for 2002, we do not use 2002 estimates available through the Census Bureau's American Community Survey (ACS) for selected spatial boundaries, nor do we adjust the Census data to reflect population changes between 2000 and 2002. This was done to avoid introducing error by making projections at different spatial scales and/or through mixing ACS sample data with data from the Decennial Census. Since population grew by just 0.3% between 2000 and 2002, and since changes in the spatial distribution of population are likely to have been equally small, this is not likely to be a large source of error in our per-capita estimates.

Table 6
Ratios between direct final consumption per capita in each urban/rural category and average direct final consumption per capita in the United States.

Classification system	Buildings and industry		On-road transportation		Total direct fuel consumption
	Natural gas and LPG	Fuel oil	Gasoline	Diesel	
Census					
Urbanized area	0.95	0.88	0.83	0.70	0.87
Urban cluster	1.71	2.15	1.32	1.57	1.63
Urban (urbanized areas+clusters)	1.05	1.05	0.89	0.82	0.97
Not urban	0.80	0.80	1.41	1.68	1.12
Metropolitan counties					
Metropolitan (all metropolitan counties)	0.96	0.91	0.95	0.87	0.94
Metropolitan county >1 mil	0.89	0.64	0.91	0.75	0.84
Metropolitan county >250 K	1.09	1.23	1.02	1.01	1.08
Metropolitan county <250 K	1.09	1.67	1.06	1.26	1.16
Adjacent to metropolitan >20 K	0.93	1.20	1.14	1.39	1.12
Not adjacent to metropolitan >20 K	1.31	0.86	1.05	1.27	1.18
Adjacent to metropolitan >2.5 K	1.45	2.04	1.35	1.84	1.51
Not adjacent to metropolitan >2.5 K	1.52	1.20	1.28	1.71	1.40
Adjacent to metropolitan <2.5 K	0.69	3.02	1.57	2.17	1.88
Not adjacent to metropolitan <2.5 K	1.19	0.72	1.46	1.95	1.32
County character					
Urban county	0.92	0.67	0.88	0.66	0.84
Mixed urban county	0.85	0.69	0.98	0.93	0.88
Mixed rural county	1.15	1.50	1.08	1.24	1.17
Rural county	1.19	1.46	1.40	1.92	1.42
Commuting					
Urban core	0.99	0.96	0.89	0.77	0.92
High commuting to urban core	1.06	0.77	1.76	1.99	1.37
Low commuting to urban core	1.06	1.09	2.03	2.47	1.54
Large town core	1.19	1.58	0.82	1.01	1.12
High commuting to large town core	1.14	1.13	1.56	1.99	1.35
Low commuting to large town core	1.42	4.52	1.20	1.48	1.60
Small town core	1.12	0.91	1.00	1.37	1.08
High commuting to small town core	0.78	0.38	1.24	1.59	0.98
Low commuting to small town core	0.34	0.41	0.91	1.08	0.61
Rural	0.69	0.98	0.94	1.22	0.94

A value of 0.87 for total direct final consumption in urbanized areas indicates that the typical resident of an urbanized area consumes 13% less energy than the typical US resident.

To compare per-capita consumption with per-capita income, we used county-scale data on per-capita income from the Bureau of Economic Analysis (US BEA, 2008).[37]

Table 5 summarizes population and per-capita income data for selected urban/rural classification schemes. The population distribution is highly skewed: 68% of the population lives in urbanized areas that span just 2% of the land area, more than half of whom live in large, urbanized areas with more than 1 million people. Thus, urban/rural classification systems generally show greater population variance in urban categories than in rural categories, which can increase the difficulty of deriving an urban threshold that groups localities with similar character.

One classification system that does not exhibit this property is Census urban areas: the standard deviation of population density in less dense urban clusters is higher than in denser urbanized areas. Urban areas are constructed block by block, with stricter requirements for urbanized areas than urban clusters, explaining the lower variance in population density. But classification systems based on jurisdictional boundaries are appealing from the perspective of benchmarking and target setting.

4. Results

We find that, depending on the definition of urban, 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 (Fig. 5). Results were similar for both sectors, although we found that the urban share of fuel consumption tended to be higher for buildings and industry compared with the transportation sector. We report all results in energy units, rather than compare energy and CO_2 emissions, because the exclusion of electricity means the two are highly correlated within each sector.[38] A detailed analysis of differences between local energy consumption and CO_2 emissions is beyond the scope of this paper.

Along with metropolitan areas, Census urban areas and GRUMP urban extents were at the upper end of this range. For example, 76% of direct final consumption occurs in Census urban areas, with 59% occurring in urbanized areas and 17% occurring in urban clusters.[39] However, it is likely that urban energy consumption was overestimated for the latter two spatial scales due to error introduced by the imperfect match between

[37] The Census releases estimates of per-capita income based on pre-tax cash income, but the BEA estimates are more complete. Ruser et al. (2004) describes the differences between the two datasets. BEA data are not available at higher resolution than counties. Although per-capita income data are available through the Census down to the block scale, aggregating these data to estimate per-capita income in each Census urban area was beyond the scope of our analysis.

[38] At the county scale, the correlation between buildings and industry energy consumption and CO_2 emissions is 0.99 and the correlation between transportation energy consumption and CO_2 emissions is also 0.99.

[39] Note that the 76% figure for direct final consumption in US urban areas is lower than the 80% figure reported in the IEA analysis. Although Vulcan was used in both analyses, the methodology was different. Also, unlike the present analysis, the IEA analysis included final consumption of electricity.

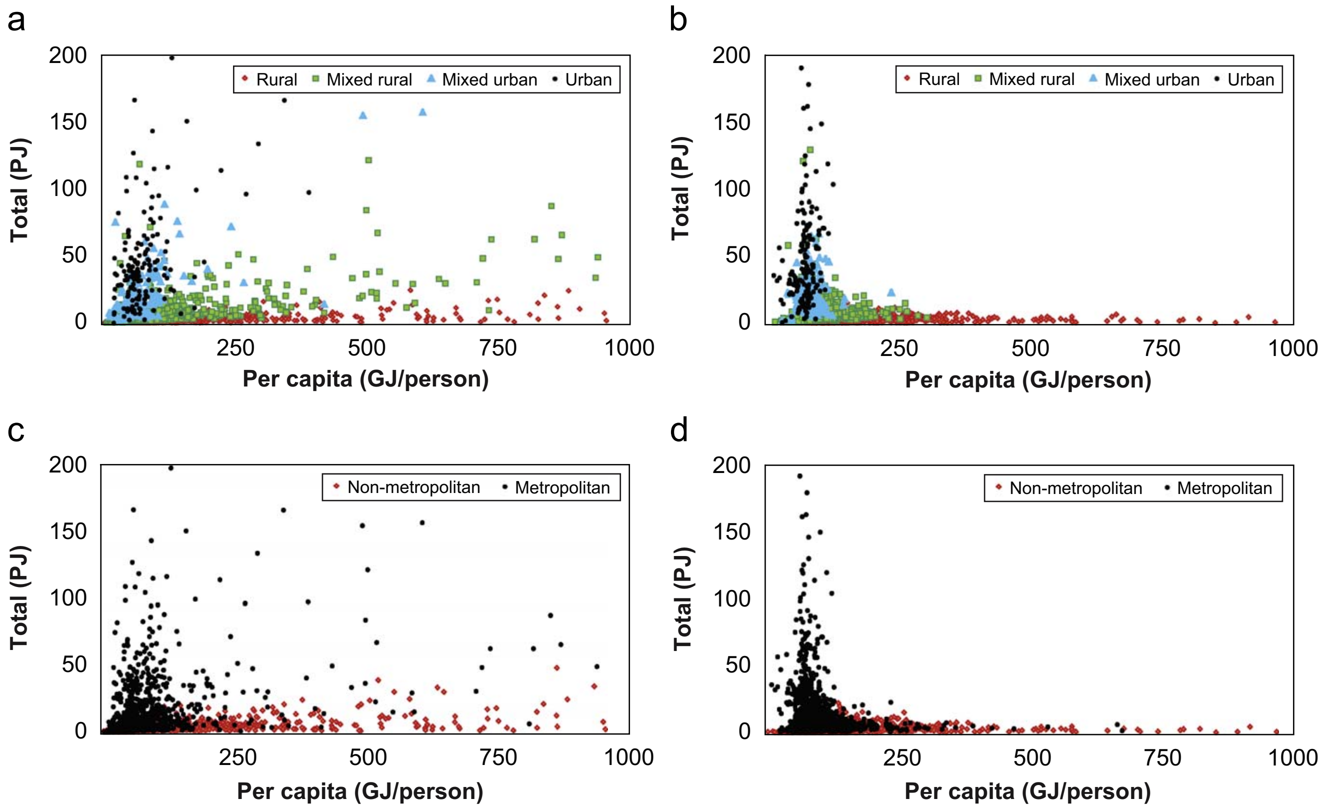

Fig. 6. County per-capita consumption versus county total consumption. (a) Direct energy consumption in buildings and industry, with counties classified by urban/rural character. (b) Direct energy consumption for transportation, with counties classified by urban/rural character. (c) Direct energy consumption in buildings and industry, with counties classified as metropolitan or non-metropolitan. (d) Direct energy consumption for transportation, with counties classified as metropolitan or non-metropolitan. Note that a small number of outliers are not shown on the scatter plots. PJ = Petajoule = 10^{15} J. GJ = Gigajoule = 10^{9} J.

Vulcan grid cells and urban boundaries in the spatial overlays. Therefore, we compared our estimate of metropolitan area consumption obtained from Vulcan county-scale data with an estimate obtained by overlaying the Vulcan 100 km^2 grid on metropolitan area boundaries. The estimate obtained from the spatial overlay was 15% higher than the estimate obtained from the raw county-scale data, a substantial difference, but not sufficient to eliminate the gap between the upper and lower end of the range. This confirms that estimates of urban energy consumption are sensitive to spatial scale. The relatively large error introduced by the overlays also demonstrates that tracking energy and emissions data by administrative boundaries is preferable.

Although urban areas are responsible for the majority of direct fuel consumption, they tend to consume less fuel per capita (Table 6). The differences are most pronounced for more restrictive definitions of urban such as counties with urban character, Census urbanized areas, and metropolitan counties with more than 1 million people. Based on these definitions, per-capita energy consumption in urban areas is 13–16% lower compared with the national average. Smaller urban clusters and metropolitan counties with fewer than 1 million people tend to consume more energy per capita than the US average, so when these areas are included, urban residents appear to consume just 3–6% less than the average US resident. This suggests that the choice of urban threshold can have as large an impact on results as the choice of spatial boundaries.

Fig. 6a and b show that per-capita energy consumption in urban counties varies less than per-capita energy consumption in rural counties, particularly in the transportation sector, suggesting a threshold effect above which urban areas converge on a lower

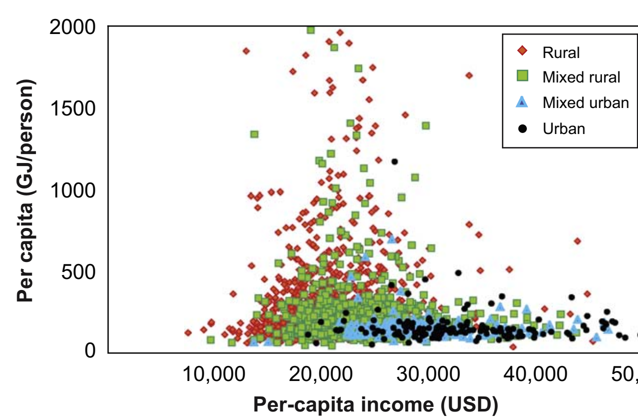

Fig. 7. County per-capita income versus county per-capita consumption, with counties classified by urban/rural character. Note that a small number of outliers are not shown on the scatter plot.

level of direct fuel consumption per capita. This effect also exists in comparisons between metropolitan and non-metropolitan counties, but to a lesser degree (Fig. 6c and d). Classifying counties based on urban/rural character may strengthen the urban signal by picking up urban attributes, such as reduced use of personal transportation, which are obscured by grouping urban and suburban portions of metropolitan areas. The weaker signal for buildings and industry compared with transportation is likely related to the strong effect of climate on heating demand in buildings as well as substantial variation in commercial and industrial energy use. Fig. 7 confirms that, although urban

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counties have higher mean per-capita income, there is no relationship between per-capita energy consumption and per-capita income in urban localities.

These findings are not intended to contribute to debates on the underlying mechanisms through which urbanization affects patterns of energy consumption and CO_2 emissions. Rather, our intention is to suggest that a national inventory at the local scale should allow for meaningful comparisons of localities with similar character, and that this requires choosing a spatial scale and urban definition for which the "urban" signal clearly differs from the "rural" signal.

5. Toward a national inventory at the local scale

Through our analysis of urban energy consumption in the United States, we have shown that the following factors are important to the design of a national inventory of local-scale energy use and related CO_2 emissions: consistency, spatial resolution, accounting framework, and attributes.

5.1. Consistency

The inventory should be built from systematic data collected for the entire country. Ideally, all raw data underlying the inventory should be derived from comparable energy-sector data on location-specific fuel consumption. In practice, comparable sources of raw data for all sectors and fuels may be impossible to find, and some data may be derived from emissions models rather than from raw energy data. The consistency of the raw data within each sector is probably more important than the consistency across sectors. Data sources, and protocols for synthesizing data into an inventory, should facilitate the release of inventories at regular intervals. Responsibility for data organization and synthesis should be centralized at a single institution, preferably a government agency, to ensure that data products are recognized as authoritative and are available to the public.

5.2. Spatial resolution

The spatial resolution should match the smallest set of continuous administrative boundaries at which energy data are available for the entire United States. Examples of continuous boundaries in the country are: states, counties, Census tracts, Census block groups, and Census blocks. Currently, counties are the highest resolution at which energy data are available. Choosing continuous boundaries, rather than discontinuous boundaries such as Census urban areas or metropolitan areas, allows for complete coverage of the country at a high spatial resolution and allows analysis at multiple spatial scales. For example, county-scale data can be aggregated to analyze metropolitan areas, micropolitan areas, and/or combined statistical areas in the United States.

5.3. Accounting framework

The inventory should be constructed according to a clearly defined accounting framework. The accounting framework should define the energy system perspective, including whether the inventory will cover direct final consumption, total final consumption, or total primary energy supply; how the inventory will allocate point source and non-point source data to localities; which fuels and/or sectors will be covered, and the scope of each sector; and how the inventory will partition data. For example, the inventory might categorize data by fuel, sector, sector and fuel, or sector and end use.[40]

5.4. Attributes

In addition to energy and CO_2 emissions data, the inventory should include consistent data for each locality on total population and spatial area. It also should designate the locality as urban or rural. These are the minimum attributes required to make meaningful cross-locality comparisons. Linking the inventory to additional climate, socio-demographic, and economic indicators would help facilitate analysis of interactions between these factors and energy consumption and emissions.

In Fig. 8, we present maps illustrating various inventory results based on our analysis with the Vulcan data product, the most consistent dataset available in the United States. The spatial resolution is counties, which are continuous in space. The accounting framework is direct final consumption, and we show results for the sector-fuel combination of gasoline consumption in the transportation sector. We compare totals for each county (Fig. 8a) as well as per-capita totals (Fig. 8b). We normalized results by dividing by the mean. In Fig. 8a and b, a value of 100% indicates that the county's consumption is no different from the average across all counties in the continental United States. In Fig. 8c, we show per-capita results normalized by the mean for counties with the same character. In this case, a value of 100% for an urban county indicates that the county's per-capita consumption is no different from the average across all urban counties in the continental United States. Closely comparing Fig. 8b and c reveals subtle differences. For example, Fig. 8b shows that the counties representing the urban core of Los Angeles consume 50–75% less gasoline per-capita than the national average, but 75–100% as much gasoline as the average urban county. Similar differences can be seen for Miami.

6. Conclusions, policy applications, and recommendations

The number of local authorities interested in addressing energy and climate concerns has been growing at the same time that new funding sources for local energy efficiency measures are becoming available. For example, the 2007 Energy Independence and Security Act established the Energy Efficiency and Conservation Block Grant Program, a $2 billion per year pool of funds that cities and counties around the country can use for energy efficiency and conservation plans and programs.[41] In early 2009, the US stimulus bill authorized funding for this program.[42] Since funds can be spent on planning as well as program implementation, baseline studies of energy consumption and CO_2 emissions are likely to proliferate. An established inventory process could ensure that baseline studies are standardized and comparable, helping localities set reasonable targets for different fuels and sectors. High-resolution data made available through inventories can also support research on the relationships between energy consumption, urban form, economic development, and socio-demographic patterns in the United States. Conducting inventories at regular intervals could help localities monitor changes over time and evaluate how local policies may be affecting energy and emissions trajectories.

[40] Bennett and Newborough (2001) discuss energy audits for cities broken down by sector and end use.

[41] The Energy Efficiency Block Grant program is described in US Conference of Mayors (2008).

[42] A statement from the US Conference of Mayors is available in PR Newswire (2009).

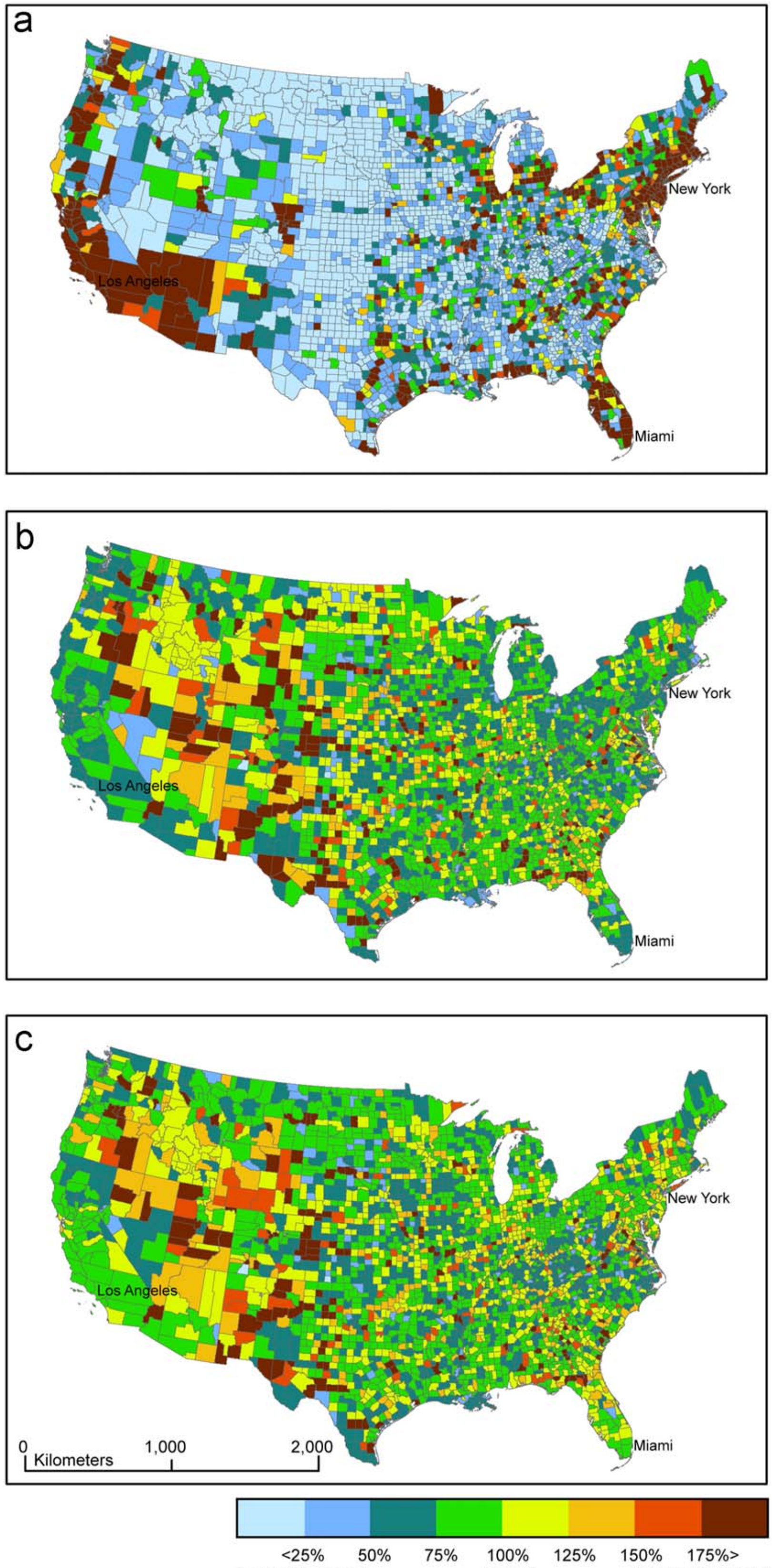

Fig. 8. Patterns of gasoline consumption across US counties. (a) County gasoline consumption compared to US average consumption. A value of 100% indicates that the county has the same total gasoline consumption as the average county in the US. (b) County per-capita gasoline consumption compared to country-wide per-capita consumption. (c) County per-capita gasoline consumption compared to per-capita average for corresponding character class.

Carbon markets are another potential source of funds. For example, the Regional Greenhouse Gas Initiative in the northeastern United States is likely to generate some funding for city-based energy efficiency initiatives. The city of San Francisco is trying to establish its own voluntary carbon market, through which it would sell emission reduction credits to organizations and individuals seeking to offset their own carbon emissions and use the proceeds to support local energy efficiency projects. Well-functioning carbon markets require strict monitoring protocols, reinforcing the need for consistent data and a coherent accounting framework.

While some mayors are emerging as leaders in the local energy policy arena, there is no federal mandate under which individual cities and towns are required to report their energy consumption or CO_2 emissions. We have proposed counties as the best spatial scale for a local inventory because raw energy data are available at this scale, counties are a recognized political unit with some authority to formulate local policy, and some cities are defined by county boundaries (e.g. Denver, Colorado) or groups of counties (e.g., New York City is 5 counties). A county-scale inventory would most directly support county-scale initiatives. But since counties rarely have the same energy policy powers available to local authorities (e.g., waste, land use, transport planning) or state government (e.g., building codes), elevating the locus of energy planning efforts to counties is problematic. An alternative is to refine federally mandated reporting requirements so that smaller entities (e.g. individual cities and towns) are required to regularly report emissions, a step that would likely require congressional action.

In this paper, we excluded the electricity sector from our analysis. Inventorying electricity consumption would help localities understand where their power comes from and clarify local differences in the carbon intensity of energy consumption. Changing the mandatory reporting requirements might enable this, but would likely require the involvement of the Federal Energy Regulatory Commission (FERC), state-level electricity regulatory agencies, and Independent System Operators (ISO). The potential costs of pursuing a change in reporting should be balanced against the capacity of local authorities to influence power supply mix. For example, a national cap-and-trade program or carbon tax targeting the power sector might leave little space for local authorities to influence the local fuel mix.

Moving toward a national inventory at the local scale requires better coordination between Vulcan-type efforts to synthesize available data and local stakeholders. Currently, Vulcan is the most comprehensive and systematic effort to develop a high-resolution CO_2 emissions inventory for the United States. We recommend that Vulcan be used as the starting point for the next phase of inventory development. Coordination with similar efforts in other countries and/or with efforts to inventory other GHGs at high resolution could facilitate the development of internationally recognized standards for local-scale energy and emissions inventories, which could help to identify low-energy and low-carbon pathways in a range of different local settings.

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