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Can sustainability plans make sustainable cities? The ecological footprint implications of renewable energy within Philadelphia's *Greenworks* Plan

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Municipal sustainability plans typically include laudable environmental goals, but they rarely explain the connection between these goals and a larger conception of sustainability. In this article, we examine one local sustainability plan, Philadelphia's *Greenworks*, through a city-based, rather than per capita-based, ecological footprint (EF) analysis. Our objective is to theoretically establish the extent to which at least one of the items in *Greenworks*—to have 20% of the city's electricity come from alternative energy sources—might reduce Philadelphia's overall energy footprint if implemented within the municipal boundaries. By moving away from the idea that per capita energy footprints add up to a citywide energy footprint, we posit that a city can reduce its overall energy footprint by utilizing internal resources, even if the total land used for that respective energy were to increase. For many cities this will result in the use of renewables, such as solar, biogas, wind, hydropower, geothermal, and other creative solutions. By extending at least one component of Philadelphia's sustainability plan through EF analysis, we provide a hypothetical example of how municipal sustainability goals might contribute to a larger goal of urban sustainability, at least in the limited sense that they become less reliant on outlying resources.

KEYWORDS: city planning, renewable energy resources, land use, environmental impact, metropolitan areas, analysis

Introduction

Municipal sustainability plans typically include laudable environmental goals, but they rarely explain the connection between these goals and a larger conception of sustainability (Dilworth et al. 2011). In this article, we introduce a relatively simple measurement—an ecological footprint (EF) measured per city rather than per capita—that could be used to gauge the extent to which sustainability plans would reduce local consumption of resources from outside the cities' limits. A city that consumes energy produced within its borders to a greater extent than previously would be more sustainable in the sense that 1) it is more self-sustaining and 2) it is less of a resource burden on the larger society. We illustrate our measurement by applying it to one target in the Philadelphia sustainability plan *Greenworks*, to increase the proportion of electricity used in the city coming from renewable sources to 20%.

EFs are typically calculated at an individual level, by multiplying the land required to sustain the consumption of one person by the number of people that live in some area of interest, such as a city. Using this system of per capita calculation, Wackernagel & Rees (1996) answer the question, "How large an area of productive land is needed to sustain a defined population indefinitely, *wherever on Earth that land is located?*" By contrast, city sustainability plans look through the opposite end of the telescope, as it were, to ask how their specific land areas, located in specific places on Earth, can be made more sustainable, no matter how many people live on that land. In this article, we thus examine the alternative energy targets within *Greenworks* regarding not only the degree to which they might reduce the city's overall energy footprint, in terms of the total land required to produce that energy, but also the extent to which their implementation could shift that energy footprint from outside to inside the city.

Since its introduction by Rees & Wackernagel in the 1990s (see Rees, 1992; Rees & Wackernagel, 1994; Wackernagel & Rees, 1996), EF analysis has become increasingly technically advanced, as our literature review describes below. This article contributes to the conceptual rather than technical advancement of EF analysis by suggesting how it might be applied to city sustainability plans and, in turn, how that application might reformulate the measurement of EFs. As we explain in more detail below, using EF analysis to evaluate a municipal sustainability plan implies that a city becomes more sustainable if it becomes more self-sufficient, and a city becomes more self-sufficient if consumption within the city is sustained to a greater extent by land that is also within the city. By this definition, a shift in consumption that increases the total land used to sustain city needs, but that reduces the amount of land used outside of a city, would make a city more sustainable. Such a scenario indicates one of the potentially perverse and unwanted (and, given typical city land-use patterns and regulations, highly unlikely) outcomes of measuring footprints per city rather than per capita, and one we address to a greater extent in the discussion section below. The point of mentioning it here is simply to illustrate the degree to which an energy footprint measured per city is qualitatively distinct from one measured per capita. And rather than resulting in such unwanted outcomes as actually increasing total resource consumption, we suggest that city-level EF analysis, at least with regard to energy, might encourage creative solutions, such as using individual properties for multiple purposes within city boundaries. The renewable energy subsections of this article include a variety of examples.

City Sustainability Plans and *Greenworks*

Only a limited number of cities in the United States participated in the earlier Local Agenda 21 initiatives sponsored by the International Council of Local Environmental Initiatives (ICLEI) in the 1990s (Lake, 2000). The more significant catalyst for American city sustainability plans was the Bush administration's decision to withdraw from the Kyoto Protocol in 2001 and refusal to sign on when the Protocol entered into force in February 2005. Seattle Mayor Greg Nickels then led an effort to get mayors in the United States to commit their cities to the Protocol and 141 mayors did so in June 2005 at the annual meeting of the United States Conference of Mayors (Sanders, 2005). More than 850 mayors in the country have since pledged to green their cities through greenhouse-gas (GHG) reductions as part of the Mayors' Climate Protection Agreement. In addition, the Large Cities Climate Leadership Group, an

international coalition known as the "C40," includes 35 of the world's largest cities, in partnership with the Clinton Climate Initiative, with leaders who work together to learn from each other, push toward urban sustainability, and reduce ecological footprints (Stewart, 2008).

Under John Street, Philadelphia's mayor from 2000–2008, the city signed on to both the Mayors' Climate Protection Agreement and the C40 initiative. Mayor Michael Nutter, whose first term began in 2008, built upon the environmental initiatives of his predecessor by establishing the Mayor's Office of Sustainability, which developed and released the city sustainability plan, *Greenworks*, in April 2009. *Greenworks* consists of more than 150 specific initiatives, categorized into fifteen targets to be reached by 2015, and grouped into five major themes: energy, environment, equity, economy, and engagement. The energy theme includes four targets: 1) lowering city-government energy consumption by 30%; 2) reducing citywide building-energy consumption by 10%; 3) retrofitting 15% of the city's housing stock with insulation, air sealing, and cool roofs; and 4) purchasing and generating 20% of the electricity used in Philadelphia from alternative energy sources (Philadelphia Mayor's Office of Sustainability, 2009).

While the first three energy targets of *Greenworks* seek to lower energy expenditure, the fourth target aims to alter municipal energy consumption by changing the energy source. While much of Target 4 is being met simply by virtue of a state mandate that electricity suppliers purchase 18% of their supply in the form of renewable energy by 2021, the city, primarily through the Philadelphia Water Department (PWD), has also invested in new alternative energy sources within its boundaries, including new solar arrays and a wastewater biogas-to-energy facility. *Greenworks* suggests that the city will ultimately reach its alternative energy target—which amounts to receiving approximately 2.93 million megawatt hours (MWh) from sources other than coal and nuclear—by making more use of solar, wind, biogas, geothermal, and hydropower (Dews et al. 2013; 2012.).

In this article, we examine the EF implications of Philadelphia achieving its alternative energy targets entirely through the use of one source. We examine in turn solar, biogas, geothermal wells, wind, and hydropower and estimate the proportion of each alternative energy footprint that can be accommodated within the city's borders. To establish a common baseline across all energy sources, we imagine that all the land within the city (141 square miles, including water) can be used to generate each type of alternative energy. Pursuing a diversified portfolio of renewable energy sources in the city would most

likely be the best strategy, but for analytical purposes, our measurement relies on the idea that all available city land would be used to produce one type of renewable, thus providing a basis for comparing the EF impacts of each renewable energy type. We then weight these estimates with an ordinal scale that estimates the extent to which city land is actually available for each energy source. The point, as previously stated, is to explore the city's potential to achieve some measure of sustainability, in the sense of reducing its EF, measured as the land it uses outside the city boundaries. Thus the goals of this article are two-fold: 1) to provide a theoretical refinement to the sustainability measurements of at least one city-sustainability plan and 2) to use that refinement as a means of providing a new unit of measurement for EF analysis.

Measuring Ecological Footprints

EF analysis is an accounting tool that measures consumption by the geographic space used to produce the resource consumed. As there are only so many hectares on the Earth, the absolute limit to consumption implied in an EF analysis provides an important baseline for defining sustainable consumption (Bendewald & Zhai, 2013). Stemming from the foundational work by Rees (1992), Rees & Wackernagel (1994), and Wackernagel & Rees (1996), EF analysis has been widely applied to all types of resources, at multiple scales, and with increasing methodological sophistication. Though EFs were originally defined holistically, in terms of the land necessary for consumption in general, they have, along with other refinements, been increasingly defined in terms of the land necessary to produce specific resources. Our analysis of energy footprints follows this trend, in defining the space needed to produce a specific resource, rather than overall production.

Following Wackernagel & Rees (1996), however, most EF analyses, no matter the scale or activity for which they determine a footprint, or the method they use to determine that footprint, rely on per-capita measurements of consumption. Research following this pattern includes Marzouki et al.'s (2012) study on the impact of tourism; Gottlieb et al.'s (2012) research on the impact of consumption at an Israeli high school; Hopton & White's (2012) determination of a footprint for southern Colorado; Chen et al.'s (2007) determination of the entire EF of China, including a per capita analysis of coal, oil, and natural gas consumption; Chen et al.'s (2006) analysis of Chinese coal mining; and McDonald & Patterson's (2004) application of input-output analysis to EF determination. Furthermore, Diaz et al.

(2012) and Chuai et al. (2012) analyze per capita EF specifically for carbon footprints from mining and energy consumption, respectively.

In addition to the foundational literature on EF, a few researchers have influenced the ideas presented in this article through their work on alternative energy options and land production or place. Dias de Oliveira et al. (2005) apply the EF model in attempts to calculate the energy balance with respect to Brazilian ethanol production. Kettl et al. (2011) and Eder et al. (2009) compare fuel types, specifically biofuels technologies, to the Sustainable Process Index used by Narodoslowsky & Niederly (2005) to understand emissions and the area necessary to embed human sustainably into the ecosphere, given outputs and inputs. Bicknell et al. (1998) and Ferng (2001), while still evaluating EF in per capita terms, focus specifically on production for individual consumers. And Kissinger & Gottlieb (2012) suggest a place-oriented global hectares approach for wheat supply in Israel.

EF Analysis, Sustainability, and Sustainable Cities

As we discuss later in this article, a city that is sustainable in the sense that it is self-sustaining most likely, but not necessarily, contributes to such larger-scale definitions of sustainability as the Brundtland Commission's criteria for sustainable development as that which "meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987), or that of the International Union for Conservation of Nature, "to improve the quality of life while living within the carrying capacity of ecosystems" (quoted in Krueger & Agyeman, 2005). By reducing the import of energy, city residents and businesses would be less of a resource burden on the larger society and less responsible for environmental destruction in other parts of the world. Furthermore, there can be an economic gain if cities, incentivized to find novel ways to generate renewable energy within their own boundaries, create innovations or recognize underutilized resources, from which other cities might learn. An additional benefit of energy that is both produced and consumed in a single city is the reduction in transmission loss. Overall, the broader impact that cities can have in reducing their energy footprints is great, since they are responsible for approximately 80% of anthropogenic GHG emissions and 75% of global energy use (Schreurs, 2008). If more of the resources consumed within a city are also produced in that city, then that city is more sustainable in the sense that it is more capable of "sustain[ing] a defined population" (Wackernagel & Rees, 1996), namely that population defined by the city's territorial boundaries. The no-

tion of self-sustaining cities can be traced back at least to urban infrastructure development in the nineteenth century (see, for instance, Tarr, 2002). As cities converted natural resources into human service-delivery systems (creeks into sewers, for instance), they also became more physically distinct, both from surrounding municipalities that had not yet adopted such systems, or which had adopted their own systems, and from the less-settled countryside. As municipal corporations, cities, at least in the United States which is the subject of this article, were (and still are) spatially-defined, semiautonomous legal entities, provided the authority to borrow money and tax residents to build infrastructural systems that were typically coterminous with their legal borders. Indeed, it was in large part through the development of independent infrastructural systems that suburban municipalities in American metropolitan regions maintained their legal independence from central cities (Dilworth, 2005).

The legal and physical development of American cities made them appear as distinct, freestanding, and cohesive entities, providing the basis by which they could be defined further as having “metabolisms” (Wolman, 1965). The notion of a city metabolism came to define a relatively small but longstanding literature in urban environmental science and policy, the premises of which, as summarized by Kennedy et al. (2011), are that:

Cities are similar to organisms in that they consume resources from their surroundings and excrete wastes....Of course, cities are more complex than single organisms... Thus, the notion that cities are like ecosystems is also appropriate. Indeed, the model of a natural ecosystem is in some respects the objective for developing sustainable cities. Natural ecosystems are generally energy self-sufficient, or are subsidized by sustainable units, and often approximately conserve mass, through recycling by detritivores. Were cities to have such traits, they would be far more sustainable.

Thus, the implicit baseline for at least some definitions of urban sustainability is of a self-sustaining city. Our baseline for measurement in this present study, which is an ideal point where all city land could be used to produce renewable energy, implies an even more ideal point at which all energy used in a city could also be produced, and all energy wastes such as GHGs assimilated, within that city. This ideal of a city with no energy footprint outside its own territory is one means of operationalizing the notion of a self-sustaining city. Thus, this paper provides a new formulation for EF analysis designed specifically for city sustainability plans, while also presenting an opportunity for evaluating the implications of the implicit ideal of a self-sustaining city.

EF Breakdown of Philadelphia Alternative Energy Sources

In this section we apply our criteria of a self-sustaining city, measured through a city-energy footprint, to the renewable energy goals of *Greenworks Philadelphia*. Table 1 provides estimates for 1) the EFs of five types of alternative energy sources, chosen because they are discussed in *Greenworks* and are geographically appropriate for the city; 2) “city capacity,” meaning the extent to which the *Greenworks* renewable energy target could be achieved using only land within the city (141 square miles, or 36,518 hectares (ha), including water), and relying on only one alternative energy source (that is, city land size in hectares, expressed as a percentage of the EF, per MWh, for each energy source, multiplied by the renewable energy goal of 2.93 million MWh—so, for biogas, for instance, 36,518/(37*2,930,000); 3) an ordinal ranking of the extent to which each energy source could make use of city land (with five being the greatest use and one being the least use); and 4) a “sustainability capacity” ranking, which is simply city capacity multiplied by the 1–5 ranking. Sustainability capacity is thus a ratio-scale measurement (city capacity) weighted by an ordinal ranking (“ability to use city land”) which, given our relatively rough measurements, means that it should also be considered an ordinal ranking.

Table 1 Ecological Footprint of Alternative Energy Sources.

Energy Source	Footprint (ha/yr/GWh)	City Capacity (city land size / (footprint * <i>Greenworks</i> renewable energy goal))		Sustainability Capacity (city capacity * ability to use city land)
		Ability to Use City Land (ordinal ranking)		
Biogas	37	0.0003	2	0.0006
Hydroelectricity	43	0.0003	4	0.0012
Solar	24	0.0005	3	0.0015
Wind	6	0.0021	1	0.0021
Geothermal	2	0.0062	5	0.0310

By “energy footprint,” we are referring throughout this article to the total land needed to produce energy. This includes two main factors. First is the space taken up by the energy-producing components (e.g., solar panels, wind turbines) and their respective accessory land areas (e.g., access roads, conversion equipment, buffers). Second is the land needed to manufacture the energy-producing components or their inputs, including land used for mineral extraction, shipping, manufacturing, and construction.

Though based on available data, as discussed below, all of the values in Table 1 are approximations used to illustrate how a city-level measurement of an energy footprint might work. The most obviously rough estimates are the ordinal rankings of the extent to which city land could be used for producing a given type of renewable energy. We based our rankings on the following criteria: 1) the extent to which there is currently unused land in the city on which energy-producing components (e.g., solar panels, wind turbines, geothermal wells) could be placed; 2) the extent to which energy-producing components could be placed on land that was already being used for other purposes; and 3) the extent to which the energy-producing components could themselves be produced in the city.

A more robust analysis would, first, replace the ordinal ranking of the extent to which each energy source could make use of city land with an actual estimate of the number of hectares in the city that could be used to produce a given type of renewable energy—a procedure far beyond the scope of this article. Such an estimate would first include not just the land that could physically be used for a given type of renewable energy, but also the likelihood that the land could be used, given probable political and legal hurdles, for instance, in getting businesses and homeowners to agree to have solar panels installed on their roofs or their willingness to live next to wind turbines. Suffice to say that our very rough rankings are simply a means for establishing entry points for further discussion, which we begin later in this article.

Second, a more sophisticated analysis would also try to determine not only the extent to which city land could be used to generate alternative energy, but also the degree alternative energy could be generated relative to the amount this is already occurring on city land, in order to estimate the present sustainability effort as a fraction of the sustainability potential for a given renewable energy source. Measuring the level at which renewable energies are being produced, on all available lands, might provide cities with a new tool to determine the returns to scale of future investments in renewable energy production. At the same time, however, since none of the alternative

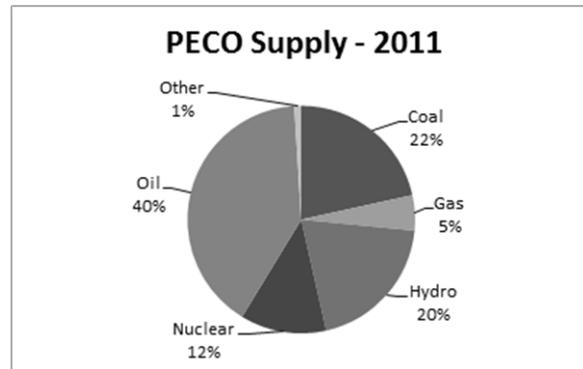


Figure 1 PECO Supply.

energies discussed here are produced from large plants, there is little reason to expect that they have high economies of scale (at least not in terms of energy production; there are more likely economies of scale in manufacturing alternative energy-producing devices).

The major energy providers for Philadelphia are the Philadelphia Electric Company (PECO), a subsidiary of Exelon, and the Philadelphia Gas Works (PGW), a municipally-owned utility company. Currently, the breakdown of generation sources for PECO is extremely fossil-fuel reliant (See Figure 1) (Devitt, 2011).

For the purposes of these analyses, our theoretical model assumes that alternative energy sources would displace the nonrenewable energy portfolio calculated through PJM Interconnection,¹ the largest regional transmission organization in the United States, currently provided through PECO. Much of the existing energy generation comes from facilities that are often far outside Philadelphia’s boundaries. Indeed, PECO gets electricity from the high-voltage grid managed by PJM Interconnection, which stretches as far west as Illinois (1,225 km) and as far south as North Carolina (800 km), though there are some generation facilities located in neighboring municipalities just outside of the city.

The following discussion of the renewable energy targets from Table 1 that could be adapted for the city of Philadelphia uses the standard calculations developed by Chambers et al. (2001) as a foundational text and methodology of EF estimation for the individual energy types. Some energy sources are already being implemented within the city; thereby, we discuss their potential for new or additional application and the land-use and/or social constraints. Our findings indicate that realistically geothermal has the

¹ As an independent neutral party, PJM Interconnection plans and facilitates the movement of electricity across thirteen states and the District of Columbia for more than 61 million people.

lowest footprint and the greatest potential for alternative energy implications given all of the parks and parking lots within the city. This beneficial double-use can help achieve energy independence and limit expansion of alternative energy into the far reaches of the suburbs and exurbs.

Solar

While solar panels can have a larger land footprint than other alternative sources, the planned arrays in *Greenworks* are on hectares within the city that already have a primary use, such as a water-treatment facility. In addition, solar panels placed on rooftops within the city can further reduce the demand for energy produced outside of Philadelphia.

Our EF estimate for solar energy of 24 hectares per year per gigawatt hour (ha/yr/GWh) assumes the use of only one type of photovoltaic (PV) cell (either cadmium telluride or copper indium selenide), includes manufacturing and land use, and assumes that fossil fuel-derived electricity is used for construction. The factor is derived from the standard calculations presented by Chambers et al. (2001). Using solar energy for manufacturing would significantly reduce the energy footprint. However, using PV panels costs more than four times as much as coal, per unit of energy, and more than twice what the production of wind power costs. Competition is lowering prices for PV but, until it is low enough, it will be difficult to demonstrate a comparatively positive return on investment (Sullivan, 2010).

The City of Philadelphia and the Philadelphia Water Department (PWD) completed a solar installation in 2011 at the city's Southeast Wastewater Pollution Control Plant, which is approximately 1.8 hectares in size, with a PV system of 250 kilowatts (KW). Plans for two other solar installations, one at the Philadelphia Navy Yard, which was to be on almost three hectares with a capacity of generating 1.5 MWh, and the other at the Baxter Water Treatment Facility in Northeast Philadelphia on the Delaware River, with potential for a PV system size of 2–5 MW, have both fallen through because of the financial instability of the solar sector and the city itself (EPA, 2009; Philadelphia Mayor's Office of Sustainability, 2009; Gajewski, 2013).

This initial commitment demonstrates a real possibility for solar within Philadelphia. The limitation is that Philadelphia would need to create incentives for private homes to use their roof spaces for solar panels, diminishing overall potential within the city. In addition, the industrial history (including manufacturing space potential) of Philadelphia and its port would position the city to reduce EF by manufacturing solar panels within the city. However, even with skilled labor and manufacturing space, imported raw

materials and equipment would be needed to build PV cells within Philadelphia. The combination of these factors, coupled with an average EF ranking, positions solar as third after geothermal and wind with respect to sustainability capacity.

Biogas

When treating wastewater, PWD uses biological or anaerobic digesters to break down the organic matter in the absence of oxygen, resulting in biogas, which is composed primarily of methane (CH₄) and carbon dioxide (CO₂), two compounds that can be combusted or oxidized with oxygen as a low-cost fuel for heating (Hilkiah Igoni et al. 2008).² If Philadelphia were to produce all of this biogas within the city's boundaries, using the standard formula calculation from Chambers et al. (2001), the EF estimate for biogas would be between 27 and 46 ha/yr/GWh. The range depends on land use and the amount of waste that would be deferred from counties external to the city. For the purposes of Table 1, we use the average energy footprint for biogas of 37 ha/year.

In partnership with Ameresco, PWD is in the process of completing a 5.6 MW biogas cogeneration facility at its Northwest wastewater-treatment facility to produce heat and electricity. This biogas facility could generate 50% of the plant's electricity and 10% of the total electricity purchased by PWD, using 2009 data. To maximize its digestion capacity and to increase its methane yield, PWD wants more high-strength industrial waste for its Northeast facility. It has thus partnered with the Philadelphia International Airport to recycle some of the one million gallons of deicing fluid used annually on airplanes, which has previously been shipped to wastewater plants in local counties surrounding Philadelphia (Philadelphia Mayor's Office of Sustainability, 2009). Enough biogas is being created there to provide fuel needed to dry seven tons of biosolids a day. The multiple use and partnership between these Philadelphia-owned properties (biogas facility and airport) eliminates the need to ship waste out and fuel in from external communities, thereby creating local renewable energy and minimizing the overall energy footprint.

The projects at the wastewater plant and with airport-deicing fluid are indeed vanguard, yet much more creativity would be required to expand upon this renewable alternative to reach the scale required under the *Greenworks* plan. It could be possible to build additional facilities within the city, ideally on brownfield industrial sites, furthering the sustainability potential of these projects. However, local resi-

² Biogas consists of 55–75% methane, 30–45% carbon dioxide, 1–2% hydrogen sulphide, 0–1% nitrogen and hydrogen, and trace amounts of carbon monoxide and oxygen.

dents must be considered, as facilities of this nature take up significant space, can be an eyesore, and often are located along rivers or in less affluent neighborhoods. Aside from the wastewater plants, at this time there is limited opportunity to expand this option due to constraints on existing land. Biogas therefore receives the fourth ranking on the basis of land unavailability. And, with its relatively high EF compared to the other alternatives, it falls to the final ranking for sustainability capacity (0.0006).

Geothermal

Geothermal wells can be developed to provide heat, air conditioning, and both cold and hot water. Given that the wells are just 350 to 400 feet deep, these facilities can use direct-use geothermal heat pumps (GHPs) for heating and cooling. In addition to the energy footprint from an operational geothermal system, the activities involved in constructing the facilities will have an overall environmental impact. Site clearance, road construction, and vehicle traffic may disturb local environments and impair air quality. Nonhazardous solid and industrial wastes will likely be produced during the construction phase. In addition, the embodied energy from construction will also affect the energy footprint. The raw materials, including their processing, manufacturing, transportation to the site, and construction, all increase the energy footprint for the city. Nevertheless, using the standard calculation from Chambers et al. (2001), the overall footprint for geothermal remains the lowest for the City of Philadelphia, resulting in 1.82 ha/yr/GWh from a 20% usage.

For a new \$10 million sewer-maintenance facility in West Philadelphia, PWD intends to use several 350- to 400-foot deep wells to tap geothermal supplies. The GHPs transfer water or other liquids through underground pipes in a continuous loop. To supply heat, the system pulls heat from the Earth through the closed vertical loop and distributes it through a conventional duct system. The process is reversed for cooling: the system pulls heat from the building and transfers it back into the Earth. The geothermal heat pump can also direct the heat to a hot water tank, producing free hot water.

Geothermal heat pumps are beneficial on multiple levels. They are approximately three to four times more efficient than the most efficient fossil-fueled furnace. There are no conversion efficiency losses—thus, while natural gas is 95% efficient and oil is 90% efficient, geothermal heating is 350–450% efficient.³ They reduce electricity use between 30–60% when compared with conventional heating and cooling

systems, since the pump transfers heat instead of creating heat from combustion (USDOE, 2012). Further, since the system simply transfers heat, GHPs (at least the smaller direct-use systems, such as the ones planned in Philadelphia) function very cleanly, requiring fossil fuels only during initial construction and to operate the pump systems (Gagliano, 2003; Lund, 2007).

A geothermal facility uses 404 square meters of land per GWh, compared to 3,632 square meters for a typical coal facility, and 1,335 for a conventional wind farm. Since the resource is tapped directly at the source, processing and transporting geothermal resources is unnecessary, unlike fossil fuels and nuclear sources (Lund, 2007). Given the small space requirements, geothermal provides great opportunity for land utilization within the city, rather than non-local properties. It is possible that existing infrastructure (e.g., subways, water mains, gas pipes) located underground could hamper this development. However, Philadelphia has a very large land area with a small subway system compared to other major cities. In addition, most mains are located under roadways. For this type of project, existing parking lots (ideally at municipal facilities like airports or train stations) and green spaces (such as city parks and lawns) must first be identified.

Geothermal has the greatest potential to reduce the overall energy footprint of Philadelphia, according to our approach. Land for geothermal within the city is extensively available and therefore geothermal receives the highest ranking in our methodology. Furthermore, similar to solar, there is very high potential to manufacture geothermal wells and heat pumps within the city boundaries. The history of Philadelphia manufacturing, the availability of warehouse space, and a skilled labor force adds to this sustainable status. Land availability and a very small energy footprint establishes geothermal as the best choice for most cities in reducing their EF with renewable sources. Exceptions will be cities with significant underground obstructions or limited parks and parking lots. Therefore, geothermal has the highest sustainability capacity score.

Wind

Philadelphia relies on the region outside of the city's boundaries for this high-tech energy solution. By demanding wind power, energy users and city residents are encouraging investment outside of the city, as far away as Illinois. Of the twelve wind farms in Pennsylvania, the nearest to the city is 100 miles away. The continued increase in wind connectivity to bolster renewable energy for *Greenworks* indicates that the energy footprint for wind goes far beyond the City of Philadelphia. As of December 2009, ap-

³ Achieving a 400% efficiency rating translates to generation of 4 units of energy for every 1 unit used.

proximately 35,000 individuals within the PECO area participated in the voluntary PECO Wind Program, the fifth largest renewable energy-market program in the United States (Reilly, 2010).

Wind power is an emissions-free power-generation technology that, as with all renewable energy sources, is based on capturing energy from natural forces. A wind turbine can offset all emissions caused by its construction within three to six months of operation and can then run carbon free for the remainder of its anticipated twenty years of operational life (Zervos et al. 2008). Wind power also has the advantage that it can be deployed faster than other energy-supply technologies; deployment after approval and siting is measured in months, and a large-scale project can start to generate power and income as soon as the first turbine is connected to the grid. By contrast, a conventional coal or nuclear power plant can take more than a decade to construct, during which time it produces no energy.

Similar to all EF calculations in this article, Chambers et al. (2001) provide the methodological basis for an EF calculation for a wind generator. The American Wind Energy Association estimates that 27 MWh of electricity is required to produce and maintain a wind generator for every GWh of energy the generator is able to produce (AWEA, 2011). The calculation for energy land is then derived by multiplying this embodied energy by the footprint for EU electricity.⁴ Using the basis from Chambers et al. (2001), the calculation $(27/1000 * 161 = 4.347 \text{ ha/GWh})$ results in 4.3 ha/GWh of delivered electricity per year. The number 27 represents the MWh of embodied energy per GWh of energy produced, and 1000 is the conversion from MWh to GWh. The number 161 represents the global average hectares per year per GWh of hard coal grid electricity, a baseline for energy across the planet. These steps support the complexity in calculating EF.

In addition to the 4.347 ha/GWh, the energy footprint must include land required by the wind-turbine generator, access roads, and maintenance facilities. This is estimated to be 1.7 ha/GWh of delivered electricity per year $(0.6 * 2.8 = 1.7 \text{ ha/GWh})$. The number 0.6 represents the degraded land estimates and 2.8 represents the equivalence factor for built-up land (Chambers et al. 2001). By adding the energy-land and the built-land estimates, the total energy footprint for wind is determined to be 6.0 ha/GWh per year regardless of location. This could be further reduced if the turbines were produced in the city. While this is possible, the scale of the project requires great manufacturing space and ease of

transportation to areas for installation. Given Philadelphia's historic streets and busy highways, only movement along the Delaware River by ship would be an option, which would also require construction on the riverbanks. Therefore, this might be a poor option. However, the city could be a good location to manufacture the many parts, lubricants, and coatings needed for wind generation, advancing the sustainability of this renewable option.

A major issue regarding the current use of wind energy in Philadelphia is the cost of transmitting this energy from the western part of PJM's region, where most of the energy is produced, to the eastern part where Philadelphia is located. To transmit 20% wind energy from the Midwest to PJM, the eastern regional transmission organization and New England independent system operator, would cost approximately \$80 billion in west-to-east upgrades (Henderson, 2008). Furthermore, as of January 1, 2010, wind accounted for only 298 MW (less than 1%) of installed generating capacity within PJM's fuel mix. There are, however, many wind projects in the PJM queue, approximately 43,843 MW, which may or may not be built (Elmy, 2010). Many wind projects are about to begin construction, adding to the renewable energy marketplace for PJM, PECO, and Philadelphia. By developing wind capacity within the city's boundaries, Philadelphia could reduce its energy footprint, reduce loss in transmission, and be closer to achieving a decentralized method of transmission.

However, the land availability for large-scale wind development in Philadelphia is very low. Turbines require large plots of land where there are no competing uses such as homes, parks, or tall buildings. In addition, there are potential social effects from the noise, flicker, and blinking lights. Even compatible city properties, such as wastewater-treatment facilities or water-treatment plants, are located too close to airport fly zones or large bridges over the Delaware River. Nevertheless, even with a low ability to use city land, the EF is very low, giving wind the second greatest sustainability capacity score.

Hydropower

Hydroelectric power plants can be divided into four categories: micro, mini, small, and large (see Table 2). The size affects the energy produced and costs to build the facility. A micro-size plant generates less than 100KW of electricity and can serve the energy requirements for one to two houses. A mini-size facility can produce power for a small community or factory because it generates 100 kW–1 MW of electricity. A small plant generates 1–30 MW of electricity, serving an entire district. A large facility has an output of more than 30MW of power, which

⁴ EU electricity is the footprint of the electricity weighted by the total energy invested into the infrastructure for electricity.

Table 2 Hydropower Scale, Production, and Cost

Micro (less than 100kw)	Mini (100kw–1MW)	Small (1–30MW)	Large (30MW+)
<100kw	500kw	5 MW	30 MW
Varies	\$3.6 million/MW	\$4.8 million/MW	\$1.7 million/MW

depending on energy use can power almost 30,000 homes (Bottoms, 2011).

Hydroelectricity already accounts for 10% of the total energy produced in the United States. In addition, there is potential to produce an additional 30,000 MW of electricity if 5,677 undeveloped sites were used. Scaled down, in Pennsylvania, hydropower could annually produce more than 5.5 million MWh of electricity (Castaldi et al. 2003).

Hydropower would be an expensive option for the city to offset fossil fuels. In reality, the scale needed to make a serious contribution would require construction outside the city's boundaries, further increasing the overall EF. There is a significant financial, environmental, and social cost for the physical space of the hydroelectric dams, which would vary depending on location. Additional costs can include land rights, land improvements, turbines, and equipment needed for construction. Development costs could include preserving historical sites and/or maintaining water quality, which is equally important for both consumers and developers. Maintenance can be expensive, ranging from hydraulic and electric expenses to rent for the land (Castaldi et al. 2003). In addition, there are a variety of environmental costs including reductions in water flow, impact on local species and biodiversity, creation of a lentic system, increased sedimentation behind dams, and reduced deposition below them (Moscovici & Wegner, 2007). However, compared to traditional fuel sources, the cost for hydropower would be minimal in the long run. Power plants and other energy-generation technologies require engineering and structural changes and upkeep, while hydroelectric power plants require minimal repairs, making them relatively cost-efficient. This research, however, does not develop a cost comparison and seeks to recommend opportunities for renewable energy generation within the city's boundaries, thereby minimizing the overall energy footprint and moving toward a sustainable energy solution.

Hydroelectric power generally entails one of two techniques for construction: 1) hydroelectric power plants, which are relatively large and 2) run-of-river, or turbines, which are typically smaller. Lenzen (2002) notes two areas where hydroelectric power produces carbon emissions: raw materials and

changes in land area. Carbon dioxide (CO₂) emissions can vary depending on changes in the land area; for example, "the flooding of valleys to create large reservoirs...could lead to biomass decay and emissions of up to 400g CO₂-e/kWh [grams of CO₂ equivalent per kilowatt hour]" (Lenzen, 2002). Unlike other renewable energies, hydroelectric power plants are similar to carbon-based energy footprints due to the raw materials (steel and concrete) to construct the dam and the required flooding and decay of vegetation in the impoundment (~10–30g CO₂-e/kWh).

By contrast, run-of-river schemes either have none or very small reservoirs (those with weirs); therefore, they do not give rise to significant emissions during their operation. Carbon footprints for this type of hydroelectric scheme are some of the lowest of all electricity-generation technologies (<5g CO₂-e/kWh) (Parliamentary Office of Science and Technology, 2006). Chambers et al. (2001), estimate the carbon footprint for hydroelectric power plants to be 10–75 ha/yr/GWh, which is similar to the approximation provided by Lenzen (2002).

Compared to the other renewable options, hydropower is ranked second on availability to use city land. Philadelphia has a unique opportunity to construct hydropower within the city boundary. Flat Rock Dam, located on the Schuylkill River, has an installed capacity, or intended full-load output, of 2500 kW. A canal and dam were first built in 1819, then rebuilt in 1977 after the original dam collapsed. In addition, the City of Philadelphia might consider adapting the Schuylkill River's Fairmount Dam, which can generate approximately 1–2 MW of electricity.⁵ These two dams, Flat Rock and Fairmount, could in theory produce about 5 MW of electricity for Philadelphia (Castaldi et al. 2003). While costly, additional impoundments on the Delaware and Schuylkill Rivers could add to generation. In addition, the city could readily position itself to build much of the equipment within available manufacturing areas as the technology and raw materials exist within the city. However, with the largest EF between the five renewable options, the availability does not propel hydropower as the best choice. With a score of 0.0012, hydropower ranks fourth with respect to sustainability capacity. Given that Philadelphia has many rivers running through and under it, small-scale hydropower (small creeks or run of river) would be a much more sustainable choice. With lower costs and less environmental and social damage, hydropower could still be a good option given the bountiful water.

⁵ While it varies widely based on individual usage, a simple conversion from MW of electricity to homes powered is to multiply by 1,000; thereby 2 MW of electricity can power 2,000 homes.

Discussion

This article explores the possibilities that 1) energy footprints could be measured not on per capita basis, but per city and that 2) city-level energy-footprint measurements could be used as metrics of city sustainability. Under typical EF analysis, a reduction in per capita consumption among the residents of a given city would reduce that city's footprint, regardless of whether the consumed resources were located or produced inside or outside the city's borders. Under the measurement proposed here, reductions in per capita consumption by city residents would lower the city's footprint, and thus count toward making the city more sustainable, only if those reductions came from resources produced or located outside the city's borders.

According to the *Greenworks* 2012 progress report, "In 2011, 12.2% of the electricity used in Philadelphia was purchased or generated from alternative energy sources, up from 2.5% in 2008" (Philadelphia, 2009). In this article, we have suggested a tool by which the steady progress toward a goal outlined in the city's sustainability plan might be measured in terms of the extent to which it satisfies more general criteria of what it means to be a sustainable city. More specifically, we examine two criteria: 1) the city becomes more self-sustaining because it relies to a greater extent on resources produced within its own boundaries and 2) in becoming self-sustaining, the city also contributes to a larger sustainability goal, such as those described by the Brundtland Commission and International Union for the Conservation of Nature (IUCN) (See WCED, 1987; IUCN, 1991).

We develop an analysis and ranking system to determine which renewable energy sources, already identified in the sustainability plan, have the lowest energy EF and greatest possibilities for implementation (wind, hydropower, biogas, geothermal, solar). There are, of course, other forms of renewable energy that might be considered. Using these criteria and our multi-factor methodology leads us to the preliminary conclusion that geothermal wells and small-scale hydropower hold the greatest potential for making Philadelphia a more sustainable city. Philadelphia has very high hydropower potential with the many rivers, streams, and creeks located with the city's boundaries. Furthermore, the city can capitalize on an immense amount of land, especially already-existing land uses, including parks, parking lots, and old manufacturing sites to bury geothermal wells and manufacture heat pumps, respectively.

To say that geothermal wells and hydropower hold the greatest sustainability potential for Philadelphia is not to say that the city should pursue only those sources of renewable energy, especially since

various types satisfy different goals—for instance, biogas production can lower energy costs and divert more wastes from landfills. Our goal in this article is to develop a new measurement tool that might inform policy decisions, rather than to make specific policy recommendations.

As a measurement tool, probably the most obvious drawback to city-level EF is the possibility of "gaming the system." A city could reduce its consumption of resources outside its borders by simply expanding so that resources previously outside the city are now inside the city (annexing the land on which a nuclear power plant resides, for instance). Indeed, municipal annexation of surrounding territory has been relatively common, especially in the southern and western United States. Thus, a city that adopted our system of EF measurement in its sustainability plan would have to account for annexation, by, for instance, scoring energy produced on land within the city as more sustainable, based in part on the time that land had been within the bounds of the city. Scoring energy produced in higher-density areas of the city as more sustainable might also accomplish the same goal.

The ability of annexation to potentially distort our EF measurement simply points to a complication in defining city sustainability on the basis of conceiving of cities as having metabolisms. Cities are not organisms or ecosystems, but rather political jurisdictions defined by relatively arbitrarily drawn borders that can be redrawn in ways that fundamentally change the resources available within those jurisdictions. Any sustainability measurement that relies on an ideal of a self-sustaining city must account for the fact that cities are malleable human constructs.

Conclusion

We have focused on the EF implications of one target in a larger plan, namely the switch to alternative energy. Future research includes not only more accurate estimates and mapping of land that could be used in the city to produce energy, but also the relative costs of producing energy from different sources and locations within the city. The measurement could also be refined to include other factors that would account for such aspects as environmental justice, for instance, whether renewable energy production would occur mostly in lower income neighborhoods within the city and generate negative social externalities. Ours is certainly not the only possible measurement of sustainability that might be derived from *Greenworks*, but we hope that it at least begins to make the connection between city sustainability plans and genuine sustainability. Self-sustaining cities are only a piece of the greater global need for sustaina-

bility. We must plan and be ready to make big changes with respect to our long-term energy future.

Properly measured and incentivized, the advantage of city-level energy-footprint measurements is that they could lead to creative technological and land-use innovations in renewable-energy production in the context of high-population density. These techniques could then diffuse to other cities nationally and internationally, helping to satisfy larger-scale definitions of sustainability.

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