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Distributed Urban Energy Systems (Urban Form, Energy and Technology, Urban Hub)

Effects of city size on the large-scale decentralised solar energy potential

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Abstract

To assess the PV-potential on rooftops for decentralized electricity supply in Switzerland, the potential is compared with the following urban-size parameters: (a) urban population, (b) number of buildings, (c) the cumulative building ground-floor area, and (d) the cumulative street length. The coefficients of determination R2 between the PV potential and these factors are: (a) 0.85, (b) 0.86, (c) 0.95, and (d) 0.93. The resulting relations show that 1% increases in factors a-d are associated with the following increases in PV-potential: (a) 0.82%, (b) 0.93%, (c) 0.94%, and (d) 1%, indicating sublinear relations with a-c, but a linear relation with d.

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Keywords: scaling relations, city size, solar PV potential

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1. Introduction

Extensive use of solar energy requires considerable land use. For example, for a 200 MW solar power station using single photovoltaic cells for generating the electricity would require about 15 km2 of land [1]. Such a land is commonly not readily available in rural areas of densely populated countries because suitable land is already used for other purposes, particularly agriculture. Urban areas, however, provide ample suitable areas for solar energy, primarily using the roofs and, to a lesser extent, the facades of buildings to locate photovoltaics (PVs) and other means for collecting and concentrating solar energy. The use of urban areas for solar energy, however, requires decentralized energy supply. This means that the energy is no longer produced in large power plants and transported through a network to the consumers, but rather produced close to, or at, the site where the energy is used, namely on the roofs of the buildings where energy is subsequently (mostly) used.

One key element in the production of electricity from PVs in urban areas is that the energy supply must be decentralized. The concept of a ‘decentralized energy supply’ means that the energy is produced close to, or at, the site of its use; in this case, mostly on the roofs of the buildings where the energy is subsequently used. By contrast, in a centralized energy supply the energy is normally produced by large power plants and transported through a network or grid to the consumers. There are many benefits supposed to be associated with decentralized energy system and supply. These include (1) reduced dependency on fossil fuels, (2) reduction in CO2 emissions, (3) reduced energy costs and risks of peaks in energy prices, and (4) greater energy security, partly through better balance between demand and supply. An additional benefit is that decentralized energy is generally from renewable sources, for example solar energy through photovoltaics (PVs) for electricity production [cf. 2]. Solar energy is, in fact, one of very few energy sources very suitable for decentralized energy supply in the urban areas.

It is estimated that urban areas account for 60-80% of the global energy use and emit more than 70% of global greenhouse gases [3, 4, 5]. Since the majority of the future population growth is expected to be in urban areas [6], one main question regarding energy planning is how the size or population of a city affects its energy use/energy production and carbon dioxide (CO2) emissions. A related question is whether cities of a particular size better meet national or regional strategies for reducing greenhouse gas emissions as well as increasing the renewable energy production. The population size of a city and its building configuration can affect renewable energy production and, in turn, reduction in CO_2 emissions. Several studies have documented a relation between city size, urban form and transport energy use and the associated carbon dioxide (CO_2) emissions [7, 8, 9, 10, 11, 12, 13]. However, hardly any study explores the relation between renewable energy production (e.g. solar energy) and city size [14]. Here we focus on the solar photovoltaic (PV) potential in the urban areas of Switzerland with a view of improving our understanding of how (i) solar PV potential varies across cities (ii) this potential correlates with various factors of city size. In particular, for a given urban area/city we explore the correlations between PV potential and (1) the population, (2) number of buildings, (3) cumulative building ground floor area, and (4) cumulative street network length.

2. Methods

The main methods used in the present study are as follows: (1) Machine-learning techniques together with GIS for modelling the potentials of PV electricity production in the urban areas of Switzerland (Fig. 1a), (2) statistical analysis of the built environment, including allometric scaling between solar PV potential and urban population, number of buildings, cumulative ground floor area, and cumulative street length. The study focuses on the solar PV potentials for urban areas of Switzerland within the communes (the smallest administrative divisions). The buildings/street networks in the rural areas are not considered (Fig. 1b to Fig. 1e). The total number of communes in Switzerland is 2477 (http://www.swisstopo.admin.ch/). However, several hundred communes have no urban areas, defined by CORINE Land Cover Switzerland [15] and thus omitted in the present study (Fig. 1b to Fig. 1e). As regards modelling, the present study uses a combination of support vector machines (SVMs) and geographic information systems (GIS) to estimate the rooftop solar PV potential for the urban areas in Switzerland [16]; Fig 1a. The rooftop solar PV potential for a total 1901 out of 2477 communes in Switzerland has been estimated. Allometry, which was originally introduced in biology [17, 18], describes how and in what way organisms, as they grow, maintain certain ratios among the various geometric aspects of their bodies [19]. Allometric scaling shows how the quantity of interest, Y, depends on the size of a system X [10, 20] through the relation

$$Y = AX^{\beta} \tag{1}$$

or, by taking logarithms on both sides,

$$\log(Y) = A + \beta \log(X) \tag{2}$$

where β is the scaling exponent or the allometric exponent, and A is a normalization constant. A straight line on the log-log plot is then a general indication of the allometric power-law relationship between the two variables X and Y. Parameter β expresses the slope of the regression line in the log–log plot and is especially important for quantifying the allometric relationship between the two variables. Various activities or performances of a city can be quantified. Many of these appear to relate to the scale or size of the city through power laws. Bettencourt et al. (2007) [21] show that cities across US follow scaling laws of different types and show allometric relations to population or city size and demonstrated that many human activities fit into three categories based on the value of β in Eqs. 1 and 2: (i) a linear relation, in which case the scaling exponent β is roughly equal to 1. (ii) a sublinear relation, in which case β is less than 1. (iii) a superlinear relation, in which case β is greater than 1. We use this method to explore the relations between the solar PV electricity potential and city size quantified by several parameters including city population, number of buildings, cumulative building ground floor area, and cumulative street network length.

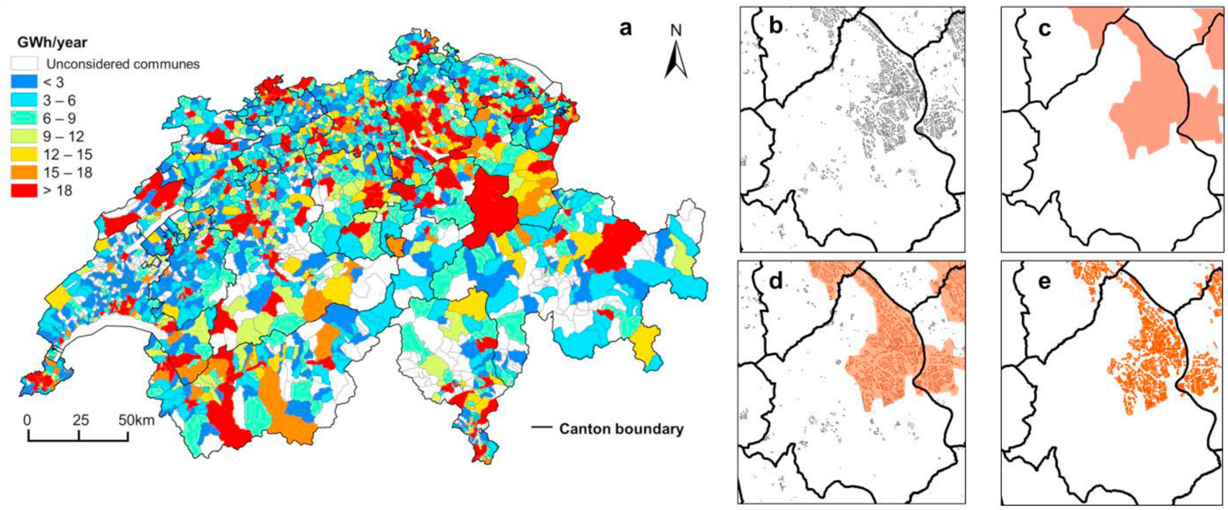

Fig. 1. (a) Potential of rooftop PV electricity production (GW h/year) for each commune in Switzerland. (b) Buildings in urban and rural areas within the commune (black line), (c) Urban area polygon layer which is defined by CORINE Land Cover Switzerland, (d) Overlaying Fig. c on Fig. b, (e) Clipped layer showing only buildings/street networks in the urban area. Buildings/street networks in the rural areas are omitted.

3. Results

The main results are presented through comparison of scaling relations between the total PV potential and the following parameters (Fig. 2): (a) urban population, (b) number of buildings, (c) the cumulative building ground-floor area, and (d) the cumulative street length.

Consider first the correlation between the PV potential and the number of people living in the urban areas, namely their populations (Fig. 2a). The coefficient of determination is $R^2 = 0.85$, meaning that about 85% of the variation in PV potential in the urban areas of Switzerland can be explained or predicted simply in terms of variation in population. What this means is that the PV potential increases with the population the urban areas, that is, with the sizes of the villages, towns, and cities. This is of course understandable, and as expected, but there are several aspects of the relation in Fig. 2a that warrant further discussion. The first one is that the relationship is sublinear. This is seen from the slope of the straight line and also from the exponent, which is less than 1.0, namely 0.82. This means that the potential increases slower than the population. The relation can also be interpreted so that 1% increase in population or city size is associated with about 0.82% increase in solar PV electricity production. There are related factors that most likely explain this sublinear relationship. One is that the horizontal solar irradiation in Switzerland is not uniform but rather varies considerably through the country. Also, largest urban areas, the cities with the greatest population, happen to be in parts of the country that are not subject to the highest irradiation. These factors are easily confirmed on maps of solar irradiation [16] and the location of the main cities. Of the five largest cities in terms of population, three, namely the largest one Zurich, the third largest one, Basel, and the fourth largest one, Bern, are all located in areas of comparatively moderate irradiation. By contrast, the second largest one, Geneva, and the fifth largest one, Lausanne, are located in areas of comparatively high irradiation. It follows that the PV potential is somewhat lower, per capita, for Zurich, Basel, and Bern than for Geneva and Lausanne, hence the sublinear relationship.

Consider next the correlation between the PV potential and the number of buildings (Fig. 2b). The coefficient of determination is R2 = 0.86, or very similar to that between the PV potential and population. More specifically, this coefficient of determination means that about 86% of the variation in PV potential in the urban areas of Switzerland can be explained or predicted in terms of variation in the number of buildings. Again, like in Fig. 2a, the relationship is somewhat sublinear. This is seen from the exponent, which is less than 1.0, namely 0.93.This means that the potential increases slower than the number of buildings. The relation can also be interpreted so that 1% increase in number of buildings is associated with about 0.93% increase in solar PV electricity production. The number of buildings clearly varies positively with population, that is, with city size. As indicated above, three of the five largest cities in Switzerland, that is, cities with the largest populations and largest number of buildings are in areas with only moderate solar irradiation, hence moderate PV potential. It follows that the relationship between the number of buildings and the PV potential is somewhat sublinear.

The third relationship that we explore here is that between the PV potential and the cumulative building ground-floor area (Fig. 2c). Here the coefficient of determination is R2 = 0.95, that is, much higher than for either the PV potential in relation with population or the number of buildings (Figs. 2a and 2b). This high coefficient of determination means that about 95% of the variation in PV potential in the urban areas of Switzerland can be explained or predicted in terms of variation in the cumulative building ground-floor area of the associated buildings. The relation is somewhat sublinear, primarily for the reasons given above, but much closer to being linear than that between the factors in Figs. 2a and 2b. This is seen from the exponent, which is less than 1.0, namely 0.94. This means that the potential increases slower than the cumulative building ground-floor area. The relation can also be interpreted so that 1% increase in cumulative building ground-floor area is associated with about 0.94% increase in solar PV electricity production. The very high correlation between PV potential and ground-floor area follows from the fact that the ground-floor area is a critical factor to estimate the solar PV potential. Clearly, the larger the ground-floor area of a building, then, other things being equal, the larger is the area available for PVs and thus the larger the PV potential. Given the very high correlation in Fig. 2c, the ground-floor area is clearly one of the best indicators of the urban PV potential.

The fourth relationship and final relationship explored here is that between the PV potential and the cumulative street length in the urban areas (Fig. 2d). Again, the coefficient of determination is $R^2 = 0.93$ is very high, similar to that for the relationship between PV potential and cumulative ground-floor area (Fig. 2c). This high coefficient of determination implies that about 93% of the variation in PV potential in the urban areas can be explained or predicted in terms of variation in the associated cumulative street length. More specifically, the street networks affect the locations of buildings and thus control the space between them. The relation is almost linear – if anything somewhat superliner – in contrast to the sublinear relations in Figs. 2a-c. Cumulative street length varies positively with the urban population and, in general, with the size of urban areas [7, 8].

Since buildings in urban areas are connected to streets, the number and cumulative ground-floor areas of buildings would normally also vary positively with cumulative street length. It follows that all the four factors, population, number of buildings, cumulative ground-floor area, and cumulative street length are related and all correlate comparatively strongly with the PV potential of urban areas. Thus, any of these factors can be used to assess the PV potential of an urban area for given climatic conditions.

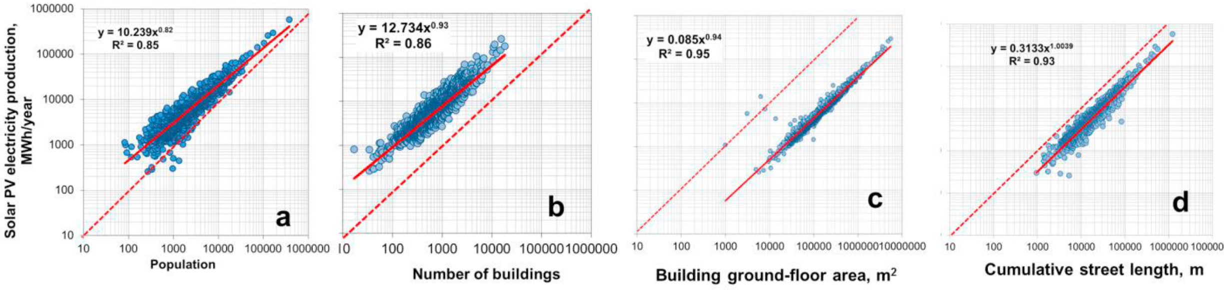

Fig. 2. The scaling relations between the PV electricity potential and (a) the city population, (b) number of buildings, (c) the cumulative building ground-floor area, (d) cumulative street length

4. Conclusion

Solar energy has many advantages and is perhaps the most promising of all the renewable energy sources. Some of its advantages include the following: (1) it is available anywhere and to anyone, that is, solar energy is not, and cannot be, owned by any company or state; (2) it is clean and non-polluting, in particular it is CO_2 neutral; (3) the energy is inexhaustible, at least on the timescale of humankind the lifetime of the sun (billions of years) is effectively infinite; (4) it is highly suitable as a source for decentralized energy supply; and (5) it is one of very few energy sources that are located and easily utilized within urban areas. The last two points constitute a focus in the present study. Here we have shown that several factors can be used to forecast the PV potential for urban areas, focusing on Switzerland (Fig. 1a). All these factors indicate that PV potential, for a given climatic conditions, increase with increasing size of an urban area, as measured in its population, number of buildings, cumulative ground-floor area of the buildings, and cumulative street length. Thus, given information about any of these factors for a given country or part of a country, a crude estimate of the PV potential can be made.

There are other factors, however, that affect the details of the PV potential of an urban area. These include obviously the solar irradiation, that is, the climatic conditions in which the urban area is located. But in addition, there are certain urban form factors that can have large effects. Among these perhaps the most noticeable is the urban compactness – that is, how dense the city is. A study of the city of Geneva indicates that solar irradiation, and therefore the PV potential, decreases with increasing compactness – normally towards the centre of the city [9]. Additionally, the results indicate that PV potential of facades is more affected by compactness than the PV potential for roof-tops. However, the results as to the effect of compactness on PV potential are so far based on a study of only one city, namely Geneva. A combination of the results presented here with more detailed studies of the compact effects in other cities in Switzerland is a clear further step in the direction of assessing the general effects of urban form on the PV potential.

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