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City-integrated photovoltaics sustainably satisfy urban transportation energy needs

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Abstract

Over half the world's population lives in urban settings, and transportation within these regions is responsible for a substantial portion of global pollution and energy expenditures. The electrification of urban transportation offers several benefits including improved urban air quality, reduced noise, and decreased dependence on fuel imports and volatile fuel prices. Additionally, electrification programs centered in urban regions present an opportunity to provide a high degree of mobility at reduced environmental impact. However, the global environmental benefit of electrifying urban transportation will largely depend on using electricity generation sources that produce minimal emissions, such as photovoltaics. In this paper, we studied the feasibility of satisfying all urban transportation energy needs with city-integrated photovoltaics for 87 cities from 43 countries with highly varied solar resources. Of the cities studied, 11 were able to satisfy their transportation needs by covering less than 5% of the city land area with photovoltaics. Nearly half of the cities (40 cities) were able to meet their needs with less than 10% covered and the majority of cities (84%) could do so with less than 15% covered. As one would expect, cities with greater annual solar insolation generally required less photovoltaic coverage. However, annual solar insolation was not the most significant factor. Data mining with an extra-trees regressor was performed to determine the relative importance of over 200 city attributes. These attributes included factors related to urban form, existing transportation infrastructure and investment, behavioral patterns, time and energy efficiency of a

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variety of modes of transportation, and transportation pricing and fines. Based on relative attribute importance, policy recommendations are offered for both existing and emerging cities.
Keywords: urban transportation, city-integrated photovoltaics, sustainability, extra-trees regressor.

1 Introduction

Today, more of the global population lives in urban areas than in rural areas. By 2050 two-thirds of the world's population is forecasted to live in cities, resulting in a net urban influx of 2.5 billion people [1]. With urban transportation systems currently strained by congestion, noise and air pollution, cities are generally not equipped to address dramatic urban growth with a high degree of mobility and reduced environmental impact. Substantial investment in sustainable transportation is required. In order to limit global climate change to 2ºC, the International Energy Agency estimates an additional global expenditure of USD 70 billion/year in the transportation sector [2].

One approach to sustainable transportation is the electrification of the urban fleet. Electrification of the transportation sector offers several benefits including improved urban air quality, reduced noise, and decreased dependence on fuel imports and volatile fuel prices. However, the environmental benefit of electrification depends on the emissions created at the source of generation. City-integrated renewable energy could substantially contribute to the environmental, economic and social aspects of urban sustainability. Four characteristic advantages of distributed energy systems include the ability to i) offer low to zero-carbon emissions, ii) offset capital-intensive investments for network upgrades, iii) impart local energy independence and network security, and iv) motivate social capital and cohesion [3].

Recent economic and technical advances have made city-integrated photovoltaics particularly attractive. Not only has the installed price of solar energy dropped by as much as 50% since 2010 [4], but the power densities have increased dramatically. In the most solar-rich places in the world, using the most-efficient laboratory tested multi-junction solar cells, the power density of photovoltaics could exceed 120 W/m^2 [5]. Since the solar resource is highly varied, 87 cities from 43 countries are considered to study the feasibility of using city-integrated photovoltaics at a commercially available 15% efficiency to satisfy all urban transportation energy needs.

2 Methodology

2.1 Calculation of required photovoltaic coverage

To determine the feasibility of using city-integrated photovoltaics, the percentage of the city's land area that would need to be covered by photovoltaics to generate all the energy required by the city's transportation sector was calculated for each of the 87 cities considered. Using the total transport energy use per capita and the urban density from the UITP Millennium Cities Database [6], the annual transportation energy density was calculated as follows:

$$Transportation\ Energy\ Density = \frac{Total\ Transport\ Energy\ Use/Capita}{Urban\ Density} \quad (1)$$

Using the horizontal solar insolation data obtained from the NASA Langley Research Center Atmospheric Science Data Center Surface meteorological and Solar Energy (SSE) [7] and assuming a commercial photovoltaic efficiency of 15%, the annual solar energy generated per square meter was calculated:

$$Solar\ Energy\ Density = Photovoltaic\ Efficiency \times Solar\ Insolation \quad (2)$$

Finally, the following equation was used to calculate the percentage of the city that would need to be covered by photovoltaics to satisfy all the transportation energy needs of the respective city:

$$\%\ Photovoltaic\ Coverage\ Required = \frac{Transportation\ Energy\ Density}{Solar\ Energy\ Density} \quad (3)$$

2.2 Attribute ranking

To better understand what makes a city a good candidate for using city-integrated photovoltaics to satisfy urban transportation needs, attribute ranking was performed. The UITP Millennium Cities Database [6] contains over 200 attributes. These attributes included factors related to urban form, existing transportation infrastructure and investment, behavioral patterns, time and energy efficiency of a variety of modes of transportation, and transportation pricing and fines. In addition to the attributes in the UITP Millennium Cities Database, the local horizontal solar insolation obtained from the NASA Langley Research Center Atmospheric Science Data Center Surface meteorological and Solar Energy (SSE) [7] was included as a city attribute.

Not all cities contained data for all attributes. Therefore, attribute ranking would be performed on a sparse matrix. To limit the bias, any attribute missing data for more than 25% of the cities investigated was eliminated from the study. Missing data in the remaining attributes was replaced by the mean value for that attribute.

Additionally, many of the attributes were highly dependent on other attributes. For example, the total public transport boardings per capita is strongly correlated with daily public transport trips per capita. These multicollinearities dilute the importance of all highly correlated attributes. To address this, a correlation matrix was constructed for all the attributes. Attributes with a covariance above 0.75 were clustered and a single representative attribute selected.

Having cleaned the data and clustered dependent attributes, an extra-trees regression from Python's scikit-learn package [8] was used to rank the city attributes based on each attribute's ability to predict the percentage of photovoltaic coverage required. The random selection of decision trees used by this particular ensemble method (the extra-trees regression) allowed for the ranking of features despite the comparatively low number of cities included in the dataset.

3 Results

Most cities required only moderate coverage of photovoltaics to satisfy their urban transportation needs. Of the cities studied, 11 cities were able to satisfy their transportation needs by covering less than 5% of the city land area with photovoltaics. Nearly half of the cities (40 cities) were able to meet their needs with less than 10% covered and the majority of cities (84%) could do so with less than 15% covered. Only 5 cities (roughly 5% of the cities studied) required more than 20% coverage of photovoltaics. In increasing order of required coverage, these cities were Bangkok, Hong Kong, Brussels, Seoul, and Taipei.

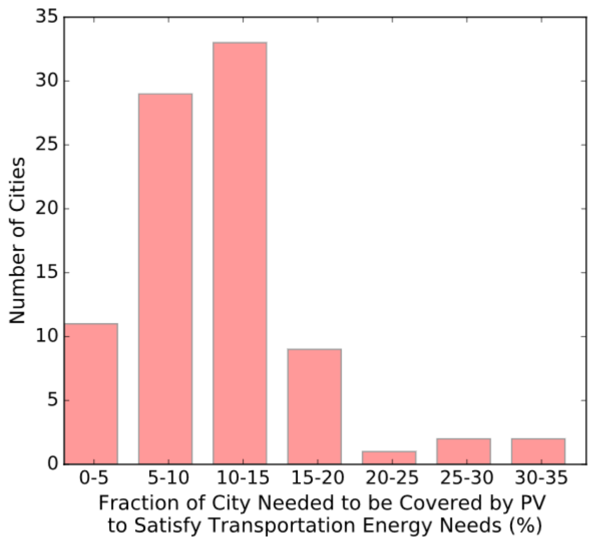

Figure 1: Histogram depicting the photovoltaic coverage needs of the 87 cities studied.

To better understand what type of cities required the lowest photovoltaic coverage, we investigated various city attributes. As expected, cities with greater solar insolation generally required less photovoltaic coverage. However, as seen in Fig. 2, there is a significant scatter (the coefficient of determination, r^2, is only 13%). The regions are indicated by color and grouped according to the classification described in the Global Energy Assessment [9] (ASIA, Asia excluding OECD90 countries; LAC, Latin America and the Caribbean; MAF, the Middle East and Africa; OEDC90, member countries of the Organization for Economic Cooperation and Development as of 1990; REF, Eastern Europe and the former Soviet Union).

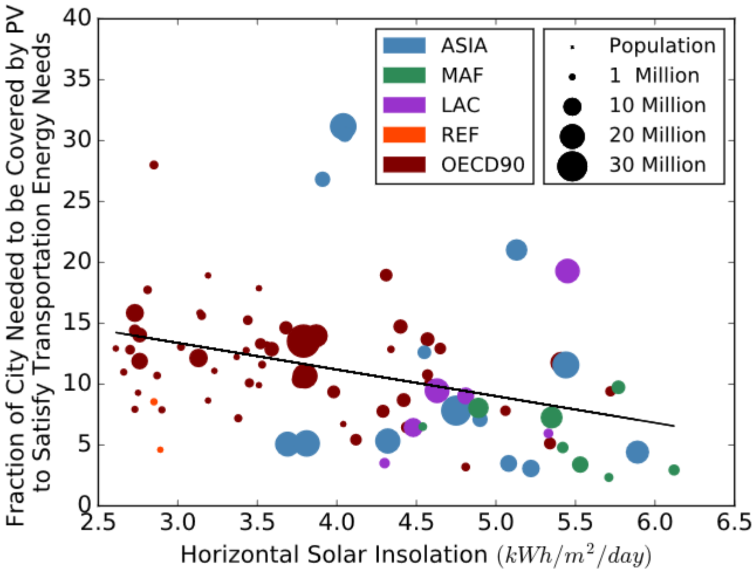

Figure 2: Solar insolation as a predictor of required photovoltaic coverage.

Using the extra-trees regression, we considered over 200 city attributes to determine the most significant attributes in predicting required photovoltaic coverage. The results of the extra-trees regressor is shown in Fig. 3. The most important city attribute is the total private passenger vehicle kilometers per urban hectare. Based on the observed error bars for the extra-trees regression, this is also the only statistically significant feature.

Recall that correlated attributes were clustered and a representative attribute selected. Two attributes were correlated to the total private passenger vehicle kilometers per urban hectare; the correlated attributes and their correlation coefficients are included in Table 1.

In Fig. 4, the most important city attribute, the total private passenger vehicle kilometers per urban hectare, is plotted against the percentage of the city that would be required to be covered by photovoltaics to satisfy the urban energy needs. The relationship to the required photovoltaic coverage is substantially more pronounced than the horizontal solar insolation was in Fig. 2. The coefficient of determination, r^2, is 70%.

Based on the residual data in Figure 5, Hong Kong (residual value of 31.5) and Brussels (residual value of 26.5) are outliers; when removed from consideration, the r^2 value improves from 70% to 79%. With data from additional cities, other important attributes may be exposed. Performing extra-trees regression on subsets of the data or normalized data based on factors such as population or urban land area could reveal additional insights. Examples of subsets of data include regional, economic, and climate clustering.

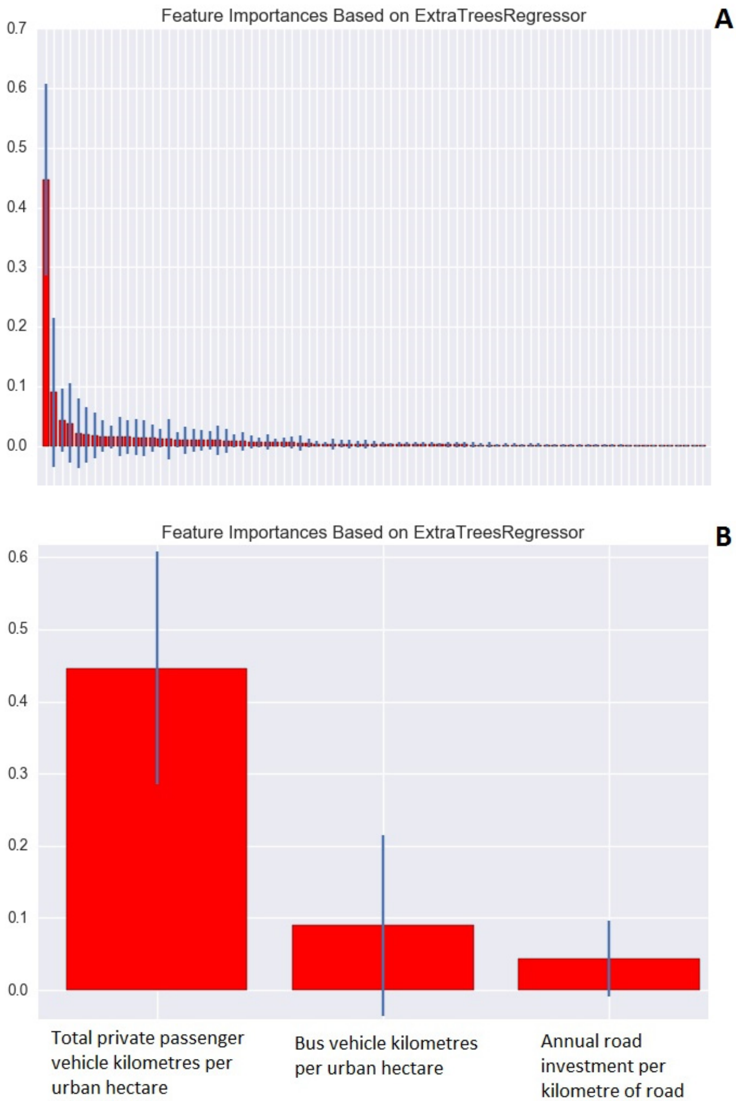

Figure 3: A Feature ranking of all city attributes; B Featuring ranking of the top three attributes.

Table 1: City attributes highly correlated to the total private passenger vehicle kilometers per urban hectare.

City attribute	Correlation coefficient
Passenger car kilometers per urban hectare	98.7%
Total private and collective passenger vehicle kilometers per urban hectare	96.7%

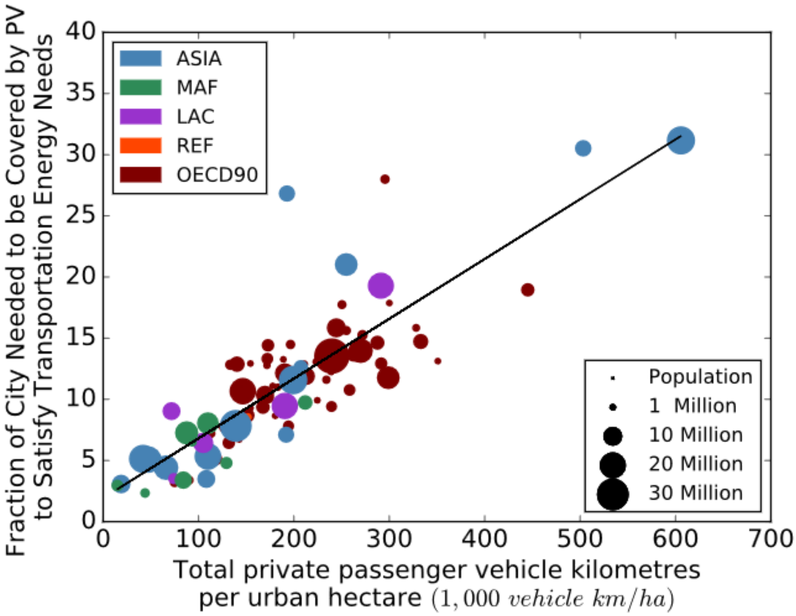

Figure 4: Total private passenger vehicle kilometers per urban hectare as a predictor of required photovoltaic coverage.

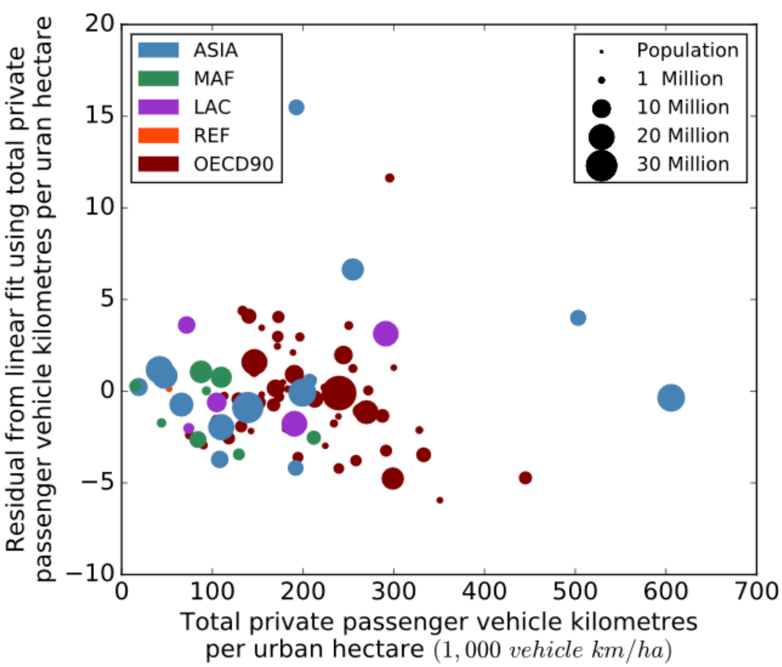

Figure 5: Residuals based on the linear fit used in Fig. 4.

4 Conclusions

The technical and economic performance of solar energy today means that city-integrated photovoltaics can now be considered a feasible technology to satisfy all urban transportation energy needs in many cities. Roughly half of the cities studied were able to satisfy their transportation needs by covering less than 10% of the city land area with photovoltaics, and the majority of cities (84%) could do so with less than 15% covered. The high density of urban areas results in limited available urban land. However, in many cities a greater percentage of the city land area relative to the required photovoltaic coverage has already been allocated to the transportation section. Parking lots in some cities occupy up to 40% of urban land [10]. For example, both Los Angeles and Orlando cover a third of the land area with parking lots [11]. Many parking lots have been covered by photovoltaics, transforming them into green charging stations. Covering parking lots with photovoltaics has thermal management benefits. The dark color, high specific heat, and low moisture content of asphalt pavement accumulates heat and contributes to the urban heat island effect. By covering parking lots with photovoltaics, not only is the urban heat island effect mitigated but also the shaded vehicles underneath are kept cooler and require less energy for air-conditioning. The practice of covering parking lots with photovoltaics is encouraged to power the entire urban transportation fleet, not only private vehicles.

To maximize the implementation of city-integrated solar energy for satisfying the energy needs of the urban transportation sector, the use of private vehicles should be limited. In this study we performed a feature ranking of over 200 city attributes through an extra-trees regression, the most important, and only statistically significant, feature for predicting required photovoltaic coverage was the total private passenger vehicle kilometers per urban hectare. Comprehensive policies are needed to not only encourage city-integrated photovoltaics for use in the urban transportation sector but also to reduce urban transportation energy needs through decreased private vehicle use.

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