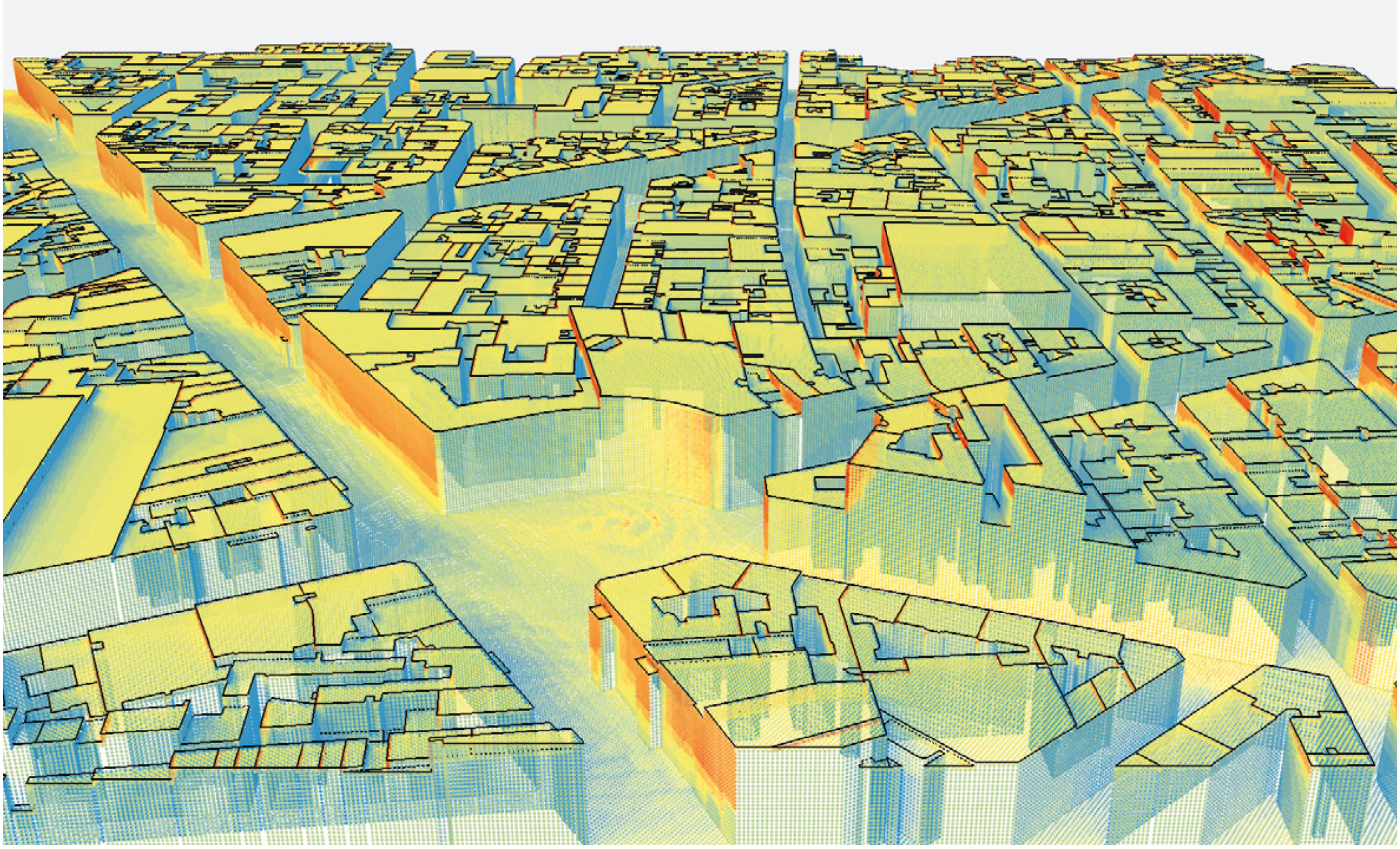

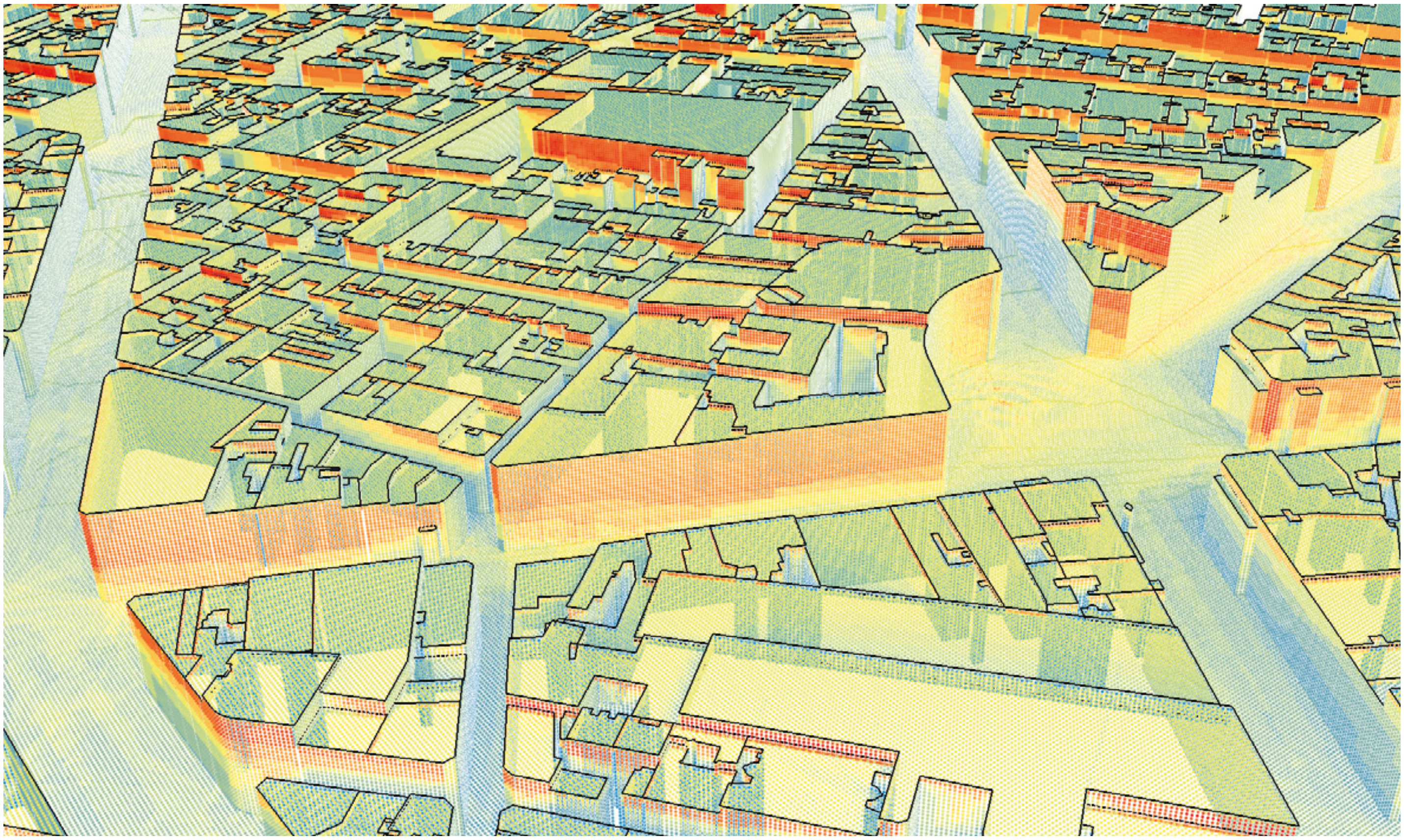

Visualisations: Rui Zhu

3D visualizations of annual solar irradiation in Paris, created as part of a study by MIT Senseable City Laboratory. They show specific instances of irradiation from two different perspectives.

Solar

The effective use of solar energy stimulates the development of liveable and sustainable cities. Solar cities began to receive attention from architects, engineers, urban designers, geographers and entrepreneurs ever since photovoltaic systems became competitive due to an increase of solar transition efficiency and a decrease of cost. The significance of using solar energy lies not only in generating green electricity with zero emission but also in creating significant social and economic impacts through the ways it is used.

RUI ZHU

Cities

Cities occupy a mere two per cent of the land on earth but consume 60 to 80 per cent of global energy, out of which more than 70 per cent result from fossil fuels that exacerbate air pollution and global warming. Fifty-five per cent of the 7.7 billion people living on Earth in 2019 inhabited cities; with the rate of urbanization growing steadily, these figures are expected to rise to 68 per cent of 9.7 billion people in 2050. It is no surprise that cities will become central places of the response to climate change, and it is clearly necessary to promote renewable energy generation with zero emission in cities. As a type of renewable energy, solar energy has been used increasingly in recent years to generate green electricity. Apart from large photovoltaic (PV) power stations, usually located on vast stretches of bare land and generating stable amounts of electricity, solar harvesting in fragmented urban areas is relevant especially if available land is scarce. The city-state of Singapore, for instance, plans to deploy PV modules on 50 per cent of the rooftops owned by its Housing & Development Board, and thus ramp up the solar capacity to meet the annual demand of 350,000 households by 2030 (Tan, 2019).

To harvest solar energy efficiently, planners prefer urban surfaces that feature quantitatively large and spatially concentrated solar irradiation. The reason is that urban morphology may radically alter solar distribution, creating solar accumulative or dispersive areas. An example would be an area that is continuously in the shadow because the surrounding buildings block sunshine throughout the year. At the other end of the spectrum would be surfaces that can melt cars and set buildings on fire because of reflective irradiation from surrounding buildings with glazed or mirrored facades (Lallanilla, 2013). It is important to calculate the spatial distribution of annual solar irradiation as accurately as possible when deploying PV modules in cities.

A study conducted by MIT Senseable City Laboratory estimated solar energy on rooftops, facades, and the ground by considering four influential factors: global solar irradiation, consisting of reflective irradiation between urban envelopes and direct and diffuse irradiation from the atmosphere; historical weather data such as cloud cover percentage; urban morphology; and geo-location (Zhu et al., 2020a). The direct and diffuse irradiation is computed as input parameter based on cloud cover, geo-location, and time. Several irradiation vectors may arrive at the same location of an urban surface, leading to the creation of a solar accumulative area. The irradiation vectors reflect remaining energy towards the sky or other surfaces. The study suggests that almost 95 per cent of irradiation will have four rounds of reflection between urban envelopes before reaching the sky. A set of albedos with a constant interval is calculated based on a series of materials commonly used in building construction: masonry brick, gypsum, asphalt, glass and concrete. Glazed surfaces have the highest albedo. An assessment of these materials leads to a more accurate estimation when incorporating reflective processes, and a specific albedo achieving the highest accuracy is used as an empirical value for all the cities that were studied: Athens (Mediterranean climate), Honolulu (semi-arid tropical), Hong Kong (subtropical), Lisbon (Mediterranean), Los Angeles (dry subtropical), Mandalay (subtropical), New York (humid continental), Paris (continental), Singapore (tropical) and Toronto (continental). An evaluation of these ten cities shows that urban morphology has a strong effect on solar capacity. New York City receives the largest amount of solar energy annually: the high density of tall buildings and the diversity of heights generate a significant amount of reflections between urban envelopes, and each reflection leads to absorption of a certain amount of energy. Similar phenomena exist in other places, such as the downtown areas of Los Angeles and Toronto, where facades usually obtain the largest proportion of solar energy, followed by rooftops and the ground. The ground has the shortest exposures to solar irradiation while near-ground facade sections have the largest accumulation of solar irradiation. By contrast, cities with a moderate density of buildings and located at a low latitude receive the largest energy on rooftops and the ground since solar irradiation can reach roof and ground surfaces directly, such as in Honolulu and Singapore. Additionally, the layout of buildings can influence annual solar irradiation.

Apart from urban morphology, cloud cover and geo-location can affect annual solar irradiation. Singapore is predestined to use solar energy since it is located close to the equator and has little cloud cover all year round. The global cities at higher latitude tend to have smaller annually maintained solar energy, suggesting that on a global scale geo-location affects annual solar energy. Notably, the effect of urban morphology on solar energy changes dynamically at a different time of a day or during different seasons. Facades facing east usually receive large amounts of solar energy in the early morning while being hidden in shadow in the late afternoon, and rooftops accumulate abundant solar energy in summer as the sun is directly overhead while inclined facades benefit from winter sunshine. Models can help to estimate solar energy accurately for different solar-related purposes, which are constrained by dynamic solar irradiation depending on the time of year. Here are three independent examples:

Solar accessibility in developing cities: A case study in Kowloon East, Hong Kong

To investigate how the solar accessibility of existing buildings is transformed through the construction of new buildings, a comparison of solar energy pre- and post-construction is required. In a case study conducted in the Kowloon East district of Hong Kong, where a large unused urban area is being transformed into a new business district, the annual solar accessibility of existing buildings is affected insignificantly (Zhu et al., 2019). There are two major reasons for this outcome: the master plan appropriately limits the heights of the buildings to be constructed, and Hong Kong is located at relatively low latitude, therefore irradiation causes only small areas of shadow.

Solar charging for shared electric scooters

To deploy solar charging platforms for electric scooter sharing services, planners prefer street locations that feature quantitatively large and spatially accumulated solar energy. When e-scooters receive solar charging at stations during daytime, sites need to meet solar energy requirements according to different daytime hours while considering the effects of surrounding buildings and structures. More relevant than the cost of electricity are the costs that arise while operating and charging the scooters. The example of two fast-growing scooter-sharing startups, Lime and Bird, illustrates this. Both companies use a similar payment model for their "juicers". Lime makes a base payment between $3 to $5 for independent contractors to charge one scooter whereas Bird pays between $3 to $20 (Hawkins, 2019). Since hundreds or thousands of trips can occur every day, the cost for charging the scooters is potentially very high. Scooter-sharing data from Singapore shows that 31.6 per cent of the total trips in Marina Bay and 7.87 per cent of the total trips in the area of the National University of Singapore were made by the operators' employees for charging purposes (Zhu et al., 2020b). If the operators pay, as Lime does, $5 for every recharge, the annual charging cost would be more than $400,000 for these two small urban areas in Singapore alone. The annual charging costs that would come with providing a scooter-sharing service for the whole city would be in the million dollar range. This can be mitigated by a system of solar charging platforms that allow scooters to be charged when they are parked there during the daytime. By considering the effects of urban morphology, real-time simulation of hourly generated electricity from solar charging platforms indicates that a significant reduction of charging trips – and consequently of operational costs – could be achieved.

Quantifying the sensing power of vehicle fleets

The estimation of solar irradiation on moving vehicles also needs to consider the effects of urban morphology along with those of road networks. A study at MIT Senseable City Laboratory deployed PV modules on the roofs of vehicles to continuously power air-quality sensors. The measurements included a frequent update of GPS positions to observe fine particular matter 2.5 (PM 2.5), temperature, and humidity. To investigate the feasibility of this approach, researchers developed an urban-sensing platform that compares estimated and observed electricity (Anjomshoaa et al., 2018; O'Keeffe, 2019). Based on continuous solar powering, ten random vehicles can measure various environmental properties within one-third of the road network every day. A large fleet of crowd-sourced vehicles could provide inexpensive sensing platforms for measurements across a large portion of a city.

Considering the effect of urban morphology on solar cities, two future research directions are relevant. Firstly, street-view images can be used to identify different textures of urban envelopes, which can then be analysed in terms of their specific albedo to estimate solar distribution. Secondly, natural terrain and vegetation partial to urban morphology can considerably influence solar distribution. Mountains may exceed the effects of buildings by creating long-term and large areas of shadow in cities. Similarly, green streets dominated by tall trees block sunshine and create shadows in their micro-environments at different times of the day. The development of solar cities can benefit from related research and needs to consider several factors, including urban morphology, historical weather data, geo-location, and albedo. Building a sustainable solar city requires more than generating green electricity with zero cost. The development of systems that achieve a higher solar transition efficiency and with larger storage capacity are major steps towards making solar energy systems more competitive. Research can help specify such systems according to the respective urban context to foster the creation of sustainable cities that offer social and economic benefits based on solar energy.

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