Opportunity of rooftop solar photovoltaic as a cost-effective and environment-friendly power source in megacities

Highlights

Develop a building-level RSPV potential assessment model for mega-cities

Show the chance to fully use RSPV potential cost-effectively and environment-friendly

The RSPV potential in the Beijing GM area amounts to 20.8% of the power demand

Deployment of RSPV system would reduce the required new transmission capacity
Opportunity of rooftop solar photovoltaics as a cost-effective and environment-friendly power source in megacities

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SUMMARY
Rooftop solar photovoltaics (RSPV) are critical for megacities to achieve low-carbon emissions. However, a knowledge gap exists in a supply-demand-coupled analysis that considered simultaneously RSPV spatiotemporal patterns and city-accommodation capacities, a pivotal way to address solar PV intermittency issues. Here, we developed an aggregated model for an RSPV + system by linking building-level potential assessment to dynamic optimization of building-related flexible loads. Taking Beijing, the capital city of China, as case in point, we show that annual RSPV potential in Beijing’s Greater-Metropolitan area amounts to 15.4 TWh, all of which could be accommodated environmentally friendly and cost-effectively through the smart operation of electric vehicles and air conditioners equipped with thermal energy storage (TES). Additionally, the RSPV + system would reduce the 8.6 GW transmission capacity otherwise required for increasing electricity demand for 2035 in Beijing. The analysis offers an important reference for sustainable RSPV development in mega-cities in China and other countries globally.

INTRODUCTION
As the world’s largest CO2 emitting country, China accounts for about 28.8% of global carbon emissions (British Petroleum, 2020). Decarbonization of China’s economy is pivotal in realizing the climate goals to limit the global average surface temperature rise well below 2 °C or within 1.5 °C by the end of this century. In 2020, China announced the target to realize carbon neutrality by 2060, which demands short-term development of no less than 1.2 TW of renewable (wind and solar) capacity to be installed by 2030, and greater expansion of renewable energy sources in the longer term (World Resource Institute, 2020). As the largest PV panel manufacturer in the world, China also plans to reach a total of 5000 GW PV capacity in 2050 (Wang, 2019). As a locally available and renewable power resource for urban residents, rooftop solar photovoltaics (RSPV) are receiving attention from decision-makers and the public in Chinese cities, where approximately 85% of the country’s energy is consumed (China Urban Energy Report Research Group, 2019). The installed capacity of distributed PV (mainly RSPV) in China has increased from 4.7 GW in 2014 to 79.9 GW in 2020, the latter of which accounted for 32.5 and 11.3%, respectively, of the cumulative PV capacity in China and globally (National Energy Administration, 2021; International renewable energy agency, 2021). Many mega-cities in China, including Beijing, have given high priority to the deployment of RSPV to fulfill their carbon peaking and carbon neutrality targets (The People’s Government of Beijing Municipality, 2020).

However, large-scale integration of RSPV may pose challenges to existing power grids owing to its inherent intermittency (Obi and Bass, 2016). A duck curve phenomenon happened in the power grid of California Independent System Operator with the relatively high penetration of RSPV, which is featured by steep power ramps and shortened capacity for the frequency response (Folsom, 2013). A number of case studies in Britain, US, Spain, and Australia further indicated that high penetration of RSPV, if not properly handled, would distort electricity market prices and incur significant financial loss (Sharma et al., 2020; Dimitriadis, 2015; Unión Española Fotovoltaica, 2018; Joskow, 2018). Therefore, future RSPV development requires the urban RSPV evaluation to be more practical, from simply answering the total potential to precisely quantifying its spatiotemporal distribution and its effective utilization. Effective utilization of RSPV requires...
coordinated consideration of both the high-resolution spatiotemporal features of the RSPV potential and the accommodation capacity from the electrical loads. The evaluation framework with high spatiotemporal resolution can not only provide important guidance for RSPV development and planning on a city scale but also detailed location information for the potential future expansion of distribution facilities of the electric grid power system. In addition, the estimated hourly RSPV outputs could support the optimization of RSPV dynamic utilization with hourly electrical loads.

Although existing studies have investigated the urban RSPV application, a potential-utilization integrated analysis remains a literature gap. Existing studies tended to treat supply and consumption separately, with a focus on either assessment of RSPV resources, or quantification of potential urban accommodation capacity. In general, the studies on urban RSPV potential assessment fell into three categories: (1) hybrid framework with sampling method that examined features from individual building samples of small city blocks and then applied to the entire urban area or even national and global scale based on population, roadmap and building density, (2) building typology assignment that classified buildings into different types and assigned corresponding availability factors to each type of rooftop, and (3) GIS-based that either characterized the structure and shade of rooftop areas based on high-resolution LIDAR data and digital surface model data to directly evaluate the potential for RSPV, or captured rooftop geometry through artificial analysis of remote sensing data (Gagnon et al., 2016; Defaix et al., 2012; Wiginton et al., 2010; Ghosh et al., 2006; Vardimon, 2011; Li et al., 2015; Song et al., 2018; Ordóñez et al., 2010; Kouhestani et al., 2019; Lee et al., 2018; Byrne et al., 2015; Bergamasco and Asinari, 2011; Peng and Lu, 2013; Izquierdo et al., 2008; Guo., 2015; Denholm et al., 2009; Singh and Banerjee, 2015; Zhang, 2017; Levinson et al., 2009; Fogl Moudry, 2016; Joshi et al., 2021; Bödis et al., 2019; Mohajeri et al., 2018; Zhong et al., 2021). For mega-cities in China, knowledge gaps still exist for RSPV potential evaluation with high spatiotemporal resolution, which considers the building-scale suitability spatially and provides the RSPV power outputs over 8760 h for a full year. In addition, studies addressed the opportunities from smartly operating electrical loads, such as electric vehicles (EVs), air conditioners (ACs), and other flexible loads to effectively use the variable power from RSPV (Litjens et al., 2018; Good et al., 2019; Shepero et al., 2020; Laine et al., 2019; Martin et al., 2022). However, they focus on individual buildings or communities and fail in characterizing the RSPV spatiotemporal features at the city level, and rarely conduct optimization models fully considering the 8760-h optimization on daily and seasonal variation of power generation and loads.

In this study, we developed a potential-utilization linked framework to investigate the opportunity for RSPV in mega-cities, by linking a high spatiotemporal resolution RSPV potential assessment module with a dynamic utilization optimization module (see Figure 1). A suite of impact factors for individual buildings were considered on hourly basis, such as building and tree shadows, roof structure and slope, and so forth. Building on this, we further applied the power system planning & optimization (PSP&O) model to investigate the synergy between the RSPV power and emerging urban loads from EVs and ACs by considering the latter’s dynamic compensation effects on the former. Here, we took Beijing, the capital city of China, as a case in point, and demonstrated a win-win situation that the locally available RSPV with a potential of 15.4 TWh in the Greater Metropolitan area (GM) of Beijing could be effectively utilized by the growing electricity demand from EVs and ACs equipped with thermal energy storage (TES) in the city in 2035, the target year of China’s Long-range Objectives for national economic and social development (2021-2035). Here, the GM area refers to the area inside 6th Ring Road (RD6) in Beijing, which mainly consists of the densely populated city area (inside RDS) and so-called “in-between city” area (Sieverts, 2003) (RD6-RDS). In Beijing, approximately 70% of electricity consumption relies on external power primarily generated from the coal-fired power plants in the northern electric power grid in China (The People’s Government of Beijing Municipality, 2013). Should all the RSPV potential be utilized in Beijing to substitute the external coal-fired power, emissions of 16.4 Mt CO2, 6.2 kt NO, 2.9 kt SO2, and 1.3 kt PM2.5 would be reduced annually, and at the same time, 8.6 GW capacity for transmission lines to Beijing can be avoided for construction. An extended statistical analysis of urban RSPV for 344 cities at the prefecture level in the Chinese mainland indicates a potential of 531 TWh, corresponding to 7.3% of the total electricity demand in these cities.

RESULT
Potential for rooftop solar photovoltaics power
Beijing GM area (inside RD6), which accounts for 80.2% of population and 13.8% of the jurisdiction area of the entire city (Beijing Municipal Bureau of Statistics, 2018), has approximately 125 km2 of the total of 235 km2 rooftop areas identified suitable for the deployment of RSPV. As illustrated in Figure 2D, the
suitable areas are mainly influenced by building shade and rooftop structure, particularly inside the core Metropolitan (RD2) areas, which are concentrated with a mixture of low-rise buildings and skyscrapers (Figure S4). The capacity potential for RSPV, the potential installed capacity of RSPV on suitable rooftop areas, was estimated at 0.6 GW inside RD2 to 5.1 GW in the ring area of RD5-RD6, with the corresponding electricity potential increasing from 0.9 TWh to 7.1 TWh. This reflects the fact that for the urban area of Beijing, the further away from the city center, the larger land area and lower plot ratio, which allows, respectively, for greater building rooftop area and better suitability factors for the deployment of solar PV panels. Should the suitability factors of RD5-RD6 hold for the peripheral area, the capacity potential of RSPV outside the RD6 area was estimated at 11.7 GW, bringing a lower boundary of 22.8 GW for the total RSPV capacity in the entire Beijing area. (Figure 2C).

Results in Figure 2 also suggest that both the capacity and electricity potentials for RSPV in the Beijing GM area increase with a distance from the city center to the suburbs. The capacity potential increases from 0.6 GW inside RD2 to 5.1 GW in the ring area of RDS-RD6, with the corresponding electricity potential increasing from 0.9 TWh to 7.1 TWh. This reflects the fact that for the urban area of Beijing, the further away from the city center, the larger land area and lower plot ratio, which allows, respectively, for greater building rooftop area and better suitability factors for the deployment of solar PV panels. Should the suitability factors of RDS-RD6 hold for the peripheral area, the capacity potential of RSPV outside the RD6 area was estimated at 11.7 GW, bringing a lower boundary of 22.8 GW for the total RSPV capacity in the entire Beijing area. (Figure 2C).

The spatial distribution of the RSPV electricity potential per land-use area and per capita exhibits distinct heterogeneity in the Beijing GM area (see Figures 3A and 3B). The RSPV potential per land area ranges from 0 kWh/m² to 35.6 kWh/m², with an average value of 7.2 kWh/m² (Figure 3A). High values for electricity potential per land-use area are concentrated inside RD4 owing to the high density of buildings. Some hotspots for RSPV potential per land-use area are located within RDS-RD6, such as Shougang Industrial Park at west RD6 and the Yizhuang Development Zone in the southeast RD6 area, reflecting the recent
urban expansion in Beijing. These areas have developed quite recently and have been concentrated with a number of companies, thus they are mainly occupied by low-rise office buildings and factory buildings with large roof areas. In contrast, the per capita RSPV electricity potential demonstrates a higher value with 1332.4 kWh on average in areas between RD4 and RD6, whereas the values for the area inside RD3 are relatively lower with 728.5 kWh on average. This reflects the trade-off between building and population densities that high population density inside RD3 drives down the per capita RSPV potential, over offsetting the increasing effects from the high building density. As illustrated in Figure 3B, the average value of the per capita RSPV electricity potential amounts to 1030.8 kWh, varying over a wide range from 182.1 kWh to 6543.3 kWh. To put this into context, the average residential power consumption per capita in Beijing was 1168.3 kWh in 2019 (Beijing Municipal Bureau of Statistics, 2021), slightly higher than the average per capita potential for RSPV.

Effective rooftop solar photovoltaics utilization through building-related flexible loads

The opportunities for the utilization of the RSPV potential in the Beijing GM area were further investigated through a power system planning & optimization model to optimize the operation of Beijing’s building-related flexible loads including EVs, ACs as well as heat storage from TES (hereafter referred to as the RSPV + system) in 2035 with a minimum cost (see in STAR Methods). As illustrated in Figure 4, results indicate that the 15.4 TWh RSPV from the Beijing GM area could be 100% effectively utilized by loads of EVs and ACs coupled with daily and seasonal TES. The annual load of EVs and ACs in the Beijing GM area are

Figure 2. Suitable rooftop area and RSPV potential in different RD locations and kinds of buildings
(A) Visualization of ring road (RD) distribution in Beijing.
(B) Suitable roof area and its ratio in different RDs, the dashed column means the estimated suitable rooftop area outside RD6.
(C and D) Capacity and electricity potential in different RDs, and (D) Impacts of limiting factors on the suitable rooftop areas for RSPV in Beijing Greater Metropolitan area (within sixth ring road, RD6).
projected to increase to 9.9 TWh and 14.3 TWh, respectively, in 2035, which together would raise the consumption ratio of RSPV potential to 61.2% (9.5 TWh) from 27.1% (4.2 TWh) in 2020 without changing their traditional pattern of electricity consumption. About 4.1 TWh electricity from RSPV can be utilized by flexibly running ACs, coupled with the 21.6 GWh daily and 1966.0 GWh seasonal TES capacities including about 0.5 TWh power loss from the TES system (Figure 4). The rest of the RSPV potential (2.8 TWh) can be further accommodated through the smart operation of EVs.

The optimal operation of the RSPV + system demonstrates distinct seasonality in terms of complementary effects (Figure 5). For most cases in summer, the peak of cooling demand is consistent with the peak of RSPV potential and the direct load from EVs and ACs could accommodate more than 95.0% of the RSPV potential (Figures 5E, 5F, 5I, and 5J). The daily TES system works mainly in utilizing RSPV to meet the extremely high demand for cooling through intra-day heating storage, while the seasonal TES system functions as a cooling supplier in early summer (Figures 5H and 5I). The daily and seasonal TES systems together facilitate increasing the ratio of electric cooling fueled by RSPV to total cooling supply from 43.5% to 58.4% in summer. In contrast, the RSPV potential and electric loads from AC heating vary discordantly in winter (Figures 5A and 5B). In this case, the daily TES system is frequently engaged to store heat when RSPV has a surplus relative to the total electric load. During peak-heating hours in winter evenings, the heating demand would be mainly satisfied by the combination of heat supply from daily TES and autumn-stored heat in the seasonal TES system. The daily and seasonal TES systems together increase the ratio of electric heating by RSPV from 30.1% to 77.8% in the total heating supply in winter (Figure 5D). The smart charging of EVs functions to shift the electric load from night to daytime, especially on the days when the RSPV is relatively abundant (Figure 5C). This implies that future EV charging may increasingly rely on public charging near offices to maximally use RSPV. During the Autumn and Spring, the requirement for AC cooling/heating load is reduced to the minimum, and the seasonal TES system stores the surplus RSPV either in the form of cold energy from March 1st to June 15th or heat from September 1st to December 15th (Figures 5m, 5n, 5p, and 5q). In addition, RSPV in Beijing tends to have higher outputs and variations in spring than in autumn, and thus more flexible loads need to be engaged in the former season. The seasonal TES system reaches its full capacity of 1965.9 GWh in spring, in contrast to only 958.6 GWh utilized in autumn. For the same reasons, the percentage of EVs load shifted by the smart charging reaches 39.2% in spring vs. 36.4% in autumn (Figures 5O and 5R).

The RSPV + system would lead to an evident reduction in emissions of CO2 and three primary criteria air pollutants (NOx, SO2, the primary PM2.5) by substituting external coal-fired electricity consumed in Beijing delivered from the northern electric power grid. Particularly, the RSPV + system would annually reduce emissions of CO2 by 16.4 Mt, NOx by 6.2 kt, SO2 by 3.0 kt, and the primary PM2.5 by 1.3 kt, accounting, respectively, for 19.3%, 6.4%, 19.7% and 4.9% of total emissions in Beijing in 2019.

RSPV + system would not only supply carbon- and pollution-free electric power to Beijing, but also lead to a potentially lower cost for electricity consumption in the future. The overall levelized cost of electricity
(LCOE) for RSPV + system in 2035 is estimated at 0.37 (0.32-0.47) RMB/kWh, with breakdowns of 0.17 RMB/kWh (0.15-0.19 RMB/kWh) from the RSPV and 0.20 RMB/kWh (0.17-0.28 RMB/kWh) from the capital expenditure of daily and seasonal TES system. Meanwhile, should 95% of the RSPV potential in the Beijing GM area be utilized (with 5% being curtailed), the cost for RSPV generation would rise to 0.18 RMB/kWh (0.15-0.20 RMB/kWh) but that for TES systems would significantly reduce to 0.13 RMB/kWh (0.11-0.18 RMB/kWh), resulting in an even lower overall LCOE of 0.31 RMB/kWh (0.26-0.38 RMB/kWh). To put this into context, the grid tariff of coal-fired power plants averaged 0.35 RMB/kWh in the northern power grid in 2019, which supplied 70% of demand for electricity in Beijing. Additionally, should all increasing electric loads from EVs and ACs in Beijing in 2035 be supplied by external electricity delivered from the northern electric power grid, it would require adding 9.04 GW of new transmission capacity. Utilization of the locally available RSPV power would avoid 8.6 GW external transmission capacity construction (with financial savings of 5.0 billion RMB) to Beijing otherwise required to meet the increasing demand for EVs and ACs.

Discussion and policy implication
This study developed a potential-utilization linked framework for the deployment of RSPV in megacities with the consideration of both the tempo-spatial characterization of RSPV resources on the supply side and the optimal accommodation using urban flexible loads on the demand side. We conducted the first of its type of analysis at a megacity scale, taking Beijing as a case in point. Our study demonstrated that approximately 15.4 TWh RSPV is available in the Beijing GM area, and the RSPV potential could be fully accommodated in an environmental-friendly and cost-effective fashion through the optimal operation of increasing electricity loads from EVs and ACs equipped with the TES systems. In addition, the deployment of RSPV + system is expected to reduce the requirements for the construction of a new transmission capacity otherwise required to meet the increasing demand for electricity in Beijing. The methods featured integrative building-scale function identification through multi-source urban information in urban planning, building-scale RSPV suitability analysis in urban geographic analysis, city-scale hourly flexible load quantification in building simulations, and newly developed PSP&O models in electric power system analysis. The results, with building suitability references, high-resolution RSPV potential locations, and local competitive renewable options, are expected to appeal to a broad range of audiences, including not only urban planners and policy makers on civil, grid, and energy systems but also scholars in energy transition, urban geographic analysis, power system planning, climate adaptation, and so forth.

The case study of Beijing may shed light on the opportunities for expanding the application of the “RSPV+” system for the 344 prefectural level cities in China. Through statistical methods based on data derived from the China Urban Construction Statistical Yearbook (Ministry of Housing and Urban-Rural Development of the People’s Republic of China, 2021), we estimated a total 531 TWh annual potential of urban RSPV for 344 cities at the prefecture level in the Chinese mainland, which accounts for 7.3% for national total electricity demand in 2020. Given the different RSPV source conditions and urban accommodation capacities, the
optimal operation strategies of the flexible loads and TES system may vary among different cities, and so do the levelized costs of the RSPV + system. In this case, the strategy of the RSPV utilization in different cities should be tailored to their local conditions to maximize their climate and environmental benefit. If such an RSPV + scheme was introduced across China and other megacities globally, the impact would be a massive reduction in greenhouse gas emissions and strongly support carbon neutrality targets.

During the development of RSPV + system, non-residential buildings, especially industry and commercial (I&C) buildings, possess relative advantages over residential buildings. The industry and commercial buildings tend to have larger individual suitable rooftop areas for the deployment of RSPV panels than residential buildings. Especially industrial buildings, they are mainly located in the suburban areas between RD6-RD5 (Figure S7), where buildings have low density and similar height. Therefore, industry buildings are impacted less by building shadows than residential buildings. In addition, I&C buildings possess a relatively large demand for electricity per unit area (Wu, 2017) and their electricity use patterns match well with the diurnal variation of the RSPV power outputs. Thus, the I&C buildings tend to have a higher self-consumption ratio of RSPV electricity, which offsets more usage of high-price electricity from the electric power grid and improves the financial competitiveness of I&C buildings. The higher electricity prices for I&C buildings also consolidate their RSPV economic feasibility. The
I&C RSPV enjoys higher IRR (8.81%) and shorter DPBP (5.93 years) relative to those for residential RSPV with an IRR of 18.52% and DPBP of 12.32 years (Table S16).

For residential RSPV application, challenges exist in terms of risks of waterproof, fireproof, and regulation violation for aged buildings, which take up 30-50% of residential buildings in mega-cities in China (Wei et al., 2017). However, those barriers could be overcome by renovation programs for old residential communities proposed in the aftermath of COVID-19, which aim at modernizing old residential buildings. In addition, the residential innovation program also allows intelligent transformation for the renovated buildings, which would improve demand-side synergistic effects from ACs and EVs as envisaged in the present analysis. Savings in cost would be realized through incorporating the deployment of RSPV + system with those community-renovation programs, which in turn synergistically brings savings in emissions of CO2 and air pollutants for mega-cities.

For the application of the flexibility in the “RSPV+” system, opportunity exists as the governmental policies in China administratively and financially encourage the development of EV smart charging (The People’s Government of Beijing Municipality, 2022) and TES implementation (National Energy Administration, 2020; Shupeidian.BJX, 2021; Shupeidian.BJX, 2022; North China Energy Regulatory Bureau of National Energy Administration of China, 2020). The recent pilot daily and seasonal TES projects have shown great success in terms of both operation and business models in Beijing and its surrounding area, such as the TES heating & cooling project in Fanshan Town in Zhangjiakou, and daily & seasonal TES project in Universal Studios Beijing (Chen et al., 2022). The daily TES could be placed along with the outdoor unit of air conditioners through retrofitting (Liu et al., 2020). In addition, existing literature also projected that the short-term storage capacities would reach 26 GWh in Beijing in 2035 (Zhuo, 2021) and future high renewable penetrated cities would require long-term storage to store around 3-5% of the city annual electricity demand, which is translated to 6-10 TWh for the Beijing’s case (Dowling et al., 2020) and consistent with the results from the present analysis. Meanwhile, the application of TES can not only provide RSPV accommodation capacity for low-carbon heating/cooling but also relieve the burden on the power grid, which is hard to be further expanded in mega-cities, through shifting the electric AC peak loads to support the future increasing power demands. To fully support the application of “RSPV+” system, future policies also need to synergistically incorporate the development of RSPV along with the flexibility sources, such as combining together the current separate financial supports or encouraging third-party on specially owning and operating “RSPV+” system to benefit the effective management.

Limitations of the study

Our results, which imply an annual 15.4 TWh RSPV potential for a year in 2020, may represent a lower boundary of the total RSPV potential for Beijing. First, the building footprints in Beijing were derived from the Web Map system, which could not fully cover some of the low-rise buildings and factory sheds in the suburban area of RD6-RDS. This is also reflected through the comparison with the literature prediction data (Li et al., 2020). Second, the research did not quantify the RSPV potential and utilization in Beijing rural area outside RD6 where RSPV is also expected to expand in the next decades, also locked the RSPV potential until estimated 2020 building stock without considering the future building stock growth until 2035. In addition, demand-side response capacities of other building appliances, such as refrigerators, dishwashers, or laundry machines, were not considered in this study, which may further improve the utilization of RSPV and relieve the required flexibility of EVs and ACs. Potentially interesting

| Table 1. Roof structure availability for buildings in Beijing |
|------------------------------------------------------------|
| Estimated parameter                                        | Value |
| Residential, height<15 m                                   | 60%   |
| Residential, height>15 m                                   | 50%   |
| Public & Commercial, height<15 m                           | 80%   |
| Public & Commercial, height>15 m                           | 60%   |
| Industry                                                   | 80%   |
research should incorporate a more detailed classification of building the property and other sources of demand response capability, to completely depict the opportunities for RSPV application in urban areas. Meanwhile, the penetration of RSPV would also probably reshape the electricity market, and even the users’ incentive to engage in the RSPV accommodation. The adoption dynamics from the perspective of consumers could be included in future research to systematically address the RSPV opportunity in the longer term.

STAR METHODS
Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION
Supplemental information can be found online at https://doi.org/10.1016/j.isci.2022.104890.

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DECLARATION OF INTERESTS
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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STAR METHODS

KEY RESOURCES TABLE

| REAGENT or RESOURCE | SOURCE | IDENTIFIER |
|---------------------|--------|------------|
| Deposited data      |        |            |
| Building scale RSPV potential in Beijing GM area | This study | N/A |
| Software and algorithms |        |            |
| ArcGIS 10.5         | Environmental Systems Research Institute | https://www.arcgis.com/ |
| Optimization algorithm | This study | See STAR Methods and supplemental information |
| MATLAB              | MathWork | https://ww2.mathworks.cn/products/matlab.html |
| CPLEX Optimization Studio 12.5.1 | IBM (International Business Machines Corporation) support | https://www.ibm.com/support/pages/downloading-ibm-ilog-cplex-optimization-studio-1251 |

RESOURCE AVAILABILITY

Lead contact
Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Xi Lu (xilu@tsinghua.edu.cn).

Materials availability
This study did not generate new unique materials.

Data and code availability
The datasets generated in this study are available from the lead contact on reasonable request.

METHODS DETAILS

Suitable rooftop area
The suitable area \( (A_{\text{suit}}) \) for the deployment of RSPV can be estimated using Equation 1:

\[
A_{\text{suit}} = (A_{\text{total}} - A_{\text{ape}} - A_{\text{bu}}) \times F_{\text{s}} \times F_{\text{a}} \times F_{\text{tilt}} - A_{\text{lma}} \quad \text{(Equation 1)}
\]

where \( A_{\text{total}} \) refers to the total rooftop area, \( A_{\text{ape}} \) indicates the inapplicable area of buildings with historic or ornamental value, \( A_{\text{bu}} \) indicates the unsuitable rooftop area due to building shadow, \( F_{\text{s}} \) is the dynamic building shadow coefficient on the suitable area, \( F_{\text{a}} \) and \( F_{\text{tilt}} \) indicate the area restriction factors from tree shadow and roof structure, respectively, and \( A_{\text{lma}} \) is the unsuitable small building area.

Special buildings
Special buildings symbolize the historical inheritance of a city, which has cultural and historical significance. Although European architects have had some experience with historical buildings and RSPV integration (Shen and Chu, 2013), rooftop construction on special buildings is regarded subject to high risks in China (Zhang, 2017), and these buildings were considered unsuitable for solar PV installation in this analysis. Areas with special buildings \( (A_{\text{ape}}) \) can be identified through the scenic landmarks in areas of interest (AOI) data from Baidu maps (Baidu Map Open, 2022).

Building shadow
The building shadow effect is an important limiting factor for RSPV deployment in urban areas, reflecting the phenomenon that high-rise buildings obstruct light to adjacent low-rise buildings. Following Gagnon et al. (2016), this analysis adopted a Hillshade modeling method to quantify the influence of building shadows using the building footprint polygon data derived from the Baidu map system. The method uses elevation information raster data, combined with solar azimuth and solar altitude at different hours, to generate a 1m*1m greyscale pixel map with values ranging from 0 (shadow) to 255 (highest normal-beam solar radiation). The greyscale for the rooftop area can be indexed by properly setting the size of the elementary cells of the raster data during conversion from the building footprint polygon data.
Seasonal variation was captured by running the simulation hourly from 8 a.m. to 4 p.m. every 15th day in the 12 months, which resulted in 108 pieces of shadow raster layers. At each hour, if the greyscale of a raster cell is lower than the maximum greyscale value on a horizontal surface for that hour in the same location, the cell is regarded as “shaded”, and the value of its effective sunlight hour is set as zero; otherwise, the value set as one. Following this rule, the 108 layers of greyscale values were converted into effective sunlight hours, the sum of which was divided by 12 to derive the daily average values. Then, we adopted the threshold suggested by the U.S. National Renewable Energy Laboratory (NREL), which requires effective rooftop areas with no less than 5 h of average daily effective sunlight (Gagnon et al., 2016). The rooftop areas below this threshold were regarded as ineffective, as indicated by $A_{\text{in}}$. In addition, an hourly dynamic factor, $F_{\text{ds}}$, was defined by the ratio of dynamically unshaded raster cells to total cells in the identified effective sunlit areas (i.e., the total surface area excluding $A_{\text{in}}$).

Tree shadow
Tree shadow is another major source of urban rooftop shade. In this study, buildings covered by tree shadows were required to meet two criteria: (1) their layouts intersect with the buffer zones of trees, and (2) their heights are lower than those of trees. For buildings identified as under the influence of tree shadow, we introduced an intensity index ($I_{\text{tree}} = \text{NDVI} - H$) to measure the influence. NDVI refers to the normalized distribution vegetation index, which was derived from satellite Landsat data in 30m resolution (Gorelick et al., 2017), and $H$ denotes the height of the buildings. We further assumed that the shadow influence factor ($F_{\text{ts}}$) was linearly proportional to the intensity index ($I_{\text{tree}}$). For the case study of Beijing, $F_{\text{ts}}$ was assumed to range from 8 to 40%, as reported in previous studies based on direct LIDAR detection sampling (Fogl and Moudry, 2016; Levinson et al., 2009; Tooke et al., 2011; Cao et al., 2014).

Roof structure
The roof structure factor refers to the influence of roof facilities on the installation and generation of RSPV systems, including elevators, parapets, water tanks, ventilation shafts and green roofs. Due to the complexity of roof structures, existing studies have assigned parameters to quantify architectural suitability based on rooftop classification (Byrne et al., 2015; Bergamasco and Asinari, 2011; Peng and Lu, 2013; Zhang, 2017; Schallenberg-Rodriguez, 2013). Following the parameter assignment in a study by Zhang (2017) on Tianjin, a mega city near Beijing, this study also distinguished the roof structure factors for individual buildings in Beijing by their type and height (Table 1). We introduced a six-step method to define individual building properties into four types (residential, public, commercial and industry) using a series of urban planning data (Detail in Table S3). The heights of buildings were derived from building footprint data.

Pitched roofs, small buildings and skyscrapers
The slope of pitched roofs is also an important factor affecting roof availability for the installation of solar PV panels. A fixed tilt and southward orientation are commonly selected for flat roofs, while along-the-roof installation is best for pitched roofs. Here, we assume all buildings with flat roofs for the three reasons: (1) from the history of architecture in northern China (Liu, 2011) and sample rooftop investigations (Song et al., 2018), pitched rooftop buildings account for a low percentage among all buildings in Beijing, (2) the difference in the panel-received radiation per horizontal projected rooftop area is estimated within 5% between the flat and pitched roofs in Beijing, and (3) buildings with pitched roofs are generally low-rise and relatively small, the suitable roof areas from pitched roofs are negligible due to exclusion by the combination of roof properties, building shadow and suitable area limits (>33 m²) (Lee et al., 2018). Meanwhile, we also excluded the skyscrapers (taller than 90m) as the unsuitable building due to their sophisticated rooftop shape, which may not accommodate the RSPV.

TECHNICAL POTENTIAL
The technical parameters pertaining to power outputs from the RSPV system include PV panel density, the impact of temperature on PV efficiency, and shading effects between panels.

PV panel density
In this analysis, we assume that all PV panels are installed southward in transverse layouts. The density of PV panels was determined to ensure that there was no obstruction between PV modules between 9 a.m. and 3
p.m. on the winter solstice (Beijing Municipal Bureau of Urban Planning, 2012). Thus, the module space, d, and the utilization rate of roof, RF_{ratio}, can be calculated by Equation 2 and Equation 3.

\[
d = l \times \cos \theta + l \times \frac{\sin \theta \times \cos \alpha}{\tanh h}
\]

(Equation 2)

\[
RF_{ratio} = \frac{1}{\cos \theta + \sin \frac{m}{\tanh h} \times \cos \alpha}
\]

(Equation 3)

where d is the module space, l is the module length, \( \theta \) is the installation tilt angle, \( \alpha \) and \( h \) are the solar azimuth and solar altitude at 9 a.m. or 3 p.m. during the winter solstice, and \( RF_{ratio} \) is the roof coverage ratio. Based on parameters selected for projects in practice (Jacobson and Jadhav, 2018), the optimal value of \( \theta \) was selected as 35° in the case study of Beijing.

The shadow areas from panel occlusion SHD_{PV} vary hourly and can be calculated as follows:

\[
M = l \times \frac{\sin \theta \times \cos \alpha}{\tanh h}
\]

(Equation 4)

\[
m = d - l \times \cos \theta
\]

(Equation 5)

\[
H_{SP} = \arctan \left( \frac{\tanh}{\cos \alpha} \right)
\]

(Equation 6)

\[
SHD_{PV} = \frac{(M - m)}{l} \times \frac{\sin H_{SP}}{\sin(\frac{\pi}{H_{SP}} - \theta)}
\]

(Equation 7)

where M is the length difference between the south-projection direction and the vertical projection of the PV panel, m is the length difference between the module space, and H_{SP} is the projection of the solar elevation angle in the south direction.

Panel occlusion has evident effects on the power outputs of solar PV systems due to the short circuit effect inside the panel, as shade on a small part of the panel may interfere with the power output due to series cell connections and hotspot effects (Chen et al., 2019). The relationship between the power loss \( F_{PVSHD} \) and \( SHD_{PV} \) can be calculated by Equation 8.

\[
F_{PVSHD} = 1 - \left( \text{floor} \left( SHD_{PV} \times 6 \right) + 1 \right) \times 1/6
\]

(Equation 8)

**Panel-received radiation**

The radiation intercepted by PV panels consists of three parts: directed tilt radiation \( (l_{DT}, \text{W/m}^2) \), scattered tilt radiation \( (l_{ST}, \text{W/m}^2) \) and reflected tilted radiation \( (l_{RT}, \text{W/m}^2) \). Through the method introduced by Masters (2005), those three streams of radiation received by solar PV panels on an hourly basis can be evaluated from the horizontal radiation data on direct radiation \( (l_{DH}, \text{W/m}^2) \) and scattered radiation \( (l_{SH}, \text{W/m}^2) \) in the GEOS-5 database (Lucchesi, 2017). The total radiation received by the panels \( (l_T) \) is the sum of those three streams of radiation:

\[
R_{DT} = \frac{\cos \theta \times \sin h + \sin \theta \times \cosh \times \cos \alpha}{\sin h}
\]

(Equation 9)

\[
l_{DT} = l_{DH} \times R_{DT}
\]

(Equation 10)

\[
l_{ST} = l_{SH} \times 0.5 \times (1 + \cos \theta)
\]

(Equation 11)

\[
l_{RT} = 0.5 \rho(l_{DT} + l_{ST}) \times (1 - \cos \theta)
\]

(Equation 12)

\[
l_T = l_{DT} + l_{ST} + l_{RT}
\]

(Equation 13)

where \( \alpha \) and \( h \) are hourly solar azimuth and solar altitude, respectively; \( \rho \) is ground reflectivity, taken as 0.2 here (Chen et al., 2019); and \( l_T \) is the total radiation received by the panel.

**Temperature influence**

In practice, working efficiency of solar PV panels are influenced by the ambient temperature. An increase in PV panel surface temperature from the test operation conditions would reduce operation efficiency from its maximum value. The hourly efficiency adjusted by the influence of ambient temperature, \( F_{TEM} \), can be calculated as follows:

\[
T_{PVB} = T_{ENV} + \left( \frac{NOCT - 20}{0.8} \right) \times 1
\]

(Equation 14)

\[
F_{TEM} = 1 + \alpha \times (T_{PVB} - 25^\circ \text{C})
\]

(Equation 15)
where $T_{PV}$ and $T_{ENV}$ are the panel surface temperature and ambient temperature, respectively; NOCT is the normal operation cell temperature, which is 45 °C; $\sigma$ is the peak power coefficient (-0.35%/°C), and $F_{TEM}$ identifies the panel efficiency adjusted by temperature.

**Hourly power outputs**

In the present analysis, we selected typical polysilicon 375Wp modules (LONGi, 2021), which occupy a relatively large share of China’s solar PV market, with a panel power efficiency, $F_{con}$, of 20.6%. System efficiency $F_{sys}$, with comprehensive consideration of nine factors of the whole process (from power production to grid connection), was determined at 80.96% (see Table S9). The final power outputs of the RSPV can be expressed as:

$$\text{Power}_{i,t} = \text{Area} \times RF_{\text{ratio}} \times IT_{ij} \left( \frac{W \cdot h}{m^2} \right) \times F_{con} \times F_{TEM} \times (1 - F_{PVSHD}) \times f_{shade} \times F_{con} \times F_{sys}$$

(Equation 16)

where $\text{Power}_{i,t}$ is the power generation in the $i$th hour of the $t$th building in the area, Area, is the suitable area of the $i$th building in the area, $IT_{ij}$ is the radiation intensity on the surface of solar panels on the $j$th hour, $F_{con}$ is the panel power efficiency, and the remaining parameters were defined above.

**POWER SYSTEM PLANNING & OPTIMIZATION MODEL FOR THE RSPV + SYSTEM**

The flexible operation of building-related loads including EVs, ACs as well as heat storage from TES were modeled to accommodate the intermittency and fluctuation of RSPV generation. “For Beijing’s case, we excluded battery storage as flexibility options mainly for two reasons. On one hand, the RSPV electricity could only be stored in batteries for a short period usually within 24 h, making it difficult for batteries to play a major role in consuming RSPV electricity in the long-term across seasons. On the other hand, the application of battery storage has aroused security concerns in densely built mega-cities in China (Chun, 2021), and to place battery storage inside the buildings is against China’s current fire control design requirements (ESCN, 2021). Two charging modes were considered for EVs: the quick-charging and slow-charging methods. We assumed 50% of quick-charging load is adjustable while all the slow-charging allows the loads to move from one period to another (Saxena et al., 2015). Here, we assumed that the storage for AC mainly included two types: daily and seasonal thermal energy storage (TES). The daily TES was considered to be daily balanced while the seasonal TES was considered to be yearly balanced. Apart from RSPV generation, the electricity from the power grid could also be used to supply the load.

In the PSP&O model, the output of RSPV generation and external power supply were separately constrained by the installation capacity of RSPV units and transmission line capacity. Actual charging behaviors of slow- and quick-charging EV loads in each period were limited by total predicted charging power capacity and the maximum percentage of adjustable loads. As for AC load, the actual flexible AC load was limited by the installed capacities of daily and seasonal TES.

The decision variables in the PSP&O model include hourly energy supply, consumption and energy storage state across three sectors: hourly power supply for different generation, load shifting for EVs and hourly energy supply and consumption from TES. $P^d_{d,t}$ and $P^T_{d,t}$ represent respectively the generation of external power supply and scheduled output of PV generation at hour in $d$ day ($d \in [1, D], t \in [1, T]$). $E^T_{d,t}$ and $E^{EV,FW}_{d,t}$, $E^{EV,BW}_{d,t}$ respectively represent forward and backward shifting load of quick- and slow-charging EVs at $t$ hour in $d$ day, and $E^{EV}_{d,t}$ represents the shifted electricity for EVs at $t$ hour in $d$ day. $Q_{d,t}$ and $Q_{d,t}$ respectively represent charging and discharging of daily TES for AC load at $t$ hour in $d$ day, while $Q_{d,t}$ and $Q_{d,t}$ respectively represent charging and discharging of seasonal TES for AC load at hour in $d$ day. $E^{AC,Cha}_{d,t}$ and $E^{AC,Dis}_{d,t}$ represent the inventory of the daily and seasonal TES for ACs at $t$ hour in $d$ day, respectively. All the parameters and variables for the power PSP&O model are summarized as nomenclature in Table S17.

The model minimizes the total costs from both annualized investment cost $C^{inv}$ and year-round operation expense $C^{ope}$ (Equation 17). The total net present value of investment cost comprises of the investment in
the external transmission, the daily and seasonal storage (Equation 18). Equation 19 calculates the annualized investment cost based on the total net present value \( C_{Inv,Pre} \) divided by the annuity present value. The operation cost only includes variable cost of external transmission power as well as operation and maintenance (O&M) cost of RSPV \( C_{O&M,RSPV} \) and thermal storage \( C_{O&M} \) (Equation 20). Equation 21 represents the O&M cost calculation of RSPV. \( p_{DSPV} \) represents the installed capacity of RSPV. The unit O&M cost of the RSPV \( C_{O&M,RSPV} \) is set as 75 CNY/kW/year (Walker, 2017), while the O&M cost of the thermal storage is assumed as 1% of the storage’s capital investments (Yang et al., 2021).

\[
\text{minimize } C_{Inv} + C_{Ope} \\
C_{Inv,Pre} = C_{Inv} \cdot p_{E} + \left( C_{DSPV,Inv} \cdot \frac{p_{DSPV}}{l_{DSPV}} + C_{DSE,Inv} \cdot \frac{p_{DSE}}{l_{DSE}} \right) + \left( C_{DSP,Inv} \cdot \frac{p_{DSP}}{l_{DSP}} + C_{DSE,Inv} \cdot \frac{p_{DSE}}{l_{DSE}} \right) + C_{FW} \cdot \gamma \cdot \left( 1 - \frac{1}{1 + \gamma} \right) + C_{DSPV} \cdot \gamma \cdot \left( 1 - \frac{1}{1 + \gamma} \right) + C_{DSP} \cdot \gamma \cdot \left( 1 - \frac{1}{1 + \gamma} \right) \\
C_{Ope} = \sum_{d=1}^{D} \sum_{t=1}^{T} C_{Ope} - p_{t} + C_{O&M,RSPV} + C_{O&M,TES} \\
C_{O&M,RSPV} = C_{O&M} + p_{E} \\
\text{(Equation 17)} \\
\text{(Equation 18)} \\
\text{(Equation 19)} \\
\text{(Equation 20)} \\
\text{(Equation 21)}
\]

where \( C_{Inv,Pre} \) and \( p_{E} \) respectively represent the unit capital cost of external power transmission and required of additional external power supply. \( p_{DSPV} \) and \( p_{DSP} \) represent respectively power capacity of daily and seasonal TES for ACs, while \( C_{DSP,Inv} \) and \( C_{DSP} \) represent respectively their unit costs. \( l_{DSP} \) and \( l_{DSPV} \) represent respectively energy capacity of daily and seasonal TES for ACs while \( C_{DSE,Inv} \) and \( C_{DSE} \) represent respectively their unit costs. \( p_{t} \) represents the generation of external power supply at \( t \) hour in \( d \) day, and \( C_{Ope} \) represents the unit power price (see Table S15).

The model considers the constraints from power balance, load shifting of EVs, charging/discharging of TES and the regulated RSPV utilization ratio. Equation 22 is the generation-load balance equation, which ensures the aggregated output of external power supply and RSPV generation units to meet the load demand on an hourly basis. Given the adjustable shifting characteristics of EV and AC load, the electricity load demand could be advanced or delayed in the time domain. The loads of quick-charging EVs and slow-charging EVs would change to \( Q_{EV}^{t,d} \) and \( Q_{EV,FW}^{t,d} - Q_{EV,BW}^{t,d} \) at \( t \) hour in \( d \) day, respectively. Two kinds of thermal storage are considered to supply the AC load, namely the daily and seasonal TES. Therefore, the charging power \( Q_{d,C}^{t,d} \) and discharging power \( Q_{d,D}^{t,d} \) could also adjust the load of ACs with storage. Meanwhile, Equation 23 ensures that the output of external power supply does not exceed the upper and lower limits from the power system transmission constraints. Equation 24 indicates that the RSPV generation units should be scheduled less than or equal to their available power output.

\[ s.t. \\
Q_{d,C}^{t,d} + Q_{d,D}^{t,d} = Q_{d}^{t,d} + \left( Q_{d,FW}^{t,d} - Q_{d,BW}^{t,d} \right) + Q_{d}^{t,d} + \left( Q_{d,FW}^{t,d} - Q_{d,BW}^{t,d} \right) \\
+ Q_{d}^{t,d} + \left( Q_{d,C}^{t,d} - Q_{d,D}^{t,d} \right) + \left( Q_{d,D}^{t,d} - Q_{d,C}^{t,d} \right), \quad \forall d, t \\
0 \leq P_{d}^{t,d} \leq P_{E}^{t,d}, \quad \forall d, t \\
0 \leq P_{d}^{t,d} \leq w_{d,t}, \quad \forall d, t \\
\text{Equation 25 and Equation 26 limit the actual load demand of slow- and quick-charging EVs at } t \text{ hour in } d \text{ day. Equation 27 calculates the shifted EV load at } t \text{ hour in } d \text{ day. Equation 28 sets the upper limit for the shifted EV load, with the assumption that 100% of the slow-charging and 50% of quick-charging load are adjustable. Equation 29 balances the shifted EV load in one day so that the shifted electricity load still fully satisfies the total electricity demand from EVs within the day.}

\[ 0 \leq \dot{P}_{d}^{t,d} + \left( \delta_{d,FW}^{t,d} - \delta_{d,BW}^{t,d} \right) \leq \delta_{d}^{t,d} \]

\[ \text{Equation 25} \]
\[ 0 \leq \frac{Q_{lEV}}{C_{lVE}} + \left( \frac{Q_{lEV,FW}}{C_{lVE}} - \frac{Q_{lEV,BW}}{C_{lVE}} \right) \leq T_{lEV} \]  
(Equation 26)

\[ E_{d,t}^{EV} = E_{d,t-1}^{EV} + \left( \frac{Q_{lEV,BW}}{C_{lVE}} - \frac{Q_{lEV,FW}}{C_{lVE}} \right), \forall d, t \geq 2 \]  
(Equation 27)

\[ E_{d,1}^{EV} = E_{d,T}^{EV} \]  
(Equation 28)

\[ Q_{lEV} \text{ and } Q_{lS} \text{ represent respectively power capacities of the quick- and slow-charging devices for EVs, and } E_{lEV} \text{ represents the maximum EV load that could be shifted.} \]

For the constraints of ACs, Equation 30 and Equation 31 indicate the charging and discharging power should not exceed the total power capacities of the daily and seasonal TES. Equation 32 formulates the operation equation in the neighboring hours. As expressed in Equation 33, the first equation describes the seasonal TES inventory change between neighboring hours in the same day, and the second one links the end hour of the first day and the start hour of the following day. Equation 34 sets the upper limits for the inventory of the daily and seasonal TES. Equation 35 balances the inventory of the daily and seasonal TES. The daily and seasonal TES inventories are considered to be daily balanced and annually balanced, respectively.

\[ \frac{P_{lS,AC,Cha}}{C_{lS,AC}} - \frac{P_{lS,AC,Dis}}{C_{lS,AC}} \leq P_{lS,AC} \]  
(Equation 30)

\[ \frac{P_{lS,AC,Cha}}{C_{lS,AC}} - \frac{P_{lS,AC,Dis}}{C_{lS,AC}} \leq P_{lS,AC} \]  
(Equation 31)

\[ E_{d,t}^{DS,AC} = E_{d,t-1}^{DS,AC} + \left( \frac{P_{lS,AC,Cha}}{C_{lS,AC}} - \frac{P_{lS,AC,Dis}}{C_{lS,AC}} \right), \forall d, t \geq 2 \]  
(Equation 32)

\[ \left\{ \begin{align*}
E_{d,t}^{SS,AC} &= E_{d,t-1}^{SS,AC} + \left( \frac{P_{lS,AC,Cha}}{C_{lS,AC}} - \frac{P_{lS,AC,Dis}}{C_{lS,AC}} \right), \forall d, t \geq 2 \\
E_{d,1}^{SS,AC} &= E_{d,1}^{SS,AC} + \left( \frac{P_{lS,AC,Cha}}{C_{lS,AC}} - \frac{P_{lS,AC,Dis}}{C_{lS,AC}} \right), \forall d \geq 2
\end{align*} \right. \]  
(Equation 33)

\[ E_{d,1}^{DS,AC} \leq E_{d,T}^{DS,AC}, E_{d,1}^{SS,AC} \leq E_{d,T}^{SS,AC} \]  
(Equation 34)

\[ E_{d,1}^{DS,AC} = E_{d,T}^{DS,AC}, E_{d,1}^{SS,AC} = E_{d,T}^{SS,AC} \]  
(Equation 35)

Equation 36 defines the constraint of the PV electricity utilization ratio \( \alpha \), which is defined as 100% in this study.

\[ \sum_{d} \sum_{t} P_{d,t}^{PV} = \alpha \sum_{d} \sum_{t} w_{d,t}, \forall d, t \]  
(Equation 36)

As a Linear Programming model, the model is solved using CPLEX 12.5.