POTSDAM-INSTITUT FÜR KLIMAFOLGENFORSCHUNG

Urban rooftops for food and energy in China

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Abstract

Urban rooftop agriculture (RA) and photovoltaics (RPV) offer sustainable solutions for energy-food system nexus in cities but compete for limited rooftop space. Here we explore the potential benefits (productivity, economic, and environmental) and allocation strategy of RA and RPV across 13 million buildings in 124 Chinese cities, considering urban characteristics and regional productivity. We found that RA yields superior economic benefits, while RPV excels in greenhouse gas emission reductions. Prioritizing either RA or RPV can only retain 0–29% of the above benefits brought by the other. However, allocating 61% of the flat rooftop area to RA and all the remaining to RPV would retain >50% of their potential, meeting 15% (mean, 0.5–99% across cities) of urban vegetable needs and 5% (0.5–27% across cities) of the electricity needs. While the productivity from RA and RPV have significant environmental and socioeconomic benefits, they require considerable water (up to 15% of urban residential water use) and materials (e.g., totaling 13 kt silver).

Introduction

Providing healthy food and clean energy is one of the most challenging and prioritized tasks among the United Nations Sustainable Development Goals. Globally, about 800 million people currently face risks in accessing adequate food[1] and electricity[2]. Conventional measures to address these challenges could place additional threats to climate change and land resources, which are already under enormous pressure. Cities are centers of consumption and pioneers in advancing sustainable food and energy systems. While ground-based agriculture and solar photovoltaics in and around cities can foster net-zero-carbon transition[3], they require a transformation of urban open space or high-quality farmland[4,5]. Given the rising number of urban buildings across the world[6], rooftop space could be used as a viable option for agricultural (RA) and photovoltaic power production (RPV)[7,8] to enhance landless and climate-neutral urban food-energy system nexus[9]. Besides, the distributed nature of rooftop production can potentially create a more resilient and sustainable urban system[10].

However, RA and RPV may vie for the limited rooftop space. City research and planning often focus on one and neglect the other[11]. In this sense, maximizing the effectiveness of rooftop exploitation involves a balanced allocation of rooftop space for RA and RPV to obtain multiple benefits, such as food and energy productivity, economic returns, and greenhouse gas (GHG) emission reduction. Several factors are intertwined when determining the space allocated to RA and RPV within a city. For instance, the benefits of RA and RPV could vary across regions and technical treatments. From a global perspective, urban agriculture (including RA) can save 100–180 million tons of food and conserve 14–15 billion kWh of energy[12]. Nations with expansive urban regions and crop combinations adaptable to both the local climate and urban farming have the potential to yield millions of tons of produce (especially in China and the USA)[12]. Studies proved that 80% of urban food demand could have been provided within 500 km distance in high agronomic suitability of urban areas[13,14]. However, the GHG reduction potential of RA across regions is unclear due to varied material and energy inputs of fragmented planting and the lower yield in cold and hot climates when adopting an open-air production system[15]. Contrastively, RPV has a definite GHG reduction capacity at city[16], regional[17], and national[18,19] levels, especially in regions with affluent solar radiation. Yet, the economic benefits of RPV could be limited due to the declining power price, for example, in China[19]. On the contrary, high-yield greenhouse RA performs better regarding provisioning and economic benefits in Mediterranean climates than solar systems[20]. Hence, allocating urban rooftop space for RA or RPV poses a dilemma due to their variations of distinctive advantages.

Indeed, producing food under photovoltaic panels (agrivoltaics) is one option. Such an integrated system could supply vegetables and electricity for individual buildings and potentially reduce GHG emissions[21–23]. However, covering more PV panels would largely hamper the crop yield under the shade[24] even for semi-transparent photovoltaics[25,26], and prioritizing vegetable production would lessen electricity supply[27]. Research indicates that up to 84% of supplementary lighting may still be required to counteract internal shading[25]. Although agrivoltaic systems could increase economic benefits with shade-tolerant crops[28], it does not apply to shade-intolerant vegetables, such as cabbage, tomato, and cucumber, common crops

in urban agriculture. Besides, small-scale and fragmented agrivoltaics installations are less economically feasible due to additional labor and management requirements[29,30]. Therefore, to obtain balanced sustainability benefits, it is necessary to determine the appropriate share of rooftop area and place RA and RPV independently within a city.

Previous studies have primarily focused on evaluating the sustainability implications of either RA or RPV[15,18,31], with few efforts to compare and coordinate their multiple benefits. Most studies analyzed a limited number of cities and spatial scales, thus lacking the regional heterogeneity of productivity and sustainability implications. For example, researchers[8] evaluated the potential for utilizing rooftops in Barcelona and the self-sufficiency potential of RA and RPV, but significant environmental and economic impacts were excluded. Besides, research on the synergistic effects of multiple benefits[32,33], even when using multi-objective optimization methods, often overlooks the food-energy nexus across cities at a continent level.

Here, we quantified the potential of food and electricity productivity (provisioning benefits), economic returns (economic benefits), GHG reduction (environmental benefits), and associated resource requirements of urban RA and RPV to synergize those benefits. We mapped the potentials of about 13 million buildings within the coherent extents[34] (urban built-up area within the administrative boundary, **Fig S1**) of 124 large Chinese cities with a metropolitan population larger than one million, totaling 0.8% of the national territorial land and 38% of the population. To evaluate the potential benefits, we strictly screened suitable roofs according to the building attributes (i.e., building function, height, age, and rooftop form—pitched or flat). The building footprints and attributes dataset is constructed with high-resolution images, data from real estate websites, and sampling surveys (see Method). We also estimated the potential water, materials, labor, and other requirements for these benefits. To envisage an optimized RA-RPV allocation scheme synthesizing various benefits, we assumed three scenarios aimed at a single objective: (1) maximizing food self-sufficiency; (2) maximizing electricity self-sufficiency as well as GHG reduction; and (3) maximizing economic benefits. Then we integrated these three objectives through the multi-objective optimization method and compared urban-level rooftop allocation schemes between all objectives. Considering the geographic heterogeneity of various benefits of RA and RPV, we provide new insights for future planning on the urban food-energy nexus.

Results

The provisioning, economic, and environmental benefits

We estimated the potential energy or food production from suitable rooftop areas and productivity per unit area. According to the requirements of green roof construction in Chinese cities and our estimates, we identified a totaled 2.9×10^3 km^2 (42% of total) low-rise flat rooftop area suitable for both rooftop agriculture (RA) and photovoltaics (RPV) productions within the urban extents in 124 cities. An additional 680 km^2 (10% of totals) pitched or high-rise flat roofs are appropriate for RPV power generations (but not suitable for RA for safety's sake). To be conservative, we assume half (need to keep enough space for other uses, such as a shelter for fire escape) of the potential roofs with larger areas could be installed for either RA or RPV.

Thus, about 1.45×10^3 km^2 of low-rise flat rooftop area is considered productive for both purposes, and an additional 340 km^2 of rooftop area could provide potential production for photovoltaic electricity.

Considering the daily vegetable consumption of the median value of the nationally recommended level, i.e., 400g/capita/day, we found that cities could source 26% (i.e., self-sufficiency, the mean value of 124 cities, varied between 3–163%) of their vegetable needs if all assumed rooftops were used for RA production. Alternatively, cities could source 10% (mean value, varied between 1–47% across cities) of their electricity demand if the rooftops were used for RPV production. Urban characteristics, such as regional climate conditions, building density, population density, and other urban morphology factors, determine RA and RPV production potentials. The RA productivity in Lhasa (vegetable self-sufficiency is 2.6%) and some midwest cities are lower owing to their drier and colder climates than cities in the eastern region. Cities with high vegetable self-sufficiency are mainly distributed in North China, like Hengshui (163%), because of their higher vegetable yield, newer buildings, and less dense population (a, b).

In contrast, for RPV, since the generating capacity has close relationships with available roof area and solar radiation, electricity self-sufficiency is relatively high in some southeastern cities like Foshan (47%) and Shantou (33%). Generally, higher urbanized and historic cities usually have higher population densities, with more high-rise and older buildings unsuitable for exploitation, thus showing lower production potentials. For example, the self-sufficiency from RA and RPV in Hong Kong is only 2.9% and 1.2%, respectively. Guangzhou and Chongqing are examples of cases where high production potential is accompanied by low self-sufficiency rates. These examples underscore the significance of accounting for urbanization mismatches between population and land in assessing RA/RPV production potentials. The urban characters explain the variation of production potential across cities.

We found that agricultural production in most cities yields better economic benefits than power generation per unit area, primarily owing to the significantly higher price of vegetables. The net economic benefit is determined by the balance between the investment and potential returns from rooftop production, measured as net present value (NPV) considering future RA and RPV productivities and discount rate of future economic returns (c, d). Cities with a higher proportion of rooftops for potential greenhouse planting tend to have higher NPV of RA, such as Shangqiu (135 CNY/m^2), although greenhouse installation requires substantial initial investment. For RPV, the mean NPV is 20 CNY/m^2, ranging from 2.6–39 CNY/m^2 among cities, showing a generally increasing trend from north to south primarily because of the gradually elevated power-grid purchase price and solar radiation abundance (**Fig S2-3**). Generally, the economic benefit potential of RA is more than three times that of RPV.

We estimated the cradle-to-grave GHG emissions of RA and RPV productions by inventorying the material and energy inputs and associated emission factors. The GHG mitigation benefits are the lessened emissions of rooftop production compared to traditional agriculture or electricity production (e, f). Applying RA, nearly 80% of cities show low or even negative values of GHG mitigation (the mean value is -1.1 kg CO_2e/m^2, varied from -3.2 to 4.2 kg CO_2e/m^2). This is predominantly attributable to the lower yield and substantial infrastructure

investment of open-air RA production compared to traditional agriculture. A few cities in middle or northeastern China have higher GHG mitigation potential (e.g., Changchun, 4.2 kg CO_2e /m^2) since the emission factor of conventional agriculture in these cities is much higher than that of urban agriculture. For RPV, annual GHG mitigation intensity (the mean value is 179 kg CO_2e/m^2, varied from 138 to 260 kg CO_2e /m^2) shows a decreasing trend from north to south. Cities in higher latitudes, such as Urumqi (138 kg CO_2e/m^2), require higher tilt angles of PV panels to adapt to the lower solar zenith angle, thus having higher costs of PV materials and GHG emission intensities. Further, the RPV mitigation potential remains higher in East China, where the emission factors of the electricity grid stay at the lowest level in China[35]. We demonstrate that RPV has nearly two orders of magnitude more considerable GHG mitigation potential than RA.

Optimal allocation of rooftop food-energy production

Rooftop photovoltaics (RPV) outperforms rooftop agriculture (RA) in GHG mitigation potential but not in economic benefit. Therefore, coordination of rooftop space is a prerequisite to balancing the benefits and enhancing urban sustainability. Using the non-dominated sorting genetic algorithm (NSGA-II, see **Method**), we set up a Pareto optimization method to synergize RA and RPV productions and each city's associated economic and GHG mitigation benefits. The NSGA-II method effectively searches for a cluster of optimal solutions to allocate the limited suitable rooftop area to RA and RPV without setting initial weight for these objectives. We show that the optimal options are to allocate 61–62% of total flat roofs to vegetable production and the rest to RPV power production. These solutions substantially differ from a simple assumption of having the rooftop space for RA and RPV production equally. As a result, exploiting urban rooftops could satisfy 15.2–15.5% of vegetable demand and 4.9–5.1% of total electricity demand across different optimized solutions (

Fig. 2 a).

The merit of these optimized allocations lies in keeping all benefits to the maximum. Compared to the scenario where all rooftops are exclusively allocated to either RA or RPV, these balanced allocation solutions maintain 50–83% of the self-sufficiency of vegetables and electricity, economic returns, and GHG reduction potentials (**Table S3**). However, if cities maximize one of the specific benefits, namely vegetable self-sufficiency, electricity self-sufficiency, GHG mitigation (highly correlated with electricity self-sufficiency), or economic returns, only 0–29% of other benefits would be maintained (**Table S3, Fig S4**). These allocations help to retain universal access to all profits of rooftop production.

We choose the optimal solution with the highest synergy among all benefits from the solutions. A synergistic solution can balance the potential of various benefits and minimize their disparity. For example, if one allocation solution could maintain 50% of the largest economic return potential and 80% of the largest GHG reduction potential when they are prioritized, the synergy index equals 1-abs (50%-80%), i.e., 0.7. The higher the synergy, the greater the balance among all benefits or objectives. Here, the optimal solution (synergy index = 0.69) is adopted to allocate 61% (mean value, ranging from 15–99% across cities) of the total flat rooftop area to RA. In doing so, cities could supply 15% (mean value, ranging from 0.8-99% across cities) of

their vegetable needs and 5% (0.2-31% across cities) of their electricity needs through RA and RPV productions (

Fig. 2 b). This allocation ratio varies across cities along with their food or energy productivity (**Table S4**). In most cities, the optimized allocation strategy suggests the deployment of more RA (exceeds 50% in 74 cities). This is mainly due to the relatively higher self-sufficiency of vegetable potential than that of electricity (16% higher overall, **a, b**). For example, in Shangqiu, only 48% of rooftops allocated to RA could provide 71% of the vegetable demand. Increasing roofs utilized for RA is very helpful in retaining higher RA potential and lower loss of RPV potential, which contributes to improved comprehensive benefits. In a few southern cities with lower vegetable productivity, more RPV production is allocated to achieve higher GHG reduction benefits. For instance, the RPV-dominated production of Hongkong (63% flat rooftop for RPV) is primarily attributed to its high mitigation potential of RPV (238 kg/m^2). This implies that the allocation ratio is correlated with the efficiency of benefits achieved through RA and production. In general, cities need to allocate more rooftop areas to leverage their strengths (e.g., high RA productivity or GHG mitigation of RPV) and to balance all benefits.

The optimal co-production of RA and RPV (

Fig. 2 b) could potentially bring considerable GHG mitigation and economic benefits. As **Table 1** shows, the total potential economic returns for all cities would amount to 2080 billion CNY (0.6-303 billion CNY across cities, **Fig S6b**), and the possible GHG reduction is 161 Mt CO_2e (0.1-17 Mt CO_2e across cities, **Fig S6a**). These benefits account for 1.7% of the national GDP (0.3%-28.3% of city-level GDP across cities) and 1.6% of national GHG emissions (0.04%-38% of city-level emissions across cities). While RA production in most cities is net-emitting, applying RPV to the remaining rooftops could reduce GHG emissions. This approach can significantly reduce emissions in urban food-energy co-production systems. Besides, this optimal rooftop allocation could potentially conserve 2.6×10^3 km^2 of cropland and 88 Mt of standard coal (**Table 1**) if the vegetables and electricity produced on rooftops are produced conventionally. This equals 0.2% of the total national cropland and 2.9% of total national coal consumption in 2022. These benefits are especially advantageous in large city clusters (**Fig S6**). We find that a sufficient exploitation of rooftop space could provide full-scale benefits.

The water and other resource requirements for these rooftop productions are substantial (**Table 1**). From our estimates of the optimal rooftop allocation, RA production necessitates 136 million tons of water for irrigation yearly[36], while RPV requires 0.6 million tons of water for cleaning throughout its life cycle[37]. These water requirements collectively constitute 1.6% of those cities' annual urban residential water use. However, in cities in Northern China with annual precipitation levels below 800 mm, this ratio could range from 5.7% to 14.7%, potentially exacerbating water scarcity issues in these urban areas. Besides, RA and RPV production entails significant quantities of metal, including copper, aluminum, and steel (**Table 1**), to produce the infrastructures[38]. Although rooftop productions are beneficial, the substantial requirements on water, metals, and other resources should be considered during urban planning.

Discussion

Our study reveals the necessity, potential benefits, and requirements of a balanced allocation of productive rooftop areas for vegetable and electricity production. We built a dataset of building footprints and attributes in 124 Chinese cities and set up selection criteria for productive rooftops. We find that rooftop agriculture (RA) and photovoltaics (RPV) exhibit distinct capabilities to augment economic returns and reduce GHG emissions. The synergistic co-production of food and energy through optimized rooftop distribution (61% flat rooftops allocated to RA and the rest to RPV) not only meets 15% of urban vegetable needs and 5% of the electricity needs but also contributes significantly to environmental and socioeconomic improvement (up to 3% of national totals). Our estimated self-sufficiency potentials show a notable variation between cities, mainly due to regional differences in natural and social attributes, rooftop agricultural yield, and solar radiation across Chinese regions. Our results are approximate to other studies (Tianjin[39] and Shenzhen[27]), in which provisioning potentials fall within the range of our research findings. We highlight that the required water and other resources (e.g., metal and fertile soil substrate) to facilitate these potential productions could pose a challenge for cities with scarce resource supply. Our findings contribute to advancing discussions on competitive rooftop utilization to improve urban sustainability and enhance energy-food system resilience.

We find that urban rooftop production, through its multiple benefits, could alleviate the grand challenge of the urban environment and the global climate crisis. Urban rooftops could serve as vital supplementary sources for food and energy production, generate revenue, and reduce GHG emissions simultaneously. We highlight that prioritizing either RA or RPV in limited rooftop space could be suboptimal. However, a balanced allocation of rooftop space for RA and RPV can retain the benefits from both sides and advance holistic sustainability. This could promote sustainable food and energy production in urban areas by reducing cropland depletion and coal combustion. Meanwhile, we recognize the regional preference towards either RA or RPV in urban planning decisions. Cities with high vegetable yields typically prioritize space for RA to leverage self-sufficiency. Conversely, cities with great GHG mitigation potential tend to allocate more space for the production of RPV. However, the allocation of RA and RPV generally depends on the urban morphology (such as building density) and climatic conditions that jointly determine vegetable and power productivity. Thus, cities around the globe could optimize rooftop utilization by assessing urban morphology and enhancing local RA and RPV advantages, thereby obtaining comprehensive sustainability benefits. For example, cities with high vegetable yields should consider using cleaner energy in RA to lower the carbon burden. Cities struggling to attain self-sufficiency in food production should contemplate strategies to bolster agricultural productivity and explore alternative urban production spaces[22,40].

Although local food and energy production can benefit urban sustainability by reducing stormwater, regulating climate, enhancing resilience and biodiversity, and lowering food wastage[41], nuanced management to reduce adverse impacts on urban food and energy transformation is indispensable[42,43]. Smart urban solutions could involve planning districts for agriculture based on food demands and other districts for photovoltaic for convenient power

transmission or demand, thus minimizing production fragmentation. From a geographical perspective, high solar power abandonment rates are observed in China's western provinces (**Table S9**), underscoring the imperative to harness local green energy consumption potential and expedite the development of outward transmission infrastructure, specifically ultra-high voltage lines, for nationwide distribution optimization. Additionally, it is necessary to explore multi-channel energy storage paths, such as pumped water storage and green electricity for hydrogen production. Integrated agrivoltaic systems also have the potential to reduce energy storage demands. More importantly, substantial resources are needed to promote and sustain green roof production. For example, crop irrigation and PV panel cleaning can exacerbate urban water shortage, collecting productive soil for RA requires cultivated soil from cropland (~220 km^2) equivalent to the area of Boston city, and decommissioned infrastructure can stress the waste treatment system. This indicates that, especially in arid northern cities, recirculating water and nutrients may play a significant role in the future sustainable development of urban agriculture[44]. Given these debates on rooftop production, publicizing successful business models is of utmost importance, e.g., Gotham Greens in Chicago city[45], emerging rooftop farms built on shopping malls in Chinese cities, and grid-connected urban RPV in Ningbo and Tianjin city[46].

The interplay among stakeholders like government, enterprises, and individuals would promote sustainable and effective rooftop exploitation through food and energy production. In alignment with recently issued Chinese directives for new construction since 2022, solar power systems with a minimum lifespan of 25 years are now mandated. Jinan city[47] in north China and Dongguan city[48] in south China have also recently encouraged plantation on newly constructed public buildings. However, future policies on green roofs should integrate the development of both RA and RPV within the city. During rooftop exploitation, the top priority is to address financing challenges to provide incentives and support for high-quality projects and avoid inefficient production. Although governmental subsidies might serve as start-up capital, investors need to be convinced of the benefits that outweigh the potential risks. Encouragingly, urban agriculture combined with involving residents in harvesting activities and tourism is emerging, and urban adaptation financing mechanisms have been implemented in many cities around the world[49]. For example, Hamburg in Germany planned to provide financial incentives to those who voluntarily install green roofs.

In conclusion, our building-scale analysis provides a scientific basis for the decision-making of roof utilization in specific cities following the unique advantages of rooftop agriculture and photovoltaic production. Our foundational framework could be applied to decision-making in other global cities to facilitate optimal rooftop utilization if combined with detailed architectural morphology. However, the framework could be further refined to support block-scale design by considering public acceptance, urban landscape, demand for heating or cooling, ecosystem services, equity[50], and other dimensions. We find optimal rooftop utilization yields conspicuous national-scale benefits in climate mitigation, economic growth, and food and energy provisioning. Scaling up rooftop production globally with caution of resource demand would have substantial benefits. An optimized allocation of rooftop areas to agriculture and solar power could comprehensively retain all benefits while advancing urban sustainability and resilience. The feasible proportion of RA and RPV offers a design strategy for using roofs

efficiently and comprehensively in a city. We argue that incorporating RA and RPV processes into the multi-factor nexus analytical paradigm is critical to identifying the hidden trade-offs.

Methods

Rooftop dataset preprocessing and screening

In this study, we identified the more than 13 million building outlines within the urban extents of 124 large cities in China (highly compacted with buildings and residents). Since the precision of digital surface model in accurately simulating small areas cannot be guaranteed, we obtained several building attributes from commercial map corporates such as Google and Baidu Map and real estate websites, which included building height, age, rooftop type, and building function. Necessarily, we identified the roof type (flat or pitched) for each building through machine learning by identifying its color (grey, red, green, or blue), since grey roofs are usually made of cement and are flat in Chinese cities. We randomly sampled over 10,000 roofs, recording their color (RGB values) and rooftop type. We then trained a random forest classification model to establish the correlation between rooftop type and color. This model, whose classification accuracy has been validated through the receiver operating characteristic (ROC) curve (**Fig S7**), was then utilized to identify the rooftop types for all based on their color values. After this, we apply a series of criteria through following steps to select rooftops suitable for rooftop agriculture (RA) and photovoltaics (RPV) according to green roof construction guidelines[51–53] in a few Chinese cities.

(1) Firstly, for all available flat roofs: building age should be less than 30 years; excluding protected buildings and view spots, space occupations (such as chimney, air conditions), aisles between columns of agricultural production or photovoltaic panels, and roof fringe (0.5 m).

(2) Secondly, the selected flat roofs were categorized into low-rise and high-rise (>40m). The former is suitable for RA installation, while the latter is ideal for RPV installation.

(3) Lastly, for RPV, it's necessary to select about 39% of the total pitched roofs for better solar energy acceptance[18], which includes rooftops facing south (including south, southwest, and southeast).

Notably, the potentially productive rooftop area of RPV is larger than RA in each city for the latter's more stringent screening, which means areas suitable for RA are necessarily suitable for RPV. More information can be referred to **Fig S8**.

Productivity of RA and RPV

We mainly considered two forms of RA, including open-air and greenhouse planting. According to extensive literature reviews, roof areas larger than 4000 m^2 were applied for high-tech greenhouse planting, and others larger than 5 m^2 for open-air systems. The vegetable yield (Y) of rooftop greenhouse production was obtained from previous studies[15,54,55], and the yield for open-air production was taken from the Global Agro-Ecological Zoning database. The

annual vegetable production (kg) in city *k* is measured with the equation below:

$$F_k = Y_{open} * S_{k-open}/r_{fresh} + Y_{greenhouse} * S_{k-greenhouse} \quad (1)$$

Since the vegetable yield from Global Agro-Ecological Zoning database is measured with dry matter, and should be transferred into fresh weight using dry/fresh ratio (r_{fresh}). Fresh vegetables are usually harvested with a 5–8% dry matter. S_k denotes the available roof area in city k (m^2). A few common vegetable species, namely cabbage, tomato, carrot, and onion, were chosen to estimate the average yield of mixed vegetable production.

In following sections, the productivity of RPV is calculated. Referring to the method introduced by Masters[56] and Qiu et al[57], the theoretical generating capacity is limited mainly by solar radiation, operating temperature, and shadow effects. Through the comparison of multiple data sources[58,59] and literatures[60–62], we used the surface incoming shortwave flux (SWGDN) hourly data from M2T1NXRAD[58] with a spatial resolution of $0.5^\circ \times 0.625^\circ$, and 2 m hourly temperature data from ERA5-Land[59], which possess low relative error. Based on the above data, the calculation of potential electricity generation was performed according to Eq. (2) below:

$$E_k = \sum_{y=1}^{n}\left(\sum_{h=1}^{m}\frac{I_{RPV_{k,h}}}{I_0} * TCF_{k,h} * SCF_{k,h} * P_k * S_k * PF_k * PR_y\right) \quad (2)$$

where E_k represents the potential electricity generation of each city (kWh); k means the city (a total number of 124) we calculate; m denotes the total number of hours in the calculated year; n denotes the 30-year lifetime of the durable monocrystalline silicon modules; I_0 denotes the solar radiation in the standard state (1 kW/m^2). Notably within this section, approximately a 10% enhancement in rear-side electricity production was observed in bi-facial module configurations[38]. Therefore, the computations of E_k will be conducted utilizing 110% of the available flat roofs.

$I_{RPV_{k,h}}$ indicates the solar radiation intercepted per unit area of the RPV module in city k and hour h (kWh/m^2) according to Eq.(3) below:

$$I_{RPV_{k,h}} = \varepsilon_{direct} * I_{direct} + \varepsilon_{diffuse} * I_{diffuse} + \varepsilon_{reflect} * I \quad (3)$$

where ε_{direct}, $\varepsilon_{diffuse}$ and $\varepsilon_{reflect}$ indicate the direct coefficient (related to k and h), diffuse coefficient (related to k), and reflect coefficient (related to k); I, I_{direct} and $I_{diffuse}$ indicate the SWGDN hourly data from downwards, direct, and diffuse.

$TCF_{k,h}$ represents the temperature correction factor in city k and hour h according to Eq. (4) below:

$$TCF_{k,h} = 1 + \varepsilon * (T_{cell} - 25)$$
$$T_{cell} = T_E + I_{RPV_{k,h}} * \left(\frac{NOCT - 20}{0.8}\right) \quad (4)$$

where ε is the temperature coefficient (-0.41%/℃); T_{cell} and T_E represent the temperature of the cell and 2 m temperature respectively; NOCT is the normal operating cell temperature of 44℃.

$SCF_{k,h}$ represents the shading factor in city k and hour h according to Eq.(5) below:

$$SCF_{k,h} = 1 - \left(\sin\sum_k \cot\beta \cos\varphi - \frac{\sin\sum_k}{\tan\beta_n}\cos\varphi_s\right) * \frac{\sin\beta_{tmp}}{\sin(\pi - \beta_{tmp} - \sum_k)} \quad (5)$$

where $\sum_k$ denotes the tilt angle of RPV modules related to the latitude of each city; β and φ represent the solar altitude and azimuth respectively while β_n and φ_s are that of 3:00 p.m. in the winter solstice; β_{tmp} denotes the projection of the solar altitude angle on the plane parallel to the north-south axis and perpendicular to the ground.

P_k denotes the peak power per unit area of photovoltaic panels in city k (kW/m^2) according to Eq. (6) below:

$$P_k = P_0 * \cos\sum_k \quad (6)$$

where P_0 denotes the rated power per unit area of the PV panel (211W); Other variables have been mentioned above.

PF_k denotes the packing factor in city k according to Eq.(7) below:

$$PF_k = \frac{1}{\cos\sum_k + \frac{\sin\sum_k}{\tan\beta_n}\cos\varphi_s} \quad (7)$$

PR_y indicates the performance ratio in year y according to Eq. (8) below:

$$PR_y = PR - DR * (y - 1) \quad (8)$$

where DR denotes the degradation rate of bi-facial modules (-0.2%)[63,64]; PR denotes the average performance ratio of the PV system (0.8) [38]; other variables have been mentioned above.

Later we calculate the self-sufficiency through Eq.(9) below:

$$D_k = \frac{E_k}{n * TEC_k} \quad (9)$$

where D_k denotes the self-sufficiency of RPV in each city; TEC_k represents the annual electricity consumption of each city (**Table S1**); More details of the all above variables can be

406 referred to previous studies[17,19,57] and **Note S2**.

407 **Economic benefit of RA and RPV**

408 Since the business opportunities of urban RA are still untapped[41], it's meaningful to estimate
409 the transformation potential of food systems, including an assessment akin to the economic
410 benefit of RPV. The Net Present Value (NPV)[65–67] of RA and RPV in a 30-year system lifetime
411 was quantified in this part, which can be calculated through Eq.(10) :

$$NPV_k = \sum_{y=1}^{n} \left(\frac{IR_k - OM_k}{(1+r)^y} \right) - C_k \quad (10)$$

412 where NPV_k denotes the net present value in city k; r denotes the discount rate (0.02 for RA
413 and 0.05 for RPV related to invest risk, the uncertainty of this rate requires more research on
414 economic benefits related to RA[65–67]). C_k represents the capital cost in city k; OM_k means the
415 operational and maintenance cost in city k; IR_k denotes the investment return in city k,
416 including vegetable production and renewable energy generation. For RA, after calculations of
417 vegetable productions, we got the detailed material and labor inputs of open-air and greenhouse
418 planting from previous studies[15,68], then we conducted online and field surveys to determine the
419 price of commodities at that time in China. For RPV, we get the installed prices referring to
420 Engineering Procurement Construction (EPC) in China (**Note S3** and **Table S5**). Owing to the
421 difference in installing area, we obtained the regionalized cleaning prices and labor prices from
422 literatures[69,70] (**Note S4** and **Table S6**), International Energy Agency (IEA), and online
423 interviews. Since the solar energy has reached grid parity from 2021 in China, IR_k of RPV
424 can be easily figured out with national feed-in tariff. Based on literature review[65,71,72], a
425 sensitivity analysis was conducted considering four potential sensitivity factors (the discount
426 rate, the capital cost, the operational and maintenance cost, cleaning and labor prices
427 (**Supplementary Discussions**).

428 **GHG mitigation of RA and RPV**

429 In this part, we used the life-cycle assessment method to estimate the Global Warming Potential
430 (GWP) of RA and RPV following the ISO 14040 and 14044 standards. For RA, the system
431 boundary includes five life-cycle stages: infrastructure construction, installation, operation, in-
432 boundary distribution, and end-of-life disposal. We first collected the material and energy
433 requirements of open-air and greenhouse production in different climatic regions from the
434 literature review (**Table S7,8**). Then we obtained GHG footprint factors (CFF) according to
435 China Products Carbon Footprint Factors Database (CPCD)[73]. Ultimately, based on the
436 productivity of RA, GWP ($kgCO_2$ e/kg vegetable) of RA is calculated as
437 Eq.**Error! Reference source not found.**. GHG mitigation of RA is measured by subtracting
438 the Chinese regional emission levels of traditional agriculture, which have been specified at the
439 city level.

$$GWP_k = \frac{\sum CFF * S_k}{F_k} \quad (1)$$

where GWP_k denotes in city k; $\sum CFF$ ($kgCO_2$ e/m^2) denotes the sum of GHG footprint factors in the life cycle of RA. Other variables have been mentioned above.

For RPV, we determined a monocrystalline silicon photovoltaic modules appropriate for China, 166-BF (72), which achieves excellent environmental performance[38]. It is a bi-facial module with a carbon footprint factor of 19 gCO_2 e/kWh. Besides, since PV module doesn't include a balance of system (BOS, mainly includes inverters and brackets) and energy storage system, which ensures the smooth process of power generation and secure access to electricity, we selected a kind of common BOS (CFF = 253 $kgCO_2$ e/kWp) and lithium iron phosphate battery (CFF = 102 $kgCO_2$ e/kWh) from previous studies[74,75].

The system boundary includes three steps namely production, installation, and operation. In the production, we know the CFF of RPV modules, BOS and batteries mentioned in the preceding text; In the installation, it requires 0.08 kWh of electricity to install 1 kWp RPV, which also needs 0.2 kWh of electricity for maintenance[74]. During the 30-year system lifetime in operation, it needs about 20 kg of water to clean the PV panels[76]. Lastly, through related literatures[76–78], we find the average CFF of coal-fired power generation (0.93 $kgCO_2$ e/kWh) and water(3.1 $kgCO_2$ e/kg water) in China. Consequently, during the 30-year system lifetime, GHG mitigation intensity of RPV can be estimated as Eq.(11) :

$$CM_k = CFF_k - \frac{GWP_k}{E_k}$$
$$GWP_k = CE * S_k \quad (11)$$

where CM_k ($kgCO_2$ e/kWh) denotes the GHG mitigation per kWh of RPV in city k; CFF_k means the baseline emission factor of city k corresponding to China's regional power grids according to the Ministry of Ecology and Environment of the People's Republic of China[35]; GWP_k denotes Global Warming Potential of RPV in city k; CE denotes the GHG emissions per m^2 area of PV system. Other variables have been mentioned above.

Multi-objective optimization for allocation of RA and RPV

To gain further insight into the development of RA and RPV in 124 cities of mainland China, a multi-objective optimization from pymoo[79] was performed (more details can be referred to **Note S5**). It is subdivided into three main phrases, namely defining optimization problems, finding (near-optimal) solutions using well-benchmarked algorithms, and making multi-criteria decisions. In this study, applying a non-dominated sorting genetic algorithm (NSGA-II), we constructed a tri-objective optimization with two variables and several constraints as follows:

(1) Objectives: Maximizing the self-sufficiency of vegetable in each city; Maximizing the self-sufficiency of electricity (as well as GHG mitigation potential) in each city; Maximizing the total economic benefits of RA and RPV.

(2) Variables: Roof areas allocated to RA and RPV in each city.

(3) Constraints: The total available urban roof area is limited to the total selected and assumed productive rooftop area; The PV module production capacity is limited in China[80]; The self-sufficiency of RA is 100% at most to avoid oversupply; The energy penetration potential of RPV, which means the ratio of the total electricity output of renewable energy units to the annual load demand (**Note S6**, **Table S9**), is limited to keep the stability of power system (50% at most)[81–83]; The total GHG mitigation is greater than zero.

Once a set of Pareto-optimal solutions are calculated, trade-offs and synergies from the combination of RA and RPV could be simulated through the comparison of properties between the optimized scenario and unoptimized ones, which are estimated as Eq.(12) :

$$rrc = 1 - \frac{benefit}{benefit_{max}}$$

$$tradeoff = Max(rrc_D, rrc_{NPV}, rrc_{CM}) - Min(rrc_D, rrc_{NPV}, rrc_{CM})$$

$$synergy = 1 - tradeoff \quad (12)$$

where $synergy$ measures the synergy index relative comprehensive benefits brought by a balanced allocation of RA and RPV; rrc denotes the relative change rate of benefit obtained from scenarios compared with the corresponding maximum benefit; $rrc_D, rrc_{NPV}, rrc_{CM}$ represent rrc of RA and RPV self-sufficiency, total economic benefit, total GHG mitigation respectively.

Limitations

Our research has the following limitations. Large-scale RA and RPV now face lots of issues to be resolved, such as complex ownership and high investment costs, leading to competition with other types of use and untransferable production capacities of cities[84,85]. Although we have conducted local life cycle assessment of RA and RPV in China, there is still potential for continuous improvement in production efficiency[38,41]. Moreover, penetration of renewable energy sources in power system[83], local preference, and varied recycling and waste disposal methods, should also be considered in future studies. In particular, to the local preference for RA and RPV, a greater quantity of data pertaining to urban characteristics that can be integrated into the constraints of multi-objective optimization is required.

Data availability

The vectorized urban extent and urban open space is available at https://doi.org/10.5281/zenodo.5168383. The GHG emission intensity used in this study is public available at http://lca.cityghg.com/. Data for water resource use is available from open-sourced Chinese statistics (https://www.mohurd.gov.cn/gongkai/fdzdgknr/sjfb/tjxx/jstjnj/index.html). The yield for open-air production was taken from the Global Agro-Ecological Zoning database (https://gaez.fao.org/). The surface incoming shortwave flux (SWGDN) hourly data from M2T1NXRAD is public available at

https://disc.gsfc.nasa.gov/datasets/M2T1NXRAD_5.12.4/summary, and 2 m hourly temperature data from ERA5-Land is public available at https://cds.climate.copernicus.eu/. Due to copyright issues, other data such as building outlines and attributes can only be made available from the authors on request.

Code availability

The vectorized and other spatial data, the building-level of potential of vegetable and PV power production, environmental and provisioning performance were processed or quantified with Excel v2021 and Python v3.7 interpreted by ArcGIS Pro. The code of multi-objective optimization was constructed utilizing open-source Python package pymoo v0.6.1.3 (https://pymoo.org/), which is available at https://github.com/Ruiyang/Urban-rooftops-for-food-and-energy-in-China.

Acknowledgment

This study was financially supported by National Natural Science Foundation of China (52100214), LIESMARS Special Research Funding and the Start-up Funding of Wuhan University awarded to Y.H; P. Pradhan acknowledges funding by the European Research Council (ERC) for the BeyondSDG project (Project number 101077492) and the Food System Economics Commission, funded by the IKEA Foundation, grant agreement no. G-2009-01682.

Author contributions

Y.H., R.Y. C.X. conceived the study. R.Y., Y.H., C.X., P.P., and H.Z. developed the methodology. R.Y., Y.H., and C.X. constructed the datasets and drafted the manuscript. L.J., X.B., Z.W., P.P., S.C., and Y.G. analyzed the results and supervised the study. All authors contributed to the manuscript.

Competing interests

All other authors declare they have no competing interests.

Tables

Table 1. Potential benefits and resource costs of optimal rooftop agriculture (RA) or photovoltaics (RPV) production in 124 Chinese cities.

	Benefits					Resource costs	
	Self-sufficiency (Mean and variation across cities, %)	Net economic return (Total, billion CNY)	Greenhouse gas mitigation (Total, Mt CO_2e)	Saved cropland (Total, km^2)	Saved standard coal (Total, Mt)	Water demand (Total, Mt)	Metal demand (Total, kt)
RA	15.2 (0.8~99.9)	1490.0	-0.7	2598.4		136.0	Copper (7.0) Aluminum (21.8)

						Steel (811.4)
RPV	5 (0.2~31.0)	590.3	161.4	87.9	0.6	Copper (96.5) Aluminum (1048.8) Silver (13.1)

Figure Legends/Captions

Fig. 1 Potential benefits in 124 cities if all productive rooftop areas were applied in either rooftop agriculture (RA) or photovoltaics (RPV) production. a, b the Annual self-sufficiency of vegetables (**a**) and electricity (**b**). **c, d** Annual average economic benefit per unit area of RA (**c**) and RPV (**d**). **e, f** Annual greenhouse gas (GHG) mitigation per unit area of RA (**e**) and RPV (**f**), a positive value shows the net reduction effect of rooftop production in the city, and a negative value indicates an adverse contribution to emission reduction. On the right of the figures, three box plots separately depict the distribution of above three potential benefits for RA and RPV among 124 cities, including the minimum value, 25th percentile, median, 75th percentile, and maximum value. The population shown in **a** and **b** only includes that within the urban extents rather than the entire population of the administrative city. Hong Kong and Macau are excluded here because their grid purchase price is too high to be comparable (**Fig S2**). We showed the regional division of the agricultural zone and electricity grid in all figures (**Fig S3**). The cities mentioned in the analyses were indicated in the figures.

Fig. 2 Optimal allocations of rooftop agriculture (RA) or photovoltaics (RPV). a Benefits comparison of all Pareto-optimal solutions. The color and size of the circles represent each solution's total annual GHG mitigation and NPV. In general, the synergy index of each solution increases progressively from red to green. There are local break points in the middle of the Pareto frontier due to numerous integer constraints, but the distribution has no practical significance and can, therefore, be ignored[32]. **b** Ratio of rooftop area attributed to RA and RPV under optimized solution (synergy index=0.69). Notably, a strong positive correlation exists between the synergy index and average RPV self-sufficiency (**Fig S5**), primarily due to the substantial influence on greenhouse gas (GHG) mitigation of its electricity production.

References

1. Van Dijk, M., Morley, T., Rau, M. L. & Saghai, Y. A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nat Food* **2**, 494–501 (2021).

2. The World Bank. Report: Universal Access to Sustainable Energy Will Remain Elusive Without Addressing Inequalities. https://www.worldbank.org/en/news/press-release/2021/06/07/report-

universal-access-to-sustainable-energy-will-remain-elusive-without-addressing-inequalities (2021).

3. Ramaswami, A., Pandey, B., Li, Q., Das, K. & Nagpure, A. Toward Zero-Carbon Urban Transitions with Health, Climate Resilience, and Equity Co-Benefits: Assessing Nexus Linkages. *Annu. Rev. Environ. Resour.* **48**, 81–121 (2023).

4. Li, Z. B., Zhang, Y. & Wang, M. Solar energy projects put food security at risk. *Science* **381**, 740–741 (2023).

5. Zhang, N. *et al.* Booming solar energy is encroaching on cropland. *Nat. Geosci.* **16**, 932–934 (2023).

6. Gu, C. *Chinese Urbanization (In Chinese)*. (Science Press, Beijing, 2021).

7. Seto, K. C. & Ramankutty, N. Hidden linkages between urbanization and food systems. *Science* **352**, 943–945 (2016).

8. Zambrano-Prado, P. *et al.* Assessment of the food-water-energy nexus suitability of rooftops. A methodological remote sensing approach in an urban Mediterranean area. *Sustainable Cities and Society* **75**, 103287 (2021).

9. Garcia, D. J. & You, F. The water-energy-food nexus and process systems engineering: A new focus. *Computers & Chemical Engineering* **91**, 49–67 (2016).

10. Qiu, J. *et al.* Scale up urban agriculture to leverage transformative food systems change, advance social–ecological resilience and improve sustainability. *Nat Food* **5**, 83–92 (2024).

11. Bai, X. Advance the ecosystem approach in cities. *Nature* **559**, 7–8 (2018).

12. Clinton, N. *et al.* A Global Geospatial Ecosystem Services Estimate of Urban Agriculture. *Earth's Future* **6**, 40–60 (2018).

13. Pradhan, P. *et al.* Urban Food Systems: How Regionalization Can Contribute to Climate Change Mitigation. *Environ. Sci. Technol.* (2020).

14. Payen, F. T. *et al.* How Much Food Can We Grow in Urban Areas? Food Production and Crop Yields of Urban Agriculture: A Meta-Analysis. *Earth's Future* **10**, e2022EF002748 (2022).

15. Goldstein, B., Hauschild, M., Fernández, J. & Birkved, M. Testing the environmental performance of urban agriculture as a food supply in northern climates. *Journal of Cleaner Production* **135**, 984–994 (2016).

16. Corcelli, F., Fiorentino, G., Petit-Boix, A., Rieradevall, J. & Gabarrell, X. Transforming rooftops into productive urban spaces in the Mediterranean. An LCA comparison of agri-urban production and photovoltaic energy generation. *Resources, Conservation and Recycling* **144**, 321–336 (2019).

17. Chen, S. *et al.* The Potential of Photovoltaics to Power the Belt and Road Initiative. *Joule* **3**, 1895–1912 (2019).

18. Zhang, Z. *et al.* Carbon mitigation potential afforded by rooftop photovoltaic in China. *Nat Commun* **14**, 2347 (2023).

19. Lu, X. *et al.* Combined solar power and storage as cost-competitive and grid-compatible supply for China's future carbon-neutral electricity system. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2103471118 (2021).

20. Benis, K., Turan, I., Reinhart, C. & Ferrão, P. Putting rooftops to use – A Cost-Benefit Analysis of food production vs. energy generation under Mediterranean climates. *Cities* **78**, 166–179 (2018).

21. Toboso-Chavero, S. *et al.* Towards Productive Cities: Environmental Assessment of the Food-Energy-Water Nexus of the Urban Roof Mosaic. *Journal of Industrial Ecology* **23**, 767–780 (2019).

22. Meng, F. *et al.* The food-water-energy nexus and green roofs in Sao Jose dos Campos, Brazil, and Johannesburg, South Africa. *npj Urban Sustain* **3**, 12 (2023).

23. Jing, R., Hastings, A. & Guo, M. Sustainable Design of Urban Rooftop Food-Energy-Land Nexus. *iScience* **23**, 101743 (2020).

24. Touil, S., Richa, A., Fizir, M. & Bingwa, B. Shading effect of photovoltaic panels on horticulture crops production: a mini review. *Rev Environ Sci Biotechnol* **20**, 281–296 (2021).

25. Bambara, J. & Athienitis, A. K. Energy and economic analysis for the design of greenhouses with semi-transparent photovoltaic cladding. *Renewable Energy* **131**, 1274–1287 (2019).

26. Mishra, G. K. & Tiwari, G. N. Performance evaluation of 7.2 kWp standalone building integrated semi-transparent photovoltaic thermal system. *Renewable Energy* **146**, 205–222 (2020).

27. Jing, R. *et al.* Unlock the hidden potential of urban rooftop agrivoltaics energy-food-nexus. *Energy* **256**, 124626 (2022).

28. Mamun, M. A. A., Dargusch, P., Wadley, D., Zulkarnain, N. A. & Aziz, A. A. A review of

research on agrivoltaic systems. *Renewable and Sustainable Energy Reviews* **161**, 112351 (2022).

29. Cossu, M. *et al.* Agricultural sustainability estimation of the European photovoltaic greenhouses. *European Journal of Agronomy* **118**, 126074 (2020).

30. Yano, A. & Cossu, M. Energy sustainable greenhouse crop cultivation using photovoltaic technologies. *Renewable and Sustainable Energy Reviews* **109**, 116–137 (2019).

31. Neupane, D., Kafle, S., Karki, K. R., Kim, D. H. & Pradhan, P. Solar and wind energy potential assessment at provincial level in Nepal: Geospatial and economic analysis. *Renewable Energy* **181**, 278–291 (2022).

32. Lin, J. *et al.* Relative optimization potential: A novel perspective to address trade-off challenges in urban energy system planning. *Applied Energy* **304**, 117741 (2021).

33. Li, S. *et al.* Integrated Agricultural Practices and Engineering Technologies Enhance Synergies of Food-Energy-Water Systems in Corn Belt Watersheds. *Environ. Sci. Technol.* **57**, 9194–9203 (2023).

34. Xu, Z. *et al.* Mapping hierarchical urban boundaries for global urban settlements. *International Journal of Applied Earth Observation and Geoinformation* **103**, 102480 (2021).

35. Ministry of Ecology and Environment of the People's Republic of China. Regional power grid baseline emission factors of 2019 annual carbon mitigation project in China (In Chinese). (2020).

36. Ministry of Water Resources of the People's Republic of China. *CHINA WATER RESOURCES*

BULLETIN. http://www.mwr.gov.cn/zzsc/tjgb/szygb/2022/mobile/index.html (2022).

37. Meldrum, J., Nettles-Anderson, S., Heath, G. & Macknick, J. Life cycle water use for electricity generation: a review and harmonization of literature estimates. *Environ. Res. Lett.* **8**, 015031 (2013).

38. Jia, X., Zhou, C., Tang, Y. & Wang, W. Life cycle assessment on PERC solar modules. *Solar Energy Materials and Solar Cells* **227**, 111112 (2021).

39. Dawei Mu & Yukun Zhang. Potential of Vegetable Production and Photovoltaic Power Generation in Rooftop Greenhouse: Taking Tianjing City as an Example (In Chinese). *Building Energy Efficiency* **48**, 83-90+125 (2020).

40. Bai, Z. *et al.* A food system revolution for China in the post-pandemic world. *Resources, Environment and Sustainability* **2**, 100013 (2020).

41. Pradhan, P. *et al.* A systematic review highlights that there are multiple benefits of urban agriculture besides food. *Global Food Security* **38**, 100700 (2023).

42. Zurek, M., Hebinck, A. & Selomane, O. Climate change and the urgency to transform food systems. *Science* **376**, 1416–1421 (2022).

43. Chen, P. *et al.* The heterogeneous role of energy policies in the energy transition of Asia–Pacific emerging economies. *Nat Energy* **7**, 588–596 (2022).

44. Rufí-Salís, M. *et al.* Recirculating water and nutrients in urban agriculture: An opportunity towards environmental sustainability and water use efficiency? *Journal of Cleaner Production* **261**, 121213 (2020).

45. De Zeeuw, H. *et al.* A Geography of Rooftop Agriculture in 20 Projects. in *Rooftop Urban Agriculture* (eds. Orsini, F., Dubbeling, M., De Zeeuw, H. & Gianquinto, G.) 309–382 (Springer International Publishing, Cham, 2017). doi:10.1007/978-3-319-57720-3_19.

46. Fang, L., Lv, J. & Huo, Y. Study of Operating Characteristics of Rooftop Distributed Photovoltaic Grid-Connected Generation System (In Chinese). *Journal of Tianjin Chengjian University* **25**, 284–289 (2019).

47. Jinan Municipal People's Government. 'Jinan City greening Regulations' implementation rules (In Chinese). http://www.jinan.gov.cn/art/2023/9/13/art_85285_307.html (2023).

48. Dongguan Municipal People's Government. Notice of Dongguan Municipal People's Government Office on issuing the Implementation Opinions on Promoting the Construction of Sponge City (In Chinese). http://www.dg.gov.cn/zwgk/zfxxgkml/szfbgs/zcwj/qtwj/content/post_591216.html (2017).

49. European Environment Agency. *Financing Urban Adaptation to Climate Change.* (Publications Office, LU, 2017).

50. Sunter, D. A., Castellanos, S. & Kammen, D. M. Disparities in rooftop photovoltaics deployment in the United States by race and ethnicity. *Nat Sustain* **2**, 71–76 (2019).

51. Beijing City Bureau of Landscape and Greening. Beijing Roof Greening Specifications. (2016).

52. Shanghai City Administration of Law Enforcement for Urban Management. Shanghai Greening Regulations Amendment. (2018).

53. Ministry of Housing and Urban-Rural Development of China. Technical regulations planted

roof engineering. (2013).

54. Proksch, G. & Ianchenko, A. Commercial rooftop greenhouses. in *Urban and Regional Agriculture* 503–532 (Elsevier, 2023).

55. Dorr, E., Goldstein, B., Horvath, A., Aubry, C. & Gabrielle, B. Environmental impacts and resource use of urban agriculture: a systematic review and meta-analysis. *Environ. Res. Lett.* **16**, 093002 (2021).

56. Masters, G. M. *Renewable and Efficient Electric Power Systems*. (John Wiley & Sons, Hoboken, NJ, 2004).

57. Qiu, T. *et al.* Potential assessment of photovoltaic power generation in China. *Renewable and Sustainable Energy Reviews* **154**, 111900 (2022).

58. Global Modeling And Assimilation Office & Pawson, S. MERRA-2 tavg1_2d_rad_Nx: 2d,1-Hourly,Time-Averaged,Single-Level,Assimilation,Radiation Diagnostics V5.12.4. NASA Goddard Earth Sciences Data and Information Services Center https://doi.org/10.5067/Q9QMY5PBNV1T (2015).

59. Copernicus Climate Change Service. ERA5-Land hourly data from 2001 to present. ECMWF https://doi.org/10.24381/CDS.E2161BAC (2019).

60. Long, Z., Li, H., Bu, X., Ma, W. & Zhao, L. Solar radiation on vertical surfaces for building application in different climate zones across China. *Journal of Renewable and Sustainable Energy* **5**, 021418 (2013).

61. Qi, Y., Fang, S. & Zhou, W. Variation and Spatial distribution of Surface Solar Radiation in

China over recent 50years (In Chinese). *Acta Ecologica Sinica* **34**, (2014).

62. Tang, W., Yang, K., Qin, J., Li, X. & Niu, X. A 16-year dataset (2000–2015) of high-resolution (3 h, 10 km) global surface solar radiation. *Earth Syst. Sci. Data* **11**, 1905–1915 (2019).

63. Ye, J. Y., Reindl, T., Aberle, A. G. & Walsh, T. M. Performance Degradation of Various PV Module Technologies in Tropical Singapore. *IEEE J. Photovoltaics* **4**, 1288–1294 (2014).

64. Luo, W. *et al.* A comparative life-cycle assessment of photovoltaic electricity generation in Singapore by multicrystalline silicon technologies. *Solar Energy Materials and Solar Cells* **174**, 157–162 (2018).

65. Fath, K. *et al.* A method for predicting the economic potential of (building-integrated) photovoltaics in urban areas based on hourly Radiance simulations. *Solar Energy* **116**, 357–370 (2015).

66. Lukač, N., Seme, S., Dežan, K., Žalik, B. & Štumberger, G. Economic and environmental assessment of rooftops regarding suitability for photovoltaic systems installation based on remote sensing data. *Energy* **107**, 854–865 (2016).

67. Mansouri Kouhestani, F. *et al.* Evaluating solar energy technical and economic potential on rooftops in an urban setting: the city of Lethbridge, Canada. *Int J Energy Environ Eng* **10**, 13–32 (2019).

68. Peña, A., Rovira-Val, M. R. & Mendoza, J. M. F. Life cycle cost analysis of tomato production in innovative urban agriculture systems. *Journal of Cleaner Production* **367**, 133037 (2022).

69. Wu, Z. Three-Dimensional Numerical Simulation of Dust Deposition on the Surface of

720 Photovoltaic Modules (In Chinese). (Nanchang University, 2022).

721 70. Zhang, Z. *et al.* Cleaning effect analysis and cleaning cycle prediction of pv modules in pv
722 power stations (In Chinese). *SOLAR ENERGY* 53–61 (2022).

723 71. Lin, J. Research on Investment Estimation of Roof Photovoltaic Power Station Project Based
724 on Life Cycle Theory (In Chinese). (Zhejiang University, 2023).

725 72. Mangiante, M. J. *et al.* Economic and technical assessment of rooftop solar photovoltaic
726 potential in Brownsville, Texas, U.S.A. *Computers, Environment and Urban Systems* **80**,
727 101450 (2020).

728 73. China City Greenhouse Gas Working Group (CCG). China Products Carbon Footprint Factors
729 Database[E]. (2022).

730 74. Li, Y. Life Cycle Assessment of Crystalline Silicon Modules in China (In Chinese). (Shanghai
731 Jiao Tong University, 2015).

732 75. Cheng, D. Study on environmental benefits of lithium-ion batteries in life cycle based on green
733 development concept (In Chinese). (Guangdong University of Technology, 2019).

734 76. Jia, X., Lv, F., Li, P. & Wang, W. Life-cycle assessment of p-type multi-Si back surface field
735 (BSF) solar module in China of 2019. *Solar Energy* **196**, 207–216 (2020).

736 77. National Bureau of statistics of the People's Republic of China. *CHINA ENERGY*
737 *STATISTICAL YEARBOOK (In Chinese)*. (2020).

738 78. Liang, J. Environmental Effects Investigating for the Grid-connected BAPV (In Chinese).
739 (Tianjin University, 2012).

79. Blank, J. & Deb, K. Pymoo: Multi-Objective Optimization in Python. *IEEE Access* **8**, 89497–89509 (2020).

80. China Photovoltaic Industry Association. *China PV Industry Development Roadmap (In Chinese)*. http://www.chinapv.org.cn/road_map/1137.html (2023).

81. Zhao, B., Zhang, X. & Hong, B. Energy penetration of large-scale distributed photovoltaic sources integrated into smart distribution network (In Chinese). *Electric Power Automation Equipment* **32**, 95–100 (2012).

82. Zhao, B., Xiao, C., Xu, C., Zhang, X. & Zhou, J. Pentration Based Accommodation Capacity Analysis on Distributed Photovoltaic Connection in Regional Distribution Network (In Chinese). *Automation of Electric Power Systems* **41**, 105–111 (2017).

83. Zhuo, Z., Zhang, N., Xie, X., Li, H. & Kang, C. Key Technologies and Developing Challenges of Power System with High Proportion of Renewable Energy (In Chinese). *Automation of Electric Power Systems* **45**, 171–191 (2021).

84. Specht, K. *et al.* Urban agriculture of the future: an overview of sustainability aspects of food production in and on buildings. *Agric Hum Values* **31**, 33–51 (2014).

85. Lang, T., Gloerfeld, E. & Girod, B. Don′t just follow the sun – A global assessment of economic performance for residential building photovoltaics. *Renewable and Sustainable Energy Reviews* **42**, 932–951 (2015).