A sustainable solar city: From utopia to reality facilitated by GIScience

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Global cities occupy only 3% of Earth's land surface but are responsible for 75% of all CO_2 emissions.[1] Thus, cities are the primary battlefields to achieve the United Nations' Sustainable Development Goals on carbon neutrality. To accomplish such goals, solar farming has experienced significant growth in recent years and "*a sustainable solar city*" was proposed to effectively collect, store, and utilise solar energy to create a sustainable urban environment.[2] However, the development of such a solar city faces several challenges, such as intermittency, spatiotemporal heterogeneity, and energy storage complexity. We believe that Geographical Information Science (GIScience) plays a key role in addressing these challenges. As shown in Figure 1, we propose five pathways for the future solar cities, and demonstrate that GIScience can contribute to the development of a solar city in five aspects. As a result, a solar city will exhibit three remarkable features: liveable and sustainable with sufficient production of daily living materials, self-sufficient in solar energy supply, and real-timely interactive between the real-virtual worlds. Finally, we suggest that the advancement of GIScience and interdisciplinary collaborations are needed to transform a solar city from utopia to reality.

DEVELOPMENT DIRECTIONS OF SOLAR CITIES

A solar city should collect solar energy from different surfaces, including land, water, and outer space. Although there is a limit to the amount of solar energy a city can capture, the capacity can grow with the expansion of three-dimensional urban surfaces. With an increasing rate of energy consumption, it is hard for a city to be fully self-sufficient. To achieve the ambitious goal of replacing conventional fossil fuels with solar energy, it is mandatory to seek external energy supplies. This means that a great amount of electricity should be generated from utility-scale solar farming plants on remotely bare lands and offshores. Meanwhile, scientists have been exploring the possibility of harvesting solar energy directly from outer space, and wirelessly transmitting the generated electricity through the air, the same as the forward idea raised by Nikolas Tesla more than one hundred years ago.

A solar city should facilitate the production of essential daily living materials. The above vision enlightens us to penetrate a solar city into nature more deeply with a better built-environment design. This means that solar energy will not be necessarily used for powering; it can be sustainable in producing essential daily living materials. For instance, solar energy is essential for rooftop and vertical urban farming, which can simultaneously clean the air and reduce indoor air temperatures. Besides, solar energy can collect and clean water for drinking by daytime evaporation, and even dispose waste through degradation under the daylight.

A solar city should be three-dimensional, expanding both upwards towards the sky and downwards beneath the ground. In recent years, several governments have implemented regulations to govern land reclamation during the urbanization process. For example, the Chinese government has formulated the "reconstruction of the old city" policy to build tall buildings, and the Singaporean government has established a master plan to develop an underground city in the next decade. In this context, the indoor environment and

Figure 1. An overview of GIScience facilitating the development of solar cities.

underground space will heavily rely on artificial lighting. Thanks to new technology and innovative design, a tubular daylight device featuring the world's most reflective material has been developed. This device can be installed in solar abundant locations to collect daylight from rooftops and carry the light to the indoor environment.

A solar city should be interspersed with energy storage technologies. Electricity storage technology has emerged as a key solution to address the spatiotemporal heterogeneity between energy supply and demand. We suggest that hydrogen storage could be a promising solution because of its fast inflation, large storage capacity, and zero-emission. Additionally, since electric vehicles (EVs) have been experiencing fast growth, it is reasonable to foresee that EVs are also going to be a prominent, mobile, and flexible energy storage. Concurrently, facilitated by solar PV highways equipped with a wireless charging capability,[3] the vehicle-to-grid technology can efficiently return EV electricity through discharging to provide demand-responsive services. This will reduce higher loads to the grid during peak hours, eliminate the uncertainty of the solar farming systems, and enable a dynamic balance between supply and demand.

A solar city should be a digital twin city. A solar city is a digital symbiosis consisting of a projection between the physical city and the digital city. This allows holographic simulation, dynamic monitoring, real-time diagnosis, and accurate estimation of the interactions between distributed solar energy systems and the integrated end-users in the real world. Therefore, the digital twin city offers a platform that not only creates a virtual world based on the current scenario but also extends the temporal domain to multiple instances. This helps to distinctly understand urban evolution and provide a feasible path for planning a future solar city.

CONTRIBUTIONS FROM GISCIENCE

We believe that GIScience – the discipline that studies geospatial data structures and computational technologies to collect, represent, process, and analyse geographic information[4] – will be the foundation for developing a solar city. This is because GIScience exhibits unique capabilities in successfully implementing a solar city, following the five possible pathways.

GIScience can play a crucial role in producing solar-related spatiotemporal big data by seamlessly coupling it with other geospatial technologies. A collection of multi-sourced geospatial datasets is needed to develop the proposed solar city. These include, but are not limited to, land surface solar irradiation maps to quantify solar potential, 3D city models to estimate the 3D solar distribution, building rooftop area maps to plan PV installation, and installed-PV area maps to evaluate socio-economic and environmental impacts. These datasets were created based on GIScience data modelling theories and methods, which are fundamental for developing a solar city aligning with the speculated directions.

GIScience can provide crucial methods to model spatiotemporal solar distribution on 3D urban surfaces. The variable nature of solar energy, influenced by weather conditions and shadow cast by buildings, vegetation, and terrain variations, makes it essential to obtain statistically significant estimations of solar distribution over a long period on land or water surfaces. This is critical for effectively planning electricity generation and urban farming. Building rooftop PV systems, for instance, prefer solar abundant locations, whereas building greenery and urban agriculture usually requires moderate sunlight. This presents the capability of GIScience in modelling solar distributions that are affected by geo-location, time, unstable weather, and varying shadows from urban objects.

GIScience can reveal dynamic changes in solar distribution along with urban reforming. GIScience demonstrates its extraordinary capability in tracking and analysing dynamic geo-evolutionary processes over time and space to address the daylighting issue when developing a 3D solar city. Based on a series of spatial analytic and statistical methods, GIScience can reveal transformed solar accessibility caused by urban transformations. This is essential for assessing shadow effects on existing buildings, assisting urban designers in optimising building daylight accessibility, and identifying long-term daylight areas suitable for equipping tubular daylight devices.

GIScience can provide a unique capability in multi-scale and multi-objective optimization for a dynamic balance between energy demand and supply. At the microscopic level, a PV system can be optimised by estimating its annual PV potential with systematic adjustment of the PV size, location, orientation, and array spacing, considering the real geo-environment. At the local scale, solar farming in each urban district can be optimised through multi-objective optimizations, considering technical, economic, and environmental feasibilities throughout the entire life cycle. At the global scale, solar framing can be optimised by designing near-real-time dispatching to maximize energy demands across all urban districts in a city. All of these can be addressed by GIScience through time-space-associated complex network analysis.

GIScience provides scientific guidance, theory foundation, and technological support for the development of a digital twin city. GIScience with its strong capabilities in spatial thinking, professional mapping, and 3D geovisualization improves our in-depth understanding of solar energy utilisation integrated with various urban systems and effectively aids policy and decision-making. In terms of digital-city development, GIScience presents its functionality in digital earth innovation, including 3D city construction, virtual-real integration, intelligently spatiotemporal optimization, and geospatial big data computation.[5]

SOLAR CITIES FROM UTOPIA TO REALITY

Once the five development directions discussed above are realized, a solar city could transform from utopia to reality, functioning as a standalone micro-ecosystem and as a network of interconnected systems across the globe. This could contribute to the effective restoration of the global ecological environment. To achieve such a vision, we still need interdisciplinary collaborations and further development of GIScience.

GIScience can play a pivotal role in interdisciplinary collaborations to realize the solar city. A seamless collaboration between multi-disciplines such as GIScience, urban planning, computer science, and artificial intelligence is necessary to achieve the vision of the solar city. GIScience plays a pivotal role in this regard by constructing complex geospatial scenarios for planning, analysing, and optimising the solar city based on the latest progress of scientific research.

GIScience needs further advancement of its theory and methods to facilitate the utopia-to-reality transformation. The society will experience disruptive changes with the development of the proposed solar city, as people's daily activities extend across multiple time-space domains, encompassing the past, present, and future, as well as land, water, sky, underground, and outer space. In the face of such momentous changes when time-space interacts between virtual and reality, GIScience must advance its capability of real-time geospatial scenario reconstruction and space-thinking. A strategic embrace of artificial intelligence is necessary to achieve this goal. This will enable efficient resource sharing, interoperability, and unification in the top-level design of the solar city.

The concept of solar city can play a crucial role in facilitating energy transition, combating climate change, and achieving carbon neutrality. The integration of GIScience can facilitate the effective utilization and management of solar energy resources. By fostering interdisciplinary research, GIScience is well-positioned to make a compelling contribution to realizing this vision, advancing its theory and methods to move the idea of solar city from utopia to reality.

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DECLARATION OF INTERESTS

The authors declare no competing interests.