Infrastructure-scale sustainable energy planning in the cityscape: Transforming urban energy metabolism in East Asia

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Abstract
Transformation of the urban energy metabolism is possible when sustainable energy is positioned as an infrastructure-scale tool. A review of urban energy planning research is complemented by an examination of assessment methods in use to gauge the feasibility of planning sustainable energy as a new infrastructure to power cities. A case study analysis of the city of Daejeon is offered to operationalize this planning strategy. In particular, the integrated application of the “savings city” and “solar city” concepts where, respectively, citywide deployment of energy efficiency and rooftop photovoltaic energy systems is envisioned at a large-scale, is explored for Daejeon through the innovative use of geospatial assessment methods and a visualization tool that can guide urban policy. This assessment and its visualization illustrates not only grid energy use divisions throughout the city but also reveals possible energy planning trajectories in pursuit of positioning sustainable energy as urban infrastructure. The assessment finds that cities like Daejeon could fulfill over half of their electricity service needs through in-city deployment of sustainable energy at the infrastructure-scale. Cities that embark on this “sustainable city” trajectory essentially reform the lived experience of “the city” and reshape the city-energy relationship.

1 | INTRODUCTION

Daily life is structured in large part by decisions that were made at the infrastructure-scale. The result of infrastructure-scale decisions is apparent in the world’s cities: much of the built environment is the result of meticulous coordination...
and planning as metropolises oversee the bustling daily city life of millions. This active environment is accompanied by a high “urban energy metabolism”\(^1\): for example, 27 of the world’s megacities account for 9.3% of global electricity use (Kennedy et al., 2015). Yet, urban energy metabolisms typically rely on ex-urban energy resources that limit city control and constrain community prioritization and energy future visioning. Commitments to power and expand city life have, as a result, long-lasting consequences as these decisions can amplify the city’s constant need for abundant energy, increase the city’s reliance on ex-urban energy resources, and lead to the construction of energy infrastructure with a high carbon load and associated climate damage.

Cities can take advantage of the large and structured layout offered by the hundreds of thousands or even millions of buildings to deploy modular sustainable energy at the infrastructure-scale. Local governments essentially oversee a rich asset-base for potential sustainable energy deployment and self-sufficiency achievement if policy consideration is implemented at the city-scale. To capture this opportunity, cities have to prioritize a high level of energy efficiency and renewable energy autonomy through on-site generation and savings as critical components of the services portfolio of a city.

The challenge ahead is no less than the metabolic remodeling of citywide energy use and generation patterns which will have profound consequences for what it means to be a city down to the neighborhood and even individual household level (Scheer, 2008; Taminiau & Byrne, 2020). In this energy future, the urban energy metabolism shifts from a system built predominantly on importing energy to one constructed around city community sharing and exchange (Taminiau & Byrne, 2020). When combined with other tools at the disposal of city decision-makers, this shift could play a meaningful role in the achievement of globally relevant climate and energy objectives (Kona et al., 2018).

Scaling this challenge will require the development of tools and visualizations that can guide the integrated application of energy reduction and on-site renewable energy generation strategies. To that end, the paper addresses the integration of “savings city” (i.e., the citywide deployment of energy efficiency interventions) and “solar city” (i.e., the citywide deployment of rooftop photovoltaic [PV]) concepts and how they could play a role as urban energy visions (Section 2). The promise and performance of both concepts is critically dependent on the positioning of energy as an urban infrastructure option. The paper then turns to the case study analysis of Daejeon, South Korea to illustrate the benefits and consequences of seeing sustainable energy as essential infrastructure for future city development (Sections 3 and 4). This evaluation is conducted through the assembly of a detailed energy consumption and building-based data repository that enables assessment of the ~140,000 buildings of the city. The integration of energy efficiency and rooftop PV at the city-scale is facilitated through the construction of a geospatial profile consisting of geometric division of the city in strategic and manageable units for program development that are independent from administrative, topological, historical, or other boundaries. This visualization tactic illustrates not only grid energy use divisions throughout the city but also reveals possible energy planning trajectories and strategic insight into the potential programmatic application of a “savings + solar city.” Relevant insights and concluding remarks are provided in Section 5.

2 | REIMAGINING CITIES AS SUSTAINABLE ENERGY LEADERS

A first necessary step to imagine cities as sustainable energy leaders, relying heavily on in-city renewable energy and energy efficiency, is to identify citywide potential for such a transition.\(^2\) Advancements in measurement and analysis techniques have enabled detailed profiles for citywide renewable energy potential, especially rooftop solar (Taminiau & Byrne, 2020). These techniques rely on sophisticated data such as the remotely sensed physical profile of cities in three dimensions.\(^3\) Built out of billions of data points, these high-resolution 3D models enable clear insight into, for instance, the rooftop dimensions of cities to establish the suitable rooftop space for rooftop PV deployment and to determine a city’s technical potential (e.g., Assouline et al., 2018; Byrne et al., 2017; Margolis et al., 2017; Taminiau & Byrne, 2020). A literature review of studies of this kind found that cities can commonly expect to serve around one-third of their annual electricity services from rooftop PV when these technical potentials are fully deployed (Byrne et al., 2017). Combined, these “solar city” investigations have identified hundreds of gigawatts (GW) of rooftop solar PV potential across the cities of the world (Byrne et al., 2017). Extrapolation of these findings to untested cities suggests that aggregate rooftop PV potentials are in the terawatt-scale (Byrne et al., 2017).

Citywide energy efficiency opportunities, similarly, are recognized as an important potential accelerator for the (urban) transition to sustainable energy. A critical component to establishing citywide energy efficiency potential is to accurately catalog citywide energy consumption patterns (e.g., Howard et al., 2012; Kontokosta & Tull, 2017). Urban building energy models have been introduced to assess such large-scale consumption patterns using advanced modeling
and simulation (Reinhart & Cerezo Davila, 2016). Efforts to identify citywide energy efficiency commonly find energy saving potentials ranging from 20 to 40% (e.g., Chen et al., 2017; Mastrucci et al., 2014; Pasichnyi et al., 2019; Shahrokni et al., 2014; Tong et al., 2016). For instance, evaluation of Rotterdam, the Netherlands finds energy savings options as high as 70% for older dwellings and ranging from 24 to 61% for dwellings built post-1945 and before 1991 (Mastrucci et al., 2014). Citywide energy efficiency achievements of 13–14% are recorded for New York City through local energy disclosure practices (Meng et al., 2017).

City leaders increasingly recognize that continued infrastructural expansion of ex-urban energy resources with a high carbon load is contradictory to established local and global policy ambitions (Chan et al., 2015). As a case in point, Seoul Metropolitan Government (SMG) launched its “Solar City Seoul” initiative to install one gigawatt (GWp) of solar electricity capacity throughout the city by 2022 in November 2017 ( Hankyoreh, 2017). Likewise, New York City has its own 1 GWp rooftop and canopy solar target (NYC, 2016) and London has followed suit with its 1 GWp objective (Mayor of London, 2018). Leading cities similarly argue in favor of whole-city energy use reduction efforts, illustrated by Seoul’s multiphase “One Less Nuclear Power Plant” (OLNPP) strategy to improve the city’s energy efficiency to a point where the city’s energy reduction is equivalent to the output of a nuclear energy power plant (Cho, 2019; Lee et al., 2014).

Geospatial and temporal accounting of technical potentials suggests clear distinctions exist between city sections, enabling planning and policy options for their development (Byrne & Taminiau, 2018; Mikkola & Lund, 2014; Taminiau & Byrne, 2020). For instance, New York City sustainable energy potentials differ substantially between the dense, vertical, and high-energy use sections of the city in Manhattan and the surrounding boroughs (Taminiau & Byrne, 2020). In addition, these assessments commonly find that, on an hour-to-hour basis, these effects are exacerbated. Informed energy planning, therefore, could develop large-scale rooftop solar PV strategies in, for example, the exterior boroughs of New York City that supply power to Manhattan during certain moments of the day and year (Taminiau & Byrne, 2020).

The identification of citywide sustainable energy potential requires follow-up strategies that pursue the actual deployment of in-city renewable energy and energy efficiency. Here, practical tools to develop citywide energy potentials are limited. Existing tools are often focused on providing “front-end” insights to households and citizens interested in selecting sustainable energy options (Byrne et al., 2017; Byrne & Taminiau, 2018; Kanters et al., 2014). Due to their “front-end” focus, these tools typically do not provide infrastructure-scale insights or integration of multiple technologies. To illustrate, so-called “solar maps” of cities commonly provide consumers with data on building-level electricity generation, net-present value, system size and cost, and other information necessary to support individual purchasing decisions. Municipal development of rooftop solar at the infrastructure-scale, however, requires involvement of many more decision-makers and decisions (e.g., Kanters & Wall, 2016).

The “solar city” and “saving city” evaluations are examples of infrastructure-scale reasoning regarding urban energy – these concepts provide limited additional insight at the individual building scale relative to methods developed to evaluate such small-scale opportunities but, instead, emphasize the citywide and integrated potential for transformative-level change. Careful consideration of “solar city” and “savings city” options opens up new questions and policy strategies. In particular, policy strategies that start from the position of placing sustainable energy as a component of urban infrastructure represent a step-change away from previously common policies that aim to influence private purchasing decisions. In other words, “back-end” tools and visualizations, which enable city decision-makers to select and design energy planning strategies at the citywide level are needed to drive the urban energy metabolism transformation envisioned under local and national policy ambitions (Byrne et al., 2017; Byrne & Taminiau, 2018).

3 | TRANSFORMATION OF THE URBAN ENERGY METABOLISM IN KOREAN CITIES

Using cities in South Korea as an example, an exploration of urban metabolism in light of national energy and climate policy ambitions is possible. Strong state backing helped orchestrate the development of centralized energy infrastructure in Korea (Lee et al., 2019). Recent energy visions proposed by the national government of Korea supports and will help drive the transformation of urban energy economies toward sustainable energy. For instance, Korea envisions a transition trajectory where greenhouse gas emissions are 37% below a business-as-usual forecast (Republic of Korea, 2015). Existing reliance on coal-fired power will need to be downscaled to achieve this objective and the national government hesitates to expand reliance on nuclear power (Kim, 2017; Yoon-Seung, 2019). Instead, a strategy to
accelerate the deployment of sustainable energy options is employed to transform the country’s energy mix. The national effort, called the “Renewable Energy 3020 Implementation Plan,” declares a country-wide objective of increasing renewable energy from its 2017 level of 7% of the country’s energy mix to 20% by 2030 (MOTIE, 2018). The ambitious strategy can count on reliable public support (Kim, Park, & Lee, 2018).

Full-fledged transformation of the Korean energy economy is likewise pursued under renewed commitments to Green New Deal (GND) planning. A GND effort was announced by the country’s President ahead of the 2020 April parliamentary election with plans to invest 12.9 trillion Won (approximately $10.5 billion) over the next 2 years in an attempt to establish 133,000 new jobs (Smith & Cha, 2020). The framework aims to expand energy efficiency, deploy low-carbon power, and triple renewable power output by 2025 by installing 42.7 GW of solar and wind capacity (Lee, 2020). By 2030, the country aims for a renewable energy base of 54.2 GW (Lee, 2020). Successful achievement of the policy targets could improve Korea’s energy security conditions, deliver substantial job creation, and could significantly contribute to lowering the country’s GHG emissions (Hong et al., 2019; Park et al., 2013).

Korea’s metropolitan regions are expected to play a major role in the achievement of these targets (Lee & Kim, 2016; Mah, 2019; Park, 2017; Wolfram, 2019). This contribution will rely, in large part, on the transformation of the urban energy metabolism of Korea’s cities. Currently, ex-urban sources drive the urban energy metabolism, establishing a remote relationship between a city’s activities and its energy consumption (Byrne & Taminiau, 2018). This

FIGURE 1 Centralized energy infrastructure overview of Korea, emphasizing the connection between large energy infrastructure and dense urban areas. Large-scale energy infrastructure, in the form of thermal power and nuclear facilities in excess of 500 MW, are connected to dense urban areas (in red) through a network of transmission lines

Source: Population data from National Geographic Information Institute (NGII) National Atlas (2017), power plant data from Electric Power Statistics Information System (EPSIS) (2020) and geocoded using Google Geocoding API, and transmission line data from OpenStreetMap (OSM, 2020) and OpenInfraMap (OIM, 2020)
dynamic is especially visible in South Korea where, geographically, the large electricity generation facilities are predominantly located along the country’s coastlines and the electric grid is tasked with transmission of electricity to inland population and load centers (Figure 1). Large load centers like Seoul and Daejeon consumed 47,810 GWh and 9649 GWh in 2018 but generated 640.7 GWh and 183.7 GWh within city borders, respectively (Korea Electric Power Corporation [KEPCO], 2020). In other words, these cities achieved annual self-sufficiency rates of less than 2%.

Transformation of the urban metabolism in Korean cities toward reliance on in-city sustainable energy would raise self-sufficiency rates far above current levels of ~1–2%. As a case in point, a study of Seoul established that around 10 GWp of rooftop solar PV could be deployed across the hundreds of thousands of rooftops in the city (Byrne et al., 2015). A PV system of this scale could support ~30% of annual and about 67% of daytime electricity needs in the city (Byrne et al., 2015). Closer evaluation of the Gangnam district in Seoul finds that the area could be home to almost 5 million m² of suitable rooftop space across its 27,000 buildings (Hong et al., 2017; Lee, Hong, Jeong, et al., 2018a; Lee, Hong, Jeong, et al., 2018b). An evaluation of 710 projects of the Korean Local Energy Savings Program (2012–2014) likewise found that cities in Korea could expect energy savings ranging from 18 to 45% with an average 30.5% savings through cost-effective implementation of various energy efficiency interventions (Yoon et al., 2017). Through ambitious local planning for energy autonomy, Seoul achieved energy use reductions of 2 million tons of oil equivalent 6 months ahead of its OLNPP schedule (Cho, 2019). A recently published prototype renewable energy hosting capacity map shows that Seoul, and its surroundings could be home to an estimated 61.7 GW of renewable energy. Daejeon and surrounding areas could host over 10 GW in renewable energy capacity. Likewise, a feasibility study found that the top five most promising cities for solar PV deployment are Andong, Busan, Daegu, Daejeon, and Jinju (Nematollahi & Kim, 2017).

A transformation of this magnitude could address several other system-wide limitations resulting from the spatial mismatch between supply and demand. For instance, the reliance on far-away electricity generation can create vulnerable systems where local failures have region- or country-spanning consequences (Kim et al., 2017). Vulnerabilities in the system can produce significant economic losses when outages are propagated through the network as was evident during sudden country-wide rolling blackouts in 2011 (Kim & Cho, 2017). Further, review of the balance of risk profiles associated with nuclear energy generation and the benefits from such efforts for South Korea underscores a risk displacement from population centers to coastal communities (Lee & Byrne, 2019). Finally, climate risk is exacerbated as urban centers represent outsized shares of national greenhouse gas emissions: Gwangju, Daejeon, Daegu, Busan, and the country’s capital, Seoul, together account for an estimated 56% of the country’s greenhouse gas emissions (Moran et al., 2018). Concerted effort by local governments can, therefore, address several critical deficiencies of modern centralized systems, contribute to local, regional, national and global policy commitments, and create a more equitable, sustainable, self-sufficient, and resilient energy system in the process.

### 4 | CITYWIDE ENERGY PLANNING AND VISUALIZATION

The City of Daejeon, South Korea is located in the center of the country (Figure 1). Aggregate statistics collected by the Korean Ministry of Land, Infrastructure and Transport (MOLIT) Green Architecture Portal show that the City of Daejeon consumed approximately 9.7 billion kilowatt-hour (kWh) of electricity, 30 billion megajoule (MJ) in city gas, and 616 megacalories (Mcal) in district heating in 2018 (MOLIT, 2018). At a self-sufficiency rate of less than 2%, very little of the electricity demand is procured from within city boundaries. Among prominent users of electricity in Daejeon are single family residential houses, industrial factories, and educational research institutes - each of these consume over 1 billion kWh per year and are together responsible for about 1/3 of the city’s electricity consumption (MOLIT, 2018). The City of Daejeon has a population of about 1.5 million people and the city’s ~147,000 buildings are concentrated in the center of the city, with several extensions including to the north, northwest, and south.

Daejeon offers a good opportunity to assess the potential impact and energy planning visualization of an integrated “solar city” and “savings city” approach. Daejeon is similar in size and consumption to several other Korean cities and around the world. For instance, Daejeon’s consumption level is about equal to Gwanju (8.8 billion kWh in 2018), Jeju (~5.3), and Sejong (~3.1) (MOLIT, 2018). Findings extracted for Daejeon, as such, can be expected to be relevant for several other cities both in Korea as well as internationally. The local government of Daejeon has introduced policies with the aim to reduce the negative consequences of its energy consumption. For example, the city plans to increase the use of solar PV within city boundaries (Kim et al., 2019). One of these policy efforts was the publication of a solar energy estimator, the so-called Solar Estimator for Daejeon or SEED (Kim et al., 2019). The effort showcased that
Daejeon could be home to a substantial solar PV potential but highlighted that additional research was necessary (Kim et al., 2019). Similarly, work by Koo et al. (2014) estimates that 72.38% of the electricity consumption of the 141 elementary schools, 86 middle schools, and 49 high schools evaluated can be offset by rooftop PV system deployment. In addition, the city has pursued innovative solutions and a recent ranking of “smart cities” placed Daejeon in eighth place out of 152 Korean cities tested (Lim et al., 2019). Finally, as given in Figure 1, the city is far removed from large-scale energy generation infrastructure, exacerbating the challenges discussed so far.

4.1 | Daejeon’s electricity consumption profile

To estimate the transformative potential of the urban energy metabolism for the City of Daejeon, it is first necessary to develop a geospatial accounting of electricity consumption. To parse out these profiles, urban building energy modeling efforts have relied on broad data inputs ranging from geometric depictions of buildings and neighborhoods to microclimatic data patterns, building codes, energy disclosures, utility billing data, and many more (e.g., Howard et al., 2012; Kontokosta & Tull, 2017; Reinhart & Cerezo Davila, 2016; Shahrokhni et al., 2014). Overviews of solar PV and energy efficiency potential are commonly structured along administrative city divisions, indicating the energy opportunity for instance at the zip-code or district-wide level (e.g., Howard et al., 2012; Taminiau & Byrne, 2020).

One way to facilitate the integration of energy efficiency and rooftop PV potentials is to extract a geospatial profile of the city through geometric division of the city in strategic and manageable units for program development that are independent from administrative, topological, historical, or other boundaries. To illustrate the benefit of independent,
equal-area units for program development, consider that administrative organization in Korea recognizes a broad range of administrative levels, dividing a city like Daejeon based on cultural, historical, topological, administrative, legal, and economic patterns that can be confusing and provide limited insight into the actual sustainable energy profile and opportunity throughout the city. For example, administrative levels include “gus” (i.e., districts), “administrative dongs,” and “legal dongs” that have overlapping and intersecting boundaries with differing authorities.5

Here, the City of Daejeon is divided into equal-area geometric divisions by means of “fishnet” overlay. For each cell of the “fishnet,” the annual electricity consumption pattern is estimated (Figure 2). The outer municipal boundary as well as the five districts are illustrated in Figure 2 for context as well. The assessment shows that Daejeon is home to a downtown area of high annual electricity consumption while outside areas of the city are much less densely populated and consume considerably less electricity per year. The three smaller subplots on the right of the main map in Figure 2 clearly outline this effect: the 274 “fishnet” cells of the city are divided into three main categories of consumption. First, there are 26 cells, each 2 km² in size, that see annual electricity consumption in excess of 125 GWh/year and another 42 cells that have annual electricity consumption ranging between 50 and 125 GWh/year. The remaining area of the city, constituting of 206 cells, each consume less than 50 GWh per year.

The estimated geospatial electricity consumption pattern illustrated in Figure 2 is the result of a regression-based extrapolation of a building electricity consumption sample for the entire year of 2018. This sample covers 33,895 separate buildings in the city and consists of a total of 356,367 observations of monthly electricity consumption. In other words, the sample covers approximately 23% of the city’s buildings. High resolution light detection and ranging (LIDAR) data, consisting of over 2 billion data points and covering the entire city, was used to construct a three-dimensional model of the built environment of Daejeon. From the 3D model, the physical attributes of each building in...
the city are extracted (building height, shape, size, vertex count, internal volume, surface area, and surface area to volume ratio). Existing geographic information system (GIS) files detail several other relevant building-level attributes such as building age, use case, location, and underground floor count. The electricity consumption sample data is used to establish a relationship between these attributes and the electricity consumption pattern. For similar applications of the regression analysis performed here, see Kontokosta and Tull (2017) and Mastrucci et al. (2014). The assessment estimates citywide electricity consumption from the built environment at 9.4 billion kWh in 2018, within 2% of available aggregate statistics.

4.2 Daejeon as a “savings city”

Previous research efforts indicate cities could expect citywide electricity consumption reductions ranging from 20 to 40% when energy efficiency interventions are deployed at scale (Shahrokni et al., 2014; Pasichnyi et al., 2019; Chen et al., 2017; Mastrucci et al., 2014; Tong et al., 2016; Wilson et al., 2017). For instance, calculation of residential retrofits along the US single-family housing stock finds that this sector can develop at least 245 terawatt-hours (TWh) of energy savings per year, equivalent to 22% of electricity used by the single-family detached housing stock in 2012 (Wilson et al., 2017). Similarly, Shahrokni et al. (2014) find that the city of Stockholm, Sweden can achieve a 33% electricity use reduction if broad-based savings measures are introduced. Analysis of cost-effective interventions in Korea found average energy use reduction of 30.5% (Yoon et al., 2017). When applied as an infrastructure-scale solution, economies of scale and integrated deployment of interventions are likely to achieve higher electricity savings. Literature on so-called...
Deep retrofits suggests that broad-based efficiency interventions can achieve savings in excess of 50% relative to preretrofit consumption profiles (e.g., Carmichael & Gartman, 2015).

The energy planning strategy proposed here separates the city of Daejeon into equal-area cells of 2 km², each cell containing a mixture of different building types and use cases. To estimate the performance of a strategic citywide intervention that is organized as an infrastructure-scale program, electricity consumption reductions of 30% in each cell of the city are considered achievable. The spatial assessment of energy efficiency, as illustrated in Figure 3, provides insight into potential energy planning strategies. For example, those areas of the city where annual electricity consumption can be reduced below preset threshold levels can be prioritized for first-stage program intervention. Similarly, a portfolio of intervention programs, targeting a mixture of different areas of the city could be established, where achieved energy savings are used to support the roll-out of the program. Additional layers of information, such as data on grid constraints and capacity, could be employed to facilitate portfolio development.

The preretrofit profile of a high-intensity city center begins to dissipate after a citywide deployment of high-efficiency equipment as only 12 fishnet cells, with annual consumption in excess of 125 GWh remain (Figure 3). Likewise, only 38 cells are expected to reach annual electricity consumption levels ranging from 50 to 125 GWh.

4.3 Daejeon as a “solar city”

Using accepted “solar city” methods (see, e.g., Gagnon et al., 2016; Margolis et al., 2017; Taminiau & Byrne, 2020), the available high-resolution LIDAR data was used to estimate the city’s rooftop solar potential. For each building in the city, the analysis method identifies possible constraints on rooftop PV deployment due to shading and the rooftops’ morphological
The analysis identifies just under 14.8 million m$^2$ of potentially suitable rooftop space. Combined, this rooftop asset spread out over the city's ~147,000 buildings is equivalent to almost 2.3 GWp of rooftop capacity.

The rooftop profile of the city consists of approximately 8.6 million m$^2$ of flat rooftop space and about 1–1.5 million m$^2$ for each of the considered orientations of west, southwest, south, southeast, and east. Using this profile, the electricity generation potential from the combination of rooftop slope and orientation is calculated by grouping slope categories (see Gagnon et al. (2016) and Margolis et al. (2017)). The annual electricity generation opportunity per rooftop segment is calculated using the US National Renewable Energy Laboratory (NREL) System Advisor Model (SAM). A module power density of 200 Wp/m$^2$ is used. The result is that a Daejeon solar city could expect about 2.3 billion kWh per year from a citywide deployment of rooftop PV. For comparison, as of 2019, Daejeon is currently home to 30,570 kW of solar PV capacity, generating 32.2 million kWh in 2019 (KEPCO, 2020).

Combining the spatial overview of Figure 3 with a spatial layout of rooftop solar electricity generation illustrates the integrated contribution of a “savings + solar city” (Figure 4). The overview in Figure 4 shows that almost no high-intensity electricity consumption areas remain in the city: only two communities would continue to see annual consumption in excess of 125 GWh. Twenty-five communities in Daejeon would remain in the 50–125 GWh group. Critically, the combined application of savings technology and on-site generation technology transforms several communities in the city to “net-plus communities” where their annual electricity consumption is less than the savings and electricity generation these communities could offer: 17 communities could become net contributors of electricity to the rest of the city on an annual basis.

4.4 | Daejeon as a “sustainable city”

As the analysis reveals, Daejeon could cover ~56% of annual energy services with PV and energy efficiency with portions of the city becoming “net-plus” communities, delivering more electricity on an annual basis than they consume. In other words, more than half of the city's energy needs can be covered through the deployment of citywide sustainable energy using currently available technology. The 56% self-sufficiency rate is substantially above Daejeon's current achievements of less than 2%. In essence, the integrated application of “savings city” and “solar city” concepts to Daejeon produces an urban energy metabolism of a “sustainable city.”

Figure 5 shows that the integration of these concepts empower many communities in the city to obtain a majority of their electricity service needs through on-site generation and a more efficient use of electricity. For instance, by count, 118 communities in Daejeon could expect to cover more than 60% of their annual electricity service needs through the combined use of rooftop solar PV and high-efficiency end-use equipment. There are an estimated 40 communities in the city that could expect as much as 80% of their annual service needs to be covered. Higher levels of self-sufficiency are achieved when considering monthly or hourly rates due to the temporal pattern of electricity needs and solar electricity generation. The combined deployment of energy efficiency and rooftop PV would create many surplus hours where the community generates electricity in excess of its electricity needs and can, where grid conditions allow, export the surplus to other parts of the city (e.g., Taminiau & Byrne, 2020). Deployment of additional technologies, such as citywide energy storage options or electrification of mobility, could complement the implementation of a Daejeon “sustainable city.”

The findings provide practical sustainable energy planning guidance. In particular, positioned as a “back-end” planning tool, the findings enable decision-makers to consider the citywide picture. Community level performance and potential as uncovered by the visualization enables prioritization and grouping based on city-articulated objectives. As a case in point, Daejeon could organize aggregated tranches of sustainable energy deployment in series where each deployment targets a collection of communities (captured as “cells” in the visualization) and elevates the self-sufficiency of those communities. Inclusion of cells in early tranches for transition management can, for instance, be structured around the achievement of “net-plus” communities – the benefits of surplus energy generation in these communities can support further roll-out of subsequent tranches.

5 | URBAN TRANSFORMATION TOWARD “SUSTAINABLE CITIES”

The Korean national government expects to add ~49 GW of new renewable energy generating capacity, with plans to have about 63% of this increase to be delivered by greater use of PV technology. The analysis results for Daejeon show
that policy- and decision-makers can pursue these ambitious policy objectives through a strategic and concentrated effort at reforming the urban energy metabolism of the country’s cities. Cities like Daejeon could deliver valuable contributions to local, national, and global energy and climate policy objectives. Energy planning of this kind could accelerate the achievement of national strategies like Korea’s 3020 renewable energy plan. As a case in point, the rooftop solar PV estimate of over 2 GWp could deliver about 26% of Daejeon’s electricity per year, well above the 20% objective stated in the national policy. In combination with energy efficiency, 56% of the city’s annual electricity service needs can be covered.

A main contribution of this paper is to consider the geometric accounting of urban sustainable energy potential as it enables geospatial energy profiling and subsequent establishment of strategic and manageable units for program development. City decision-makers can determine areas ready for transition to “net-zero” or “net-plus” communities through this accounting strategy and resources can be allocated based on these insights. Operated as a “back-end” tool by the city planning and energy departments, the serial, strategic, and integrated application of citywide programs of this kind can deliver these benefits for decades to come. Moreover, additional layers can be added to strengthen the proposed tool. Other technologies, like sustainable (micro-)mobility, canopy solar, building-integrated PV (BIPV) and others are not accounted for in the visualization. Additionally, analysis efforts could focus on adding grid-level conditions through, for instance, “hosting capacity” maps—databases showing locations in the city most available for hosting additional renewable energy generation. Practical implementation of the potential could likewise take into account local conditions such as distributions of socioeconomic position. For example, the evaluation shows that outer areas of the city, which are areas of relatively low electricity consumption could, through the combined deployment of energy efficiency and rooftop solar PV, essentially become “net-plus” communities where close to or more than 100% of energy services and needs can be served with sustainable energy. Such an intervention could substantially advance local quality of life while contributing to the City’s overall energy autonomy and low-carbon future.

The transformation is more than “just” bringing energy generation closer to the city. The fundamental reshaping of currently distant and unequal city-energy relationships toward local and community-appropriate interactions transforms the city-energy relationship itself. Material energy and environmental justice improvements can accompany this transformation. As a case in point, “solar city” and “savings city” deployment can lead to a combined capture of transformative-level and individual-level change: the modularity and building-level application of both rooftop solar PV and building energy efficiency can help pursue “deep decarbonization” at the infrastructure-scale while retaining the advantages and benefits associated with decentralization of energy supply, including energy security, avoidance of transmission losses, alignment with end-user energy needs, community control, and others (Byrne & Taminiau, 2018). These policy strategies can, in addition, operate for the benefit of a wider public. Efforts to reduce energy consumption and generate electricity on-site lowers risk displacement resulting from centralized power plants, improves resiliency, and enhances local air quality. For example, citywide energy efficiency could help lower electricity demand across the year and rooftop solar PV could help reduce peak demand challenges during summer months. The accounting of sustainable energy potential at community levels (visualized in the proposed tool as “fishnet cells”) enables community-level pursuit of energy futures, consistent with energy and environmental justice principles of self-governance and authorship.

There are 1065 cities in the world with a population between 500,000 and 5 million people (UN, 2016). Together, these cities represent 1.34 billion people, equal to approximately 17.5% of the world’s population (UN, 2016). These cities, like the case study of Daejeon illustrates, could establish substantially different urban energy metabolisms through the integrated application of sustainable energy technologies at the infrastructure-scale. Integrated application of “solar city” and “saving city” concepts enables extraction of benefits for the end-user, for all city inhabitants, for the surrounding area, and even for global communities through greenhouse gas emission reductions. Essentially, the transformation of the urban energy metabolism that is possible when sustainable energy is positioned as a tool of urban infrastructure, reforms the concept of urban sustainability and the lived experience of “the sustainable city.”

CONFLICT OF INTEREST
The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS
Job Taminiau: Formal analysis; methodology; software; visualization; writing-original draft; writing-review and editing. John Byrne: Conceptualization; formal analysis; investigation; project administration; supervision;
visualization; writing-review and editing. **Jongkyu Kim:** Data curation; funding acquisition; investigation; project administration; resources; supervision. **Min-Hwi Kim:** Data curation; software. **Seo Jeongseok:** Data curation; resources.

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**ENDNOTES**

1. The 1965 introduction of the “urban metabolism” innovation by Abel Wolman conceptualizes monitoring of inflow and outflow rates of urban resources to, among others, identify system-wide impacts of consumption and production within the urban environment (Wolman, 1965). Helpful definition of the idea is provided by Kennedy et al. (2007): “the sum total of the technical and socioeconomic process that occur in cities, resulting in growth, production of energy and elimination of waste.” A recent bibliometric study of the field finds that research should now focus on (a) the inclusion of both spatial and temporal dimensions of energy metabolic systems and (b) the provision of tools and insights that help describe the interactions of the metabolism in a dynamic manner (Tang et al., 2021). The tool introduced in this article is cognizant of this proposed direction as it enables spatial and temporal distinction of sustainable energy options and allows for trade-offs and dynamic system-wide considerations.

2. The potential of cities to become sustainable energy leaders is not limited to citywide rooftop PV and energy efficiency. As a case in point, Kobashi et al. (2020) review the implications for sustainable mobility in connection with citywide rooftop solar PV.

3. Continued advancement in measurement capability and use of different techniques will produce assessments of increasing fidelity. To illustrate, Nelson and Grubesic (2020) review the relative accuracy of high-resolution LIDAR captures to those obtained via unmanned aerial vehicle (UAV), showing that improvements in accuracy are possible with recent advancements in technology.

4. These 1 GW renewable energy plans implement the concept of the “solar city” that traces back to at least the late 1970s when US Department of Energy (DOE) Office of Scientific and Technical Information (OSTI) researchers envisioned a hypothetical city in the year 2025 and reviewed a possible energy future of maximum in-city use of solar technologies (Milne et al., 1979; Ritschard, 1979).

5. For a detailed ontology model that enables semantic expression of the administrative districts that are commonly used in publicly available data of Korea, see Kim (2018).

6. No consideration of ground-mount, building integrated PV (BIPV) or canopy solar is included in this assessment.

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