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Abstract

As with urban planning, which promotes fair access to fresh air, sunlight, and water for buildings through policies, zoning regulations, and building codes, renewable-energy-dependent buildings also require equitable access to renewable energy sources such as solar or geothermal energy. Achieving this requires the development of an integrated planning framework that can ensure equitable access to these resources. To this end, we propose an extension to the Infomorphism framework, which optimizes urban local energy networks to enable the exchange and sharing of renewable energy resources among buildings. This paper demonstrates how the extended Infomorphism framework can be used to explore potential planning policies aimed at providing equitable access to local renewable energy for buildings. Specifically, it was found that the ability to rezone as well as the ability to change the Floor Area Ratio (FAR) of building blocks in an urban fabric can reduce the levelized energy cost and increase renewable energy integration while maintaining common access to it.

Highlights

• Managing renewable energy as common-pool resources
• Evaluating zoning regulations with equitable renewable access
• Establishing renewable energy rights for cities
• Maximizing cities’ local renewable production and utilization

Introduction

Throughout history, architects, designers, and planners have sought to envision the future city. This process has always been influenced by people’s perceptions of their environment and assumptions regarding emerging technologies, which for them always had a significant impact on how we live and how society will evolve. As a result, future city scenarios were often shaped by these assumptions and the potential implications of new technologies. Technological advancements have been a key factor in shaping the discussion around the future of cities, continuously pushing the boundaries of theory and redefining what we envision for urban scenarios. Looking back at history, we can see examples of this in Georges-Eugène Haussmann’s renovation of the Paris plan between 1853-1870 (Moncan, 2019, p10-40) and the Electronic Urbanism proposed by the Greek architect Takis Zenetos Charitonidou (2021), both of which introduced new technological drivers (sanitation movement and communication technology, respectively) to create a new form for the city. In hypothetical city projects proposed by Archigram (Sadler, 2005, p161), the focus shifted from geometry and materiality to the topological information networks associated with urban events and their intersection with socio-spatial urban contexts Shepard (2011). These examples demonstrate the significant impact that technology has had on urban development and how it has challenged traditional notions of what a city can be.

All of the above examples imply that there are always dynamic relationships between technology development and new urban morphology. Today, given emerging technologies, such as Artificial Intelligence, Ubiquitous Computing, micro-grids, or Autonomous vehicles, the fundamental question to ask is still, how can these technologies affect the future status of a city? In the meantime, with the increasing awareness of global climate change and population growth as well as the impending urban sprawl, envisioning a future status of a city that has high energy efficiency among buildings and can accommodate the increasing population is imminent. In the context of urban planning, it is crucial to recognize the current limitations in considering Variable Renewable Energy (VRE) and Distributed Energy Resources (DER) as firm resources in the system planning process. The existing planning models and tools fail to accurately incorporate the intricate operational parameters and capabilities of these new technologies. However, as VRE and DER increasingly take center stage as generation sources in the power grid, it becomes imperative to undertake substantial changes in the system planning processes. Aligning urban planning strategies with the integration of VRE and other distributed energy resources will be vital to optimize their contributions and fully leverage their potential in building sustainable and resilient cities. In this case, renewable integration at the urban level becomes an inevitable process as part of city development in the future.

Designing a renewable-based city that fully integrates renewable energy sources is a complex challenge that requires a systems-level approach. Every aspect of the urban environment, from building envelope design to zon-
ing regulations, must be optimized to ensure optimal renewable energy integration. This, in turn, requires a deep understanding of the different renewable energy resources available and the rights to use them. Today, many renewable energy resources can be transformed into different forms of energy and managed at the grid level using various building-integrated technologies. However, in a future scenario, if renewable energy resources can be accessed and transformed locally within a city, it will challenge the fundamental principles of organizing these resources. This shift in paradigm towards renewable integration technologies will require a re-examination of how we organize, manage, and distribute these resources.

The specific technology that we are addressing with the infomorphism framework is the Zero Energy Buildings (ZEBs) technology (Derkenbaeva et al. (2022)). Unlike traditional "green" buildings that rely on independent passive systems, ZEBs integrate control and management systems to optimize energy efficiency through interaction with the building’s immediate environment. ZEBs make buildings more independent and detach them from the central energy grid by utilizing renewable energy resources such as solar, geothermal, or wind energy.

A specific characteristic of ZEBs is that, renewable energy resources when harvested, could be stored and eventually shared with other buildings in a selected community. In other words, ZEB technology transforms renewable energy into a common resource, shared by many within the same broader neighborhood or community. Organizing renewable energy as a common-pool resource, similar to all other natural resources used by different individuals in common, requires an intellectual framework to systematically understand the issues and bases of their governing process, which is known as governing the commons (Ostrom (1990)).

In an ideal scenario where there are no restrictions on the use of renewables, the corresponding common resources will eventually be depleted due to the increasing demand from each individual user or participant. This phenomenon, known as the "tragedy of the commons" (Hardin (1968)), has been discussed by Garrett Hardin. In this scenario, participants with access to a public resource act in their own interest and ultimately deplete the resource without bearing the full costs of their actions. Instead, the costs of overuse or depletion are spread among all participants of the resource and society as a whole. This can lead to a situation where everyone tries to extract as much benefit as possible from the resource, resulting in its degradation or exhaustion. With this critical dimension under consideration, a careful planning of ZEB buildings and neighborhoods becomes a new vehicle and offers insight into urban renewable integration strategies and the fundamental principles of renewable management.

To avoid such "tragedy" situations, a comprehensive strategic planning approach is necessary, which includes policy incentives, public engagement, infrastructure investment, and technological development. For instance, Elinor Ostrom, a political scientist and Nobel Prize winner in Economics in 2009, studied the governance of common-pool resources and highlighted the significance of developing or upgrading rules and regulations at the community level. Her work suggests that common-pool resources, like renewable energy resources, can be managed sustainably without resorting to state control or privatization (Ostrom (1990)). By cooperating and creating rules that regulate the use of the common resource, individuals can prevent the "tragedy of the commons" and ensure the resource is used sustainably for all.

From an urban planning perspective, the principles and rules for governing the commons can be translated into computational tools to help allocate and manage resources in an optimized format. One example is the Infomorphism computational urban planning framework (Li et al. (2022)), which explores how cities can detach from the grid and use local renewable energy to address the challenges of global climate change, population growth, and increasing energy demand. Infomorphism uses ZEBs as the main drivers to envision a future city scenario where renewable energy resources such as solar and geothermal energy belong to everyone. The ZEBs are designed to metabolize renewable energy locally, communicate with neighborhoods, and interact with the central grid to ensure equitable access to renewable energy resources.

Within the Infomorphism framework, each urban block with a maximum allowable built volume is considered a basic unit called an Energy Parcel (EP) (Li et al. (2022)). When EPs share accessible renewable energy resources as a collective, they form an Energy Parcel Neighborhood (EPN) (Li et al. (2022)). The Infomorphism framework aims to establish a local energy exchange network that connects all EPs and enables equitable sharing of renewable energy, such as solar and geothermal energy, within an EPN. These EPs are linked through an energy exchange infrastructure, such as a local electric grid or district heat network, allowing each EP to access renewable energy based on equitable network availability.

The integration of renewable energy into urban planning requires the consideration of a complex set of policies and regulations to govern the commons. When considering EPs as basic units for an urban network, it is necessary to introduce a fundamental "right to renewable energy access" into the framework, similar to how urban planning ensures equitable access to fresh air, sunlight, or water through policies and regulations. This right would entail zoning regulations for the installation of renewable energy systems, the types of systems allowed, and the necessary height and setback requirements to minimize their impact on surrounding properties. These planning changes can also promote the deployment of distributed energy systems like rooftop solar or geothermal systems, which can increase the resilience of the central electric grid. The framework design principle suggests a new urban scenario where basic social contracts and relationships between resources and participant accessibility have been redefined.
through network chaining.

Contribution

In this paper, we build upon the Infomorphism framework by placing a strong emphasis on renewables as common-pool resources and renewable energy access as a fundamental right, making them the driving force behind urban design and city development. Our focus is on analyzing rezoning policies that impact urban morphology, including changing energy demand and assigning potential Floor-Area-Ratio (FAR) values for selected urban blocks. By doing so, we are able to gain insights into how current zoning regulations affect renewable energy accessibility and how we can improve these regulations to optimize the renewable capacity of an EPN while ensuring equitable access to renewables. Through our analysis, we contribute to the understanding of how urban planning policies and regulations can be improved to create more sustainable and equitable communities.

Methodology

We used network optimization to generate optimized network connections from the initial street network paths. More specifically, two distinct networks, one for electricity and one for heat, align with the street network. The local energy exchange network is defined as a district-level system utilizing water pipes for heat exchange and cables for electricity transmission. Solar energy captured during the quantification process is converted into electricity and heat. Geothermal energy integration within an EPN serves as a decision variable in the optimization model. The existing street grid configuration is also utilized as input for the optimization model, which generates optimal energy exchange network patterns. Each EP is connected to a district energy exchange network based on the street grid. By treating EPs as dual supply and demand nodes and utilizing street intersections as transition nodes, the framework promotes efficient energy exchange within local networks. The network optimization model aims to minimize grid dependence and reduce overall renewable energy costs. Further details and insights can be found in (Li et al. (2022)). The primary objective behind the development of local energy exchange networks is to establish a common-pool energy resource, where renewable energy is dynamically distributed throughout the network and made accessible to all energy participants (EPs).

There are several principles that can be applied to ensure equity in an energy exchange network. Each node in this network has the choice to either prioritize the utilization of its stored energy or contribute the energy it has stored to the common resource pool or back to the network. The first option leads to nodes becoming greedy as they prioritize their own energy needs, while the second option encourages nodes to be generous by prioritizing the contribution of energy to the shared resource pool. This classification, whether a node is greedy or generous, significantly impacts the overall objective of the network. In this study, each EP does not have a connection path to itself, and it is therefore designated to become a generous node re-directing all available renewable energy metabolized from the urban envelope to the common network of available energy.

The renewable energy "floating" in the network becomes a common-pool energy resource that is shared with all the EPs. After announcing the demands from each different EP at specific time periods, each EP will start to request a certain amount of energy from the common pool based on network connection availability. We prioritized the local energy exchange networks as an equitable platform to allow network participants to fully meet their energy demand requests, rather than prioritizing individual demand requests. As a result, possible supply nodes based on the optimization rules will be activated to create energy flows forming energy exchange patterns. The exchange process will be terminated until the demands have been fulfilled, and optimized energy network graphs will emerge from the street network.

Data Explanation

This paper presents two scenarios that investigate the relationship between equitable access to renewable energy resources and urban zoning regulations. In scenario A, we rezoned certain districts of Manhattan to vary energy demand and generated 356 EPNs based on the parametric translation of zoning regulations. However, the function of each EP could change from one land use class to another, including commercial, residential, manufacturing, and public space. For instance, if buildings in an urban block changed from commercial to residential or mixed-use types, the energy demand would change due to the different patterns of building energy use. Therefore, the algorithm maintained the same total demand for an EPN generation while randomly changing the energy demand distribution.

For scenario B, we generated 180 EPNs with a random FAR distribution based on new FAR lists for EPs generated by the equations described in Equation 1 - Equation 4. The total percentages of land use classes remained the same, but the neighborhood no longer followed Manhattan’s current zoning regulations. The first 100 EPNs’ allowed floor area was constrained based on the high-performance EPN in the previous Infomorphism results (Li et al. (2022)), which had $3.70 \times 10^6$ m$^2$ total floor area. However, the generated EPs’ total floor area may fluctuate by approximately 15%, even though the total allowed built space was constrained by the equations 1 - 4. Therefore, the total generated floor area may not be the same as that of the high-performance EPN. We also generated 80 EPNs without area constraints to validate the effectiveness of the optimization model in handling uncertain or random inputs. The purpose of developing the last two datasets for the optimization model is to compare whether the renewable energy penetration rate and the total levelized energy cost can be lower than the previous best performance EPN generation with the same allowed built space limitation under accepted fluctuation, even if the generated EPN has
larger floor areas than the most efficient one in the previous Infomorphism results (Li et al. (2022)).

**Mathematical Explanation**

\[
\sum_{k \in K, t \in T} ypf_{k,t} = \sum_{k \in K} pArea_k \forall k \in K, \tag{1}
\]

\[
\sum_{t \in T} ypf_{k,t} \div p_f k \leq p_f AR_k \forall k \in K \forall t \in T, \tag{2}
\]

\[
\sum_{t \in T} (ypf_{k,t})(p_f AR_{ML,k}) = 1 \forall k \in K \tag{3}
\]

\[
ypf_{k,t} \geq 0 \tag{4}
\]

where:

- \( p_f AR_k \): FAR constraint for parcel \( k \)
- \( p_f AR_{ML,k} \): Adjacency matrix of allowed land use class for parcel \( k \) with type \( t \)
- \( ypf_{k,t} \): parcel \( k \)'s assigned floor area with land use type \( t \) [m\(^2\)]
- \( pArea_k \): input floor area of parcel \( k \) with land use type \( t \)

Equation 1 guarantees that the maximum floor area allowed for an EPN with a random FAR distribution is equivalent to that based on current zoning regulations. This equation implies that the newly generated EPN can accommodate almost the same amount of population and basic operations as the district function of the areas in a city. Equation 2 ensures that the randomly generated FAR list is limited based on the original parcel’s footprint. Equation 3 assigns a type \( t \) to each parcel \( k \) based on the allowed parcel type matrix for all the parcel \( k \). Equation 4 satisfies non-negativity constraints for decision variables. From an urban planning perspective, these equations ensure that the newly generated EPNs comply with the previous data descriptions and are feasible for implementation.

**Results and Discussion**

The optimization model generated results for various datasets, which were documented in Excel spreadsheets along with the corresponding EPN names. The output data was organized in ascending order based on the total levelized energy cost, and the spreadsheets included ranking lists that highlighted the most efficient EPNs with the lowest levelized energy cost. To assess the impact of specific urban planning policies on the network’s performance in terms of renewable integration rate and levelized energy demand, we conducted a comparative analysis (see Table 1) between the results of the current paper and those of a previous result (Li et al. (2022)).

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<tr>
<th>Case Study A: Manhattan Rezoning: Changing Function without Changing FAR (122-Parcels)</th>
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<tr>
<td>For the first EPN dataset A, the optimization model suggested that the generation with the highest local renewable energy efficiency achieved 78.2% of the total energy demand from solar and geothermal energy combined. For a predicted energy demand of 2,062,515,828.5 kBtu per year in the high-performance EPN, the optimization model suggested 36.0% from solar energy and 42.2% from 49 geothermal heat pumps at designated locations. 1,295,391,444.9 flows of energy were exchanged via the heating network, 767,124,383.6 flows of energy were exchanged via the electric network. The total levelized energy cost for this EPN was $44,806,738.57.</td>
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**Case Study B: Manhattan Rezoning: Changing FAR and Function (122-Parcels)**

For the last EPN dataset B, by looking into the optimal results, “EPN_Generation_12” had a slightly higher floor area (3.72 \( \times \) 10\(^6\) m\(^2\)) than the high-performance EPN. However, the total energy cost was $44,619,367.6, which was lower than the optimal number $45,427,016.89 in the previous result (Li et al. (2022)). For a predicted energy demand of 2,040,683,102.5 kBtu per year in this EPN, the optimization model suggested 35.6% from solar energy and 41.0% from 47 geothermal heat pumps at designated locations. 1,251,856,438.0 flows of energy were exchanged via the heating network, 788,826,664.5 flows of energy were exchanged via the electric network. This result implies the selected city’s overall capacity to absorb renewable energy can still be optimized by changing EPs’ FAR at the planning level. The other 80 fully random-generated EPN datasets were also performed through the optimization model for validating the effectiveness of the model. The optimal result
based on the optimization model showed that with a predicted energy demand of 1,202,863,378.7 kBTu per year, the optimization model suggested 39.4% from solar energy and 41.7% from 45 geothermal heat pumps at designated locations. 773,112,246.3 flows of energy were exchanged via the heating network, 429,751,132.4 flows of energy were exchanged via the electric network. The total levelized energy cost for this EPN was $25,919,707.3.

**Discussion**

The framework presented in this paper evaluates the relationship between specific zoning regulations and the overall energy efficiency of a city with an equitable renewable access setting. The results show that changing certain programs in existing buildings or the land use for urban blocks can result in high renewable energy integration with lower levelized cost.

For example, by comparing the results between Case A and Case B, the results of the first case study showed that local renewable energy from building-level solar and geothermal, shared across an optimal energy exchange network, could supply 78.2% of the total energy demand of the urban form, with the remainder supplied from the centralized power grid. The total levelized cost for this case was $44,806,738.57. Compared to the cost result of $456,494,20.69 with 74.0% renewable integration rate following the existing zoning distribution (Li et al. (2022)), the total renewable energy efficiency increased from 74% to 78.2%.

The decrease in cost indicates that changing certain programs in existing buildings or land use for urban blocks could result in higher renewable energy integration with lower levelized costs. For instance, the EPN Generation 227 performed less efficiently in terms of cost than the most efficient one (EPN Generation 225) in the previous Infomorphism results (Li et al. (2022)). However, the best-performing EPN, EPN Generation 225, was replaced by EPN Generation 227. The improvement in energy efficiency from EPN Generation 227 was due to the changes in demand distribution at the planning level.

The second case study showed that EPN Generation 12, which was generated by maintaining the total percentage for each land use class and randomly assigning a new FAR value to each EP, achieved better energy performance in terms of levelized energy cost in the latest dataset. This finding suggests that rezoning policies that maintain the basic operation of a city, while redistributing building functions, such as converting a commercial building into a mixed-use building with residential units, can increase the overall renewable energy efficiency of a city.

This observation implies that the current renewable energy capacity of a city can be further optimized through policy and regulation, such as by re-distributing the building function through zoning. Rezoning the city to maintain the same capacity for population and basic operation can affect the overall renewable energy efficiency if the total percentages for all land use classes remain the same. For instance, converting manufacturing space into additional commercial units or mixing residential units with commercial buildings can change the renewable energy efficiency of a city.

From a planning perspective, the FAR distribution can significantly impact energy efficiency because it serves as a primary constraint in urban planning, determining the configuration of an EP. Any variations in the EP configuration can create fluctuations in both renewable energy absorption and demand forecasting, making it vital to consider the FAR in the optimization process. However, it is important to note that human interventions and unexpected urban decisions may not always prioritize energy efficiency in the general urban development process. Therefore, rather than providing a definitive conclusion on the perfect FAR distribution for a city, the developed framework aims to create an open workflow for designers and planners to evaluate decisions by prioritizing equitable access to renewable energy as a primary concern for developing cities.

**Conclusion**

The development of local energy exchange networks has expanded the scope of urban planning to include system policies and regulations related to emerging energy rights. The Infomorphism framework’s modules have been developed to create a co-optimization workflow that can be transformed into an industry-standard software or analytical tool for exploring equitable renewable rights. This integrated planning tool can provide design instructions for new developments in a city, and with potential software interfaces being designed in the future, it can be integrated with other tools for transportation, real estate, and other infrastructure system designs.

In conclusion, the Infomorphism framework provides a computational approach to address the challenges of local renewable energy integration in urban areas. It offers a tool for planners and designers to evaluate urban development decisions based on equitable access to renewable energy. This would enable a comprehensive analysis of a city’s energy efficiency and offer insights into resilient urban development.

**References**


Derkenbaeva, E., S. H. Vega, G. J. Hofstede, and E. van...


