DECENTRALISED SOLAR ECONOMY: UNATTENDED AND SMART SOLAR ENERGY URBAN SYSTEM (UNSSEUS)

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Abstract. Planners often go out of the city when planting large-scale solar farms due to requirements for huge, flat surface areas. This reduces urban proximity to renewable energy sources, causing dissipation during energy transfer and a waste in solar energy unused within urban areas. This paper aims at understanding the prospect and challenges in transforming buildings from passively consuming energy to actively generating energy for cities. As every building has a different renewable energy capacity, how may we re-distribute power amongst a network of users, forming a socio-economy around distributed power generation? This paper first presents its theoretical approach learning from fields of biology and information theory as a source of inspiration for its design methodology. It then presents a context study of Hong Kong and its Feed-in Tariff scheme that incentivizes distributed power generation, and identifies the challenges. Afterwards, it defines 'Unattended and Smart Solar Energy Urban System' and proposes the parameters which the system should comprehend on its dashboard for demand-side management of energy. Finally, preliminary results of using a sudoku algorithm in distributing time and pricing factors of energy exchange are presented. This on-going research project aims at SDG goals 7 and 11.

Keywords. Distributed Power Generation; Sudoku Gameplay; Unattended and Smart, Solar Energy; Urban System; SDG 7; SDG 11.

1. Introduction

Distributed generation is 'electrical generation and storage performed by a variety of small, grid-connected or distribution system-connected devices' (VirginiaTech, 2007). In particular, distributed solar power generation may enable individuals to supply and trade energy they harvested locally with photovoltaic (PV) elements. In densely populated urban environments, emerging smart materials such as thin-film and perovskite that are semi-transparent, flexible and economical in construction enables

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light-harvesting on facades and other building surfaces (MacDonald et.al, 2019). With computational advancements in generative and predictive methods, novel networking strategies may enhance efficiency in energy exchanges and self-organisations. Information systems that feedback between a distributed network of users requires the design of mass sensing, actuating, and controlling components - a smart system. This highlights distributed generation not merely as a problem of technical engineering, but also socioeconomic engineering - a decentralised solar economy. This paper aims at discussing the significance of distributed generation in formulating unattended and smart solar energy urban systems (UnSSEUS) .

2. An Info-biological Approach to Solar Design

There is an increasing amount of research that looks at organisms and their interactions with information theory, which enables socio-biological processes to be captured computationally. Krakauer's (2020) Information Theory of Individuality (ITI) and Friston's (2019) Free Energy Principles (FEP) are two leading theories that relate entropy and prediction with scaled self-organisations. In particular, to understand energy exchanges in organisms through how information is acquired, disseminated, and used amongst individuals; this information can be inherited or inferred - from DNA topology to natural languages. The study of ITI and FEP may help us to map the limit to growth, networking between individuals, and a scaled measure of energy sustainability.

These info-biological theories aim at identifying an individual from its environment, providing philosophical and technical approaches towards understanding 'intelligence' (Krakauer, 2020). Within rapid socio-biological exchanges, the boundaries that set one individual apart from another becomes less apparent, where we may have common assumptions on individuality, with diverging views on its definition (Ng, Odaibat, Doria, 2020). When applied in data analysis of a dynamic environment, statistical boundaries may be mapped from input data, with no definite means to setting apart anomalies in a discriminative model. This illustrates why the identification of an individual might be crucial in dealing with mass exchange processes; with which we may begin to gain insights towards how one interacts with another, and how to enhance energy and information exchanges.

ITI and FEP both follow an entropy approach in identifying an individual within a complex system. In FEP, Friston (2019) stated that an individual is one that maintains equilibrium using an internal generative model to predict incoming sensory data and minimise entropy (i.e. surprises or disorder in information) towards its immediate environment - a form of active inference. Thus, intelligence is negentropic (i.e. negative entropy). The measure of entropy change over time within a dynamic system provides us with information towards the future evolution of the system, and act as a guide towards how much available energy a system should have in doing useful work (i.e. second law of thermodynamics)

(Ben-Naim, 2010). In ITI, West and Brown (2005) stated that living organisms tend to minimise energy consumption by a quarter everytime it doubles in size, as the pace of life becomes slower (e.g. lower heart rate) - nonlinear power scaling. Currently, our cities generally consume 15% more energy everytime it doubles in size (West, 2014). The exponential power-scaling of urban organisation in contrast to quarter power-scaling of biological organisation shows us an entropy limit that may help to guide our solar strategies. An entropy limit captures the loss in energy 'over the range of motion of the working body'; meaning, our current urban organisations have to reach a higher level of negentropic capacity (~40%) for it to be efficient within the Earth's energy chains (Krakauer, 2020).

From distributed communication of ants, regulatory systems of cells, to feedback dynamics of neural nets, ITI and FEP define quantitative measures for networking within self-organisations. The study of which may help in tackling scalability issues - efficiency in synchronising information - which defines the limit to growth and resist the tendency to disorder (Friston, 2009). Networks can be captured and described using topologies and simulated through combinatorial games (Xu, 2001). The former is the arrangement of nodes and their connections in a communication network, and may be depicted physically or logically; logical topology determines how data flows in a network using system protocols (Groth & Skandier, 2005; Wynekoop, 2003). The latter is a branch of game theory and theoretical computer science that 'draws tools from combinatorics, algebra and number theory to generate results for itself' (Fraenkel, 1996). This paper will later focus on applying sudoku - a one-player combinatorial puzzle - in simulating energy networking between architectural components.

3. Context Study - Hong Kong

Hong Kong (HK) is one of the most densely populated cities, implying a high level of concentrated energy consumption. In 2019, HK launched a 'Feed-in Tariff' (FiT) scheme, where electricity generated with solar power can be sold back to electricity companies up to 5 times higher than normal electricity tariff rate (HKSAR, 2020). There are many FiT initiatives worldwide, HK's FiT goal is to incentivise private sectors (mainly low-rise buildings like village houses) to install PV systems to compensate for HK's modest renewable energy potential due to natural and geographical constraints.

Table 1: Ballpark parameters of a typical village house in HK for PV systems (HKSAR, 2019)

Number of village houses in HK	~ 30,000
Average roof area	~ 700 square feet
Annual electricity consumption	~ 4560 kW (380 units x 12 months)
Annual electricity generation by PV	~ 7000 kW
PV construction / installation cost	~ HK$210k - 350k
Payback period	~ 4-7 years (based on a FiT rate at HK$5 per kW)

It can be expected that most village houses are likely to generate much more electricity than the household would consume if they fully utilise their rooftops. On the other hand, emerging smart materials may help in utilising building facades and even bringing PV elements to the interior (Papakonstantinou, 2021). This makes the need for a localised energy distribution strategy, where adjacent buildings can collaboratively generate and consume solar power.

4. Unattended and Smart Solar Energy Urban System (UnSSEUS)

Table 2: Objectives for an Unattended and Smart Solar Energy Urban System (UnSSEUS)

Unattended	Any system that can be left unattended for its self-sufficient network that harvest energy from renewable sources; a system that 'intelligently manages energy transfer for perpetual operation without human intervention or servicing' (Jiang, et al., 2005).
Smart	A network of sensing, actuating, and controlling components, 'making decisions based on available data in a predictive and adaptive manner' (Rodrigues, 2020).
Solar Energy	Solar energy is a renewable energy source, generating electricity with PV elements.
Urban	Instead of transporting solar energy from afar locations, more organic designs can help to embed solar devices in urban structures. Also, to prevent the loss of solar energy in cities from direct and indirect sources (e.g. reflections from buildings and reflective surfaces, corners unused, large open spaces at public areas like universities, etc.).
System	A network strategy that does not promote congestion due to differences in protocols and varying development rates across urban fabrics. This would require collaborative dynamics between adjacent buildings, and across various building scales: Micro (building components and their formal organisations) Intermediate (components ensembles into local feedback groups at the building scale) Macro (building and infrastructural populations adapt, change, and grow)

Almost every city has relative proximity to solar energy with potential for decentralisation - light harvested in an area can be localised and used without having to be transmitted back and forth to central power stations (e.g. charging your phone directly from light harvested on a plaza bench). The immediate advantage would be a reduction in energy absorption by the power grid, which is often sustained using fossil fuel, thus becoming environmentally friendly (Miozzo, 2014). Primary batteries 'do not scale up well for long term installations. Instead, energy harvesting methods must be used' (Kimball, et al., 2009). Within rigorous energy and information feedback between a network of buildings, UnSSEUS can help in self-organisation and maintaining equilibrium between different parts and components of the city's power grid - demand-side management (DSM). It is 'the planning, implementation, and monitoring of those utility activities designed to influence customer use of electricity [...] changes in the time pattern and magnitude of a utility's load' (Smith & Parmenter, 2016). Any city-wide DSM would require control rooms that give access to urban data and enable real-time coordination; within which, urban dashboards (UD) gravitate the coordination.

4.1. URBAN DASHBOARD (UD)

UD is a 'visual display of the most important information needed to achieve one or more objectives; consolidated and arranged on a single screen so the information can be monitored at a glance' (Mattern, 2017). UD may assist coordination amongst the following issues:

1. Grid integration - PV devices would be 'built at locations close to the end users to fulfil their own electricity needs, or supplement part of their electricity needs', and 'can be designed either as standalone systems or grid-connected systems' (HKSAR, 2020). UD helps to analyse energy generation data, integrate grids, locally distribute energy, and balance between PV and conventional fossil supplies. Within such 'complex, decentralised systems with bi-directional electricity flow', UD can also help prevent grid congestion between a delivery network of substations, cable, and overhead lines (Mortier, 2020).

2. Weather forecast - Before the rise of smart systems, weather forecasts were based on weather models that do not comprehend microclimatic data which most affect PV performance; HK Observatory (2020) has recently formulated a deep learning model for nowcasting, increasing forecast abilities from a few days up to hours ahead. When paired with diversified PV designs (silicon, dye sensitised, Perovskite, carbon nanotube, etc.) that are good at working under different light conditions, UD can help activate and shut down various PV systems according to forecast data to decrease operational costs and solar power curtailment.

3. Minimise internal system load - Conventional silicon-based PV designs are ideal for the sun's electromagnetic spectrum, especially within the red bands, but they do not work so well on cloudy days (MacDonald, et.al, 2019). To perform sun tracking, they generally have to install motors, which implies an internal system load. UD's ability in coordinating diverse devices working from high to low lighting decreases start / shutdown costs of motors and conventional generators.

4. Local feedback group - Electricity generated from an area is best consumed locally to minimise energy dissipation. This implies grouping problems of how electricity circulates within an area; generation and load data are not static but have a statistical boundary. Bi-directional current helps in formulating an iterative approach to adapt to the everchanging supply and demand. A more organic management system can help in meeting the quarter power scaling goal between local feedback groups to minimise absorption by the power grid.

5. Asset management - Energy leakage and health of devices are important factors that sustain the life cycle of UnSSEUS. Algorithms that 'can learn to distinguish and precisely categorise normal operating data from defined system malfunctions' may be utilised to minimise disruption and lost-production costs for the industry (Mortier, 2020).

6. Intelligent storage - As FiT users can choose between a standalone or grid-connected scheme, UD can help in the management of a network of batteries within standalone systems, where only solar generation data is synchronised without having to connect to the power grid. In prediction of a peak during hours of the day, batteries can be activated quickly to maintain system equilibrium, relieve grid congestion, and reduce back-up use from fossil generators.

7. Policy design - data gathered and analysed provides a good guide during policy design processes. Take FiT as an example, an economy of scale was implied - the more electricity you generate, the cheaper it sells to utility companies. On what

basis do we set these financial standards as incentivisation? What secondary effect would it bring? UD helps in visualising data derivatives to comparatively analyse the effects of different technical tools and financial instruments.

4.2. DEMAND-SIDE MANAGEMENT (DSM)

UD provides centrality to operations, UnSSEUS can be technically distributed but socioeconomically decentralised, supporting a DSM. Within any large-scale information system, data direct and derivatives are useful functions in tackling information overload problems. Data direct can take forms of personalisation, where specific information is directed to users in need, and is a technique that social media use in collaborative filtering of information (Kalinski, 2019). Energy supply and demand can be analysed to tailor more suited energy plans to each individual, exploring new service models (e.g. to-go plans), and users can manage their monthly/weekly consumption under a certain margin. This not only helps users to manage energy use, but also informs them of their consumption. For instance, participating in peak energy hours contribute to larger operational costs and loads in the power grid, if users can be informed, they might wish to turn on their dish washer at other hours to help save energy.

Personalisation may also help local PV devices to manage system 'heating and cooling at the correct times' as part of a regional distribution strategy (Mortier, 2020). As such, it performs two major negentropic functions: minimise disorder in information and reduce internal energy entropy. Prediction-based actions and real-time communication would assist a network of users to make decisions at the appropriate time - design beyond traditional personalisation (suggestions are made after your decision) to hyper-personalisation (suggestions are made before your decision). In this sense, UnSSEUS aims at exploring algorithms that are light-weight to relieve runtime and scalability issues. Attention should also be paid to statistical boundaries with time components. During festive holidays or large-scale international events, hyper-personalisation may coordinate a network of batteries and activate them in advance to relieve consumption from backup energy in diesel generators (Mortier, 2020).

5. Personalised Information Feedback System with Sudoku Gameplay

In applying such research on the building level of architecture, UnSSEUS sought to investigate information feedback strategies to solve energy-sharing problems. Particularly, this test looked into predicting and preempting supply and demand to optimise energy logistic operations. This is a response to the PV units distribution requirements within a building tower context, a thriving green economic sector that can be hindered by traditional energy distribution because it needs responsive measures to manage the scattered and rapid exchanges from PV units to each compartment and interconnected towers. In this context, a prediction algorithm could assist in the negotiation between different actors - a network of users and IoT devices, minimising information entropy and addressing the data overload problem.

The strategy is based on Sudoku, a combinatorial game based on a 9-by-9 grid that can be populated by 9 distinct items (fig. 1). This same grid was used to discretize and encode energy exchanges into an architectural system, each computationally associated with a number from 1 to 9. Our initial experiment was based on a building tower that is equally distributed into 9 units, but such formulation can be altered to adapt to diverse building topologies.

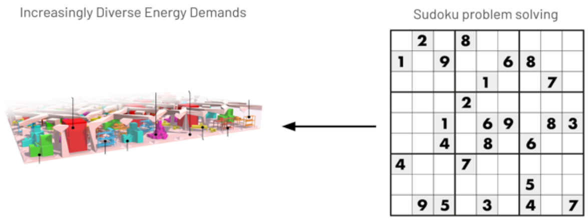

Figure 1. Applying sudoku - a combinatorial game strategy in energy distribution.

The computational game-playing strategy can then be used to solve the organisation of energy by finding optimal solutions for the games that are created and modified through informational feedback. Thereby, the system is able to consider energy as time and pricing factors between the 9 units to define different organisational solutions for different games and states (fig. 2).

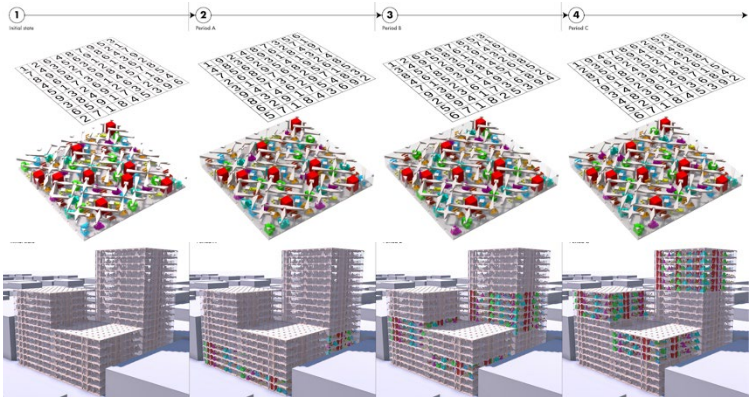

Figure 2. Solar supply and demand data cascade up interconnected buildings using sudoku.

The initial stage sensed changes in energy consumption from the ground floor, Period A redistributed pricing factors between the units on ground floor, which then cascaded up each floor until equilibrium. The state to which each game has been solved is the negentropic stage in the energy system, which feedback to the initial stage. As opposed to identifying users / units that consume the most, the combinatorial game simulates changes in pricing factor, revealing energy demands at different times of the day / year - the events that consume the most. Such awareness may help to prevent energy surge, which is one of the main challenges in renewables. Users can arrange their schedule according to these pricing factors that is determined by the amount of light-harvested during the day and local energy demands.

This has potential to go beyond the 9x9 grid through fractal strategies (fig. 3). It can be applied to a wider spectrum of spatial configuration problems for agility beyond residential contexts, like warehouses, vehicle charging, and office spaces. During times of pandemics, individual work units are constrained by distancing parameters, users can rent units according to changes in schedule by week, and matchmake individual energy consumption to prevent excessive load.

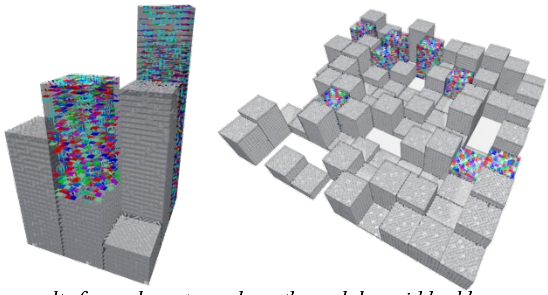

Figure 3. Preliminary results from phase two where the sudoku grid had been expanded to 9x9^10 to accommodate a larger spectrum of urban distribution problems.

6. Discussion

Distributed generation is still being developed and far from being exploited in its full capacity. In the interim, the key is to understand the dynamics of development. How to incentivise participation in public and private sectors? What are the different kinds of participatory models, and how we might visualise the process to communicate progress?

Take HK's FiT program as an example, the paradox lies in the fact that rural areas have larger roof footprint to harvest energy; at the same time, these areas are less developed in infrastructural support. This contributes to grid congestion, where most users are unable to connect to the grid to transmit and share their generated solar power. Inevitably, infrastructural investment is needed, but the immediate return is not apparent enough for businesses, as the area is relatively sparsely populated. To start building up local infrastructure capacities, instead of having every house to connect to the main grid individually, which adds up to a larger cost, smaller local webs may be built between adjacent buildings to exchange with one another and accumulate momentum for the area - a decentralised topology. The energy and information chain can be two separate but parallel chains; energy circulates locally, but they complete their accounting profile using the FiT scheme. Once the regional participation adds up to an incremental level, it can branch out to meet with other regional groups, just as how slime moulds grow, for a more organic development strategy. The immediate advantage is agility and resilience during development stages, but this can only be achieved through standardisation of protocols (i.e. physical/logical topology, soft/hard wares) to ensure compatibility within public-private-partnerships.

Another way to stimulate participation would be to utilise media platforms. AMG (advanced micro grid) 'optimises the bidding of energy assets in wholesale markets using AI software', incorporating an intelligent battery system to automate the trade

(AMS, 2020). For instance, Tesla is developing a real-time trade platform with Hornsdale Power Reserve (HPR) in South Australia adding competition to drive down energy prices. This further illustrates the algorithmic need for personalisation, especially during the development stage, to organically incentivise participation and balancing out energy markets owned by diesel generators with PV systems.

Current PV strategies largely try to come up with a uniformed solution that is scalable in solving energy problems. This is analogical to thinking that a singular cell, if it is to scale, will produce the same ratio of value of effort to result. In reality, most organisms require diverse cells in order to minimise entropy. A biological system is more than a singular organism working independently, but a collective of all organisms that sustain a system to become self-sufficient. This is where our current energy systems fall short because the amount of energy we can produce and our operational costs multiplies simultaneously. This provides a different perspective to our current industrial practises, where the idea of an economy of scale is deeply embedded: the more we produce using the same method the cheaper it is. But it has been forgotten that we live in a complex environment with ever changing solar dynamics. A singular approach to PV will not win over diverse solar vectors, thus, would not result in a solar economy of scale. In contrast, scaling should promote diversity.

7. Conclusion

This paper translates concepts interdisciplinary from engineering to design, including ‘Unattended’, ‘Smart’, ‘Solar Energy’, and ‘Urban System’ (UnSSEUS). It first introduces emerging info-biological theories in complexity sciences with the aim of translating existing models in nature. From these theoretical approaches, this paper exemplifies its arguments with a design research UnSSEUS, and discusses its potentials in implementation by looking at the existing renewable energy challenges in one of the most densely populated cities - Hong Kong.

The study analysed the relationship between a singular unit and its larger structure, considering efficiency not as the amount of energy needed to overcome the disadvantages by scaling a singular solution, but to distribute power generation, and decentralise their exchange and communication, aggregating the effort of the many. The key is designing towards compatibility and standardisation of protocols.

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