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TRANSITION TOWARDS LOW CARBON CITIES USING RENEWABLE AND WASTE-TO-ENERGY TECHNOLOGIES: A SINGAPORE CASE STUDY

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ABSTRACT

Energy consumption in cities can be a great environmental burden. Renewable energy and waste-to-energy technologies are promising methods to assist the transition of energy- and carbon-intensive urban environment towards low carbon cities. This study aims to investigate the economic and environmental feasibility of renewable energy and waste-to-energy technologies in cities for low carbon transition. Being a well-known city-state, Singapore is taken as an example for the case study. An optimization-based decision support framework is used to estimate the optimum energy mix that minimizes the greenhouse gas emissions of the urban energy system while meeting the energy demand of Singapore. It is found by incorporating solar PV and waste-to-energy facilities to the current natural gas dominating energy system, a 9-10% of renewable energy penetration is achievable in Singapore.

Keywords: urban energy systems, hybrid renewable energy system, wastes to energy and resources, urban emissions mitigation, biochar

1. INTRODUCTION

In response to the Paris Agreement [1], many countries have set up relevant strategies and policies to reduce their domestic emissions. Energy consumption in cities can be a major environmental burden. For example, the power sector accounts for 43% of greenhouse gas emissions in Singapore and has the largest carbon footprint of all sectors [2]. Therefore, apart from generating affordable electricity to satisfy the energy demand, it is important to decrease the carbon footprint of power generation to ensure sustainable development.

A previous study found that it is feasible to design an economically viable negative emission hybrid renewable energy system (NEHRES) to provide electricity, digest wastes, and absorb greenhouse gas [3]. This hybrid system converts solar energy, wind energy, and bioenergy derived from agricultural wastes into electricity using a mixture of renewable energy technologies - solar PV, wind turbines, incineration, gasification, and pyrolysis. Among the technologies, incineration, gasification, and pyrolysis convert wastes into primary energy products (such as heat and syngas) and electricity. Therefore, these three technologies are referred to as waste-to-energy (WtE) technologies [4]. By taking in renewable biomass feedstock, gasification and pyrolysis produce biochar, a stable and porous product mainly composed of fixed carbon. Biochar is recognized as a carbon abatement product since the carbon dioxide capture by the plants through photosynthesis is fixed into stable biochar that can be stored in the soil for a long time [5]. In addition to the carbon abatement benefit, the application of biochar to soil amendment could also improve crop yields [6].

In our previous study, we have found feasible application of the biochar producing HRES on a remote rural area for self-sufficient power supply and carbon sequestration [7]. This establishes the potential of NEHRES application to provide affordable access to electricity for remote rural areas using a negative emission technology for carbon abatement. Although this system is found to be feasible in a rural area, applying this system to an urban area is a different story. The source of organic wastes and the demand profile for

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urban and rural environments are greatly different. It can be an easy task to build up a standalone HRES for rural areas but meeting 100% of a city's electricity demand of urban cities using renewable energy is a challenging task due to the disparity in the scale of resource availability and energy demand. Fossil fuel energy might be necessary to fully meet the electricity demand of an urban area. However, there is no relevant research in studying the potential of biochar producing HRES for an urban area so far.

Correspondingly this study models an urban energy system with electricity and biochar production seeking to achieve the lowest carbon emission in cities with the help of mathematical optimization. Singapore, a well-known city-state which strives for its sustainable development [8] and an iconic urban model, is investigated as a case study.

2. MATERIAL AND METHODS

The case study consists of three steps: data collection, model building, and system optimization.

As a starting point of the study, the current situation of Singapore is analyzed. Natural gas accounts for 95% of Singapore's current energy mix [9]. Due to the lack of wind energy, geothermal energy, and hydropower, only solar energy and biomass energy are feasible renewable resources in Singapore. As a summary, the key meteorology data and the waste data for Singapore are presented below:

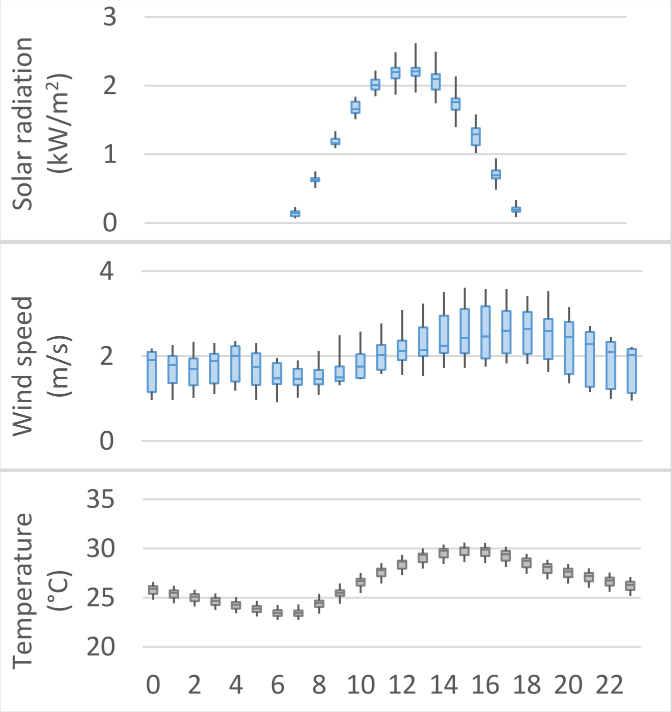

Figure 1. Solar radiation, Wind speed, and temperature of a typical day in Singapore.

Table 1. Biomass waste availability in Singapore [10].

	Horticultural	Wood	Food
Yield (ton/yr)	151,100	131,800	636,900
Hourly yield (ton/hr)	17.25	15.05	72.71
Lower heating value (MJ/kg)	8.9	15.4	4.1

Food waste consists of the majority of organic waste in Singapore. Due to the composition of food waste, it is more suitably treated using anaerobic processes. The non-food biomass wastes - horticultural waste and wood waste - can be treated using gasification, pyrolysis, or incineration processes.

Based on Singapore's specific data, we add the natural gas power generation pathway and AD technology to our previously developed system configuration consisting of gasification, pyrolysis, incineration, solar, and wind components. These two new technologies are added to deal with treatment of wet food waste and address the possible shortages of renewable energy.

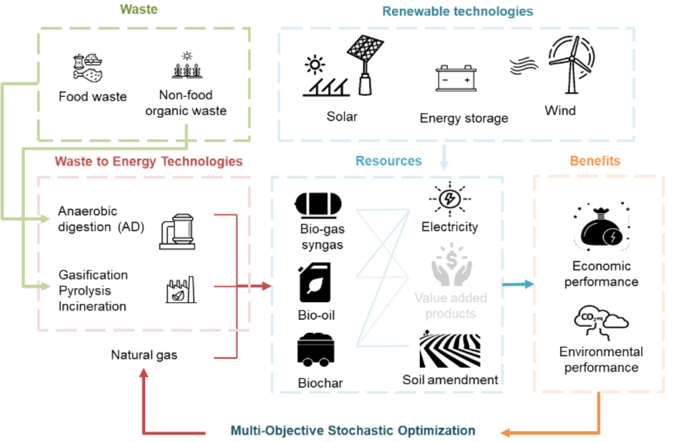

Figure 2. Possible urban energy system configuration for Singapore.

Modeling and optimization also follows the methods outlined in the previous article [7]. To adapt to the new system configuration, an anaerobic digestion (AD) model and a natural gas power generation component are added. We have developed a decision support framework that integrates all the models for different components in the system. The economic and environmental performance of the hybrid system are quantified using the levelized profit and carbon footprint. An optimization algorithm is used to identify the best system design and operating conditions that maximize the profit and minimize the carbon emissions.

Weather, waste generation, energy demand, and market data are required in the decision support.

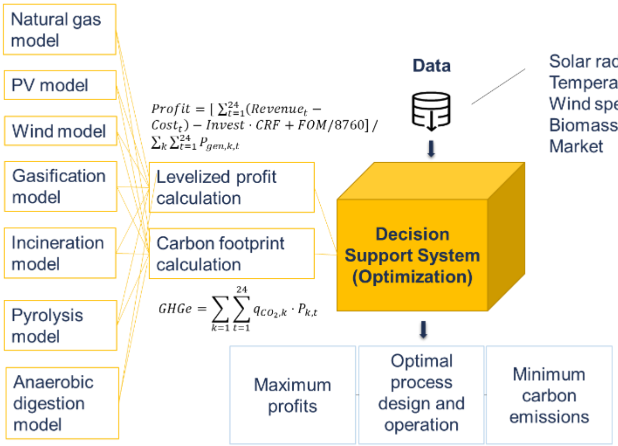

Figure 3. Proposed decision support framework.

The mathematical optimization model is formulated as follows:

$$Maximize\ (Profit, -GHGe)$$
$$s.t.$$
$$\sum_i P(i,t) - S_{in}(t) + S_{out}(t) \geq D(t)$$
$$\sum F(j,t) \leq F_r(j,t)$$
$$N(i) \cdot A(i) \leq L(i)$$
$$P_{sell} \leq D$$
$$S_{out}(t) \cdot \Delta t \leq E(t)$$
$$S_{in}(t) \cdot \Delta t \leq E_{max}$$
$$\Delta x \leq dP_x \left(x = P(i,t), S_{in}(t), S_{out}(t)\right)$$
$$N_w, N_s, F(j,t), P_{sell}(t), S_{in}(t), S_{out}(t) \geq 0$$
$$t = 1,2,\dots,24$$
$$i = \text{natural gas}, solar, wind, incineration, gasification, pyrolysis, AD$$
$$j = horticultural\ waste, wood\ waste, food\ waste$$

where $Profit$ is the profit in US dollar (USD), $GHGe$ is the greenhouse gas emission (kg $CO_{2\text{-eq}}$), P is the power generated by the system (kW), S_{in} is the power flowing into the energy storage (kW), S_{out} is the power flowing out of the storage system (kW), D is the electricity demand (kW), F is the feeding rate of the biomass waste (kg/h), F_r is the maximum feeding rate of the biomass waste (kg/h), N is the number of each HRES component, A is the footprint occupied by one unit of the selected technology (m^2), L is the available land area for each technology (m^2), P_{sell} is the power sold (kW), $\Delta t = 1$ is the time interval (h), E is the accumulated energy stored in the energy storage system (kWh), Δx means the change of the time dependent variable x during each time interval, dP_x is the maximum changing rate of variable x, and subscript max denotes the maximum value of the parameter or variable.

3. RESULTS AND DISCUSSION

The profit and carbon emission for the scenario that emission is minimized are returned by the optimization. The total greenhouse gas emissions are 50,594,979 kg $CO_{2\text{-eq}}$.The total profit is USD 15,054,113.

Table 2 shows the optimum design capacity of the components in the urban energy system for Singapore. It is not able to meet the demand using exclusively renewable resources. Natural gas dominates the design capacity. Solar energy has the largest potential among the renewable energies in Singapore. AD is used to treat food wastes and pyrolysis replaces combustion as it more effectively minimizes greenhouse gas emissions. Wind energy is not utilized since it has limited potential.

Table 2. Optimum design capacities of the urban energy system for Singapore.

	Capacity (MW)
Natural gas	5,654
Solar	1,476
AD	79
Pyrolysis	15

The operation of the system for the urban case is shown in the figure below. The majority of the electricity demand is satisfied by power produced from natural gas. Solar energy is used to shave the peak at noon. The ratio of AD to pyrolysis is about 5 to 1. Energy storage is not required.

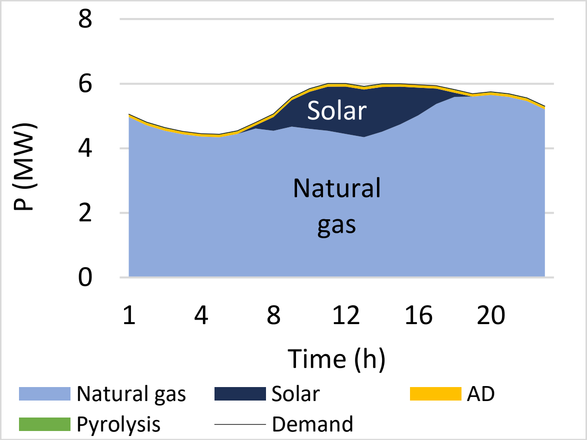

Figure 4. The optimum power generation profile.

In terms of economic performance, the urban HRES is similarly profitable to a natural gas energy system. The proposed optimum system also emits less greenhouse gases than natural gas. Correspondingly, it also has a lower carbon footprint than Singapore's 2018 grid emission factor (GEF=0.4192 kg $CO_{2\text{-eq}}$/kWh).

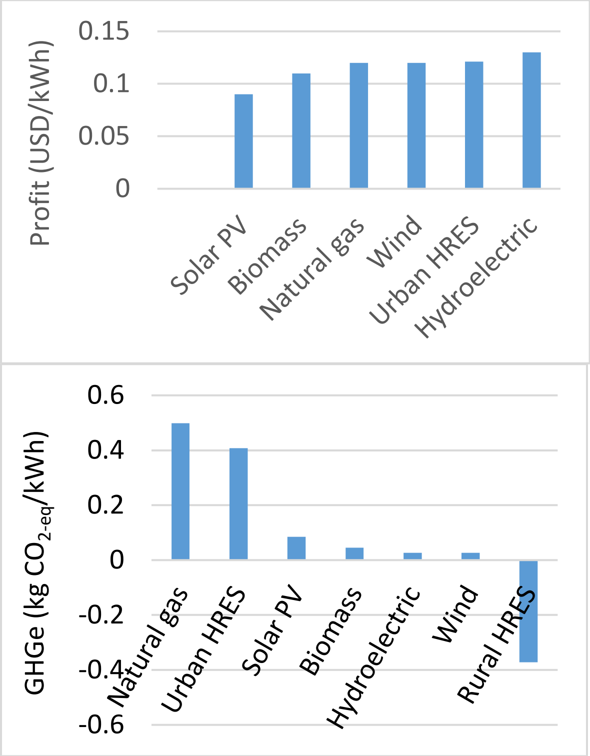

Figure 5. Economic and environmental performance of the optimum system.

We also study the scenario when the profit is optimized. As shown in Table 3, the Maximum Profit scenario earns USD 18,553 (by 0.1%) more than the Minimum Emission scenario, but it emits 297,603 kg $CO_{2\text{-eq}}$ (by 0.6%) more than the latter.

Table 3. The profit and emission for minimum emission scenario and maximum profit scenario.

	Minimum Emission	Maximum Profit
Profit (USD)	15,054,113	15,072,666
GHGe (kg $CO_{2\text{-eq}}$)	50,594,979	50,892,581

To understand the trade-off between profit and emission, the Pareto curve is plotted as shown below.

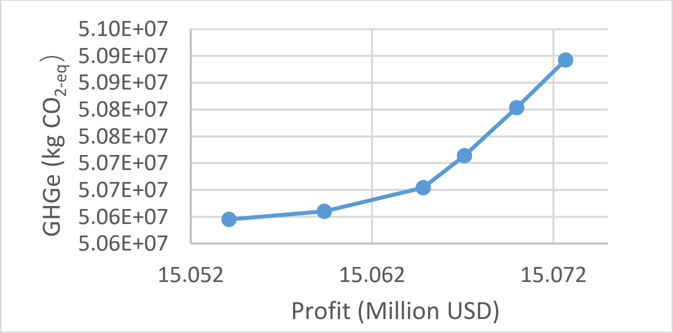

Figure 6. Trade-off between emission and profit.

At the beginning where emission is minimized, the biomass is completely converted by pyrolysis. When the emission allowance is relaxed, part of the feedstock originally fed to pyrolysis is now fed to gasification, generating more electricity and profit. With the gradual shift of the waste stream to gasification and incineration, less biochar is produced but more electricity is generated. Finally, a system consisting of natural gas, solar, AD, and incineration components gives the optimum profit.

The current stage of renewable penetration in Singapore is 2.7% (WtE 1.9% and solar PV 0.8%). This optimization study finds that 10% of the energy demand in Singapore can be met by renewable energy when profit is maximized, and a 9% renewable energy penetration is achievable when greenhouse gas emissions are minimized.

4. CONCLUSIONS

This study finds that the renewable penetration of Singapore can be increased to 9-10% by installing rooftop PV in residential buildings in Singapore and using waste-to-energy technologies. Conventional energy sources are still needed to satisfy Singapore's daily energy demand. A combined usage of conventional energy (Natural gas 5,654 MW) and renewable energy (solar 1,476 MW – AD 79 MW – pyrolysis 15 MW) can achieve the lowest carbon emission of 0.407 kg $CO_{2\text{-eq}}$/kWh, which is 18% lower than the 2009 level. The proposed urban energy system is also economically competitive compared to the current energy system in Singapore.

ACKNOWLEDGEMENT

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