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An energy - waste disposal combined sustainable urban system based on microbial hydrogen production

Xiyan Li[1,6,*,†], Chenxuan Feng[2,7,†], Qihang Lin[3,8,†], Weitao Wang[4,9,†], Yuze Yang[5,10,†]

[1]College of Environmental Science and Engineering, Nankai University, Tianjin, 300350, China
[2]School of Energy, Power and Mechanical Engineering, North China Electric Power University, Beijing, 102200, China
[3]School of Energy, Power and Mechanical Engineering, North China Electric Power University, Baoding, 071003, China
[4]School of Ecology and Environment, Southwest Forestry University, Kunming, 650224, China
[5]Rong Qiao Sedbergh School, Fuzhou, 350207, China

[6]xliii@connect.ust.hk
[7]13137527772@163.com
[8]wy15325082046@126.com
[9]3026973312@qq.com
[10]yang-quqingyuxin@foxmail.com
*correspondind author
[†]These authors contributed equally to this work and should be considered as co-first author.

Abstract. Climate change, carbon neutrality, and sustainable development are undoubtedly the hottest public issues in the world in the past decade. In the face of the increasing frequency of extreme weather and the environmental pollution caused by industrialization in the past few hundred years, the concept of sustainable development is being practiced in more and more industries. Since the Copenhagen Climate Summit in 2009, many countries and regions with international influence have put forward their carbon neutrality plans, striving to explore a new development model that meets the higher quality of life standards while demonstrating their international influence. One of the most important issues is the structural design of the city of the future. In a few decades, a green, clean, and sustainable city should be different from today's cities in many ways, such as waste recycling, energy supply, public transportation, etc. In the context of China's 2030 carbon peak and 2060 carbon neutrality plan, this study takes Shenzhen as an example to propose a system that uses dark fermentation to treat urban organic waste to produce hydrogen, hydrogen power generation, and empower the electric vehicle industry in the form of electricity subsidies, to replace part of the existing waste incineration in Shenzhen and help the ongoing process of replacing fuel vehicles with electric vehicles. This study proposes a model to simulate the development of the system, taking into account economic benefits and carbon emissions. It simulates how the two development models will evolve in the coming decades. This study provides new insights into the design of future city.

Keywords: Future city, Dark fermentation, Green hydrogen, electric vehicle, Sustainable development.

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1. Introduction

Human cities occupy about 2% of the surface, they however consume 60–80% of global energy[1]. Under the background of carbon neutrality and sustainable development, new design of future cities, from ideas to practice, is in urgent demand. The emerging of Electric Vehicle(EV) is an aspect of environmental-friendly and sustainable development in transportation and automotive industry[2]. Hydrogen power plays an ideal role in power supply in a future city[3]. The production of hydrogen from municipal biomass waste is possibly proceeded in this system.

Dark fermentation combined with Photo fermentation can sufficiently produce hydrogen from row organic waste in a low carbon-emission way

The electric power generated from organic waste will be deployed to the yield of electricity. To maximize the efficiency of deployment, the solution to provide a part of power for free is adopted. The solution will work to promote the development of the EV market, and minimize the total cost for government from vehicle yield.

There has been some research on the relationship between subsidy and the situation of electric vehicles (EV) market. Most of the research focus on the qualitative analysis of the relationship, aiming to advise the government[4]. A small amount of the research builds a systematic model to analyze the problem, but the analysis always be limited to some specific situations[5].

To maximize the efficiency of deployment, a forecasting-optimization model is built to search for the best solution for EV subsidy. Based on previous research, this model comprehensively considers the impact of economic and environmental benefits, and introduces the concept called Interest, which refers to the willingness of citizens to purchase EV. The model establishes the relationship between Interest, subsidy amount, and market share of EV. It further calculates the changes in the internal combustion engine vehicles (ICEV) and EV markets under specific subsidy amounts, as well as the corresponding municipal total costs over 30 years. Based on evaluation criteria, the model optimizes the amount of subsidy to control the municipal total cost to the lowest degree. Last, the article shows the minimum cost and the corresponding EV subsidy amount to help the government make decisions, which serve as the model's result. As an addition, the article puts the model on Shenzhen and gets a rough outcome to verify the reliability of the model.

2. Material and Methods

2.1. Energy production system

Raw material of biological hydrogen production system

Table 1 shows several different kinds of raw materials that can be used for hydrogen production systems and the composition of waste that can be used as a raw material. In this case, we will use food waste as an example.

Table 1. The component content of solid waste in Shenzhen[6]

Solid waste component content	Dry mass/%	Carbon Content/%	
	Default Value	Default Value	Range
Paper	90	46	42~50
Fabric	80	50	25~50
Food waste	40	38	20~50
Wood	85	50	46~54

The dry mass in food waste is fully utilized for hydrogen production through microorganisms, the specific steps are as follows:(1)convert food waste into dry matter through treatment; (2)convert the dry matter from step I into carboxylic acids and hydrogen through Dark fermentation; (3)convert carboxylic acids into hydrogen and carbon-based material through Photo fermentation.

Where dark fermentation:

butyrate(LBu) produced ($C_6H_{12}O_6 \rightarrow CH_3CH_2CH_2COOH+2CO_2 + 4H_2$)

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acetic acid(HAc) produced ($C_6H_{12}O_6+2H_2O \rightarrow 2CH_3COOH+2CO_2 + 4H_2$)

Photo fermentation (C_2/C_4 acid$+O_2 \rightarrow CO_2 + H_2$)

The process mainly consumes food waste, combined with an in-situ electricity production process powered by produced green hydrogen. The sludge treatment process can be landfill and recycling in the system. The majority of CO_2 can be settled in the solid ground rather than becoming emission into the atmosphere. The green electricity produced by this process is designed to be the supply of EV market.

Table 2 shows the hydrogen yield of the two-step process. Fig.1 simplified flow chart for biohydrogen production (process details are not covered as the focus of this paper is on process optimization).

Table 2. Hydrogen yield of the two-step process

Substrate	Dark fermentation inoculation	Photo-fermentative inoculation	Hydrogen production per kg of substrate/kg
Food Waste (Water Content 60 per cent)	Caldicellulosiruptor saccharolyticus DSM 8903	Rhodobacter sphaeroides	0.02

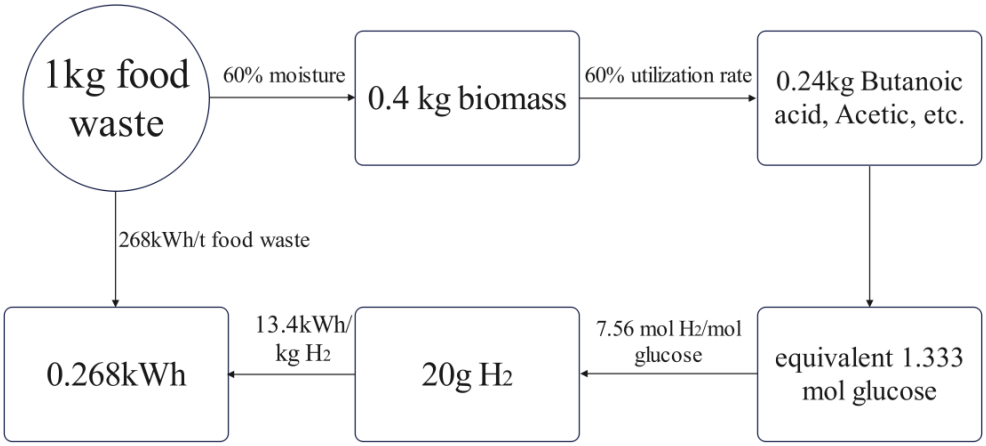

Figure 1. Overall mass and energy conversion of the two-step process

2.2. Cost prediction models using different waste treatment methods

The comparison of Biological hydrogen production and Waste incineration plant in a construction cost of about 1:3. Because the construction cost is an approximate growth model with a decreasing growth rate, the data of two waste incineration plants located in Shenzhen with a treatment capacity of 4,250t and 5,100t[7] are used to establish a linear correlation model to simulate the construction cost and power generation of a waste incineration plant with a treatment capacity of 5,500t/d.

The cost of using different methods of waste disposal is shown in Table 3. The cost prediction model is shown in Table 4.

Table 3. Cost of different cases of incineration plants [8]

Initial Investment	Maintaining Cost	Power Generation Efficiency	Year	Annual Capacity	Cost
1200M $	0.5 % * 1200 M $	276kWh/t waste	10	5000t	1260M $
386M $	0.5 per cent * 386 M $	268kWh/t waste	10	5000t	405M $

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Table 4. Cost results of two types of waste treatment systems[8-9]

waste incineration plant	
Treatment capacity t/d	5500
Years/year	10
construction cost	¥4,489,042,400.00
maintenance cost	¥224,452,120.000
Capacity 100,000 tonnes/year	20.2
Power generation units per day	5,462,400
Carbon emissions 100,000 tonnes/year	12.515
Carbon price/tonne	¥500.00
biological treatment plant	
Treatment capacity t/d	5500
Years/year	10
construction cost	¥1,370,000,000.00
maintenance cost	¥68,500,000.000
Capacity 100,000 tonnes/year	20.2
Power generation units per day	1,483,178

The data in Table 3 was used to derive the unit cost of waste incineration and to build a model for predicting the unit cost of different treatment methods for waste Table 4. Table 5 shows the unit cost of two different waste treatment methods over ten years.

Table 5. Unit cost of two types of waste treatment systems [10-12]

vintages	Unit cost of waste incineration $/tonne	Unit cost of biological treatment $/tonne
1	(¥1,979.90)	(¥528.66)
2	(¥868.75)	(¥189.55)
3	(¥498.36)	(¥76.52)
4	(¥313.17)	(¥20.00)
5	(¥202.06)	¥13.91
6	(¥127.98)	¥36.52
7	(¥75.07)	¥52.67
8	(¥35.38)	¥64.78
9	(¥4.52)	¥74.20
10	¥20.17	¥81.73

Note: Values in parentheses are negative, meaning cost; The remaining values are positive, meaning profit.

2.3. Modeling

Previous studies have shown that municipal subsidies for electric vehicles significantly influence their market share. Due to this effect, supplying a portion of the benefits from the waste-to-hydrogen system to cover the daily use of private EV may increase the overall efficiency of the circular system. To meet the best solution, this paper establishes an EV subsidy model aimed at finding an optimized subsidy model, combined with the waste-to-hydrogen system, to provide an overall urban waste management solution.

Assumptions

a) Only the impact of subsidies on private cars is considered, and vehicles are simplified into two types: electric vehicles (EV) and internal combustion engine vehicles (ICEV).

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b) The total demand for urban transportation remains constant. It means that the average annual mileage per private car is constant, and the total number of EV and ICEV is also fixed.

c) In this model, only municipal costs are considered. Costs like production costs that do not require direct payment by the government are not included. Additionally, all carbon emission processing costs are accounted for within the cost in the model.

d) All carbon emission processing costs for the government are accounted for within the cost in the model and considering the economic feasibility, this will be calculated by a carbon tax as a punishment policy to the government. It will be established to control the whole carbon emission of the area.

Model content

Based on assumptions, a forecasting-optimization model is built to minimize the total cost of government for vehicle market. The model will focus on the dynamic changes of vehicle market and its total cost for 30 years.

Through the analysis of vehicle market, the model proposes a new concept called Interest, which means the willingness of consumers to purchase EV. Because it's an abstract concept, the main work for modeling is to quantify the relationship between Interest and other factors. According to the marginal diminishing effect, the Interest will increase through the subsidy amount. The interest will increase quickly when the subsidy is small and turns to small growth when the subsidy is huge.

$$I = 1 - \exp\{-b \cdot s\} \tag{2-1}$$

Where I is interest, the willingness to purchase EV; b is a coefficient to quantify the interest;s is the subsidy for single EV.

Through the modeling analysis, there is a directly proportional relationship between Interest and market penetration rate.

$$Q_i^{EV} = Q_{i-1}^{EV} + Q_{i-1}^{ICEV} \cdot k \cdot I \tag{2-2}$$

$$Q_i^{ICEV} = Q^{total} - Q_i^{EV} \tag{2-3}$$

Where Q_i^{EV} is the quantity of EV in the year i; Q_i^{ICEV} is the quantity of ICEV in the year i; k is the coefficient of the relationship between Interest and market penetration rate; Q_i^{ICEV} is the total quantity of vehicles in the market.

To obtain the total municipal cost for a specific market share, it's necessary to evaluate the cost per private vehicle. In this model, costs are categorized into two types: fixed costs and variable costs. Fixed costs are those unrelated to the use of vehicles. In this model, fixed costs only account for the economic cost of vehicle situation. Variable costs are related to the use of vehicles. Since the model does not consider economic factors incurred by the municipality in it, only the environmental cost of energy consumption is considered. All of the costs, both fixed and variable, include economic costs and environmental costs. For environmental costs, the model uses the average price of the carbon trading market for equivalent calculations.

Based on the data obtained through these calculations, the annual municipal costs can be determined, and summing these up yields the total municipal cost over 30 years.

$$C_j = C_j^{econ} + E_{CO2} \cdot P_{CO2} \tag{2-4}$$

$$C_i = C_f^{EV} \cdot Q_i^{EV} + C_f^{ICEV} \cdot Q_i^{ICEV} + C_v^{EV} \cdot Q_i^{EV} \cdot M + C_v^{ICEV} \cdot Q_i^{ICEV} \cdot M + s \cdot \left(Q_i^{EV} - Q_{i-1}^{EV}\right) \tag{2-5}$$

$$C_{total} = \sum_{i=1}^{30} C_i \tag{2-6}$$

After the construction of the mathematical model, the model can minimize the total cost, and give the government the best solution for subsidy.

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Parameters and Application example

There are several parameters in the model, which significantly influenced the simulation results of the model. However, the values of the parameters are based on the specific urban situation. So it's necessary to apply the model to a specific city.

The city of Shenzhen is viewed as an excellent example. Shenzhen has a quick improvement in EV market share in the current year, and the government has introduced a series of policies to support the development of EV. So, the analysis of Shenzhen will be very significant.

According to the real situation of Shenzhen, the following shows the values of parameters to analyze the improvement of EV market for Shenzhen, and evaluate the effect of the model.

Table 6. Specific values of model parameters

b	2.1×10^{-5}
Q_0^{EV}	1.0×10^{6}
Q^{total}	4.2×10^{6}
k	1
P_{CO2}	500(CNY/ton)
C_f^{EV}	1000(CNY/y)
C_f^{ICEV}	926(CNY/y)
C_v^{EV}	0(CNY/y/km)
C_v^{ICEV}	0.1(CNY/y/km)
M	1.5×10^{4}(km)

The value of coefficients b and k is obtained by fitting. The model gets the information of EV market penetration rate and relevant subsidy from the government, and takes a suitable value to adopt the data. For Q_0^{EV}, Q^{total} and M, the value is searched from the government report. Through the analysis of the current carbon price in the market, P_{CO2} is set to a levelized value to simulate the reality.

For the cost, there are some simplifications. C_f^{EV} and C_f^{ICEV} are only focused on the environmental cost among the running of vehicle situation. The situation construction cost for EV is 10,000k CNY, while ICEV one will be around 30,000k. The cost should be divided by the length of the life cycle and the quantity a situation can service, the values turn to 1000CNY for C_f^{EV} and 926 CNY for C_f^{ICEV}. For the CO_2 emission for EV is too little to be considered, the value of C_v^{EV} is set to 0. The source of C_v^{ICEV} is the same as the fixed cost, while the object turns to the environmental cost for fuel use.

3. Results and discussion

3.1. Application Results

Through the model and specific parameter values, there is a solution and related forecasting situations in Shenzhen.

Fig. 2 establishes the forecasting of the relationship between the municipal cost of government and the subsidy per EV. As seen in Figure 2, the municipal costs decrease rapidly as the subsidy amount increases, reaching a minimum before rising more slowly. So, there exists an optimal subsidy solution that minimizes municipal costs. This optimal solution involves providing a total subsidy of 8,138 CNY to each owner who switches from a gasoline car to an electric vehicle. At this point, the total municipal subsidy for 30 years would be only around 178 billion CNY. Compared to the no-subsidy scenario, the subsidy scheme reduces the municipal costs by 33.5%.

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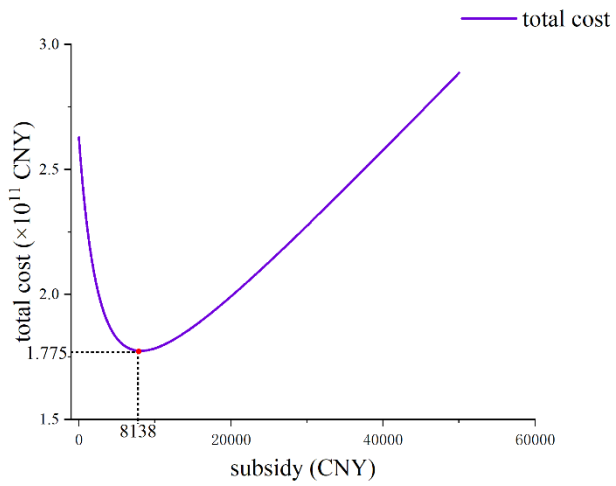

Figure 2. The relationship between total cost and subsidy

Based on the best subsidy solution, the model gives the forecasting for the changes in vehicle market. Figure 3 shows the change in the quantity of EV over time under the optimal subsidy solution. It can be seen that the quantity of EV will gradually increase, starting at a fast pace and then slowing down over time. By the third year, EV will have replaced ICEV as the dominant force in the vehicle market. After 30 years, the number of EV will reach 4.18 million vehicles, accounting for 99.4% of the market.

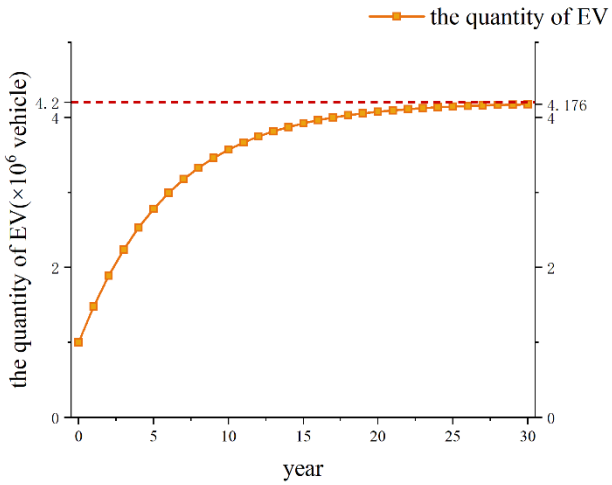

Figure 3. The situation of the EV market changes

Fig. 4 establishes the annual expenditure on subsidies. To avoid an explosive increase in expenditure at the beginning, the solution distributes the subsidy amount over two years after the purchase of EV. The subsidy cost for the government initially rises and then gradually decreases over time. The highest subsidy cost occurs in the second year, with a total expenditure of 27.4 million CNY/year. Since the subsidies in this solution are offset by the electricity generated from waste treatment, as an electricity price of 0.5 CNY/kWh, this means the government would require the bio-treatment plant to provide up to 55 million kWh of electricity.

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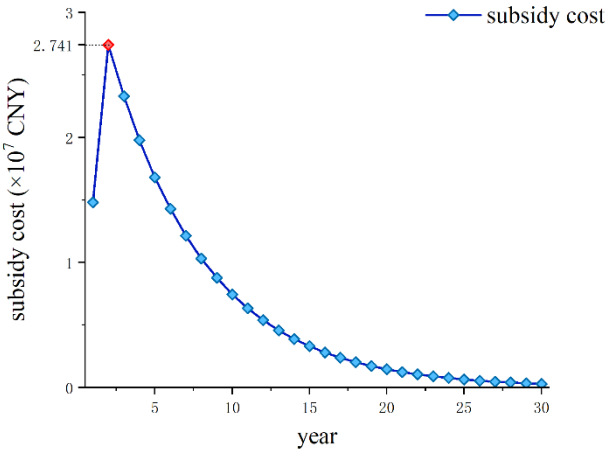

Figure 4. The changes in cost for subsidy for a single year

3.2. Discussion

The modeling result shows that the subsidy model is effective and practical. According to Figure 1, through the set of subsidy, the total cost of government decreases obviously. At the same time, the subsidy will significantly promote the development of the EV market. (Figure 3) Based on Shenzhen's actual waste production, a biogas power plant can generate around 180 million kWh of electricity per year, which covers the cost of subsidy per year (Figure 4). It indicates that this plan is feasible for the government.

However, there are still some defects in the model. Due to the lack of direct supporting data, there is room for further research into the accuracy of formulas and data in the model. Additionally, as L.D. Danny Harvey writes, through systematic analysis of government subsidy policies, that excessive government subsidies may encourage the production of larger vehicles, indirectly increasing carbon emissions; at the same time, they might suppress research and development efforts in EV technology[9]. These factors can be taken into account in further research.

4. Conclusion

By applying a subsidy model, the government will get a huge and practical efficiency. As the application in Shenzhen, the total cost will reduce by 33.5%, and the share of EV quantity will increase to 99.4% in 30 years. The model is a simplified edition. It will be more effective if the data is more accurate or if some other factors, like research motivation in EV, are considered.

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Xiyan Li, Chenxuan Feng, Qihang Lin, Weitao Wang and Yuze Yang contributed equally to this work and should be considered co-first authors.

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