CHEMICAL ENGINEERING TRANSACTIONS
VOL. 113, 2024
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Jeng Shiun Lim, Bohong Wang, Guo Ren Mong, Petar S. Varbanov

ISBN 979-12-81206-14-4; **ISSN** 2283-9216
DOI: 10.3303/CET24113002

Modelling and Optimisation in the Design of Green Hydrogen Cities - A Case Study of Shanghai

Haofu Wang[a,b,*], Guoqu Cui[a,b], Yiying Guo[c], Juan Jiang[a,b]

[a]Sino-Portuguese Centre for New Energy Technologies (Shanghai) Co., Ltd., Shanghai 200335, China
[b]Shanghai Investigation, Design & Research Institute Co., Ltd., Shanghai 200335, China
[c]School of Social Development, East China University of Political Science and Law, Shanghai 201620, China
wanghaofu@sidri.com

Given the urgent necessity of addressing the climate crisis, there is a worldwide tendency to achieve rapid decarbonisation across various sectors of the economy, especially within the urban areas. Recently, hydrogen has been considered as a solid solution of the future urban net-zero energy system. Due to its high energy density, hydrogen has great potential to decarbonise the key urban sectors such as transportation, heating, and electricity. The objective of this study is to not only provide an overview on the concept of Green Hydrogen City but to develop a comprehensive energy planning methodology utilising hydrogen as the main source through a detailed case study of Shanghai. In this context, a hydrogen-based energy system model is presented and applied to Shanghai. This model evaluates the feasibility of utilising renewable energy sources for local hydrogen production, storage, and consumption across Shanghai's electricity, heating, and transportation sectors. It considers operational, technical, and resource constraints to optimise the integration of hydrogen technologies within the urban energy system. It can be concluded that the green hydrogen city concept holds substantial promise for future urban implementation, and this study offers methodological guidance to smart city planners and decision-makers striving for decarbonization solutions and a carbon-free urban economy.

1. Introduction

In the recent decades, the worldwide research communities and governments have been realising the importance of decarbonisation and have started setting a series of actions to reduce the dependence on the traditional fossil fuels such as coal, petroleum (oil) and natural gas that were buried deep into the earth. This awareness towards decarbonisation was not only because of the energy crisis in the past decades but also due to the critical environment pollution such the greenhouse gases, CO_2 and methane that generated by the use of fossil fuels. In the context of urban areas, this transition was also related to the worldwide ongoing urbanisation, industrialisation, and population growth which had a rapid increase since the 1950s (Liu and Bae, 2018). In addition, according to the World Urbanization Prospects from the UN in 2018, it is projected that around two-thirds of the global population will migrate to the urban areas by 2050 (UN, 2018). Following this trend, there emerges a consequential surge in the demand for energy sources in urban areas.

As a result, with the characteristics of inexhaustible, efficient, and non-polluting, renewable energy sources are now considered to be a key solution for the future urban energy systems (Tiwari et al., 2024). There have already been various solutions recently to decrease the CO_2 emissions and improve the efficiency of urban energy systems with renewable energy sources (Barros et al., 2024). Within the spectrum of low-carbon energy alternatives, hydrogen emerges as a versatile energy carrier with considerable potential in mitigating pressing energy challenges. Traditionally employed in industries such as refining and chemicals, its production from fossil fuels has significantly contributed to CO_2 emissions. Nevertheless, the advent of clean hydrogen, sourced from renewable origins offers a pathway to decarbonize sectors including the important sectors within the cities such as transport, industry, and electricity (Balta and Balta, 2022).

To achieve the goal of a sustainable city, the concept of a 'Hydrogen City' was first proposed by Lodhi in 1987, advocating for the utilisation of abundant energy sources like solar and sea water for hydrogen production (Boretti, 2022). The vision of Lodhi (1987) represents a pioneering approach towards sustainable urban energy

Paper Received: 11 April 2024; Revised: 27 July 2024; Accepted: 31 October 2024
Please cite this article as: Wang H., Cui G., Guo Y., Jiang J., 2024, Modelling and Optimisation in the Design of Green Hydrogen Cities - A Case Study of Shanghai, Chemical Engineering Transactions, 113, 7-12 DOI:10.3303/CET24113002

systems, envisioning a model city that produces and operates on hydrogen to meet its energy needs. In the last few years, some of the scholars studied the potential of electrolytic hydrogen as the energy source in the urban areas and considered cost of energy system and hydrogen production as the economic indicator. Among the reviewed literature, Juárez-Casildo et al. (2022) assessed the feasibility of solar hydrogen production in urban areas of Mexico using Geographic Information Systems (GIS). Their study evaluated monthly and annual solar hydrogen potential and examines the cost (LCOH) of replacing gasoline with hydrogen for light transportation, highlighting the practicality of hydrogen cities. You and Kim (2020) and Khalil and Dincer (2023) developed the optimisation models to design and analyse a 100 % renewable energy network including wind and solar PV as the energy sources and PEM electrolysers for hydrogen production to meet various energy demands. You and Kim compared the hydrogen city model with the electrified city model in various aspects including technology costs, demand structures, and renewable source potentials and applied both models to Jeju Island, Korea. Whereas Khalil and Dincer assessed the potential of renewable power generation and hydrogen production for four different locations and provided each location with the ideal installed capacities of wind and solar PV power system based on the climate conditions. Across these studies, scholars have widely acknowledged that the potential of hydrogen as a key element in urban energy systems, despite their approaches and focuses vary.
The objective of this study thus is to build a mathematical model within the concept of green hydrogen city to utilise hydrogen produced fully by renewable energy sources to replace the traditional energy supplies within the urban energy systems to meet the energy demand. What’s more, following the Carbon Peaking and Carbon Neutrality Goals set by the Chinese government in 2021, the study aims to apply the model to the real-life scenario of Shanghai and optimise the efficiency and cost through the production, distribution, and consumption process.

2. Shanghai Energy Sector Profile

As the world's second most populous country and second largest economy, China faces a significant challenge in utilising fossil fuels to sustain its industrial and economic activities. According to the 2024 Statistical Review of World Energy by The Energy Institute, fossil fuels accounted for 81.64 % of China’s energy consumption, slightly higher than the global average of 81.47 % (The Energy Institute, 2024). This heavy reliance on fossil fuels is reflected in Shanghai, the focus of this research. Shanghai, covering an area of 6,340.50 km² with a population of 24.76 M, is not only one of China’s primary economic centres with the highest GDP in the country but also exhibits diverse energy consumption patterns with a significant dependence on fossil fuels.

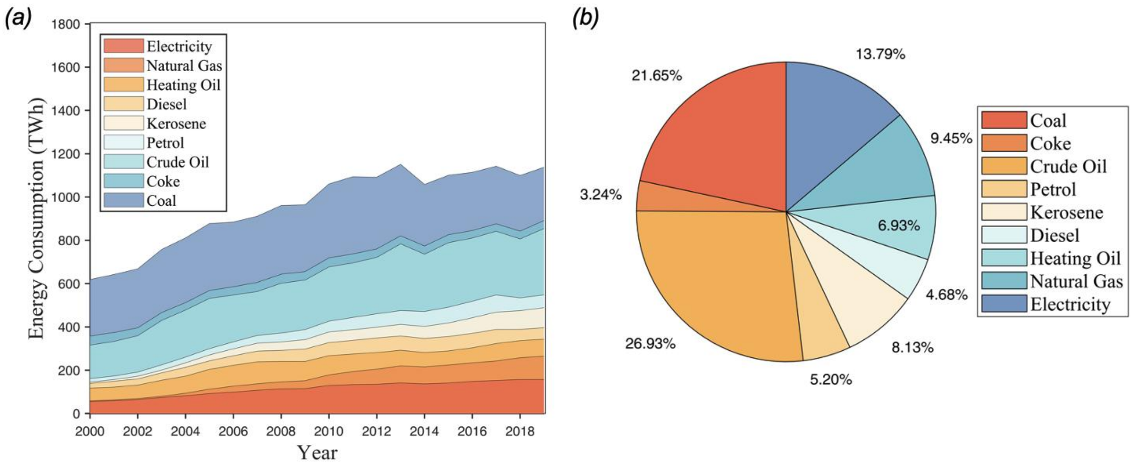

Figure 1 : Main Sources of Energy Consumption in Shanghai (a) Historical Yearly Trend from 2000 to 2019; (b) Percentual Results in 2019.

As illustrated in Figure 1a, the period from 2000 to 2019 witnessed a significant increase in total energy consumption, rising by 83.8 % from 619.2 TWh to 1,137.8 TWh (Shanghai Statistics Bureau, 2020). This increase is primarily attributed to the wider utilisation of natural gas and crude oil. Notably, natural gas usage exhibited the most substantial growth, as depicted in Figure 1b. Analysis reveals that the natural gas sector accounted for nearly 40 % of Shanghai's total energy consumption. Meanwhile, over the past two decades, coal has gradually diminished in importance as a mainstream energy source in Shanghai's energy system, with renewable energy sources being developed to take its place in electricity generation (Li et al., 2010). Despite these shifts, fossil fuel sources continue to dominate primary energy consumption, underscoring the need for this research on how to effectively utilise renewable energy sources and hydrogen to replace traditional energy supplies and achieve the goal of a green hydrogen city.

3. Methodology

3.1 Description of the Model and System

The approach focuses on the key question of how much hydrogen will be necessary to be produced in order to satisfy the city's energy demand. The mathematical model is established to simulate utilising hydrogen to replace traditional energy supplies within urban energy systems to meet this demand. Electrolyser, where the water electrolysis reaction takes place, can range in size from small, appliance-sized equipment suitable for small-scale distributed hydrogen production to large-scale, central production facilities that can be directly connected to renewable energy sources, making it perfectly fit for this model. Wind energy system and solar PV energy system are selected as the input sources of the electrolyser because of their availability across the globe and energy independence from fossil fuels.

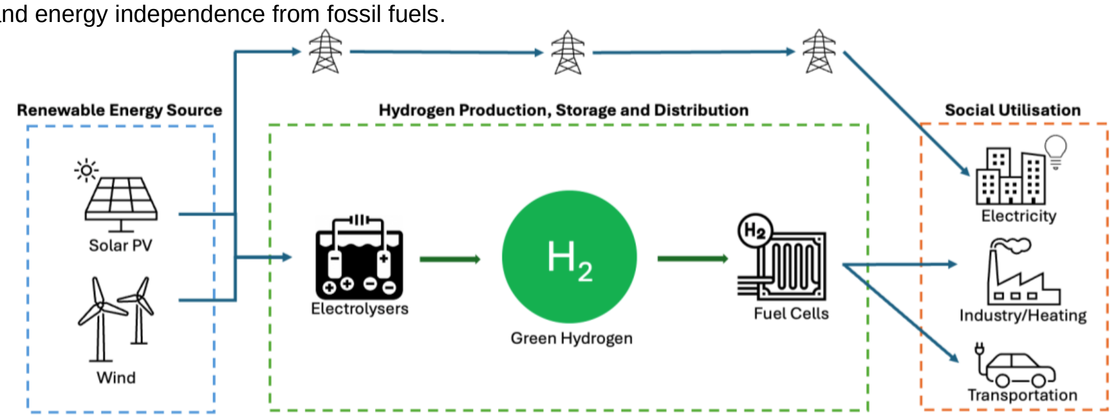

Figure 2: Scheme approach to Green Hydrogen City.

After the production of hydrogen, the model will simulate the process of fuel cells converting hydrogen to electrical and thermal energy, which is then supplied to the city via pipelines. To create a realistic scenario, as presented in Figure 2, the energy demand structure at the utilisation end of this model is divided into three categories: Electricity, Heating, and Transportation. However, the electricity demand will not go through the process of hydrogen distribution to minimize energy loss and increase system efficiency.
To determine the optimal ratio and amount of required solar PV and wind turbine installed capacity to meet the demand for utilising hydrogen to power the city, Matlab is used in this study. With the help of the optimisation algorithm tool within Matlab, it is possible to prioritise the lowest cost, which is the total annual cost of this potential modification to the city's energy system ($Total\ Annual\ Cost$), including installation, operation, and maintenance, while meeting the energy demand at the same time. The objective function of this mathematical model can be represented by Eq(1).

$$\min(Total\ Annual\ Cost) = Capacity^{PV} * Cost^{PV} + Capacity^{wind} * Cost^{wind} \quad (1)$$

In Eq(1), $Capacity^{PV}$ and $Capacity^{Wind}$ represent the installed capacity of solar PV and wind energy system. $Cost^{PV}$ and $Cost^{Wind}$ are the capital expenses of solar PV and wind energy system associated with purchasing and installing the equipment necessary to generate solar and wind energy.

3.2 Solar PV Generation

In this study model of Shanghai, solar PV panels would only be considered for installation on land due to the limited use of floating PV near Shanghai. To estimate the theoretical solar PV generation for Shanghai, the solar PV generation profile is introduced, which is calculated from the data of the average monthly sum of Global Incident Irradiation ($GlobInc_m$) and average monthly environmental temperature ($\bar{T}_m$). $GlobInc_m$ is derived from the Global Horizontal Irradiation ($GlobHor_m$) and Diffuse Horizontal Irradiation ($DiffHor_m$) via PVsyst, a professional photovoltaic system software. Both of $GlobHor_m$ and $DiffHor_m$ are obtained from SolarGIS. Considering the constrains such as Shadings Loss, Soiling Loss, Transformer Loss, and System Unavailability, it can be assumed that the typical system losses of the solar PV energy system ($Loss_{PV}$) are 17.5 %. Using Eq(2), it can determine the theoretical profile of monthly electricity generation from solar PV of Shanghai.

$$Profile_m^{PV}\left(^{kWh}/_{kWp}\right) = (1 - Loss_{PV}) * GlobInc_m \times \frac{(1-\alpha(\bar{T}_m - 25))}{1000}, m \in \{1, 12\} \quad (2)$$

α stands for the temperature coefficient in Eq(2), which is −0.5 %/°C in this case. With this theoretical profile, the monthly generation of solar PV energy system (PV_m) can be determined through Eq(3):

$$PV_m(kWh) = Capacity^{PV} * Profile_m^{PV}, m \in \{1, 12\} \quad (3)$$

3.3 Wind Power Generation

To determine the theoretical generation pattern of the wind power energy system, it is important to select a specific wind turbine and a certain region to gather the relevant meteorological data required for the calculation. In this case study, a 10 MW wind turbine is selected. As for the region, the Fengxian Offshore Wind Farm, one of the representative large-scale offshore wind power projects located in the northern sea area of Hangzhou Bay, China, is taken as a reference. The theoretical profile calculation begins by estimating the available kinetic wind power (P^{wind}) and extractable power from wind (P_m) via Betz's Law, as presented by Eq(4):

$$P_m(W) = P^{wind} * C_P = \frac{1}{2}\rho A \bar{v}_m{}^3 C_P, m \in \{1, 12\} \quad (4)$$

where several variables are involved. The air density (ρ) of Shanghai is 1.222 kg/m^3. The wind power coefficient (C_P) is 0.5 for the selected 10 MW modern wind turbine. The rotor area (A) can be calculated via the radius of the turbine blade which is 89.15 m for the selected wind turbine. At last, the average wind speed v_1 per month, which varies between 3.6 m/s and 7.4 m/s, is collected from the aforementioned region. Based on Eq(4), it can evaluate the theoretical profile of the monthly wind turbine generation by Eq(5):

$$Profile_m^{wind}\left(^{kWh}/_{kWp}\right) = P_m * GEAH_m * \frac{1}{Turbine}, m \in \{1, 12\} \quad (5)$$

where $GEAH_m$ is the monthly Generating Equipment Availability Hours of the selected wind turbine and $Turbine$ represents the power capacity of the selected turbine, 10 MW. Following this, the monthly generation of the wind energy system ($Wind_m$) is determined via Eq(6):

$$Wind_m(kWh) = Capacity^{wind} * Profile_m^{wind}, m \in \{1, 12\} \quad (6)$$

3.4 Hydrogen

In this study, to simulate the entire production and distribution process of hydrogen, the efficiency of both the electrolyser, which is used to convert the energy sources to hydrogen, and the fuel cell, designed for distributing hydrogen to electrical and thermal energy, will be taken into consideration. the efficiency of the electrolyser is estimated to be 50 kWh/kg, and the efficiency of the Fuel Cell is assumed to be 39.4 kWh/kg. As a result, the hydrogen generated from the energy sources ($H2_m^{Generated}$) and the monthly storage of hydrogen utilising to balance the generation and the demand ($H2_m^{Stored}$) can be determined by Eq(7) and Eq(8):

$$H2_m^{Generated}(kg) = {}^{(PV_m + Wind_m - Load_m^{Ele})}/_{50}, m \in \{1, 12\} \quad (7)$$

$$H2_m^{Stored}\ (kg) = {}^{Load_m^{HT}}/_{39.4} - H2_m^{Generated}, m \in \{1, 12\} \quad (8)$$

where $Load_m^{Ele}$ represents the monthly Electricity Demand, while $Load_m^{HT}$ stands for the energy demand from Heating and Transportation section of the city.

3.5 Constrains

To set the operational limitations to the optimisation problem, the constraints involved in the model can ensure not only that the annual total energy generated from solar PV and wind can match the annual total energy demand, including the Electricity, Heating, and Transportation sections of the city but also that the annual hydrogen generated from the electrolyser can cover the annual hydrogen utilised to supply the final end. As a result, the inequality constraints can be given by Eq(9):

$$\sum_m H2_m^{Stored} \geq 0,\ m \in \{1, 12\} \quad (9)$$

3.6 Case Study

The methodology is applied to Shanghai, China. The monthly electricity, heating and transportation demand used as the parameters in the study corresponded to the actual energy demand in 2019 which was obtained from (Shanghai Statistics Bureau, 2020) and (Shanghai Government, 2019). Regarding the financial parameters of the problem, such as the cost of solar PV energy systems and the operational cost of the system, the data is collected from the International Renewable Energy Agency as the reference (International Renewable Energy Agency, 2022). These parameters utilised in the optimisation model are presented in Table 1. The energy demands are presented as an annual total.

Table 1: Essential Parameters

$Cost^{PV}$ (EUR/kW)	$Cost^{wind}$ (EUR/kW)	Electricity Demand (GWh/y)	Heating Demand (GWh/y)	Transportation Demand (GWh/y)
1,100	900	156,860	237,178	197,142

4. Results and Discussion

After analysing the model's application to Shanghai's energy sector, due to the large difference of the theoretical profiles between the monthly wind turbine generation and monthly solar PV generation, the distribution between two renewable energy sources, wind and solar PV, leans to one side inevitably. Although the model has successfully demonstrated the ability to create an energy system of a city powered by hydrogen and renewable energy sources at the minimal cost, it is impractical for the energy system's operation of the entire city to fully rely on the single renewable energy source. Consequently, it is essential to explore the second scenario.
In the second scenario, the model takes into account the available resources. Utilising the data from (Shanghai Statistics Bureau, 2020), the maximum potential for solar PV generation is calculated based on the available rooftop area, where 1 m² of rooftop space can contain 0.2 kW of solar PV panels. The remainder of the energy demand is then met by the wind power generation. This approach provides a more realistic estimation of the installed capacity needed for each renewable source. The necessary installed capacity of wind can be estimated by the generation profile and the required area for wind turbine can be estimated through 1 m² of sea area can install 0.8 kW of wind turbines. The total cost, the recommended installed capacities, and the required area in the second scenario are listed in Table 2.

Table 2: Results of the system to be installed in Shanghai.

Energy Source	Scenario 1		Scenario 2		
	Capacity (GW)	Total Cost (EUR)	Capacity (GW)	Total Cost (EUR)	Required Area (m^2)
Solar PV	≈0	≈0.43	379.8	4.178×10^{11}	1.899×10^{9}
Wind	1,127.131	1.014×10^{12}	1,126.136	1.014×10^{12}	1.408×10^{9}
Total	1,127.131	1.014×10^{12}	1,505.936	1.431×10^{12}	3.307×10^{9}

In Figure 3, the year-round operation of the green hydrogen energy system is studied. The figure presents the monthly renewable energy generation, the essential hydrogen storage and discharge, and the energy demands, which are categorised into electricity, heating & transportation, and electrolyser. It is evident in the figure that the designed energy system of Shanghai is impacted by seasonal variations, with wind generation accounting for a significant proportion of the year's output from February to June. Figure 3 depicts that the total generation matches the total demands, the sum of electricity and electrolyser demand. In this system, during the periods of higher generation, surplus hydrogen is stored to supply the future need. It is important to note that although the data spans from January to December, the energy system is designed for continuous yearly operation. Consequently, it is acceptable for the system to require hydrogen discharge in the first month of the year.

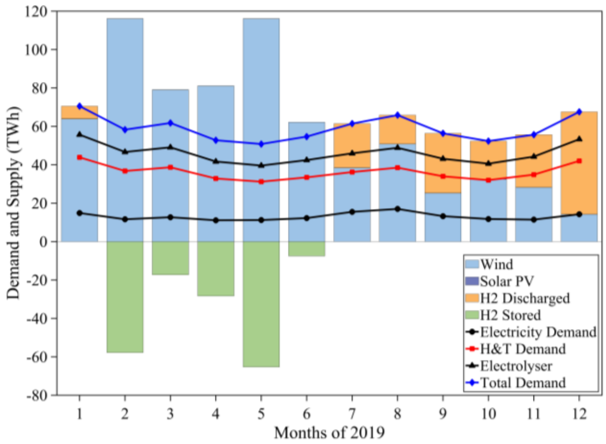

Figure 3: Supply and demand of the green hydrogen energy system.

5. Conclusion

This research explores the green hydrogen concept and introduces a green hydrogen energy system model for Shanghai's electricity, heating, and transportation sectors. The model optimises renewable energy sources, hydrogen production and storage, and energy sector demands based on costs and available resources. By calculating Shanghai's monthly theoretical generation profiles, the model estimates the ideal capacities of renewable energy sources to meet urban energy demands. The model is simulated under two scenarios to optimise minimal costs and efficient use of area resources. In Scenario 1, the minimal cost is estimated at 1.014×10^{12} EUR, while in Scenario 2, the required area is 3.307×10^{9} m^2. Both scenarios offer valuable guidance for applying the green hydrogen concept to urban energy systems. It is essential to provide the following future directions. The model's reliance on monthly data might overestimate the need for hydrogen storage. If data were available on an hourly basis, the requirement for hydrogen storage could likely be reduced, allowing for a more precise match between supply and demand. Additionally, future studies could incorporate a wider range of renewable energy sources to develop a more comprehensive and feasible energy model for urban areas.

Acknowledgments

The funding received from the scientific research projects of Shanghai Investigation, Design & Research Institute (Contract number: 2023QT(83)-008) is gratefully acknowledged.

References

Balta, M. Ö., Balta, M. T., 2022, Development of a Sustainable Hydrogen City Concept and Initial Hydrogen City Projects, Energy Policy, 166, 113015.

Barros, L. M., Silva, J. F. L., Anchieta, C. G., Maciel Filho, R., 2024, Assessment of Energy Efficiency of Green Hydrogen Produced from Biomass and Green Ammonia, Chemical Engineering Transactions, 109, 511-16.

Boretti, A., 2022, Hydrogen Key Technology to Cover the Energy Storage Needs of Neom City, International Journal of Hydrogen Energy, 47, 14371-74.

International Renewable Energy Agency, 2022, Renewable Power Generation Costs in 2020 <irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020> accessed 11.07.2024.

Juárez-Casildo, V., Cervantes, I., González-Huerta, R. d. G., 2022, Solar Hydrogen Production in Urban Areas of Mexico: Towards Hydrogen Cities, International Journal of Hydrogen Energy, 47, 30012-26.

Khalil, M., Dincer, I., 2023, Development and Assessment of Integrated Hydrogen and Renewable Energy Systems for a Sustainable City, Sustainable Cities and Society, 98, 104794.

Li, L., Chen, C., Xie, S., Huang, C., Cheng, Z., Wang, H., Wang, Y., Huang, H., Lu, J., Dhakal, S., 2010, Energy Demand and Carbon Emissions under Different Development Scenarios for Shanghai, China, Energy Policy , 38, 4797-807.

Liu, X., Bae, J., 2018, Urbanization and Industrialization Impact of CO2 Emissions in China, Journal of cleaner production, 172, 178-86.

Lodhi, M., 1987, Hydrogen City, International Journal of Hydrogen Energy, 12, 783-803.

Shanghai Government, 2019, Shanghai Monthly Energy Operation Report, Shanghai Government < jjyx.sheitc.sh.gov.cn/detail.jsp?articleId=3193&channelId=02 > accessed 14.06.2024. (in Chinese)

Shanghai Statistics Bureau, 2020, Shanghai Statistics Yearbook 2023, <tjj.sh.gov.cn/tjnj/tjnj2020e.htm> accessed 14.06.2024.

The Energy Institute, 2024, 2024 Statistical Review of World Energy, <energyinst.org/statistical-review> accessed 12.06.2024.

Tiwari, M., Babu, M. P., Vinu, R., 2024, Hydrogen and Bio-Oil Production from Diverse Biomass through Microwave-Assisted Pyrolysis, Chemical Engineering Transactions, 109, 253-58.

UN, 2018, 2018 Revision of World Urbanization Prospects, United Nations <un.org/en/desa/2018-revision-world-urbanization-prospects> accessed 14.06.2024.

You, C., Kim, J., 2020, Optimal Design and Global Sensitivity Analysis of a 100% Renewable Energy Sources Based Smart Energy Network for Electrified and Hydrogen Cities, Energy Conversion and Management, 223, 113252.