Applied Energy Symposium 2020: Low carbon cities and urban energy systems
October10-17, 2020
Paper ID: CUE2020-D-150

Valorisation of Municipal Combustible Waste as Injected Fuel for the Blast Furnace Ironmaking process

Lian Ye[1], Guangwei Wang[1], Chen Wang[2], Jianliang Zhang[1], Xiaoming Mao[2], Haipeng Teng[1], Chuan Wang[3*]

1 School of Metallurgical and Ecological Engineering, University of Science and Technology Beijing, Beijing 100083, China

2 Baosteel Research Center, No. 889 Fujin Road, Baoshan District, Shanghai, 201900, China
3 Swerim AB, SE-971 25 Luleå, Sweden
(*Corresponding Author: Chuan.Wang@swerim.se)

ABSTRACT

With the development of China's urbanization process, steel plants are gradually surrounded by cities. The coexistence of steel industries and cities has become inevitable. This paper presents a concept of upgrading and using municipal combustible waste (MCW) and in the ironmaking process as fuel. Blast furnace (BF) injection of MCW can reduce the environmental hazards of the MCW disordered treatment, and it can also reduce the consumption of fossil fuels in ironmaking. However, the low energy density, high content of harmful elements and difficulties in grindability and injection limit its application in BF injection. This research innovatively proposed a new technical route that uses hydrothermal carbonization technology (HTC) to treat MOW and applies the prepared hydrochar to BF injection. The research results showed that the energy density of hydrochar is significantly increased, the content of harmful elements is greatly reduced, and the grindability is significantly improved. Meanwhile, compared with the bituminous coal, the hydrochar has better combustion performance and can be used as an alternative fuel for BF injection. It can foresee that the steel plant may facilitate on building up a low carbon city by valorizing and using MCW in the ironmaking process for the substitution of fossil fuels.

Keywords: Municipal combustible waste, Blast furnace injection, Hydrothermal carbonization, Hydrochar, Combustion

NONMENCLATURE

Abbreviations	
MCW	Municipal Combustible Waste
BF	Blast Furnace
HTC	Hydrothermal Carbonization
PET	Polyethylene Terephthalate
PVC	Polyvinyl Chloride
SS	Soybean Straw
WS	Wheat Straw
MS	Maize Straw
CC	Corncob
SH	Shenhua Bituminous Coal
YQ	Yangquan Anthracite
HHV	High Calorific Value

1. INTRODUCTION

China became the largest steel producer in 2006, and its steel production has been increasing since then. Even during the COVID-19 epidemic when the world crude steel production had, a 7.0 % decrease compared to June 2019, China produced 91.6 million tons of crude steel in June 2020, an increase of 4.5% compared to the same period in2019[1]. As an energy and resource-intensive industry, steel production is second only to the power industry in CO_2 emissions in China. In order to reduce the CO_2 emissions of steel production, a lot of researchers have turned their attention to recyclable resources such as crop straw and MCW. China is the most populous country in the world, and there are a large number of crop straws in the vast rural areas

Selection and peer-review under responsibility of the scientific committee of CUE2020

every year. However, due to the low energy density of crop straws, it is difficult to collect, transport and store them, and the resource utilization rate of crop straws is low at present[2]. At the same time, China is also the country with the largest scale of urbanization in the past 30 years. With the development of social economy, China is also faced with the problem of MCW disposal. If the waste biomass, waste plastics and other MCW resources can be applied to BF iron-making production, on one hand, the problem of harmless treatment of MCW can be solved, and on the other hand, the consumption of fossil energy in iron-making production can be reduced.

In order to solve the problems of low energy density, high content of harmful elements and difficulty in grindability of crop straw and MCW, the HTC was put forward to improve the quality, and the prepared hydrochar was injected into BF [2]. HTC is a thermochemical process that can transform organic matter into rich carbon product-hydrochar[3]. Hydrochar prepared from crop straw and MCW by HTC has the characteristics of high energy density, low content of harmful elements and easy to grind. Based on the previous researches, this paper used HTC to treat common crop straws and plastics in MCWs. The feasibility of the prepared hydrochars for BF injection was analyzed, which provides important support for the efficient application of crop straw and MCW for the ironmaking production.

2. MATERIALS AND METHODS

The experimental materials include two types of waste plastics: polyethylene terephthalate (PET), polyvinyl chloride (PVC) and four types of crop straws: soybean straw (SS), wheat straw (WS), maize straw (MS) and corncob (CC). The proximate analysis, ultimate analysis results are shown in Table 1. It can be seen that the fixed carbon content of the six raw samples is relatively low, and the MS sample with the highest fixed carbon content is only 16.17%.

The HTC experiment was carried out in an autoclave of 250 ml, about 20 g sample was added into the reactor, and then 60 ml of deionized water was added and sealed for heating. The HTC temperature and reaction time were controlled at 280 °C and 60 min by the proportional integral derivative controller (PID). After the heated process, the HTC reactor was automatically cooled to room temperature, and then opened the reactor cover to take out the solid-liquid reaction products for suction filtration. The solid products obtained were hydrochar, named H-PET, H-PVC, H-SS, H-WS, H-MS, H-CC. The hydrochars were dried at 105°C for 24h. After that, the dry hydrochars were crushed and screened to the size below 74 μm, then set them aside in the sealed bag for following tests. In order to further compare the similarities and differences between hydrochar and pulverized coal injection in BF, Shenhua bituminous coal (SH) and Yangquan anthracite (YQ) were selected as the comparison objects.

Table 1 Proximate and ultimate analyses of different samples

Sample	Proximate analysis (wt, %)			Ultimate analysis (wt, %)				
	FC_d^a	A_d	V_d	C_d	H_d	O_d^a	N_d	S_d
PET	1.79	-	98.21	74.76	11.12	13.99	0.10	0.03
PVC	1.55	-	98.48	46.76	5.60	--	0.02	0.21
SS	14.50	5.52	79.98	41.98	6.35	45.03	0.92	0.20
WS	14.02	8.56	77.42	44.52	5.97	40.56	0.26	0.24
MS	16.17	5.46	78.37	45.30	5.85	42.40	0.78	0.21
CC	14.92	1.87	83.21	45.18	6.26	46.06	0.490	0.14

3. RESULTS

3.1 Composition analysis of hydrochar

In order to clarify the composition change rules of waste plastics and crop straw after HTC, the proximate and ultimate analysis of hydrochars were carried out and the results are shown in Table 2. It can be seen that the volatiles content of PVC and four types of biomass are significantly reduced after HTC, and the fixed carbon content is increased. Among them, the fixed carbon content of H-CC was the highest, reaching 51.29 %. The composition of the PET sample did not change much after HTC. The volatile content in the PET sample was 98.21%, and the volatile content in the H-PET sample decreased slightly, reaching 96.67%.

The other important observation was that with the removal of volatiles, the ash content of four types of biomass did not increase after HTC, but decreased significantly. The main reason is that there are rich water-soluble minerals (K, Ca, Na) in crop straw. During the HTC process, a large amount of soluble minerals enters the water, which makes the ash content in the prepared hydrochar significantly reduced. The ash content of SS sample was 5.52%, H-SS sample was 3.67%, WS sample was 8.56%, H-WS sample was 6.64%, MS sample was 5.46%, and H-MS sample decreased to 2.07%. Compared with the above four types of crop straws, the ash removal rate of CC sample was the highest, the ash content of CC original sample was 1.87%, and the ash content of H-CC sample obtained by HTC was reduced to 0.14%. Higher fixed carbon content and lower ash content are conducive to BF injection, which can provide more heat and reducing agent for BF smelting, reduce the amount of iron slag and improve the economic and technical performance indicators.

The results of ultimate analysis show that the carbon content of H-PET and H-PVC was 78.34% and 84.58%, respectively. The carbon content of four types of crop straw hydrochar ranged from 69.41% to 72.98%. The oxygen content was greatly reduced compared to the raw sample, which is mainly caused by the decarboxylation reaction during the HTC process. In addition, it can also be noticed that the sulfur content in the six types of hydrochar were relatively low, and the sulfur contents in the H-PET and H-MS samples were only 0.03% and 0.14%. The lower sulfur content is beneficial to reduce the sulfur load of BF smelting, and improve the quality of hot metal while reducing the fuel ratio. Comparing the change of hydrogen content in hydrochars, it is found that the content of hydrogen in six types of hydrochar were between 5.12% and 10.52%. Due to the diffusion and reduction ability of H_2 in BF is better than that of CO, the higher hydrogen content is beneficial to improve the reducibility of the ore in the BF and to the smelting production.

In order to further compare the combustion heat release of different hydrochars in front of tuyeres, the high calorific value (HHV) of hydrochars was calculated by using the following equation.

Table 2 Proximate, ultimate and HHV analyses of hydrochars

Sample	Proximate analysis (wt, %)			Ultimate analysis (wt, %)					H/C	O/C	HHV(MJ/kg)
	FC_d^a	A_d	V_d	C_d	H_d	O_d^a	N_d	S_d			
H-PET	3.33	-	96.67	78.34	10.52	10.90	0.21	0.03	1.61	0.10	38.62
H-PVC	43.31	4.43	52.26	84.58	7.27	3.41	0.08	0.23	1.03	0.03	37.21
H-SS	43.05	3.67	53.28	69.73	5.69	19.38	1.29	0.24	0.98	0.21	28.99
H-WS	44.64	6.64	48.72	69.41	5.41	17.13	0.97	0.44	0.93	0.19	28.73
H-MS	47.28	2.07	50.65	72.98	5.36	18.09	1.36	0.14	0.88	0.19	29.89
H-CC	51.29	0.14	48.57	72.92	5.12	20.97	0.70	0.15	0.84	0.22	29.42
SH	56.77	8.10	35.13	73.58	4.44	12.54	0.91	0.43	0.72	0.13	29.49
YQ	81.55	11.21	7.24	82.33	2.36	2.43	1.05	0.62	0.34	0.02	31.10

[a] Calculated by difference. FC, fixed carbon; A, ash; V, volatile matter; d, dry basis.

$$HHV = 0.3491 \cdot C + 1.1783 \cdot H + 0.1005 \cdot S - 0.1034 \cdot O - 0.0015 \cdot N - 0.0211 \cdot A \quad (1)$$

where, C, H, S, O, N and A represent the mass percentage of carbon, hydrogen, oxygen, nitrogen, sulfur and ash content on dry basis. The HHV of hydrochars (H-SS, H-WS, H-MS and H-CC) are similar, 28.99 MJ/kg, 28.73 MJ/kg, 29.89 MJ/kg and 29.42 MJ/kg, respectively. It is close to the HHV of bituminous coal injected into BF.

The two types of waste plastic hydrchars have high HHV because of their higher carbon and hydrogen content. The HHV of H-PET was 38.62 MJ/kg and H-PVC was 37.21 MJ/kg, which is much higher than anthracite used for BF injection. The higher HHV can provide

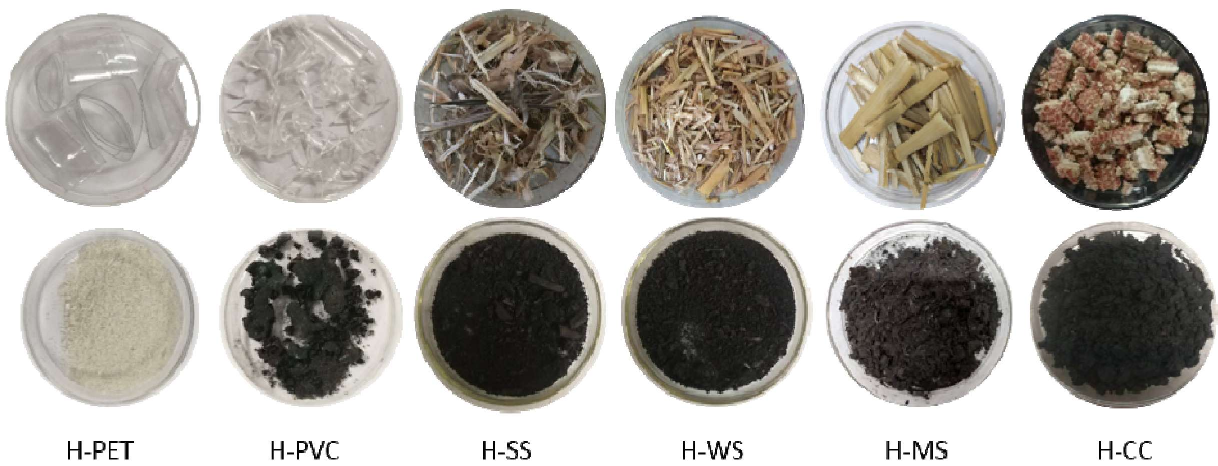

Fig 1 Image of raw samples and hydrochars

sufficient heat for the high-temperature zone of the BF, increase the replacement ratio of injected fuel and coke, which is of great significance for reducing the amount of coke smelted in the BF.

3.2 Morphology changes after HTC

Fig.1 shows the morphology of six raw samples and hydrochars. It can be seen that the PET sample is transparent and thin, with certain strength and good flexibility, and can only be cut with scissors. The H-PET sample is granular and easily broken into powder. PVC samples are similar to PET, they are also transparent flakes, and have good flexibility and but are difficult to crush. The samples after HTC treatment have been obviously carbonized, and some samples adhere to form coke-like particles with irregular shapes, which can be crushed by extrusion. The crop straw hydrochars form a porous coal-like material, which can be pulverized using a ball mill or a medium-speed mill. The above analysis shows that the hydrochars of waste plastics and biomass have good pulverizing performance, and can be crushed and injected by the existing pulverizing and injection equipment of iron and steel enterprises

3.3 Migration of harmful elements during HTC

The four types of biomass are rich in alkali metals (K, Na), which are easily dissolved in water during HTC and removed. In order to clarify the influence of HTC process on the migration of harmful elements of alkali metals(K+Na), the alkali metal content of samples after HTC was determined by chemical analysis method. The alkali metal content of four crop straws were SS(0.68%), WS(1.35%), MS(0.86%), CC(0.47%), respectively. Four hydrochars were H-SS (0.120%), H-WS(0.055%), H-MS(0.038%), H-CC(0.043%), respectively.

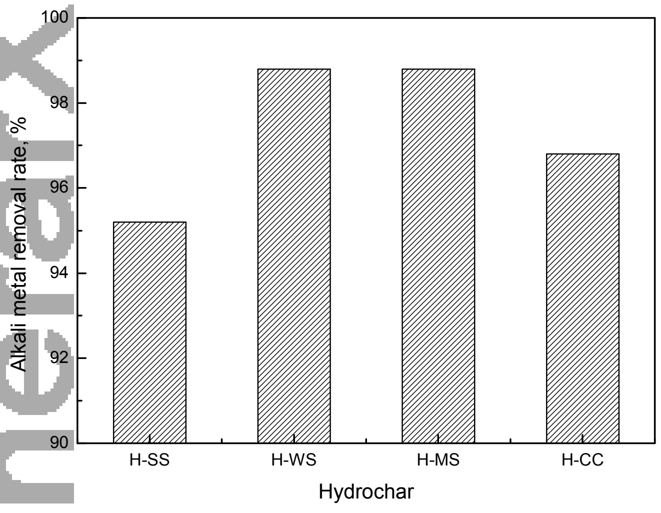

Fig 2 Alkai metal removal rate after HTC treatment

Combined with four crop straw hydrochar yields data that H-SS (29.3%), H-WS (37.0%), H-MS (35.8%), H-CC (44.8%), the alkali metal removal rate of hydrochars can be obtained, and the results are shown in Fig. 2. It can be seen that the removal rates of alkali metals were 95.2% in H-SS, 98.8% in H-WS, 98.8% in H-MS and 96.8% in H-CC. The removal rate of alkali metals by HTC is all over 95%.

Alkali metals have a serious harmful effect on BF smelting, which can promote the degradation of coke and ore in the BF, affect the gas and liquid permeability, cause the damage of refractory materials and campaign of BF smelting. At present, there are strict restrictions on the alkali metals load in the BF at home and abroad, so as to avoid the cyclic enrichment of alkali metals in the BF, which has a negative impact on the economic and technical performance indicators of BF smelting.

As a renewable and clean energy, biomass has been considered as one carbon source to replace fossil carbon in the ironmaking process. However, due to the high content of alkali metals, it has not been applied yet. The high efficiency of alkali demineralization of HTC provides a new method for the application in BF. In addition, subcritical water can also remove some harmful elements, for instance the chlorine element in PVC waste plastics. Under the condition of not adding other reagents, the dechlorination effect can be achieved more than 95% at the HTC temperature of 280°C and time of 60 min.

3.4 Combustion characteristics

The combustibility of the samples was carried out under a light atmosphere using a thermogravimetric analyzer. All samples were tested under air condition at the heating rates of 20 °C/min. As shown in Fig.3, six types of hydrochar and SH combustion curves are concentrated in the 250°C to 650°C. Two types of waste plastics hydrochar burning process are divided into two distinct stages, especially the conversion rate curve is divided into two combustion peaks, and the first peak significantly greater than the second combustion. The main reason is that the volatile contents are higher. The combustion curves of the four crop straw hydrochars are similar to those of SH. In the conversion rate curve, only one weight-loss stage can be seen, and only one obvious combustion peak and an insignificant shoulder peak can be seen at about 350°C in the conversion rate curve.

In order to quantitatively compare the differences between six hydrochars and SH in combustion process, the combustion characteristics were extracted[4], the results are shown in Table 3. As shown in the table, the initial temperature (T_i) of H-SS sample is 246.9°C. The lower T_i is conducive to the rapid ignition and combustion of BF injection, but it will have a negative impact on the safety performance of pulverizing, storage and transportation. The burnout temperature (T_b) of six hydrochars is higher than SH, which indicates that the burnout performance of hydrochars is slightly worse. Compare different hydrochars comprehensive combustion index S values, it can be found that only the H-MS sample is much smaller than SH, other hydrochar values are close to or higher than SH. The higher value indicates that the comprehensive combustion performance of hydrochars is better, thus the utilization efficiency in BF can be ensured when it is injected.

more than 5 billion tons, but the harmless treatment rate is less than 10%. A large number of wastes are transported to the suburbs of the city for bare stacking, occupying more than 500 million m^2 of land[5], and most cities are surrounded by urban waste. At the same time, as a large agricultural country, China is rich in biomass energy. The total amount of agricultural and forestry wastes generated each year reaches 1.6 billion tons. If half of them are used as biomass fuel, they can be converted into about 400 million tons of standard coal. In addition, since the reform and opening up, China has made great achievements in social and economic development. In 2019, China's crude steel output exceeded 980 million tons, accounting for more than 53 % of the world's steel output. Meanwhile, the energy

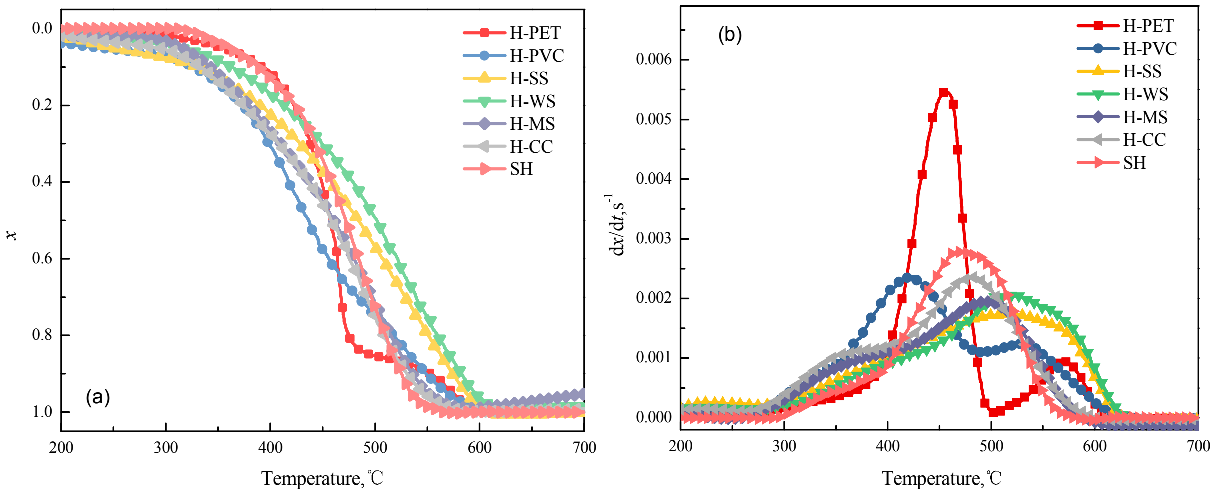

Fig 3 The combustion curves of different samples (a) Conversion rate, (b) Reaction rate

Table 3 The combustion characteristics parameters of different samples

Sample	T_i(°C)	T_b(°C)	R_{max} (s^{-1})×10^3	R_{mean}(s^{-1})×10^4	S×10^{15}
H-PET	353.6	575.2	5.44	8.09	13.2
H-PVC	265.6	570.0	2.35	7.77	7.5
H-SS	246.9	588.0	1.80	7.61	5.9
H-WS	303.0	599.2	2.09	7.73	5.6
H-MS	309.4	552.1	2.01	6.28	4.5
H-CC	275.7	547.0	2.37	7.53	7.2
SH	363.6	541.1	2.79	6.86	5.8

Note: T_i, initial temperature; T_b, burnout temperature; R_{max} and R_{mean}, maximum reaction rate and mean reaction rate; S, comprehensive combustion index.

4. Discussion

China's annual output of urban waste is about 150 million tons, with an annual growth rate of 8% - 10%. Over the years, the stock of urban waste has reached

consumption of domestic iron and steel industry ranks first among all process industries, accounting for 12% - 20% of the total energy consumption. Among them, the energy consumption and CO_2 emissions from the ironmaking process account for about 70% of the total iron and steel industry. Therefore, the ironmaking process is the focus of energy conservation and emission reduction in the iron and steel industry.

BF as a high temperature metallurgical furnace, if the MCW can be successfully consumed, it can save piling up and landfill land for the expansion of urbanization, and also avoid the waste pollution of soil and water source. It is worth noting that if MCW is piled up for a long time without proper disposal, a large amount of methane gas will be generated, thus accelerating the climate warming, because the greenhouse effect potential value of CH_4 is 21 times higher than that of CO_2. Therefore, the absorption of MCW will cut off the pollution from the source. Maximization of energy and resources at the same time of harmlessness, that is, to achieve the purpose of disposing MCW, and relieve the pressure of energy consumption. This is of great significance to ecological and environmental protection, national economic development and energy structure adjustment.

BF injection of MCW technology has not been widely applied. The main reasons include the following three aspects: 1) combustible waste recycling. It is difficult to provide stable and high-quality combustible waste for BF injection due to the fact that the collection of combustible waste is not scale-up, the effect of classification and recovery is not ideal, and the absolute supply is insufficient; 2) pulverization and transportation of MCW. The BF injection technology requires that the solid fuel has a very small particle size. At present, the granulation efficiency is low, energy consumption and pollutant emission are enlarged, and the granulation products have the disadvantages of coarse particle size and poor uniformity, so the traditional BF coal pulverizing and conveying system cannot be used for MCW, and the construction of special equipment will greatly increase the investment and operation cost; 3) harmful elements in MCW. Especially alkali metals in biomass and chlorine in PVC waste plastics, which are directly injected into BF without classification or dealkali metal and dechlorine treatment, will have an impact on BF smelting and ancillary equipments. In addition, some waste plastics also contain heavy metal elements, which will cause secondary environmental pollution if not handled properly. With the implementation and advancement of waste classification and straw resource utilization policy, and the influence of the restrictive link in the BF injection technology is gradually weakened. It is key to promote and implement the MCW injection technology to find a method that can effectively remove the harmful elements while improving the grindability performance and make use of the existing system of pulverizing, conveying and spraying of MCW.

After the HTC treatment of MCW, the hydrochar with similar performance to coal can be obtained, and its crushing and transportation performance can be improved obviously. HTC can remove a large number of water-soluble elements (K, Na, Cl, etc.) in the raw materials, and greatly reduce the content of ash and harmful elements in the products. Due to the strong oxidation of subcritical water, organic pollutants such as dioxins and furans can be completely decomposed, thus reducing the generation and release of secondary pollutants during HTC process. It is an important way for urban construction and green production of iron and steel to combine HTC technology and blast furnace injection to explore a new injection technology of green, efficient, low energy consumption and low cost of MCW.

5. Conclusions

Combined with the needs of urban construction and green steel production technology, this paper put forward a new injection technology of MCW using HTC. The hydrochars prepared from waste plastics and crop straw has the characteristics of high energy density and low content of harmful elements. It can be used for pulverization and injection production with the existing equipment of iron and steel enterprises. It is a high-quality fuel to replace bituminous coal injected. This technology solves the problems of low energy density, high harmful elements, crushing and injection difficulties of MCWs, and it is an important technological breakthrough for the construction of urban steel industries and the deep integration of steel production and urban construction.

ACKNOWLEDGEMENT

This work was supported by the NSFC (No. 51804026), VINNOVA (dnr:2017-01327) and SK funding of Swerim (pnr:70.101155.10).

REFERENCE

[1] Monthly Steel Production Review. Steel Production Report. https://www.steelonthenet.com/production.html [accessed June 2020]

[2] Wang GW, Zhang JL, Lee JY, Mao XM, Ye L, Xu WR, Ning XJ, Zhang N, Teng HP, Wang C. Hydrothermal carbonization of maize straw for hydrochar production and its injection for blast furnace. Applied Energy 2020; 266:114818.

[3] Zhao PT, Shen YF, Ge SF, Kunio YSKW. Energy recycling from sewage sludge by producing solid biofuel with hydrothermal carbonization. Energy Conversion and Management 2014; 78:815-821.

[4] He C, Giannis A, Wang JY. Conversion of sewage sludge to clean solid fuel using hydrothermal carbonization: Hydrochar fuel characteristics and combustion behavior. Applied Energy 2013;111:257-266.

[5] Fu J, Han XK, Li G. Research on the classification of urban household garbage and organic waste treatment methods in China. China Resources Comprehensive Utilization 2014;33:30-33.