Energy 236 (2021) 121505

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Transformation of low-rank coal to clean syngas and power via thermochemical route

Muflih A. Adnan [a, **], Arif Hidayat [a], Mohammad M. Hossain [b, c, ***], Oki Muraza [d, *]

[a] Department of Chemical Engineering, Islamic University of Indonesia, Sleman, Daerah Istimewa Yogyakarta, 55584, Indonesia
[b] Department of Chemical Engineering, King Fahd University of Petroleum & Minerals, Dhahran, 31261, Saudi Arabia
[c] Center of Research Excellence in Nanotechnology, King Fahd University of Petroleum & Minerals, Dhahran, 31261, Saudi Arabia
[d] PT Pertamina (Persero), Sopo Del Building, 51st Fl. Jl. Mega Kuningan Barat III, Jakarta Pusat, 12950, Indonesia

ARTICLE INFO

Article history:
Received 19 May 2021
Received in revised form
23 June 2021
Accepted 13 July 2021
Available online 15 July 2021

Keywords:
Thermochemical conversion
Carbon conservation
Low-rank coal
Thermodynamic analysis
Clean technology

ABSTRACT

An emerging gasification was proposed for the transformation of low-rank coal to clean syngas and electricity. The excess heat from char combustion was used to evaporate moisture in coal and to generate power via steam turbine generator. The simulation was developed in the Aspen Plus based on the proper thermodynamic model. The validation exhibited a good concurrence between the present model and the experiments under the same condition with the relative error <10% in the pyrolysis stage. The moisture content reduced the energy efficiency by ~10% but increased the H_2 production by ~50% which results in the increase of H_2/CO up to 10. The highest energy and exergy efficiencies (91% and 79%, respectively) was observed on the O_2 equivalence ratio and steam to ratio of 0.21 and 0.06, respectively. O_2 is an appropriate gasifying agent to produce syngas as the energy source, while steam gives high-quality syngas as the feedstock for chemical industries. The CO_2 emission of the proposed configuration is below 50 kg CO_2/GJ (half of the conventional coal combustion, ~100 kg CO_2/GJ) when the fraction of char to combustor is less than 0.4.

1. Introduction

Coal is a promising energy resource due to its abundant deposits in many countries. Coal is intensively utilized via direct combustion to supply the energy demand. Consequently, coal combustion is the majority responsible for the increase of CO_2 emission, as compared to natural gas and oil [1]. Coal is also targeted to substitute natural gas [2] and oil [3], and as the feedstock of petrochemical industries [4] and synthetic fuel (i.e. dimethyl ether) [5]. An appropriate conversion technology of coal into energy is crucial to meet the worldwide demand for energy and petrochemical products. Gasification is a suitable process for coal utilization due to its ability to convert coal into various products at high efficiency (up to 81%) [6].

Gasification is a thermal conversion process which converts coal into syngas, with a major constituent of H_2 and CO. The syngas composition is strongly influenced by the coal properties, which widely diverse due to the natural source [7]. In addition, the composition of gasifying agents [8] and gasifier operating conditions [9] strongly affected the syngas quality. It is worth noting that the composition of syngas is crucial when syngas is targeted as an intermediate chemical to produce petrochemical products. For instance, the methanol synthesis reactor required syngas with a H_2/CO ratio of 2.0 [10]. Meanwhile, for the power generation purpose, the syngas composition delivers a minor influence on the process given it only focuses on the conversion of thermal energy [11].

One should note that the H_2/CO ratio is strongly affected by the natural properties of coal (i.e., coal composition) [12]. For instance, Wang et al. [13] reported that different H_2/CO molar ratios were observed on the gasification (fixed bed down-draft gasifier) of three types of coal from different mining sites in China. Considering this nature challenge, various efforts (i.e., addition of steam, incorporation of catalysts, and gasifier design) have been conducted to adjust the syngas composition in order to satisfy the required petrochemical feed specs, particularly the H_2/CO ratio [14].

The selection of steam (H_2O) gasifying agents has been reported

* Corresponding author. PT Pertamina (Persero), Sopo Del Building, 51st Fl. Jl. Mega Kuningan Barat III, Jakarta Pusat, 12950, Indonesia.
** Corresponding author. Department of Chemical Engineering, Islamic University of Indonesia, Sleman, Daerah Istimewa Yogyakarta, 55584, Indonesia.
*** Corresponding author. Center of Research Excellence in Nanotechnology, King Fahd University of Petroleum & Minerals, Dhahran, 31261, Saudi Arabia.
E-mail addresses: muflih.adnan@uii.ac.id (M.A. Adnan), mhossain@kfupm.edu.sa (M.M. Hossain), oki.muraza@pertamina.com (O. Muraza).

https://doi.org/10.1016/j.energy.2021.121505
0360-5442/

as a promising strategy to adjust the H_2/CO ratio. The introduction of steam into the gasifier increases the H_2/CO ratio as steam provides H atom for H_2 formation. Kumar et al. [15] conducted gasification experiments using Indian coal with the mixture of air and steam as the gasifying agent. They reported that the increase of steam flow into the gasifier delivers a positive effect on the H_2/CO ratio. A similar conclusion also has been reported by Crnomarkovic et al. [16] using lignite Kolubara coal in an entrained flow gasifier. One should note that increasing the H_2/CO ratio by the addition of steam technically promotes the water-gas shift and endothermic steam reforming reactions [17]. Therefore, in an auto-thermal gasification system, the high steam flow reduces gasifier temperature, which inhibits the rate of both reactions. Therefore, though the addition of steam successfully enhances the H_2/CO ratio, the obtained results still require improvement to meet the required syngas quality due to the trade-off between the steam injection and gasifier temperature.

Another way to adjust H_2/CO ratio is by introducing catalysts to the gasification process. In the gasification process, catalysts have a substantial role to facilitate tar reforming reaction (i.e., converting tar into H_2 and CO) [18]. To cite a few, the Ni/$CeZrO_2$ catalysts have been reported to facilitate the reforming of tar in a modeled gasification of coal at the gasification temperature above 700 °C, which results in the increase of the H_2/CO ratio up to 1.92 [19]. The addition of K_2CO_3 catalysts also showed a positive effect on the H_2 concentration in gasification of sub-bituminous coal under high-pressure condition (3.5 MPa), with the highest H_2/CO ratio of ~5.5 [20]. The incorporation of Ni on the gasification of coal also boosted the H_2 production, which results in a positive effect on the H_2/CO ratio [21]. Zhang et al. [21] reported that the gasification of coal using Ni catalysts produced syngas with the highest H_2/CO ratio of 6. Though the catalytic gasification exhibited good performance, the operating cost will significantly increase due to the catalyst's expenses.

The modification of gasifier design can be an alternative strategy to improve the H_2/CO ratio by avoiding additional costs for catalysts procurement. A number of researchers reported the configuration of the coal gasification process both numerically and experimentally. A numerical investigation is an attractive approach due to its effectiveness in terms of time and cost. Chen et al. [22] studied numerically integrated supercritical gasification of coal to enhance energy efficiency. In their configuration, the boiler feed water was generated by using the hot gasifier products prior to entering the boiler, which results in increased energy efficiency. The identical configuration was proposed by the same group [23] with an addition of a combined cycle to improve electricity production. Yilmaz et al. [24] proposed integrated coal gasification to produces high-quality syngas and electricity by the combination of a multi-generation plant including gasification, power generation and electrolyzer. Based on the mentioned literature earlier, hydrogen production is solely enhanced by maintaining the gasifier temperature. Indeed, higher gasification temperatures promote hydrogen production. However, higher temperature results in higher operating cost. An interesting gasification design was reported by Xiao et al. [25], which proposed dual-loop gasification to minimize tar content and enhance H_2 concentration. Olivine was circulated between the reactors and played a role as a catalyst for tar minimization. With this configuration, the high-quality syngas (H_2/CO ratio varies between 4.8 and 6.8) were successfully produced from the gasification of Shenmu bituminous coal by varying the operating temperature from 700 to 850 °C. However, the implementation of circulating solid is a strenuous process and requires high operating costs [26].

Aiming to avoid the dependency on the catalysts or requiring intensive energy which leads to high operating cost, the present study proposes the development of a highly efficient gasification process by proposing an emerging configuration of low-rank coal gasification to produce high-quality syngas and electricity. The low-rank coal was selected as the feedstock given it is evenly distributed worldwide with an attractive price [27]. In contrast to the earlier reported strategies (i.e., utilization of catalyst, modification of the gasification with looping heat carriers, and addition of steam), the proposed novel configuration allows the adjustment on the wide-range H_2/CO ratio by controlling the amount of char into the gasification and combustion chambers, as illustrated in Fig. 1 (detail process description is presented in Section S1, Supplementary Information). A novel model of pyrolysis is used to accommodate tar formation during coal thermal decomposition. The proposed configuration was developed in Aspen Plus simulation software which allows the main chambers including reforming, gasification and combustion operate at the thermodynamic equilibrium. The gasification performance is assessed based on the syngas quality and the energy conversion with varying the flow rate of gasifying agents (i.e., O_2 and steam). The energy conversion is evaluated based on overall energy efficiency, overall exergy efficiency and cold gas efficiency. The quality of syngas is determined by the composition of major components (H_2, CO and CO_2) and the H_2/CO ratio. Regarding low-rank coal, the operation and economic problem of low-rank coal majorly depend on the moisture content [28]. Thus, the effect of coal moisture on the process performance was also evaluated in the present study.

2. Performance evaluation

As mentioned above, the performance evaluation was conducted in both terms: energy conversion and syngas quality. The quality of syngas was measured by the flow rate, H_2/CO ratio and distribution of major constituents (H_2, CO, and CO_2). The cold gas efficiency (CGE) is the energy ratio of the syngas to the feed, which is defined as:

$$CGE(-) = \frac{m_{sg}\,LHV_{sg}}{m_{cl}\,LHV_{cl} + H_s m_s} \quad (1)$$

where *LHV*, *m*, and *H* are lower heating value, mass flow rate, and enthalpy, respectively. The subscript *sg*, *cl* and *s* denote syngas, coal and steam, respectively. The overall energy efficiency (η_{en}) is the ratio of the input energy to the output energy, which is illustrated in the following equation:

$$\eta_{en} = \frac{E_{out}}{E_{in}} \quad (2)$$

where E_{out} and E_{in} are the total energy that enters and leaves the system, respectively. E_{out} is a summation of various types of energy including the energy contains in the syngas, the heat taken by the coolers and the generated electricity. E_{in} is a total energy input including the energy contains in the feed, the heat required by boiler, the energy to drive CO_2 compressor, the energy to produce O_2 (1.098 MJ/kg pure O_2 [29]) and the energy required by CO_2 absorber (3 GJ/ton of CO_2 captured) [30].

The exergy represents the maximum amount of work that can be obtained from a system which goes to the equilibrium condition of its environment [31]. The exergy analysis is referred to the earlier literature [32]. The overall exergy efficiency is defined as the ratio of the exergy in the outlet streams ($\xi_{sy,out}$) to its counterpart in the inlet streams ($\xi_{sy,in}$), as shown in Eq. (17) [33]:

$$\eta_{ex} = \frac{\xi_{sy,out}}{\xi_{sy,in}} \quad (3)$$

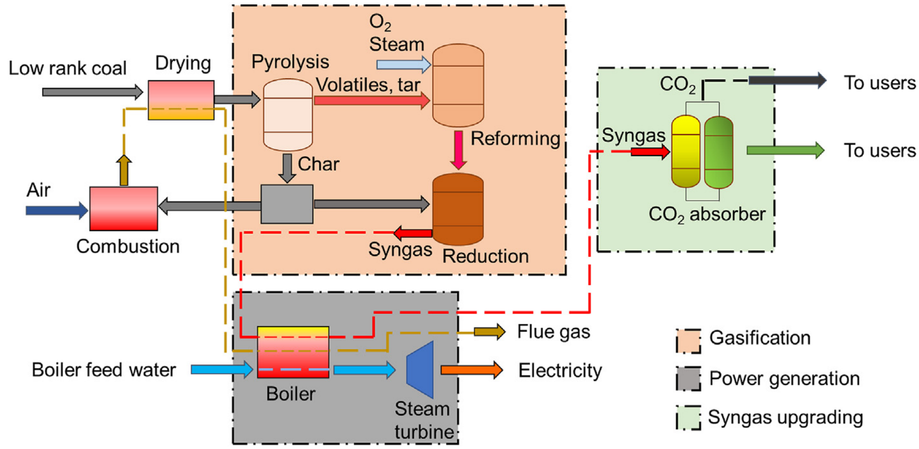


Fig. 1. Scheme of the integrated configuration for gasification of low-rank coal with char combustion for drying and power generation.

The calculation of exergy system is discussed in Supplementary Information (Section S.3).

3. Model validation

The validation was carried out by comparing the results of this study with the literature. One should note that in addition to designing the gasification process, we also proposed the pyrolysis model to accommodate tar. Firstly, we compare the pyrolysis product from the simulation with the literature. The experimental results of the pyrolysis of low-rank coal have been reported in the literature [34]. One can clearly see in Table 1 that the pyrolysis product was dominated by tar. This expected distribution is due to low pyrolysis temperature (723.15 K) as a number of researchers [35] reported that lower pyrolysis temperature promotes the formation of tar. Table 1 shows that the distribution of major pyrolysis products obtained from the model was comparable with the one obtained from the experimental literature. The lowest relative error was found on tar compounds, while the highest relative error was observed on char products. However, the results were acceptable given the relative error remains below 10%. Secondly, we compare the product of the entire gasification system under similar operating conditions. It can be clearly seen in Fig. 2 that the syngas flow rate and gasification temperature of the present study are in line with its counterpart from the literature [36,37]. This is in line with the previous literature [36–39] that reported good accuracy of the thermodynamic approach to simulate the gasification process. The slight difference between this study and the literature can be attributed to the presence of tar formation in our model, while the tar formation phenomenon is neglected in the literature [37]. Consequently, the estimated gasification temperature in this study is slightly lower than the one in the literature due to the occurrence of endothermic tar reforming reaction (Eq. S8, Supplementary Information).

Table 1
The composition of the pyrolysis product.

Comp.	Literature [34]	This study	Error
Volatile matter	13.3%	14.2%	7%
Tar	52.0%	54.0%	4%
Char	34.7%	31.7%	9%

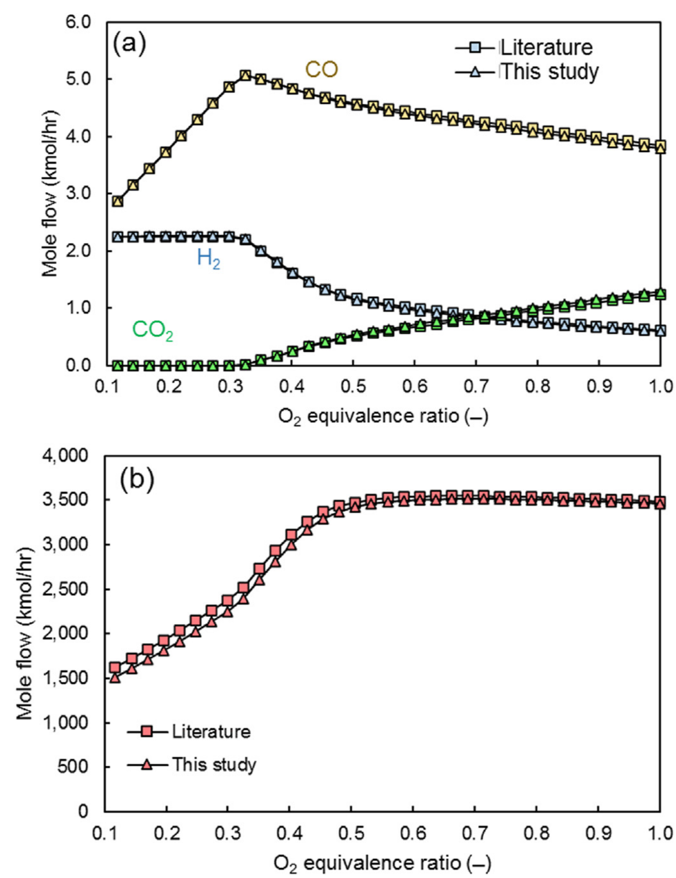


Fig. 2. The effect of O_2 equivalence ratio on (a) the syngas flow rate and (b) gasification temperature. The triangle marks indicate the results from our study, while the square marks indicate its counterpart from literature [36,37].

4. Results and discussion

The gasification performance was assessed by varying the flow rate of the gasifying agent at different coal moisture contents. In addition, the effect of char distribution into the combustion stage (CR) and the reduction (RD) was also evaluated in this study. The term “char to CR” represents the fraction of char from the pyrolysis (PR) to CR. For instance, char to CR of 0.1 indicates that 10 wt% of char from PR is directed to the CR, while 90 wt% of char goes to RD.

Those parameters were selected due to their strong influence on gasification performance [40]. The discussion on the gasification performance begins with the syngas quality in terms of its composition including the H_2/CO ratio. The discussion continues with energy production in the form of syngas and electricity. Finally, the overall gasification performance is presented in terms of energy and exergy efficiencies.

4.1. Oxygen equivalence ratio

The study was conducted by flowing different flow rates of high-purity O_2 into the reformer (RE) with a constant coal flow rate, which leads to the variation of O_2 ER between 0.0 and 1.0. Meanwhile, no boiler feed water was directed to the boiler (BR) to maintain the S/C ratio of 0.0.

The major component of syngas on a dry basis significantly changes with the change of O_2 ER, as illustrated in Fig. 3a. One can notice that a higher amount of O_2 promotes the formation of CO and CO_2. Meanwhile, the mole fraction of H_2 was significantly diminished. For instance, the mole fraction of CO and CO_2 increased from 0.52 to 0.75 and 0.00 to 0.04, respectively, while the mole fraction of H_2 reduced from 0.46 to 0.15, when the O_2 ER was added from 0.12 to 1.00 on the char fraction to the CR of 0.1 with the coal moisture content of 15%. This finding can be related to the oxidation reactions (Eq. (S1) – (S3)) due to the interaction between char, H_2 and CO with the sufficient amount of O_2 to produce CO_2 and H_2O. An identical trend is also found in the gasification of low-rank coal with the moisture content of 30% and 40%. In addition, the gasification at various char fractions (0.4 and 0.7) showed a similar trend, as illustrated in Fig. 3b and c, respectively, with different magnitudes for each configuration. This is in line with the experiments by Xiao et al. [25], using Shenmu bituminous coal. They reported that increasing the O_2 flow rate delivers high CO productions but suppresses the formation of H_2. The same group [41] also reported a similar conclusion using lignite coal.

One can easily notice from Fig. 3a that moisture has a positive effect on H_2 production, while the negative influence of moisture was found on CO. For instance, the H_2 mole fraction increased from 0.46 to 0.61, while the mole fraction of CO reduced from 0.52 to 0.22 when the moisture content elevates from 15% to 45% at the O_2 ER of 1.1 and char fraction to CR of 0.1. This is because the presence of water promotes steam reforming reaction (Eq. (S6)), as reported experimentally by Jia-liang et al. [42], who reported higher char conversion with elevating the steam concentration. In addition, water also promotes the water-gas shift reaction (Eq. (S5)), which further converts CO and H_2O into CO_2 and H_2. This is confirmed by the elevation of the CO_2 mole fraction as the moisture content increased. Again, the comparable fashion is also found on the char fraction to CR of 0.4 and 0.7, as illustrated in Fig. 3b and c, respectively. A similar results are also reported by Spiegl et al. [43], who carried out gasification experiments using German lignite coal in a bench-scale fluidized bed reactor.

The effect of char distribution to CR and RD on the syngas composition can be noticed by comparing Fig. 3a, b and c. From Fig. 3 one can see that a higher fraction of char to CR delivers a negative influence on the H_2 concentration. Interestingly, the CO concentration increased with increasing char flow rate to CR, while the concentration of CO_2 remained constant. For instance, the mole fraction of H_2 depleted from 0.50 to 0.43, while the mole fraction of CO elevated from 0.44 to 0.50 when the char fraction to CR was raised from 0.1 to 0.7, using coal with the moisture content of 45% at the O_2 ER of about 0.30. This result indicates the occurrence of exothermic partial oxidation (Eq. (1)), to produce CO. Meanwhile, the minimum amount of char promotes H_2 oxidation into H_2O (Eq.

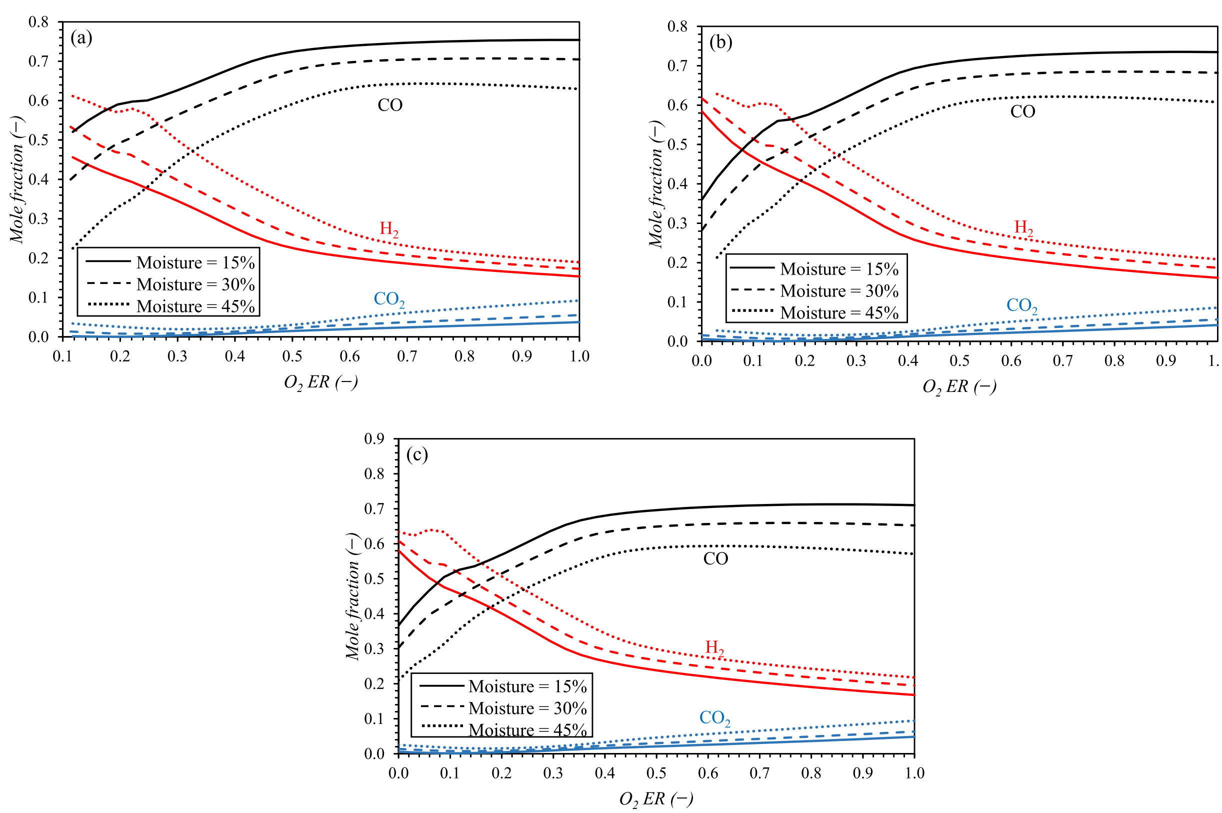


Fig. 3. The effect of O_2 ER ratio on the major constituents in the syngas at different char distributions: (a) char to CR = 0.1, (b) char to CR = 0.4 and (c) char to CR = 0.7.

(2)) given H_2 is highly reactive under O_2 atmosphere [44]. An identical trend is also observed on other moisture contents.

The variation of syngas composition indeed influences the H_2/CO ratio. One can notice from Fig. 4 that the present configuration produced a wide variation of the H_2/CO ratio by varying O_2 from 0.00 to 1.00. In addition, the higher moisture content gave a good effect on the H_2/CO ratio due to high H_2 production. An interesting result was found on the char distribution. The higher fraction of char to CR has an adverse effect on the H_2/CO ratio. This indicates that minimum carbon supply by reducing char into RD suppresses both CO and H_2 production. Furthermore, the decrease of H_2 production due to increasing char to CR is higher than the decrease of CO production. The reason for this can be explained by the excess amount of O_2 at a high fraction of char into CR, which promotes H_2 oxidation reaction (Eq. (S2)) instead of partial oxidation of carbon (Eq. (1)) due to the absence of carbon source.

The syngas composition also strongly influences the cold gas efficiency as the representation of syngas heating value. One can clearly see in Fig. 5 that each gasification configuration exhibited the highest cold gas efficiency at different O_2 ER. For instance, the highest CGE of 0.92 was observed on the gasification of coal with 15% moisture content at O_2 ER 0.22. The addition of O_2 supply above O_2 ER 0.22 results in lower CGE. This result strongly relates to syngas production, where at low O_2 ER, the syngas flow rate is minimal due to incomplete conversion of coal. Consequently, the unconverted coal was disposed of from the system instead of being converted into syngas. This is in line with the earlier literature [45], showing the strong influence of syngas flow rate on the CGE on biomass gasification. It is worth noting that high O_2 ER results in a low H_2 concentration, while the CO concentration is high. This also can be the reason for the decrease of CGE with increasing O_2 ER as the heating value of H_2 is much higher than its counterpart of CO. A similar finding was also reported in the earlier literature [46] using coal and biomass as the feedstock. One can notice that the present configuration suppresses the amount of unconverted coal by directing char into the CR. In this configuration, the CGE reduces with increasing the char fraction into the CR, but it is counterbalanced by the increase of power generation, as shown in Fig. 5. For instance, the CGE diminished from 75% to 49%, while the electricity production increased from 28 to 72 kW, when the char fraction to CR was augmented from 0.1 to 0.7 on the gasification of coal with 15% moisture content at the O_2 ER of about 0.37.

The energy and exergy balances gave a comprehensive insight into the heat and energy flow within the gasification system. The O_2 flow rate strongly influenced the energy conversion performance, as illustrated in Fig. 6. The addition of O_2 ER has a positive influence on the overall efficiency until the optimum O_2 ER is reached. For instance, the gasification of coal with 15% moisture content and char fraction to CR of 0.1 exhibited the optimum O_2 ER of 0.22 with the overall energy efficiency and the overall exergy efficiency of 89% and 76%, respectively at the O_2 ER of 0.22, as depicted in Fig. 6a. The increase of O_2 ER above 0.22 slightly reduced the energy efficiency, but significantly suppressed the exergy efficiency. This finding can be explained that energy efficiency only considers the energy balance, regardless of the syngas composition. Thus, the decrease in energy efficiency only comes from the losses in the equipment as listed in Table S1. On the other hand, in the exergy evaluation, syngas composition is considered as a part of energy quality. With this end, the decrease of exergy efficiency is also associated with the increase of CO_2 concentration and the decline of H_2 concentration as the O_2 ER ratio elevated. The comparable trend is also found on the char fraction into CR of 0.4 and 0.7, as illustrated in Fig. 6b and c, respectively. The specific CO_2 emission is also lower at the optimum O_2 ER (Figure S2, Supplementary

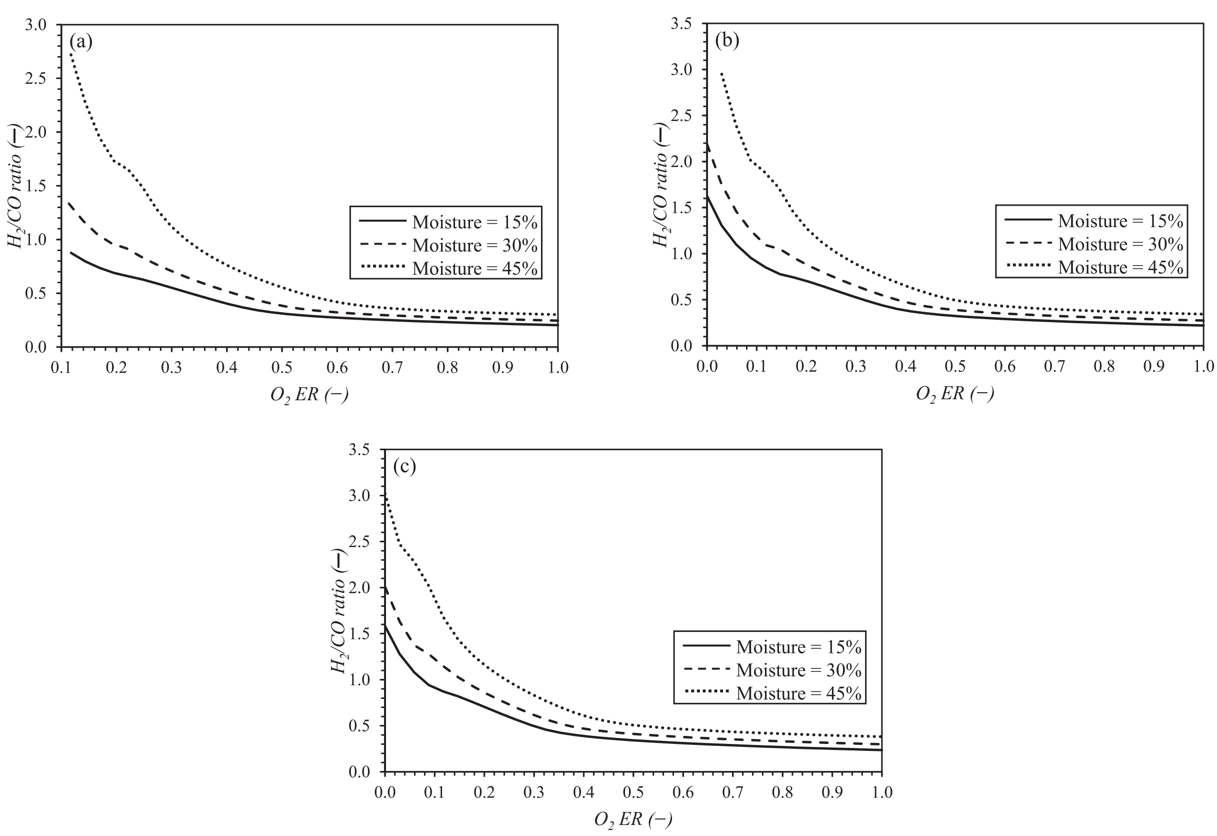


Fig. 4. The effect of O_2 ER ratio on the H_2/CO ratio in the syngas at various char distributions: (a) char to CR = 0.1, (b) char to CR = 0.4 and (c) char to CR = 0.7.

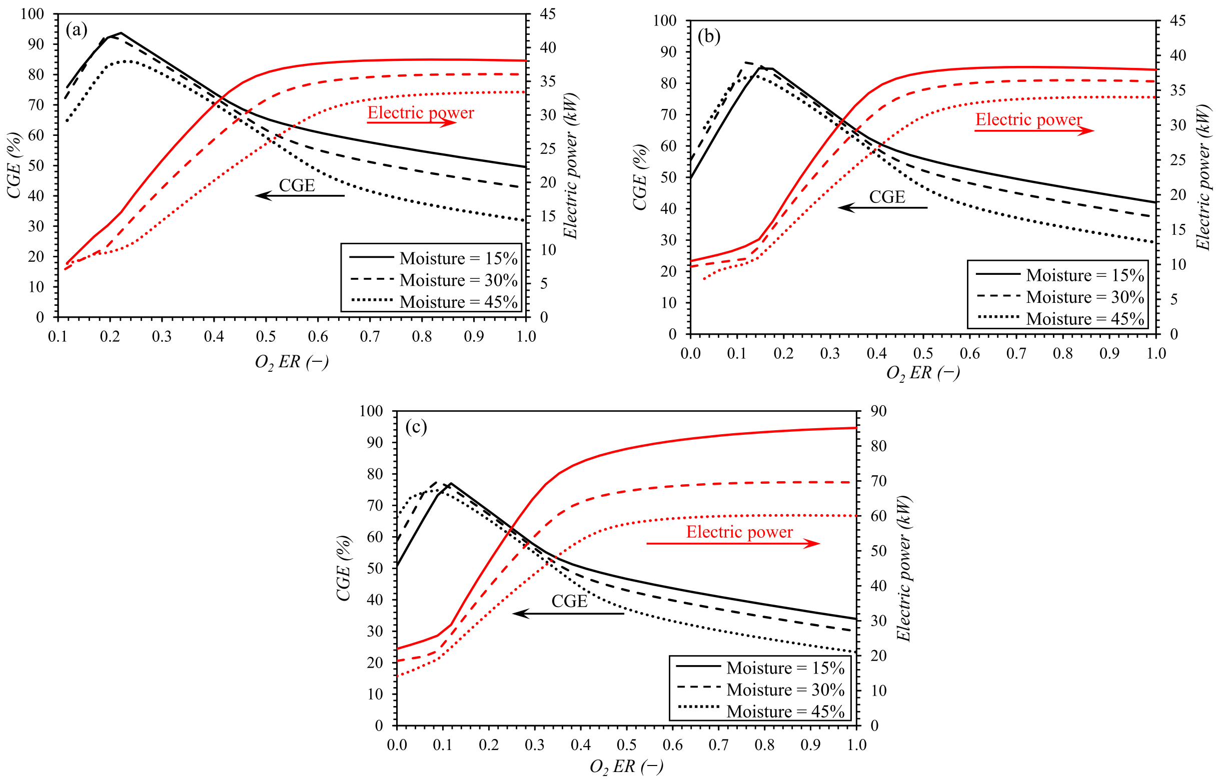


Fig. 5. The effect of O_2 ER ratio on the cold gas efficiency and electricity production at various char distribution: (a) char to CR = 0.1, (b) char to CR = 0.4 and (c) char to CR = 0.7.

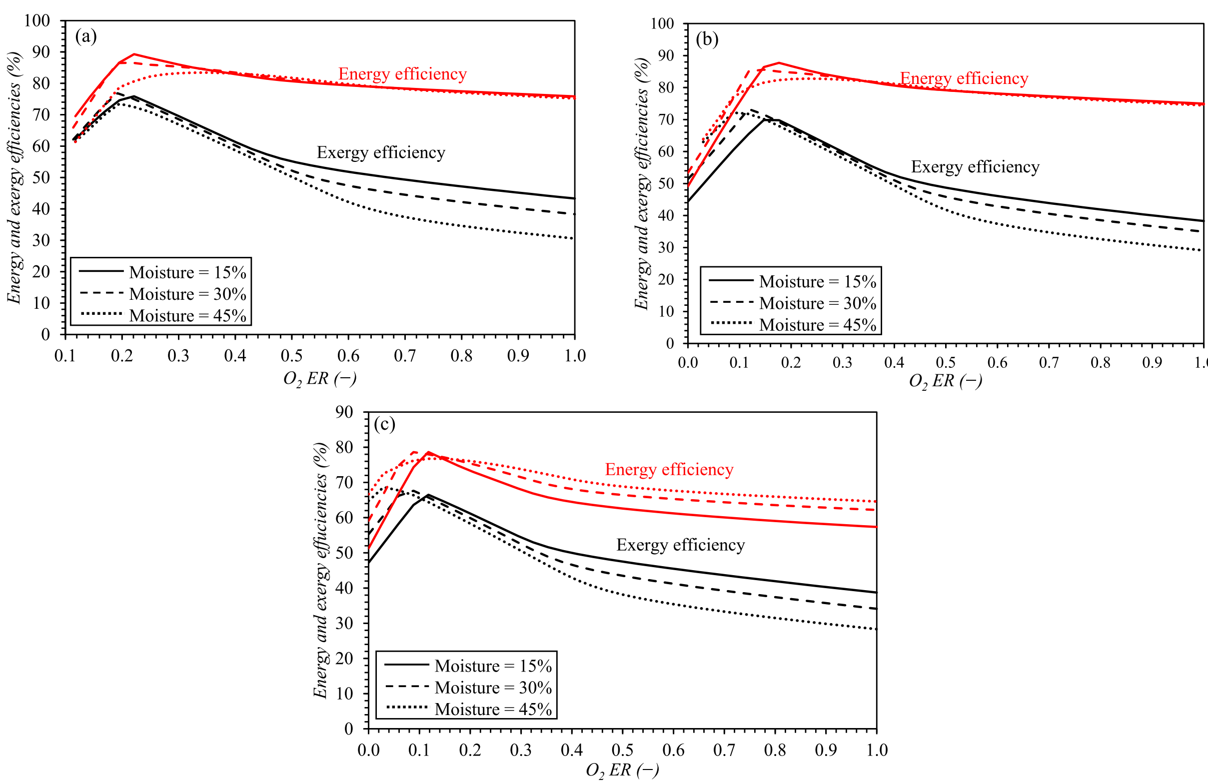


Fig. 6. The effect of O_2 ER ratio on the overall energy efficiency and overall exergy efficiency at various char distribution: (a) char to CR = 0.1, (b) char to CR = 0.4 and (c) char to CR = 0.7.

Information).

Indeed, the char distribution also has a strong influence on the energy and exergy efficiencies. For instance, the increase of energy and exergy efficiencies from 75% to 86% and 67% and 70% were found on low O_2 ER (0.14) when the char fraction to CR was elevated from 0.1 to 0.4, as depicted in Fig. 6a and b, respectively. This positive finding can be related to the minimum amount of unconverted char at a higher char fraction into CR due to a minor concentration of O_2 in the GR. An interesting finding was found when the char fraction into CR was augmented from 0.4 to 0.7 as the energy and exergy efficiencies went down from 86% to 77 and 70%–65%, respectively. This observation indicates that at low O_2 ER, the excessive char into CR delivers a negative effect on the gasification performance due to the low flow rate of syngas, though, the electricity production significantly increased with increasing char fraction into CR. In addition, there is energy lost during the conversion of thermal energy into electricity which contributes to the decrease of gasification performance.

4.2. Steam to carbon ratio

The investigation was implemented by flowing different flow rates of boiler feed water (BFW) into BR at a constant flow rate of coal feed, to obtain the S/C ratio between 0.0 and 1.0 with a constant O_2 ER of 0.21. One can easily notice that the steam addition has a good effect on the formation of H_2 and CO_2, as illustrated in Fig. 7. For instance, the mole fraction of H_2 and CO_2 elevated from 0.40 to 0.62 and 0.00 to 0.04, respectively, when the steam is added from the S/C ratio of 0.0–1.0 at the char fraction to CR of 0.1 and the moisture content of 15%, as depicted in Fig. 7a. This expected observation can be associated with the existence of steam reforming of carbon reaction (Eq. (S6)) under H_2O atmosphere, which converts steam and carbon into H_2 and CO. Furthermore, the CO reacts with the excess H_2O to form CO_2 and H_2 by facilitating the water gas shift reaction, which also explains the decrease of CO mole fraction at a high S/C ratio. This explanation also valid for the identical phenomena when the moisture content was increased from 15% to 45%. The earlier experiments by Vijay et al. [15] using Indian coal also showed a similar conclusion that the injection of steam promotes H_2 production. The identical trend was also observed on the various char fraction into CR, as shown in Fig. 7b and c, respectively. It is worth noting that the gasification of coal with the moisture content of 45% exhibited a slight decrease of H_2 production at a high S/C ratio. This finding can be attributed to lower RD temperature, which inhibits the steam reforming reactions due to the excess amount of steam. The identical fashion is reported by Yang et al. [47] in their experiments using Mengdong coal in the absence of iron ore.

One can see that the effect of char fraction into CR on the syngas composition depends on coal moisture content, as shown in Fig. 7a, b and c. For the coal with a moisture content of 15%, the change of char fraction into CR has a minimum effect on the syngas composition. However, the char fraction into CR gives a strong influence on the distribution of major constituents in the syngas at the coal moisture of 45%. The reason for this lays in the amount of char in the RD which tends to react with steam. At low moisture content, H_2O plays a role as a limiting reactant given it enables the steam reforming of carbon reaction (Eq. (S6)), to convert char into syngas. The minor effect of char fraction into CR on the syngas composition indicates that the char fraction into CR up to 0.7 still resulted in the unconverted char due to lack of H_2O. Meanwhile, the high moisture content of coal gives sufficient H_2O for the complete conversion of char into syngas, which results in a significant change of syngas composition when the char distribution was varied. One can clearly

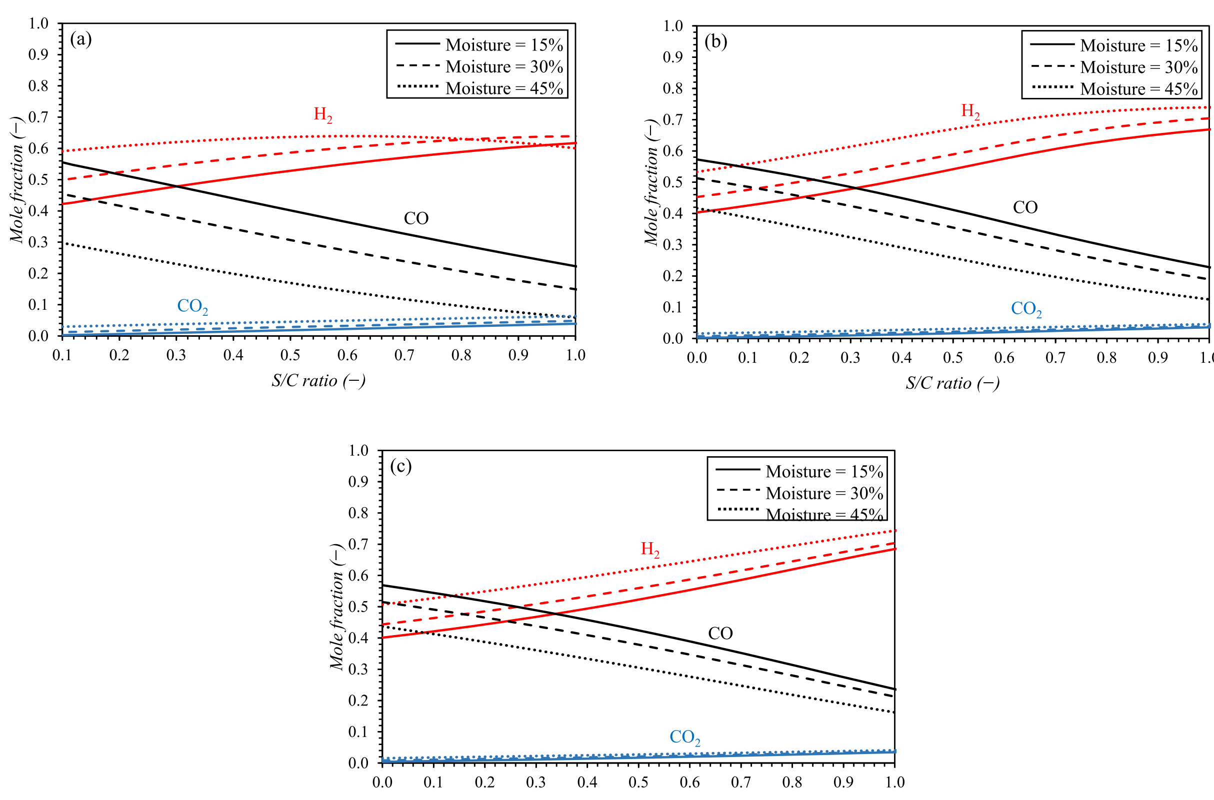


Fig. 7. The effect of S/C ratio on the major constituents in the syngas at different char distributions: (a) char to CR = 0.1, (b) char to CR = 0.4and (c) char to CR = 0.7.

notice that the increase of char fraction to CR diminished the H_2 mole fraction, while a positive effect was found on the CO mole fraction.

This result can be explained by higher RD temperature at higher fractions of char to CR due to the minimum amount of char in the GR, which promotes the reverse water-gas shift reaction (Eq. (S5)). This reason is supported by the fact that the CO_2 mole fraction declines at higher char fractions to CR. Murakami et al. [48] also reported low H_2 production at lower steam gasification temperature using Indonesian sub-bituminous coal in their experiments. The comparable results also reported by Wang et al. [49].

The change of the H_2/CO ratio with respect to the S/C ratio is presented in Fig. 8. One can see in Fig. 8 that the S/C ratio has a positive influence on the H_2/CO ratio. This is expected given high H_2O supply to the RD promotes H_2 production via water-gas shift reaction (Eq. (S5)). The comparable phenomena were also observed on higher moisture contents. This finding is in line with the experimental work by Xiao et al. [50], showing the increase of the S/C ratio elevates the H_2 production due to water-gas shift reaction. In addition, high moisture content allows the gasification system to provide a wide range of H_2/CO ratios. For instance, the H_2/CO ratio varies between 2.0 and 10.2 when the S/C ratio was changed between 0.1 and 1.0 at the char fraction to CR of 0.1, as shown in Fig. 8a. The effect of the S/C ratio on the H_2/CO ratio diminished when the char fraction to CR was increased to 0.4 and 0.7, as illustrated in Fig. 8b and c, respectively. The explanation of this result lays in the fact that a lower amount of char in the RD elevates the operating temperature which promotes the reverse water-gas shift reaction (Eq. (S5)). Thus, the steam injection is a suitable approach when one targets the specific value of the H_2/CO ratio in the syngas.

In regard to energy production, the gasification performance based on the CGE and power generation is depicted in Fig. 9. One can see that both the CGE and power generation slightly decreased with increasing the S/C ratio. The decrease of CGE indicates that the energy required for steam generation is higher than the energy produced in the syngas. In addition, the high S/C ratio also diminished the power generation given the excess steam suppressed the RD temperatures. An interesting result was found when the char fraction to CR was varied from 0.1 to 0.7. At this range, the CGE decreased, while the power generation increased with increasing char fraction to CR. This result can be explained by the lower amount of syngas flow rate due to the minimum amount of char in the GR. This also causes a higher temperature of RD as the endothermic steam reforming of carbon (Eq. (6)) is minimal. Consequently, the CR received more char which leads to high temperature flue gas. The high-temperature of RD and CR products provide high energy in the power generation system, which results in an increase in electricity production.

The evaluation of the entire process showed that the addition of steam slightly reduced the gasification performance in term of energy conversion, as shown in Fig. 10. The explanation of this finding can be related to the decrease of syngas flow rate and heating value. This is confirmed by the identical trend of the CGE with increasing S/C ratio, as indicated in Fig. 9. One can clearly see that the overall energy efficiency is higher than the overall exergy efficiency. Again, this is because the exergy evaluation also considers the energy quality. This also explains the decrease of overall exergy efficiency with increasing the char fraction to CR, while the overall energy efficiency was relatively constant. One should note that at high char fraction to CR, most of the char is converted into CO_2 by complete oxidation, which contains lower energy quality (i.e., lower chemical exergy) than its counterpart of CO. In addition, the energy loss in the power generation system also contributes to reduce the overall exergy efficiency.

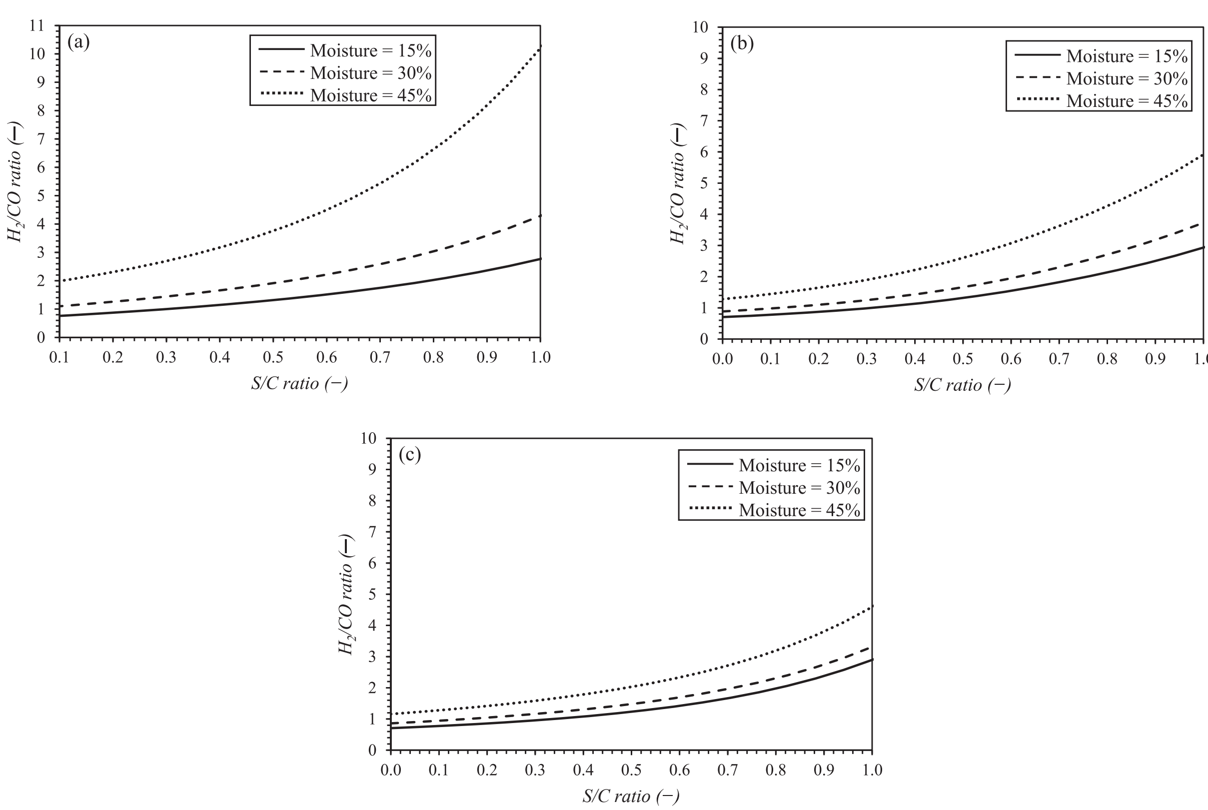


Fig. 8. The effect of S/C ratio on the H_2/CO ratio of the syngas at various char distribution: (a)char to CR = 0.1, (b) char to CR = 0.4and (c) char to CR = 0.7.

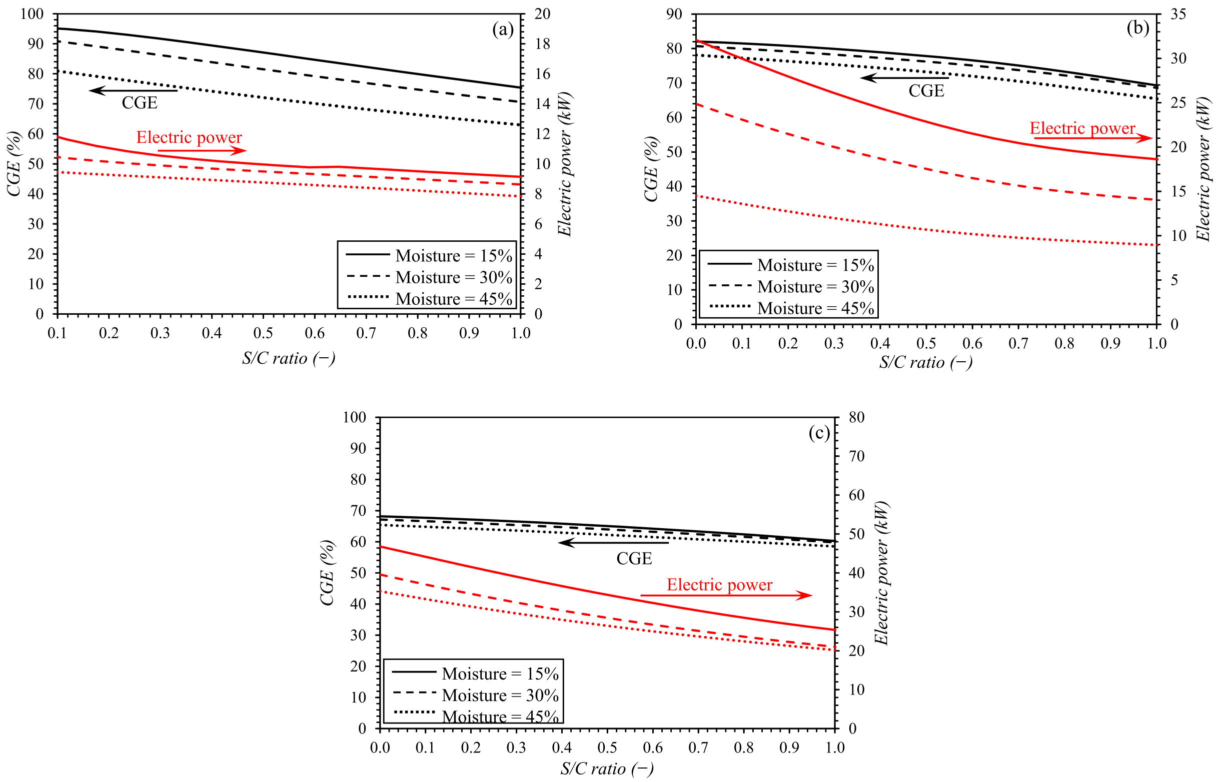


Fig. 9. The effect of S/C ratio on the CGE and electricity production at various char distribution: (a) char to CR = 0.1, (b) char to CR = 0.4 and (c) char to CR = 0.7.

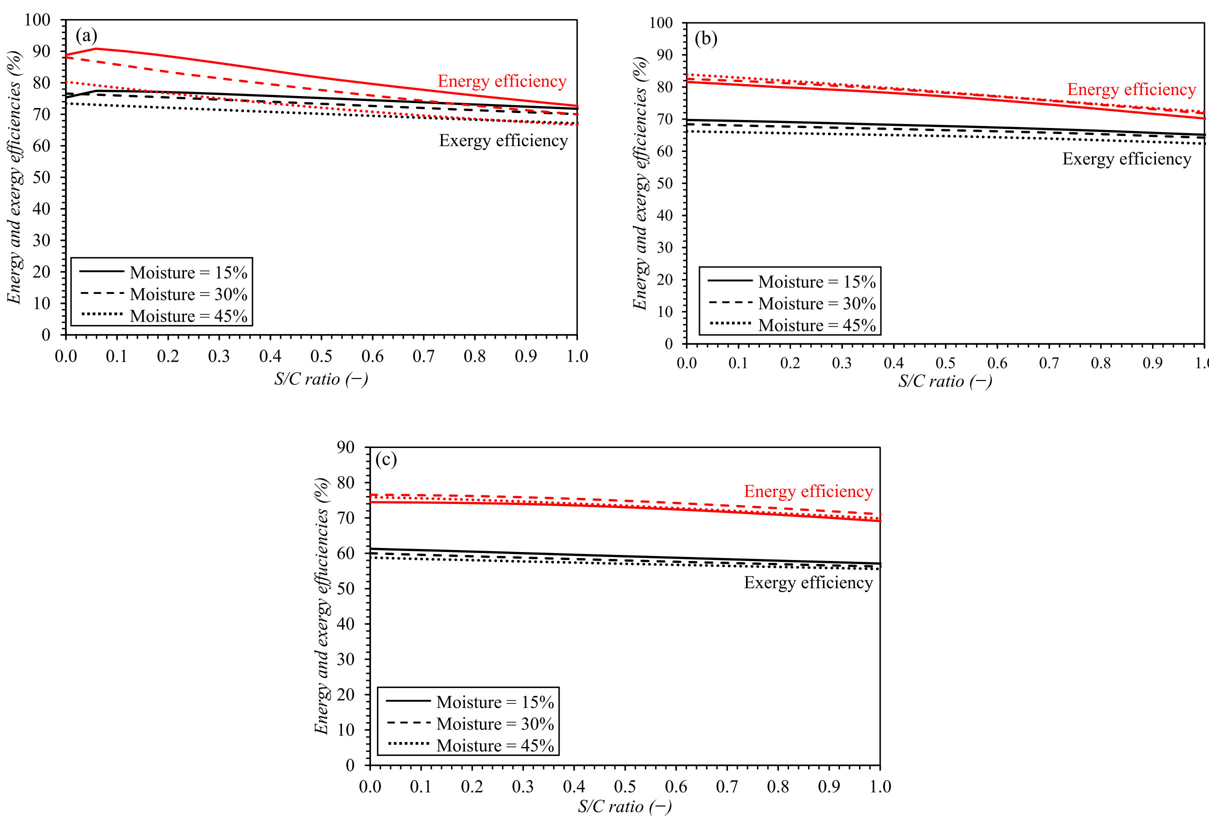


Fig. 10. The effect of S/C ratio on the overall energy and exergy efficiencies at various char distribution: (a) char to CR = 0.1, (b) char to CR = 0.4 and (c) char to CR = 0.7.

5. Conclusions

A novel gasification configuration was proposed to convert the low-rank coal into syngas and electricity. The gasification performance was evaluated based on the thermodynamic model in order to obtain the benchmark for the pilot-scale experiment. The present model exhibited a good agreement with the experimental parts as indicated by low relative error (below 10%) on the pyrolysis stage.

The use of O_2 as the gasifying agent provided high-quality syngas, which was indicated by high cold gas efficiency (up to 92%). The distribution of char into CR diminished the H_2/CO ratio, but increased the electricity production. The present model enabled the adjustment of syngas composition, particularly the H_2/CO ratio, by varying the steam flow rate and the char distribution to CR. The H_2/CO ratio varied between 0.7 and 10.2. The moisture content of low-rank coal suppressed the gasification performance in terms of energy conversion (i.e., CGE, the overall energy efficiency and the overall exergy efficiency), but increased of H_2/CO ratio of the produced syngas. The highest performance in terms of the overall energy efficiency (91%) and the overall exergy efficiency (79%) was found on the O_2 ER and S/C ratio of 0.21 and 0.06, respectively, with the char fraction to CR of 0.1.

The adjustable H_2/CO ratio of syngas enables syngas utilization in the petrochemical industry. This can minimize the CO_2 emission given some portion of carbon from the low-rank coal is stored as petrochemical products. Recently, low-rank coal is only consumed by limited number of power generation station which leads to weaken its bargaining value from the economic perspective. The proposed gasification process potentially elevates the economic value of low-rank coal given it facilitates converting low-rank coal into flexible intermediate products with various application.

Statement of author

M.A.A: Conceptualization, simulation and writing first draft. AH: Editing and revision. OM: Conceptualization, editing and revision. MMH: Simulation and revision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the financial support by the Deanship of Scientific Research (DSR) at King Fahd University of Petroleum & Minerals (KFUPM) through project No. IN161022. The author (s) also would like to thank the Directorate of Research and Community Service (DPPM) at Universitas Islam Indonesia for the support based on the contract No. 01/Dir/DPPM/70/Pen.Unggulan/PII/XI/2019.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2021.121505.

References

[1] Cao Y, Zhao Y, Wen L, Li Y, li H, Wang S, et al. System dynamics simulation for CO2 emission mitigation in green electric-coal supply chain. J Clean Prod 2019;232:759–73.
[2] Wang C, He S, Li S, Gao L. Water saving potential of coal-to-synthetic natural gas. J Clean Prod 2021;280:124326.
[3] Kong Z, Dong X, Jiang Q. The net energy impact of substituting imported oil with coal-to-liquid in China. J Clean Prod 2018;198:80–90.
[4] Xiang D, Li P, Yuan X, Cui P, Huang W. Highly efficient carbon utilization of coal-to-methanol process integrated with chemical looping hydrogen and air separation technology: process modeling and parameter optimization. J Clean Prod 2020;258:120910.
[5] Masudi A, Che Jusoh NW, Muraza O. Recent progress on low rank coal conversion to dimethyl ether as clean fuel: a critical review. J Clean Prod 2020;277:124024.
[6] Ariyoshi D, Takeda S, Kosuge K, Mizuno M, Kato K. Development of high-efficiency coal gasification technology. Conference development of high-efficiency coal gasification technology, Singapore. Springer Singapore, p. 617-619.
[7] Adeyemi I, Janajreh I, Arink T, Ghenai C. Gasification behavior of coal and woody biomass: validation and parametrical study. Appl Energy 2017;185: 1007–18.
[8] AlNouss A, McKay G, Al-Ansari T. Production of syngas via gasification using optimum blends of biomass. J Clean Prod 2020;242:118499.
[9] Yang S, Xiao Z, Deng C, Liu Z, Zhou H, Ren J, et al. Techno-economic analysis of coal-to-liquid processes with different gasifier alternatives. J Clean Prod 2020;253:120006.
[10] Xiang D, Liu S, Xiang J, Cao Y. A novel path toward methanol and olefins production fueled by syngas via a coupling of coke-oven gas reforming with pulverized coke chemical looping combustion. Energy Convers Manag 2017;152:239–49.
[11] Chen Z, Zhang X, Han W, Gao L, Li S. Exergy analysis on the process with integrated supercritical water gasification of coal and syngas separation. Appl Therrm Eng 2018;128:1003–8.
[12] Mansouri Majoumerd M, Raas H, De S, Assadi M. Estimation of performance variation of future generation IGCC with coal quality and gasification process – simulation results of EU H2-IGCC project. Appl Energy 2014;113:452–62.
[13] Wang Y, Liu Q. Production of syngas from steam gasification of three different ranks of coals and related reaction kinetics. J Energy Inst 2019.
[14] Śpiewak K, Czerski G, Porada S. Effect of K, Na and Ca-based catalysts on the steam gasification reactions of coal. Part II: composition and amount of multi-component catalysts. Chem Eng Sci 2021;229:116023.
[15] Vijay Kumar K, Bharath M, Raghavan V, Prasad BVSSS, Chakravarthy SR, Sundararajan T. Gasification of high-ash Indian coal in bubbling fluidized bed using air and steam – an experimental study. Appl Therrm Eng 2017;116: 372–81.
[16] Crnomarkovic N, Repic B, Mladenovic R, Neskovic O, Veljkovic M. Experimental investigation of role of steam in entrained flow coal gasification. Fuel 2007;86(1):194–202.
[17] de Lasa H, Salaices E, Mazumder J, Lucky R. Catalytic steam gasification of biomass: catalysts, thermodynamics and kinetics. Chem Rev 2011;111(9): 5404–33.
[18] Lu W, Cao Q, Xu B, Adidharma H, Gasem K, Argyle M, et al. A new approach of reduction of carbon dioxide emission and optimal use of carbon and hydrogen content for the desired syngas production from coal. J Clean Prod 2020;265: 121786.
[19] Łamacz A, Babiński P, Łabojko G. The impact of components of synthesis gas from coal gasification on conversion of model tar compounds over Ni/CeZrO2 catalyst. Fuel 2019;236:984–92.
[20] Zhou X, Zhao J, Guo S, Li J, Yu Z, Song S, et al. High quality syngas production from pressurized K2CO3 catalytic coal gasification with in-situ CO2 capture. Int J Hydrogen Energy 2018;43(36):17091–9.
[21] Zhang J, Xie W, Li X, Hao Q, Chen H, Ma X. In situ generation of nickel/carbon catalysts by partial gasification of coal char and application for methane decomposition. Int J Hydrogen Energy 2019;44(5):2633–44.
[22] Chen Z, Gao L, Zhang X, Han W, Li S. High-efficiency power generation system with integrated supercritical water gasification of coal. Energy 2018;159: 810–6.
[23] Chen Z, Zhang X, Gao L, Li S. Thermal analysis of supercritical water gasification of coal for power generation with partial heat recovery. Appl Therrm Eng 2017;111:1287–95.
[24] Yilmaz F, Ozturk M, Selbas R. Design and thermodynamic analysis of coal-gasification assisted multigeneration system with hydrogen production and liquefaction. Energy Convers Manag 2019;186:229–40.
[25] Xiao Y, Xu S, Song Y, Wang C, Ouyang S. Gasification of low-rank coal for hydrogen-rich gas production in a dual loop gasification system. Fuel Process Technol 2018;171:110–6.
[26] Consonni S, Lozza G, Pelliccia G, Rossini S, Saviano F. Chemical-looping combustion for combined cycles with CO2 capture. J Eng Gas Turbines Power 2006;128(3):525–34.
[27] Kou M, Zuo H, Ning X, Wang G, Hong Z, Xu H, et al. Thermogravimetric study on gasification kinetics of hydropyrolysis char derived from low rank coal. Energy 2019;188:116030.
[28] Wu J, Wang J, Liu J, Yang Y, Cheng J, Wang Z, et al. Moisture removal mechanism of low-rank coal by hydrothermal dewatering: physicochemical property analysis and DFT calculation. Fuel 2017;187:242–9.
[29] Tijmensen MJA, Faaij APC, Hamelinck CN, van Hardeveld MRM. Exploration of the possibilities for production of Fischer Tropsch liquids and power via biomass gasification. Biomass Bioenergy 2002;23(2):129–52.

[30] Peters L, Hussain A, Follmann M, Melin T, Hägg MB. CO2 removal from natural gas by employing amine absorption and membrane technology—a technical and economical analysis. Chem Eng J 2011;172(2):952−60.

[31] Hajjaji N, Pons M-N, Houas A, Renaudin V. Exergy analysis: an efficient tool for understanding and improving hydrogen production via the steam methane reforming process. Energy Pol 2012;42:392−9.

[32] Adnan MA, Xiong Q, Muraza O, Hossain MM. Gasification of wet microalgae to produce H2-rich syngas and electricity: a thermodynamic study considering exergy analysis. Renew Energy 2020;147:2195−205.

[33] Demirel Y. Chapter 4 - using the second law: thermodynamic analysis. In: Demirel Y, editor. Nonequilibrium thermodynamics. third ed. Amsterdam: Elsevier; 2014. p. 177−264.

[34] Byambajav E, Paysepar H, Nazari L, Xu C. Co-pyrolysis of lignin and low rank coal for the production of aromatic oils. Fuel Process Technol 2018;181:1−7.

[35] Wang M, Jin L, Zhao H, Yang X, Li Y, Hu H, et al. In-situ catalytic upgrading of coal pyrolysis tar over activated carbon supported nickel in CO2 reforming of methane. Fuel 2019;250:203−10.

[36] Adnan MA, Susanto H, Binous H, Muraza O, Hossain MM. Feed compositions and gasification potential of several biomasses including a microalgae: a thermodynamic modeling approach. Int J Hydrogen Energy 2017;42(27):17009−19.

[37] Chaiwatanodom P, Vivanpatarakij S, Assabumrungrat S. Thermodynamic analysis of biomass gasification with CO2 recycle for synthesis gas production. Appl Energy 2014;114:10−7.

[38] Hantoko D, Yan M, Kanchanatip E, Adnan MA, Antoni, Mubeen I, et al. Supercritical water gasification of sewage sludge and combined cycle for H2 and power production − a thermodynamic study. Int J Hydrogen Energy 2019;44(45):24459−70.

[39] Adnan MA, Susanto H, Binous H, Muraza O, Hossain MM. Enhancement of hydrogen production in a modified moving bed downdraft gasifier − a thermodynamic study by including tar. Int J Hydrogen Energy 2017;42(16):10971−85.

[40] Susanto H, Beenackers AACM. A moving-bed gasifier with internal recycle of pyrolysis gas. Fuel 1996;75(11):1339−47.

[41] Xiao Y, Xu S, Tursun Y, Wang C, Wang G. Catalytic steam gasification of lignite for hydrogen-rich gas production in a decoupled triple bed reaction system. Fuel 2017;189:57−65.

[42] Jiang S, Shen L, Wu J, Yan J, Song T. The investigations of hematite-CuO oxygen carrier in chemical looping combustion. Chem Eng J 2017;317:132−42.

[43] Spiegl N, Berrueco C, Long X, Paterson N, Millan M. Production of a fuel gas by fluidised bed coal gasification compatible with CO2 capture. Fuel 2020;259:116242.

[44] Stylianidis N, Azimov U, Birkett M. Investigation of the effect of hydrogen and methane on combustion of multicomponent syngas mixtures using a constructed reduced chemical kinetics mechanism. Energies 2019;12(12).

[45] Adnan MA, Hossain MM. Gasification of various biomasses including microalgae using CO2 − a thermodynamic study. Renew Energy 2018;119:598−607.

[46] Adnan MA, Hossain MM. Co-gasification of Indonesian coal and microalgae − a thermodynamic study and performance evaluation. Chem Eng Process 2018;128:1−9.

[47] Yang Z, Hu J, Li Y, Chen Y, Qian K, Yang H, et al. Catalytic steam gasification of Mengdong coal in the presence of iron ore for hydrogen-rich gas production. J Energy Inst 2019;92(2):391−402.

[48] Murakami K, Sato M, Tsubouchi N, Ohtsuka Y, Sugawara K. Steam gasification of Indonesian subbituminous coal with calcium carbonate as a catalyst raw material. Fuel Process Technol 2015;129:91−7.

[49] Wang D, Li S, He S, Gao L. Coal to substitute natural gas based on combined coal-steam gasification and one-step methanation. Appl Energy 2019;240:851−9.

[50] Xiao Y, Xu S, Liu Y, Qiao C. Catalytic steam co-gasification of biomass and coal in a dual loop gasification system with olivine catalysts. J Energy Inst 2020;93(3):1074−82.

ScienceDirect

Energy

Supports *open access*

13.4
CiteScore

8.857
Impact Factor

Submit your article

Guide for authors

Menu

Search in this journal

Latest issue

Volume 273

In progress • 15 June 2023

About the journal

The International Journal

Energy is an international, multi-disciplinary journal in **energy engineering** and research. The journal aims to be a leading peer-reviewed platform and an authoritative source of information for analyses, reviews and evaluations related to **energy**. The journal covers research in mechanical …

View full aims & scope

0.9 weeks
Publication Time

View all insights

Articles

Latest published | Articles in press | Top cited | Most downloaded | Most popular

FEEDBACK

Research article Full text access

Thermodynamic performance study and RSM based optimization of SI engine using sewage sludge producer gas blend with methane

Priyaranjan Jena, ... Jeewan Vachan Tirkey

15 June 2023

View PDF

Research article Full text access

Digital twin in battery energy storage systems: Trends and gaps detection through association rule mining

Concetta Semeraro, ... A.G. Olabi

15 June 2023

View PDF

Research article Full text access

Thermodynamic study on the effects of operating parameters on CaO-based sorption enhanced steam gasification of biomass

Chongcong Li, ... Yan Zhang

15 June 2023

View PDF

Research article Full text access

Optimal planning of Electricity–Hydrogen hybrid energy storage system considering demand response in active distribution network

Jiale Li, ... Yunfeng Yan

15 June 2023

View PDF

Research article Full text access

A novel aging characteristics-based feature engineering for battery state of health estimation

Jinyu Wang, ... Jingcai Du

15 June 2023

View PDF

Research article Full text access

Predicting the energy consumption in buildings using the optimized support vector regression model

Wei Cai, ... Jianguo Xu

15 June 2023

View PDF

Research article Full text access

Energy consumption of two-stage system of biomass pyrolysis and bio-oil reforming to recover waste heat from granulated BF slag

Xin Yao, ... Shuhuan Wang

15 June 2023

View PDF

Research article Full text access

Energy security and CO2 emissions: New evidence from time-varying and quantile-varying aspects

Kai-Hua Wang, ... Oana-Ramona Lobonţ

15 June 2023

View PDF

Read latest issue

Calls for papers

The Role of Smart Technologies in Energy Engineering

Guest editors: Sandro Nižetić, Müslüm Arıcı, Amin Shahsavar, Dong Li, Mohammad Hossein Doranehgard Submission deadline: 1 March 2024

This virtual special issue will cover wide spectra of contributions that discusses role of smart technologies with particular focus on the energy engineering field. The digitalization made various technological solutions that are especially crucial …

Micro/Nano Energy

Guest editors: Omid Mahian; Liu Yang; Sébastien Poncet; Mehrdad Mesgarpour Submission deadline: 1 October 2023

The focus of the special issue will be on the fascinating field of micro/nano energy. This encompasses not only the application of micro/nanoparticles for enhancing the performance of energy systems, but also the examination of energy systems at a …

Energy Scientific and Technological Advances – Special issue for 3rd Global Chinese Energy and Environment Conference

Energy Scientific and Technological Advances – Special issue for 3rd Global Chinese Energy and Environment Conference

View all calls for papers for special issues

More opportunities to publish your research:
Browse open Calls for Papers beta

Special issues and article collections

ENERGY Special Issue devoted to the XV RESEARCH & DEVELOPMENT IN POWER ENGINEERING Conference, RDPE 2021

Edited by Henrik Lund, Wojciech Stanek, Wojciech Bujalski

5 January 2023

Energy Scientific and Technological Advances – Special issue for 2nd Global Chinese Energy and Environment Conference

Edited by Xudong Zhao, Lingai Luo, Yanping Yuan, Zhiqiang (John) Zhai, Yanjun Dai

16 November 2022

Special issue on Smart Energy Systems SESAAU2021

Edited by Henrik Lund

7 November 2022

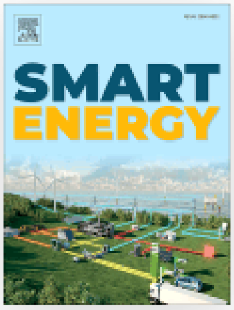
Special Section on Highlighting Energy research by authors based in the Global South

30 October 2022

View all special issues and article collections

View all issues

Partner journals



Smart Energy

Open access

Related journals

Carbon Capture Science & Technology

Carbon Capture Science & Technology

Online ISSN: 1873-6785
Print ISSN: 0360-5442

For Authors

Track your accepted paper

Journal Finder

Researcher Academy

Rights and permissions

Journal Article Publishing Support Center

For Editors

Publishing Ethics Resource Kit

Guest Editors

For Reviewers

Reviewer recognition

ScienceDirect

Energy

Supports *open access*

13.4
CiteScore

8.857
Impact Factor

Submit your article

Guide for authors

Menu

Search in this journal

Volume 236

1 December 2021

Download full issue

< Previous vol/issue

Next vol/issue >

Receive an update when the latest issues in this journal are published

Sign in to set up alerts

Full text access

Editorial Board

Article 122224

View PDF

Review Article

Review article Full text access

Characterizing pore-level oil mobilization processes in unconventional reservoirs assisted by state-of-the-art nuclear magnetic resonance technique

Xiang Zhang, Bing Wei, Junyu You, Jiang Liu, ... Jing Tong
Article 121549

View PDF Article preview

Review article Full text access

Fuel poverty in industrialized countries: Definition, measures and policy implications a review

Dorothée Charlier, Bérangère Legendre
Article 121557

FEEDBACK

View PDF Article preview

Full Length Articles

Research article *Open access*

Low-cost, low-emission 100% renewable electricity in Southeast Asia supported by pumped hydro storage

Bin Lu, Andrew Blakers, Matthew Stocks, Thang Nam Do
Article 121387

View PDF Article preview

Research article Full text access

Sustainable economic growth and export diversification potential for Asian LNG-exporting countries: LNG–petrochemical nexus development using product space model

Syed Fahad Ali Shah, Muhammad Abdul Qyyum, Kinza Qadeer, Moonyong Lee
Article 121334

View PDF Article preview

Research article Full text access

Prediction of three-phase product distribution and bio-oil heating value of biomass fast pyrolysis based on machine learning

Erwei Leng, Ben He, Jingwei Chen, Gaoliang Liao, ... Jiaqiang E
Article 121401

View PDF Article preview

Research article Full text access

Quantification of climate-induced interannual variability in residential U.S. electricity demand

Hadi Eshraghi, Anderson Rodrigo de Queiroz, A. Sankarasubramanian, Joseph F. DeCarolis
Article 121273

View PDF Article preview

Research article Full text access

Advanced thermo-economic scheme and multi-objective optimization for exploiting the waste heat potentiality of marine natural gas engine

Tiancheng Ouyang, Zhiping Wang, Geng Wang, Zhongkai Zhao, ... Xiaoqing Li
Article 121440

View PDF Article preview

Research article Full text access

Biofuel potential of compost-like output from municipal solid waste: Multiple analyses of its seasonal variation and blends with lignite

Agapi Vasileiadou, Stamatis Zoras, Andreas Iordanidis
Article 121457

View PDF Article preview

Research article Full text access

Waste heat recovery of a combined regenerative gas turbine - recompression supercritical CO_2 Brayton cycle driven by a hybrid solar-biomass heat source for multi-generation purpose: 4E analysis and parametric study

Yan Cao, Hamed Habibi, Mohammad Zoghi, Amir Raise
Article 121432

View PDF Article preview

Research article Full text access

Investigation of adsorption kinetics of CH_4 and CO_2 on shale exposure to supercritical CO_2

Chao Qin, Yongdong Jiang, Shuangying Zuo, Shiwan Chen, ... Zhengjie Liu
Article 121410

View PDF Article preview

Research article Full text access

Reaction performance of $CaCO_3$/CaO thermochemical energy storage with TiO_2 dopant and experimental study in a fixed-bed reactor

T.X. Xu, X.K. Tian, A.A. Khosa, J. Yan, ... C.Y. Zhao
Article 121451

View PDF Article preview

Research article Full text access

Analysis and optimization of a natural gas multi-stage expansion plant integrated with a gas engine-driven heat pump

Xiao Xu, Liang Cai, Tao Chen, Zhixing Zhan
Article 121321

View PDF Article preview

Research article Full text access

Thermodynamic evaluation and modelling of an auto-thermal hybrid system of chemical looping combustion and air separation for power generation coupling with CO_2 cycles

Xudong Wang, Yali Shao, Baosheng Jin
Article 121431

View PDF Article preview

Research article Full text access

Determination of the effects of oxygen-enriched air with the help of zeolites on the exhaust emission and performance of a diesel engine

Hanbey Hazar, Remziye Tekdogan, Huseyin Sevinc
Article 121455

View PDF Article preview

Research article Full text access

The optimization and thermodynamic and economic estimation analysis for CO_2 compression-liquefaction process of CCUS system using LNG cold energy

Yue Xin, Yindi Zhang, Peng Xue, Ke Wang, ... Paitoon Tontiwachwuthikul
Article 121376

View PDF Article preview

Research article Full text access

Thermo-hydraulic coupled simulation and analysis of a real large-scale complex district heating network in Tianjin

Xuejing Zheng, Qihang Sun, Yaran Wang, Lijun Zheng, ... Kaiyu Shi
Article 121389

View PDF Article preview

Research article Full text access

Dispersion characteristics of hydrogen leakage: Comparing the prediction model with the experiment

Zhiyong Shu, Wenqing Liang, Xiaohong Zheng, Gang Lei, ... Hua Qian
Article 121420

View PDF Article preview

Research article Full text access

Modeling and optimization of combined heat and power with power-to-gas and carbon capture system in integrated energy system

Yiming Ma, Haixin Wang, Feng Hong, Junyou Yang, ... Jiawei Feng
Article 121392

View PDF Article preview

Research article Full text access

A critical analysis of shale laboratory permeability evolution data

Rui Shi, Jishan Liu, Xiaoming Wang, Mingyao Wei, Derek Elsworth
Article 121405

View PDF Article preview

Research article Full text access

An improved system for evaluating the adaptability of natural gas flooding in enhancing oil recovery considering the miscible ability

Yong Tang, Yulin Chen, Youwei He, Guangming Yu, ... Yong Wang
Article 121441

View PDF Article preview

Research article Full text access

Characterization of double-entry turbine coupled with gasoline engine under in- and out-phase admission

Ahmed Ketata, Zied Driss
Article 121447

View PDF Article preview

Research article Full text access

An indirect reinforcement learning based real-time energy management strategy via high-order Markov Chain model for a hybrid electric vehicle

Ningkang Yang, Lijin Han, Changle Xiang, Hui Liu, Xunmin Li
Article 121337

View PDF Article preview

Research article Full text access

Hydrothermal liquefaction of residues of *Cocos nucifera* (coir and pith) using subcritical water: Process optimization and product characterization

Marttin Paulraj Gundupalli, Debraj Bhattacharyya
Article 121466

View PDF Article preview

Research article Full text access

Numerical simulation of CO formation and reduction on flame propagation due to heat loss through the cooled wall

Keita Yunoki, Reo Kai, Shinpei Inoue, Ryoichi Kurose
Article 121352

View PDF Article preview

Research article Full text access

Multi-objective gear ratio and shifting pattern optimization of multi-speed transmissions for electric vehicles considering variable transmission efficiency

Kihan Kwon, Junhyeong Jo, Seungjae Min
Article 121419

View PDF Article preview

Research article Full text access

Sequential coalition formation for wind-thermal combined bidding

Feixiang Peng, Shubo Hu, Xuanxuan Fan, Hui Sun, ... Wenzhuo Song
Article 121475

View PDF Article preview

Research article *Open access*

Evaluation of open photovoltaic and wind production time series for Norwegian locations

Miguel Muñoz Ortiz, Lisa Kvalbein, Lars Hellemo
Article 121409

View PDF Article preview

Research article Full text access

Numerical investigation of the effect of mixing vanes on subcooled boiling in a 3×3 rod bundle channel with spacer grid

Peng Yang, Ting Zhang, Lulu Hu, Liu Liu, Yingwen Liu
Article 121454

View PDF Article preview

Research article Full text access

State-of-charge estimation of lithium-ion battery based on clockwork recurrent neural network

Xiong Feng, Junxiong Chen, Zhongwei Zhang, Shuwen Miao, Qiao Zhu
Article 121360

View PDF Article preview

Research article Full text access
High performance energy harvesting from flow-induced vibrations in trapezoidal oscillators

Hongjun Zhu, Tao Tang, Tongming Zhou, Mingjin Cai, ... Junlei Wang
Article 121484

View PDF Article preview

Research article Full text access
Numerical analysis of gas production from large-scale methane hydrate sediments with fractures

Yongchang Feng, Lin Chen, Yuki Kanda, Anna Suzuki, ... Shigenao Maruyama
Article 121485

View PDF Article preview

Research article Full text access
Quality improvement and tar reduction of syngas produced by bio-oil gasification

Jae Gyu Hwang, Myung Kyu Choi, Dong Hyuk Choi, Hang Seok Choi
Article 121473

View PDF Article preview

Research article Full text access
Application of a Stochastic Multicriteria Acceptability Analysis to support decision-making within a macro-scale energy model: Case study of the electrification of the road European transport sector

Daniele Lerede, Giuseppe Pinto, Mirko Saccone, Chiara Bustreo, ... Laura Savoldi
Article 121444

View PDF Article preview

Research article Full text access
Offshore wind can power Canada

Cong Dong, Guohe (Gordon) Huang, Guanhui Cheng
Article 121422

View PDF Article preview

Research article Full text access
Study on the feasibility of the micromix combustion principle in low NO_x H_2 burners for domestic and industrial boilers: A numerical approach

G. Lopez-Ruiz, I. Alava, J.M. Blanco
Article 121456

View PDF Article preview

Research article Full text access

Thermal performance investigation of a premixed surface flame burner used in the domestic heating boilers

Ziaulhaq Ahmadi, Mohammad Zabetian Targhi
Article 121481

View PDF Article preview

Research article Full text access

Energy management and emission control for range extended electric vehicles

Yaxin Wang, Diming Lou, Ning Xu, Liang Fang, Piqiang Tan
Article 121370

View PDF Article preview

Research article Full text access

Mortar dynamic coupled model for calculating interface gas exchange between organic and inorganic matters of shale

Gaohui Cao, Wenbin Jiang, Mian Lin, Lili Ji, ... Fang Hao
Article 121449

View PDF Article preview

Research article Full text access

Effect of blade thickness on rotating stall of mixed-flow pump using entropy generation analysis

Leilei Ji, Wei Li, Weidong Shi, Fei Tian, Ramesh Agarwal
Article 121381

View PDF Article preview

Research article Full text access

Thermal performance investigation of a novel heating terminal integrated with flat heat pipe and heat transfer enhancement

Hongli Sun, Mengfan Duan, Yifan Wu, Borong Lin, ... Haitian Zhao
Article 121411

View PDF Article preview

Research article Full text access

Parametric modeling of a solid state Ericsson cycle heat engine

Timothy F. Miller
Article 121413

View PDF Article preview

Research article Full text access

Dynamic modeling and control of direct air-cooling condenser pressure considering couplings with adjacent systems

Yi Zhang, Jinfeng Liu, Tingting Yang, Jianbang Liu, ... Fang Fang
Article 121487

View PDF Article preview

Research article Full text access

Thermodynamic analysis of the 2nd generation pressurized fluidized-bed combustion cycle utilizing an oxy-coal boiler and a gasifier

Taewoo Kim, So Dam Park, Uen Do Lee, Byeong Cheol Park, ... Jongsup Hong
Article 121471

View PDF Article preview

Research article Full text access

Integrated modelling and optimal operation analysis of multienergy systems based on Stackelberg game theory

Tianyu Guo, Peng Li, Zixuan Wang, Ruyu Shi, ... Jianyi Li
Article 121472

View PDF Article preview

Research article Full text access

Total solar irradiance's effect on the performance of empirical models for estimating global solar radiation: An empirical-based review

Javier Almorox, Cyril Voyant, Nadjem Bailek, Alban Kuriqi, J.A. Arnaldo
Article 121486

View PDF Article preview

Research article Full text access

Experimental and numerical study on self-sustaining performance of a 30-kW micro gas turbine generator system during startup process

Jin Guan, Xiaojing Lv, Catalina Spataru, Yiwu Weng
Article 121468

View PDF Article preview

Research article Full text access

A novel asynchronous deep reinforcement learning model with adaptive early forecasting method and reward incentive mechanism for short-term load forecasting

Wenyu Zhang, Qian Chen, Jianyong Yan, Shuai Zhang, Jiyuan Xu
Article 121492

View PDF Article preview

Research article Full text access

Predicting winners and losers under time-of-use tariffs using smart meter data

Y. Kiguchi, M. Weeks, R. Arakawa
Article 121438

View PDF Article preview

Research article Full text access

Direct and indirect energy consumption in farming: Impacts from fertilizer use

Vítor João Pereira Domingues Martinho
Article 121504

View PDF Article preview

Research article Full text access

Genetic algorithm based optimized model for the selection of wind turbine for any site-specific wind conditions

A. Petrović, Ž. Đurišić
Article 121476

View PDF Article preview

Research article Full text access

Numerical simulation and production prediction assessment of Takigami geothermal reservoir

Saeid Jalilinasrabady, Toshiaki Tanaka, Ryuichi Itoi, Hiroki Goto
Article 121503

View PDF Article preview

Research article Full text access

Exploring the driving forces of distributed energy resources in China: Using a semiparametric regression model

Bin Xu, Yuemei Luo, Renjing Xu, Jianbao Chen
Article 121452

View PDF Article preview

Research article Full text access

Techno-economic assessment of CO_2 capture integrated coal-fired power plant with energetic analysis

Seokwon Yun, Sunghoon Lee, Mun-Gi Jang, Jin-Kuk Kim
Article 121493

View PDF Article preview

Research article Full text access

Efficiency based optimization of a Tesla turbine

K. Rusin, W. Wróblewski, S. Rulik
Article 121448

View PDF Article preview

Research article Full text access

Single-pot upgrading of run-of-mine coal and rice straw via Taguchi-optimized hydrothermal treatment: Fuel properties and synergistic effects

Sandile Fakudze, Yingyuan Wei, Qianqian Shang, Ru Ma, ... Chengguo Liu
Article 121482

View PDF Article preview

Research article Full text access

Experimental study on the evaporation characteristics of biodiesel-ABE blended droplets

Kai Han, Yu Liu, Chengxin Wang, Junjian Tian, ... Kesheng Meng
Article 121453

View PDF Article preview

Research article Full text access

Empirical BAC factors method application to two real case studies in South Italy

Marina Bonomolo, Gaetano Zizzo, Simone Ferrari, Marco Beccali, Stefania Guarino
Article 121498

View PDF Article preview

Research article *Open access*

The impact of the thermal lag on the interpretation of cellulose pyrolysis

Krzysztof M. Czajka
Article 121497

View PDF Article preview

Research article *Open access*

Techno-economic assessment of thermal energy storage technologies for demand-side management in low-temperature individual heating systems

Yichi Zhang, Pär Johansson, Angela Sasic Kalagasidis
Article 121496

View PDF Article preview

Research article *Open access*

Electric water heater flexibility potential and activation impact in system operator perspective – Norwegian scenario case study

Venkatachalam Lakshmanan, Hanne Sæle, Merkebu Zenebe Degefa
Article 121490

View PDF Article preview

Research article Full text access

Soft computing analysis of a compressed air energy storage and SOFC system via different artificial neural network architecture and tri-objective grey wolf optimization

Seyed Mojtaba Alirahmi, Seyedeh Fateme Mousavi, Pouria Ahmadi, Ahmad Arabkoohsar
Article 121412

View PDF Article preview

Research article *Open access*

Financial and energy performance analysis of efficiency measures in residential buildings. A probabilistic approach

Federico Scarpa, Luca A. Tagliafico, Vincenzo Bianco
Article 121491

View PDF Article preview

Research article Full text access

An interval scheduling method for the CCHP system containing renewable energy sources based on model predictive control

Deyin Ma, Lizhi Zhang, Bo Sun
Article 121418

View PDF Article preview

Research article Full text access

Transformation of low-rank coal to clean syngas and power via thermochemical route

Muflih A. Adnan, Arif Hidayat, Mohammad M. Hossain, Oki Muraza
Article 121505

View PDF Article preview

Research article Full text access

Enhancement of low grade waste heat recovery from a fuel cell using a thermoelectric generator module with swirl flows

B. Singh, W.A.N.W. Mohamed, M.N.F. Hamani, K.Z.N.A. Sofiya
Article 121521

View PDF Article preview

Research article Full text access

Dynamic self-adjusting classification for global wave energy resources under different requirements

Chong-wei Zheng
Article 121525

View PDF Article preview

Research article Full text access

Thermodynamic analysis and high-dimensional evolutionary many-objective optimization of dual loop organic Rankine cycle (DORC) for CNG engine waste heat recovery

Xu Ping, Baofeng Yao, Hongguang Zhang, Fubin Yang
Article 121508

View PDF Article preview

Research article *Open access*

Centralized vs. distributed energy storage – Benefits for residential users

Behnam Zakeri, Giorgio Castagneto Gissey, Paul E. Dodds, Dina Subkhankulova
Article 121443

View PDF Article preview

Research article Full text access

Analyzing the impact of three-dimensional building structure on CO_2 emissions based on random forest regression

Jinyao Lin, Siyan Lu, Xiaoyu He, Fang Wang
Article 121502

View PDF Article preview

Research article Full text access

Dynamic performance and control strategy comparison of a solar-aided coal-fired power plant based on energy and exergy analyses

Hui Yan, Ming Liu, Daotong Chong, Chaoyang Wang, Junjie Yan
Article 121515

View PDF Article preview

Research article Full text access

Flame structures and thermoacoustic instabilities of centrally-staged swirl flames operating in different partially-premixed modes

Xinyao Wang, Meng Han, Xiao Han, Chi Zhang, Chih-Jen Sung
Article 121512

View PDF Article preview

Research article Full text access

Sizing utility-scale photovoltaic power generation for integration into a hydropower plant considering the effects of climate change: A case study in the Longyangxia of China

Zhikai Yang, Pan Liu, Lei Cheng, Deli Liu, ... Qian Xia
Article 121519

View PDF Article preview

Research article Full text access

Bi-level optimal configuration strategy of community integrated energy system with coordinated planning and operation

Peng Li, Zixuan Wang, Haitao Liu, Jiahao Wang, ... Yunxing Yin
Article 121539

View PDF Article preview

Research article Full text access

A novel Monte Carlo simulation on gas flow in fractal shale reservoir

Jinghua Yang, Min Wang, Lei Wu, Yanwei Liu, ... Peng Xu
Article 121513

View PDF Article preview

Research article Full text access

A variable inductor based harmonic filter design for multi-phase renewable energy systems with double closed-loop control

Shiqi Jiang, Panbao Wang, Zhaozhao Mei, Wei Wang, Dianguo Xu
Article 121522

View PDF Article preview

Research article Full text access

Longitudinal–vertical comprehensive control for four-wheel drive pure electric vehicle considering energy recovery and ride comfort

Junjiang Zhang, Yang Yang, Minghui Hu, Zhong Yang, Chunyun Fu
Article 121417

View PDF Article preview

Research article Full text access

Location assessment for producing biodiesel fuel from Jatropha Curcas in Iran

Fatemeh Najafi, Ahmad Sedaghat, Ali Mostafaeipour, Alibek Issakhov
Article 121446

View PDF Article preview

Research article Full text access

Time-of-Use feature based clustering of spatiotemporal wind power profiles

Chantelle Y. van Staden, Hendrik J. Vermeulen, Matthew Groch
Article 121474

View PDF Article preview

Research article Full text access

Acquisition of full-factor trip information for global optimization energy management in multi-energy source vehicles and the measure of the amount of information to be transmitted

Yan Kong, Nan Xu, Yuanjian Zhang, Yan Sui, ... Zhe Xu
Article 121423

View PDF Article preview

Research article Full text access

The new generation of District heating & cooling networks and their potential development in France

Rémi Patureau, Cong Toan Tran, Valentin Gavan, Pascal Stabat
Article 121477

View PDF Article preview

Research article *Open access*

Sewage sludge and the energy balance of Jerusalem artichoke production - A case study in north-eastern Poland

Krzysztof Józef Jankowski, Bogdan Dubis, Marcin Kozak
Article 121545

View PDF Article preview

Research article Full text access

Wind speed behaviors feather analysis and its utilization on wind speed prediction using 3D-CNN

Xiaoxun Zhu, Ruizhang Liu, Yao Chen, Xiaoxia Gao, ... Zixu Xu
Article 121523

View PDF Article preview

Research article Full text access

Fast microgrids formation of distribution network with high penetration of DERs considering reliability

Tongxu Yang, Limei Zhang, Linteng Zhen, Yongfu Liu, ... Wei Tang
Article 121524

View PDF Article preview

Research article Full text access

Optimization of energy consumption using data envelopment analysis (DEA) in rice-wheat-green gram cropping system under conservation tillage practices

Snehasish Bhunia, Subrata Karmakar, Suvendu Bhattacharjee, Kingshuk Roy, ... Biswapati Mandal
Article 121499

View PDF Article preview

Research article Full text access

Wind farm site selection considering turbulence intensity

Meysam Asadi, Kazem Pourhossein
Article 121480

View PDF Article preview

Research article Full text access

Performance analysis of large-scale industrial gas turbine considering stable combustor operation using novel blended fuel

Yeseul Park, Minsung Choi, Dongmin Kim, Joongsung Lee, Gyungmin Choi
Article 121408

View PDF Article preview

Research article Full text access

Oil price changes, uncertainty, and geopolitical risks: On the resilience of GCC countries to global tensions

Abdullah Alqahtani, Tony Klein
Article 121541

View PDF Article preview

Research article Full text access

The electrification of transportation in energy transition

Meng Yuan, Jakob Zinck Thellufsen, Henrik Lund, Yongtu Liang
Article 121564

View PDF Article preview

Articles from the Special issue on ULTRALOWHEAT; Edited by Giulio Santori, Ruzhu Wang

---

Research article Full text access

Adsorptive conversion of ultralow-temperature heat: Thermodynamic issues

Yu.I. Aristov
Article 121892

View PDF Article preview

Articles from the Special Issue on Energy Advances - GCEEC; Edited by Xudong Zhao, Lingai Luo,Yanping Yuan, Zhiqiang (John) Zhai, Yanjun Dai

---

Research article Full text access

Coupling optimization study of key influencing factors on PCM trombe wall for year thermal management

Na Zhu, Renjie Deng, Pingfang Hu, Fei Lei, ... Zhangning Jiang
Article 121470

View PDF Article preview

Articles from the Special issue on SESAAU2020; Edited by Henrik Lund

---

Research article Full text access

Heat pump efficiency in fifth generation ultra-low temperature district heating networks using a wastewater heat source

Tobias Reiners, Michel Gross, Lisa Altieri, Hermann-Josef Wagner, Valentin Bertsch
Article 121318

View PDF Article preview

Articles from the Special issue on PRES' 2020; Edited by Petar Varbanov, Ting Ma, Pawel Ocłoń, Bohong Wang

---

Research article Full text access

Solution strategy for increasing the efficiency of turbochargers by reducing energy losses in the lubrication system

Pavel Novotný, Jiří Vacula, Jozef Hrabovský
Article 121402

View PDF Article preview

Articles from the Special issue on SDEWES 2020 ; Edited by Neven Duić, Natasa Markovska, Antonio Piacentino, Brian Vad Mathiesen

---

Research article Full text access

Transition towards urban system integration and benchmarking of an urban area to accelerate mitigation towards net-zero targets

Şiir Kılkış
Article 121394

View PDF Article preview

Research article Full text access

An exergy-based minimum carbon footprint model for optimum equipment oversizing and temperature peaking in low-temperature district heating systems

Birol Kilkis
Article 121339

View PDF Article preview

Articles from the Special issue on SI_CPOTE_2020; Edited by Wojciech Stanek, Wojciech Adamczyk

---

Research article *Open access*

Engineering thermodynamics and sustainability

Ron Zevenhoven
Article 121436

View PDF Article preview

Articles from the Special issue on EMP-E 2020 Green Deal; Edited by Hans Auer, Pedro Crespo del Granado, Anthony Patt, Jessica Streffler, Laura Talens Peiró, Gabriele Frambini

---

Research article Full text access

Stochastic modelling of variable renewables in long-term energy models: Dataset, scenario generation & quality of results

Pernille Seljom, Lisa Kvalbein, Lars Hellemo, Michal Kaut, Miguel Muñoz Ortiz
Article 121415

View PDF Article preview

Research article *Open access*

Dynamic allocation of peer-to-peer clusters in virtual local electricity markets: A marketplace for EV flexibility

Naser Hashemipour, Pedro Crespo del Granado, Jamshid Aghaei
Article 121428

View PDF Article preview

Previous vol/issue Next vol/issue

ISSN: 0360-5442