# Thermochemical conversion of biomass: Potential future prospects

Yuzhuo Wang, Jun Jie Wu [*]

*Department of Engineering, Faculty of Science, Durham University, Durham, DH1 3LE, UK*

## ARTICLE INFO

## ABSTRACT

The thermochemical conversion of biomass is potentially vital to meeting global demand for sustainable transport fuels so besides combustion; torrefaction, liquefaction, pyrolysis and gasification are reviewed. The merits and demerits of these processes and examples of industrial applications are evaluated, and two promising avenues for future development are identified. The future of biomass upgrading via thermochemical processing will depend on sector coupling, both within the energy sector and with sectors such as food production. Owing to environmental constraints and the need to maintain food production, the availability of traditional feedstocks for biofuels, such as corn, will be limited in the future. Now given the ambitious targets for sustainable aviation fuel – a higher quality fuel – reserving appropriate feedstocks for aviation fuel will be necessary. Such a policy would open opportunities for the commercial development of the sustainable production of such liquid fuels via liquefaction and pyrolysis. The second avenue of opportunity links to the fact that biomass in the form of wooden pellets has established itself as an essential fuel. In the UK and elsewhere, it is already contributing to the decarbonisation of the electricity grids. So worldwide, a positive future for biomass combustion, aided where appropriate by torrefaction, is envisaged as increasingly crucial for the abatement of greenhouse gas emissions. Alongside battery storage and pumped hydroelectric storage, the contribution of biomass processes, such as torrefaction, to tackling the storage problem arising from the intermittent nature of wind and solar energy has been clarified for the first time.

## 1. Introduction

Rapid industrialisation and the improvement of the living standards of society rely heavily on the steady supply of energy, with the consumption of fossil fuels (coal, petroleum, natural gas) accounting for 80% of the energy demand around the world [1]. A significant amount of this energy is used to produce electrical power, which the developed world expects to be available 24/7. However, the excessive use of fossil fuels causes resource depletion and produces air pollution and global warming, creating irrevocable harm to the environment [2]. Dire consequences rising from a rise in global temperatures by 2 °C above the pre-industrial norm have been predicted both for people and the environment (for example, it has been reported that hundreds of millions of people will face death and that there will be an extinction of millions of faunal and floral species [3]). It is universally recognized that restructuring our energy sectors is crucial for sustainability and long-term energy security. Indeed there is broad acceptance that having a path to eliminate fossil fuel dependency should guide short- and long-term energy policies. Energy-related emissions account for three-quarters of

global CO$_2$ emissions [4].

Thus, to alleviate global environmental problems and satisfy the energy requirements of modern society, a range of renewable energy resources have come to the fore as sustainable alternatives to traditional fossil fuels [5,6]. Currently, the renewable energy processes of commercial significance are hydroelectric, solar and wind [7]. Both solar and wind energy depend on the weather, and solar energy is only available for part of the day. The growth of wind and solar energy in Great Britain, and the demise of power production from coal, are illustrated in Fig. 1.

Hydroelectric comes with its accompanying energy storage; a reservoir of water at a high elevation and the associated potential energy is the ultimate energy source from which hydroelectricity is created. Storage of fossil fuels such as coal and natural gas is also straightforward, but solar and wind energy cannot be stored in primary form. This presents a problem because there are periods, as illustrated in Fig. 2 when Great Britain experiences a lack of wind that reduces the output level to around 20% of the typical current output of *circa* 10 GW. Indeed recently, in the week beginning March 2022, only 2.3 GW of wind generation occurred, whereas the yearly average is 8.66 GW [7].

**Abbreviations**

| | | | |
|---|---|---|---|
| ASTM | American Society for Testing and Materials | HHV | higher heating value |
| BEIS | Department for Business, Energy and Industrial Strategy (United Kingdom) | HVO | hydrogenated vegetable oil |
| | | MCDM | multi-criteria decision-making |
| BTG | Biomass Technology Group (Netherlands) | PE | polyethene |
| CEA | Commissariat à l'énergie atomique et aux énergies alternatives (France) | PM | particulate matter |
| | | PRO | Pressure-Retarded Osmosis |
| E | experimental distribution | PS | polystyrene |
| ETIA | Evaluation Technologique, Ingénierie et Applications (France) | RED | Reverse Electrodialysis |
| | | RH | rice husk |
| FAME | fatty acid methyl ester | SAF | Sustainable Aviation Fuel |
| FC | fixed carbon | SCB | sugar cane bagasse |
| GHG | greenhouse gas | SESG | sorption-enhanced steam gasification |
| GREET | Greenhouse gases, regulated emissions, and energy use in transportation | SEBSG | sorption-enhanced biomass steam gasification |
| | | SMR | steam-methane reforming |
| GTI | Gas Technology Institute (United States) | T | theoretical distribution |
| HDPE | high-density polyethene | TFEC | total final energy consumption |
| | | VM | volatile matter |
| | | WGS | water-gas shift |
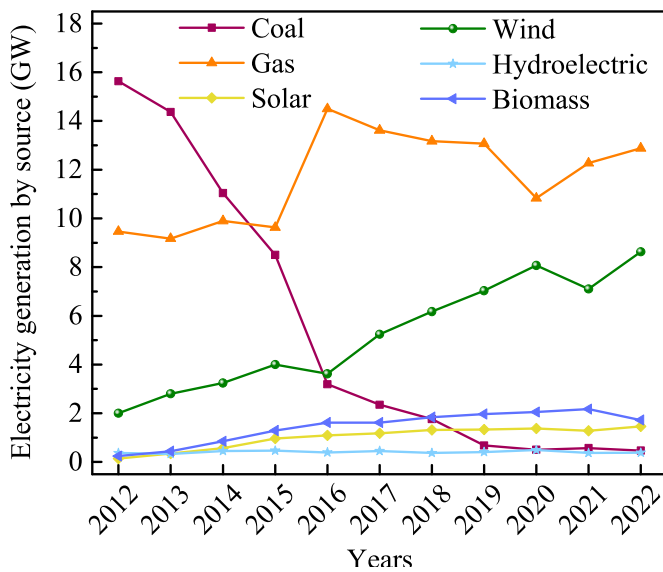


**Fig. 1.** Electricity generation by different sources in Great Britain from 2012 to 2022. Source of data [7].



**Fig. 2.** Electricity generation by wind energy in Great Britain from February 28 to May 30 in 2022. Source of data [7].

Occasionally a "wind drought" that slows or even halts wind turbines across the country occurs. In July 2018, as reported elsewhere, wind energy output can be significantly reduced compared to the previous year despite more wind turbines being installed in the interim [8]. This variability means that the deployment of solar and wind energy needs to be accompanied by the development of storage and complementary processes that can be ramped up during periods when supply from wind and solar is low. A biomass related avenue for addressing the energy storage problem is considered in Section 3.

When electricity generation from wind energy is low, natural gas is the "go-to" fuel to take up the slack. In a country like the UK, natural sources of hydroelectricity are minimal because of the country's geography; likewise, the potential of pumped storage is constrained. Hence exploitation of solar and wind energy needs to be accompanied by the development of storage and complementary processes. Before considering neo-traditional biomass such as wooden pellets, a broader overview of the potential of utilizing biomass for renewable energy production and reducing greenhouse gas emissions, particularly the thermochemical conversion for the production of biofuels, is considered
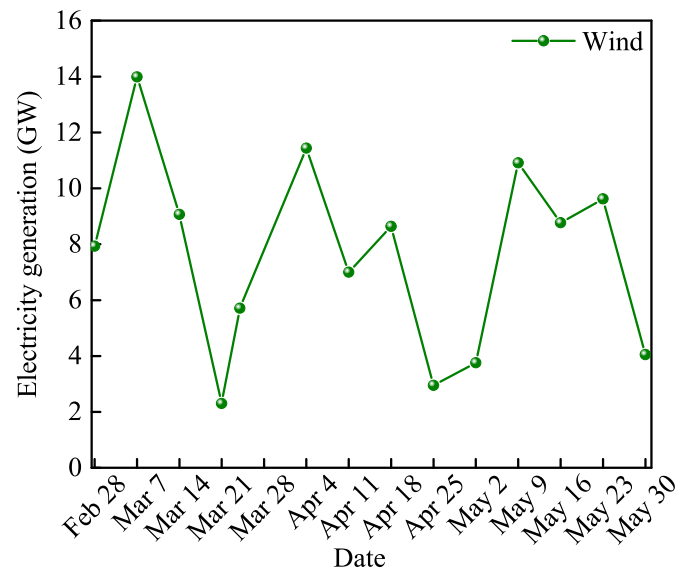
in section 2.

To appreciate the research gap being addressed brief mention is made of the political context. Worldwide there is an agreement in principle on the need to switch away from fossil fuels, and the text of the outcome from COP27 reaffirms the commitment to limit global temperature rise to 1.5° Celsius above pre-industrial levels. However, the final decision text, known as the Sharm el-Sheikh Implementation Plan, noted "a clear emissions gap between current national climate plans and what's needed" for this target to remain realistic [9] Currently, whilst Secretary-General of the United Nations, António Guterres, has said that investment in new oil and gas production was "economic and moral madness", the CEO of Shell stated in an interview with the BBC's Business Editor that cutting oil and gas production would be "dangerous and irresponsible" and that world still "desperately needs oil and gas" because moves to renewable energy were not happening fast enough to replace it [10] This timely review focuses on the potential contribution that the thermochemical conversion of biomass could make to accelerating the green transition by contributing to the production of those products that are essentially the sole preserve of the oil and gas industry.

The second research gap this review also examines is the potential contribution of biomass to the storage problem. As wind energy cannot be stored in primary form, energy storage is becoming a high priority worldwide. Observations on the contribution that biomass combustion can make to the resolution of this problem are reviewed in section 3.

For the powering of the electricity grid, alternative processes that can operate 24/7 have an inherent attraction.Particularly if like salinity gradient power processes, they are based solely upon the controlled mixing of seawater and fresh water. To complete the contextual introduction, mention is made of two salinity gradient power processes that have been developed. The one that has been the focus of most attention is Pressure-Retarded Osmosis (PRO) which exploits the difference in osmotic pressure between seawater and fresh water. The other is Reverse Electrodialysis (RED) which exploits a different aspect of the chemical potential difference between salt and fresh water. The first PRO pilot plant was opened by the Norwegian energy company Statkraft in 2009 but closed in 2014 due to the lower-than-expected output [11]. Commercial developments of both salinity gradient power processes have ceased. Thus, whilst both processes are technically feasible, their future contribution to rebuilding electricity grids can be disregarded.

By contrast, one of the promising sources of clean and green fuels is biofuels due to their low cost, topographical independence, and net carbon neutrality [12]. Biomass is globally considered a kind of zero-carbon energy due to the carbon cycle in vegetation and has become the fourth largest energy after coal, oil, and natural gas. Bioenergy has significant potential to reduce greenhouse gas (GHG) emissions. In addition, combining carbon capture and storage technology with bioenergy can create negative carbon emissions, which could become an essential process for environmental remediation.

Biomass resources can be placed mainly in four categories: agricultural biomass, kitchen waste, livestock excrement, and microalgae, composed of soluble saccharide, lignocellulose, protein, and fats [13]. Agricultural biomass has the simplest ingredients among the above-mentioned resources, so it is utilised most broadly. It has been reported that 1 billion tons of agricultural biomass equals 0.55 billion tons of standard coal and theoretically, its use reduces $CO_2$ emission by 1.5 billion tons [14]. Thermochemical conversion of biomass is a feasible and frequently explored route to convert biomass to biofuels. Through the optimisation of the process parameters and the addition of additives, it can yield high selectivity of desired products and reduce unwanted

byproducts [15,16]. However, the proper accounting of net carbon benefits should consider the carbon loss derived from land-use change. To achieve carbon benefit, the carbon generated by displacing fossil fuels must overtake the carbon sequestration forgone directly and indirectly by land-use change [17,18]. This paper focuses on the first of the four categories mentioned above because the use of livestock excrement, its potential for biogas production, and the prospects for microalgae as a crucial future feedstock for the production of third-generation biofuels have been discussed elsewhere [18,19]. Fig. 3 schematically presents a segmentation of the thermochemical processes by which biomass may contribute to tomorrow's energy mix, and then the individual processes are discussed in subsequent sections.

The pathway on the righthand side of Fig. 3, namely the sourcing of biomass, then production of solid fuel followed by combustion to drive a steam cycle to power electricity generation, currently accounts for around 6% of Great Britain's electricity production [7]. Combustion is briefly mentioned in the next section and then covered in more detail in Section 3. This review focuses mainly on the upgrading processes that are the other part of Fig. 3. These are biomass thermochemical conversion processes (torrefaction, liquefaction, pyrolysis, and gasification) that can produce biochar, bio-oil and syngas. Their limitations and technical challenges are summarised to provide more specific improvement directions. Later contextual comments on the potential of biomass to contribute to both the liquid fuels market and electricity production are given, and bioethanol and biodiesel production is introduced at that stage.

## 2. Thermochemical conversion of biomass

### 2.1. Combustion

Generally, biomass thermochemical conversions consist of combustion, liquefaction, torrefaction, pyrolysis, and gasification technologies. The operating conditions and main products are summarised in Fig. 4 [20]. Biomass can be incinerated directly as an alternative to coal to produce heat and electricity in power plants. However, the high contents of O and the moisture of the biomass lead to it having a low calorific value. So generally, it must be dried before burning. Also, a greater mass of biomass is needed to release the same heat as coal, which raises storage and transport costs [21]. The variation of compositions and
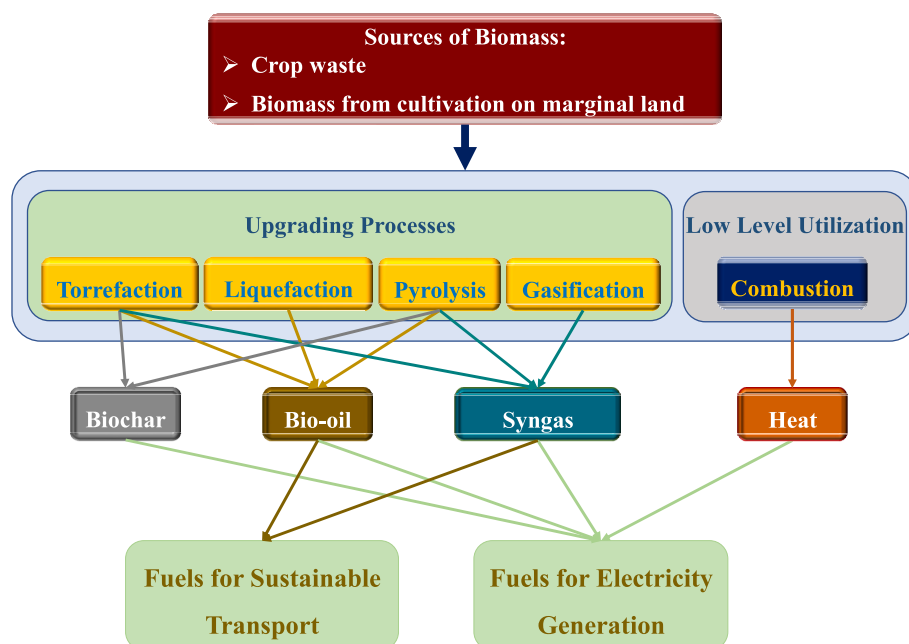


**Fig. 3.** Thermochemical Conversion of biomass: Schematic diagram showing the potential routes by which biomass could contribute to the future energy mix.
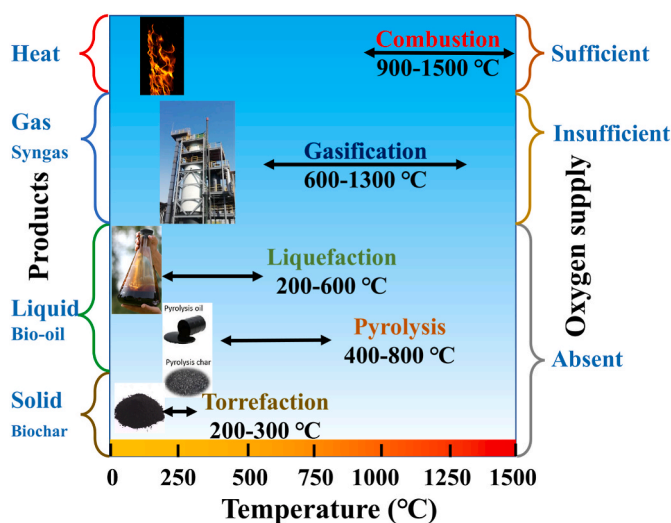
**Fig. 4.** A schematic diagram of biomass thermochemical conversion technologies. Source [20].

properties brings difficulties in adjusting the unit parameters. As indicated above, biomass combustion is a low-grade recycling approach. The reason for labelling the combustion of wooden pellets, in section 1, as a neo-traditional method, will be discussed in section 3.

### 2.2. Torrefaction

Biomass torrefaction is a variety of high-temperature drying or low-temperature pyrolysis technology performing at 200–300 °C in an oxygen-reduced or inert atmosphere [22]. The tenacity and fibrous structure of biomass are damaged by carboxylation and dehydration reactions, which help to remove oxygen and water from the feedstock [23]. The torrefied biomass (biochar) presents improved properties compared with ordinary biomass: it has higher energy and mass density, higher heating value, better hydrophobicity, and improved powder grindability and flowability, giving it somewhat similar properties to coal [24,25]. The fuel characteristics of raw biomass, biochar, and coal are summarised in Fig. 5. Compared with residence time, moisture content, and particle size of biomass, the most significant factor affecting an improvement in biomass properties is torrefaction temperature. Pimchuai and co-researchers [26] investigated the effects of

temperature (250–300 °C) and residence time (1–2 h) on bagasse torrefaction. Compared with residence time, temperature had a more dominant effect on mass and energy yields, as shown in Fig. 6. Several researchers (Huang [27], Kanwal [28], and Tumuluru [29]) also found the significance of temperature in the biomass torrefaction process. Appropriate preparation conditions contribute to the coal-like physico-chemical properties of biochar, which is promising for future transformation in energy structure.

Although the abovementioned advantages exist, several challenges must be solved before widespread use. Self-heating can be a severe problem inhibiting the use of biochar. When, in a biochar stockpile, the heat removal rate is slower than the heat release rate, the temperature will rise significantly, followed by self-ignition and even explosion [30, 31]. Thus from a safety perspective the reasonable storage of biochar is a crucial issue [32]. Furthermore, the ash content is increased after the torrefaction process, which gives rise to ash-related issues such as slagging, corrosion, and agglomeration in furnaces, as shown in Fig. 7 [33]. As for economic viability, the significant challenges in biomass torrefaction are product availability and commercialisation. The investment and operating costs of the torrefaction process, including pretreatment (chipping, screening, and storage), torrefaction (reactor maintenance and energy consumption) and posttreatment (milling and pellets forming), are higher than those of coal. A quality standard for biochar would make for more reliable operation and better exploitation of this resource.

### 2.3. Liquefaction

Biomass liquefaction is a prospective thermochemical conversion technique which converts biomass into bio-oil (target product, 40–60%), biochar (10–12%), and gases (35–45%). It is often performed in a solvent, such as water, ethanol, acetone, glycerol, phenols, and tetralin, at relatively low temperature (200–600 °C) and under high pressure (5–25 MPa) [34]. The product compositions and consequential properties depend primarily on the process parameters, such as biomass type, reaction temperature, pressure, residence time, solvent, catalyst, etc. [35]. To achieve efficient and high-quality production of bio-oil, optimisation of process parameters is necessary. Xue et al. [36] pointed out that biomass containing more cellulose and hemicellulose could yield more bio-oil. The simple structure and low decomposition temperatures of cellulose and hemicellulose made them more accessible to be liquefied. The reaction temperature is a significant parameter in biomass liquefaction, significantly influencing bio-oil compositions and calorific values. Wu et al. [37] investigated the hydrothermal
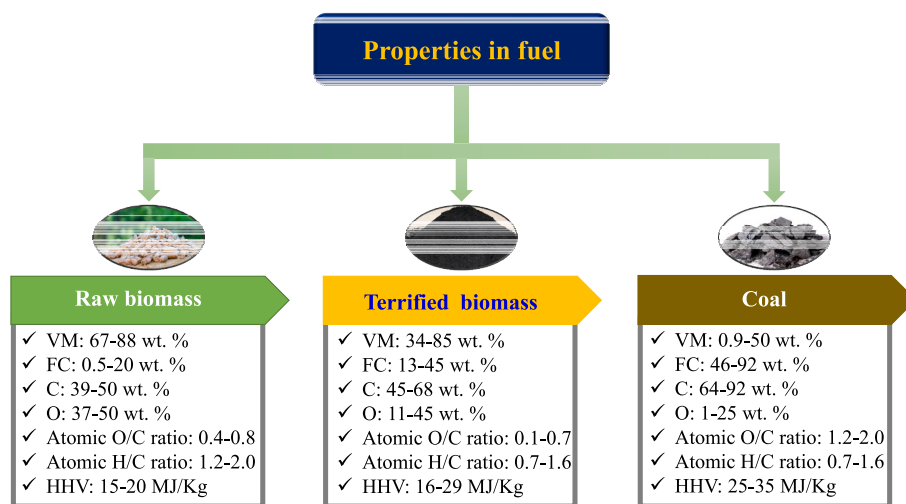


**Fig. 5.** Fuel characteristics of raw biomass, biochar, and coal. (FC: fixed carbon, HHV: Higher heating value, VM: volatile matter. Other symbols have their ordinary meaning.) Source [20].
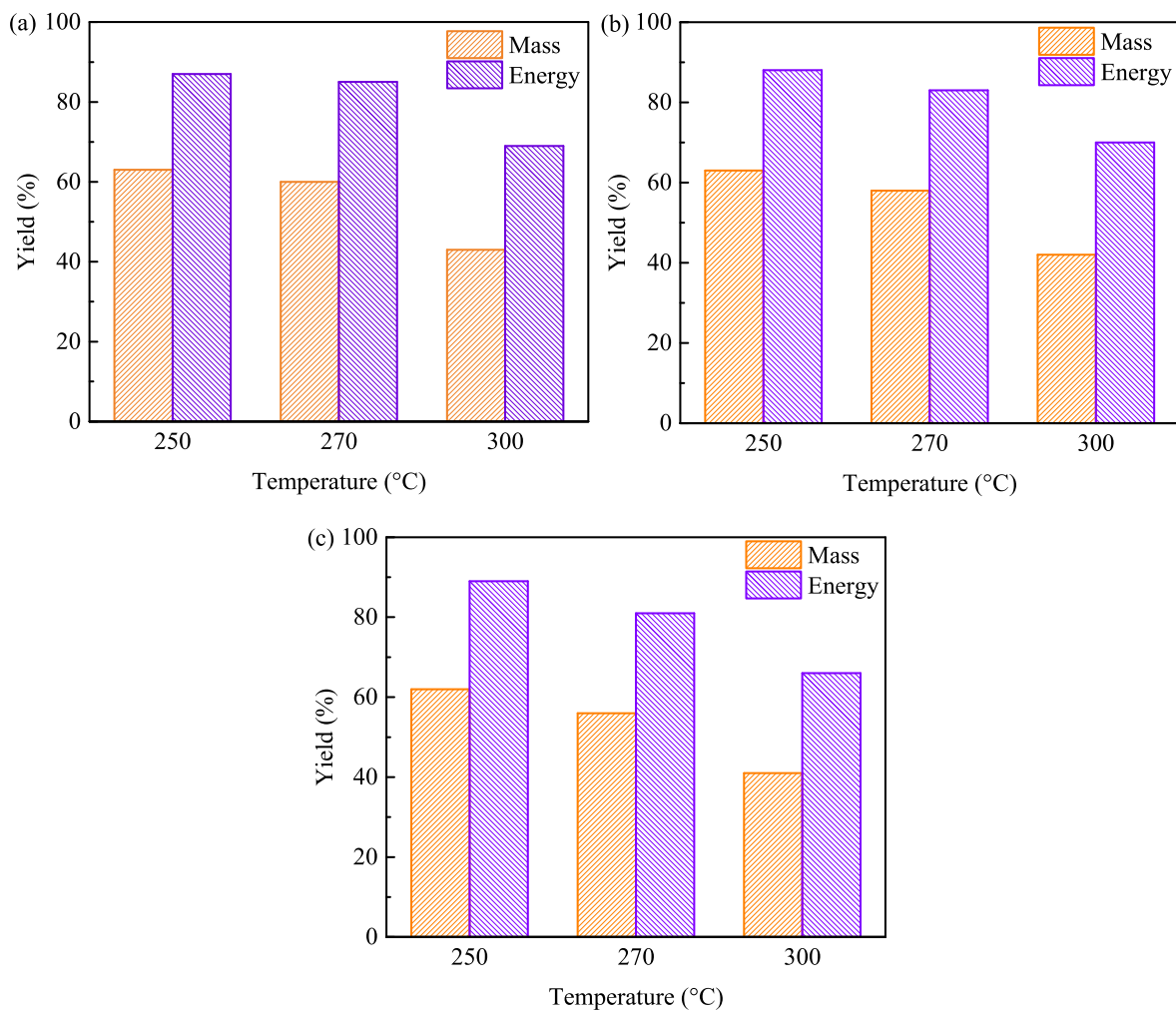
**Fig. 6.** The mass and energy yields of bagasse at different conditions: (a) 1 hour (b) 1.5 hours and (c) 2 hours. Source [26].
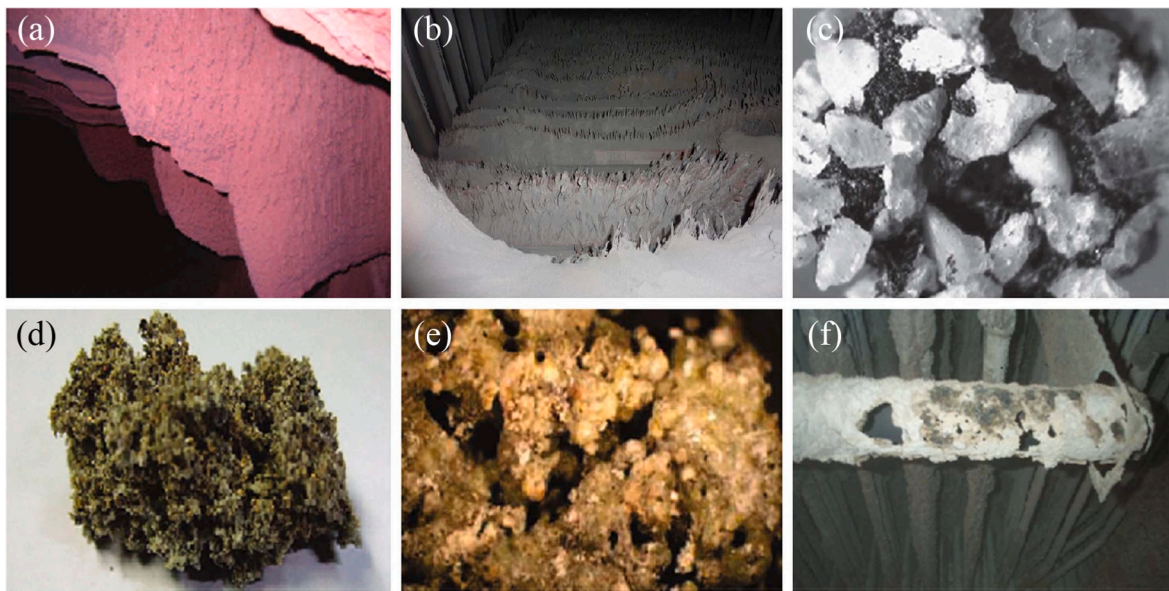


**Fig. 7.** Various ash-related issues in biomass-fired furnaces: (a) and (b) alkali-induced slagging, (c) agglomeration, (d) and (e) silicate melt-induced slagging (ash fusion), (f) corrosion [33].

liquefaction of poplar (a tree with a high growth rate) at 220–280 °C for 30 min and found that the bio-oil yield initially increased and then slightly decreased. The highest bio-oil yield (19.88%) and calorific value (27.97 MJ/kg) were obtained at 260 °C. Gai et al. [38] performed the hydrothermal liquefaction of *C. pyronoidosa* and rice husk mixture (1:1) with a retention time of 60 min. As shown in Fig. 8, the maximum bio-oil yield of 43.6% was acquired at 300 °C, then decreased with a further increase in the reaction temperature to 350 °C.

In biomass liquefaction, high pressure facilitates the penetration of solvents into the biomass which aids decomposition of the macromolecules and consequentially improves conversion rates [39]. Basar et al. [40] studied the effect of pressure (200–400 bar) on biomass liquefaction. They found that the pressure no longer significantly impacted the bio-oil yield above the critical value of 221 bar. Furthermore, high pressures are usually along with high temperatures, which usually causes adverse effects beyond critical values. Appropriate retention time also contributes to biomass decomposition and bio-oil production. While overlong retention time intensifies the condensation reactions and bio-oil cracking, the intermediate products re-polymerize to gas or coke, thus decreasing the bio-oil yield. Eboibi et al. [41] used a kind of halophytic microalga as the raw material, and the yield of bio-oil rose with longer residence time when the temperature was set at 310 °C as shown in Fig. 9. Further increasing the temperature to 350 °C, the extension of the residence time led to a decrease in bio-oil yield. The optimal residence time is closely related to the reaction temperature.

Solvents should not negatively affect bio-oil yields and chemical compositions. Isa et al. [42] suggested that some solvents, including alcohol, glycerol, decalin and tetralin, could also act as •H donors, which upgraded the bio-oil quality via declining O content. In addition, catalysts have also been widely investigated to improve further the yield and quality of bio-oil. Homogeneous catalysts, like Na and K alkali salts [43,44] and zeolite-based heterogeneous catalysts [45,46], are mostly used for biomass liquefaction. Jindal et al. [47] conducted a comprehensive study in a batch reactor to reveal the effect of alkali salts (NaOH, KOH, $Na_2CO_3$ and $K_2CO_3$) on hydrothermal liquefaction of sawdust. The operating temperature and residence time were 280 °C and 15 min, respectively. The highest bio-oil yield (34.9 wt%) containing low O content was achieved when 1.0 mol/L of $K_2CO_3$ catalyst was used.

However, the higher heat values (HHV) of liquefied bio-oil are still lower, and the chemical compositions are more complicated than those of liquid fuels (gasoline, diesel. et al.) abstracted from crude oil.
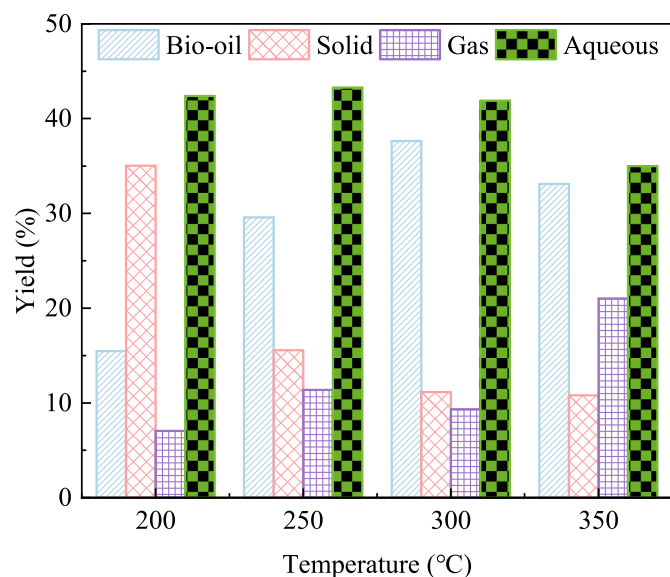
Furthermore, the scale of industrial application for biomass liquefaction is limited because this process is performed under high pressure with the consumption of additives, which increases the complexity, risks and costs of the reactor system [48].

## 2.4. Pyrolysis

Pyrolysis is an efficient thermochemical conversion technique to produce bio-oil, which occurs at 400–800 °C (as indicated in Fig. 4) in an oxygen-free environment. The reaction temperature, pyrolysis rate, and residence time are the main factors that affect pyrolysis products, and the lower half of the temperature range just indicated is necessary when the objective is the maximisation of the yield of liquid products. The crude bio-oil (also known as pyrolysis oil or biocrude) is a viscous liquid with a dark brown colour and a pungent smell that is unsuitable for direct applications because it is a complicated mixture of carboxylic acids and other oxygenated compounds [49,50]. The high O and water content of crude bio-oil results in a relatively low calorific value almost half that of the petroleum-derived fuels. Furthermore it contains carboxylic acids which cause corrosion and aggregation of other components in the bio-oil [51]. Therefore upgrading will be essential for improving the physicochemical properties of bio-oil if it is to be considered a possible alternative to petroleum.

Co-pyrolysis of biomass with other raw materials has attracted much attention due to its prospect of improving the quality of pyrolysis products [52,53]. In co-pyrolysis, other raw materials (coal, plastics, tyres, sludge, etc.) are introduced into the biomass pyrolysis system and decomposed with biomass simultaneously [54,55]. The synergistic effect between free radicals released from feedstocks plays an essential part in the co-pyrolysis system [56]. Hassan et al. [57] investigated the co-pyrolysis of sugar cane bagasse (SCB)/high-density polyethene (HDPE) in a fixed-bed reactor. They suggested that the •OH generated from SCB significantly influenced co-pyrolysis products. As displayed in Fig. 10, when the ratio of HDPE:SCB was 40:60, the theoretical values of co-pyrolysis products presented distinctive differences from their weighted individual experimental values, which indicated a strong synergistic effect between SCB and HDPE. However, Montiano et al. [58] evaluated the co-pyrolysis of sawdust, coal, and tar mixtures. No synergistic effect was found when comparing the experimental and theoretical results following Ferrara et al.'s study [59]. Therefore, the synergistic effect and detailed interaction mechanism are still unclear in the co-pyrolysis of biomass/other raw materials and these could be beneficially explored further.

Introducing suitable catalysts is also helpful in upgrading biomass pyrolysis oil. Various types of catalysts, such as metal oxides (CaO, $Al_2O_3$, MgO et al.), inorganic salts ($K^+$, $Na^+$, $Mg^{2+}$, $Ca^{2+}$, $Zn^{2+}$, $Fe^{3+}$ et al.), zeolites (HZSM-5, MCM-41, etc.), have been developed for biomass catalytic pyrolysis [60,61]. Dai et al. [62] found that the HZSM-5 catalyst treated with the NaOH solution (0.3 M) contributed to producing more aromatics and less coke, and the selectivity towards benzene series (benzene, toluene, and xylene) was notably improved. Che et al. [63] proposed the highest selectivity of aromatics was achieved with the CaO-ZSM-5 dual catalyst, which reached 6.14% higher than that of the pure ZSM-5 catalyst. On this basis, the catalytic co-pyrolysis of biomass/other raw materials have been investigated to offset the drawbacks in biomass catalytic pyrolysis, like low bio-oil yield and quality and the deactivation of catalysts due to coke formation. Hassan et al. [64] prepared a faujasite-type zeolite rich in mesopores and performed the catalytic co-pyrolysis of SCB and HDPE. Under optimal operating conditions, the catalytic co-pyrolysis bio-oil yield and HHV could reach 68.56 wt % and 44.94 MJ/kg, respectively.

Recently, some advanced pyrolysis technologies, like microwave-assisted and solar-assisted pyrolysis, have attracted plentiful attention due to their superiority over conventional biomass pyrolysis, assisted by electricity or heat [65,66]. As for microwave-assisted pyrolysis, microwave energy is converted into heat energy by molecule agitation in the
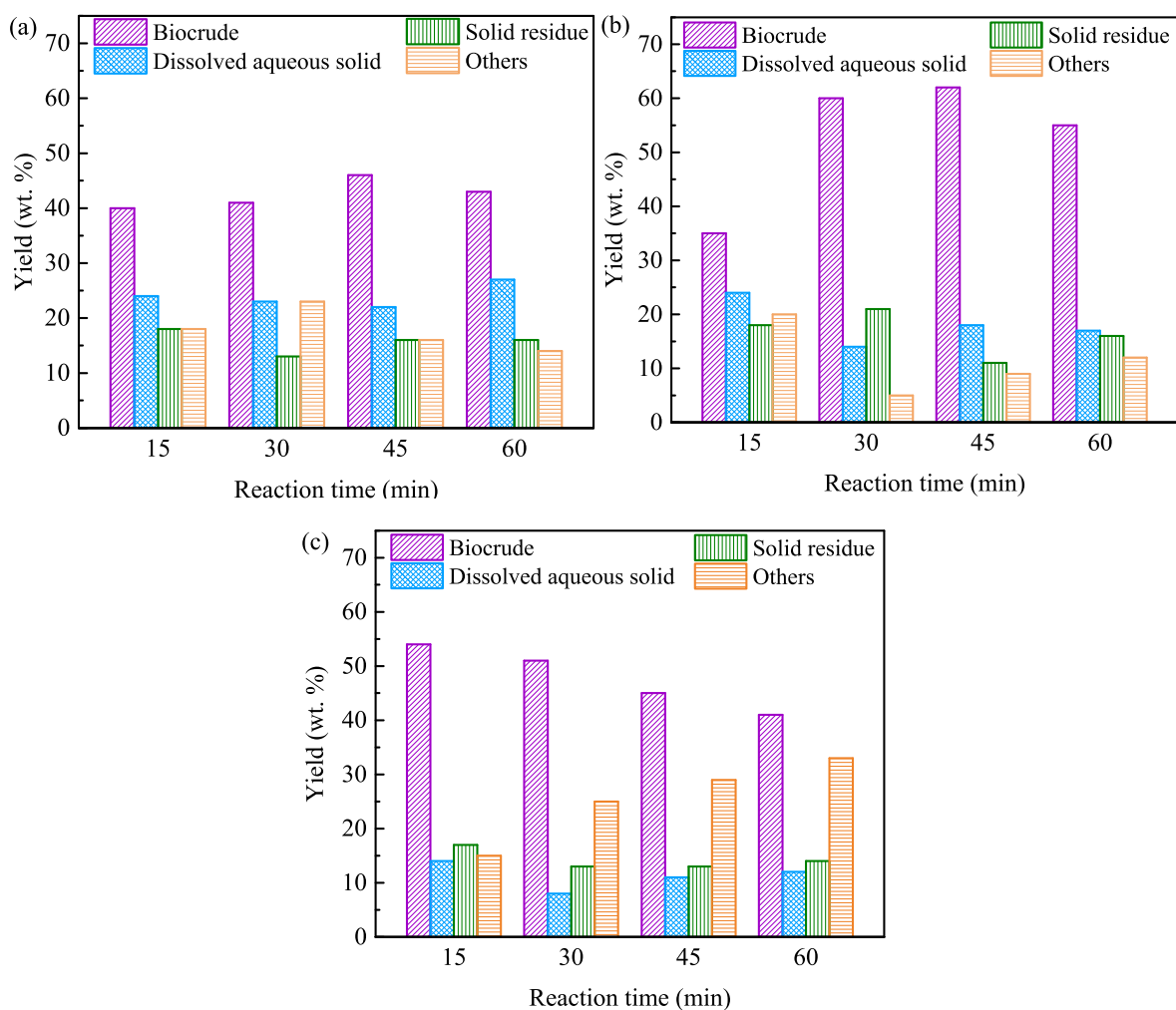


**Fig. 8.** Effect of liquefaction temperature on the yields of products. Source [38].

**Fig. 9.** Mass yields in liquefaction of halophytic microalga at (a) 310 °C (b) 330 °C and (c) 350 °C with holding time varying from 15 to 60 min. Source [41].
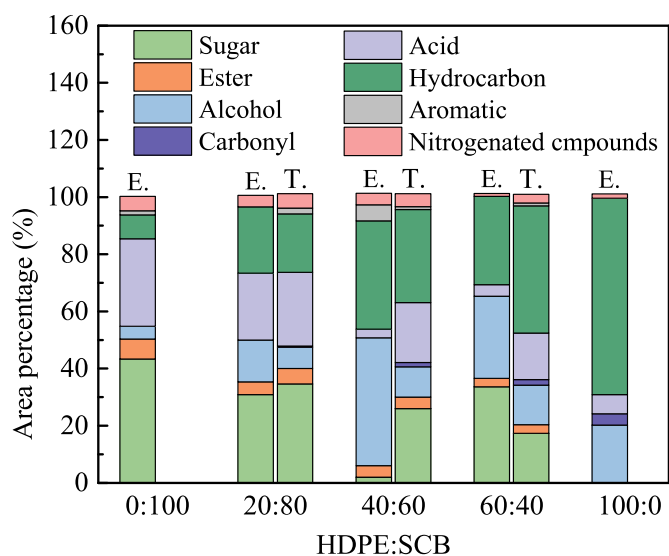


**Fig. 10.** Effect of HDPE:SCB ratio on the experimental (E.) and theoretical (T.) distribution of co-pyrolysis products. Source [57].

electromagnetic field. The generated heat energy diffuses from the inside to the outside of the materials realizing a temperature increase [67, 68]. Fig. 11 illustrates the difference between conventional and microwave heating methods and implicitly indicates why the latter is often more energy efficient [69]. In terms of solar-assisted pyrolysis, the solar energy is initially collected by a solar concentrator and then converted to thermal energy for biomass pyrolysis. The diagram of the solar-assisted pyrolysis system is displayed in Fig. 12 [70]. Suriapparao et al. [71] conducted co-pyrolysis of rice husk (RH)/polystyrene (PS) assisted by microwave. They reported that microwaves gave promising improvements in the quality of products whilst achieving high process efficiency, energy yield and HHV (63–68%, 80% and 38–42 MJ/kg, respectively). Weldekidan et al. [72] studied the solar-assistance pyrolysis of chicken litter waste with the catalysis of 50% CaO. The minimal concentrations of fatty acids in the bio-oil were respectively only 8% and 3% in the in-situ and ex-situ pyrolysis systems.

Although co-pyrolysis presents advantages in removing O and upgrading oil products, the produced co-pyrolysis oil still cannot be utilised directly as a substitute for petroleum. The synergistic effects in co-pyrolysis of biomass and different raw materials are also unclear, which suggests that a deep investigation is needed to provide theoretical indications regarding the possibility of achieving higher-quality products. As for catalytic pyrolysis, catalyst deactivation due to coke deposition is the critical problem inhibiting the deployment of advanced catalysts, which ideally would possess high catalytic activity, stability, good adaptability, and be available at low cost. In conclusion, for pyrolysis more research on exploring synergy mechanisms, optimizing catalyst designing, and upgrading system regulation is desirable.
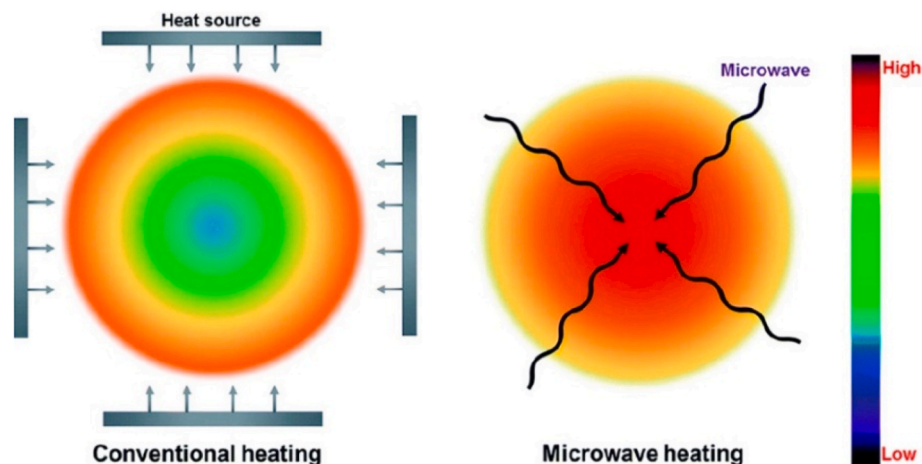
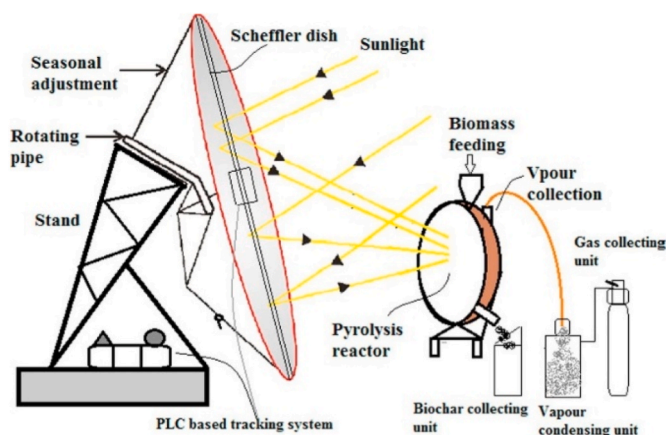**Fig. 11.** Difference in operating principle between conventional and microwave heating methods [69].



**Fig. 12.** Diagram of solar-assisted pyrolysis system [70].

## 2.5. Gasification

Gasification is an endothermic process where biomass is partially oxidised at higher temperatures (600–1300 °C) with the help of gasification agents like air/$O_2$, steam, and $CO_2$ [73]. The gaseous products consist of CO, $CO_2$, $H_2$, $CH_4$, and hydrocarbons. Steam is the optimal gasification agent to improve the calorific values and compositions of gasification products because it introduces a H resource (steam) and offsets the drawback of high O contents of biomass to some extent [74]. The main reactions in biomass steam gasification are shown in Table 1. The existence of a large amount of $CO_2$ limits $H_2$ production due to the restraint of reactions such as the steam-methane reforming (SMR) and

**Table 1**
Main reactions in biomass steam gasification for $H_2$ production.

| Reactions | Equation | $\Delta H$ (kJ/mol) | Serial number |
|---|---|---|---|
| Pyrolysis | Biomass $\xrightarrow{\text{pyrolysis}} C_xH_yO_z + C_nH_m + H_2 + CO + CO_2$ | >0 | (1) |
| Tar Reforming | $C_xH_yO_z + (2x - z)H_2O \rightarrow xCO_2 + \left(2x + \frac{y}{2} - z\right)H_2$ | >0 | (2) |
| SMR | $CH_4 + H_2O \rightleftharpoons CO + 3H_2$ | 206 | (3) |
| Coal Gasification | $C + H_2O \rightleftharpoons CO + H_2$ | 132 | (4) |
| Boudouard Reaction | $C + CO_2 \rightarrow 2CO$ | 162 | (5) |
| WGS | $CO + H_2O \rightleftharpoons CO_2 + H_2$ | −41 | (6) |

water-gas shift (WGS) equilibrium reactions [75,76]. According to Le Chatelier's principle, if $CO_2$ is removed in situ from the gaseous products, the gasification equilibrium will be displaced towards $H_2$ production [77]. The deployment of this process is called sorption-enhanced biomass steam gasification (SEBSG). CaO is considered the most applicable sorbent to remove $CO_2$ in situ due to its affordability, high theoretical $CO_2$ storage ability and fast sorption-desorption kinetics [78,79]. The CaO-based SEBSG schematic diagram is shown in Fig. 13 [74]. Biomass is gasified in the gasifier under a steam atmosphere. The generated $CO_2$ is immediately captured by CaO, promoting a shift in the equilibrium of the gasification reaction and movement towards greater $H_2$ production. Then, the carbonated CaO ($CaCO_3$) and unreacted biochar are transferred to the regenerator, where $CaCO_3$ is calcined with the heat from oxyfuel combustion [80,81]. The highly concentrated $CO_2$ will be collected for storage or utilisation [82,83]. Furthermore, due to the carbon neutrality of biomass, the $CO_2$ in-situ removal in SEBSG could realise negative carbon emissions, which promises to contribute to the mitigation of the global warming problem.

Although the reaction equilibrium can be shifted due to in situ $CO_2$ removals in the SEBSG process, the rate is still relatively low [82,84]. Catalysis/sorption bi-functional materials were used to maximise high-concentration $H_2$ generation [85,86]. The commonly used Ca-based sorbents are abundant and accessible, involving natural dolomite, limestone, olivine, marble, etc. Alkali metals (Li, Na, K) and transition metals (Ni, Cu, Co, Fe, Ce, etc.) have been widely investigated as catalysts in biomass gasification.

Yang and co-researchers [87] investigated the SESG of wheat straw and found that 0.25 wt% KCl effectively enhanced the cyclic $CO_2$ capture ability and stability of CaO and decreased the $CO_2$ concentration by 9.13 vol% while increasing the $H_2$ concentration by 7.3 vol%, as displayed in Fig. 14. Sun co-researchers [88] studied the catalytic $H_2$ production performance of $Ca_2Fe_2O_5$ in the SESG of pine sawdust. They found that $Ca_2Fe_2O_5$ increased the gas yield, carbon conversion and tar conversion by 13.4%, 11.7% and 17.3%, respectively. The $H_2$ production was dramatically increased by 78.98% in the first 10 min, and the $Ca_2Fe_2O_5$ maintained stable catalysis over 20 gasification/regeneration cycles. Yan et al. [89] studied the $H_2$ production performance of $CeO_2$–CaO–$Ca_{12}Al_{14}O_{33}$ bi-functional material in the SESG of bagasse. After 10 gasification/regeneration cycles, the $H_2$ concentration and yield in the presence of $CeO_2$–CaO–$Ca_{12}Al_{14}O_{33}$ were respectively 85 vol% and 0.13 L/g, which were 13.3% and 44% higher than those without $CeO_2$ catalysis.

However, low H contents and high O contents of biomass are detrimental to the production of $H_2$ and lead to the formation of a large amount of coke and tar, which cause severe problems in the regular operation of the SEBSG system. The deposition of coke tends to cause
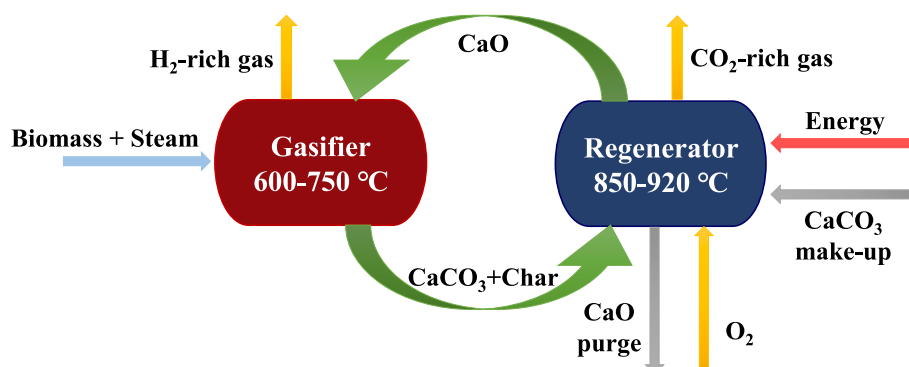
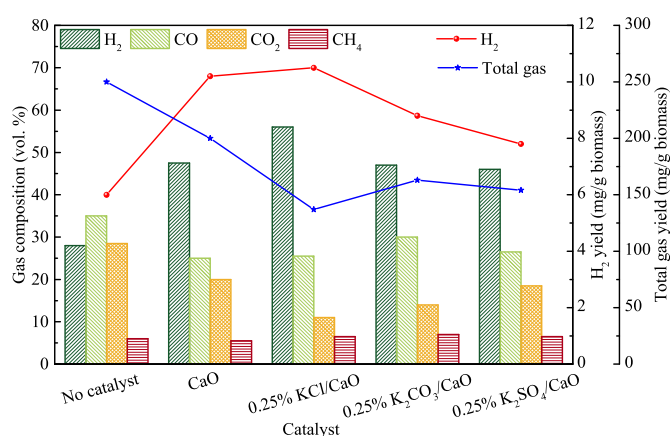**Fig. 13.** Schematic diagram of CaO-based SEBSG system [74].



**Fig. 14.** The compositions and yields in the SESG of wheat straw using different K/Ca bi-functional materials. Source [87].

considerable deactivation of bi-functional materials [90]. Tar can corrode the inner walls of reactors and create problems for human health [91].

As waste plastics, such as polyethene (PE) and polypropene, are decent H donors, the co-gasification of biomass/waste plastics mixtures can offset the abovementioned drawbacks of gasification of biomass alone [92]. Additionally, co-gasification is beneficial to alleviate the threats posed by waste plastics to the environment due to their non-degradable characteristic, which not only causes litter but leads to harmful bioaccumulation in creatures [93]. Chai et al. [94] designed the Ni–CaO–C bi-functional material and studied the effect of PE on $H_2$ production in the co-gasification of it with pine sawdust. With PE proportion rising from 30 to 70 wt% in the mixed feedstock, $H_2$ concentration increased from 70.34 to 91.42 mol%. This indicated that the blending of PE favoured upgrading $H_2$ concentration. In addition, CaO in the bi-functional material promoted $CO_2$ capture with a $CO_2$ concentration of only 10 mol% in the product. Arregi et al. [95] investigated the effect of PE content on $H_2$ production in the SESG of pine sawdust/PE mixture under the action of Ni–Ca–Al bi-functional material (NiO content of 14%). They found a linearly positive correlation between the $H_2$ yields and the content of PE. When PE content increased from 0 to 100 wt%, the $H_2$ yield dramatically increased from 10.9 to 37.3 g/g. In addition, the decrease in pine sawdust was beneficial in reducing the amount of oxy compounds in the gaseous products and the deposition of coke on the bi-functional surface, which significantly mitigated the deactivation of the bi-functional material.

Even though there are promising advantages with the SESG of biomass/plastics mixtures, many significant issues need to be addressed. The first challenge is the severe sintering and aggregation of Ca-based sorbents in multiple gasification/regeneration cycles, which leads to

blockage and/or collapse of the pores [96,97]. The decreased specific surface areas and obstructed gas diffusion will limit $CO_2$ capture, which ultimately gives rise to adverse effects on $H_2$ production. Regarding catalysts, the fast reductions of catalytic activity and lifetime caused by sintering and coke deposition are also two non-negligible problems. In addition, considerable tar is still generated in the SESG of biomass/plastics mixture. Besides the adverse characteristics of tar itself, generating too much tar also means low carbon conversions and gasification efficiency. Furthermore, the industrial application of SESG technology is still in a fledging period. It has not been popularised on a large scale because of the extremely high capital investment required for power plant transformation, the make-up of bi-functional materials, the downstream processing of $H_2$ (purification, storage, and transport), plus the high operational and maintenance costs of a SESG system.

### 2.6. Limitations and technical challenges with the thermochemical conversion processes

The thermochemical conversion of biomass, including liquefaction, torrefaction, pyrolysis, and gasification technologies, has attracted worldwide attention because these processes can convert biomass into alternative, sustainable, and eco-friendly fuels, such as biochar, bio-oil, and $H_2$-rich gas. However, there are some significant disadvantages, as summarised in Table 2. Further discussion on the potential and future prospects of biomass utilisation is considered after a short section on biomass combustion.

### 3. Energy storage and the combustion of biomass

Due to the move away from coal, as illustrated in Fig. 1, nine of Great Britain's coal-fired power stations were closed between 2012 and 2015 and its largest power station was converted to burn wood pellets imported from North America [7]. Unlike general biomass, such biomass does not have a high O content and is of relatively uniform composition. Now in a three-way segmentation of the modes of electricity production between renewable sources, fossil fuels and other sources, biomass is often put in the third category along with nuclear and pumped storage [7]. This is partly due to its higher carbon footprint than solar and wind; more $CO_2$ is emitted than was initially sequestered through photosynthesis. On the other hand, the environmental impact is significantly lower than that due to fossil fuels.

At an estimated 44 EJ (EJ), bioenergy represents around 12.3% of global total final energy consumption (TFEC) [4]. More than half of this (*circa* 44 EJ) was the traditional use of biomass for cooking and heating in developing and emerging economies where woody biomass or charcoal (or in some locations, dung and other agricultural residues) are burnt in simple and inefficient devices. Other more modern and efficient uses of bioenergy account for the balance, which amounts to 5.6% of TFEC [4]. The difference between the two categories relates to the devices used rather than the fuel itself, which is why the combustion of

**Table 2**
Features, advantages, limitations and industrial applications of primary biomass thermochemical conversion processes.

| Process | Key Features | Advantages | Limitations | Industrial Applications |
|---|---|---|---|---|
| Combustion | T: 900–1500 °C.<br>A: Oxyfuel condition. | • Replace coal to some extent. | • High O contents and moisture lead to the low calorific value of biomass.<br>• More biomass is needed to release the same heat as coal, which raises storage and transport costs.<br>• Variation of compositions and properties brings difficulties in adjusting the unit parameters. | Austria has proposed the BioCAT project (Clean Air Technology for Biomass Combustion Systems) to reduce air pollution emissions from residential wood combustion [98]. Integration into combustion appliances and optimisation of integrated honeycomb catalysts has been performed. Reductions of up to 80% and 50% in CO and PM emissions, respectively achieved. |
| Torrefaction | T: 200–300 °C.<br>A: Oxygen-reduced or inert atmosphere.<br>Main products: Biochar. | Compared with biomass, biochar presents:<br>• Higher energy and mass density.<br>• Higher heating value.<br>• Better hydrophobicity.<br>• Improved powder grindability and flowability.<br>• Similar properties to coal. | • Biochar self-heating, self-ignition and even explosion due to the low heat removal rate.<br>• Ash-related issues in furnaces, like slagging, corrosion, and agglomeration.<br>• Investment and operating costs are higher than those of coal at present.<br>• A quality standard is needed to make biochar more reliable and available. | MOBILE FLIP (Mobile and Flexible Industrial Processing of Biomass) project in the European Commission proposed mobile technologies for small-scale torrefaction in 2018 [99]. ETIA built a new type of torrefaction unit, feasible for mobile applications. CEA investigated biomass torrefaction using various processing equipment and conditions. |
| Liquefaction | T: 200–600 °C.<br>P: 5–25 MPa.<br>A: Oxygen-reduced or inert atmosphere.<br>Main products: Bio-oil. | • Complete conversion of biomass organic components can be achieved. Fats, carbohydrates, and proteins can be converted into bio-crude oil.<br>• There is no need to dry the raw materials, and the biomass with high water content (more than 70%) can be liquefied. | • High-pressure conditions and additives consumption increase the complexity, risks and costs, thus limiting industrial application.<br>• HHV of liquefied bio-oil is still low.<br>• Chemical compositions are more complicated than gasoline, diesel, and other petroleum-based liquid fuels. | A Danish-Canadian company Steeper Energy constructed a Hydrofaction plant linking with Silva Green Fuel, a Norwegian-Swedish venture, in 2019 [100]. It was operated at supercritical conditions and used woody residues as feedstock to produce fuel for transport. One million tons of fuel was estimated to be produced annually [101]. |
| Pyrolysis | T: 400–800 °C.<br>A: Oxygen-reduced or inert atmosphere.<br>Main products: Bio-oil and biochar. | • Co-pyrolysis presents certain advantages in removing O and upgrading oil products.<br>• Catalysts help upgrade biomass pyrolysis oil.<br>• Microwave-assisted and solar-assisted pyrolysis are promising alternatives to conventional biomass pyrolysis. | • Co-pyrolysis oil cannot be utilised directly as a substitute for petroleum.<br>• Synergistic effects in co-pyrolysis of biomass and different raw materials are still unclear.<br>• Catalyst deactivation derived from coke deposition is a critical problem.<br>• Adjustment and control operation between co-pyrolysis and catalytic pyrolysis needs further investigation. | BTG successfully operated a world-first fast pyrolysis biorefinery pilot plant in 2018. It was an essential step in commercialising fast pyrolysis-based biorefinery [102]. The design capacity was 3 tons of pyrolysis liquid daily to produce high-value products. |
| Gasification | T: 600–1300 °C.<br>A: Air/$O_2$/$CO_2$/steam.<br>Main products: Syngas (CO, $CO_2$, $H_2$, $CH_4$, hydrocarbon and oxy compounds). | • Steam gasification improves syngas' calorific values and compositions by introducing H resources.<br>• In SEBSG, the in situ $CO_2$ capture moves gasification equilibrium to more $H_2$ production and realises negative carbon emissions.<br>• Catalysis/sorption of bi-functional materials can maximise high-concentration H2 generation.<br>• Co-gasification of biomass and waste plastics (H donors) can reduce the production of char and tar. | • Sintering and aggregation of Ca-based sorbents lead to pores block and collapse. The decreased specific surface areas and obstructed gas diffusion limits $CO_2$ capture and causes adverse effects on $H_2$ production.<br>• Catalyst deactivation caused by sintering and coke deposition reduces reaction rate and raises investment costs.<br>• Tar is still a challenging problem in the SESG of biomass/plastics mixture.<br>• Industrial applications are highly disadvantaged by very high capital investment and high maintenance costs. | Cranfield University cooperated with GTI, Doosan Babcock and BEIS Energy Innovation program in the UK, constructing a 1.5 MWth plant in 2021. The constructed system was speculated to achieve a ~20% reduction in the levelised cost of $H_2$ with an $H_2$ purity of around 96% [103]. |

Note: PM, particulate matter; ETIA, Evaluation Technologique, Ingénierie et Applications (France); CEA, Commissariat à l'énergie atomique et aux énergies alternatives (France); BTG, Biomass Technology Group (Netherlands); GTI, Gas Technology Institute (United States); BEIS, Department for Business, Energy and Industrial Strategy (United Kingdom).

wooden pellets was labelled as a neo-traditional method in the Introduction. Despite the growth in solar and wind energy, bioenergy represents around half of global renewable energy use, down from *circa* 54% in 2010 to an estimated 47% in 2020 [4]. As noted above and elsewhere [104], torrefaction and densification improve the properties of biomass, and the deployment of such feed preparation methods ahead of combustion can be classified, due to the upgrading of the feedstock, as being beyond a neo-traditional use of biomass. Although a 2015 review of torrefaction [104] suggested that the overall cost in the European market for torrefied pellets can be comparable to, if not lower than, regular wood pellets, a more recent update led by the same senior researcher has concluded that their "economic analysis shows that torrefied biomass is not yet competitive to wood pellets, mainly because of the additional investment for the torrefaction reactor" [20]. They noted that the developers of torrefaction are small companies with limited access to finance. Also as we have noted, product standardisation

would aid development. Despite the lack of competitiveness, they concluded that "one or more torrefaction concepts will emerge out of a large variety of technologies and initiatives" [20].

Modern bioenergy schemes can supply heat for industry and buildings, using systems that are much more efficient than open fires whilst simultaneously achieving low emission levels. Also, bioheat can be produced and distributed via district heating networks and used as fuel in combined heat and power (CHP) systems to co-generate electricity and heat. Such schemes have been growing in Europe, and it has been reported that within the EU, the share of bioenergy in total heat supply increased from 17.6 to 19.5% over the five years from 2015 to 2020 [4].

Occasionally a "wind drought" that slows or even halts most wind turbines occurs across a large region. The UK has the world's largest installed capacity of offshore wind, but the energy production is inconsistent. Thus energy storage systems, such as batteries, are a crucial component for maintaining a consistent supply from renewable sources,

which fluctuate over time. Currently natural gas is the main current buffer source of energy [7] whose contribution increases when that from renewable sources is constrained. However non-fossil fuel alternatives are required and energy storage is a declared top priority for the UK as it seeks to achieve a net zero carbon economy [105]. The current emphasis for developing a smarter electricity grid has been on battery storage systems but full reporting of their contribution is not yet available [7]. Although it has been reported that in the UK more than 16.1 GW of battery storage capacity is operating, under construction or in the pipeline across 729 projects [105], it is already clear from data on the UK's largest battery energy storage project that battery storage will contribute only to the smoothing over relatively short timescales. The battery systems with an output of 320 MW only store a total amount of energy of 640 MWh [105]. Thus at full output the amount stored will be used in 2 h.

Fluctuations that occur over longer timescales are readily evidenced at [7] when one selects "Past year". To combat these fluctuations, non-fossil fuel alternatives beyond batteries are required. To support the much larger role for biomass, it is envisaged that torrefied pellets should be used as well as regular wood pellets. As noted above others already expect that "one or more torrefaction concepts will emerge out of a large variety of technologies and initiatives" [20]. If policy makers were to see such an emergence as a contribution to the solution of the storage problem, progress would be more rapid.

## 4. Potential and future prospects of biomass upgrading via thermochemical processing

The products from thermochemical processes are highly oxygenated and require further upgrading before practical industrial applications. The co-thermochemical conversions of biomass and H-rich raw materials could be alternative methods to offset the adverse effects of pure biomass [106,107]. While the synergy mechanism between feedstocks is still unclear, tar production is a crucial challenge for bio-oil quality and equipment operation. Developing affordable, efficient, and stable additives, like sorbents and catalysts, is necessary to conquer the deactivation problem, and currently there is still a long way to go. Despite increasing fossil fuel prices, producing renewable fuels is more expensive than conventional fuels. Thus, before realizing efficient industrial applications, low-grade products and process costs are two significant issues that should be overcome, especially in the production of liquid fuels. Progress in this area is expected to be significant because energy demand for transport accounts for nearly one-third of global final energy consumption, and currently, it is dominated by fossil fuel consumption, with renewables accounting for 3.7% in 2019, having grown from 2.4% in 2009. So whilst electric car sales have increased in certain cities, current demand as well as the overall global demand is still being met principally by automobiles using gasoline.

Bioethanol and traditional biodiesel are not the subjects of this review, but looking at prospects for fuels produced via thermochemical conversion, it is interesting to briefly review the current contribution of established biofuels where bioethanol remains the leading source. Production increased 26% overall between 2011 and 2021 to 2.3 EJ (105 billion litres) [4]. However, production is very country-specific, with the United States and Brazil being so dominant that together they account for 80% of global production, and China has become the third largest ethanol producer whilst providing just 3% of the global supply (70 PJ or 3.3 billion litres) in 2021 [4]. The USA mainly uses corn, while Brazil's primary feedstock is sugar cane. Biodiesel is produced mainly by two processes: FAME (fatty acid methyl ester) biodiesel and increasingly via HVO (hydrogenated vegetable oil). The former reacts a feedstock of oil/fat with methanol, which yields the methyl ester, the biodiesel, plus glycerol as a byproduct. Both bioethanol and biodiesel can be used in vehicles designed for fossil fuels, either as blends with petrol and diesel fuels or with relatively minor engine modifications. In Europe, petrol is typically an E10 fuel which is 90% regular unleaded petrol from fossil fuel and 10% ethanol – hence the E10 name. Whilst some sources, e.g. Ref. [2], cite three barriers inhibiting the global uptake of biofuels, namely higher costs than conventional fuels, limited availability of certain feedstocks and the need to manage the sustainability risks carefully, the latter is of most significant concern. In particular, "land-use change" needs to be considered.

Many have thought the development and utilisation of biofuels would reduce GHG because of the carbon sequestration during vegetation growth. However, this advantage is not guaranteed. It is critical to evaluate whether the selected feedstock for biofuel production will trigger significant carbon emissions due to land-use change [108]. For example, most previous accountings only considered the carbon benefits of using biofuels but failed to count the carbon costs, which are derived from sacrificing and converting existing land (forest and grassland, etc.) to new cropland to complement the grain diverted to biofuels. The loss of forests and grasslands not only foregoes the ongoing carbon sequestration but also releases carbon previously reserved in plants and soils. Additionally, diverting the existing cropland into biofuels indirectly causes similar carbon emissions following the increase in crop prices. Increasingly, more and more forests and grassland will be cleared and replaced by crops for feed and food. GREET (Greenhouse gases, regulated emissions, and energy use in transportation) computer model showed that if gasoline was replaced by corn ethanol, 20% GHGs would be reduced, excluding land-use change in the 2015 scenario. However, considering the land-use change, it will take 167 years to "payback" carbon emissions derived from corn ethanol, meaning GHG will continuously increase for 167 years [109]. Therefore, feedstocks, such as waste biomass, waste byproducts, and crops from carbon-poor lands, should be the first choice to reduce the enormous carbon emissions from land-use change.

Combustion is the easiest way to consume biomass, which can be burned alone or co-fired with coal, especially when pretreated, as mentioned in the previous section. Interestingly, a 2022 report has remarked that the debate continues regarding the carbon savings and other environmental impacts associated with wood pellet production from forestry materials and their use in power generation (see Ref. [4] p105). On the other hand, mention was made that Japan is enacting sustainability criteria aimed at reducing the use of palm-based products but increasing the use of certified wood pellets. The prospects for more widespread use of forestry materials (and other materials via torrefaction) seem reasonable. Also, unlike bioethanol, its use is likely to be widespread globally.

The REFuelEU Aviation package of the EU, which is part of its "Fit for 55" initiative, has a target of 2% Sustainable Aviation Fuel (SAF) for all flights taking off from within the EU by 2025. The use of SAF is planned to rise to 63% by 2050. The definition of SAF, according to the International Civil Aviation Organisation, is a fuel produced from one of three families of bio-feedstock: the family of oils and fats (i.e. triglycerides), the family of sugars and the family of lignocellulosic feedstock. Now switching to SAF is a significant challenge because aviation fuels must meet strict standards set by ASTM (American Society for Testing and Materials). To date, eight production routes have been approved and these are all based on the hydrogenation of vegetable oils and fats (i.e. their reaction with hydrogen). Such processes are similar to the HVO process for biodiesel but tuned to optimise a jet fuel product.

As today most biofuels are used in road transport, the use of the HVO process for aviation fuel is likely to be constrained by the availability of suitable and sustainable feedstocks unless there is a switch to use such feedstocks for aviation fuel rather than road transport. Thus, sector coupling must be acknowledged in developing and commercialising biofuels, and policies must be developed accordingly. Owing to environmental constraints and the need to maintain food production, ambitious targets for SAF are unlikely to be met unless natural resources are reserved for its development. Such a re-direction would open up opportunities for the commercial development of sustainable production of liquid fuels via liquefaction and pyrolysis. To help open new

routes for sustainable biofuels across multiple sectors, beneficial holistic interactions between policy, regulations and research is required so as to have a roadmap that meets the claimed ambitions expressed by most governments.

Commercial developments involving pyrolysis albeit for tyres and not biomass are moving from the pilot scale to the commercial scale. "Fuel from your wheels" describes a process that has been developed by Wastefront in Norway which will see the building of a giant tyre recycling plant in the North-East of England starting in 2023 [110]. Instead of just stockpiling old tyres as waste (in storage yards that occasionally catch fire), or burning them as a co-fuel in an incinerator (which produces greenhouse gases) the new process can produce a climate friendly fuel. Prior to the pyrolysis the tyres are shredded, and the steel removed. The remaining material is subjected to pyrolysis which results in a residue of carbon black that can be re-used in making new tyres and an off gas that is a mix of hydrocarbons. Upon cooling a portion of the off gas condenses into a liquid that is labelled as tyre derived oil (TDO) which is similar to crude oil and well suited to making diesel. Compared with conventional diesel that from TDO results in a 80–90% reduction of carbon dioxide. The hydrocarbons that are not condensed to form TDO are gaseous hydrocarbons including methane. These are recycled as fuel to the pyrolysis reactor. Overall the pyrolysis of the old tyres generates by weight 40% TDO, 30% carbon black, 20% steel and 10% gas. Such a process contributes to both waste reduction and decarbonisation, both of which are key to addressing current environmental challenges and the future prospects of biomass upgrading via thermochemical processing will involve similar drivers.

In section 2.4 on pyrolysis it was mentioned that co-pyrolysis of biomass with other raw materials can improve the quality of pyrolysis products [52,53]. Although Wastefront, the developers of the above project, probably see advantages in having a well-defined feedstock, co-pyrolysis of the tyres with other raw materials such as biomass may well improve the quality of the pyrolysis products. Whilst the possibility of achieving higher-quality products through such co-pyrolysis is high the complexity of pyrolysis is such that further investigations would be essential.

As evidenced throughout section 2, the thermochemical conversion of biomass is complex but also timely. Consequently, it is posited that Multi-criteria Decision Making (MCDM) will be valuable in assessing the potential of biomass thermochemical conversion and in aiding the development of chosen processes. MCDM is an evaluation methodology that integrates usually conflicting criteria into a whole in order to evaluate alternatives. MCDM is designed to help decision-makers better assess the relevance and importance of criteria and use available information to evaluate alternatives. Firouzi et al. [111] suggested a hybrid MCDM approach to choose an appropriate biomass resource for biofuel generation from local biomass resources. Ten criteria and eleven alternatives were investigated. Second-generation biomass resources, such as municipal solid and sewage, forest and wood farming wastes, and livestock and poultry wastes, were found to be appropriate feedstocks for biofuel production. Narayanamoorthy et al. [112] studied multiple factors (fuel cost, technical cost, environmental safety, and $CO_2$ emission levels) and selected the most appropriate biomass conversion methods using fuzzy MCDM models. Bioethanol was reckoned a viable industrial option due to its low carbon footprint and environmental viability but it will be noted that the implications of land-use change and food security were not included in the criteria used. As noted earlier in the Introduction it is important to account for carbon sequestration forgone directly and indirectly by land-use change [17,18]. Also the importance of food security has been emphasized by the global impact of recent geopolitical events in Eastern Europe.

Khadivi et al. [113] applied the MCDM model to the case study of a large Kraft pulp mill in Canada to identify the best investment alternative for syngas and renewable natural gas (RNG) production through biomass gasification. In large-scale biomass gasification technology, producing RNG in addition to syngas can increase the net present value of the investment and reduce greenhouse gas emissions. It was found that future development would require technological advancement in RNG production, government incentives to reduce the high capital investment, changes to carbon accounting, and stabilisation of the RNG market to minimise investment risk. This emphasises the importance of Regulations and Policy which is why they have been given equal importance in the graphical abstract that is reproduced as Fig. 15.

As the renewable energy electricity supply network is optimised, a future role for torrefaction is envisaged because biofuel will surely be needed to overcome the energy storage problem as mentioned in section 3. Although occasional, "wind droughts" are a problem that battery storage is ill-equipped to handle. Together with demand side incentives the ability to use extra biomass during such periods is envisaged as a policy solution. The future of biomass upgrading that involves the generation of biochar will depend on sector coupling within the energy sector. A policy that guards against over dependency on imported wood chips would further encourage technological progress in the area of torrefaction. Owing to the extant energy storage problem this is one of the two promising avenues for future development that have been identified because as highlighted in section 2.2, biochar can with appropriate processing display coal-like physico-chemical properties. As noted herein and elsewhere, a quality standard for biochar would make for more reliable operation and better exploitation of this resource.

Sustainability concerns will ensure that biomass supply will be from waste biomass or specifically from crops grown on marginal land. However this will limit the supply. So, to meet most governments' claimed ambitions, the optimal use of biomass for selected biofuel production will need to be determined. It is posited that MCDM would probably show that Sustainable Aviation Fuel (SAF) is an area where the beneficial interactions between policy, regulations and research could have the greatest impact. This is a clear second avenue of opportunity for biofuel development. Indeed, as mentioned above the EU envisages that for all flights taking off from within the EU will by 2050 use 63% SAF.

## 5. Concluding remarks

The potential of each category discussed in sections 2.1 to 2.5 needs to be considered with due allowance for both sector coupling and coupling beyond the energy sector, such as considerations of land-use change and the importance of food security. Whilst realizing that further in-depth evaluations are required, promising avenues for the exploitation of thermochemical conversion of biomass were identified.

As aviation fuels need to be of high quality (and account for 12% of total energy consumption for transport which in turn is 32% of TFEC [4]), a holistic policy would likely reserve traditional sources of biofuels for this sector so that SAF can be produced via the HVO process or one akin to it. Then because of land-use change considerations, bioethanol and biodiesel would need, as a minimum, to have their growth constrained to allow for these aviation fuels. The corn used in the USA and elsewhere for biofuels would probably need to be used exclusively for SAF. Such a scenario creates a need for sustainable road fuels that must be met via new fuels to which TDO, which was mentioned in section 4, can contribute. As the quantity via TDO will be modest, liquid biofuels via thermochemical upgraded biomass is anticipated to be an important part of the energy market of the second quarter of the twenty-first century. As indicated in Fig. 15, governmental regulations and policy, as well as technological developments, will affect progress. Also, unlike bioethanol, whose production is concentrated in essentially two countries, such progress is likely to be geographically widespread.

Whilst electric vehicle sales are growing rapidly in those Western countries with compact geography, the global need for liquid fuel for road transportation will likely remain up to and beyond 2050. This gap could be filled by pyrolysis and gasification of biomass such as switch grass grown on marginal land. To achieve this, billions of US dollars would need to be invested. Sums of this magnitude were mentioned in a recent review of solar technology [114]. Whilst the development of solar
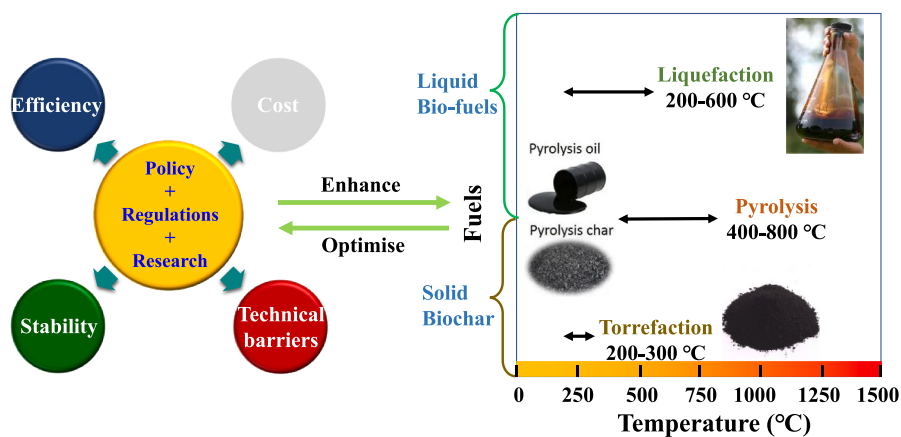
**Fig. 15.** Diagrammatic summary of the influences that will determine the extent to which thermochemical upgrading of biomass contributes to the energy market of the second quarter of the twenty-first century. Technological progress, governmental regulations and policy will all have an important influence.

power is a key solution to fulfilling the increasing demand for clean energy, it is a solution to the problem of decarbonizing the electricity grid. Solutions and concomitant investments are required for liquid fuels, and biomass thermochemical conversion should be a vital component in the coming decade. More research efforts should enhance the efficiency, stability and reactor costs of liquefaction and pyrolysis and aid the surmounting of the technical barriers identified throughout Section 2 and summarised in Table 2. Combining co-pyrolysis and catalytic pyrolysis is one promising approach that deserves further investigation. Feasibility at a commercial scale is essential and will determine the established process or processes. Examples of various pilot plants are given in Table 2. It is to be hoped that the fiscal burden of developing and evaluating various process options will be reduced through incentives.

Overall, it is concluded that despite the various processes' current drawbacks, biomass thermochemical conversion processes are promising renewable energy processes and that some need to be harnessed as part of a holistic across-sector approach to achieve net-zero by 2050. In particular, having noted that a world-first fast pyrolysis biorefinery pilot plant was successfully operated in 2018 at a design capacity of three tons of pyrolysis liquid per day [102], and the need for liquid fuels, liquefaction and pyrolysis will be utilised. Like Chen [20], a future role for torrefaction is envisaged because biochar, whose cost is similar to that of wood pellets, will be an increasingly important fuel for the powering of the electricity grid. Displacement of fossil fuels would be aided by policy initiatives such as a carbon price being placed upon the utilisation of natural gas and petroleum derived products.

## 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.

## Data availability

Data will be made available on request.

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