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Concentrated solar thermochemical gasification of biomass: Principles,
applications, and development
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1 Abstract

Bioenergy production is one of the most reliable strategies for replacing fossil fuels and 2 reducing CO₂ emissions. Gasification-based bioenergy generation has been extensively 3 studied; however, it is still facing the challenges of limited energy efficiencies, especially 4 5 upon small-scale development. Concentrated solar thermochemical gasification of biomass 6 (CSTGB) where the endothermic reactions of gasification are driven by concentrated solar 7 thermal energy serves as a promising solution to improve the efficiency of gasification. 8 This review summarized recent development in modelling concentrated solar 9 thermochemical gasification of biomass, the method of concentrated solar thermal for gasification, and applications and development of concentrated solar thermal biomass 10 gasification. The influences of operating parameters toward the performance of the 11 technology were studied, which determine the optimum parameters for maximizing the 12 energy conversion efficiency of the technology. The concentrated solar thermochemical 13 14 gasification of biomass system could improve the utilization of biomass feedstocks and the total energy efficiency by 30% and 40%, respectively by effectively storing solar energy 15 in the producer gas as compared to conventional gasification. 16

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1	Highlights:

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3	• Solar collector (SPTs and PDCs) and heat transfer fluids were studied.
4	• Gasification reactors, gasifying agents and process conditions were studied.
5	• Thermodynamic equilibrium, kinetic and CFD models were presented.
6	• One-stage and two-stage CSTGB with tank storage systems were studied.
7	• Specific efficiency and methodology of recent development of CSTGB systems
8	were studied.
9	• Insulation and internal material as challenges of CSTGB systems were studied.
10	
11	Keywords: Biomass; Gasification; Concentrated solar thermal; Modelling
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13	Word Counts: 10,574 words
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1 Nomenclature

2 Abbreviations

Concentrated Solar Thermochemical Gasification of BiomassPM **CSTGB** 3 4 Particulate Matter Volatile Organic Compounds **VOCs** 5 CPV/T Concentrated Photovoltaic Thermal 6 7 NCCs Non-concentrated Collectors CCs **Concentrated Collectors** 8 STs 9 **SolarTowers Central Receiver Collectors** CRCs 10 MTCR Multi-tube Receiver 11 Multi-tube External Receiver 12 MTER VCR Volumetric Receiver 13 Direct-absorption Receiver 14 DACR PDCs Parabolic Dish Collectors 15 CSP **Concentrated Solar Power** 16 HTF 17 Heat Transfer Fluid **UFBGs** Updraft Fixed Bed Gasifiers 18 MSW Municipal Solid Waste 19 Fluidized Bed Gasifiers 20 FBGs SDFBG Solar-driven Dual Fluidized Bed Gasifier 21 22 LHV Low Heating Value 23 EFGs **Entrained Flow Gasifiers**

S/B	Steam to Biomass
ERs	Equivalent Ratios
TE	Thermodynamics Equilibrium
S	Stoichiometric
NS	Non-stoichiometric
CFD	Computational Fluid Dynamic
E-L	Eulerian-Lagrangian
E-E	Eulerian-Eulerian
RMSE	Root Mean Square Error
CBP	Carbon Boundary Point
CST	Concentrated Solar Thermal
TES	Thermal Energy Storage
SHS	Sensible Heat Storage
THS	Thermochemical Heat Storage
LHS	Latent Heat Storage
РСМ	Phase Change Material
CBG	Conventional Biomass Gasifier
LCA	Life Cycle Assessment
IEA	International Energy Agency
TEA	Techno-economic Analysis
LCA	Life-cycle Assessment
FEM	Finite Element Method
	S/B ERs TE S NS CFD E-L E-E RMSE CBP CST TES SHS THS LHS PCM CBG LCA TEA TEA FEM

1

2 1. Introduction

The depletion of fossil fuels and climate change are two of the most significant global challenges. Renewable energy plays a critical role for meeting the growing energy demand and serves as an essential means to mitigate climate change. Biomass is one of the primary renewable energy sources [1]. It accounted for 977–1051 TWh (29.9–32.53%) electricity generation in the European Union between 2017 and 2018 [2] 15–20% of the world's fuel consumption in 2018 [3].

9

10 Gasification is one of the main technologies for energy recovery from biomass. It refers to the incomplete combustion of biomass materials in an oxygen-limited environment to 11 convert the carbonaceous materials into synthesis gas (or syngas, mainly a mixture of 12 hydrogen, carbon monoxide and methane) and a solid residue by-product consisting of ash 13 14 and biochar. The heat required for conventional gasification is supplied by the combustion of feedstock [4]. High energy efficiency is critical for the economics and widespread 15 implementation of the technology, especially for small-scale development [5]. The 16 17 technology of concentrated solar thermochemical gasification of biomass (CSTGB) is one of the attempts to enhance the efficiency of gasification (Figure 1). In this process, solar 18 19 energy is utilized to drive biomass gasification, aiming to increase biomass utilization rate 20 and the quality of product gas, and reduce pollutant emissions (e.g. NO_x , PM_{10} , and VOCs) 21 as compared to the conventional gasification process [6]. In a CSTGB system, as shown in 22 Figure 1, concentrated solar collectors (e.g. solar tower and solar dish) absorb solar 23 radiation and convert it to thermal energy that is further transferred to the gasifier. The

solar concentration ratio that defines the enhancement in the incident energy flux ranges from 250 to 3000 [7]. It is carried by a thermal fluid (e.g. molten solar salt) with a temperature range of 523–2273 K serving as the heat source of the gasification process where biomass is converted into syngas as a chemical energy carrier [8]. Table 1 shows that CSTGB could generally achieve a higher (25–50%) efficiency than the conventional gasification process, and had the potential of reducing the amount of feedstock for the same level of energy production.

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- 9
- 10 Figure 1. An illustration of a CSTGB system.
- 11
- 12 Table 1. The comparison between CSTGB and conventional gasification.

CSTGB	Conventional gasification
COTOD	Conventional gasification

Feedstock	Efficiency ^a	Syngas Yield	Efficiency ^a	Syngas Yield	Ref(s)
		(mmol/gbiomass)		(mmol/gbiomass)	
Beech wood	58.7-73%	H ₂ :31.9-41.9	65%	H ₂ :2.65-12.35	[<u>9</u> , <u>10</u>]
		CO: 26.8–31.1		CO: 6.61–14.26	
Straw	79%	H ₂ : 18	42%	H ₂ : 9.71–26.8	[<u>11</u> , <u>12</u>]
		CO: 52		CO: 0.69–18.14	
		CH4: 9			
				CH4: 0-12.67	
Sugarcane	61.5–99.9%	H ₂ : 30.054.5	60%	H ₂ : 25-31	[<u>13</u> , <u>14]</u>
bagasse		CO: 30.7–34.3		Syngas: 57–60	
		CH4: 0.8–13.4			

^a The efficiency is defined as a ratio of the calorific value of product gas to the heating
 value of feedstock.

3

Desipte the advantages of CSTGB applications for enhancing bioenergy recovery, there 4 5 are limited reviews on analyzing CSTGB from a whole system perspective. For example, 6 Loutzenhiser et al. summarised the CSTGB system, including thermodynamic and kinetic 7 analyses as well as modelling, fabrication and testing of thermochemical reactors [15]. Pramanik et al. was demonstrated that the use of CSTGB systems to produce syngas is a 8 promising renewable pathway that effectively reduce CO₂ emission (<100 kg/MWh) [16]. 9 Puig-Arnavat et al. described that the CSTGB system is an interesting alternative to 10 11 conventional gasification process, capable of producing high quality synthesis gas and high 12 yield [17]. The CSTGB system allows chemical storage of solar energy in the form of easily transportable fuel, among other advantages. 13

14

This article will fill this knowledge gap in previous articles on the optimal models, 1 parameter settings, and economic challenges. It summarized the principles, applications, 2 recent developments, and challenges of CSTGB systems. Specifically, it will review a) 3 fundamentals and development status of the technology, b) efficiency research and barriers 4 5 of the technology, and c) studies on the latest development and applications of gasifiers in 6 relation to CSTGB. Significant novelty of this work includes comprehensive updating of recent development on CSTGB, systematic summary of existing CSTGB prinipcles, and 7 identification of future directions of CSTBG research and development. 8

9

10 **2. Solar Thermal**

At the Earth's surface, the energy density of solar radiation is approximately 1000 W/m^2 11 on a clear day, and the world's solar energy is 301 times of all existing coal power plants 12 [18]. The International Energy Agency (IEA) World Energy Balance report claimed that 13 14 solar energy accounted for 19% of renewable electricity generation in 2018 [3]. The solar installations are experiencing significant growth with Eureopean Union-28 encouraging 15 significant solar thermal development [19]. Extensive studies have been performed to 16 17 utilize concentrated solar energy as an economically viable and environmentally friendly heat source. Li et al. proposed a new coupled optical, thermal and electricity model (model 18 19 accuracy is 94.47%). They applied it to predict the performance of the concentrated 20 photovoltaic thermal (CPV/T) system under various operating conditions (i.e. locations, irradiance, temperature, wind speed and incidence) from 8 April to 5 July. They found that 21 the CPV/T system generated 6 h of peak instant electricity per day (50 W/m^2) and produced 22 0.22 kWh/m² of electricity between May and July [20]. 23

1

2 2.1.1 Solar Collectors Types

3 A solar collector is an energy exchanger that converts solar energy to thermal energy. There are two categories of solar thermal collectors (i.e. non-concentrated collectors (NCCs) and 4 concentrated collectors (CCs)). The efficiency of the CSTGB system depends on the 5 6 temperature and concentration ratio of solar energy (1000–3000 kW/m²) [21, 22]. NCCs 7 allow heat transport, but the solar thermal concentration ratio is less than 1, and thus they are conventionally used in applications of domestic hot water and space heating [23-25]. 8 9 CC technology is more suitable for CSTGB because it has very high concentration ratio (800-2000 kW/m²) [26, 27]. Sun et al. summarized and elaborated on two types of 10 concentrated collectors (line-focus and point-focus). Line-focus collectors (i.e. parabolic 11 trough collector and linear Fresnel reflector) are unsuitable for CSTGB system because 12 they have a relatively low operating temperature (approximately 423–823 K), generally a 13 low efficiency (14–22 %) and low concentrating ratio (30–80 kW/m²). Point-focus 14 collectors (i.e. central receiver system and parabolic dish) are suitable for CSTGB system 15 because of their high operating temperatures (872–1773 K) and concentrating ratio (200– 16 3000 kW/m^2) [27]. 17

18

Solar towers (STs), also known as central receiver collectors (CRCs) are a type of CCs that consist of a heliostat field, a receiver mounted on a tower, thermal energy storage, and a gasifier. The mirror array reflects incident sun lights to an ordinary tower, where the central receiver absorbs solar radiation and converts solar radiation to high-temperature heat that can be directly transferred to thermal fluids like molten salts [25]. There are four typical receiver configurations for ST systems, i.e. multi-tube receiver (MTCR), multi-tube
 external receiver (MTER), volumetric receiver (VCR), and direct-absorption receiver
 (DACR) [28, 29].

4

5 The MTCR technology has a thermal efficiency around 27.65–29.50% and an exergy 6 efficiency around 29.58–31.56% [30]. Qiu et al. found that the maximum solar concentrated ratio for a MTCR system was 5.141×10^5 W/m² based on a real-time optical 7 performance analysis [29]. Due to the uneven distribution of sunlight on the tubes, the 8 9 multi-point aiming and tracking technology was used to reduce the uneven sunlight distribution. They reported that the absorbed energy of the MTCR technology was 10 increased to 65.9% efficiency. Lubkoll et al. found that the MTER is a relatively 11 12 inexpensive and straightforward technology as compared to the MTCR [31]. The absorber 13 of MTER consists of vertical tubes mounted on an external receiving tower. For the MTER 14 technology, convection and radiation cause a large amount of heat loss. The maximum temperature of MTER receiver was reported to be 873 K. 15

16

Avila-Marin et al. summarized the development of VCR technologies including structure
(configuration, geometry, dimensions, materials, etc.), efficiency, temperature and overall
system performance [32]. They suggested that most of the VCR technologies can reach
over 1073 K, and some ceramic-made receivers have the capability of reaching 1243–1773
K.

22

The black liquid solar collector first proposed by Minaridi and Chuang directly absorbed solar heat by a high-absorbable 'black' fluid (water and ink) [33]. Subsequently, carbon nanofluids with improved thermophysical properties (endothermic and heat transfer) were also applied. Simonetti et al. found that the DACR technology could utilize transparent shell made of plastic materials to reduce costs and provide more complex geometric pattern designs for solar concentrating collectors [34]. As shown in Table 1, the solar concentration ratio of SPTs is around 250–1500 W/m² (operating temperature is 523–2273 K).

8

9 Parabolic dish collectors (PDCs) use the parabolic dish mirrors to concentrate solar radiation onto the receiver located at the focal point of the dish mirrors, where the heat 10 transfer fluid is heated to required operating temperature and pressure [21, 35, 36]. 11 Although PDCs are the most expensive point-focus technology, it can provide a relatively 12 higher solar concentration ratio and thermal efficiency. The operating temperature range 13 of PDCs is from 673 K to 1773 K with a concentration ratio between 1000 and 3000 W/m^2 , 14 an average thermal efficiency of 18–25% and a peak thermal efficiency is 28–32% [21, 27, 15 37]. Sinha et al. found that the radiant heat loss increased with the increase of cavity wall 16 17 temperature, aspect ratio and emissivity [<u>38</u>]. Some factors (i.e. temperature, aspect ratio and emissivity) can increase the total loss of the entire cavity by 14%. 18

19

20 Table 2. Characteristics of CSTGB technologies.

	Land	Thermo	Operating temperature	Solar concentration	Reference
	occupancy	efficiency	range (K)	ratio (W/m ²)	
SPT	Medium	High	573-838	250-1500	[<u>39</u>]

SPT	Medium	Medium	523-923	300-1000	[<u>21</u> , <u>22</u>]
SPT	Small	High	873–2273	1000	[40]
PDC	Small	High	1073	1000-3000	[21, 22]
PDC	Small	Medium	-	1300-1600	[<u>37]</u>

1

2 2.1.2 Influential Factors

The solar radiation is much stronger at higher altitude where it is distributed over a smaller geographic area. The intensity of solar radiation is mainly determined by direct solar radiation under a clear sky; it is depended on scattered radiation when the sky is overcast; the intensity of direct radiation decreases and the intensity of scattered radiation increases when the sky is partly cloudy [41]. Overall, 20% of the solar radiation is absorbed or scattered by aerosols in the atmosphere. As the elevation increases, there is less solar radiation absorbed by the atmosphere [42].

10

The distribution of concentrated solar flux in a concentrated solar power (CSP) system is 11 12 non-uniform, resulting in high local temperature and large temperature gradient in a solar 13 receiver. The non-uniform solar flux has a great impact on both line-focus collectors (i.e. 14 PTC) and point-focus collectors (i.e. ST). The non-uniform solar flux caused a large 15 amount of heat concentrated at the bottom of the receiver tube [26]. Due to the limited thermal conductivity and heat convection ability of the receiver, the non-uniform flux 16 17 distribution inevitably leads to a non-uniform temperature field on the receiver's wall [43, 18 44]. The high local temperature pose great challenges for the safety and efficient operation of the system. Yu et al. found that there would be a safety risk to the receiving system of 19

CSP when the solar flux value exceeds 580 W/m² [45]. When the local solar flux is too
high, the coating tends to degrade, which will limit the maximum operating temperature.
Additionally, the high local temperature may lead to the decomposition of heat transfer
fluid (HTF) [46, 47].

5

Most CSP systems use basic HTFs (e.g. liquid sodium: 1.2-1.5 W/m², molten nitrate salt: 6 0.7 W/m², liquid water: 0.7 W/m², air: 0.2 W/m²), and their peak heat transfer values are 7 around 0.2–1.5 W/m², which cannot cope with excessive local temperature caused by non-8 9 uniform solar flux. Enhanced heat transfer is important for overall efficiency improvement. Nanofluids that refer to colloidal suspensions of nano-ions in basic heat transfer fluids have 10 been proved to be effective for enhancing thermal performance. Adding suspending nano-11 particles (i.e. diphenyl oxide, biphenyl and Ag) to HTF boosted the thermal conductivity 12 (increased by 6%) and intermediate efficiency (increased by 3%) [48]. 13

14

15 **3** Gasification

16 CSTGB systems use the solar thermal energy to fulfill the heat generated from the 17 combustion stage to achieve a higher efficiency and biomass utilization rate. Figure 2 is a schematic diagram of a typical CSTGB system. The CSTGB system accumulates solar heat 18 19 through the solar tower and transfers the heat through the HTF, such as salt and sand, to 20 the gasification reactor to gasify the biomass feedstock into syngas (H_2 , CO, CH₄, ect.). 21 The syngas can be converted to electricity via the integrated gasification combined cycle 22 (IGCC) system or to liquid fuels via the Fisher Tropsch synthesis method. The gasification 23 reactor of the CSTGB system could be similar to a conventional gasifier.

2 The gasification process generally consists of four stages (i.e. drying, pyrolysis, combustion, and reduction) [49]. The moisture content of biomass is usually reduced to 5– 3 10% in the drying stage [50, 51]. In the pyrolysis stage, biomass is decomposed into 4 5 volatile matter and char in the absence of oxygen [52]. In the reduction stage, the char is 6 reduced to generate hydrogen, carbon monoxide, etc. In the combustion zone, the most amount of heat is from the volatile gas reacting with steam/air or oxygen at high 7 temperature. It provides heat for the whole gasification process for a conventional 8 9 gasification process.



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14 **3.1 Types of Gasification Reactors**

15 Gasification reactors could be classified into fixed bed ones (e.g. downdraft and updraft

- 16 gasifiers), fluidized bed ones (e.g. bubbling fluidized bed and circulating fluidized bed
- 17 gasifiers), and entrained flow ones.
- 18

1 (1) Fixed Bed Gasification

2 The downdraft fixed bed gasifier is not suitable for CSTGB because it has relatively low 3 heat transfer rates than others (i.e. upgraded, fluidized bed gasifier, etc.) limiting the efficiency of solar thermal energy utilization in thermochemical reactions and potentially 4 5 reducing the calorific value of syngas. In a downdraft reactor, the gasifying agent (e.g. air) 6 and feedstocks are introduced from the upper part and products leave from the bottom. 7 Lenis et al. simulated a central receiver tower CSP combined with a downdraft fixed bed gasifier and they showed that the maximum syngas yield was 134.01 kmol/h with an 8 9 efficiency of 45.9%, and the syngas was composed of 47.2% CO, 46.9% H₂, 3.3% CH₄ 10 and 2.6% CO₂. Besides, a large amount of heat is expelled from the bottom with the syngas, and it ultimately reduces the overall efficiency of the system [54]. 11

12

For an updraft fixed bed gasifier, gasifying agents and feedstocks are usually introduced 13 14 from the bottom and syngas leaves from the top with thermochemical reactions generally 15 occurring at the bottom near the grate [55]. Tar formation is one of the major technical 16 challenges of updraft gasification. Cerone et al. found that the type of gasifying agent 17 residence time and average reaction temperature affected the tar yield [56]. Specifically, the tar yield was 137 g/kg in air gasification and 163 g/kg in the air/steam gasification. The 18 19 tar yield was inversely proportional to the residence time and proportionate to the average 20 temperature of the reactor.

21

From the perspectives of CSTGB, upgraded/modified updraft fixed bed gasifiers (UFBGs)
with combined heat storage and control systems have been used as they facilitate the

storage and control of thermal energy. Table 3 shows that the upgraded/modified UFBGs 1 2 are suitable for small biomass particles and have such advantages such as a stable 3 thermochemical reaction process, high product yield rates, high conversion rates, and high feedstock utilization rates [57-60]. Boujjat et al. found that variability in solar energy 4 5 (caused by cloud passages and shut off at night) created inherent obstacles to the utilization 6 of solar assisted thermochemical processes [61]. They built a dynamic model for a large-7 scale concentrated solar thermal gasification reactor to determine the temperature and 8 syngas production evolution during day and night considering both solar-only and hybrid 9 solar/autothermal modes. They found that storing intermittent solar energy into a heat 10 storage system could stabilize process operation and ensure continuous production of syngas during the night and during cloudy periods. Jin et al. developed a thermodynamic 11 model for solar-driven supercritical water gasification that includes solar storage 12 equipment to overcome the disadvantage of solar discontinuity [60]. They found that the 13 14 mole fraction of hydrogen in the model reached 65.6% at 1023 K. At 873-973 K, the highest energy and exergy efficiency was 74.84% and 34.87%, respectively and the syngas 15 yield efficiency was 18.15%. 16

17

10 I able 5. Opgraded/mounted aparant fix bed Co I OD system studied.

	Type of gasifier	Feedstock	Parameter(s)	Finc	lings	References
	studied	used	studied			
Upgraded	Solar gasification	Municipal	Biomass	•	Overheating reactors	[<u>58]</u>
/modified	reactor of vertical-	solid waste	feeding rate,		and excessive	
updraft	axis parabolic	(MSW)	syngas yield,		temperature changes	
Fixed Bed	concentrator		temperature		will lead to more heat	
Gasifier					loss.	

			•	The H ₂ :CO ratio in	
				syngas composition	
				reduced during night.	
Solar jet spouted	Beechwood	Temperature,	•	Direct heating the	[<u>59]</u>
bed reactor for		biomass		reactor can increase	
biomass gasification		feeding rate,		the H ₂ yield.	
		particles	•	Smaller particles	
		velocity		could increase both	
				the solid and gas	
				residence times.	
Tubular solar	Woody	Temperature,	•	Maximum H ₂ and	[<u>57]</u>
reactor for biomass	biomass	mass balance,		minimum CH4 yields	
gasification		energy		at 1673 K	
		conversion	•	93.5% of carbon	
		efficiencies,		conversion rates is	
				generated during solar	
				runs.	
Solar driven	Biomass	Temperature,	•	The maximum of	[<u>60]</u>
supercritical water		molar fraction		hydrogen productions	
biomass gasification				generated, when the	
				temperature reaches to	
				1023 K.	
			•	Solar energy provides	
				75% energy and 35%	
				exergy efficiency.	

1

2 (2) Fluidized Bed Gasification

Fluidized-bed gasifiers (FBGs) are more suitable for CSTGB systems than a fixed bed and
entrained flow gasifiers because of their enhanced heat and mass transfer by the
gasification flow fluidizing the bed material [62]. FBGs offer the enhanced interaction

1 between the gas and solid phases leading to higher hydrogen concentrations in the gas product in Table 4 [62-64]. They also offer higher flexibility in terms of the selection of 2 feedstocks [65]. FBGs are further classified into the bubbling and circulating ones. 3 Bubbling beds ones have lower gas velocities than circulating bed ones that are enhanced 4 5 by a pneumatic flow [66]. In an FBG, biomass particles are suspended, providing a larger 6 surface area for thermochemical reactions and improving the utilization of solar thermal energy. Suarez-Almeida et al. proposed a method for biomass steam gasification using 7 solar energy in a solar-driven dual fluidized bed gasifier (SDFBG) and reported an increase 8 9 of the efficiency by 115% under optimal gasification temperature conditions (1173–1273 K) as compared to the conventional (non-solar) one [67]. They also claimed that the 10 SDFBG technology has a 78% char conversion rate and shorter reaction time (20–30mins) 11 12 as compared to the conventional one (average char conversion rate of less than 50%).

13

Type of Gasifier	Feedstock	Parameter	Fine	dings	References
studied	used	studied			
Solar gasification of	biomass	Internal solid	•	Solar gasifier system	<u>[67]</u>
biomass in a dual		circulation		has high char	
fluidized bed		ratio, biomass		conversion rate (80%)	
		space-time,		at summer. During	
		the char		winter, the char	
		residence time		conversion rate is 18–	
		in the gasifier,		60%.	
		char	•	The solar thermal	
		conversion		storage system makes	
		ratio, syngas		the solar gasifier more	
	Type of Gasifier studied Solar gasification of biomass in a dual fluidized bed	Type of Gasifier Feedstock studied used Solar gasification of biomass biomass in a dual fluidized bed	Type of GasifierFeedstockParameterstudiedusedstudiedSolar gasification ofbiomassInternal solidbiomass in a dualcirculationratio, biomassfluidized bedratio, biomassspace-time,the charresidence timein the gasifier,charcharcharin the gasifier,charconversionratio, syngas	Type of GasifierFeedstockParameterFindstudiedusedstudiedSolar gasification ofbiomassInternal solid•biomass in a dualcirculationratio, biomassfluidized bedratio, biomassspace-time,the charresidence timein the gasifier,charchar•conversionratio, syngas	Type of GasifierFeedstockParameterFindingsstudiedusedstudied-Solar gasifier systemSolar gasification ofbiomassInternal solid•Solar gasifier systembiomass in a dualcirculationhas high charhas high charfluidized bedratio, biomassconversion rate (80%)space-time,space-time,at summer. Duringthe charwinter, the charconversion rate is 18–in the gasifier,conversion60%.char-The solar thermalconversionratio, syngas-the solar gasifier more

14	Table 4.	Fluidized	bed	gasifiers	used	for	CSTBG.
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		yield, solar		stable, and char	
		share.		conversions in gasifier	
				can take place	
				throughout the whole	
				year.	
Solar-driven steam	Sewage	Molar flow	•	The fluidized bed	[<u>62</u>]
gasification with	sludge	rate, particle		reactor provides fast	
indirectly irradiated		density,		heat and mass transfer.	
fluidized-bed		diameter,			
reactor		shape,			
		gasifying			
		agent,			
		superficial/mi			
		nimum			
		fluidization			
		velocity, solar			
		flux.			
Bubbling fluidized	Coconut husk	Gas yield,	•	Fluidized bed	[<u>64]</u>
bed gasification		temperature,		gasification provides	
		air humidity.		higher H ₂	
				concentration in the	
				fuel gas than fixed bed	
				gasification.	
Solar-driven steam	Sewage	Total molar	•	The yield of H ₂	[<u>62</u>]
gasification with	sludge	flow rate,		obtained by solar	
indirectly irradiated		temperature,		gasifier is 61.2–67.6	
fluidized-bed		solar power,		σ/kσ	
reactor		gas	•	Increasing the content	
		concentration,	-	of $H_2\Omega$ in gasifying	
		location at bed		agent the lower	
		hight, LHV,		agein, me iowei	

H ₂ yield, H ₂ O	heating value of cold
content, gas	gas can be improved
composition.	(from 1.54 to 9.73
	MJ/m ³)
•	Increasing the H ₂ O
	content reduces the
	solar upgrade ratio
	and solar to fuel
	efficiency.

2 (3) Entrained Flow Gasification

3 Entrained flow gasifiers (EFGs) are fed with small particles, in which oxidants (air/oxygen) and water are introduced at the same time. The oxidant and steam surroundings cause solid 4 5 particles to be entrained as they pass through the reactor [68]. They have high feedstock 6 conversion rates (98–99.5%) due to high operating temperatures (1200–1400 K), fine 7 pulverization and an extremely turbulent flow [69]. Biomass can be introduced either in a 8 dry form (using a lock hopper system) or as biomass slurry (using high-pressure water 9 pumps). Although the biomass slurry mode is more natural to operate, it introduces an additional portion of water into the gasifier, which requires extra heat for evaporation. This 10 method increases the H₂/CO ratio of syngas and decreases the thermal efficiency of the 11 process [70]. Van Eyk et al. investigated the effect of high-flux solar irradiation on 12 carbonaceous feedstock gasification in an entrained-flow reactor [71]. They showed that 13 14 the carbon in the gasification stage can be converted more quickly with sufficient solar energy (4 MW/m^2). The combined concentrated solar thermal with gasification technology 15 increased the H₂/CO ratio from 0.77 to 1.4, while the CO₂/CO ratio decreased from 0.29 to 16 17 0.05 as the solar flux increased from 0 to 100% of the maximum requirement. Besides, the instantaneous solar share increased from 0 to 37% and the upgrade factor ((*LHV*_{syngas}.
m_{syngas})/(*LHV*_{feed}.m_{feed})) increased from 78 to 140%, when the solar flux rose from 0
to 100%.

4

5 3.2 Gasifying Agent

A gasifying agent such as air, oxygen, air-steam, and steam serves as oxygen sources of
the gasification process. The equipment required for air gasification is simple, easy to
operate and maintain, and with low operating cost [72-74]. However, air gasification loses
additional heat in the form of nitrogen; nitrogen is not conducive to gasification reactions
and reduces the calorific value of product gas.

11

Oxygen gasification can achieve a higher reaction temperature and higher efficiency as
well as a higher calorific value of product gas than air gasification. Siwal et al. found that
increasing the amount of oxygen supply for gasification increased the lower heating value
(LHV) of gas produced by nearly 30–40% [75].

16

For steam gasification, the supply of steam drives the reversible water-gas shift (WGS) reaction in the foward direction $(CO + H_2O \leftrightarrow CO_2 + H_2, \Delta H^\circ = \pm 41 \, kJ \, mol^{-1})$ and promotes production of H₂ and the calorific value of the product gas [76]. Additionally, the use of steam would intend to decrease the gasification temperature. The WGS reaction is exothermic and thus is thermodynamically unfavourable at a high temperature. This is illustrated by the continuous decreases in Gibbs free energy as a function of temperature and the corresponding decrease in equilibrium constants with increasing temperature. Hence, the lowered temperature due to the use of steam would also promote the WGS
reaction in the forward direction. Meanwhile, Caitlin presented that the WGS reaction is
temperaturesensitive, possessing a faster reaction rate with increasing temperature [77].
They demonstrated a 20–40 times increase in the WGS reaction rate at temperatures from
600 K to 2000 K. Tang et al. also presented that the H₂ concentration increased from 1.2%
to 17.1% within the temperature increased from 523K to 823K [78].

7

The steam to biomass (S/B) ratio has a significant impact on the composistion of the 8 9 product gas. The solid carbon and methane are formed at low S/B ratio. As more steam is 10 supplied, the solid carbon and methane are converted to CO and H_2 . As the steam supply exceeds the biomass content, the formation of solid carbon and methane would decrease, 11 and the yield of CO and H₂ would increase. Overall, the increases in steam greatly 12 facilitates the formation of H₂ in gasification. However, excess steam reduces the reaction 13 14 temperature to the extent that large amounts of tar are produced, which is associated with the fact that the provision of excess steam lowers the reaction temperature resulting in a 15 rapid reduction in the WGS reaction rate. Therefore, an optimized S/B ratio is desirable. 16 17 Sepe et al. stated that the S/B ratio directly affects the yield of H₂, and the relatively high S/B ratio also increases the yield of CO₂ due to the saturation of the WGS reaction and the 18 19 consequent consumption of CO [79]. They used the CSTGB system and set the S/B ratio 20 from 0.5 to 3 (the feedstock moisture is 10% wt), and the obtained product gas had H₂ 21 content increasing from 52% to 55.6% and CO content decreasing from 13% to 8%.

22

23 **3.3 Process Conditions**

The CSTGB technology is influenced by various process conditions such as biomass
 particle size, temperature, the existence of catalyst, etc.

3

4 3.3.1 Particle Size

5 The size of biomass particles can impact thermochemical reaction processes, especially the 6 heat transfer rate [63]. Chuaboon et al. conducted experimental studies on different 7 biomass feedstocks using a 1.5 kW_{th} solar steam gasification device [80]. They found that 8 the yield of syngas (especially H₂) was 83.2 mmol/g_{biomass} in the range of 0.3–0.4 mm in 9 particle size. Krishnamoorthy et al. indicated that the heat transfer on the surface and inside of particles becomes lowered with the increase of particle size, affecting the yield and 10 composition of product gas (high heating rates corresponding to more small-molecule 11 gases, and less char and tar) [81]. Besides, Safine et al. presented that the heating rate of 12 small particles is higher because of larger specific surface areas, improving the heat and 13 14 mass transfer between the particles during the thermochemical reaction process and thus the efficiency of gasification [82]. Hernández et al. indicated that the pyrolysis reactions 15 were enhanced as the particle size was reduced [83]. They found experimentally that the 16 17 release of volatiles and particle carbonization in the pyrolysis phase gradually increased as the feedstock particle size decreased from 8 mm to 0.5 mm. For the particle size below 1 18 19 mm, the char gasification reaction would be more intensive. Kodama et al. investigated the 20 effect of particle size (i.e. 200 μ m and 300 μ m) on the behaviour of gasification [84]. The 21 fludization porosity increased when the particle size decreased from 300 µm to 200 µm, 22 resulting in a 33% increase in the bed height, which led to an increases in the diffusivity of 23 incident thermal radiation through the bed. When the particle size reduced, the total heat 1 transfer area for a given volume increased more favourably for a fast and homogenous 2 reaction. They also emphasised that over-small particle sizes led to increased heat loss through the reactor wall. When the particle size was reduced from 300 μ m to 200 μ m, the 3 reactor wall temperature increased by 15%. The optimal particle size is summarised in 4 5 Table 5 as 0.28–2 mm, with over-low or over-high particle size increases the char yield 6 and reduces the gas yield. The optimal particle size improves the purity and syngas yield; reduces the CO₂ and tar/char content of the product; makes efficient and rational use of 7 8 thermal energy and promotes fast and homogeneous reactions.

9

10 T	able 5.	Impacts	of	particle	size on	CSTGB.
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Feedstock	Particle Size	Temperature	Char Product	Oil Product	Gas Product	Ref (s)
			Yields	Yields	Yields	
Beech	0.21–0.5 mm	573-1173K	17-39 wt.%	44–53 wt.%	18–27 wt.%	[85]
wood	0.85–1.70 mm		17–49 wt.%	36–55 wt.%	15.5–25 wt.%	
	2.06-3.15 mm		20-55 wt.%	32-56 wt.%	13–22 wt.%	
Beech	0.28 mm	1473 K	25-30 wt.%	17-35 wt.%	4053 wt.%	<u>[86</u>]
wood						
Beech	0.5 mm	1373—1573 К	7 wt.%	N.A	22 wt.%	[<u>87</u>]
wood	2 mm		33 wt.%	N.A	37 wt.%	
	4 mm		30 wt.%	N.A	22 wt.%	
	8 mm		36 wt.%	N.A	19 wt.%	

11

12 3.3.2 Temperature

For CSTGB, a higher temperature is conducive to increase the yield of H₂. Chuayboon et 1 2 al. conducted an experimental study based on three lignocellulosic biomass feedstocks 3 (beech, pine and spruce wood) using a $1.5 \text{ kW}_{\text{th}}$ solar steam gasifier and presented that the feeding rate must be increased at the same time as the supply temperature, it improves the 4 5 yield of syngas and keeps the carbon conversion rate above 90% [80]. Thus, the optimal 6 temperature provided by the solar thermal collector is one of the critical design parameters. 7 Ravenni et al. presented a series of tar cracking and adsorption tests under different 8 temperature conditions (523-1073 K) [88]. The aromatic compounds in the char bed were 9 decomposed to produce H_2 when the temperature of the char bed rose to 873 K. As the 10 temperature rose to 1073 K, the yield of H_2 increased significantly. At higher temperature, the secondary tar cracking reactions at pyrolysis are accelerated, which would increase the 11 H₂, CO, and hydrocarbon generation and enhance the decomposition of tars. Salem et al. 12 established the modelling of tar formation, conversion and destruction along a downdraft 13 14 gasifier to reduce and eliminate the tar formation [89]. Their model included sensitivity analyses of four major tar species (i.e. benzene, naphthalene, toluene and phenol) at 0.2-15 0.35 equivalent ratios (ERs) and three different temperature (1073, 1173 and 1373 K). They 16 found that the tar yield was lower $(0.01-6 \text{ g/Nm}^3)$ when the ER value was 0.24–0.36, and 17 the water content was less than 10 wt.%. 18

19

20 3.3.3 Catalysts

There are limited studies about the use of catalysts to promote CSTGB. It is expected that the accumulated knowledge about the use of catalysts in the conventional gasification process could be applicable to that of CSTGB, though increasing research is needed to adapt the relevant principles for the optimization of CSTGB by considering the specific
 features of CSTGB. Typical catalysts used in the process of conventional gasification
 include dolomite catalysts (e.g. CaO and MgO), alkali metal catalysts (e.g. Li, Na, K, Rb,
 Cs, and Fr), and noble metal catalysts (Pt, Pd, Au, etc.) [90].

5

6 The utilization of catalysts can be an effective method to address the tar formation problem 7 faced by CSTGB. Physical purification (wet purfication and dry purification) and 8 chemical purification (thermochemical reduction and catalytic reduction) are commonly 9 used methods to remove tar. Ren et al. argue that the physical purification has non-neglible disadvantages, wet purification results in liquid mist in the syngas, equipment is difficult 10 to be cleaned, purified liquid is difficult to recycle and cannot withstand high gasification 11 temperature [91]. The drying purification technology has a wide range of tar adaptability 12 and high removal rates. However, it makes the equipment costly and inconvenient to 13 14 operate. They concluded that the use of catalyst reduction methods (i.e. heterogeneous 15 catalysts, nickel-based catalysts, noble metal catalysts, natural catalysts and wood charcoal 16 catalysts) could effectively reduce tar production and increase hydrogen production to 17 achieve efficient use of combustible gases at low temperatures. They presented that catalysts can reduce the activation energy required for pyrolysis reaction, reduce the input 18 19 of gasification media and achieve more useful products through directional catalytic 20 cracking of tars in biomass gasifier. Lind et al. used the FeTiO₃ as a catalyst to reduce the tar content of gasification production (original tar content: -30 g_{tar}/N m³) from Chalmers' 21 22 gasifier by 35% [92]. They observed that the FeTiO₃ catalyst remained active throughout 23 the reaction, and the carbon deposites on FeTiO₃ were continuously removed by oxidation

to carbon dioxide. The results demonstrated that the use of $FeTiO_3$ as a catalyst resulted in 1 2 an increase in the H_2/CO ratio from 0.7 to 3. Simell et al. presented that the dolomite 3 catalyst demonstrated 100% conversion of tar produced in an updraft gasifier and 99% conversion of tar produced in a fludized bed gasifier in a laboratory-scale reactor [93]. 4 5 They could increase the syngas yields at the expense of liquid products and achieve a 6 theoretical 0% tar formation [90, 93, 94]. Alkali catalysts can be directly added into 7 biomass by wet impregnation, which significantly reduces tar content and reduces the 8 methane content of product gas. Qin et al. applied a scanning electron microscopy and 9 energy-dispersive X-ray spectrometer to analyze the morphology and elemental composition of product char [95]. They found that alkali catalysts increased the gasification 10 conversion rate by 30%. Alkali catalysts can also act as secondary catalysts because of 11 their high resistance to carbon deposition, but they are difficult to recover and relatively 12 costly [95-98]. 13

14

15 Compared with alkali metal catalysts, noble metal catalysts have higher and more stable 16 activity in partial oxidation [99]. Noble metal catalysts have high reducibility because of 17 special electronic, optical and catalytic properties, and excellent chemical stability. Haldar et al. found the reducibility of a Cu-Ag-Au based noble catalyst was as high as 98.6% [100]. 18 19 The activity of noble metal catalysts in the gasification of biomass to syngas was found to 20 decrease in the order of Rh>Pd>Pt>Ru at 800 K [101]. Sikarwar et al. summarized that 21 noble metal catalysts had excellent properties for cellulose gasification in the range of 800– 22 920 K and about 98–99% of the carbon in biomass feedstocks was converted to gas at 873 23 K [102]. The carbon conversion rates for the conventional nickel-based and dolomite catalysts were 73% and 43% under the same condition. It also effectively reduced the sulfur
 and carbon contents in the syngas.

3

In summary, heterogeneous catalysts are active in syngas production. Nickel based catalysts, noble metal based catalysts, and natural catalysts were shown to be highly active for de-tarring. Volatiles are deposited on the active surface of the catalysts, forming char and syngas, and the char can be oxidized for further degradation. The use of catalysts in CSTGB systems is worth investigating in the future, and it is expected that it could effectively reduce the output of low value products (tars) and improve syngas production and quality.

11

12 4 CSTGB Modeling

To model CSTGB systems, a whole system perspective (reactor, heat storage and solar energy field) is needed with separate models for gasification and solar thermal. Gasification process models can be divided into two categories: one is equilibrium models based on the feedstock material balance, energy balance and thermochemical balance; the other is kinetic models based on the kinetic characteristics of the gasification process.

18

4.1 Thermodynamic Equilibrium Models

Thermodynamic Equilibrium (TE) model is based on the axiomatic concept of thermodynamics to consider the internal state of a single thermodynamic system. There is no macroscopic change in an equilibrium system (i.e. thermal, mechanical, chemical and radiation equilibrium). For a thermodynamic equilibrium state dictated by pressure and temperature, the Gibbs free energy is less than any other states at the same pressure and temperature. Introducing the standard Gibbs free energy in a thermodynamic model has a potential to calculate the maximum of reversible work at constant temperature and pressure, and to recognize if a reaction is spontaneous (ΔG <0) or non-spontaneous (ΔG >0) [103]. Li et al. showed that adding a non-stoichiometric (NS) equilibrium model improved the prediction performance for gasification through the equilibrium model and the NS model evaluates the steam demand based on the water balance of feedstock and products gas [104].

8

9 The TE model is the most suitable for preliminary studies about the effects of fuel types 10 and process parameters and could also be used to predict the temperature of various parts 11 of the gasifier and solar energy system. Wang et al. used a TE model to analyze a CSTGB process and estimated the product gas composition (17.7% CO, 19.6% CO₂, 3.03% CH₄, 12 59.18% H₂, 0.43% N₂) and supplementary energy (310 kW biomass energy and 60 kW 13 14 solar energy) based on the initial conditions of reaction temperature (1176 K) and feedstock compositions (45.17% C, 5.75% H, 35.66% O, 0.86% N, 0.14% S), into the TE model to 15 16 calculate the product gas specie moles [105]. The results showed that CST technology 17 could replace biomass combustion for heat generation and improve the utilization rate of 18 biomass by 9.22%. Gomaa et al. used a TE model to analyze the concentrated solar thermal 19 fluidized bed gasifier [106]. Lignite (77.3% C, 5.31% H, 19.3% N, 14.2% O) and olive 20 pomace (48.42% C, 5.96% H, 0.97% N, 34.09% O) were blend together into the fluidized 21 bed with steam as the agent and temperature set at 1100–1250 K. They found that 22 increasing the proportion of lignite in the mixture could increase the yield of H₂. The model 23 confirmed that the concentration of H₂ and CO in the syngas increased when the temperature increased from 1000 to 1200 K. At the appropriate temperature (1387–1400
K), more O₂ lowered the content of H₂ and but increased the content of CO in the resulting
syngas. An increase in the H₂O level led to a greater H₂ production because the H₂O:C
ratio had a strong negative correlation with temperature.

5

6 4.1.1 Kinetic Models

7 Kinetic models are often used to design and optimize the gasifier in a CSTGB system. 8 Kinetic models are based on the estimation of main reactions' kinetics and the transfer 9 phenomena for each phase in a gasification process, and it can be used to estimate the production of gas compositions under different operating temperatures [107]. Some 10 researchers developed kinetic models for biomass gasification are based on the shrinkage 11 core models considering heterogeneous non-catalytic reactions. In these models, biomass 12 particles act as porous media allowing water vapor and volatiles to escape into the reactor 13 14 environment during the stage of pyrolysis. These models allow a detailed demonstration of transport phenomena and reaction kinetics within a biomass particle, including changes in 15 16 temperature and reactant concentration gradients within the particle, as well as changes in 17 the thermophysical properties (i.e. conservation of mass, energy and momentum) of reactants [108]. Considering that biomass particles have different sizes and shapes, the 18 19 effect of particle volume shrinkage during pyrolysis is generally not negligible. The 20 shrinkage core models are based on the following assumptions: the biomass particle 21 remains spherical, the thermal energy of the first order chemical reaction during pyrolysis 22 is constant, the gas and solid phases within the biomass particle remain in thermal

equilibrium, the thickness of the reaction zone is constant, and the diffusion and mass
 transfer coefficients cannot change during the process [109].

3

Some kinetic models can clearly demonstrate the reaction process in different zones of the 4 5 gasifiers and the suitable parameters for this zone could be defined easily. For example, 6 Salem et al. modelled four zones of a downdraft gasifier and found that the yield of syngas was higher when the moisture content was less than 10%, and the equivalent ratio was 0.3– 7 8 0.35 [110]. Dejtkulwong et al. used a kinetic model to simulate the drying zone for the 9 downdraft gasification of biomass with a wide range of composition (38<C<52%, 10 5.5 < H < 7%, and 36 < O < 45%) [42]. It is shown that the water began to evaporate as the temperature reached 368 K and the pyrolysis process started at 473 K [111]. 11

12

Sharma has developed a kinetic model of a downdraft biomass gasifier to present that the 13 14 oxidation zone provides the heat needed for drying and pyrolysis [112]. Biomass combustion requires air to be completed, the process of gasification and reduction 15 processes are performed to produce syngas if the air is less than the required stoichiometry. 16 17 They summarized that the oxidation order depends on the reaction rate of pyrolysis products and chemical reactions of the oxidation process: (1) hydrogen-containing 18 19 substances are first oxidized, (2) CO oxidation occurs, (3) the CH₄ produced by pyrolysis 20 is oxidized if the oxygen remains (4) if more oxygen is available, the oxidation of the tar 21 and char is re-oxidized. Hameed et al. conducted the kinetic model analysis of five biomass 22 feedstocks (i.e. wood sawdust, douglas fir bark, bagasse, rice husk and peanut hull) under

- isothermal conditions [113]. They found that the rate of syngas formation increased from
 0.05 to 0.15 within a temperature range of 1000–1200 K.
- 3

The kinetic model is based on the kinetic rate for the reaction, which is appropriately used to study CSTGB systems. Li et al. established a kinetic model for the sludge gasification process and found that increasing H₂O content in the gasifier agent could increase the lower calorific value from 1.54 to 9.73 MJ/m³ at 1000 W/m² [62]. The H₂ yield range around 61.2–67.6 g/kg was achieved by solar steam gasification of sewage sludge which was affected by H₂O content and solar radiation. The efficiency decreased by 18.5–32.9% when the H₂O content in sewage sludge from 0 to 100 wt.%.

11

12 **4.1.2 CFD Models**

Computational fluid dynamics (CFD) modelling is a method to analyze, design, and 13 14 optimize the performance of gasifier that is appropriate for the development of multidimensional gasification models [114]. CFD models have been used to predict the 15 distribution of temperature, concentration, and gas yield in a reactor [115]. CFD models 16 17 are based on the set of equations for the solution of mass, momentum, energy conservation, and species in a gasifier. CFD simulations are classified into two types of methods, the 18 19 Eulerian-Lagrangian (E-L) approach and the Eulerian-Eulerian (E-E) approach. In the E-L 20 approach, the gas phase is described by the Navier-Stokes equations and the solid phase is 21 treated as discrete. Newton's law calculates the trajectory of each particle and the collisions 22 between particles are defined by the soft-sphere model or the hard-sphere model. In 23 contract, the E-E approach treats the solid phase as a continuum and requires less computation, the method used the kinetic theory of granular flow to estimate the transport
 characteristics of a solid phase [116].

3

Boujjat et al. established two CFD models [117]. The first method used the E-L approach 4 to simulate the flow of fluid into the fixed bed. For the governing transport equation, they 5 6 considered the mixture of fluid and solid particles to determine the temperature and 7 tracking discrete particles in the fixed bed. In order to simulate the directly irradiated 8 sputtered bed particle, the second model used the E-E method, which analyzes momentum, 9 energy and radiation intensity transfer. The E-E approach consumed less computing resources, and both gas and particle phases were considered as an interpenetrating 10 continuum. CFD modelling studies of CSTGB systems are summarised in Table 6. The 11 CFD models can combine the continuity, motion, and energy equations with the kinetics 12 of homogeneous and heterogeneous reactions to calculate the mass and energy transfer in 13 14 CSTGB systems. The simulation results are generally in good agreement with experimental 15 data [114, 118, 119].

16

Table 6 summarises some of the studies that have simulated biomass gasification using thermodynamic equilibrium, kinetic, and CFD models. The thermodynamic equilibrium approach applies Gibbs free energy minimisation to reveal the thermodynamic boundary for a given condition [120, 121]. A kinetic model provides a more detailed and accurate description of the gasification process than an equilibrium model. It considers the kinetic information and hydrodynamic properties of the gasification reactions. Some studies have obtained accurate results by means of finite element method (FEM) [122, 123] and finite

1	volume method (FVM) [108, 124]. Meanwhile, it was also demonstrated that CFD
2	modelling could achieve more detailed and accurate results as it incorporates the factors of
3	reactor design, fluid mechanics, mass and heat transfer, etc [125, 126]. Highly accurate
4	simulations become necessary and useful for predicting product composition and optimal
5	process condition [127-129], as well as providing the basis for downstream techniques such
6	as techno-economic analysis (TEA) [130, 131] and life-cycle assessment (LCA) [132, 133].
7	

	Feedstock	Temper	Model studies	Parameter studies	Fir	ndings	Reference
		ature					
Downd	Rice Husk,	873—	Thermodynamic	Air Flow Rate,	•	Apply chemical	[<u>134</u>]
raft	Wood	1473 K	equilibrium model	Temperature, Bed		equilibrium results	
	Pellet		& Gibbs free	Height		taken from the	
			energy, kinetic			combustion zone that	
			model			can increase the	
					accuracy in kinetic		
					modelling.		
Downd	Corn Cobs,	1073 K	Thermodynamic	Oxygen content in	•	Root mean square error	[135]
raft	Corn		equilibrium model	air, ER, calorific		(RMSE) added into	
	Stover		& Gibbs free	value	thermodynamic		
			energy		equilibrium model		
					improved the		
					prediction of the		
						calorific value.	

8 Table 6. Equilibrium & CFD models of gasification.
Downd	Brewers	973 K	Thermodynamic	H ₂ /CO & CH ₄ /H ₂	•	Carbon boundary point	[<u>136</u>]
raft	spend grain		heterogeneous	molar ratio of ER,		(CBP) concept applied	
	pellets		equilibrium,			to the stoichiometric	
			stoichiometric			could increase the	
			equilibrium			accuracy	
Downd	Biomass	400—	CFD model	Syngas	•	CFD model hardly	[<u>114</u>]
raft		1000 K		composition, ER,		presents the syngas	
				volatile matter		compositions.	
				decomposition	•	CFD model is suitable	
						for displaying the	
						temperature in each	
						reaction zone.	
Fixed	Leaf pellets	873—	CFD model	Temperature,	•	CFD model quickly	[<u>118</u>]
bed		923 K		syngas		presents physical and	
		, 20 11		compositions		thermochemical	
						conversion process	
Fluidiz	Coal	700—	CFD model	Gas compositions,	•	CFD model is more	[<u>137</u>]
ed bed		900 K		angle, temperature,		suitable for S/B ratio	
		,		S/B ratio,		analysis and	
				efficiency, heating		simulation.	
				value, used agent			
Fluidiz	Wood	1473—	CFD model	Temperature,	•	Al ₂ O ₃ bed material has	[<u>117</u>]
ed bed		1573 K		heating value,		the best resistance to	
		10,011		carbon conversion		thermal shocks and	
				efficiency, cold gas		chemical inertness.	
				efficiency, solar-to-	•	The influence of bed	
				fuel efficiency		material on the	
						composition of syngas	
						remains very low (less	
						than 7% for H ₂)	

1

2 4.2 CSTGB System

3 The first solar biomass fixed bed gasifier is based on one-stage concentrated solar thermal (CST) biomass fix bed gasification [138]. This system transfers the indirect heat of 4 5 concentrated solar radiation to the packed bed through a quartz window, while steam and 6 feedstock are injected from the bottom of the gasifier during the solar day [139]. The solar 7 packed bed gasifier provides reliable operation and robust performance for a wide range of 8 carbonaceous feedstocks (e.g. lignocellulosic biomass, sewage sludge, etc.). This system 9 has a heat-transfer limitation because of the indirect solar thermal transfer through an emitter plate and lack of heat storage, causing the system only operatable at a solar day 10 [140]. It has the disadvantage of high thermal inertia, corresponding to a long preheating 11 period of 2–4 hours. It is possible to use a heat storage system to avoid the preheating time 12 for each solar day or replace the fixed bed reactor with a fluidized bed reactor to increase 13 14 the heat and mass transfer rates. Pantoleontos et al. conducted a dynamic simulation of a heat storage system in CSTGB, where a cobalt oxide redox pair system was considered for 15 the reforming of reduction zone reactions [141]. They found that this storage system could 16 17 provide 24% of the required reaction energy during the night, and the rest had to be provided by an external heat source. 18

19

Gokon et al. proposed a one-stage CST biomass gasification system consisting of an internally circulating fluidized bed reactor combined with concentrated solar radiation [142]. In the proposed system, line-focus or point-focus solar collectors were employed to provide concentrated solar thermal energy (1300–1800 K). This system applied a beam-

down configuration: a set of secondary mirrors mounted on the tower top redirected the 1 2 solar radiation to the bottom. They found that the peak photochemical energy conversion 3 rate (or chemical storage efficiency) was about 12% for an internally circulating fluidized bed reactor after 5 minutes of light-irradiated reaction. The internal circulation fluidized 4 5 bed was changed into a spouting bed to improve the heat transfer rate of the bed and the 6 heat recirculation. Nathan proposed a method to improve the efficiency of this system by 7 increasing the heat flux on the bed surface, building large-scale heat recirculation, and 8 utilizing the free-board material to absorb the irradiation [143]. Bellouard et al. claimed 9 that the total thermochemical efficiency of a high-temperature solar biomass gasifier could 10 be increased to 28% at 1400 K [57]. In general, one-stage solar gasification has many limitations, such as low entire energy efficiency, low solar-to-chemical efficiency, high 11 exergy loss, etc. Multi-stage gasification needs to be introduced to significantly increase 12 the system efficiency, feedstock utilization rate, and syngas generation rate. 13

14

15

16 Two-stage CSTGB system utilizes two different types of solar-collect techniques (line-17 focus and point focus collectors) to collect solar thermal energy. Bai et al. proposed a CSTGB power generation system with an integrated two-stage gasifier, where the solar 18 19 thermal energy concentrated by parabolic solar collector [144]. A point-focus collector 20 (PFC) is used to reflect the concentrated solar beam to provide the heat of the gasification 21 reaction. Impurities (e.g. ash and H_2S) are removed from the produced syngas by 22 condensation and purification. The qualified syngas is fed as gaseous fuel directly into the 23 combined cycle power generation system, which consists of a dual pressure heat recovery

1 steam generator (HRSG). Two types of solar collectors were used to provide different 2 levels of solar thermal energy to drive biomass pyrolysis (643 K) and gasification (1150 3 K), respectively. The total energy efficiency of this system was 26.72% and the net solar power efficiency was 15.93%. The exergy loss from the solar collection and gasification 4 5 process was reduced by 19.3% as compared to the one-stage design. The energy level 6 upgrade ratio of the two-stage CSTGB system was as high as 32.35%, as compared to 7 21.62% for a one-stage system. The daily average net solar-to-electric efficiency was 8.88– 8 19.04%, as compared to 9.97–15.71% for a one-stage system.

- 9
- 10

Instability in solar thermal energy generation is one of the major barriers against the 11 application of CSTGB systems. The variation and intermittence of solar radiation and 12 sunshine duration, in this case, lead to the temperature variation of gasification. Heat 13 14 storage is a promising approach to address the instability problem to sustain the operation 15 of the process for continuous syngas production under a stable temperature condition. With 16 a heat storage system, the CSTGB system can proceed throughout all day and avoid 17 preheating time, leading to a 2.77-time increase in the product gas yield as compared to a conventional CSTGB system without heat storage [145]. 18

19

The tank storage CST uses thermal energy storage (TES) to store the concentrated solar thermal energy into a power block where water in a heat exchanger is heated to steam or superheated steam before the energy is transferred to a gasification process [146, 147]. TES systems can be roughly divided into three categories: sensible heat storage (SHS),

thermochemical heat storage (THS), and latent heat storage (LHS). SHS stores heat by 1 raising the temperature of substances stored in solids, liquids and gases [148]. THS is based 2 3 on reversible chemical reactions, in which charging and discharging are carried out through endothermic and exothermic reactions, respectively [115]. Carrillo et al. found that the 4 optimal operation requirement of the system to meet a series of an ideal storage medium 5 6 and the characteristics of conceptual design included high energy storage density (about 144 kWh·m⁻³), high stability of material (30000 h test or expected >30 years), high 7 operation temperature (about 838 K), high heat transfer rate (λ =0.5 W·m⁻¹·K⁻¹), and low 8 9 toxicity, cheap and abundant materials (20 -33 \$/kWh) [115]. The LHS technology stores 10 heat in the form of phase change material (PCM) fusion latent heat. Gokon et al. studied 11 the application of iron-germanium alloy (Fe-Ge alloy) as a phase change material in an 12 LHS system at 1073 K [149]. They evaluated the cyclic performance, short- and long-term 13 thermal stability of the alloy through thermal reliability tests. Compared to solar salt, the 14 Fe-Ge alloy shows excellent potential as the next generation for solar thermal application due to a variety of strengths, such as higher storage capacity, rapid heat response, and 15 thermodynamic stability of the structure. 16

17

18 **5** CSTGB Development

19 5.1 Feedstock

Existing studies have paid little attention to studying the impacts of feedstocks on CSTGB.
However, the diversity of feedstocks (i.e. agricultural wastes, energy crops, forestry wastes,
industrial wastes, etc.) makes it important to characterise the impacts thoroughly for
CSTGB optimisation, as this directly affects the syngas yield and compositions [150].

1 Table 7 compares the syngas yields produced by the CSTGB system and the conventional gasification using same feedstocks and finds that the CSTGB system has higher syngas 2 yield (20-50%) than conventional one. It is necessary to conduct more detailed 3 investigation into the study and characterization of biomass that can be used for CSTGB. 4 5 As shown in Table 6, micro-algae have recorded unsatisfactory results in gasification 6 processes (low syngas yield, low H₂ and CO content), so it is not recommended for use in 7 CSTGB systems. Beech wood and surgarane bagasses have proven to be more suitable for 8 CSTGB systems, with some studies demonstrating that they could achieve high syngas 9 yields with H₂ contents of 30-54.5 mmol/gbiomass and CO contents of 26.8-34.3 mmol/gbiomass. 10

11

	CSTGB System			Conventi	onal Gasification	
Feedstock	Temperature	Syngas Yield	Ref (s)	Temperature	Syngas Yield	Ref(s)
		(mmol/gbiomass)			(mmol/gbiomass)	
Beech	1373–1573K	H ₂ :31.9-41.9	[9]	1173–1473K	H ₂ :2.65-12.35	[<u>151</u>]
wood		CO: 26.8–31.1			CO: 6.61–14.26	
Micro-	1073–1223K	H ₂ : 8–9	[11]	973–1123K	H ₂ : 2–7	[152]
algae		CO: 12			CO: 10–15	
					CH4: 0	
Straw	953–1223K	H ₂ : 18	[<u>11</u>]	773–1273K	H ₂ : 9.71–26.8	[<u>12</u>]
		CO: 52			CO: 0.69–18.14	
		CH4: 9				
					CH4: 0-12.67	

12 Table 7. Biomass feedstocks for CSTGB systems.

Sewage	1093K	H ₂ : 9–15	[<u>11</u>]	1023–1073K	H ₂ : 7.6–16.8	[<u>153</u>]
sludge		CO: 15–30			CO: 6.1–12.7	
					CH4: 2.7-3.4	
Sugarcane	1073–1573K	H ₂ : 30.0–54.5	[<u>13]</u>	1073-1273K	H ₂ : 25–31	[<u>14</u>]
bagasse		CO: 30.7–34.3			Syngas: 57–60	
		CH4: 0.8–13.4				

1

2 **5.2 Potential**

Climate change mitigation is one of the major drivers for the development of CSTGB
systems [154-156]. In some countries with high dependency on fossil fuel imports, such as
China, the United States, and India [157], CSTGB systems have great potential for energy
diversification and increasing the share of renewable energy supply [158].

7

Table 8 shows that CSTGB systems have 30% higher biomass utilization rate than conventional biomass gasification systems [159], and they can produce hydrogen with a purity of approximately 99.99% with significantly lower CO₂ emissions [159-161]. CSTGB systems not only increase the energy/exergy efficiency as compared to conventional biomass gasification, but they also reduce the carbon emissions to 99% theoretically [105, 162]. CSTGB systems also need to be built close to the raw materials availability sites leading to lower transportation costs [154].

- 15
- 16 Table 8. Recent development of CSTGB systems.

Feedstocks	Temperature/	Methodology	Specific efficiency	Reference(s)

		pressure				
Solar Driven	Biomass	1073 K	Modularization	•	Biomass utilization	[<u>6</u>]
Supercritical Water		25 MPa	Design Method,		increase 30% wt than	
Gasification			LCA		CBG.	
				•	Hydrogen purity	
					increases to 99.99%.	
				•	Carbon conversion from	
					feedstock to products is	
					less than 1%.	
Solar Driven	Biomass	1150-1200	Mathematical	•	Energy efficiency	[<u>159</u>]
Biomass		К	Model,		reaches to 51.89% than	
Gasification		1.8 MPa	Economic		CBG.	
			Evaluation and	•	Exergy efficiency	
			Cost Sensitive		reaches to 51.23% than	
			Analysis,		conventional biomass	
			Equilibrium		gasification	
			Analysis	•	The monthly average	
					production rate	
					increases 46.65%	
					~49.05% than CBG	
				•	Biomass consumption	
					rate is reduced by	
					27.33% than CBG	
Solar Driven	Biomass	1150 K	Thermodynamics	•	Power efficiency	[162]
Steam/Air Biomass			Analysis		increased by 36.55%	
Gasification					than air biomass	
					gasification.	
				•	Power efficiency	
					increases by 38.86%	
					steam BG.	

Solar Thermal	Biomass	723—1073 К	Energy and	•	Energy efficiency	[<u>105</u>]
Biomass		92 kPa	Exergy Analysis		increases by 56%.	
Gasification				•	Exergy efficiency	
					increases by 28%.	
				•	Syngas yields reach to	
					55.09% than CBG.	
Solar-assisted	Wet wood,	1300 K	Life cycle	•	The energy efficiency	[<u>160</u>]
Biomass	Sawdust,		assessment		has been raised 41.85%	
Gasification	MSW,		(LCA)		(wood) and 38.68%	
	Animal				(sawdust) than	
	waste				conventional biomass	
					gasification.	
Concentrated Solar			Thermodynamics	•	CO ₂ emission reduces	[<u>159</u>]
Thermal Biomass			& LCA		45% than CBG,	
Gasification						
Solar Based	Biomass	1500 K	Exergy Analysis,	•	The hydrogen injection	[<u>161</u>]
Biomass			Exergy-		can decrease by 0.24%	
Gasification			economic		exergy destruction than	
System			Analysis,		CBG.	
			Thermodynamic	•	Decreasing CO ₂	
			Analysis		production by 2% and	
					reduce the system	
					product cost 3% than	
					CBG.	

1

2 **5.3 Challenges and Perspectives**

3 5.3.1 Economics

4 Lu et al. carried out a techno-economic analysis of a CSTGB system for H_2 production and

5 concluded that the conversion process was fully renewable compared to other forms of

solar chemical hydrogen production [163]. They found that the CSTGB system could 1 2 achieve the maximum desired external energy efficiency (about 0.5–0.55) at a temperature 3 of 700–900K with an estimated H₂ cost of 6.05/kg at a processing capacity of 1 tonne/hour. As the capacity increased from 1 to 10 tonnes/ hour, the H₂ cost decreased to 3.95\$/kg. 4 5 Rodat et al. also considered applying CSTGB system to convert natural gas to H₂ with the 6 yield of 436 kg/day and the cost of 1.42\$/kg [164]. Onigbajumo et al. used Aspen Plus 7 model to simulate the CSTGB system using algae as a feedstock [165]. The result of the 8 techno-economic analysis showed minimum fuel selling price (MFSP) of 40–56 \$/GJ, 9 effectively reducing the MFSP by 77% compared to the conventional gasifier. They realized that MFSP is influenced by discount rates and energy cost, which are easily 10 influenced by solar infrastructure costs or fossil fuel prices at higher capital costs. With the 11 progressively higher prices of fossil fuel, carbon tax credit, and government policies makes 12 CSTGB system economically viable and 100% renewable in the future. 13

14

15 **5.3.2 HTF Material**

16 One of the critical technical challenges facing CSTGB development stems from the 17 property of HTF and materials (insulation and internal materials). HTF is heated by radiation and converted through solar collector walls. Karim et al. studied the molten salt 18 19 nanofluid with the composition of graphite as nanoparticles in LiCO₃ – K₂CO₃ based 20 molten salt by using the CFD model [166]. They found that the solar receiver efficiency 21 (from 60-75%) and total efficiency (40-48%) decreased at higher operating temperature, 22 while the Carnot efficiency (61.5–68%) increased slightly with the increase of the receiver 23 length. In most CSTGB systems, a CST unit is connected to a biomass gasifier via a heat

transfer tube. Through the study of 1m heat transfer tube in a CSTGB system, they found 1 that the HLT temperature dropped sharply at the output point as the increases of tube length 2 3 and HTL input speed. Finally, they summarized that the $LiCO_3 - K_2CO_3$ based molten salt has no apparent effect on the overall efficiency, and it is more suitable for heat storage and 4 heat transfer at higher operating temperatures (1071 K). Saha et al. presented a numerical 5 6 investigation to simulate the water-based Al₂O₃ and TiO₂ nanofluids flowing through a horizontal circular pipe under uniform heat flux boundary condition with some setting 7 values (i.e. Reynolds number $Re=10\times10^3$, Prandtl number Pr=7.04-20.29, nanoparticle 8 volume concentration χ =4–6%, and nanoparticle size diameter d_p =10, 20, 30, and 40 nm) 9 [167]. They found that the heat transfer rate increased with increasing particle volume 10 concentration and Reynolds number when the particle diameter decreased. Thus, they 11 12 believed that water-based Al₂O₃ nanofluid had a higher average shear stress ratio, higher 13 thermal conductivity and higher thermal performance factor than TiO₂ nanofluids.

14

15 **5.3.3 Solar Collector Materials**

The insulation and internal materials of the solar collector must be able to withstand high 16 temperature (1500 K), large thermal gradients and high heating rates [168, 169]. Lab-scale 17 18 systems have used energy-intensive materials (i.e. alloy, ceramics, metal) to resist the 19 thermal stress caused by concentrated solar radiation [170]; however these materials cannot protect the interior of the reactor due to the severe thermal shock that often occurs in 20 21 concentrated solar radiation applications. Thermal shock is a type of fast transient 22 mechanical load caused by a rapid change in temperature at a certain point. It can cause differential expansion of different parts in a CSTGB system. When this stress exceeds the 23

tensile strength of the material, cracks will be formed, leading to system breakdown.
Evangelisti et al. showed that external thermal shock testing was essential, which can
provide information about the collector's ability to withstand severe thermal shock
(accidental thunderstorms on sunny days) [171]. They believed that thermal insulation
materials in solar collectors had not been thoroughly studied. Thus, a more comprehensive
investigation may help to understand the strengths and weaknesses of material in this sector.

7

8 5.4 Others

9 Even though CSTGB system is positioned and has many advantages for the production of high quality syngas, its development is still at an early stage. In contrast to the conventional 10 gasifier, the CSTGB system has not yet been demonstrated on a pilot scale [172, 173]. 11 CSTGB still remains economically challenging, requiring incentive-based environmental 12 policies. Neither technology player nor research and government support for the 13 14 widespread exploitation of the CSTGB system appear to be capable of successfully commercializing and disseminating the technology. Significant challenges remain in 15 proving the efficiency of the process, which relate to the cost of solar concentrators, 16 17 receivers, HTF materials, gasifiers, etc. Finally, Piatkowski et al. claimed that CSTGB would be difficult to develop in arid regions with large solar resources (DNI>2000 kWh/m²) 18 19 per year) due to the scarcity of water resourcs [174].

20

21 **6** Conclusions

This work reviewed the development of CSTGB based on consideration of two major units(i.e. concentrated solar thermal and biomass gasification) of the technology. Several types

of gasifiers (fixed bed, fluidized bed, and entrained flow) and influence factors (agents, 1 2 catalysts, particle size, and temperature) have been discussed, and the application of 3 complementary high-temperature (523–2273 K) solar energy has been highlighted. The SPT solar collector and fluidized bed gasifier were preferred for a CSTGB system. The 4 5 MTCR technique in the SPT solar collector could provide a 2000–3000 kW/m² solar flux 6 (approximately 873–2273 K), increasing the thermal efficiency by 27.65–29.50% and the energy efficiency by 29.58–31.56%. Molten salt is the most suitable HTF because of its 7 high heat transfer value (0.7 M/Wm²). For CSTGB, the ideal feedstock particle size is the 8 9 range of 0.28-2 mm. The use of steam as the gasification agent (S/B ratio approximately equal to 3) would increase the H₂ content of syngas (55.6%). The use of catalysts has been 10 effective in reducing tar production and increasing H₂ production for conventional 11 gasification, while their impacts on CSTGB needs more studies. CSTGB has been found 12 to achieve an energy efficiency of 74.84% and an exergy efficiency of 51.23%. 13

14

The TE model has been beneficial in predicting the behavior of CSTGB systems, especially of the SPT solar collector. For fluidized bed gasifier, the TE model accurately predicts the temperature profiles of gasification products in the oxidation zone. Some modified TE models incorporating empirical parameters and relevant experimental research achieved higher accuracy. Introducing S and NS models into the TE model, which can compute the predicted equilibrium product's composition based on using thermodynamic property data.

The kinetic model is a powerful tool to analyze the fluidized bed gasifier in the CSTGBsystem; it utilizes mass and energy balance rules to accurately and precisely calculate the

product content (gas, tar, char) under given operating conditions. The kinetic model can
 predict the progress and product composition along with the different locations of the
 reactor (i.e. pyrolysis, combustion, and reduction zone).

4

5 CFD model has been used as an essential tool to study the behavior of gasifiers. However, 6 in order to conduct a comprehensive CFD model of the CSTGB system, detailed and 7 accurate studies of the gasification process and solar thermal conversion, combined with

8 specific numerical methods for multiphase flows, are required.

9 CSTGB is still at an early stage of development. CSTGB is still economically challenging
10 and requires incentive based environmental policies. Further research about the techno11 economic analysis of pilot-scale deployment of CSTBG as compared to conventional
12 gasification, and HTF and solar collector materials is needed for practical and widespread
13 uptake of the technology.

14

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