CHAPTER 2

CHAPTER 2

REVIEW OF LITERATURE

The review of literature was conceived to understand the developments in the various facets of biomass gasification based electricity generation systems. The chapter presents a review of literature on decision support systems for bioenergy application and modeling techniques used to study biomass gasification based electricity generation systems. The objective of the review of literature is to identify appropriate techniques to formulate the methodology of the present work.

2.1 Decision Support Systems for bioenergy application

Decision Support Systems (DSS) are basically computer-based systems with an interactive interface that helps the user in judgment and choice activities [1]. The architecture of the DSS allows for storage and retrieval of data like a traditional information access and retrieval system but with integration of models that correlate the various parameters related to the system. This allows for problem solving, modeling and support framing. Over the years many models with decision support system capability have been developed in the bioenergy field.

In the late 1980's, a DSS was developed utilising the data from a series of trials of harvesting, storage and drying of wood for fuel from conventional forestry. Named 'The Aberdeen University Harvesting Decision Support System (AUHDSS)' it estimated the species/tree size/terrain/harvesting system and cost per unit of output (\$/gt, \$/odt, \$/m^3, \$/GJ, etc.) for individual stages in the supply chain (harvesting, comminution, storage and drying, transport) [2]. The user had the choice to select from a range of option at each stage in the supply. The DSS allowed either the user to make the selections or determined the optimum solution for a given set of circumstances itself. AUHDSS which was written in the C language for a MS Windows environment. It was developed further under versions 2 and 3 in MS Excel and Visual Basics with MS Access database environment respectively in order to increase the processing speed and ability to handle changes in the database.

In another instance two DSS applications were developed to model the costs of growing short rotation coppice under different climatic conditions. The DSS were based on information and data collected from actual field trials. In the first DSS named Coppice Decision Support System (CDSS) was a spreadsheet model that could be used to model the costs of growing short rotation coppice under UK conditions [3]. The user had the choice of selecting either willows or poplars, select a cutting cycle, select the operations to be performed by farm labour or contractors, and estimate yield. Land rent was considered and there was an option to include subsidies. CDSS calculated the cost of production in terms of $/wet tonne; $/dry tonne; $/GJ and net present value once a discount rate was selected.

The second type was the Coppice Harvesting Decision Support System (CHDSS) [4] written in Visual Basic. CHDSS was based on data and functions collected and derived through field trials of harvesting, storage, drying and delivery systems conducted in Europe [5]. CHDSS could model the supply chain from the standing coppice crop through harvesting, storage and transport and contained extensive information about each of the harvesters evaluated in the field trials.

An integrated biomass to electricity model (BITES), was developed interlinking existing models and decision support systems. The BITES model was used to investigate the interface between supply and conversion and to assess the impact of different feedstock and conversion processes on the costs of generating electricity. BITES model was extended under the auspices of International Energy Agency and subsequently became known as the Bio-Energy Assessment Model – BEAM [5]. BEAM allows for the techno-economic assessment of biomass to electricity and woody biomass to ethanol facilities. It is a spreadsheet based model and was found to be very useful as a tool to examine bioenergy systems. However, BEAM faced limitations in terms of feedstock options, conversion processes and outputs as well as the number of variables that could be altered.

National Renewable Energy Laboratory (NREL) in the United States developed HOMER which is a free software application to design and evaluate technical and financial options for off-grid and on-grid power systems for remote, stand-alone and distributed generation applications [6]. HOMER allows for the choice of a large number of technology options to account for energy resource availability and other variables. HOMER was first created in 1993 for internal DOE (Department of

Energy) use to comprehend the trade-offs between various energy generation options. A few years after the first version, NREL made a variant publically accessible for free to serve the developing network of system designers intrigued by renewable energy. From that point forward HOMER has remained a free programming application which has developed in to a powerful tool for demonstrating both conventional and renewable energy technologies. HOMER has been extensively used for techno-economic evaluation of renewable energy based electricity generation [7–15].

Mathematical optimization has been used effectively as a decision making tool concerning multiple decisions. The technique evaluates a best solution out of the possible options available. The approach has been applied for the modeling of biomass supply chains in which multiple bio-products from multiple biomass feedstock are produced. A network was synthesized for energy and bio-products supply using a mixed integer linear programming (MILP) approach for which multiple technologies to produce energy and food were admitted revealing that it was more economical to produce the former [16]. This model was subsequently extended to integrate considerations for energy, water, and processing including food production [17] and to include a multi-period formulation [18]. In another approach, a multi-objective optimization structure was coupled with life cycle assessment to ensure sustainability aimed at designing of a generic biomass feedstock for bioethanol production by employing an input–output analysis [19]. In a related work, a mixed-integer nonlinear programming (MINLP) optimization based modeling was used to develop a county-level biofuels supply chain in Illinois [20]. The model was further enhanced to consider financial aspects such as transfer price and revenue sharing within a game-theoretic framework [21]. A decision support tool with integrated optimization of various model components of a region-specific biofuel supply chain involving disparate knowledge fields was also developed [22]. In a more specific approach, multiple-feedstock multiple-product supply chain optimization of oil palm empty fruit bunch in Malaysia was attempted [23]. In an interesting approach, sustainable electricity generation from steam power plants including biomass feedstock use by applying multi-objective optimization incorporating economic and environmental metrics is also reported [24]. Multiple bioconversion pathways involving a comprehensive product and process network was also developed using an uncertainty model [25]. The approach elaborated multi-objective optimization modeling structure applied for solving piecewise linear approximation of the primary nonconvex MINLP model [26]. Biomass supply chain optimization involving feedstock selection and potential co-production of energy and materials were also attempted [27,28]. Other related studies focused on logistical aspects such as transport and storage [29–32]; and utilization of third generation feedstock such as algae [33,34].

Although various DSS exist for bioenergy applications, a dedicated DSS for biomass gasification based electricity generation taking into account the uncertainties associated with the system is not available. The development of a DSS for biomass gasification based electricity generation involves the development of various modules related to different aspects of the system. The modules are based on mathematical models of aspects concerning gasifier performance with different feedstock and economics of electricity generation. The following sections discusses the various biomass gasification modeling techniques.

2.2 Models of biomass gasification based energy generation (This section is adapted from Author’s own publication [35])

Feed stock flow rate, gasifying agent flow rate, equivalence ratio, reactor pressure and reactor temperature are some of the important operating parameters which influence the gasification process [36]. Change in any of the parameter has considerable effect on the end-gas composition and hence on the performance of the gasifier [36]. Also, different feedstock has inherent heterogeneity in terms of their composition and thermo-chemical properties [37]. It is also observed that the parameters affecting the gasification process exhibit an interrelated behaviour [38]. Thus, experimentation to find the optimum conditions for a given reactor design utilizing a certain feedstock becomes time consuming and expensive. Under such conditions, mathematical modeling has been found to serve as an important tool to study the gasifier behaviour in order to optimize its design and operation without going for physical experimentation. Mathematical models are developed to give a good representation of the chemical and physical phenomena occurring inside the reactor of a gasifier [36]. Reactor environment inside a gasification system varies at each point in space and time. Statuses at any point within the reactor are going to vary due to dynamic changes in the variables affecting the processes occurring inside the reactor. The major variables within the reactor are pressure, temperature, velocity of flow, density and concentration of each species [39]. These variables are interdependent and have dynamic variability. Chemical reaction, fluid flow, molecular transport and radiation result in the change of these properties at any point [39]. It is noteworthy that the predictive ability of a mathematical model of the gasification process solely depends upon the capability of the model to represent these variables as realistically as possible. The modeller while developing the model may be tempted to ignore some of the variables or to make a simplifying assumption in order to truncate the complexity of the model. This causes errors in the model results. Thus, utmost care has to be taken in formulating the model so as to minimise the errors in the results. An example in this regard is the Babu and Seth's equilibrium model which incorporated the variation of char reactivity factor (CRF) along the reduction zone of the downdraft biomass gasifier. In the study it was found that exponentially varying CRF along the length was found to have better agreement with experimental results in comparison to the linearly varying CRF [40]. Though it is imperative to make assumptions during the formulation of a model, but resorting to over-simplifying assumptions may cause large errors in the results.

Nevertheless, mathematical models have been found to be effective in providing qualitative guidance on the effect of design, operating and feedstock parameters on the gasifier performance [36]. Due to the inherent complexity of biomass gasification processes, modeling for simulation and prediction of performance of the processes is still an emerging area of research [41]. Approaches for mathematical modeling of gasification process are categorised into (i) thermodynamic equilibrium, (ii) kinetic and (iii) artificial neural network (ANN) routes. In the following sections a review of work done by various authors using different modeling approaches are discussed. Each modeling approach has been discussed by giving an introduction to the approach followed by key results from different studies. The studies have been arranged based on the model considerations, the feedstock used and the parameters studied.

2.2.1 Thermodynamic equilibrium model

A thermodynamic equilibrium model is used to predict the composition of the product gas based on the assumption that the reactants react in a fully mixed condition for an infinite period of time [36]. Equilibrium models are further categorised as stoichiometric models and non-stoichiometric models. Stoichiometric models are based on equilibrium constants [42]. In this modeling approach the specific chemical reactions are identified and used for the estimation of end gas composition. In this approach some of the most important reactions are considered while some other reactions are omitted. This results in errors in the prediction of the developed model. This difficulty is overcome by the non-stoichiometric modeling approach which involves minimization of the Gibbs free energy [43]. This process is more complex but it is advantageous because the identification and consideration of the chemical reactions are not needed [36].

Equilibrium models allow a practical description of the gasification process. In particular, the results of its application can highlight the thermodynamic limits and the relations between different gasification parameters and the composition of the flowing out gas. Although the equilibrium models are simple, they can describe gasification processes with good approximation, such as those occurring in downdraft gasifiers. This kind of gasifier usually operates close to equilibrium conditions. Moreover, thermodynamic equilibrium calculations, which are independent of the gasifier design, may be more suitable for process studies on the influence of the most important fuel and process parameters [44]. Although the pure equilibrium approach is relatively easy to implement and converges rapidly it has inherent thermodynamic limitations. This can be illustrated by the fact that thermodynamic equilibrium in not fully attained during relatively low operation temperatures (product gas outlet temperatures range from 750 to 1000 °C) [45]. Thus, the equilibrium approach does not give a true representation of the process during low operation temperatures. Another such example is the inability of the equilibrium models for fluidised bed gasifiers in predicting some of the kinetically and hydro-dynamically controlled phenomena such as unconverted solid carbon and the formation of gaseous hydrocarbons [46].

Nevertheless, equilibrium models have been used successfully by many researchers in modeling the gasification process in downdraft gasifiers. Some of the recent works are listed in Table 2.1.

Table 2.1: Equilibrium model in the study of downdraft gasifiers

Sl. No.	Author(s)	Feedstock used/ Molecular formula	Parameters studied
1	Babu and Sheth [40]	$CH_{3.03}O_{1.17}$	Char reactivity factor
2	Melgar et al, [47]	Rubber wood	Air fuel ratio and moisture content
3	Gao and Li [48]	$CH_{3.03}O_{1.17}$	Temperature of the pyrolysis zone
4	Sharma [49]	Douglas fir bark	Moisture content, pressure, equivalence ratio in gasifier, initial temperature in reduction zone
5	Barman et al [50]	$CH_{1.54}O_{0.62\ 2}N_{0.0017}$	Air fuel ratio, mole of moisture per mole of biomass
6	Azzone et al [51]	Corn stalks, Sunflower stalks and Rapeseed straw	Pressure, temperature, biomass humidity and oxidant agent composition
7	Antonopoulos et al [52]	Olive wood, Miscanthus and Cardoon	Reactor temperature, feedstock moisture content

As seen from Table 1, these models differ with respect to the feedstock and process variables considered for the model formulation.

One of the models attempted to predict the steady state composition and temperature profiles incorporating the variation of the char reactivity factor (CRF) along the reduction zone of the downdraft biomass gasifier [40]. CRF is a key parameter in modeling the downdraft gasifier as it represents the reactivity of the char in the reduction zone. Appropriate pattern of CRF were investigated along the length of the reduction zone, through modeling, which were then verified with experimental results. An exponentially varying CRF along the length was found to have better agreement with experimental results. Thus, in developing equilibrium models for downdraft gasifiers, consideration of variation of CRF results in better predictive ability of the models. Also, consideration of exponentially varying CRF yields better result in comparison to linear variation.

Another approach considered the laws of conservation of energy in an open system, the chemical laws of conservation of atomic species and the laws of chemical equilibrium and combined them in order to predict the final composition of the producer gas as well as the reaction temperature [47]. The model was validated with experimental results and then the influence of the moisture content and the gasifying relative fuel/air ratio on the producer gas composition and the process characteristics were studied for different biomasses with defined ultimate composition and moisture content. The ease of implementation and predictive accuracy of the model makes it a good mathematical model. Also, the combination of thermal and chemical equilibrium conditions is advantageous in developing equilibrium models.

As already discussed, the gasification process proceeds in a series of steps occurring inside the gasifier. The most important step having critical influence on the end composition is pyrolysis. It is observed that the more detailed the pyrolysis step is, the better is the prediction of the model [53]. While modeling the pyrolysis step it becomes essential to describe the temperature of the pyrolysis zone. One such study aimed to simulate the behaviour of a fixed bed biomass gasification reactor to study the effect of a continuously increasing heating rate and fixed temperature of the pyrolysis zone on the end gas composition in the reduction zone [48]. In the study both the pyrolysis zone and the reduction zone were modelled together. It was observed that for a continuous heating rate of the pyrolysis zone, the concentrations of hydrogen and carbon monoxide increased while those of nitrogen and carbon dioxide decreased with increasing reaction temperature. The methane content increased during the reaction time and at the end of the reaction the concentration decreased. Similar observations were made for water fraction. For a constant pyrolysis temperature, nitrogen and carbon dioxide decreased and methane, hydrogen, carbon monoxide and water content increased with reaction time. In both the modes, the trends of temperature profile and species concentrations were found to be very different. Thus, it is observed that while modeling the pyrolysis and reduction zones together, the temperature profile of the pyrolysis zone has significant effect on the gas composition in the reduction zone. Accordingly, one must take utmost care in modeling the pyrolysis zone in terms of its parameters. In this regard the temperature of the pyrolysis zone is one of the most important parameter having significant influence on the gas composition.

Also, proper mathematical representation of the reduction zone is also critical as chemical reactions among the hydrocarbons in fuel, steam, carbon dioxide, oxygen, and hydrogen in the reactor, as well as chemical reactions among the evolved gases occur in this zone. Of these the char gasification reactions has been found to be the most important. A full equilibrium model of the global reduction reactions involving char-gas and gas-gas interactions for a downdraft biomass gasifier in order to predict the accurate distribution of various gas species, unconverted char and reaction temperature is available [54] . The proposed equilibrium model for the reduction zone was able to predict full equilibrium composition and equilibrium constants precisely. It is observed that consideration of a representative char bed length and initial temperature of the reduction zone helps in improving the predictive ability of the model.

Consideration of the uncertainty concerning composition and quality of tar is a difficult issue of gasification modeling. An attempt was made to develop a model for a downdraft fixed bed biomass gasifier taking into consideration representative tar composition as model parameter [50]. This study showed that, if the tar mass was accounted for in the mass balance, the rest of the gasification product (permanent gas species, including moisture vapour) may be predicted with considerable degree of accuracy by simple equilibrium model, considered with deviation from the equilibrium for the methane reaction.

Biomass gasifiers have been reported to utilize agricultural residues and municipal wastes in addition to woody biomass for gas generation. An equilibrium model for the simulation of thermochemical gasification and application to agricultural residues was developed [51]. The model behaviour was analysed by varying process parameters (pressure, temperature), biomass humidity and oxidant agent composition. By increasing the pressure in the gasifier, the methane fraction increased. This was due to the fact that the equilibrium constant is inversely proportional to the process pressure. The model, however, overvalued the quantity of hydrogen and underestimated the production of methane. This was attributed to the typical behaviour of the equilibrium model. It was commented that this behaviour could be explained by considering that the methane generated in the low temperature zone could bypass the reaction zone and avoid its reduction.

Equilibrium modeling for downdraft gasifiers has been found to be very useful in predicting the behaviours of downdraft gasifiers. It is because in downdraft gasifiers both pyrolysis and gasification products are forced through the hottest zone (oxidation zone) so that equilibrium is established after a relatively brief time period [49]. In most of the studies discussed above, the effect of reactor temperature and moisture content of the feedstock in a downdraft gasifier were evaluated using the equilibrium models [40,48,51,52,54]. It was observed that H_2 and CO_2 concentrations decreased by the increase in temperature while the concentration of CO increased in high temperatures [48,52]. By increasing process temperature the syngas lower heating value (LHV) was found to decrease. This behaviour was attributed to the fact that the combustion process proceeded further in order to increase the process temperature [49]. Moisture content was found to reduce CO fraction in syngas significantly, thus reducing higher heating value (HHV) of the gas [52].

In addition to its use in studying downdraft gasifiers, equilibrium models have also been used extensively to study the performance of fluidised bed gasifiers (Table 2.2). In fluidised bed gasifiers the bed particles are kept in a state of suspension by blowing a gasifying agent through the bed of solid particles at a high velocity. This helps in instantaneous heating of the fuel particles which are introduced at the bottom of the reactor because the fuel particles mix quickly with the bed material. This results in a very fast rate of drying and pyrolysis. The resultant product is a component mix with a relatively large amount of gaseous materials. Further gasification and tar-conversion reactions occur in the gas phase. Char is carried away with the gas. In order to minimise this internal cyclone is used.

Depending upon the fluidisation technique the reactors are classified as either bubbling fluidised bed or circulating fluidised bed. Oxygen and steam are basically used as the gasifying agent and depending upon the pressure of the gasifying agent the reactors are classified as atmospheric or pressurised reactors.

Equilibrium models for fluidised bed gasifiers fail to predict some of the kinetically and hydro-dynamically controlled phenomena such as unconverted solid carbon and the formation of gaseous hydrocarbons [46]. In order to overcome these problems, the equilibrium models are usually adjusted using empirical parameters or correlations to match measured data from the gasification reactors. Equilibrium modeling in studying fluidised bed gasifiers are based on either one dimensional or three dimensional stoichiometric equilibrium approach [55–59] or Gibbs free energy minimisation approach [46,60]. Fluidised beds exhibit very complex hydrodynamics due to the non-linear interactions between the two independent media with their own individual movement tendencies - the particles and the fluid [56]. Accordingly, the models are based on two phase theory of fluidisation.

The key parameters influencing the performance of a fluidised bed gasifier are temperature of reactor, average temperature of incoming bed material, equivalence ratio, moisture content of feedstock, steam to feedstock ratio in case of steam blown gasification and feedstock particle size [56]. Equilibrium models have been used to study the effect of these parameters on the gasification process and reasonable agreement has been found with experimental results in most cases. Some key findings are discussed below.

The producer gas composition depends on the thermodynamic behaviour of the reactions which are greatly affected by the temperature. High temperatures improve product formation in endothermic reactions (Boudouard reaction, water-gas reaction, steam-methane reforming reaction) whereas they favour reactants in exothermic reactions (Methanation reaction, CO shift reaction). High bed temperatures result in less char and tar formation and high gas yields due to improved carbon conversion and steam cracking and reforming of tars [56,60]. Thus an increase in reactor temperature results in production of a gas mixture rich in H_2 with small amounts of CH_4 and higher hydrocarbons [55,57–60].

Table 2.2: Equilibrium model in the study of fluidised bed gasifiers

Sl. No.	Author(s)	Model considerations	Feedstock used	Parameters studied
1	Hannula and Kurkela [46]	Equilibrium model using Aspen plus simulation	Crushed wood pellets and forest residues.	Heat losses, gasification pressure, steam/oxygen ratios, filtration temperature and reformer conversion levels, reforming temperature and drying percentage
2	Kaushal et al [55]	One dimensional steady state model	Wood chips	Mixing of devolatilized gas, average temperature of incoming bed material, moisture content of biomass, steam to biomass ratio
3	Gungor [56]	One-dimensional, isothermal and steady state and the fluid-dynamics are based on the two-phase theory of fluidization. Tar conversion is taken into account in the model.	Biomass	Gasifier temperature, bed operational velocity, equivalence ratio, biomass particle size and biomass-to-steam ratio
4	Loha et al [57]	Equilibrium Model	Rice husk, sugarcane bagasse, rice straw and groundnut shell	Gasification temperature, steam to biomass ratio
5	Xie et al [58]	The model uses an Eulerian method for fluid phase and a discrete particle method for solid phase, which takes particle contact force into account.	Pine wood	Reactor temperature, equivalence ratio, steam to biomass ratio
6	Nguyen et al [59]	Empirical model including biomass pyrolysis, char–gas reactions and gas–phase reaction	Pine wood chips	Gasification temperature, steam to fuel ratio
7	Doherty et al [60]	Based on Gibb's free energy minimisation approach.	Hemlock wood	Equivalence ratio, temperature, level of air preheating, biomass moisture and steam injection

With an increase in the temperature of the incoming bed material the H_2 concentration in product gas was found to increase while the concentrations of CH_4 and CO_2 decreased [55].

Equivalence ratio (ER) plays an important role in gasification. Equivalence ratio is defined as the ratio of the actual fuel air ratio to the stoichiometric fuel air ratio where the stoichiometric air is the amount of air required for complete combustion of one unit of the fuel. Equivalence ratio for biomass gasification using fluidised bed has been found to vary in the range of 0.10 – 0.30 [56,58,60]. It was suggested from these studies that too small ER's tend to lower reaction temperature, which does not favour biomass gasification. On the other hand, too large ER's result in consumption of more H_2 and other combustible gases through oxidization reaction causing a decrease in the HHV of the end gas. Thus, ER is found to have two opposing effects and as such there exists an optimum ER for each reactor which is dependent upon the operating parameters and the reactor design [56,58].

Moisture content in the feedstock has been found to have a very deteriorating effect on the quality of the product gas. It is observed that with the increase of the fuel moisture content, the average temperature of the gasifier goes down due to production of H_2O. As a result of the decreasing temperature the reaction rates slow down and eventually result in lower heating value and inferior quality of product gas [55,56].

The steam to biomass ratio has been found to vary depending upon the gasifier temperature. In a study it was found that for a gasification temperature of 800°C, increasing steam to biomass ratio increased hydrogen production [56]. On the one hand, the gasifier needed more heat for higher gasification temperature; whereas, steam needed to absorb much more heat to reach in-bed temperature.

It has been found that small biomass particles contribute to large surface area and high heating rate thereby improving H_2 composition. For small particle sizes the pyrolysis process is mainly controlled by reaction kinetics; as the particle size increases, the product gas resultant inside the particle is more difficult to diffuse out and the process is mainly controlled by gas diffusion [56].

Equilibrium models have also been used to study different types of gasifier designs as shown in Table 2.3.

Experimental and modeling analysis of a batch gasification pyrolysis reactor with the help of an equilibrium model was attempted [61]. The overall agreement between model predictions and experimental results were reasonably satisfactory; in particular the residual solid yield (char) obtained experimentally at 800 °C was very close (in the range -5% to +15%) to the value obtained by the simulation. Considering the gas phase, the agreement was quite good also for CO and CO_2, it was fair for H_2, while it was poor for CH_4. It was commented that the computed compositions were representative only of processes where the residence time was long enough to establish thermodynamic equilibrium conditions.

Table 2.3: Equilibrium model in the study of some specific gasifier designs

Sl. No.	Author(s)	Type of gasifier studied	Feedstock used	Parameters studied
1	Baggio et al [61]	Indirectly heated batch reactor set in an external furnace	Spruce wood	Char yield
2	Deydier et al [62]	Travelling Bed Gasifier	Coal, wood and grass	Air-fuel ratio for drying and gasification
3	Nilsson et al [63]	Three-stage system and a stand-alone fluidized bed gasifier	Dried sewage sludge	Equivalence ratio, steam to oxygen ratio, reactor temperature
4	Bhattacharya et al [64]	Oxygen blown biomass gasifier followed by a water gas shift reactor for the production of hydrogen.	Wood	Equivalence ratio, amount of water injected in the shift reactor for complete conversion of carbon monoxide and percentage of oxygen in the gasifying agent
5	Pirc et al [65]	Universal gasifier	Various biomass	Type of wood, amount of wood moisture, outlet temperature of the syngas, oxidant (oxygen or air).

A mathematical model for the prediction of the influence of the operating parameters of a gasification process composed of a drying and a gasifying section (travelling bed gasifier) was also developed [62]. The effect of the ratio of mass flow rate of air used for drying to the mass flow rate of incoming biomass and the ratio of the mass flow rate of air for gasification to the mass flow rate of incoming biomass was studied. An optimal value of the ratio of mass flow rate of air used for drying to the mass flow rate of incoming biomass was found to exist and this value corresponded to the complete and exact drying of the biomass. Optimal value of the ratio of the mass flow rate of air for gasification to the mass flow rate of incoming biomass was found to be associated with the exact and complete gasification of solid carbon.

In another approach, a model of a new three-stage gasification system was used to compare the performance of a three-stage system and a stand-alone fluidized bed gasifier (FBG) using dried sewage sludge as fuel [63]. The equivalence ratio (ER), steam to oxygen ratio (SOR) and reactor temperature were the process parameters whose effect on the system was studied. It was found that for a given SOR there was an optimum range of ER within which the cold gas efficiency (CGE) was maximum. As SOR increased, CGE decreased. The Carbon Conversion efficiency increased as reactor temperature increased up to a certain reactor temperature and then remained constant. The results showed that the reforming of tar in the gasifier is not significant for temperatures below 900°C. When increasing the steam to oxygen ratio the temperature decreased, leading to less reforming of tar and higher tar content in the gas. These results suggested that the addition of steam is not suitable to enhance tar reforming for atmospheric auto-thermal FBG.

A thermodynamic model to evaluate the yield of hydrogen from biomass through gasification in an oxygen-rich environment followed by carbon monoxide shift reaction with the injection of water was also attempted [64]. Effect of gasifier equivalence ratio, amount of water injected in the shift reactor for complete conversion of carbon monoxide and percentage of oxygen in the gasifying agent were studied using the model. The hydrogen yield was found to be marginally affected by the percentage of oxygen in the gasifying agent. However, was commented that higher the oxygen percentage, less would be the nitrogen in the gas mixture and easier would be the purification process to obtain hydrogen. The energy consumption per unit mass of hydrogen generated was higher or the higher purity of oxygen in the gasifying agent. Also, it was commented that the energy consumption could be reduced with multi-staging of the compressor and intercooling between the successive stages.

A model for a theoretical universal biomass gasifier capable of producing different syngas compositions is also available [65]. It was reported that when the syngas consisted of methane, hydrogen and carbon monoxide, the highest net efficiency of the system was achieved. Producing syngas for methanol synthesis was found to be interesting area due to its use in a mobile technique. The lowest net efficiency of gasification was achieved when producing a hydrogen-rich syngas; this was because of water reduction, which was an endothermic reaction. It was sensible to use a hydrogen-rich syngas in fuel-cell systems. Using oxygen as an oxidant was found to be efficient in all cases.

It may be observed that equilibrium models have been successfully utilised in the study of different types of gasifiers. It is also seen that modification of the equilibrium models by incorporating empirical correlations based on experimental studies helps in increasing the accuracy of the models.

2.2.2 Kinetic Model

A kinetic model is used to predict the gas yield and product composition that a gasifier achieves after a finite time (or in a finite volume in a flowing medium) [36]. A kinetic model can predict the profiles of gas composition and temperature inside the gasifier and overall gasifier performance for a given operating condition and gasifier configuration.

Kinetic model takes into consideration both the kinetics of gasification reactions inside the gasifier and the hydrodynamics of the gasifier reactor. This becomes important if the residence time required for complete conversion is long which occurs when the reaction rate is very slow at low reaction temperatures. Thus, kinetic modeling is found to be more suitable and accurate at relatively low operating temperatures compared to equilibrium model.

Kinetic modeling incorporates both reaction kinetics and reactor hydrodynamics. While reaction kinetics involves the knowledge of bed hydrodynamics and mass and energy balances to obtain the yields of gas, tar, and char at a given operating condition, reactor hydrodynamics involves the knowledge of the physical mixing process.

The rate of the char gasification reaction is expressed in terms of the external surface area of the biomass char or in terms of the reactor volume. This is because as the gasification of a biomass particle proceeds there is mass loss which is manifested either through reduction in size with unchanged density or reduction in density with unchanged size. Again, where the reaction is made up of char alone, the reaction rate is based on reactor volume. Accordingly, the char gasification reaction of biomass is studied using the shrinking core model or the shrinking particle model or the volumetric reaction rate model.

Further, based on the reactor hydrodynamics the following types of models, with increasing sophistication and accuracy are used: zero dimensional (stirred tank reactor), one dimensional (plug flow), two dimensional and three dimensional.

The kinetic model is also sensitive to the gas–solid contacting process involved in the gasifier. Based on this process, the model may be divided into moving or fixed bed, fluidized bed and entrained flow.

Kinetic models are accurate and detailed but are computationally intensive. It may be noted that the complexity and dimensions of the model increases with the desired outputs of the model i.e. more detailed analysis of the system involves incorporation of more detailed reaction kinetics and/or reactor hydrodynamics. The complexity of the models can however be reduced by making simplifying assumptions within the different chemical reaction classes but the levels of simplification have to be carefully evaluated to make them coherent with the final aim of the model [66]. Nevertheless, many researchers have focused extensively on kinetic models of biomass gasification. Table 2.4 enlists some recent works based on kinetic modeling for biomass gasification.

A comprehensive process model was developed based on reaction kinetics and reactor hydrodynamics for biomass gasification in an atmospheric fluidized bed gasifier using the ASPEN PLUS simulator [67]. After satisfactory validation of the model using experimental values, the effect of reactor temperature, equivalence ratio, steam to biomass ratio and biomass particle size were investigated using the model. Higher temperature was found to improve the gasification process. It increased both the production of hydrogen and the carbon conversion efficiency. Carbon monoxide and methane showed decreasing trends with increasing temperature. Carbon dioxide production and carbon conversion efficiency were found to increase by increasing the ER. Although, hydrogen, carbon monoxide, and methane decreased when ER was increased, increasing steam-to-biomass ratio increased hydrogen and carbon monoxide production and decreased carbon dioxide and carbon conversion efficiency. Particle average size did not show a significant influence on the composition of product gases.

Table 2.4: Kinetic model in the study of specific gasifiers designs

Sl. No.	Author(s)	Type of gasifier studied	Feedstock used	Process variables
1	Nikoo and Mahinpey [67]	Fluidized bed gasifier	Pine wood	Reactor temperature, equivalence ratio, steam to biomass ratio and biomass particle size
2	Saravanakumar et al [68]	Updraft fixed bed gasifier	Long stick wood	Air-fuel ratio, gasification temperature
3	Gordillo et al [69]	Downdraft solar packed bed gasifier	High carbon content feedstock	Gas flow rate, reactor height, reactor temperature
4	Inayat et al [70]	Steam gasifier	Oil palm empty fruit bunch	Temperature and steam to biomass ratio

A computational model to evaluate the anticipated performance characteristics of an updraft fixed bed gasifier utilizing long stick wood as the source of fuel was attempted [68]. The computational model indicated that all incoming air was consumed in the charcoal combustion region, and that maintaining a specific air/fuel ratio could lead to a poor measure of gasifier performance. Higher combustion temperature was found to enhance the gasification time, but could waste more energy due to energy carried out by the hot exhaust gases. It was commented that air to fuel ratio could be a more useful measure when moisture was present in the lower portion of the bed to maximize/minimize specific gasification products.

In a related study [69], a numerical model of a solar downdraft gasifier, utilizing high carbon content feedstock viz. biomass char (biochar) with steam, based on the systems kinetics with CFR varying exponentially was developed. The model was aimed to calculate the dynamic and steady state profiles while also predicting the temperature and concentration profiles of gas and solid phases, based on the mass and heat balances. The study suggested that downdraft set-up could be a great solution in order to improve the performance of the packed bed and fluidized bed gasifiers with concentrated solar radiation in the upper side of the reactor. The gas produced was found to be high quality syngas, in which the hydrogen was the principal component followed by carbon monoxide; the carbon dioxide yield was small because no combustion was conducted. The system efficiency was reported to be as high as 55% for small steam velocities. The energy conversion efficiency was found to decrease when the steam velocity was increased and when the bed was heated quickly. The model predictions were in very good agreement with the trends found experimentally and reported in the literature. Moreover, varying CRF exponentially was found to improve the representation of the heat transfer throughout the bed.

The results of a parametric study performed using process modeling for hydrogen enriched gas production via steam gasification in the presence of CaO are also reported [70]. The model incorporated the reaction kinetics calculations of the steam gasification with in-situ CO_2 capture, as well as mass and energy balances calculations. Temperature and steam/biomass ratio were reported as the most important variables, as the hydrogen concentration in the product gas increased on increasing the value of both variables. Hydrogen efficiency was found to decrease on increasing steam/biomass ratio as more energy was required for additional steam usage despite the increased hydrogen yield. Additionally, it was observed that temperature had a more significant influence on the hydrogen yield compared to the steam/biomass ratio.

Kinetic rate models contain parameters that limit their applicability to different plants. Also, with increasing complexity in the design of the gasifiers, the complexity of the model increases because the models are based on reactor hydrodynamics.

Equilibrium or kinetic models or combination of both have their own advantages and disadvantages. Whereas equilibrium models are simpler in formulation but do not yield satisfactory results for complex reactor designs, the kinetic models are complex in formulation but their predictions are more accurate compared to equilibrium models for complex reactor designs. Computational Fluid Dynamics (CFD) serves as a tool to study the behaviour of a given gasifier design by incorporating the advantages of both models. Artificial Neural Network modeling is also coming up as a useful tool in analysis of biomass based gasifiers.

2.2.3 CFD and ANN model

CFD models are used to predict distribution of temperature, concentration, and other parameters within the reactor. CFD models are based on solutions of a set of simultaneous equations for conservation of mass, momentum, energy, and species over a discrete region of the gasifier. CFD models are found to be highly accurate in predicting the temperature and gas yield around the reactor if the reactor hydrodynamics are well known. CFD modeling of biomass gasification involves the combination of dense particulate flow and very specific chemistry [71]. These two aspects are very challenging in CFD. For example, the composition of biomass itself is very complex due to its dependence on feedstock, age, geographic location and time of the year. CFD models have been used extensively to study the performance characteristics of different types of biomass gasifiers. Table 2.5 enlists some recent works based on CFD modeling.

A detailed CFD model of a cyclone gasifier, based on the Fluent package is available [72]. Models of sawdust pyrolysis and combustion of volatiles and char were added to the standard model. The model provided information on the gas temperature in the gasifier and the composition of the outlet gas. The effect of equivalence ratio was studied and validated experimentally. For the cyclone gasifier, the carbon conversion was found to vary between 77.0-94.2% and the cold gas efficiency varied between 53.6-63.0% when equivalence ratio (λ) was varied in the range of 0.23-0.35. The maximum lower heating value of the produced gas was 5.7 MJ/Nm^3 when λ was 0.23-0.26. Models of sawdust pyrolysis and combustion of volatiles and char were added to the standard model. The model was found to under predict the concentrations of CO and CO_2. The predicted gas temperatures and the produced gas concentrations were found to follow the same trend as the experimental ones, and it was suggested that developed numerical model could provide a good reference for the development of biomass gasifier.

CFD model of a high pressure entrained flow gasifier is also available [73]. Steady balance equations for mass, momentum, energy and several species were solved using a finite volume solver. Atomization quality of twin fluid nozzles as a function of gas velocity and reactor pressure was analysed. The developed and characterized atomizers were used in the atmospheric entrained flow gasifier, to detect the influence of spray quality on gasification process. Sauter Mean Diameter (SMD) of the produced spray was found to be significantly influenced by gas velocity and reactor pressure. Increasing reactor pressure was found to increase the drop diameter whereas increasing gas velocity decreased the SMD. An influence of SMD on gasification process was observed from organic carbon and methane concentration measurements as well as from the radial temperature profiles at various positions along the reactor centreline. The CFD model of high pressure entrained flow gasification of biomass based slurries showed a very pronounced influence of drop size distribution on gasification quality.

Table 2.5: CFD and ANN models in the study of biomass gasifiers

Sl. No.	Author(s)	Type of gasifier studied	Feedstock used	Model considerations	Parameters studied
1	Gao et al [72]	Air cyclone	Sawdust of walnut	Detailed CFD model of a cyclone gasifier. Models of sawdust pyrolysis and combustion of volatiles and char have been added to the standard model.	Equivalence ratio, gas composition
2	Jakobs et al [73]	Entrained flow gasifier	Ethylene glycol	CFD model. Steady balance equations for mass, momentum and energy are solved using a finite volume solver.	Spray quality
3	Janajreh et al [74]	Downdraft bioamss gasifier	Woody biomass	The numerical simulation is conducted on a high resolution mesh accounting for the solid and gaseous phases, k–e turbulence, and reacting CFD model	Gas composition, cold gas efficiency, carbon conversion efficiency, reactor temperature
4	Arnavat et al [75]	Circulating fluidized bed gasifiers (CFB) and bubbling fluidized bed gasifiers (BFB)	Woody biomass	Feed-forward ANN model	Ash, moisture, biomass composition, equivalence ratio, gasification temperature for CFB and BFB respectively , steam to dry biomass ratio (kg/ kg) for BFB only
5	Sreejith et al [76]	Fluidised bed gasifier	Wood sawdust	Feed-forward ANN model and equilibrium correction model incorporating tar (aromatic hydrocarbons) and unconverted char	Product gas composition, heating value and thermodynamic efficiencies

The conversion efficiency in a small scale, air blown, downdraft gasification system operated using wood was also investigated using CFD modeling [74]. The experimental investigation of the temperature field inside the gasifier was followed by high fidelity numerical simulation using CFD to model the Lagrangian particle coupled evolution. The numerical simulation was conducted on a high resolution mesh accounting for the solid and gaseous phases, k–ε turbulence, and reacting CFD model. The downdraft gasifier was modelled using the finite volume code coupled with a conjugate heat transfer with the bulk metal separators and insulation. The temperature distribution and the evolution of species were computed and compared with the experimental results and with the ideal equilibrium, zero dimensional case. The average temperature computed using CFD was higher compared to that measured experimentally. The CFD computed cold gas efficiency (CGE) was found to be 19 points less of that calculated for the ideal case. It was commented that due to the complexity of the flow inside the downdraft gasifier, equilibrium modeling could not capture the physics and chemistry inside the downdraft gasifier compared to other types of gasifiers especially those characterized by their high temperatures such as the entrained flow gasifiers. To account for the particle size of the wood, de-volatilization kinetic data for particles of 1 cm length were used to offset the effect of the particle diameter (0.1 mm) modelled using the discrete phase method (DPM) in ANSYS. The corresponding CFD and experimental temperature profiles suggested that this assumption was reasonable.

A more recent approach for simulation of gasifier is the neural network analysis in which the neural network learns by itself from sample experimental data mimicking the working of the human brain and providing some human characteristics in solving the models. Although this method cannot produce an exact analytical solution but it gives numerical result. A neural network may return poor results for data that differ from the original data it was trained with [36]. This happens sometimes when limited data are available to calibrate and evaluate the constants of the model. Thus, one has to be very diligent in applying the ANN approach. One must ensure that he/she has sufficient data in order to formulate the model. This technique has been used with reasonable success to predict gas yield and composition from gasification processes. Some recent works on ANN modeling have been included in Table 5 and discussed below.

Arnavat et al [75] developed two ANN models; one for CFB and the other for BFB. Both models were used to determine the producer gas composition (CO, CO_2, H_2, CH_4) and gas yield. The effect of ash, moisture, carbon, oxygen and hydrogen content of dry biomass, equivalence ratio and gasification temperature were studied for CFB and BFB whereas the effect of steam to dry biomass ratio (kg/ kg) was studied for BFB only. The two ANN models developed for CFB and BFB gasifiers showed the possibility that ANN may offer some contribution to research in the area of biomass gasification modeling. The results obtained by the two ANN's showed high agreement with published experimental data used: very good correlations ($R > 0.98$) in almost all cases and small RMSE. Biomass composition (C, H, O) in CFB represented between 31.7% and 54.1% of the importance on CO, CO_2, H_2 and CH_4 prediction and in BFB between 28.9% and 52.3%. In the case of producer gas yield prediction, in CFB, the ER input was found to be the most important variable (37.6%) while in BFB model it decreased down to 10.8%.

In a related study, a feed-forward artificial neural network (ANN) model for the prediction of gasification temperature and product gas composition and a Redlich–Kwong real gas equilibrium correction model incorporating tar (aromatic hydrocarbons) and unconverted char to predict the product gas composition, heating value and thermodynamic efficiencies was developed [76]. Good accuracy of ANN prediction with experimental results was reported which was based on the computed statistical parameters of comparison such as coefficient of correlation, root mean square error (RMSE), average percentage error and covariance. The corrected equilibrium model developed by introducing correction factors for real gas equilibrium constants showed satisfactory agreement ($RMSE = 5.96$) with the experimental values. Maximum concentration of hydrogen achieved experimentally was 29.1 % at the equivalence ratio $= 0.277$ and steam to biomass ratio $(SBR) = 2.53$. The corresponding predicted values were 28.2 % for ANN model and 31.6 % for corrected equilibrium model. The corrected equilibrium model for wood sawdust was validated with major air–steam gasification experimental results of other biomass materials and was found to be 95.1 % accurate on average. It was revealed from the study that the ANN model (RMSE = 2.64) was a better predictor for the product gas composition than the corrected real gas equilibrium model (RMSE = 5.96). The study proposed a more comprehensive ANN model capable of simulating various process conditions in fluidised bed gasification applicable to variety of biomass feedstock.

Various modeling techniques of biomass gasification have been discussed. All the techniques have their own advantages and disadvantages. Equilibrium modeling for downdraft gasifiers has been found to be very useful in predicting the behaviours of downdraft gasifiers. This can be attributed to the fact that in downdraft gasifiers both pyrolysis and gasification products are forced through the oxidation zone which has the highest temperature. This enables establishment of equilibrium in a relatively brief time period. Although simple in formulation, equilibrium models have inherent limitations. It is also observed that modification of the equilibrium models by incorporating empirical parameters or correlations based on experimental studies helps in increasing the accuracy of the models.

Kinetic modeling incorporates both reaction kinetics and reactor hydrodynamics. While reaction kinetics involves the knowledge of bed hydrodynamics and mass and energy balances to obtain the yields of gas, tar, and char at a given operating condition, reactor hydrodynamics involves the knowledge of the physical mixing process. Kinetic models are accurate and detailed but are computationally intensive. Kinetic models have the ability to predict the progress and product composition at different positions along a reactor. Kinetic model proves to be a very powerful tool in analysing gasification systems.

CFD has served as an important tool in order to study the behaviour of gasifier design by incorporating the advantages of different models. It may however be noted that studies involving detailed and accurate chemistry of the gasification process combined with detailed numerical methods for multi-phase flow are also essential in order to develop a comprehensive CFD simulation of the gasification process. Also, CFD models are limited by their applicability to the specific reactor design parameters under consideration.

Neural Network modeling is also being utilised by some authors as a novel approach in studying biomass gasification. ANN serves as an alternative to the sophisticated modelling of the complex gasification process. Although ANN cannot produce analytical results, it gives numerical results. Also, ANN models are capable of providing better prediction with the same or lesser number of input variables in comparison to other modeling techniques.

Choice of a modeling technique depends upon the intended application. The present study centres on the development of a DSS for biomass gasification based DEG. Use of downdraft gasifiers in DEG is discussed in Chapter 1. Also, based on the relative merits of the modeling techniques, as discussed above, Kinetic and ANN modeling of fixed bed downdraft gasifiers have been considered for the present study. Chapter 4 presents the details of the Kinetic and ANN models developed for the analysis.

Apart from the performance evaluation of gasification systems, the economics of electricity generation based on biomass gasification is an important aspect. The following section discusses the modeling approaches for evaluating the said economics.

2.3 Models of economics of biomass gasification based energy generation

Many instances of techno-economic analysis of biomass gasification based energy generation are available. These studies aim at estimating the economics of biomass gasification based energy generation technology for electricity generation, biofuel production, hydrogen production, etc.

A comprehensive overview of the principal renewable energy sources explaining the underlying techno-economic principles is available [77]. The study also examines the environmental impact and future prospects of the technologies. However, the economic analysis presented is very straight forward and does not take into account the uncertainties associated with the technologies.

Some attempts have been made to evaluate the economics of biomass gasification based energy generation. In one of the studies an attempt was made to compare different biomass to transportation fuels conversion processes with standard underlying economic and environmental assumptions [78]. The study considered second-generation conversion processes utilizing biochemical and thermochemical gasification technologies. It was reported that although the biochemical and thermochemical processes of ethanol production had their individual strengths and weaknesses, the two processes had very comparable yields, economics, and environmental impacts. Also, no significant economic or environmental impact differences between biochemical and thermochemical gasification processes for second generation ethanol production could be established.

In another related study, the techno-economic analysis of hydrogen production by gasification of biomass was presented [79]. The study evaluated the economics of hydrogen production by gasification of three biomass candidates: bagasse, switchgrass, and nutshells. The study suggested the general framework for economic analysis of hydrogen production by gasification of biomass.

A comparative techno-economic analysis of Organic Rankine cycle (ORC) and gasification for bioenergy applications is also reported [80]. Comparison of the two technologies showed that gasification offered improved yield for the investment, mainly due to the higher electrical efficiency factor. The study also drew the attention on the increased investment risk of gasification projects which could be an aversive factor for some investors.

The effects of logistic variables on the economics of biomass energy utilization in combustion and gasification plants was also studied [81]. The study evaluated the economics of the two technologies over a capacity range from 5 to 50 MW, taking into account total capital investments, revenues from energy sale and total operating costs, along with a detailed evaluation of logistic costs. The effects of logistic variables such as specific vehicle transport costs, vehicles capacity, specific purchased biomass costs and distribution density were examined in order to evaluate the impact of logistics on the bio-energy plants profitability. A mapping of logistic constraints on plant profitability in the specified capacity range was also presented.

Technologies and costs involved in an integrated system for the production of electricity from biomass, particularly wood, has been reviewed [45]. The study inspected the economics of gasification and commented that the potential for this form of renewable energy lies in either processing low-cost wastes or depending on financial incentives, even at relatively larger scales of operation and with high-efficiency processes.

Results of a techno-economic evaluation of biomass gasifier based projects for decentralized power supply for remote locations in India are presented [82]. An analysis of influence of capital costs of different components of the system (diesel engine generator sets, dual fuel engine generator sets and 100% producer gas engine generator sets) on the levelized unit cost of electricity delivered by the same was presented. In a similar study issues related to economics of decentralized power generation in India using biomass gasification were highlighted [83]. The study reviewed various technical options for biomass gasification based low, medium and large scale power generation. The merits and demerits (operational and other problems) of different systems were discussed. The study also discussed the principal factors influencing the viability of the biomass-based power generation.

In a different approach, life cycle cost analysis of renewable energy systems and grid extension was attempted [84]. The study provide for the estimation of an economical distance limit for different renewable energy systems capacity. Sensitivity analysis of economic distance limit on grid availability and operation hours was also presented.

In all of the studies discussed above the general principle underlying the economic evaluation is the estimation of costs related to feedstock, capital costs, fixed and variable operation and maintenance costs. A guideline to develop an economic analysis model for the present study could be conceptualised based on the above discussion. The development of the economic model to support the DSS is discussed in Chapter 5.

2.4 Summary

Uncertainties in biomass gasification based electricity generation is multifaceted. Availability of feedstock, cost of feedstock, feedstock characteristics, feedstock handling and processing requirements, gasification performance, electricity generation, electricity distribution, capital cost, and operation and maintenance cost are the major influencing variables. Interrelations between these factors have complex interactions and influences the viability of the. These complex interrelation of different aspects associated with the system is an unexplored area of research. As discussed in the preceding sections, many studies are available on different aspects of biomass gasification based electricity generation. However, a platform amalgamating the uncertainties at different levels of the biomass gasification based DEG system with an ability to interlink them is still not available. The present study aims at developing a platform which will allow to predict the viability of using a given gasifier system for a range of energy demand and feedstock supply scenarios and to determine the optimum mix of different aspects where energy demand and feedstock supply issues are known. DSS based modeling has been considered for the analysis. The DSS integrates the multifaceted and interrelated aspects associated with the overall supply chain, conversion process, electricity generation and distribution along with the associated economics at every stage into a single platform and provides for the analysis of various combinations of the aspects to assist in decision making regarding them. GIS based biomass resource assessment, artificial neural network based performance analysis of gasifier, scale based cost estimation of equipment and levelised cost of electricity (LCOE) is considered in the DSS. Performance of the integrated tool for a given representative rural area of the Sonitpur district of Assam, India is presented. Conditions of some specific biomass feedstock (Dhaincha, Rice husk pellet, Bagasse pellet, Jute stalk pellet and Bamboo), specific design of gasifier (downdraft), specific materials of construction of the gasifiers [mild steel gasifier (MSG) and stainless steel gasifier (SSG)] and options of power generation [dual fuel mode (DFP) and producer gas mode (PGP)] are evaluated. The following Chapters discusses the chronological development and utilization of the DSS.

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