In this chapter, a literature review is provided, which illustrates how the technology has been developed and how biomass gasification can be more effectively integrated with Combined Cooling, Heat and Power (CCHP) systems, and then highlights some of the key observations and results reported which have been then used as a platform in the present work.

2.1 INTEGRATION OF BIOMASS GASIFICATION WITH CHP

CHP applications by biomass gasification started at the beginning of the 1990s (Kirkels et al., 2011). An internal combustion engine based small mobile agricultural-residue gasification unit was used for gasification of biomass materials for CHP production. The effect of various biomass materials, gasification parameters and engine intake mixture on long-term operation and energy output of the unit has been studied. The data obtained can also be optimized for aid in possible commercialization of the CHP systems (Mertzis et al., 2014). A pre-existing municipal heating plant, which used coal as a fuel source integrated with biomass gasification cogeneration block had been analyzed for technical and economic benefits of retrofitting. It had been concluded that the best technical and economic results have been obtained for combined cycle gas and steam turbine plant integrated with gasification of biomass with steam (Kalina et al., 2010). A hybrid combined cooling, heating and power (CCHP) system driven by biomass and solar energy had been studied by Wang and Yang et al. 2016. A biomass gasification sub-system, solar evacuated collector, internal combustion engine and dual-source powered mixed-effect absorption chiller were put together to form a CCHP system. Their analysis showed that the biomass subsystem makes a greater contribution to the total system in terms of exergy efficiency.

A building cooling, heating and power (BCHP) system integrated with biomass gasification has been analyzed and an optimized design model has been proposed along with a case study in Harbin, China. The BCHP system was then compared with Separation production (SP) system using energetic, economic and environmental performance parameters. The work stipulated that optimal biomass BCHP system reduces 90.4% CO_2 emission than the SP system (Wang et al., 2014). A CHP biomass bubbling fluidized bed gasification unit coupled with an internal combustion engine (ICE) has been assessed by Damartzis et al., 2012 via a mathematical model built in Aspen Plus process Simulator. The best conditions of biomass gasification for producing maximum syngas were reported as T = 750 °C and ER = 0.2. The cold gas efficiency was reported as 70% and the thermal efficiency was approximately 33.5% at T = 750 °C and ER = 0.2. Kabalina et al., 2016 studied the feasibility of retrofitting for district heating and cooling (DHC) systems with refuse-derived fuel (RDF) gasifiers and gas upgrading equipment. The proposed system was based on trigeneration namely heat, power and syngas production. Kabalina et al., 2017 also evaluated exergy and exergoeconomic parameter (s) of the polygeneration DHC system which utilizes natural gas as fuel with a nominal capacity of 29 MW heat, 35 MW of cold, and 5 MW of electricity. The exergy analysis revealed that the polygeneration system presents adequate performance at all scenarios established. The outcomes of the exergoeconomic analysis support the exergy results. The study concluded that the introduction of the gasification and SNG units is beneficial for the system performance even in the scenario when the minor value-added product char is produced.

Preliminary conclusion: From the above considerations, it can be easily concluded that for heat and power production systems integrated with biomass gasification, maximum performance index with respect to heat and power output has been opted as the designing criterion. However, the best performance in terms of heat and power output does not simultaneously ensure a good amount of syngas and hydrogen production and vice-versa.

2.2 MERGING WITH COMBINED COOLING, HEAT AND POWER SYSTEM

Goswami et al., 2000 designed a novel cycle providing both power and refrigeration effect (RE), where the conventional condensation process has been replaced by absorption condensation. The cycle used ammonia-water mixture and could be operated with heat sources having temperatures lower than 500K. This cycle was optimized for maximum second law efficiency by Hasan et al., 2002 and the maximum second law efficiency was found to be 65.8 % at the source temperature of about 420 K. A parametric study was carried out on that cycle to observe the effects of different parameters on the performance and predicted very high thermal efficiencies for various source temperatures; however, more experimental studies were required to prove the practicality of the cycle (Goswami et al., 2004). Similar observations were reported by Tamm et al., 2004. However, results obtained from their simulation were also compared with the experimental system, which showed that absorption condensation process work experimentally as well. Yidal et al., 2006 performed exergy analysis on that cycle and found exergy effectiveness of 53%. That cycle was further investigated by Vijayaraghavan et al., 2006 for achieving maximum resource utilization efficiency and observed that the efficiency increases by 25% after the implementation of thermal distillation scheme. A tradeoff exists between power output and refrigeration effect was quantified by the help of a new parameter, effective COP. It was reported that unit of refrigeration effect produced in a combined power and cooling system comes at the expense of nearly an equal amount of power unit (Martin et al., 2007). This approach was implemented by Sadrmeli et al., 2007 and found the simulation results which were in good agreement with the experimental data. Kalina cycle was altered by Zheng et al., 2006 to suggest a new combined power/cooling cycle. A rectifier was added in place of the flash tank to obtain a high concentration ammonia-water vapor for refrigeration. A novel ammonia–water based cycle for the cogeneration of power and refrigeration was suggested by Liu and Zhang et al., 2007. Furthermore, Zhang and Lior et al., 2007 designed a new system which consists of an ammonia–water Rankine cycle and an ammonia refrigeration cycle running parallel to each other, intertwined by heat transfer, absorption and separation processes. They also discussed the thermal design of combined refrigeration and power systems for higher energy and exergy efficiencies (Zhang et al., 2007). A combined steam power and ejector refrigeration cycle has been analyzed by Alexis et al., 2007. A novel combined power and ejector refrigeration cycle with ammonia-water mixture as the working fluid was proposed by Barkhordarian et al., 2007, which utilizes two evaporators to produce refrigeration effect.

ERC does not have a high COP but it possesses a few benefits which include less movable parts leading to low wear of the equipments, and low operating, installation and maintenance cost and many research works were conducted on it. An ejector based organic flash combined power and refrigeration cycle was designed by modifying a conventional organic flash power cycle with the help of an ejector. The proposed cycle can yield higher thermal efficiency as compared to conventional one (Mondal et al., 2017). Two natural refrigerants, Nitrous oxide and carbon dioxide were used in a novel ejector expansion transcritical cascade refrigeration system. The transcritical carbon dioxide was employed in a Rankine cycle to produce additional work output, which increases energy efficiency of the system (MegdouliK et al., 2017). Energetic and exergetic analysis of a modified ejector expansion cycle was performed by Megdouli et al., 2017. The cycle has higher COP and exergy efficiency than conventional ejector expansion cycle and basic throttling cycle. This cycle uses zeotropic mixtures (R290/R600a) as the working fluid and can be utilized in freezer applications. An experimental investigation of a novel ejector enhanced refrigeration cycle was carried out to justify its use in refrigerator-freezer system (Yan et al., 2015) and showed less energy consumption than conventional refrigeration cycle. A modified dual-evaporator CO_2 transcritical refrigeration cycle (MDRC) was proposed and investigated based on energetic and exergetic analyses (Wang et al., 2016) and showed that the two-stage ejector was more effective than the single ejector under the given operating conditions. A novel modified ejector-expansion vapor-compression refrigeration cycle was analyzed and showed that the cycle exhibits better COP and volumetric refrigeration capacity than conventional one.

However, the studies on biomass fuelled CCHP system are very limited. Maraver et al., 2013, used Life Cycle Assessment to compare biomass-fueled CCHP systems with conventional on-site generation systems to determine the potential environmental and primary energy savings benefits. Huang et al., 2013, analyzed a CCHP system with Organic Rankine Cycle (ORC) which uses biomass materials a fuel source. It supplied electricity from the ORC, and uses the waste heat from exhaust gases resulting by the combustion of biomass to supply hot water, heating, and running an absorption chiller. Willow chips, straw and rice husk were taken as Biomass materials and the process efficiency was similar for each type of biofuel.

Preliminary conclusion: The review of literature shows that many studies were carried out on waste heat based CCHP systems. Similarly, many studies were also carried out on biomass gasification and subsequent syngas production. However, the studies integrating syngas production along with CCHP systems have not yet been reported. Furthermore, the previous CCHP systems mainly used vapor absorption refrigeration cycle whereas ejector refrigeration system has been used in limited capacity.

2.3 Integration of Solar assisted Biomass gasification System

There are a few solar technologies aimed at the gasification of biomass materials (Perkins et al., 2009- Piatkowski et al., 2011) with steam and/or CO_2, where the solar irradiance is utilized in the form of process heat needed to drive the reaction. The calorific content of the feedstock is increased about the same amount as to be equal to the enthalpy change of the endothermic reaction and it enhances the feedstock to be able to store solar energy in chemical form. Thus, this carbonaceous feedstock is transformed into a fuel with a broader range of more efficient applications. For syngas production as mentioned above solar irradiance of the order of 1000 suns (where 1 sun = 1 kW/m^2) is required which can be collected at Solar facilities like power towers which are fitted with secondary concentrators coupled to arrays of heliostat fields and parabolic dishes. Several thermo chemical pathways have been proposed and investigated to produce syngas by harnessing the power of the sun (Steinfeld et al. 2005).

The concept of a hybrid solar/conventional thermal gasification system has been proposed to address the problem of intermittence and randomness of the solar radiation (Hathaway et al., 2013- Kaniyal et al., 2013). A 1.5 kW^{th} solar-hybrid steam gasification prototype have been designed and analyzed by Muroyama et al., 2018. A stream of pure oxygen was fed into the prototype to increase the temperature of the system. Maximum cold gas ratio was found to be 1.16 whereas solar-to-fuel efficiency was reported up to 22.1%.

Preliminary Conclusion: Solar assisted gasification is more desirable when compared to conventional gasification processes where the process heat is obtained from the combustion reactions as a result of pure oxygen reacting with a portion of the feedstock, consequently, decreasing the total energy content of the products. Conventional gasification products contains combustion products and tars which are absent in case of solar-driven gasification processes. Therefore, solar gasification will be beneficial to include in the present system.

2.4 Inclusion of solid oxide electrolytic cells (SOEC)

Syngas, which compromises of hydrogen and carbon monoxide, can also be produced by steam electrolysis and high temperature co-electrolysis (HTCE) using solid oxide electrolytic cells (SOEC) (O'Brien et al., 2009). In the industrial sector, huge amount of wind power can be combined with carbon dioxide (obtained from traditional pulverized coal fired power plants) to generate Syngas from co-electrolysis process. The products of the co-electrolysis can then be used to obtain liquid fuels via Fischer-Tropsch (F-T) process. However, the technology for the capture of carbon dioxide post combustion requires very high amounts of energy and lowers the efficiency of the coal power plants (Klara et al., 2009, Braun et al., 2012). Solid oxide electrolysis technology can be more efficient compared to alkaline and PEM electrolysis technology and offers the advantage of allothermal operation when combined with other systems (Ali).

Syngas and/or Hydrogen production by co- electrolysis has been studied by a few researchers (O'Brien et al., 2009, Udagawa et al., 2007, Sigurvinsson et al., 2007, Jensen et al., 2007, McKellar et al., 2010). Udagawa et al., 2007 developed a one-dimensional simulation model of a cathode-supported planar intermediate temperature solid oxide electrolysis cell (SOEC) and studied the dynamic behaviour of the model. Sigurvinsson et al., 2007 developed a techno-economic optimization model devoted to a high-temperature electrolysis (HTE) process which includes electrolysers as well as a high temperature heat exchanger network. The model uses geothermal energy to recuperate part of heat needed for the high temperature steam electrolysis process. An optimization of the model was performed to ascertain whether the geothermal source will be necessary to integrate with the given network. Jensen et al., 2007 developed a testing cell consisting of a hydrogen electrode supported SOFC (solid oxide fuel cell), it was divided in three layers- Oxygen electrode, hydrogen electrode and support layer. A high current density was observed and it was used to obtain an estimation of the price of hydrogen produced from the SOFC. O'Brien et al., 2009 analyzed a model of SOEC integrated with HTCE which produced syngas on a large-scale (300 MWe) and it was supplied power and heat from a nuclear reactor. A cobalt catalyst -based Fischer tropsch reactor was used to determine the desired operating conditions of the model. It was reported that the model used high pressure (3.5 MPa) and a syngas product H_2: CO ratio of 2.1:1. Steam was generated by the heat obtained from the nuclear reactor process, preheating of the feed gas was also carried out by the same process. Lastly, McKellar et al., 2010 modelled Sabatier process and the bosch process integrated with HTCE systems for space applications in which the primary products were oxygen and either methane or carbon depending upon the process chosen.

Preliminary Conclusion: One of the challenges of the 21st century is to reduce the production of carbon dioxide from fossil fuels. An interesting solution to this challenge is to produce synthetic fuels by the help of SOEC which are CO_2 neutral. A SOEC can be used to convert electricity (obtained from renewable sources), water and CO_2 to Syngas.

2.5 BIOMASS SELECTION

Agriculture is the backbone of Indian economy. The common biomass feedstocks which have very good potential for power generation in India include sugarcane bagasse, rice straw (and rice husk), wheat straw, coconut shell, cotton stalk, spent coffee grounds (SCG) etc. Apart from this, a large scale use of forest residue is also reported as cooking fuel. The country produces 686 MMT (million metric ton) gross residue annually, out of which 234 MMT (34% of gross) are available as surplus [Ravindranath etal., 2005, Hiloidhari et al., 2014]. India accounts for 31% of world's coconut production and is one of the major players in coconut trade globally. It is also world's third largest producer of coconuts, producing 21,665 million nuts in 2014 [Website of Coconut Board, Govt. of India]. The coconut shells generated from oil industry may also be utilized efficiently for energy production. Besides, the bovine population in India including cow, buffalo etc. is one of the largest in the world (about 294 million in 2005) [Rao et al., 2010]. The dung available from cattle and buffalo was estimated to be 730 Mt in 2010. The post-monsoon estimate of coffee production in India in 2016-17 is approximately 316,700 MT [www.indiacoffee.org]. The spent coffee ground (SCG) is nearly 45-50% of the coffee cherry (fruit) [Vega et al., 2015]. The paper manufacturing industry in India is very old and produces about 11 million tons of paper annually and one ton of paper produces approximately 40-50 kg of dry sludge [Deeba et al., 2016]. India is the second largest producer of sugarcane after Brazil. Currently, sugarcane cultivation is carried out in approximately 4 million hectares of land and average yield is seventy tons per hectare [Rao et al., 2010].

India is one of the major leather producing countries in the world. It imports hides (skin of slaughtered animal) from countries which have a large meat production industry, such as the

United States, Australia, and the European countries European Commission report (European Commission report, 2003). According to the data provided by the European Commission (EC), the amount of solid waste generated by tanning industry depends upon the type of leather processed, source of raw hides, and the technology used. About 20 wt% of the raw material gets converted to (grain side) leather (Sarkar, 2015). India is a leading exporter of leather products as well. In 2015, leather footwear costing approximately 1.92 billion USD was exported from India (Marquesa et al., 2017). Kaul et al, 2001, outlined the need of huge quantity of water during tanning process and also discharge of significant quantity of waste-water from these industries. Also, it has been described by some researchers that over 55,000 ha of land have been contaminated by waste generated by tanneries and consequently, around 5 million people have been affected by the degraded quality of environment and drinking water (Project Proposal to ACIAR by CSIRO, 2001 and Sahasranaman et al., 2005).

Pulp and paper industry is one of the topmost pollution generating industries in the world and specifically in India (Sahasranaman et al., 2005; Bajpai, 2015; Ince, 2011; Naidu, 2013; Working Group Report On Pulp & Paper Sector for 12th Five Year Plan, 2011). India produces about 10.11 million tons of paper per annum which is 2.6% of world's overall production of paper (Working Group Report on Pulp & Paper Sector for 12th Five Year Plan, 2011). It may be mentioned that 1 tonne of paper produces about 40 to 50 kg of sludge (dry) (70% primary sludge and 30% secondary sludge) as a by-product in a paper mill (Bajpai, 2015). Currently, much of this sludge is being disposed by the processes such as land filling and land spreading which need significant expenditure. Hence, this process is not economical.

In India, biomass fuels dominate the rural energy consumption patterns, accounting for over 80% of total energy consumed. Fuelwood, crop residues (including plantation crops) and livestock dung are the biomass fuels used in rural areas. Fuelwood is the preferred and most dominant biomass source accounting for 54% of biofuels used in India [Ravindranath et al., 1995]. Scarcity and increasing prices of fuelwood have been altering the biofuel consumption pattern. Biomass fuels are he most favorable renewable energy and CO_2 neutral sources; they can be a preferable choice for the replacement of conventional fossil fuels in the near future. Nowadays, biomass has become a very interesting fuel for electricity generation because its CO_2 emissions reduction potential and its suitability for small and medium scale energy production facilities. The ultimate analysis of all the above discussed biomass materials have been presented in table 2.1.

Table 2.1 The ultimate analysis of selected biomass material(s)

Biomass material		C	H	O	N	S	HHV (MJ/kg)
1	Cow Manure (CM)	58.6	7.7	30.5	2.9	0.3	25.2
2	Sugarcane Bagasse (SB)	44.6	6.2	46.8	1.8	0.5	17.7
3	Spent coffee (SC)	57.2	7.6	33	2.1	0.1	25.4
4	Paper Mill Sludge Cake (PMC)	34.2	4.7	60.5	0.5	0.1	10
5	Paper Residue Sludge (PR)	43.6	5.7	49	1.3	0.2	15.7
6	Leather Waste (LW)	52.1	9.0	23.4	13.1	0.9	25.5
7	Wood (W)	42.8	6.2	50.4	0.1	0.4	18.2
8	Rice Husk (RH)	34.4	5.2	57.7	2.4	0.3	12.2

9	Wheat straw (WS)	39.4	5.2	54.9	0.5	0	19
10	Coconut Shell (COCO)	50.2	5.4	43.4	0.94	0.06	21

2.6 KEY OBJECTIVES

Based on this literature review, there have not yet been a combined system which would yield hydrogen/ syngas along with simultaneous maximization of the Performance Index for different types of biomass materials. Despite the vast amount of information in the literature on waste heat based CCHP systems, the integration of syngas production with CCHP systems has not yet been reported.

Based on this review, it was decided to fulfil following key objectives in this thesis:

a) Development of a model to examine the key technical issues for biomass powered cogeneration integrated with an Organic Rankine Cycle (ORC) and to establish the correct operating conditions suiting the environment.

b) Development of a model to utilize the advantages of the CHP and Ejector Refrigeration cycle (ERC) along with the production of eco-friendly syngas which uses biomass as a fuel source.

c) Determination of optimum design parameters for maximum syngas /hydrogen production and hydrogen economy.

d) Different types of biomass available under Indian condition would be compared and suitable one would be chosen based on performance in regard to heat, cooling and power generation as well as syngas production.

e) Determination of the optimum gasification temperature for the given biomass so as to obtain maximum Refrigeration Effect.

f) Integration of a Concentrated Solar Thermal Assisted Biomass Gasification System

g) Conjunction of Solar ORC with SOEC System.