CHAPTER 1

CHAPTER 1

INTRODUCTION

Society, in all its aspects – social, economic, cultural and political, is experiencing a rapid change. To keep up with this change, the needs of the society are also changing. Central to supplementing the needs of a society along with ensuring a satisfactory quality of life and promoting economic development is the access to energy services. A precondition for ensuring sustainable development is the adequate and reliable supply of energy services viz. heat, light and motive power [1]. Issues relating to sustainable development such as energy security, climate change, food production, and strengthening economies while protecting ecosystems is dependent on the access to energy [2]. The International Energy Agency defines energy access as "*reliable and affordable access to both clean cooking facilities and to electricity, which is enough to supply a basic bundle of energy services initially, and then an increasing level of electricity over time to reach the regional average*" [3]. This implies that access to electricity is an important aspect in improvement of services relating to education, health, comfort, protection, productivity, and entertainment. Electrification rate is used as an indicator of the development level of a region. Conversely, electricity access may be used as a good proxy for other indicators of wealth and opportunity in a region.

The access to electricity is not uniform across the regions of the world as evident from Fig. 1.1. It is estimated that around one billion people (13% of the total population) worldwide do not have access to electricity in their homes [4]. Approximately 95% of these people are located in Africa and Asia [3]. It is also noteworthy that most of the people who do not have access to electricity belong to the rural areas which is evident from the fact that about 84% of people without access to electricity live in rural areas [3]. Fig. 1.2 shows the percentage of population with access to electricity in different regions of the world during 2000, 2005, 2010 and 2017. It may be observed that there has been considerable efforts to increase the level of access to electricity in all parts of the world. The essence of this increase is embedded in the Sustainable Development Goal (SDG) 7.1 – "*Ensuring universal access to affordable, reliable, sustainable and modern energy by 2030*" adopted by 193 countries in 2015 at the United Nations Sustainable Development Summit under the United Nations Development Programme (UNDP).

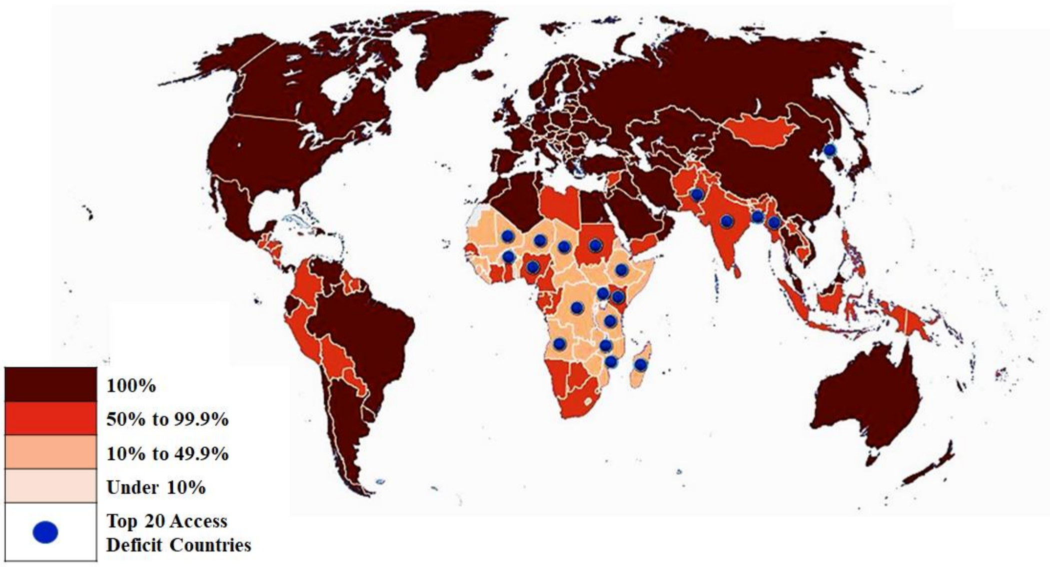

Fig. 1.1 Share of population with access to electricity in 2017 (%)
{Source: World Bank [5]**}**

Normally, electricity access is provided through extension of the centralized electricity grid. Grid electricity is generated through large power plants (e.g. coal, natural gas, hydro), and also from distributed generation such as solar photovoltaic (SPV), wind farms or biogas units. Expansion of access to electricity involves extension of the existing electricity supply infrastructure to the unserved areas. Extension of grid requires addition to power generation capacity to meet the added demands in order to ensure reliability. Along with this, installation of new transmission and distribution (T&D) lines and additional infrastructure such as feeders and transformers are also required. Cost effective investment in developing T&D depends upon the quantum of electricity demand. Electricity demand depends upon the commercial, industrial, farming, household and other ancillary activities of the population. In general, grid extension appears cost effective for a complementary demand-supply scenario. In spite of the advantage in terms of cost in some cases grid extension is not feasible due to complex terrain and regulatory and institutional hurdles [3]. While 97% of the world's urban population is connected to electricity, only 79% of the rural population has access to electricity [3]. Provisioning of electricity access in rural areas faces issues in terms of higher cost of grid extension, inadequate generation capacity, transmission infrastructure issues and cost to consumers [6]. In this regard decentralized electricity generation is a potential option.

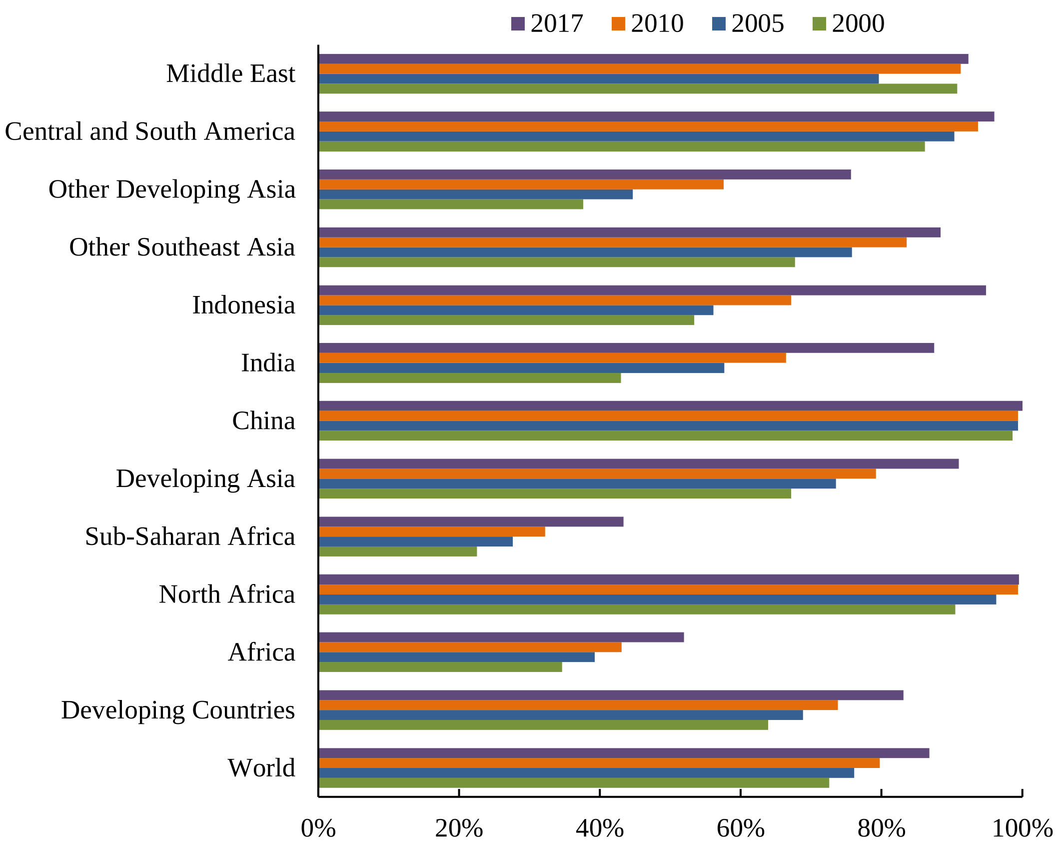

Fig. 1.2 Percentage of population with access to electricity in different regions of the world {Source: Author's own representation based on data of IEA [3] }

1.1 Need of decentralized electricity generation

Decentralized electricity generation involves development of an electricity generating system and distribution of the generated electricity within a specific region. There is also possibility of integrating the systems to the grid but in most cases these systems are completely off-grid. Decentralized electricity generation (DEG) is in fact considered as an important option to meet the SDG 7.1. It is observed that DEG units are generally small scale energy generating units [7]. DEG has been an element of the electricity generation mix of most regions for a long time [8]. The added advantages associated with decentralized systems is in providing socio-economic benefits to the region. Unlike centralized system, decentralized system allows for participation of the local people along different segments of the value chain. Engaging local population at all stages of the project development has been evidenced to improve sustainability and maximise benefits [9]. This is achieved by promoting local ownership which helps in establishing links with end users and promotes income-generating activities for the local people.

In recent times there has been a notable increase in the contributions of DEG. For example, in Germany, DEG accounted for roughly 30% of the total electricity generation capacity in 2016, up from 24% in 2011 [10]. In the US, in 2016, 3.4 GW of SPV based DEG was added resulting in doubling of the capacity of SPV between 2014 and 2017 [11]. During 2014 to 2017 in New Zealand, the number of DEG connection points at residential, commercial and industrial sites saw an increase from just over 4,000 to more than 15,000 [12]. Renewable energy based DEG is a prime contributor to the total installed DEG worldwide. This is evident from the fact that there was a six-fold increase in the number of people benefitting from renewable based DEG between 2011 and 2016 worldwide [13]. Alongside, off-grid renewables capacity increased three-fold from under 3 GW in 2008 to over 6.5 GW in 2017 (Fig. 1.3) [13].

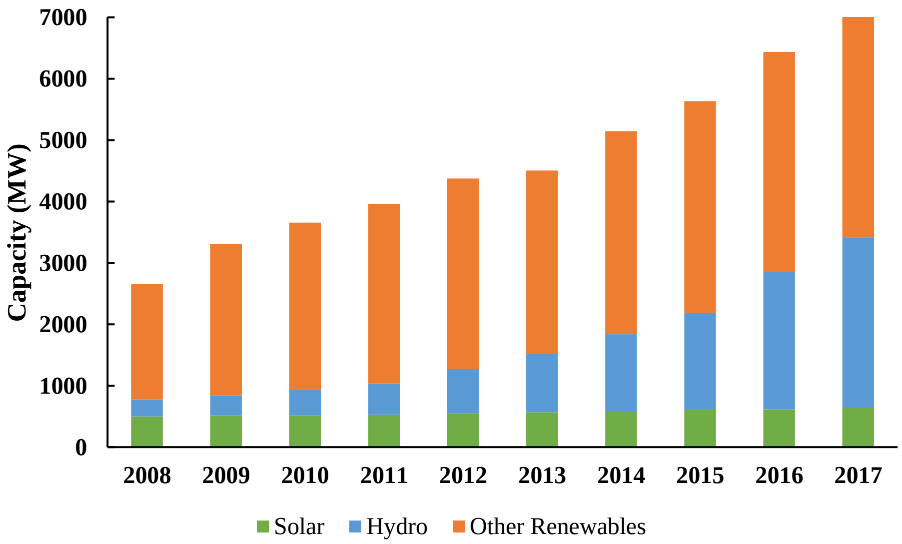

Fig. 1.3 Global off-grid renewable capacity 2008-2017
{Source: Author's own representation based on data of IRENA [13]**}**

DEG has adaptability in providing electricity access to different end users. This is evident from the fact that a fraction of the deployed DEG supports household electrification while a majority of it (83%) is used in industry, commercial and public services [14]. Improvement in efficiency accompanied with reduction in cost of technology are the main drivers of the increasing pace and extent of DEG growth in recent years. However, it is evidenced that efficient electricity production is dependent upon the capacity factor of the system. In recent times, considerable efforts are being made to develop a smart grid that detects and reacts to local changes in the demand [15]. Smart grid is based on the concept of generating reliable security of supply and ensuring quality of electric energy [16]. Integration of a smart grid infrastructure coupled with communication technology like Internet of Things (IoT) with the DEG system has the potential to provide a sustainable and environmentally benign electricity generation and utilization option.

Traditionally, DEG units are powered by fossil fuels, such as diesel generators. However, fossil fuel based electricity generation emits greenhouse gases (GHG) that highly effect the environment. In fact, among all energy sources, emissions from fossil fuel (coal, gas, and oil) is the highest as indicated in Table 1.1.

Table 1.1 Emission factors of fossil fuels for electricity generation [17]

Fuel	**Emission factor (kg/kWh)**		
	CO_2	**SO_2**	**NO_x**
Coal	1.1800	0.0190	0.0052
Petroleum	0.8500	0.0164	0.0025
Natural Gas	0.5300	0.0005	0.0009

In order to put a check on the GHG emissions the Paris Agreement was signed in 2016 by members of the United Nations Framework Convention on Climate Change (UNFCCC). The goal of the Agreement is to keep the increase in global average temperature below 2°C above pre-industrial levels and to limit the increase to 1.5°C, as this would considerably reduce climate change. Nationally determined contributions (NDCs) are central of the Paris Agreement and the achievement of these long-term goals [18]. NDCs are basically plans that each country adopts to reduce their national emissions and adjust to the impacts of climate change. Almost every country that has submitted their intended nationally determined contributions (INDCs) lays emphasis on increasing the share of electric power installed capacity from non-fossil fuel based energy resources. It is evident that renewable based electricity generation are driven by climate change mitigation strategies. Thus, the share of renewable energy based electricity generation is expected to flourish in the future. It is noteworthy that renewable energy based DEG, especially in rural areas far from the centralized grid, offer important and often cost effective options [19].

1.2 Renewable energy based electricity generation

Renewable energy sources offer viable option to address the energy security and climate change concerns of a region. Renewable energy sources, unlike fossil fuels, are not depleted over time. Renewable sources of electricity generation have a significant share in the global power generation mix as is evident from Table 1.2.

Table 1.2 Share of renewables in global electricity generation (TWh) during 2012-2017

Technology	2012	2013	2014	2015	2016	2017
Renewable hydropower	3437.37	3493.09	3682.59	3787.36	3903.81	3897.26
Marine	0.51	0.56	0.96	0.92	1.00	1.01
Onshore wind	335.45	422.09	511.12	616.00	687.37	792.04
Offshore wind	6.64	10.39	13.37	19.11	24.66	36.21
Solar photovoltaic	32.16	62.44	96.35	131.70	183.94	242.37
Concentrated solar power	1.66	3.06	5.03	6.22	9.04	10.26
Renewable municipal waste	39.66	40.71	41.01	43.66	46.47	49.89
Bagasse	33.21	32.96	37.50	42.89	46.91	49.37
Other solid biofuels	192.72	209.88	228.56	243.03	264.51	275.39
Liquid biofuels	5.30	3.65	3.97	4.60	5.20	5.88
Biogas	46.13	53.82	64.58	73.64	80.06	84.63
Geothermal	68.45	69.74	70.72	72.13	77.16	81.05

Source: IRENA [13]

Fig. 1.4 shows the renewable energy output as percentage of the total electricity output of different regions of the world. Climate policies of countries along with significant lowering of development cost has led to the gain in momentum of renewable energy based energy generation. In 2017, solar and wind were the highest contributors to the additional power generation accounting for 20% and 30% respectively. In fact, share of renewables in the power mix is nearly 1/3rd in Europe, 1/4th in China and 1/6th in the United States, India and Japan [20].

Deployment of renewable energy technologies are believed to contribute significantly to energy independence of the region along with associated economic and environmental benefits. However, for DEG, deployment of certain renewable energy technologies has some limitations. Intermittency of sunshine related to time of the day and climatic conditions coupled with additional storage requirements are some issues related to the sustainable deployment of SPV based DEG systems. Specific topographical requirements for hydro and wind based DEG hinders their applicability. In this regard, biomass has come up as a major source of alternative energy having widespread availability and comparatively lower environmental impact.

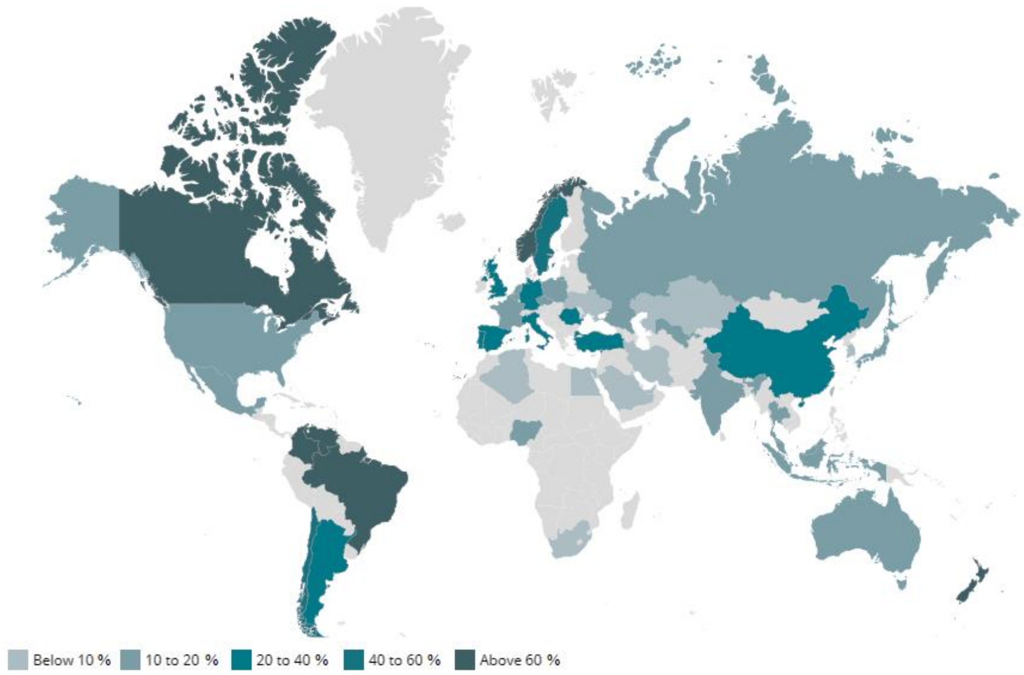

Fig. 1.4 Share of renewable in total electricity output in 2017 (%) {Source: World Bank [5]**}**

1.3 Biomass based electricity generation

Electricity from biomass is the 3rd largest renewable electricity source globally after hydropower and wind. In 2017, 495 TWh of biomass based electricity was generated globally of which 70% was from solid biomass sources like wood chips, wood pellets and bagasse, 11% from municipal and industrial waste followed by 18% from biogas [13]. Fig. 1.5 depicts the increase in the biomass based electricity generation from different sources during 2000-2017. Biomass is widely available worldwide and represents a growing renewable energy source with high growth potential [21]. However, there is inherent heterogeneity in the composition and thermo-chemical properties of different biomass which are distributed over large geographical areas. There also exists spatial and temporal variability in the availability of biomass. In such cases, remote sensing and geographical information system (GIS) tools are helpful in not only assessing the biomass resource availability but also in the decision making processes concerning its utilization. These tools have been used for biomass resource assessment, land use land cover assessment, biomass resources assessment, biomass based power plant design and biomass transportation cost assessment [22]–[29]. Bulkiness and inconvenient form of biomass also hinders its convenient utilization. Also, most forms of biomass have low energy density in comparison to fossil fuel. For example, energy content of air dried woody biomass is around 12-15 GJ/t whereas for sub-bituminous coal it is around 20-25 GJ/t (low heat values) [30]. Handling, storage and transportation of biomass in its raw form thus becomes more costly in comparison to conventional fuels. Thus, to fruitfully utilise biomass, it becomes necessary to improve its properties which elevate its handling, storage and transportation ability. One such method is to convert solid biomass into liquid or gaseous fuels. This can be achieved via either one of the two ways viz. biochemical and thermochemical conversion. Within the thermochemical route, biomass gasification is a major technology that is being extensively used due to its capability of handling wide range of biomass feedstock. Biomass gasification involves the partial oxidation of solid biomass, in presence of heat, into gaseous or liquid fuels.

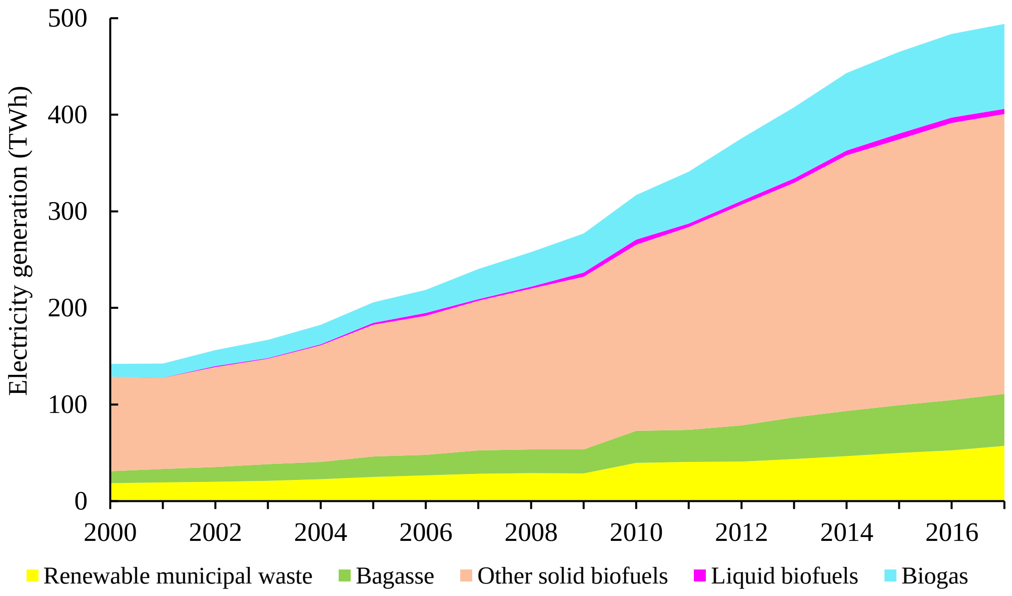

Fig. 1.5 Year wise biomass based electricity generation from different sources worldwide {Source: Author's own representation based on data of IRENA [13]**}**

1.3.1 Biomass gasification

Biomass gasification is a complex thermal process. The process involves a complex interaction of various chemical reactions, mass transfer processes, heat transfer processes along with changes in pressure. An understanding of the various processes and parameters effecting the gasification process is needed to help in gaining an insight into the operation of the gasifier. In the biomass gasification process, the biomass feedstock is converted into useful gaseous fuel (producer gas) that may be utilised for thermal energy generation by direct burning or used for electrical energy generation by using in an electricity generating unit. The gasification process involves a partial thermal oxidation of the feedstock resulting in a gaseous fuel, referred to as producer gas, having higher hydrogen-to-carbon ratio. The overall gasification process involves four steps viz. drying, pyrolysis, reduction (char gasification) and oxidation (combustion).

In the drying stage, the moisture content of the biomass (usually in the range of 5-35%) is reduced. This occurs at about 100 - 200°C resulting in a reduction of the moisture content of the biomass below 5%. The pyrolysis stage involves the decomposition of the biomass in the absence of oxygen or air. During this process, there is reduction in the volatile matter which results in the release of hydrocarbon gases. It is observed that biomass feed stocks tend to have more volatile components (70-86% on a dry basis) than coal (around 30%) [31]. Thus, pyrolysis plays a larger role in biomass gasification than in coal gasification. Pyrolysis also results in the production of tar (a black, viscous and corrosive liquid composed of heavy organic and inorganic molecules) and char (a solid residue mainly containing carbon) [32]. The oxygen supplied to the gasifier reacts with the combustible substances present, resulting in the formation of CO_2 and H_2O, which subsequently undergo reduction upon contact with the char produced from pyrolysis [33]. There is one more combustion reaction occurring inside the gasifier which is the oxidation of hydrogen in the fuel resulting in the production of steam. The reduction reactions occurring inside the gasifier are endothermic in nature and the energy needed for these reactions is practically provided by the oxidation or combustion of char. Reduction yields combustible gases such as hydrogen, carbon monoxide, and methane through a series of reactions, the four major reactions being (a) Water–gas reaction, (b) Boudouard reaction, (c) Shift conversion and (d) Methanation [33]. It is seen that the output gas of the gasification process depends upon the properties of the char that is produced in the pyrolysis step. In general, the reactivity of the char determines the rate of the reduction reaction and thus determines the residence time of the gasification process [34]. Gasification reactivity of chars depends upon many factors, such as pyrolysis temperature, heating rate, inorganic constituents and pyrolysis pressure [35].

Gasifiers are categorised as (a) fixed bed (also known as moving bed), (b) fluidised bed and (c) entrained flow gasifiers depending upon how the gas and fuel contact each other [35]. Depending upon the pressure used the reactors are classified as atmospheric or pressurised reactor. Also, if the reactors are heated by an external source then they are known as allothermal or indirectly heated reactors and if the heat is provided by the partial combustion of feedstock they are known as auto-thermal or directly heated reactors [36].

Biomass gasification based DEG involves utilization of the producer gas in an electricity generating unit. The small-scale generation through biomass gasification associated to an internal combustion engine (ICE) has been shown to be relatively cheaper in comparison to other similar technologies like biomass boiler-steam engine or steam turbine, bio-methanation followed by use in ICE and external combustion engine [37]. It is, however, observed that producer gas as an ICE fuel has a poorer quality in comparison to other commonly used fuels such as gasoline, natural gas or diesel [38]. Also, utilisation of producer gas in ICE requires minimum tar and particulate concentration [39]. Downdraft gasifier systems have been evidenced to provide allowable quality of producer gas for utilization in ICEs [39]. Other added advantages of high char conversion, lower ash and tar carry over, quick response to load change and simple construction makes downdraft gasifiers one of the most widely used type of gasifiers for small scale application [38].

Performance vis-à-vis end-gas composition of a biomass based gasification process is dependent upon the feedstock characteristics, the reactor design and the operating parameters [40]. Biomass characteristics that have been found to have major influence on the gasification process are moisture content, volatile matter, ash content, char, thermal conductivity, organic constituents and inorganic constituents [40]. Mathematical models become a useful tool in representing the real life situation viz. the gasification process, in pertinence to our discussion, with the help of mathematical equations. This representation of the gasification process in mathematical terms helps in gaining an insight about the significance of the operating parameters affecting the gasifier performance. Various studies have been carried out to model the gasification process in order to predict the performance of a biomass gasifier for a given feedstock. The gasification models developed are utilised to study the thermochemical processes occurring during the gasification of the feedstock and to evaluate the influence of the operating parameters, such as moisture content, air/fuel ratio, producer-gas composition and the calorific value of the producer gas. Various models for predicting the gasifier performance have been developed. Mathematical modelling of gasification process can be categorised into (i) thermodynamic equilibrium, (ii) kinetic (iii) artificial neural network (ANN) and (iv) computational fluid dynamics (CFD) routes. The different modelling techniques have their own level of robustness and present their own level of complexity. Choice of a particular modelling technique depends upon the expected outcome.

Apart from the biomass characteristics and performance of gasification systems utilizing them, the economics of electricity generation is a major parameter influencing the viability of biomass gasification based electricity generation. There are reported studies which aim at estimating the economics of biomass gasification based electricity generation [41]–[49]. The general practice is to determine the levelised cost of electricity (LCOE). LCOE represents the unit of electricity generation that is required to recover the costs of setting up and operating an electricity generating system during an assumed financial life and duty cycle [50]. LCOE helps is comparison of the cost of biomass gasification based electricity generation with other electricity generation pathways. LCOE determination involves capital, fuel, fixed and variable operations and maintenance, and distribution costs. The importance of each of these costs varies with the uncertainties associated with them. Thus, accurate estimation of these costs is essential in arriving at an acceptable LCOE.

Research has been done in respect of feedstock characterization, feedstock assessment, gasification performance and economic analysis of gasification based electricity generation systems. Gasification technology has been perfected at the research and development level. Still, biomass gasification based DEG has experienced a lower level of success in comparison to SPV and Wind based systems. Lower success of biomass gasification based DEG appears to be linked to the planning of the system that may have overlooked the uncertainties associated with different aspects. It may be pointed out that in comparison to other DEG systems like SPV, small hydro and wind turbine the uncertainties in biomass gasification based electricity generation is multifaceted. Some important factors are 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. Viability of the system is dependent on the interrelations between these factors which have complex interactions. Considering the uncertainties associated with a biomass gasification based energy generation system, the complex interrelation of different aspects associated with the system is an unexplored area of research. A platform amalgamating the uncertainties at different levels of the biomass gasification based DEG system with an ability to interlink them is required. Such a platform 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. Decision Support System (DSS) is one such tool that helps in organizing information, inter-linking different aspects of the information and providing the end user an interface to analyse different scenarios based on the choices made regarding the aspects. There are three basic elements of a DSS. Firstly, modules of different aspects of the system capable of manipulating the data and information based on their relationships. Secondly, a database of appropriate and relevant information which can be linked to the modules and thirdly, a user interface where the user can analyse different scenarios involving the variations in the different aspects. DSS has found applicability in fields including, but not limited to, evaluating engineering projects, medical diagnosis, agricultural production planning, forest management, business management and verification of credit loan. A DSS for biomass gasification based DEG is desired that allows the user to analyse different scenarios involving variations in the feedstock, feedstock handling and processing requirement, gasifier capacity, gasifier performance, energy demand, electricity generation unit and electricity distribution network. This would in turn allow the user to take educated decisions regarding the efficient planning of the system.

1.4 Objectives of the research

Keeping in view the above discussion, the present study has been conceived to develop a decision support system for biomass gasification as decentralized energy generating source with the following objectives.

I. To investigate biomass feedstock supply chain
II. To investigate gasifier performance under a range of biomass feedstock variability for DSS
III. To investigate the scope of biomass gasification based DEG using the DSS.

1.5 Organisation of the thesis

The text of the thesis is organised as below.

Chapter 1: Introduction

In this current Chapter, the utility of decentralized electricity generation systems is elaborated upon. The usefulness of biomass based electricity generation is discussed with special emphasis on biomass gasification. The usefulness of mathematical modelling of gasification systems in this regard is also discussed. Importance of economic analysis of biomass gasification based electricity generation is also elaborated.

Having emphasized the importance of biomass based energy generation especially through gasification, the need for a tool to empower the users to take decisions regarding a gasification based DEG is established.

The rationale of the present work is discussed in line with the above and the objectives of the present study is laid down.

Chapter 2: Review of literature

With an aim to identify appropriate techniques for forming the framework of the Decision Support System a literature review on decision support systems for bioenergy application and modelling techniques used to study biomass gasification based electricity generation systems is discussed in the Chapter.

Chapter 3: Assessment of biomass supply chain for gasifier operation

This Chapter discusses the biomass related parameters in the entire supply chain for gasification based electricity generation system. The procedures followed for determination of biomass properties is also presented. Characterization of some locally available biomass feedstock is also presented.

Chapter 4: Assessment of biomass gasifier operating performance

This Chapter discusses the development of gasification performance models based on a two stage approach involving Artificial Neural Networking (ANN) and Kinetic modelling. The validation of the models and applicability in complementing the DSS is also presented.

Chapter 5: Decision Support System for biomass gasification based electricity generation

This Chapter presents the development of a DSS for biomass gasification based decentralised electricity generation. Applicability of the DSS is tested for a representative rural area and the results are presented.

Chapter 6: Summary and Conclusions

This Chapter presents a general summary of overall findings and conclusions including scope for further research that have emerged from this study.

The thesis ends with Appendix and List of publications.

REFERENCES

[1] Overcoming barriers : Human mobility and development. Human Development Report - 2009, United Nations Development Program, 2009.

[2] Energy Education - Access to electricity. Retrieved on 19 Jun. 2019 from https://energyeducation.ca/encyclopedia/Access_to_electricity#cite_ref-1

[3] World Energy Outlook:2017, International Energy Agency, 2017.

[4] Understanding Poverty. Retrieved on 19 Jun. 2019 from https://www.worldbank.org/en/topic/poverty/overview

[5] World Bank Group, Energy Sector Management Assistance Program, Climate Investment Fund, and Sustainable Energy for All Regulatory indicators for Sustainable Energy: A Global Scorecard for Policy Makers. International Bank for Reconstruction and Development / The World Bank, 2016.

[6] Rawn, B., Louie, H. Planning for Electrification: On- and Off-Grid Considerations in Sub-Saharan Africa. *IDS Bulletin*, 48 (5-6): 9-28, 2017.

[7] Vezzoli, C., Ceschin, F., Osanjo, L., M'Rithaa, M. K., Moalosi, R., Nakazibwe, V., Diehl, J. C. Distributed/Decentralised renewable energy systems. *In Green Energy and Technology*; pages 23-39. Springer-Cham, 2018.

[8] Alstone, P., Gershenson, D., Kammen, D. M. Decentralized energy systems for clean electricity access. *Nature Climate Change*, 5(4):305-314, 2015.

[9] Haggett, C., Aitken, M. Grassroots Energy Innovations: the Role of Community Ownership and Investment. *Current Sustainable/Renewable Energy Reports*, 2(3):98-104, 2015.

[10] World Energy Scenarios: 2016. World Energy Council, 2016.

[11] Electric Power Monthly with Data for June 2017. US Energy Administration, 2017.

[12] Suomalainen, K., Sharp, B. Electricity sector transformation in New Zealand: A sustainability assessment approach. *Journal of Renewable and Sustainable Energy*, 8(3):035902, 2016.

[13] Renewable Energy Statistics 2017. IRENA, 2017.

[14] Off-grid renewable energy solutions to expand electricity access : An opportunity not to be missed. IRENA, 2019.

[15] Lund, H., Østergaard, P.A., Connolly, D., Mathiesen, B.V. Smart energy and smart energy systems. *Energy*, 137:556-565, 2017.

[16] Islam, M.A., Hasanuzzaman, M., Rahim, N.A., Nahar, A., Hosenuzzaman, M. Global renewable energy-based electricity generation and smart grid system for energy security. *Scientific World Journal*, 2014:197136, 2014.

[17] Mahlia, T. M. I., Yanti, P. A. A. Cost efficiency analysis and emission reduction by implementation of energy efficiency standards for electric motors. *Journal of Cleaner Production*, 18(4):365-374, 2010.

[18] Aggregate effect of the intended nationally determined contributions: an update. UNFCCC, 2016

[19] Renewables 2017 Global Status Report. REN21 Secretariat, Paris, 2017.

[20] Global Energy Statistical Yearbook 2018. Retrieved on 21 Jun. 2019 from `https://yearbook.enerdata.net/`

[21] Li, Y., Rezgui, Y., Zhu, H. District heating and cooling optimization and enhancement – Towards integration of renewables, storage and smart grid. *Renewable and Sustainable Energy Reviews*, 72:281-294, 2017.

[22] Brahma, A., Saikia, K., Hiloidhari, M., Baruah, D. C. GIS based planning of a biomethanation power plant in Assam, India. *Renewable and Sustainable Energy Reviews*, 62:596–608, 2016

[23] Guerrero, A. B., Aguado, P. L., Sánchez, J., Curt, M. D. GIS-Based Assessment of Banana Residual Biomass Potential for Ethanol Production and Power Generation: A Case Study. *Waste and Biomass Valorization,* 7:405–415, 2016.

[24] Guilhermino, A., Lourinho, G., Brito, P., Almeida, N. Assessment of the Use of Forest Biomass Residues for Bioenergy in Alto Alentejo, Portugal: Logistics, Economic and Financial Perspectives. *Waste and Biomass Valorization*, 9:739–753, 2018.

[25] Haase, M., Rösch, C., Ketzer, D. GIS-based assessment of sustainable crop residue potentials in European regions. *Biomass and Bioenergy*, 86:156–171, 2016.

[26] Ketzer, D., Rösch, C., Haase, M. Assessment of sustainable Grassland biomass potentials for energy supply in Northwest Europe. *Biomass and Bioenergy*, 100:39–51, 2017.

[27] Hiloidhari, M., Baruah, D., Mahilary, H., Baruah, D. C. GIS based assessment of rice (Oryza sativa) straw biomass as an alternative fuel for tea (Camellia sinensis L.) drying in Sonitpur district of Assam, India. *Biomass and Bioenergy*, 44:160-167, 2012.

[28] Saha, M., Eckelman, M. J. Geospatial assessment of regional scale bioenergy production potential on marginal and degraded land. *Resources, Conservation and Recycling*,128:90–97, 2018.

[29] Zubaryeva, A., Zaccarelli, N., Giudice, C. Del, Zurlini, G. Spatially explicit assessment of local biomass availability for distributed biogas production via anaerobic co-digestion - Mediterranean case study. *Renewable Energy*, 39:261–270, 2012.

[30] Singh, B. P. Biofuel crops: production, physiology and genetics. CABI, Boston, USA, 2013.

[31] Kivisaari, T., Björnbom, P., Sylwan, C., Jacquinot, B., Jansen, D., Groot, A. de. The feasibility of a coal gasifier combined with a high-temperature fuel cell. *Chemical Engineering Journal*, 100:167–180, 2004.

[32] Boerrigter, H., Rauch, R. Syngas production and utilisation. In Handbook Biomass Gasification, Biomass Technology Group, Netherlands, 2005.

[33] Duman, G., Uddin, M. A., and Yanik, J. The effect of char properties on gasification reactivity. *Fuel Processing Technology*, 118:75–81, 2014.

[34] Warnatz, J., Maas, U., Dibble, R. W. *Combustion: Physical and chemical fundamentals, modeling and simulation, experiments, pollutant formation*. Springer-Verlag, 2006.

[35] Basu, P. *Combustion and Gasification in Fluidized Beds*. Taylor and Francis Group/CRC Press, USA, 2006.

[36] Basu, P. *Biomass Gasification and Pyrolysis*. Elsevier, UK, 2010.

[37] Buragohain, B., Mahanta, P., Moholkar, V.S. Biomass gasification for decentralized power generation: The Indian perspective. *Renewable and Sustainable Energy Reviews*, 14(1):73-92, 2010.

[38] Martínez, J. D., Mahkamov, K., Andrade, R. V., Silva Lora, E. E. Syngas production in downdraft biomass gasifiers and its application using internal combustion engines. *Renewable* Energy, 38:1–9, 2012.

[39] Chaves, L.I., Silva, M.J. Da, Souza, S.N.M. De, Secco, D., Rosa, H.A., Nogueira, C.E.C., Frigo, E.P. Small-scale power generation analysis: Downdraft gasifier coupled to engine generator set. *Renewable and Sustainable Energy Reviews*, 58:491-498, 2016.

[40] Sharma, A. K. Experimental investigations on a 20 kWe, solid biomass gasification system. *Biomass and Bioenergy*, 35:421–428, 2011.

[41] Mahapatra, S., Dasappa, S. Rural electrification: Optimising the choice between decentralised renewable energy sources and grid extension. *Energy for Sustainable Development*, 16(2):146-154, 2012.

[42] Nouni, M. R., Mullick, S. C., Kandpal, T. C. Biomass gasifier projects for decentralized power supply in India: A financial evaluation. *Energy Policy*, 35(2):1373-1385, 2007.

[43] Larson, E. Small-Scale Gasification-Based Biomass Power Generation. Retrieved on 23 Jun. 2019 from http://pssurvival.com/ps/Gasifiers/SmallScale_Gasification-Based_Biomass_Power_Generation_1998.pdf

[44] Voets, T., Kuppens, T., Cornelissen, T., Thewys, T. Economics of electricity and heat production by gasification or flash pyrolysis of short rotation coppice in Flanders (Belgium). *Biomass and Bioenergy*, 35(5):1912-1924, 2011.

[45] Singh, J. Management of the agricultural biomass on decentralized basis for producing sustainable power in India. *Journal of Cleaner Production*, 142:3985-4000, 2017.

[46] Paisley, M. A., Anson, D. Biomass Gasification for Gas Turbine-Based Power Generation. *Journal of Engineering for Gas Turbines and Power*, 120(2):284-288, 1998.

[47] Foust, T. D., Aden, A., Dutta, A., Phillips, S. An economic and environmental comparison of a biochemical and a thermochemical lignocellulosic ethanol conversion processes. *Cellulose*, 16(4):547-565, 2009.

[48] Dasappa, S. Potential of biomass energy for electricity generation in sub-Saharan Africa. *Energy for Sustainable Development*, 15(3):203-213, 2011.

[49] Mitchell, C. P., Bridgwater, A. V., Stevens, D. J., Toft, A. J., Watters, M. P. Technoeconomic assessment of biomass to energy. *Biomass and Bioenergy*, 9(1-5):205-226, 1995.

[50] Levelized Cost and Levelized Avoided Cost of New Generation Resources. Annual Energy Outlook: 2019, EIA, 2019.