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Biogas as a Potential Renewable Energy Source A Case of Bhutan

BACHELOR'S THESIS

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Declaration

I hereby declare that I have done this thesis entitled Biogas as a Potential Renewable Energy Source – a Case of Bhutan independently, all texts in this thesis are original, and all the sources have been quoted and acknowledged by means of complete references and according to Citation rules of the FTA.

In Všenory 14th of April 2021

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Nikola Kadeřábková

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Abstract

Bhutan's development, as of any developing country, is besides other determinants dependent on the stability of energetic security. The country is rich in renewable sources of energy, however, strongly depends on the import of fossil fuels from abroad like petroleum products and coal and its derivatives. Further analyses of the potential of renewable energies could drive the shift from non-renewable to renewable sources of energy to reach energy security based on clean energy. These sources are not yet fully explored and therefore utilized in Bhutan. This thesis entitled "Biogas as a Potential Renewable Energy Source – A Case of Bhutan" was written as a literature review that examined the information concerning the energetic situation in Bhutan and particularly the biogas utilization and its feasibility in local conditions. Further mapping of the energy sources in Bhutan and specifically of solar, wind and biogas plants showed that there is a potential for expansion in domestic usage as well as for the export of energies. A closer focus on biogas plants revealed solid implementation capacity in the residential sector where the usage serves as a substitution mainly to fuelwood and liquified petroleum gas. The resources used for the literature review were mostly based on reports from Bhutan state's administration and associated international organizations as well as on information from scientific articles published by various scientific web databases. It revealed a gap in the insufficient research into the potential in the usage of renewable energy sources, including the predominantly examined biogas technology.

Keywords: energy consumption; fuel sources; domestic energy; biogas technology; waste management

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List of the abbreviations used in the thesis

BBP – Bhutan Biogas Project

BGP – biogas plant

CH4 - methane

CO2 – carbon dioxide

FYP – a five-year plan

GDP – gross domestic product

GGC – Gobar Gas Company

GW - gigawatt

GWh – gigawatt-hour

HP – hydropower plant

kg - kilogram

kW – kilowatt

kWh – kilowatt-hour

kWp – kilowatt-peak

LDC – Least Developed Country

LPG – liquified petroleum gas

M3 – cubic meter

MASL – meters above sea level

MT – metric tons

MTOE – megatonnes of oil equivalent

MU – million units

MVA – megavolt ampere = MW – megawatt

NU – Bhutanese Ngultrum

PRISMA - Preferred Reporting Items for Systematic Reviews and Meta-Analyses

PV - photovoltaics

TOE – a tonne of oil equivalent

US $ - United States dollar

WB – World Bank

yr - year

1. Introduction

This Bachelor Thesis was focused on the energetic situation in Bhutan, a country located in the central Himalayas, and especially on diversification of the fuel mix used by the country by renewable sources, particularly by biogas technology. Countries landlocking Bhutan, China and India, are well known for ranking among one of the major carbon dioxide (CO_2) producing countries worldwide. Bhutan is the very opposite of these two countries due to the fact, that the country is not only carbon-neutral but is also a sink of carbon emission from the neighbouring countries. At the same time, the country is listed among the Least Developed Countries. Energetic security goes in hand with sustainable development while Bhutan's energetic security is dependent almost solely on hydropower sources which bring high revenues, on the other hand, these revenues are reduced by the import of non-renewable energy sources that are still widely used across all sectors. It shows how intricate the situation is. It is an example worth following, there is a 100% electrification via renewable energy, and the country's long-time perspective is to maintain 70% forestation of the total land, nevertheless, the country struggles with ensuring the security of other basic human needs – food security, good health, clean water and sanitation, modern infrastructure, and other social services.

As already mentioned, the country's energy security is dependent on a single source of electricity to the grid – the hydropower. Its position on the south foot of the Himalayas provides the country with the richness in water resources originating in the mountain peaks, plus the monsoons bring an additional amount of water to the water cycle. Notwithstanding, the security is threatened by the changing climate and possible future shortages in the water supply. That is the biggest reason for the diversification of the energy supply mix by other renewable sources. The country has already installed PV stations, grid-connected as well as off-grid connected, and shows a good wind energy generation potential. On top of that, there have been programs on biogas technology promotion and implementation, however, the programs as far as the literature tells are not of sufficient scale and use as it is for example in Nepal, a country very similar to Bhutan.

To conclude, Bhutan is at the breaking point where the future prosperity of the country is determined by the solutions made at present. If the country wants to stay an example of sustainable management of natural resources whilst continuing its overall development, the usage of biogas technology can be one of many solutions to take. It would further diversify the energy mix, as well as it has the potential to improve sanitation and indoor health conditions, and it provides a by-product slurry that sustains the use of natural fertilizers to synthetic ones. It is worth noting that the technology has started its implementations, but further expansion to larger-scale biogas project might ensure future usage by other sectors than the private one (farmers and households alone).

The Thesis analyses sources mainly from Bhutan's national administration and international organizations involved in energy sector development and biogas project implementation and funding. It uses assessment reports as well as final reports and statistics published periodically. That refers to Household Living Standard Surveys, Livestock Statistics, and datasets published by the national organization administering the energy sector. The main part of the Thesis, the literature review, is focused on mapping the energy sector in Bhutan regarding energy generation and subsequent consumption. The residential sector plays a crucial role in the initial biogas generation in Bhutan. For that reason, the chapter is expanded on the energy end-uses summary. Biogas is analysed regarding its historical implementation development in the country, the main obstacles in the implementation and its feasibility indicators reflecting the near past.

2. Aims of the Thesis

This study aimed to reveal the current situation in Bhutan regarding the status of energy consumption, regarding the status of biogas technology and subsequently analyse biogas as a potential renewable energy source with its potential benefits and drawbacks.

Furthermore, the aim of the study was to examine the relevance of biogas as a source of energy and to find gaps in the energy production where biogas might serve as a substitution or complement to other sources already used or to fill the gap where no energy is produced.

3. Methodology

This Thesis was written as a literature review. Therefore, partly PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach was utilized, which allowed evidence-based minimum set of necessary sources needed for appropriately reporting about the topic of the current situation in Bhutan regarding the status of energy consumption and regarding the status of biogas technology. That included collecting of previously published articles from scientific databases such as ScienceDirect, Elsevier and Google Scholar, plus from officially published datasets and literature by the state administration and international organizations (e.g. Department of Livestock of the Royal Government of Bhutan and Asian Development Bank) regarding Bhutan energy sector and waste management sector. The scientific data search was completed through the keywords such as biogas, energy consumption, energy generation, fuel sources, domestic energy and waste management and others with the application of the Boolean operators.

Sources from scientific databases, departments of two ministries of Bhutan (Ministry of Economic Affairs, Ministry of Agriculture and Forest) and international organization (e.g. World Bank) were collected and examined if there are correlations to the aims of the thesis. Together with datasets by the National Statistics Bureau and the Department of Livestock and Department of Agriculture, the collected information was systematically reviewed and condensed into three main chapters: Energy Sector in Bhutan, Biogas and Biogas Feasibility proceeded by a chapter called Background. All the collected data were critically and constructively analysed through summary, classification and comparison.

The potential of biogas generations in Bhutan was calculated using multiplication of the number of animals, divided into two categories (cattle, and local species of the bovine family), and estimated availability of dung. The result was furthermore multiplied by estimated biogas yields giving the final gas volume results for both categories of dung origin. The calculation was relying solely on previously published data.

4. Literature Review

4.1. Background

Bhutan is a mountainous country in which climate varies due to the changing elevations (CIA 2021). The surface is characterized by steep mountains ranging up to 7,500 masl on the North, deep valleys (WB 2019), together with foothills and plains along the Indian border on the South where elevations decrease to about 200 masl. Southern plains are humid with a subtropical climate, the middle part of Bhutan is characterized by a cool temperate climate while the north is very cold with permanent snow. The temperatures fluctuate according to the elevations and monsoon season (FAO 2011).

It is a democratic constitutional monarchy landlocked between two states – India and China (ADB et al. 2013). Bhutan keeps a strong economic relationship with India. It is the biggest exporting country for Bhutan with 522 million US$, followed by Bangladesh (39 million US$) and Nepal (7 million US$) in 2019 (UNCTAD 2020). Even though Bhutan shares similar cultural and religious traditions with neighbouring China (Tiber region) and occupies a strategic position in the Himalayan region, the countries don't have diplomatic relations and have few trade exchanges (Mathou 2004).

Bhutan's development is guided by so-called Five-Year Plans (FYP). The most recent Five-Year Plan covers the years 2018-2023. In his final year, Bhutan is going to graduate from being a Least Developed Country (LDC) (DOA 2019). The status refers to underdevelopment of the country characterized by the state of nutrition, health, school enrolment and literacy, and a state of deep poverty measured by per capita income with economic vulnerability, meaning the ability to cope with external shocks such as economic, natural or man-made (UNCTAD). For graduation to post-LDP life, Bhutan has already improved its human assets and level of poverty, however, the economic vulnerability is still a concern (DOA 2019). Therefore, the 12th FYP is the last plan as LDC.

The country has a unique way to determine its development – Gross National Happiness (WB 2019). However, to reach a more stable growth, the country must support more diverse economic drivers (ADB et al. 2013). So far, the revenues from hydropower enabled large investment into human capital which led to improvements in service delivery and educational and health conditions (WB 2019), nonetheless, the revenues are dependent on a sector that is based solely on natural resources. Other sectors remain largely underdeveloped. Moreover, the infrastructure is poor, especially in the rural areas, in particular transport and connectivity. There is a lack of access to financial services, market failures that limits the competitiveness, unequal condition of education and limited state budget for investments (ADB et al. 2013).

The rate of gross domestic product (GDP) growth, after reaching a high of 18.36% in 2007 has moderated to 11.95% in 2010 and 8.12% in 2016 (WB 2019 a.). Hydropower, cement, wood and food products constitute the major economic activities of the country, with agriculture (17% of GDP in 2012), construction (16% of GDP in 2012) and electricity and water supply (12% of GDP in 2012) (IRENA 2019). The continuation of economic growth is largely dependent on the development of hydropower generations. Bhutan, together with Nepal, is a net-exporters of electricity to the Indian market and Bangladesh (IHA 2019). Similar to other least developing countries, the reliance on energy for social and economic development and poverty reduction is the preponderating issue for Bhutan. Various resources show that economic development goes in hand with an increase in energy consumption which has been rising rapidly and stood at 650,220 tonnes of oil equivalent (toe) in 2014 (DRE MEA 2016 a.).

80% of the population is entangled in the agricultural sector (Beaudoin 2014). In general, it is the main source of livelihood for 57.2% of the total population (GNHC 2018) with women earning 95% of their income from agricultural activities. Rice is the staple crop, together with cultivated maize and wheat (Beaudoin 2014). Other cultivated crops are tuber crops, i.e. potatoes, oilseeds, pulses, with main cash crops apples, oranges and cardamon. Due to the diversified terrain, only around 3% of the total land was under cultivation in 2009 (FAO 2009).

4.2. Energy Sector in Bhutan

The total energy consumed in Bhutan according to the Bhutan Energy Efficiency Baseline Study released in 2012 was 326,687 MTOE. Out of the total energy consumption, electrical energy consumption accounted for 42.6%, and the remaining 57.4% was covered by thermal energy consumption (Jamtsho 2015). There was a significant shift where the electricity consumption decreased to 28% with hydroelectricity power generation remaining the major source of electricity. Thermal energy sources fill the remaining 72% of which one-half accounts for biomass, followed by petroleum products (22%) and coal and its derivatives (15%) (DRE MEA 2016a.).

The electrification rate reached 100% in 2018 through both grid-connected and off-grid power generating means (WB 2020). Off-grid power sources were built in places with low reachability due to the rugged terrain. That includes mostly solar home systems (stand-alone photovoltaic systems) and stand-alone generators (DRE MEA 2016a.). Any kind of fossil fuels must be imported, which means all consumption of coal, diesel, kerosene, petrol and LPG in each sector. It amounted to 205,784 TOE in 2014, with diesel accounting for more than half of it. These imports of fossil fuels create a burden for the economy. In 2017, it was estimated at 9,984 million NU (144 million US$), which covered 84% of the revenues from exporting electricity (IRENA 2019).

Bhutan's richness in water sources and its hydropower infrastructure enables the country to export the net power surpluses (mostly to India). This export is the main driver of the economy, accounting for 19.45% of domestic revenue, 34.15% of total export earnings and 8% of GDP in 2016 (IRENA 2019). The excess of supply covers the present account deficit, however, it makes the country dependent on the export of electrical energy to maintain its economic development as it depends on the availability of relatively cheap hydroelectricity (DRE MEA 2016a.). Moreover, Bhutan generates surplus power to export during the monsoon season (around 70% each year goes to India). Conversely, the dry monsoon period leads to decreased river flow, leading to imports of electricity from India (which amounted to 4% of total domestic electricity demand in 2017) (IRENA 2019). Not only the seasonal reduced river flow endangers the country's ability to maintain its levels of power generation but also climate change (SEFA 2012), and its subsequent extreme weather event, resulting in flooding, glacial lake outburst floods and the changing vegetation and forestry (IRENA, 2019), all that might bring more frequent or prolonged power shortages in the future (SEFA 2012). Additional wind power generation has the potential to complement hydropower due to the wind generation profile that is promising just during the winter months. A diversified supply mix that constitutes several renewable energy technologies can also increase the resiliency to the impacts of climate change (IRENA 2019). Bhutan can also develop the use of biogas as an alternative to wood used for cooking in rural areas where the household is still highly dependent on fuelwood for cooking and heating purposes. Besides, such renewable energy produced by grid-connected solar, wind and biomass generation plants can provide additional surpluses for export through networks (DRE MEA 2016a.).

Newly established renewable energy generators can support household energy use and energy for productive use which will potentially take down the demand on the grid outside remote areas and eventually diversify energy supply (Aravindh & Giri 2016). Bhutan targets to develop a total of about 20 MW of renewable energy by 2020-25, with 5 MW capacity each from the electricity generated by solar, wind (the country plans to install 360 kW of pilot wind energy plants at three sites) and biomass energy and remaining coming from biomass and solar thermal systems (SEFA 2012). Extra 2,022 MW of hydropower capacity is projected to be installed by 2023 (given by the baseline of 1,488 MW in 2013) (PATA 2014). The sustainable use of biomass has the potential to result in the installation of biogas plants and improved cookstoves (SEFA 2012).

4.2.1. Transmission Network and Energy Efficiency

The mountainous terrain makes it difficult to develop a transmission line to transmit electricity to rural areas. For that reason, there has been developed decentralized sources of energy such as solar PV whereas sustained traditional biomass usage or LPG and kerosene must be imported to the country. The expansion of the transmission network is crucial not only for the domestic supply but also for the export of electricity to India (Aravindh & Giri 2016; DRE MEA 2016a.; ADB 2014).

National transmission grid master plan 2020 formulates further development of new transmission lines to reduce losses incurred in the low voltage lines (Aravindh & Giri 2016). Longer lines with lower voltage can lead to higher losses in the system (DRE MEA 2016a.).

Energy intensity in Bhutan, meaning the energy inefficiency of the economy, is very high, above the energy intensity in most Asian countries. This infers that Bhutan does not constructively use the abundance of hydropower resources and needs to improve its energy efficiency (IRENA 2019). Even though electricity is extensively used across all sector in Bhutan, the residential sector still vastly uses traditional sources of energy for cooking and heating purposes which shows inefficient energy savings. The sector displays a need for improvements such as better designed improved cookstoves, space heaters and efficient household or i.e. community level biomass and biogas energy systems (SEFA 2012).

4.2.2. Energy Supply Mix

Bhutan's energy supply mix is dominated by thermal energy (72%) out of which biomass is the largest source of energy in the form of fuelwood, biogas and briquettes used mainly in the residential segment (36%), followed by petroleum products which form 21% (16% diesel, 5% other) and coal consumption by industries which contribute 15% of demand. The remaining source of energy is electricity with the domination of hydropower that accounts for 28% of the fuel mix in the economy (DRE MEA 2016a.; IRENA 2019). Solar energy, wind energy and municipal solid waste bring possibilities to diversify the fuel mix and shift the demand towards clean forms of energy generation.

In 2014, the total domestic energy supply accounted for 650,220 TOE, out of which thermal energy stood for 470,128 TOE and electricity for 180,092 TOE. The table below demonstrates the proportion of each fuel used in the supply mix:

Table 1. The proportion of Thermal Energy and Electricity in the Energy Supply Mix

Thermal Energy	**470,128 TOE**	**72%**
Coal and derivatives	97,567 TOE	15%
Diesel	102,107 TOE	16%
Petrol	19,658 TOE	
Kerosene	7,901 TOE	5%
LPG	8,526 TOE	
Biomass	234,369 TOE	36%
Electricity	**180,092 TOE**	**28%**

Source: DRE MEA 2016a.

In 2017, total electricity generation was calculated at 7,729 gigawatt-hours (GWh), which exceed the domestic electricity requirement more than three times. The total installed capacity was 1.6 gigawatts (GW) (IRENA 2019). In 2018, the total electricity generation was estimated at 6,940.58 Million Unit (SYB 2019)

Connection to the grid makes electricity available to meet basic needs and for productive energy use (SEFA 2012). Electricity, together with LPG and biogas substitutes the use of fuelwood for cooking while the energy used from fuelwood for space heating is being substituted merely by electricity (DRE MEA 2016a.). It is becoming an elementary fuel over firewood in the residential sector (SEFA 2012) but still, around 4,000 rural households remained unconnected to the grid due to the remoteness of the area. Those are delivered energy through decentralized forms – generator and solar (NSB 2017).

4.2.3. Thermal Energy Fuel Sources

4.2.3.1. Coal

Coal is mainly used for heating processes exclusively in the industry sector, mostly in the cement and ferroalloy industries and for construction purposes in the country. The usage of coal as the heating agent in the industrial processes has started to be replaced by the effortlessly available electricity. Derivatives of coal such as coke and semi-coke serve as an effective reducing agent in the industrial processes of heavy industries (DRE MEA 2016a.).

The only deposits of coal are extracted solely from the mine located in Rishore, Samdrup Jongkhar with a production of 85,164 tonnes of sub-bituminous type of coal for the year 2015. Therefore, the country is dependent on imports of higher-grade coal, mainly bituminous type of coal and anthracite (DRE MEA 2016a.). Figure 1 represents a changing pattern in coal production between the years 2005 to 2015.

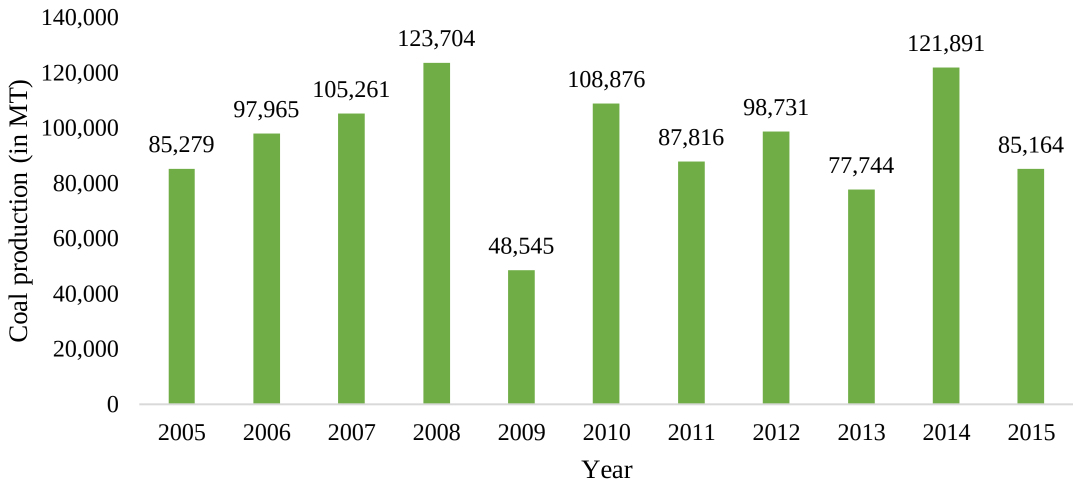

Figure 1. The trend in Domestic Coal Production from 2005 to 2015

Source: DRE MEA 2016a.

Altogether domestic consumption and import, the total coal consumption amounts to 190,422 metric tons (MT) which constitutes 1,876 MT of anthracite, 98,355 MT of sub-bituminous, and 90,191 MT of other coal (mostly lignite) plus another 41,137 of coke and semi-coke of coal (DRE MEA 2016a.).

4.2.3.2. Petroleum

Diesel generators have a capacity of 10.73 mega-volt amperes (MVA) (SEFA 2012). Bhutan is dependent on diesel generator in hydropower plants and for several usages in industry and agriculture. The predominant petroleum fuel use includes diesel, petrol, LPG and kerosene (DRE MEA 2016a.). There are not any discovered petroleum reserves in Bhutan, therefore, all the petroleum must be imported from abroad. Bhutan has an agreement with India for the supply of petroleum products which are distributed by three distributors: Bhutan Oil Distributor (part of the Tashi Group of Companies), Damchen Petroleum and Druk Petroleum Corporation Limited (SEFA 2012).

4.2.3.3. Biomass

According to the Bhutan Energy Data Directory report from 2015, energy demands from the residential sector for cooking and space heating was mainly satisfied by the use of biomass as fuelwood cater. Nonetheless, electricity has started taking place over fuelwood in the last ten years. The number of firewood consumed in 2005 constituted 91% of the total fuel-mix of the residential segment and decreased to 87% in 2014 (DRE

MEA 2016a.). The decreasing numbers of the amount of firewood consumed may not seem prominent as the amounts of firewood in the form of backloads per month and truckloads per year are increasing as shown in Figure 2 and Figure 3 (NSB 2003; NSB 2007; ADB & NSB 2013; NSB 2017). However, the indications were made that the energy dependency of residential households started trending towards a shift from biomass to electricity (DRE MEA 2016a.).

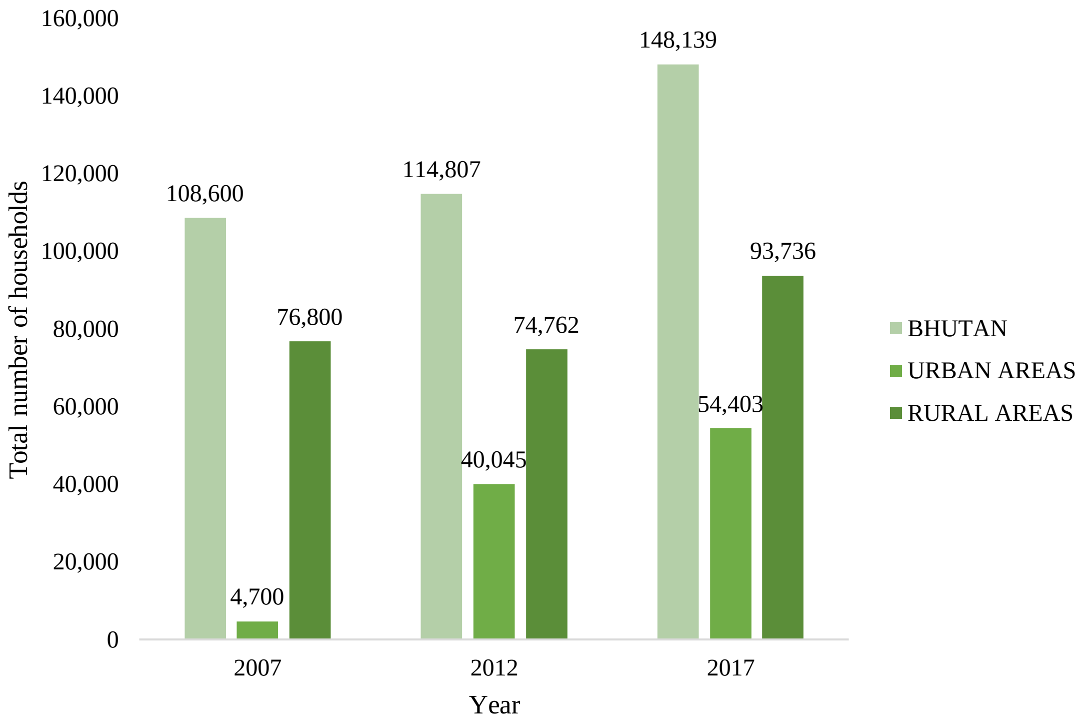

Figure 2. Distribution of Households According to the Quantity of Firewood Used in Backloads per Month

Source: NSB 2003; NSB 2007; ADB & NSB 2013; NSB 2017

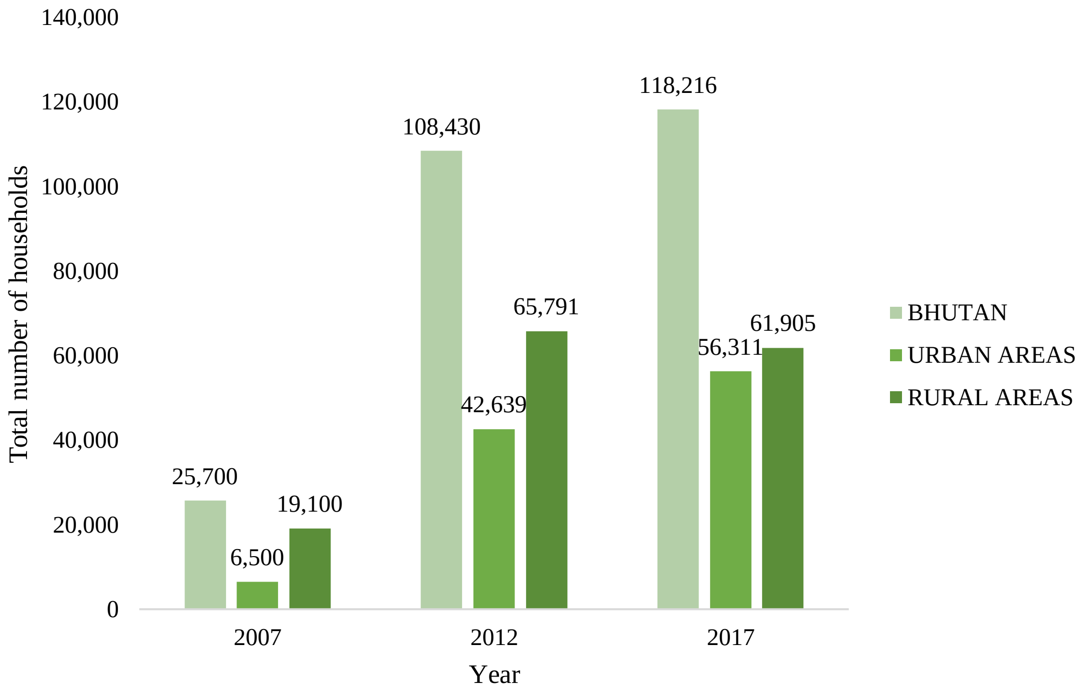

Figure 3. Distribution of Households According to the Quantity of Firewood Used in Truckloads per Year

Source: NSB 2003; NSB 2007; ADB & NSB 2013; NSB 2017

4.2.4. Electricity Power Sources:

4.2.4.1. Hydropower

Bhutan's richness in water sources enables electricity generation almost exclusively from hydropower. Figure 1 shows the dense network of rivers in Bhutan. With an estimated generation from hydropower alone at 1,606 MW, the summer months electricity demand is satiated. Nonetheless, the power generated throughout the year is dependent on the amount of water flowing through the riverbed which fluctuates seasonally. On the other hand, it has a little effect on the environment due to the hydro-power resources that are mainly run-of-the-river type and built on deep gorges resulting in much lesser submergence of land (DRE MEA 2016a.).

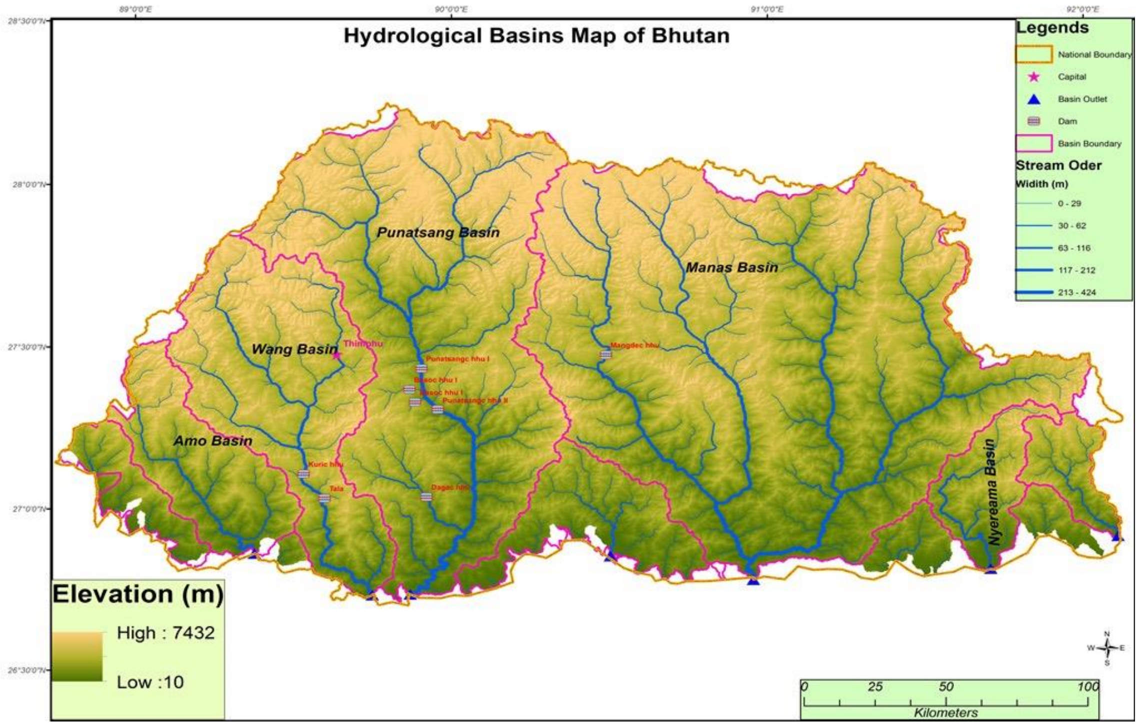

Figure 4. Hydrological Basin Map of Bhutan

Source: Fakhruddin 2015

Two energetic companies have wide-ranging influence over the energy sector in Bhutan. Druk Green Power Corporation Limited (DGPC) possess large hydropower plants in the country, and the Bhutan Power Corporation (BPC) owns plants below 5 MW, that include the mini and micro-hydro, plus diesel power plants. BPC also manages the transmission and distribution system, as well as the, retails of the electricity to customers (SEFA 2012).

There are five large hydropower electricity plants in Bhutan: Basochhu Hydropower Plant (HP), Chhukha HP, Kurichhu HP, Tala HP, and Dagachhu HP.

The generation units of Basochhu HP have a total capacity of 64 MW and a mean annual generation capacity of about 291 million units (MU). The Chhukha HP is the oldest mega power plant. Most of the electricity generated goes to India. It has a total capacity of 336 MW and a mean annual generation capacity of about 1,800 MU. The Kurichhu HP has an installed capacity of 60 MW and a mean annual energy generation capacity of 400 MU. The Tala HP is the largest hydropower plant (91 m high (FAO 2011)) with a total installed capacity of 1,020 MW and a mean annual energy generation capacity of 3,926 MU. All of the electricity generated is traded to India (DRE MEA 2016a.). The

Dagachhu HP has a total installed capacity of 126 MW and a mean annual energy generation capacity of 515 MU. It has been commissioned by Tata Power Trading Company together with Druk Green Power Company in 2015. Tata Power Trading Company signed an agreement for 25 years to export all electricity generated at the site to India (IHA 2019).

Apart from those major HP electricity plants, there are two operating plants constructed by the Department of Renewable Energy, namely Sengor (100 kW) and Chendebji (70 kW). These are operated by local communities as an off-grid power source. The micro/macro HP on average generate 20 GWh of electric energy annually (DRE MEA 2016a.).

The total installed capacity from hydropower plants reaches 1,488.12 MW. The overall estimated output of hydropower plants is around 30,000 MW of which 23,760 MW is promising to be techno-economically feasible for development (SEFA 2012).

4.2.4.2. Solar Photovoltaic

Bhutan has the potential to attain sufficient solar power generation from Solar Photovoltaic. In 2009, the U.S. Department of Energy's National Renewable Energy Laboratory calculated the solar potential for generating solar power with 4.0 to 5.5 peak sun hours per day. The theoretical productivity of Solar Photovoltaic power generation reaches 3,706,328 MW, considering the whole solar irradiance obtainable to the country's landscape. Despite the fact, that several regions show convenient solar radiation and temperature, other parts of the country have a limited potential for solar PV development due to the rugged terrain, nationally protected areas and other restrictions (DRE MEA 2016a.; IRENA 2019).

Therefore, the theoretical development reach is reduced to approximately 12,000 MW. It has been estimated for the year 2014 that 4,598 solar systems are operating in the country out of which 2,750 are turned on-grid systems whilst 1,848 are off-grid systems. The annual electricity generation was 0.14 GWh, with 2,392 solar PV home-lighting systems operating at a capacity of 50 Watt-peak (DRE MEA 2016a.).

Satellite map displayed in figure 5 display that photovoltaic power potential can vary from 1,000 to 2,045 kWh/kWp/yr. The country shows a better irradiation rate than many regions in the world which already achieved a substantial share of power generation from solar energy (for example Germany and the United Kingdom) (IRENA 2019).

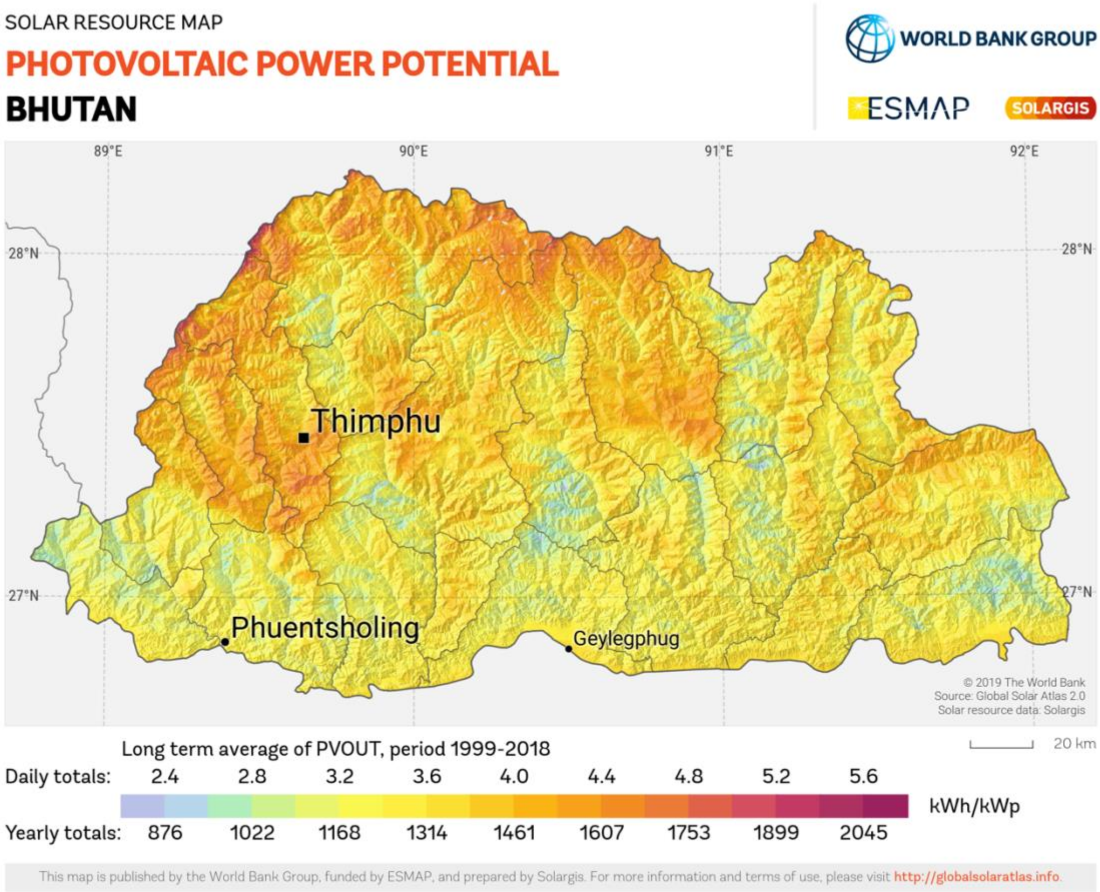

Figure 5. Photovoltaic Power Potential Map of Bhutan

Source: Solargis 2019

4.2.4.3. Wind Energy

Bhutan shows a promising resource potential for wind power development, but limitations such as the complexity of the terrain (slope and elevation levels), road distances, inhabited areas and restricted areas (e.g. agricultural lands, forests, protected areas), and technical restrictions/limitations impede further development. Some regions with high-speed wind are in many cases located in high altitudes in the north which makes them inapproachable for setting up large scale wind turbines. Hence, the best wind potential is concentrated in the valleys where the roads and electricity transmission networks are located. The most inviting sites for wind power development in terms of technical feasibility and logical access are Wangdue Phodrang, Mongar and Chhukha

(IRENA 2019). The total restricted theoretical development potential of wind power for Bhutan is estimated to be around 761 MW, with the highest potential assessed to be 141.7 MW at Wangdue Phodrang followed by Chukha with 91.8 MW (DRE MEA 2016a.). Moreover, the valleys near Wangdue and Punakha, Trashiyangtse, and Dungkhar indicate especially good wind resource (Gilman et al. 2009).

Wind power generation shows the potential to complement hydropower generation and reinforce the stability of domestic electricity generation. The wind in Bhutan is affected by the seasonal monsoon resulting in higher wind speeds from November to April when the river flow is low leading to reduced water mass in the rivers and therefore lower hydroelectricity yields. The remaining rain-bearing months feed the rivers in Bhutan with water (IRENA 2019).

The technology has some negative aspects which challenge the expansion of wind turbines based on their environmental impacts, such as habitat disruption, avian mortality, and impacts on nearby communities (Gilman et al. 2009).

4.2.5. Energy Consumers by Economic Sectors

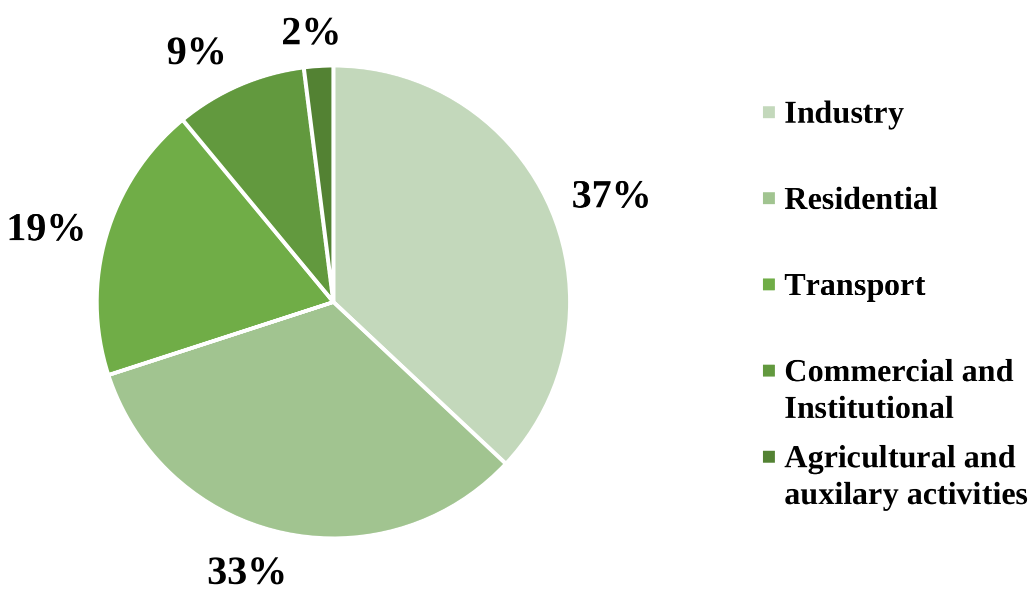

Figure 6. Energy Consumption by Economic Sector in Bhutan

Source: IRENA 2019

Figure 6 illustrates that three sectors dominate the energy consumption in Bhutan: the largest is Industry Sector (37%), followed by Building Sector (Residential (33%) + Commercial and Institutional (9%)), and Transport Sector (19%), the smaller share goes to Agricultural and auxiliary activities (2%) (DRE MEA 2016a.). Energy consumption grows rapidly across all sectors (with a compound annual growth rate of 5.49% since 2005) (IRENA 2019).

Bhutan reached overall access to electricity in 2018 (WB 2020). Four years before that, there were 153,842 electricity consumers (sharing a total of 1912,03 GWh). The largest energy consumer, the industry, accounted for 83.36% of total electricity consumption. The residential sector used only 11.03% of all electricity consumption but accounted for nearly 90% of all electricity consumers. The commercial and institutional sector (tourism, commercial establishments such as offices, hotels, shops and restaurants) also used energy for productive use and accounted for about 5.61% of all electricity consumption (DRE MEA 2016a.; NSB 2017).

4.2.5.1. Industry Sector

The industry sector key source of energy is electricity (57%) used by ferroalloy, steel and cement-based industries, however, the country shows a need for fossil fuels, specifically diesel and coal of various types (coal is the second most used fuel in the sector (40%). The high voltage industries are the principal consumers of energy, consuming around 60% of the total energy in the industry. Together with heavy industries, they have the most diverse fuel mix, while the medium and cottage and small industries are mainly reliant on electricity as the base fuel (IRENA 2019). Bhutan has low deposits of coal that would satisfy the domestic urge and most of the domestically extracted coal (sub-bituminous) is exported to India and Nepal. That makes the industry dependent on imports of fossil fuels, especially bituminous coal from neighbouring India (DRE MEA 2016a.). The import of coal is burdensome for the economy as it uses around 70% of the total revenue from electricity export (IRENA 2019).

4.2.5.2. Residential consumers

Based on the data from the Household living standard survey from 2017, 164,011 households lived both in rural and urban areas across all Dzongkhags. The total estimated population was 692,895 out of which one-third (231,805) lived in urban areas while the remaining two thirds (461,090) lived in rural areas (NSB 2017). About 95% of Bhutanese inhabitants are settled in the southern plains and the mid-mountainous valleys (FAO 2011).

Table 2 presents the changing patterns in the number of households with a percentage of access to electricity, plus the electrification rates over time, the proportion of urban and rural households that have access to electricity, and the percentage of those connected to the national grid:

Table 2. The trend in the numbers of households and related electrification data patterns in 2003, 2007, 2012 and 2017

	2003	2007	2012	2017
N of households	106,900	125,500	127,942	164,011
Access to electricity according to the WB database (%)	41.1	71.8	91.5	97.7
Electrified according to the Households Living Standard Surveys (%)	43.3	71.8	91.5	99
Of which from urban areas (%)	97.5	98.73	99.6	100
Of which from rural areas (%)	27.3	60.3	87.3	98.4
Connection to the grid (%)	41.1	69.1	88.3	98

Source: NSB 2003; NSB 2007; ADB & NSB 2013; NSB 2017; WB 2020

In the last two decades, Bhutan more than doubled the distribution of electricity across the country and reached nationwide access to electricity in 2018, according to the WB database. The year before, in 2017, 100% of urban households have the access to electricity, out of which 99.7% of urban households were connected to the grid. In rural households, 98.4% of households were electrified, while 97.1% were connected to the grid. Of all households, 99% were electrified, of which 98% with grid connection, 0.2%

with a generator, and 0.8% utilizing solar energy. In the Household Living Standard Survey from 2017, more than half of the unelectrified households stated to be out of the reach of the source. The lowest rate of electricity provision was in the Dhongkhags Zhemgang (95.6%) and Haa (95.7%) while the rest of the Dhonkhags have more than 98% electrified households (NSB 2017).

Rural households use six times more solar energy than urban households due to the remoteness of the areas where there is no connection to the grid (NSB 2017). The highest electricity consumers in the building sector – the urban residential households – Thimphu Dzongkhag uses around 60% of the electricity. The per capita electricity consumption in the average urban household is close to 2.5 to 3 times higher than the one of the rural households. The total consumption of electricity in the building sector amounts to 319.13 GWh. Based on the trend observed, the expectations are that per capita electricity consumption would increase over the next ten years (DRE MEA 2016a.).

4.2.5.3. End Uses

Heating, cooking and lighting are the main energy end-uses in the residential energy consumers (DRE MEA 2016a.).

Electricity is the most widely used source of energy for lighting (98.6%) and cooking (94.9%). Heating is ensured either by electricity or by Bukhari (25%). Besides electricity, around 1% of households use kerosene or gas lamp as a source of lighting for their dwellings (NSB 2017). Rural Bhutan uses traditional stoves with low efficiency and high smokiness. The introduction of smokeless stoves in the mid-eighties was not successful since the new cookstoves did not meet the needs of traditional cuisine (SEFA 2012).

There was a total of 164,011 households in both rural and urban Bhutan in 2017. Lightly less than one-third of households had no heating in their facility, in the rest Bukhari (wood/coal stove) was the most used source of energy for heating by 25.15%, proportionally by 31.3% in rural areas and 13.9% in urban areas, followed by electric heaters (24.23%), Traditional stove called thab (18.54%) and by kerosene heater (1.91%) (NSB 2017). A higher proportion of urban households (50.7%) in using electricity for heating of their dwelling than among households in rural areas (10%). The usage of thab is higher in rural households (31.3%) compared to urban households (0.6%) (SEFA 2012;

NSB 2017). Kerosene heater registers higher usage in urban areas (4.5%) to rural areas (0.5%). Gas heater and straw/manure/brush stove are used in a few households (NSB 2017).

In 2017, electricity served for cooking in 155,572 households followed by gas (116,465), and wood (35,552). Only 2,319 households used biogas for cooking. Kerosene, dung-cakes and coal were not used in more than 100 households (NSB 2017). The proportions of fuel used for cooking purposes are displayed in the table below:

Table 3. Source of fuel for cooking in 2017

Fuel use	**ALL households (164,011)**	%	**URBAN**	%	**RURAL**	%
Electricity	**155,572**	94.9	**57,781**	99.1	**97,790**	92.5
Gas	**116,465**	71.0	**55,415**	95.0	**61,050**	57.8
Wood	**35,552**	21.7	**380**	0.7	**35,172**	33.3
Biogas	**2,319**	1.4	**34**	0.1	**2,286**	2.2
Kerosene	**355**	0.2	**38**	0.1	**317**	0.3
Dung-cake	**152**	0.1	**0**	0.0	**152**	0.1
Coal	**20**	0.0	**0**	0.0	**20**	0.0
Other	**803**	0.5	**39**	0.1	**764**	0.7

Source: NSB 2017

4.2.5.4. Transport Sector

Almost all the energy used in the transport sector is derived from imported fossil fuels. Transport sector project the promotion of usage of electricity-based technologies (DRE MEA 2016a.).

4.3. Biogas

4.3.1. Biogas Technology

There are three main types of biogas plants (BGP): fixed, floating and plastic tubular (balloon or bag digester in some literature) type, all in various sizes (DRE MEA 2020) ranging from a small-scale BGP used by households (mostly from 4-10 m^3) to large-scale communal or industrial digesters (IRENA 2016). The loading ratio, that is the amount of raw material fed to the digester per day per unit volume of digester capacity, is dependent on four factors: substrate, temperature, volumetric burden and type of plant. A plant that is fed by cow-dung, feedstock broadly used in Bhutan, needs mostly to input 7.5 kg of fresh dung per m^3 size of digester in lowlands whilst it is 6 kg in highlands (Nakarmi et al. 2016). Feedstock retention (detention) time is the average time the material remains in the digester before it is pushed through the outlet pipe. It is calculated as the digester volume divided by the total feedstock volume. The volume capacity is the maximum content of both, gas and slurry in the biogas plant. If the conditions are optimal, a plant produces a "rated daily gas production", that is the volume of gas a plant is designed to produce. It is measured in m^3/day. For a plant designed for energy production, the energy content is dependent on methane content that should be about 65%, meaning not all gas production can be taken into account when converting gas production to energy content. The total plant volume is the amount of two quantities: the digester volume and the gas storage volume. Total feedstock volume refers to the amount of waste and water added to the plant each day (IRENA 2016).

The selection of the biogas plant type is based (not only, but mainly) on the availability of construction materials (for example bricks are not easily available in Bhutan in compare to neighbouring India), the complexity of construction, lifespan and cost, ease of use and maintenance intensity, and suitability of construction in different terrains (PIU 2012). The fixed dome biogas plant has a long-life span with a simple design, on the other hand, the construction requires skilled masons, due to the need for gas-tight construction and the plant can be hard to fix if gas leakage occurs. A floating drum biogas plant is easier to construct, nonetheless, the main problem is the cost and potential corrosion of the metal parts (steer drum) that shortens the life span of the plant. Plastic tubular is cheap, easy to construct and maintain, on the other hand, the life span is relatively short and the digester bag is susceptible to damage (Roubík 2018). Each type of biogas plant has multiple models and designs (Nijaguna 2002).

As was indicated above, the main part of the plant is the digester which creates an airtight environment in which the anaerobic fermentation transforms the organic waste. The main product of anaerobic fermentation is a gas (biogas) (IRENA 2016). Biogas is a flammable gas that constitutes methane (55-75% of CH_4) and carbon dioxide (CO_2) (Flotats). Other than biogas, a liquid waste (slurry) is by-produced and can serve as a fertilizer (IRENA 2016). Other parts of a biogas plant are the inlet pipe (less than 1 meter in diameter) and compost pit (typically 1 meter by 2 meters by 3 meters). All the components except the inlet pit through which the mixed dung and water are fed into the digester are built underground. The biogas produced and located in the dome space is piped to the household's kitchen for use on demand. The bio-slurry is stored in the underground compost pit (DRE MEA 2016b.). Figure 7 demonstrates the dismantled biogas plant (fixed-dome type).

In general, biogas plant requirements for operation are an airtight digester with no oxygen, moderate temperature, no light, and small feedstock particles with broken down fibres and minimal lignin (wood) content (IRENA 2016).

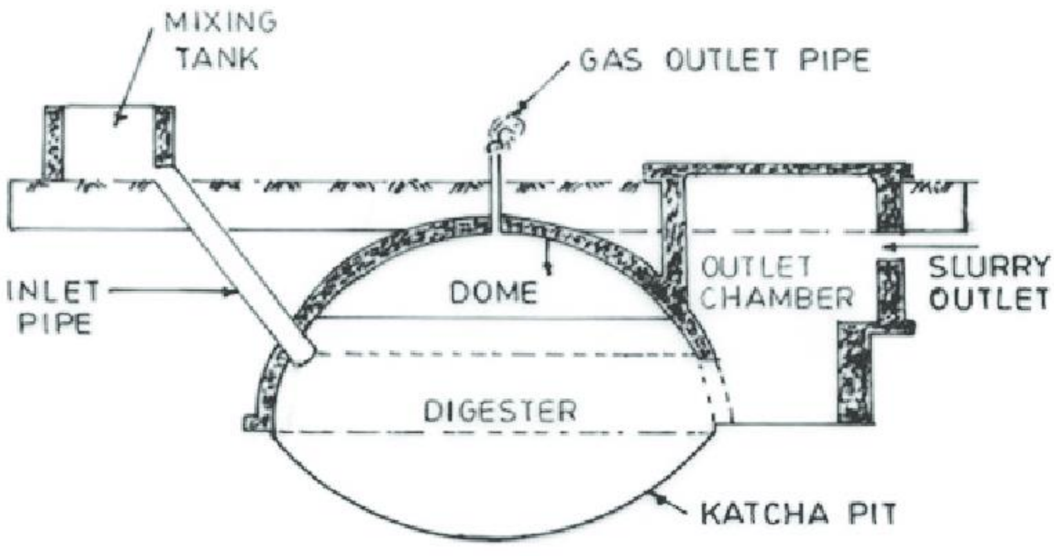

Figure 7. Parts of Biogas Plant, fixed-dome type

Source: Kingdom BioEnergy Limited 2018

4.3.2. **Benefits of Biogas Generation**

Biogas, if used properly, improves the access to modern cooking and heating with clean renewable energy (PIU 2012). It reduces indoor air exposures from firewood, improves health conditions (Bajgain 2008) and helps to reduce amounts of collected firewood from the forest (PIU 2012), plus it decreases imports of fossil fuels (Seadi et al. 2008). The use of biogas plant helps to maintain clean surrounding using cattle-dung into the digester and along with toilet connection improves sanitation conditions (Bajgain 2008). An additional benefit is the waste reduction, due to the possibility to feed the digester with waste material (Seadi et al. 2008).

Moreover, bioslurry, the by-product of BGP, is an excellent fertilizer (PIU 2012) that also protects water quality by reducing harmful substances associated with manure from entering the surface or underground water (Chen & Neibling 2014). Digester slurry contains more nutrients than traditional compost (DRE MEA 2020). Odour is reduced, viruses, bacteria and parasites are inactivated by the anaerobic digestion process, the germination capacity of weed seeds is decreased and the digestate is more gentle to the plants on the field (Seadi et al. 2008).

Biogas technology is not suitable in case the operator cannot keep the required number of cattle. Another challenge might be to sustain daily feeding dung and water, which bring extra workload. The initial investment is high for low-income households for a facility susceptible to natural calamities like earthquake, landslides, floods along with the inability to move the plant in case of moving elsewhere. In case more gas is required, the plant isn't able to fulfil the need, due to the fixed amount of gas produced per day (Bajgain 2008).

A main providing of the BGP plant is gas that is in developing countries primarily used for cooking (Nakarmi et al. 2016). A plant producing 2 m^3 gas per day satisfies the intake of two stoves (usually one with 0.22 m^3 and the other with 0.44 m^3 per hour capacity) for one hour and a half two times a day to meet the cooking requirements of a 6 members family (DRE MEA 2020). Generally, the capacity of the stove varies from 0.22 to 1.10 m^3 gas consumption per hour, of which the 0.22 m^3 and 0.44 m^3 are the most popular. Under Indian or Nepalese conditions, that are similar to Bhutan conditions, a gas requirement of 0.33 m^3 per person per day is estimated to be sufficient (Nakarmi et al. 2016).

For households needs, biogas can be used for lighting in lamps such as a gauze mantle lamp (DRE MEA 2020). Biogas can serve for heating, too, as a heater in the house or other facilities. It can be used as a cooling source as well, to power an absorption type refrigerating machine (Rich 2010). Kerosene powered refrigerator can be adapted to run on biogas (DRE MEA 2020).

It is possible to use biogas as a fuel for vehicles. Biomethane (upgraded biogas, that is biogas without any contaminants and substances other than methane) can be used the same way as vehicles powered by natural gas. It reduces the emission of carbon dioxide, particles and soot and Non-Methane Hydrocarbons. Biogas can be also utilized for electricity generation (Seadi et al. 2008).

4.3.3. Biogas in Bhutan in the Last Century

Biogas was first introduced during the late 80s by installing 54 biogas plants in southern sub-tropical parts of Bhutan (Nepal & Ghirime 2009). The model picked for these plants was a Deenbandhu type-fixed dome digester of 4 m^3 and 6 m^3 capacity. The majority of the plants stopped functioning after a few years due to gas leakage and moisture trap (Bajgain 2008). There hadn't been any other attempts on biogas promotion till 2011 when the Bhutan Biogas Project started its pilot stage (DRE MEA 2020) though some plants were notified to be installed in Punakha and Paro Dzongkhag by individuals. It is reported that the installations of biogas plants were not done properly, masons were not trained (Nepal & Ghirime 2009) and lacked technical expertise, as well as the users, were not trained in maintenance. Unavailability of spare parts for repairments and difficulties with sufficient dung collection (Bajgain 2008) due to the poor selection of biogas users caused a quick loss of interest in repairment and maintenance of the technology. The users also weren't aware of bio-slurry usage (Nepal & Ghirime 2009) which is an additional benefit of the technology.

4.3.4. Programmes on Biogas Promotion Since 2000

Back in the first decade of the new century, Bhutan was among the leading countries in fire-wood consuming nations (DRE MEA 2016b.). 91% of the population was dependent on biomass as a source of energy (DRE MEA 2016a.). Consequently, the officials in Bhutan expressed the need for a biogas programme in Bhutan. Not only the dependence on firewood as a source for cooking was an issue, but also the use of non-renewable sources of energy (LPG, kerosene) whose purchases created a financial burden to households in long-term use. Clean energy promotion was crucial for the government with the view of climate change and environmental protection (Bajgain 2008). The energy supply mix changed rapidly and electricity in 2020 was a common source of energy among all households in Bhutan with 94.9% of households that use it for their cooking purposes (DRE MEA 2020). Nevertheless, electricity is used mainly for cooking rice and is complemented with gas that is used by 71.7% of households for cooking purposes (NSB 2017).

In 2008, the SNV Netherlands Development Organization released findings and recommendations on a study about the feasibility of biogas in Bhutan. Domestic use in Bhutan seemed to have a potential for biogas programme, but some difficulties were present for further consideration. The market in Bhutan had been underdeveloped to attract the private sector for investments. The suggestion of suitable sites for the construction of BGP was challenging due to the changing climate within a short distance (Bajgain 2008). Nonetheless, about 16,000 biogas plants were estimated to be technically feasible and cost-effective (PIU 2012) in southern parts of Bhutan and inner mountain valleys where the temperatures are optimal. The numbers of cattle for dung were sufficient there and cattle rearing is more permanent to mountainous areas where the herd must travel to find suitable pastures. The government of Bhutan also intended to develop a program to shift from free-grazing cattle to more stabling which would help to collect more dung (Bajgain 2008).

The technology was new therefore the country was missing a capacity for construction and maintenance of BGP. Another concern was the willingness of households to adopt biogas, however, the released findings indicate that households have a positive relationship to new technologies. The investment return in comparison to other energy sources such as LPG, firewood and electricity are higher and eventually financially beneficial (Bajgain 2008).

In 2011, The Bhutan Biogas Project (BBP) was launched as a joint programme of the Asian Development Bank, Department of Renewable Energy, Department of Livestock, Netherlands Development Organization and Bhutan Development Bank Limited (DRE MEA 2020). Bhutan Biogas Project was at its pilot stage implemented in four districts namely Tsirang, Sarpang, Chhukha, and Samtse. Its goal was to construct

1,600 BGPs by 2014. BBP was a pilot program after which a large-scale biogas program proceeded (PIU 2012). Eventually, the BBP was extended until the end of 2016 to assist farmers in south Bhutan in 17 districts. The target was set at 3,600 biogas plants for the whole period of 6 years (DRE MEA 2016b.).

An investment cost was estimated to be about 37 million NU since around 50% of the plants might require credit. A construction cost for 6 m^3 is estimated at 25,000 NU of which about 9,000 NU was proposed to be a subsidy for farmers to reduce the investment costs (Bajgain 2008). Bhutan Biogas Project combined the biogas plants construction, utilization of the biogas, and maintenance of the plant, plus it focused on other benefits that evolve to the households such as bio-slurry pits and know-how of proper use of bio-slurry on their farms (PIU 2012).

Bhutan Energy Data Directory from 2015 released finding that the country has established 1,048x 4 m^3 biogas plants with a productivity of 1.2 m^3 of each per day, 374x 6 m^3 biogas plants with a productivity of 2 m^3 of each per day, 4x 8 m^3 biogas plants and 3x 10 m^3 biogas plants with a productivity of 2.8 m^3 and 3.6 m^3 of each per day, respectively. Altogether, the daily production across the country is 2,027.6 m^3 (DRE MEA 2016a.).

4.3.5. Proposed Biogas Plant Design

The plant design GGC 2047 (Gobar Gas Company Design), popularized in Nepal and Laos (DRE MEA 2016b.), was proposed to adopt in Bhutan (Bajgain, 2008) with additional technical modification to suit the local environment (PIU, 2012).

GGC 2047 plant design is a fixed dome digester (Lohani) constructed entirely at sire using cement, stones and concrete (Bajgain 2008) and its size ranges from 4-20 m^3 (Lohani). In Bhutan, the Bhutan Biogas Project scheduled usage of 4, 6, 8 and 10 m^3 biogas plants. The 6 m^3 plant was suspected to become the most popular. Daily gas production of BGP constructed under the BBP was estimated to be 1 m^3 to 3 m^3 per day (PIU 2012).

Modifications for Bhutan GGC type of BGP according to Project Implementation Unit of the Bhutan Biogas Project were:

- Increase of the gas storage capacity to 60% in comparison to the original 35%. This modification takes into account the cooking pattern of Bhutanese people

- The retention time has been adjusted to 50 days from Nepalese 70 days given the climatic condition in BGP districts
- The location of the outlet tank has been re-designed to ensure necessary pressure at the point of application. The overflow level has been modified so the bio-slurry flows by gravity to the slurry compost pill
- The orientation of the outlet tank was changed for the better hydraulic flow of the digester slurry
- If the brick is used, the thickness of masonry was changed to fit their size

The proposed BGP uses cattle dung that is clean and renewable with bio-slurry as a by-product (PIU 2012).

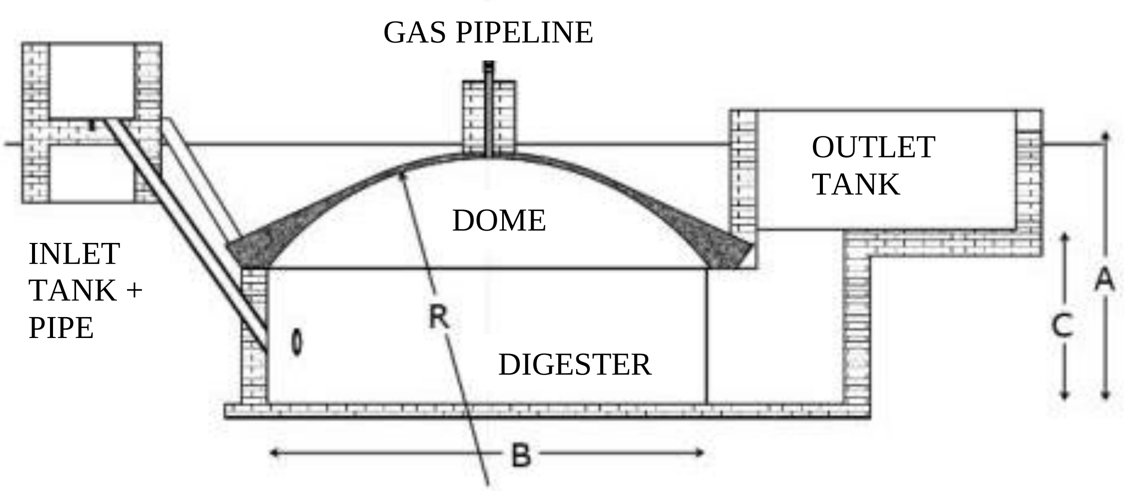

Figure 8. GGC 2047 model of fixed dome biogas plant

Source: Kingdom BioEnergy Limited 2018

4.4. Feasibility of Biogas in Bhutan

The agriculture sector is predominant in Bhutan and it consists largely of subsistence farming and animal husbandry (Bajgain 2008). About 90% of the rural household own livestock. The total livestock population is a little less than 400,000 that include cattle, buffalos, horses, yaks, Mithun (domesticated free-range bovine species), zo-zom (hybrid female and male progeny of yak bull and cattle) (DL MAF 2019).

The potential of biogas in Bhutan can be calculated by relating the numbers of cattle and therefore the quantity of dung available to feed the BGP and the climatic condition of different regions of Bhutan. Table 4. shows that there is a total of 369,466 animals with a total dung production of 3,954,735 kg per day which has the potential to produce 142,370.46 m^3 of biogas. According to the National Biogas Implementation Strategy, only 75% of calculated volume in such type of calculations would be available (i.e. 106,777.85 m^3) insomuch as not all households have the required amount of cattle to feed at least the smallest size of BGP (DRE MEA 2020), The calculations do not comprise manure from pigs, goats and poultry. Also, the table does not take into account the required temperature for BGP processing.

Table 4. Calculation of Potential Biogas Generation

Animal	**Number**	**Dung available per animal per day (kg)**	**Total dung available per day (kg)**	**Biogas yields /kg of dung (m^3)**	**Gas volume (m^3)**
Cattle	**317,451**	10	3,174,510	0,036	114,282.36
Mithun, Yak, Zo-Zom, Buffalo	**52,015**	15	780,225	0,036	28,088.1
Total	**369,466**		**3,954,735**		**142,370.46**

Source: DRE MEA 2016b.; DL MAF 2019

4.4.1. Availability of Feed for BGP

Biogas can be generated not only from animal waste but also from agricultural residues (animal waste, crop waste, dedicated energy crop), forest and industrial waste (wastewater, sludge, by-products), municipal origin (municipal organic waste, sewage sludge), and from kitchen organic waste (Balat & Balat 2009; DRE MEA 2016b.) The amount of biogas generated from each material is dependent on how much of it the bacteria in the digester can convert. That depends on two variables: the total solid content and volatile solid content. The total solid content is the dry matter of the feedstock, measured as the weight of the dry matter divided by the total weight of the material and is recorded as a percentage of the total weight. The volatile solid content is the proportion of the solid material that can be digested by the bacteria and converted into biogas. Estimates of the total volatile content in the materials are generalized across biogas literature (IRENA 2016).

General practice in Bhutan is to use only cattle for biogas production (DRE MEA 2016b.). Pigs and goats are not very common among Bhutanese households. The number of goats is regulated by law and pigs are not kept for religious reasons (Ghirime & Nepal 2009). Cattle usually stay on the long-term pasture that makes the dung collection easier. Nonetheless, most of the households keep the cattle free grazing during the day which decreases the potentially collected amounts. For Bhutan, the estimations were in 2008 that each cattle provide 6 kg of dung per day in the yard and the number might increase to 8 kg if the cattle were stabled. Therefore, for the smallest biogas plant (4 m^3) there is a need for a minimum of 5 adult cattle and the yield would satisfy 3-4 hours of cooking requirement per day (Bajgain 2008). The daily requirement of feed to the digester ranges between 25 to 100 kg of dung, depending on the size of the BGP (PIU 2012).

Bhutan Biogas Implementation Strategy published in 2020 estimates the dung availability to be up to 10 kg of dung per day per animal for cattle and up to 15 kg for other suitable species from the bovine family. Calculation based on the total amount of cattle in Bhutan multiplied by the average amount of dung available (10 kg) gives 3,954,735 total dung available. A further calculation can undercover the higher potential of feedstock amounts if other materials get attention for biogas production in Bhutan.

Only two waste-water collection and water treatment projects are in Bhutan, in particular in Thimpu and Phuntsholing (FAO 2011).

4.4.2. Water and Temperature Requirements

The smallest BGP requires at least 30 litres of water per day which doesn't have to be drinkable. Water availability is not a problem in Bhutan, most of the households are located not far than in 20 minutes walking distance to the closest water source. To ensure adequate water supply, there might be an increased workload in the households (Bajgain 2008).

The speed of feedstock conversion to biogas is determined by the temperature, as well as it determines the amount of biogas produced (IRENA 2016). Anaerobic digestion works the most effectively when the temperature of the slurry is in either mesophilic conditions, at 25-40 °C or in the thermophilic range, 50-65 °C. Though, a mesophilic digester must be maintained between 30-35 °C (Balat & Balat 2009). In a colder climate, the slurry might need to be heated up (IRENA 2016). For each 6-7 °C decrease in temperature (from 35 °C), gas production falls by approximately 50% (Chen & Neibling 2014). The southern parts of Bhutan have a subtropical climate and are therefore suitable for biogas production. The mid and northern part are much colder except for the mountain valleys (like Punakha and Wangdue) that are relatively warm and also could be used for biogas generation. In 2008, about 38% of households lived in promising altitudes where the temperature is sufficient (elevations below 1,800 masl) (Bajgain 2008).

Figure 9 shows the physical features of Bhutan where the areas with sufficient elevation and therefore temperature are in blue and green colour.

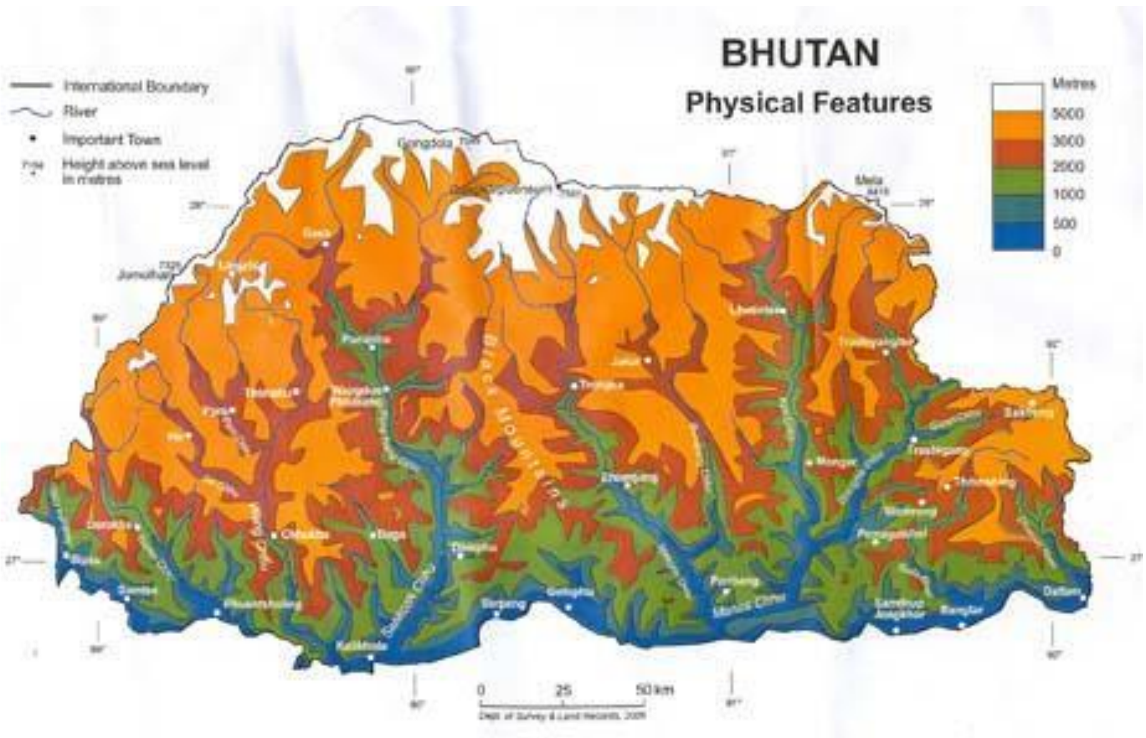

Figure 9. Hypsometric Map of Bhutan

Source: BCSEA 2016

4.4.3. Availability of Construction Materials

Local construction materials are mainly stone, sands and gravel that can be collected in the site of the households (Bajgain 2008). Bricks are too expensive to import (PIU 2012). Needed cement and pipes are available at the local market but transport to the construction site might be difficult. Biogas appliances are being sold in Nepal and Bangladesh, however, the country could produce the appliances in Thimpu (Bajgain 2008). Project Implementation Unit staff members made informational visits to manufacturing workshops in Nepal for appliance company establishment in Bhutan. The Project Implementation Unit of the Department of Livestock stated that there was no private sector producing stoves, water drains and gas valves in the country (PIU 2012).

Construction materials and needed appliances determine the price of the biogas plant. Construction masons are available locally, but their price is higher than abroad (Bajgain 2008).

4.4.4. Cost of Biogas Plant

The proposed GGC 2047 model of fixed dome biogas plant is constructed with boulder, cement, sand and gravel. Stones (boulder), sand and gravel are easily available in Bhutan (PIU 2012). Construction masons are available locally (Bajgain 2008) but their price is higher than abroad and need training for biogas plant construction. Though, at the beginning of the Bhutan Biogas Programme, a total of 74 local masons were provided with training on construction and maintenance of biogas plant (PIU 2012).

The first estimation of the BGP tentative cost from 2008 for the 6 m^3 plant, based on the Nepal GGC model plant, was estimated at 25,030 NU, plus an additional 2% investment for maintenance per year (Bajgain 2008). Later in 2012, the total cost for the 6 m^3 plant was calculated to be 29,500 NU (PIU 2012). The average saving from biogas technology for a 6 m^3 plant is estimated to be about 3,400 NU per household per year. The saving is mainly for substitution of LPG, the lowest saving is by substituting firewood with biogas (Bajgain 2008). Table 5 shows a calculation of total costs for digester of 4 m^3 to 10 m^3 sizes.

Table 5. Actual Cost of Biogas Plant

Expenditure	**Size of the digester and final costs in NU**			
	4 m^3	**6 m^3**	**8 m^3**	**10 m^3**
	Cost	**Cost**	**Cost**	**Cost**
Construction materials	12,500	14,500	16,600	19,000
Biogas Appliances	4,500	4,500	5,000	5,000
Human Resources	6,000	6,800	7,500	8,500
Equipment and Warranty	3,500	3,700	4,200	4,700
Total cost	**26,500**	**29,500**	**33,300**	**37,200**

Source: PIU 2012

4.4.5. Social Acceptance

The study on the feasibility of the biogas programme from 2008 claims that various sources show that Bhutanese people are quite open to new technologies. Social and cultural acceptance should not be a problem. The adoption of biogas technology depends on electricity tariffs since the cooking needs are satisfied with electricity (for rice cooking mainly) and complemented by firewood or LPG (Bajgain 2008).

4.4.6. Purchasing Capacity of Households

Based on the data from Households Living Standard Survey 2017, the country's unemployment rate was 2% while the data shows that unemployment is higher in urban areas (4.6%) than in rural areas (0.8%). According to the Household Living Standard Survey conducted in 2012, the annual household income is 164,829 NU, higher income was in urban areas (282,671 NU) to rural areas (104,091 NU) (ADB & NSB 2013; NSB 2017*)*. The actual cost of a biogas plant ranges from 26,500 NU for a 4 m^3 plant to 37,200 NU for a 10 m^3 plant (PIU 2012). The cost for a biogas plant is still very expensive for average rural farmers in comparison to their income level (Bajgain 2008).

4.4.7. Credit Provision and Investment Subsidy

Biogas plant does not generate income, therefore the plant needs to be paid back from other earnings. That means households, as well as financial institutions, might be hesitant for using loans, even though soft loans provision is estimated to be a determinant for the successful implementation of biogas technology within the country (Bajgain 2008). Bhutan Biogas Project goes further and the program itself provides loans to the end-users. The program provided an investment incentive of 11,700 NU per biogas plant (PIU 2012).

The provision of subsidy was another financial ease for initial investments. During the first year of the Bhutan Biogas Project, 28 households received credit in the total amount of 380,000 NU and 14 households received a subsidy in a total amount of 163,800 NU (PIU 2012).

5. Conclusions

The thesis revealed that Bhutan uses its natural resources to produce electricity which is mainly used in the building sector and industry. All electricity produced is from renewable energy sources and together fill little over one-fourth of the energy supply mix. The rest is filled with non-renewable energy sources that are imported in the country and used in the transport sector, residential as well as in the industry sector. Bhutan is projecting electricity usage in the transport sector. Additional transmission network improvements and promotion of electricity usage on the household level could increase its usage as a substitution of fossil fuels used for cooking and heating. To conclude, electricity expansion is more likely to happen in the next decade as more sectors will utilize it for their end-users.

Therefore, the expansion of the fuel mix by solar and wind energy is crucial for keeping the energy security which is dependent almost exclusively on hydropower generation. Solar energy generations already contribute to the supply mix by grid-connected and stand-alone generators. Wind energy shows good potential for further diversification as it complements hydropower sources in the lean months in the river flows with decreased electricity generation. However, the main limitation is the terrain fragmentation across the country that makes it problematic to construct wind power plants and to connect them to the grid.

Biogas technology is not primarily used for electricity generation, however, its usage can help to decrease the import of fossil fuels for household usage by substituting LPG used for cooking and an overall decrease in fuel-wood collections for cooking and heating purposes. Fuel-wood consumption was the main reason for biogas implementation programs since the last century. Fuel-wood usage together with the LPG and kerosene are burdensome for the environment and household's income. The income per capita is an indicator of economic wellbeing in the country and as is a determinant of the living standards condition. Biogas decreases the costs a household must spend on LPG and kerosene, plus it can completely substitute the non-renewable sources already used for cooking. Moreover, it helps to ensure the continuation of natural resource preservation and helps to sustain the carbon-negative status of the country. In general, the benefits of biogas usage prevail the ones of fuelwood, LPG, and kerosene in household use. Specifically, it exhibits improvement in health conditions by improving the indoor environment that has been worsened by expansive usage of biomass for cooking and heating in households. It decreases the expenditures for fuel purchase and at the same time, provide free fertilizer which is beneficial as a majority of households are involved in farming activities.

Even though biogas technology shows the highest potential in the residential sector where there is high participation in agricultural activities with easily accessible feed for the biogas plant, the theses revealed that the estimated techno-feasible potential was reported at only around 12% of total households in 2017. The highest settlement is on the south along the border with India and in the mountainous valleys, where the temperatures are promising for biogas production. Nonetheless, the main barrier in biogas implementation seems to be the climate of Bhutan. Even though the calculation of gas volume potential is promising, the climatic conditions determining other factor influencing biogas are decreasing the number of sites for biogas plant construction without major obstacles for smooth operation. The sites where the connection to the grid was impossible due to the rugged terrain, the PV were installed. These are mainly in the north where the conditions are not favourable for biogas production. Another obstacle is the small range of proposed implementations by the country authorities. So far, the country proposed the technology for households with a sufficient amount of cattle in temperature favourable sites, but an extent of the program to the community, industrial and large-scale biogas stations is missing. Moreover, there was not any project planned that would involve non-animal feed for biogas plants which limits the potential for biogas implementation in the country. The energy supply mix could be more expanded by biogas technology if the country tries to establish a biogas plant outside the residential sector. Residential sector biogas generation is dependent on the feed from livestock that is still mainly extensively kept which makes the dung collection difficult. The municipal scale biogas plants or industry scale biogas were not mentioned at all even though it might bring a solution to the waste management in urban areas together with the diversification of urban supply mix and shifts to clean energy. The literature review showed that there is little potential for small-scale BGP implementation in urban areas on account of limited cattle breeding.

Finally, the thesis aimed to examine the relevance of biogas and based on the analysis of available literature, biogas technology evinces to have little potential to enrich the fuel mix alongside other renewable energy sources. As yet, the supply mix diversification is more likely to be by wind energy and solar energy, if not by non-renewable sources. Future studies and biogas implementation projects might discover higher potential if they involve other sources of feed and project medium and large-scale biogas plants.

By the time the Thesis was written, the data available were insufficient for further analysis of biogas feasibility in the industry and transport sector, likewise for use of other sources in biogas production than animal manure. An additional calculation of biogas generation potential requires new primary data concerning the disposal of agricultural residues, waste management and wastewater treatments. These data could reveal a potential for biogas implementation in agriculture as well as in the urban areas as a fuel not only for satisfaction of household's needs but also as a fuel for public services. Together with the profound mapping of the scale of urbanization and the subsequent shift of supply mix in the urban areas, the studies might disclose expansions by diverse energy supply sources based on the end-uses and projected end-uses in the developing environment.

Furthermore, there is a need for expert-run feasibility studies as the latest biogas implementation strategies are copying published information from Nepal's documentation of its biogas projects.

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