International Journal of Energy and Environmental Science
2022; 7(5): 80-87
http://www.sciencepublishinggroup.com/j/ijees
doi: 10.11648/j.ijees.20220705.12
ISSN: 2578-9538 (Print); ISSN: 2578-9546 (Online)

A Case Study of Biomass Power Plant in Naiman Banner of Inner Mongolia

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To cite this article:

Solongo Od, Jong Bi Wei. A Case Study of Biomass Power Plant in Naiman Banner of Inner Mongolia. *International Journal of Energy and Environmental Science*. Vol. 7, No. 5, 2022, pp. 80-87. doi: 10.11648/j.ijees.20220705.12

Received: August 24, 2022; **Accepted**: September 13, 2022; **Published**: October 11, 2022

Abstract: This paper examines noble examples of forestry biomass power plants located in Inner Mongolia Autonomous Region of China, which not only bring in with economic benefits to the people, but also encourage them to plant more and more shrubs, trees, and plants in order to reduce desertification. In addition, as a case study, future utilization potential bioenergy output of mobilizing sandy areas in Naiman Banner County was estimated in this study. Our result shows that with an average transmission distance of 50 km, the collectable biomass resources can produce electric power of 20~30 MW depending upon the efficiency of thermal conversion. This paper address different types of forest residues and energy from various biomass sources, highlight the advantage and shortcoming of each type. It can provide over 543 tons of fuels at least for the biomass power plant every day, which can fully satisfy the needs of power generation of the power plant. At present, the area of sandy plants in Naiman Banner has exceeded by 200 km^2 every year, and desertification has been reduced effectively from 6,793.06 km^2 (83.71%) in 2007 to 5,284.35 km^2 (65.31%) in 2017. The desertification in Inner Mongolia Autonomous Region of China can be solved and minimized by proper harnessing the substantial forestry biomass power plants available in the Naiman Banner County. The energy conversion process from the biomass and the type of energy required plays a vital role in identifying the type of biomass required in this sustainable example of forestry biomass power plants. Its successful practice of utilizing local resources to generate power was discussed through five important questions.

Keywords: Biomass Power Plant, Inner Mongolia, Reduce Desertification, Naiman Banner County, Sandy Plants

1. Introduction

Environmentally friendly life style is the answer to many problems the world people face now. As one of the eco-friendly renewable energy sources, forestry bioenergy has become the most promising substitute for oil and liquid fuels. Thus, the development and utilization of forestry biomass resources is becoming the focus of research for scientists all over the world. According to the inventory results of forestry biomass resources in China during 2008~2013, the national forest area was 208 million ha, forest coverage rate was 21.63%, and forest stock volume was 15.137 billion m^3. Artificial forest area was 69 million ha, and the volume was 2.483 billion m^3 [1].

According to data recently released by the China's Biomass Energy Industry Promotion Association (BEIPA), the country's biomass power generation sector added 1.51 GW of new installations during the first half of year of 2020, with accumulated installation capacity reaching 25.2 GW. Of the total, 860 MW were new waste incineration power generation facilities, with total installed capacity increasing to 13 GW; 570 MW were for processing agricultural and forestry biomass, with the capacity accumulating to 11.4 GW; 80 MW were for biogas, with the overall capacity growing to 830 MW. Over the years, Chinese government attaches great importance to the exploitation and utilization of bioenergy, and has promulgated the "Renewable Energy Law". The Law has established a framework for incentives of developing renewable energy, including the special fiscal fund, national fiscal interest discount loans, and tax concessions and so on. Based on the on-grid volume of electricity generated from biomass in various provinces, the number of subsidies by the government authorities was at around 12.7 billion yuan (approx. US$1.84 billion), broken down by 8.87 billion yuan (approx. US$1.28 billion) for the agricultural and forestry biomass segment, 3.43 billion yuan (approx. US$496 million) for the domestic waste incineration segment, and 400 million yuan (approx. US$57.8 million) for the biogas segment in 2020 [2]. Figure 1 shows the biomass power plant in Naiman Banner.

Figure 1. *The biomass power plant in Naiman Banner.*

Even with the policy support, and endeavor for expansion of the bioenergy shift, there are still some barriers for the industry. They discussed the dilemmas of the development of the biomass production, and emphasized the acquisition cost of the feedstock as one of main problems. The industry is not market-oriented, the bargaining power of suppliers is rather weak, and the raw materials cultivation, collection and transportation are laborious, so the increasing costs for production caused by the growth in demand for fuel and the lack of standard to guide the fuel market make the biomass power plants' profit decline and even completely loss. Since the rising cost of fuel is out of the control for biomass power plants, the supply chain of the fuel is constraining its development [3].

Due to the issues of the availability, distribution and transportation of biomass resource, the regions have developed the biomass power generation industry accordingly. Many successful examples of bioenergy power plants across the worldwide have been encouraging more new developments that suit their local circumstances and utilize available sources efficiently. By examining carefully their key of success and special features, a sustainable decentralized system supported by local forestry biomass can be realized.

Inner Mongolia Autonomous Region (short form: Inner Mongolia), located in the north of China, and is the third largest province in area, with its land area over 1.18×10^8 ha. Inner Mongolia preserves rich forest resources with its total forest area and living forest stock volume amounting to over 23.66×10^6 ha and 13.6×10^8 m^3, respectively, ranking first among all the provinces in China [4]. With development of the biomass industry, many projects that utilize this resource went into operation in Inner Mongolia. But still there are plenty of rooms for further exploitation. They estimated that both Southwest region and Inner Mongolia contributed to 34% of the total biomass resources potential in 2016. Besides, Yunnan and Inner Mongolia were the two highest production regions. Their collectable potential was 2844 PJ, accounting for 28.3% of the total bioenergy potential in China. The density of biomass resources in the northwest China and Inner Mongolia autonomous region was low (<25 GJ/ha) due to their vast territory. The collectable biomass resource of potential forest residue from Inner Mongolian was at 383.14PJ, with 61.32PJ of which came from shrubbery forest.

Thus, the aims of this paper are firstly to analyze Inner Mongolia's special practices of utilizing sandy shrubs to generate power in order to demonstrate how man-made shrubbery forest can be mobilized to supply the feedstock, as well as prevent desertification and secondly, to discuss the main features of the sustainable supply chain of decentralized power plants.

2. Literature Survey

The strengths of biomass power are attributed to its feedstock availability agricultural and forestry residues and the socio-economic benefits, such as secure energy supply, employment creation and regional income increments for developing countries [5-7].

They took the biomass direct-fired power plant, as a case study, which is located in the Mu Us Sandland of Wushen Banner in Ordos, Inner Mongolia where relatively abundant and widely distributed biomass resources especially Salix Psammophila (Calorific value =16.72 MJ/kg) is available [8]. The biomass direct-fired power plant is designed to consume the residues of Salix Psammophila to further promote planting vegetation. The annual estimated production of Salix Psammophila in Wushen Banner was 713,000t. The power plant is designed to consume about 166,000t of Salix Psammophila with 40% moisture with an average transportation distance of 100 km. The evaluation results show that the solar transformation of biomass direct-fired electricity in 2011 is 1.14E+05 seJ/J, and highlighted that in such a sparsely populated area, the harvest and delivery of the biomass resource is not always ensured as planned during actual operation.

By developing a multi-objective linear programming model (MLP), they analyzed the trade-offs among the economic and environmental benefits of all nodes within the forest biomass power plant supply chain, including residues, and took the Mao Wu Su biomass Thermoelectric Company in Inner Mongolia as a case, which is China's first sandy shrub biomass power plant and serves as the world's first demonstration project that uses sandy shrub stubble residue for direct combustion in semiarid areas [9-11]. The findings reveal that the biggest concern in the supply chain was high supply cost (50.3% of the total supply cost). That cost of acquisition was dependent mainly on characteristics of the fuel such as broad dispersion, low density, and high moisture content and uneven seasonal availability. However, the authors emphasized that growing of the Mao Wu Su biomass Thermoelectric Company is contributing to the prevention of desertification and defense against the harsh ecosystem in semiarid areas, with completing 24,000 ha desert control, and tended 1,333,300 ha sand shrubs; it also encourages local farmers to plant much sandy shrub, thus supporting residue-resources recycling for the biomass power plant.

They presented an integrated energy, environmental, and economic evaluation for Salix in China, and chose a typical Salix direct-fired power generation system (SDPGS) in Inner Mongolia for case study. The results show that the PTW (“planting-to-wire”) energy consumption and GHG (greenhouse gas) emissions of Salix are 0.8 MJ/kWh and 114 g CO_2 -eq/kWh, respectively, indicating an energy payback time (EPBT) of 3.2 years. The paper concludes that the SDPGS is not economically feasible unless government subsidies are granted. The same issue is discussed as the previous researches: the PTW costs are dominated by feedstock cultivation, thus scientific planning is necessary to guarantee a sufficient feedstock supply.

3. Methodologies

3.1. Study Area

The Naiman Banner is a county-level division which locate in the Inner Mongolia Autonomous Region of China is one of the most seriously desert regions in the southern part of the Horqin Sandy Land. In 1985, the Chinese Academy of Sciences established the Naiman Desertification Research Station. The region has a continental semiarid monsoon temperate climate regime, with a mean annual precipitation of 366 mm, of which 70% falls from June to August, a mean annual potential evaporation of 1935 mm, and a mean annual air temperature of 6.8°C. Mean monthly temperatures range from a minimum of −13.2°C in January to a maximum of 23.5°C in July. The mean wind speed is 4.3m per second, with occasional occurrences of gales ≥20m per second in winter and spring, when the vegetation cover is lowest and the soil is driest. Figure 2 shows the geographical location of Naiman Banner. It locates on the northeast of the capital Beijing in China.

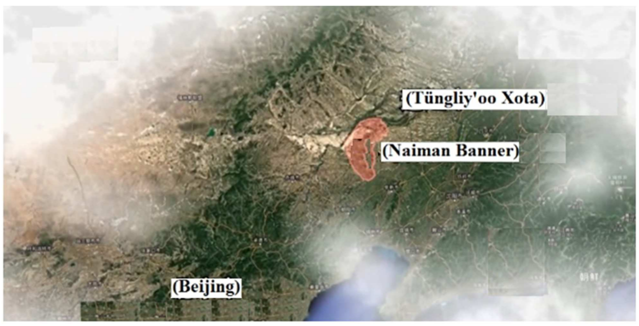

Figure 2. *The geographical location of Naiman Banner.*

Main characteristic of sandy plants is drought-enduring. Horqin Sandy Land was the main natural distribution area of Caragana Microphylla. They stated that C. Microphylla are long-lived, perennial, undergo wind pollination, have seed-based reproduction, and have a broad ecological amplitude. In northern China this characteristic may have contributed to it being a dominant species [12]. Their data show that C. Microphylla population genetic diversity is related to humidity gradients. These results indicate that desert plants would be able to adapt to an increase in humidity; indicates that genetic variation in C. Microphylla primarily depends on a greater than 5°C monthly mean temperature and soil Olsen phosphorus concentration.

The yield of seeds is high. According to Hejiawan Test Field in Zhungeer Banner, Inner Mongolia, the average yield of seeds per hectare is 440 kg. The branches of Caragana Microphylla are waxy, which can burn both dry and wet, and have strong firepower. The four-year-old branch has the largest calorific value, 20545.1kJ/kg, which is 70% of the calorific value of standard coal. Each hectare of branches and leaves is equivalent to 5.55 tons of standard coal, which is good firewood [13]. Local people of Naiman Banner call it ‘golden bowl’ because by selling it, their income has increased. Moreover, they conducted characterization of caloric value in fifteen plant species in Leymus chinensis steppe in Xilin River Basin, Inner Mongolia, and the result showed that the caloric value ranged from 16.19 MJ/kg in Kochia prostrate to 20.99 MJ/ kg in Caragana Microphylla, with a mean value of 18.76 MJ/kg which are greater than that of worldwide terrestrial plants can provide [14]. Figures 3~4 shows the aero-seeding in the rain season June to August at Naiman Banner.

Figure 3. *The aero-seeding in the rain season at Naiman Banner.*

Figure 4. *The aero-seeding in the rain season at Naiman Banner.*

In such geological conditions, apart from C. Microphylla Lam, sandy plants like Salix gordejevii, Salix mongolica, Salixmatsudana and Haloxylon ammodendron can prevent winds and fix sand as well as turning the sandy land into an oasis. Salix easily survives and grows in the desert because of its well-developed root system. More importantly, Salix has to be cut down at intervals of 3~5 years, otherwise it dies. The fast-growing plantation area and the artificial forest area has exceeded significantly. By means of planting manmade fast-growing trees like Poplar, its residual branches, tree leaves and others during the forest thinning operation, the raw energy material for power generation. They compared different wood species as raw material for bioenergy, such as white willow Salix alba L., and poplars Populus deltoides and Populus x euramericana cl. I-214. The average heating values of Willow and Poplar were 18.599 MJ/kg, 18.564 MJ/kg, respectively [15, 16].

3.2. Estimation of the Collectable Potential of Forest Residues

A series of research has studied the bioenergy potential worldwide. They use two main approaches; which are statistical analysis and geographic information system (GIS). GIS technique coupled with remote sensing, can estimate the aggregated and regionalized potentials of biomass resources. Since the primary data is comprehensive and easily accessible, statistical analysis is the most widely used method on both national and regional scales. Correspondently, the theoretical potential of biomass residues can be directly evaluated [17].

In the recent study, the biomass resources of forest residues in Naiman Banner are evaluated. Three categories of the potential availability are assessed, they are theoretical, collectable and utilizable potential; following the approach of the previous researchers [18, 19].

Theoretical potential: upper limit of biomass resources obtained in a chosen area.

Collectable potential: a certain amount of theoretical potential that can be obtained under the technical and logistics restrictions.

Utilizable potential: a certain amount of collectable potential used as energy, excluding other competing uses such as fertilizer, livestock feed and industrial raw material.

Three main types of forest residues (FR) are Salix, Poplar branches, and Caragana. The assessment parameters of FR are listed in Table 1, as (1) is used to assess the collectable potential (CP) of FR abbreviate as (CP_{FR}). The most important data of woody mass is from the prior researches, as indicated in the Table 1.

$$CP_{FR} = \sum_{i=1}^{n} Ai * Yi * Ui * LHV \quad (1)$$

Where Ai is the area of ith FR, ha; Yi is the product yield of ith FR, kg/ha; Ui is the collection coefficient of ith FR; LHV is the lower heating value of ith FR, kJ/kg.

Table 1. *Parameters for the bioenergy potential estimation of forest residues.*

Woody biomass	Product yield (kg/ha)	Collection coefficient	LHV (kJ/kg)	Reference
Shrubbery forest	938	0.50	18600	[20]
Sparse forest	1875	0.50	18600	[20]
Poplar	1200	0.50	18564	[15]
Salix psammophila	339.5	0.50	16720	[8]
Caragana microphylla	440	0.50	20545.1	[13]

Shrubbery forest means the scrublands consisting of different species of shrub plants. The estimation was calculated by the potential of shrubbery forest since the breakdown of different species plantation is now unknown [21].

According to the former researchers, when the scale of biomass power generation project increases from 1MW to 20MW, the collection coverage of biomass feedstock will increase by more than 30 kilometers from 1~4 kilometers, and the integrated costs of collection and storage management of raw materials will increase by 1 time, whereas larger scale production like more than 20MW power generation requires the collection range of 50 to 100 kilometers. Given the predicted growth of bioenergy power plants in the forthcoming, we assume that an area of 30-50km radius (from 282,700ha to 785,400ha) needs to be estimated for the area of forest residue. In our study area in Naiman Banner, approximately 35% of the sandy land has already been covered by vegetation and utilized while the rest of the 65.31% (5,284.35 km^2 or 528,400ha) is still under different level of desertification, in other words, slight desertification, moderate desertification, intensive desertification, and severe desertification [22]. Thus, the area of 528400 ha was considered.

Figures 5~6 show the large-scale planting of bush and tree with Willows (Salix) and Poplars which are mainly carry out in the Northern Hemisphere is done through agricultural tactics, and the silvicultural systems used are similar to agricultural ones. These systems include site preparation by ploughing, disking, harrowing and use of herbicide, followed by machine or hand planting of dormant cuttings about 20~25 cm long. The use of fertilizers and herbicides ensures abundant nutrient levels and weed control. Stems may be cutback after the first growing season to stimulate growth and the crop is usually harvested at 2~4 years intervals for Willow, or 8~15 years for Poplar.

Figure 5. *Utilizing sandy plants to generate power.*

Figure 6. *Large scale sandy plants to generate power.*

Figures 7~8 show the harvesting usually occurs in the winter season by using purpose-built harvesting apparatus. Harvested stems are often converted to chips on the site and then transported to the biomass power plant. After harvesting, Willow stubs are left to copse and another crop is grown in 2~4 years. Poplars can also be coppiced but are generally grown as single trunk crops and replanted after each harvest with new and improved varieties [23].

Figure 7. *Harvesting of stems in the winter season.*

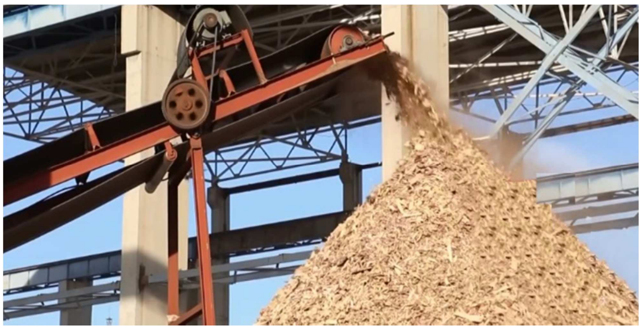

Figure 8. *Stems are often converted to chips.*

The spacing within and between the rows should be at least 0.5 m × 1.5 m. An average shrub reaches height of 58 cm and an average crown diameter of 61 cm × 65 cm for 9-year-old C. Microphylla Lam [24]. The biological characteristics of sandy plants are that it must be stumped for rejuvenation every three to five years. After one plant is cut down, about ten more plants will grow from the original one. It will form a larger area and have a better effect of sand prevention and fixation. That is, one plant can produce a cluster of a batch of plants. In addition, stumping should be in a banding area. Normally, 30 to 50 m of plants in the isolation belt will be left and 50 to 80 meters of plants will be cut down. So, it will not influence its ecological effect.

4. Discussion

The key questions discussed in this section are as follow:

1) *Environmental effects: how much wood can be sustainably harvested from the native forest?*

A vigorous, productive and sustainable forestry area with economies scale is considered as the basis of a biomass power plants based upon native forestry area. As seen from actual examples of the biomass power plant operation, forest management not only support the plant, but also protect the environment. Many other researches have confirmed that afforestation; reforestation and forest management activities can enhance carbon sequestration from the atmosphere and thus contribute to the balance of carbon budget and the mitigation of climate change. Unlike other countries that have abundant source of wood biomass, Inner Mongolia cultivates shrub lands in order to feed the industry as well as increase the vegetation area. So the amount of wood to be used as the biofuel should be calculated according to the collectable forestry biomass.

2) *Economic practicality: how much can native woody biomass power plants are sustainably mobilized for energy considering compound uses and cost effects?*

This problem explores if the mobilization cost can be considerably cheap for energy purposes in the existence of a vigorous native forestry area. Besides sandy bushes, forest biomass includes the scattered wood, residual branches, tree leaves and others during the forest thinning operation. In Inner Mongolia, reforestation practices in sandy lands have been intensively practices, but the drought and lack of water results in death of many trees. Every dead tree means a loss of money for the landowners. As there is a forest biomass power plant, they can sell the dead trees as the forest biomass fuel to the power plant. In this case, it can invisibly reduce the forest workers' loss and the risk of planting trees while increasing the local forest workers' enthusiasm for planting trees. Moreover, several wood products also become waste towards the end of their lifecycle, for example used furniture and wood from demolitions.

Driven by the forest biomass power plant, besides the sandy land which has been afforested successfully, the area of forest land needing to be planted again and renewed every year still increases further. With better infrastructure and logistics, due to the increasing wood industry in the counties, the transportation cost of supply could be reduced. From analyses of the biomass power plants' operation, it was observed seen that biomass power plants' profit decline and even completely loss due to many obstacles, but it can also clear that the forestry biomass industry helps environmental protection and can fill the gap between the utilization of forestry biomass and economic growth.

3) *Supply–demand changing aspects: how much energy demand can be met with native biomass power plant?*

A better considerate of the forms and spatial distribution of energy demand is necessary. Particularly, small- to medium-scale residential as well as commercial demands are considered the key objects in a decentralized setting. They re-examined bioenergy development in Japan (70% of the country being covered by forest) by analyzing two lines of investigation: (i) mobilizing domestic biomass resources alongside forestry revitalization in addition (ii) increasing decentralized combined heat and power (CHP) systems with bioenergy. And they estimated that in sum about 200 PJ or 11% of domestic energy demand may be possibly met with biomass. The difference in efficiency between a system that only generates power and a CHP system can be as large as 30% vs. 80%. The latter case can be more practically realized with a decentralized system supported by local forestry biomass power plants.

4) Forestry biomass power plants and people: what are the socio-economic and policy challenges?

One of sustainability factors of forest activities is that maintenance and enhancement of long-term multiple socio-economic welfares to meet the requirements of societies. Aeolian desertification harms the ecological environment, natural resources, socio-economic factors and people's life in the desert areas. According to statistics, the economic losses directly caused by Aeolian desertification were 54 billion RMB a year in China. Horqin Sandy Land is located in the eastern part of Inner Mongolia. But after the biomass power plant was established, it changed the original ecological profit and the sand fixation profit into the economic profit and increased the income of common people without damaging any ecology. In order to make the sandy bushes grow better, regular stumping and governing becomes the must jobs.

In Naiman Banner, sand blown by the wind in recent year decreases and yield of corn has increased more than before. Under the guidance of "laying down whips to herd fewer sheep but taking up shovels to plant more trees" of the local government, the past vast yellow sand becomes dense bushes. Figures 9~10 shows the new born city in the desert of Naiman Banner, which reverse the desert into an oasis state. It is a shining example of ecological system in the desert. Naiman Banner has a total of over 100 villages that plant sandy bushes, and each household of peasants and herdsmen in the whole village is responsible for about 200 mu (13 ha) of planting and managing sandy plants. When governing the desert and obtaining the green ecological benefits, herdsmen will not excessively depend on the pasturing living style any more.

Figure 9. *The forest coverage rate exceeds 30% in Naiman Banner.*

Figure 10. *The public facility in Naiman Banner.*

They found that compared to the values in the control areas, soil organic carbon (SOC) storage to a depth of 100 cm increased by 88%, 74%, and 145% at 9, 15, and 31 years after shrub planting, respectively, and confirmed that afforestation by using C. Microphylla was an effective way to sequester and to restore degraded soils, but the process was a long period of time; it would take more than 100 years to wholly restore SOC storage in active dunes through afforestation with C. Microphylla in the Horqin Sandy Land.

They proposed a recommendation that subsidy policies should be scientifically made and cautiously executed. The present policy about the on-grid price of biomass power needs adjustment. The price should be set based on the cost of power generation. The on-grid price—0.75 CNY/kWh —is not representative of the cost of all biomass power technology types. Thus, customized financial subsidy standards specific to different biomass power technologies should be adopted [24].

5) General sustainability: what are the general impacts, combined effect, and trade-offs of using local forestry biomass power plants?

The tendency concerning cleaner, greener, smaller and more decentralized energy production services in China has a positive influence on demand for biomass resources. People begin to understand that a sustainable forest management policy is a goal to be pursued by society, and participation the practice actively. The issues of sustaining forest cover, reducing deforestation, regenerating natural forests, engaging in intensive forest management, and improving the managing of agricultural and range land soils, can all be addressed through increasing bioenergy production.

Naiman Banner's sandstorms were very strong in the past year. When the wind was strong in spring and autumn after the wind blew sand into villages, cities and towns all night, people couldn't even open the doors next day. The doors were blocked. In recent years, Naiman Banner finishes artificial forest of 2.125.000 mu (1416 km^2) and sand control and forestation of 1.722.000 mu (1148 km^2) in total. Thousands of km^2 of forest land of Naiman Banner is not only the reproducible "green coalfield", but also the green base for preventing wind and fixing sand, and enriching people with increased income. Figures 11~12 shows the Naiman Banner's ecological environment has been improved greatly and people have built the new city, park and forest in the desert.

Sustainable forest management, intra-regional cash flow, and energy self-dependency may be integrally placed under the idea of 'regional circular economy'. It highlights the combined action between local action group from different areas, particularly in exchanges of goods and services, so that local communities can sustain socio-economic growth and the environment [25].

Figure 11. *The residential area in Naiman Banner.*

Figure 12. *The villages in Naiman Banner.*

5. Conclusions

This paper examines the previous case studies conducted in Inner Mongolia as good-examples of decentralized forestry biomass power plants supported by local resources. Thorough interdisciplinary cooperation, and endeavors of local government as well as herdsmen and peasants, the barren land in the past now becomes a reproducible "green coal field." The people now are not afraid of the sand anymore but use, control and love it. Their bottom-up approaches have fitted local environments, not only in a commercial sense but also based on community and social values. In the future, the leading-edge technologies for instance remote sensing and IoT can be applied to improve control and management across vast areas the regions.

Secondly, the collectable biomass resources were calculated, and the result shows that the quantity of forest biomass residue achieved with a 50% collective co-efficiency was 247819600 kg per year (198255 tons). This yields an equivalent potential energy supply of 4.6×10^{15} J per year. These biomass resources can produce electric power of 232 million kWh or 26MW, with the 18% efficiency of thermal conversion. When collective potential is fully realized, 543 tons of forest residues can be supplied every day.

Finally, this paper analyzed the development of decentralized forestry biomass power plants supported by local forestry through five questions. The concept of 'regional circular economy' and 'must job' should be integrated into the bioenergy development. While concentrations of greenhouse gases in the atmosphere from burning fossil fuels and deforestation can be gradually tackled by harnessing renewable bio-energies, livestock farming which emits a major greenhouse gas must be stopped since methane is shorter-lived in the atmosphere than carbon dioxide but is more than 30 times as effective in trapping heat.

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