ENERGY POTENTIAL ASSESSMENT AND SITE SUITABILITY OF BIOMASS-BASED POWER PLANTS IN PAKISTAN

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APPROVAL CERTIFICATE

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Dedicated to my mother,

for her belief in education and her endless inspiration,

support, and encouragement.

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TABLE OF CONTENTS

LIST OF ABBREVIATIONS

Greenhouse Gas	GHG
Combined Heat and Power	CHP
China Pakistan Economic Corridor	CPEC
Land Use Land Cover	LULC
Net Present Value	NPV
Internal Rate of Return	IRR
Lower Heating Value	LHV
Multi-Criteria Decision-Making	MCDM
Analytica Hierarchy Process	AHP
Geographic Information System	GIS
European Space Agency-Climate Change Initiative	ESA-CCI
Electricity Generation Potential	EGP
Consistency Index	CI
Special Economic Zone	SEZ
Wheat Straw	WS
Rice Straw	RS
Alternative and Renewable Energy Policy	AREP
Net Present Value	NPV
National Renewable Energy Laboratory	NREL
National Electric Power Regulatory Authority	NEPRA
Karachi Inter Bank Offered Rate	KIBOR

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Agricultural crop residue is one of the most abundantly available biomass types worldwide which can be used as a sustainable renewable alternative to fossil fuels, but its lower energy density and spatial distribution makes its collection difficult. In this study, residue availability and electricity generation potential of major crops of Pakistan i.e., wheat, cotton, sugarcane, rice, and maize were computed and mapped on district level. Energy intensity of crop residue with other geospatial factors of suitable land availability, proximity to road and existing grid-stations and baseline water stress in region were used for site suitability of crop residue-based power plants using the AHP. Results showed that 21390 GWh of electricity could be generated using these crop residues. Weighted overlay analysis resulted in highly and extremely suitable locations in central Punjab and upper Sindh provinces with some areas in north-eastern Balochistan. A total of 10 final sites for residue-based power plants were identified in Pakistan, of capacity ranging from 50 MW to 125 MW, with cumulative capacity of 930 MW. The location of Special Economic Zone (SEZ) selected as case study put to techno-economic analysis showed promising economic prospects with total capacity of 75.9 MW and Net Present Value (NPV) of 11.1 million USD. The sensitivity analysis showed that feedstock cost and discount rate are the most influencing inputs in economic analysis of crop residue-fueled power plant.

CHAPTER 1

INTRODUCTION

1.1 Background

Industrialization and population growth has increased the global energy demand and is forecasted to double by 2050 (Khan et al., 2021). This demand is met by a mix of various sources which mainly includes the coal, oil, and gas along with some renewables which include wind, solar and biofuels, and a very small portion of nuclear energy. Looking at previous consumption data, the energy usage only consisted mainly of traditional biomass up until mid of 19th century. With the start of industrialization, usage of coal spiked followed by oil and natural gas. Although renewables had been introduced in mid-20th century and there has been much pressure to increase the share of renewable energy worldwide and to limit the use of fossil fuels. But the current global energy mix is still dominated by fossil fuels, which accounts for more than 80% of energy consumed (Ritchie & Roser, 2020). The use of non-renewable energy sources, especially in developing countries with low levels of technical knowledge, not only pollutes the

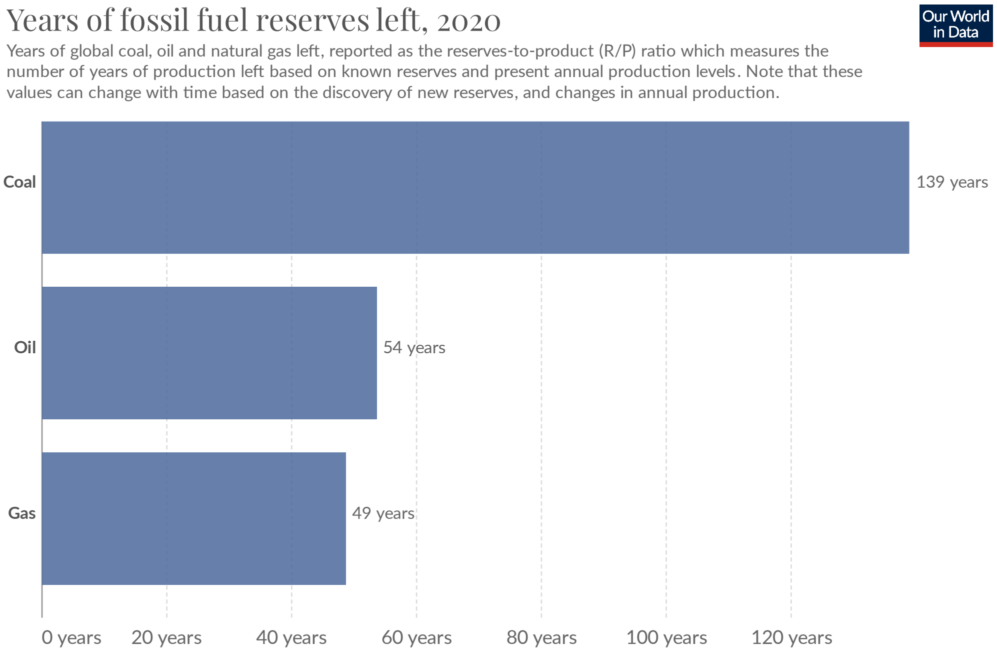


Figure 1 Years of known fossil fuel reserves left, 2020

environment but also drastically reduces these precious resources (Asakereh et al., 2022).

Availability of fossil fuels is limited since they are available at specific geographic location and in specific time-period. Another factor that makes them unsuitable for long term usage is that they have been depleting at much faster rate than ever before. The current known reserves of fossil fuels wouldn't last long, Figure 1 shows the estimated time for consumption of remaining reserves for coal, oil and gas are 139 years, 54 years and 49 years, respectively (OurWorldInData, 2020).

Consumption of fossil fuels has not only resulted in Greenhouse Gases (GHG) emissions and climate change but the consumption and depletion of these resources impact the economies and the masses (Rasheed et al., 2020). With growing energy demand, CO_2 emissions increased over 2 billion tonnes in 2021, being the largest in the history even offsetting the decline observed in the pandemic of 2020. Coal alone had a share of 40% to these emissions, followed by natural gas with CO_2 emissions of 15.3 billion tonnes and 7.5 billion tonnes (International Energy Agency, 2022). Although the increasing demand is being fulfilled using coal and oil for electricity generation worldwide but developing countries find it hard to manage it economically with ever increasing prices. So, these countries need to find sustainable, economical, and renewable sources to provide people with better access to electricity. In recent times, research is emphasized to explore the renewable energy resources as sustainable alternatives to fossil fuels, meanwhile plans and policies are being developed to establish renewables based energy sectors (Rabbani & Zeeshan, 2022). Implementation of plans and policies for deployment of large-scale renewable power generation technologies can significantly solve the energy crisis and help in curbing the climate change risk regionally and globally.

1.2 Global renewable energy scenario

In addition to reducing its negative environmental effects, renewable energy has profound social ramifications both globally and in developing nations. Theoretically, the potential worldwide capacity for the growth of renewable energy is more than the anticipated future energy demand for the year 2030. The globe generated 29% of its electricity from renewable sources, with the highest percentages coming from hydropower and wind energy in 2020, up 2% from the previous year. An extra 8% of renewable energy is anticipated by the end of 2021. Only 22% of global renewable capacity investments in 2020 (excluding China) came from developing economies. Figure 2 presents the share of renewable electricity generation as percentage in countries for year 2021 (Enerdata, 2021).

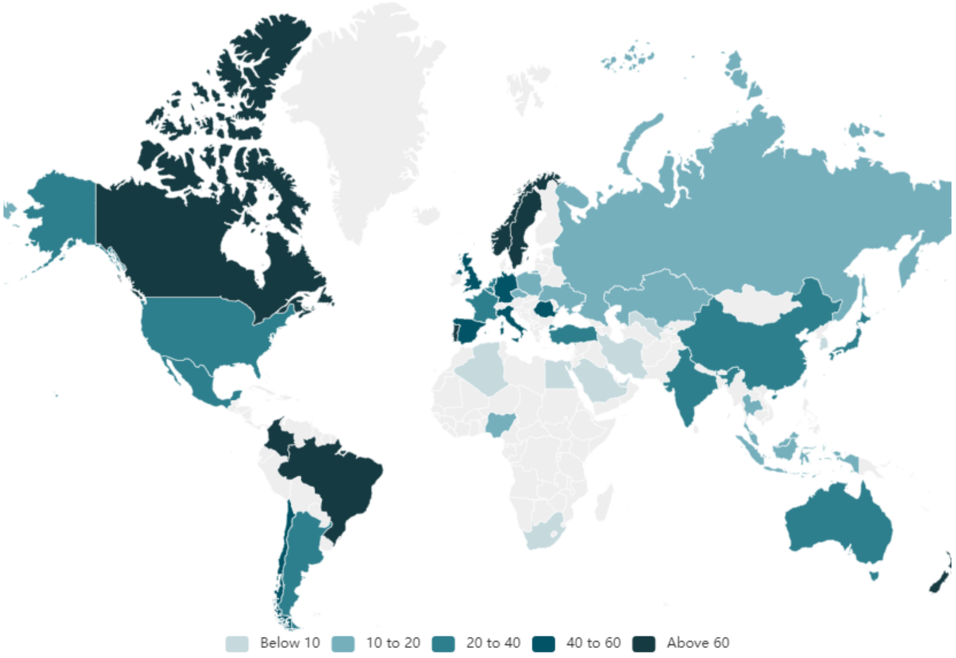


Figure 2 Share of renewables in electricity production (breakdown by country in %)

1.3 Potential and deployment of biomass energy worldwide

Biomass is considered as one of the most promising renewable energy resources as it is easily replenishable and considerably inexpensive, besides its conversion to energy through direct combustion requires minimum changes in the existing thermal power plant technology (Mana et al., 2021). Being carbon neutral, biomass fueled electricity generation shows significant reduction in GHG emissions.

In 2019, 1.17 EJ of heat from biomass-based sources was produced, 53% of which came from solid biomass and 25% from municipal solid waste. With an 88% global share, Europe leads the globe in the production of heat from biomass in power plants. In comparison to the 1.35 EJ of bioheat produced globally by CHP facilities in 2019, heat only plants produced 0.43 EJ of bioheat. The production of biofuels worldwide is dominated by America. Together, North and South America produce 70% of the world's biofuels, with Europe accounting for the remaining 15% (World Bioenergy Association, 2021).

There has been a significant increase in biomass-based power generation worldwide. Globally, 655 TWh of electricity were produced from biomass in 2019 as shown in Figure 3 (Alves, 2022). Solid biomass sources accounted for 68% of the total amount of biopower produced, while municipal and industrial waste accounted for 17%. With 255 TWh of production in 2019, Asia produced 39% of the world's biopower, followed by Europe at 35%. Power-only plants are made specifically to generate electricity. The expected amount of biopower produced in electricity-only plants in 2019 was 428 TWh. Crop residues contributed less than 3% to bioenergy generation globally in 2019 but it is estimated to meet up to 14% of global energy supply.

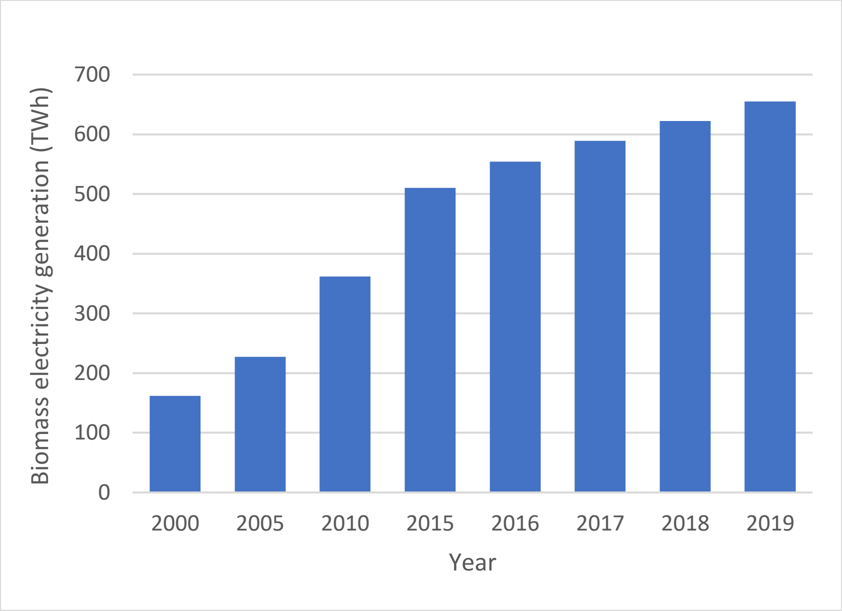


Figure 3 Global biomass electricity generation in TWh

1.4 Power generation scenario in Pakistan

Pakistan is a developing economy with a mainstay shifting gradually from agriculture to industry. Pakistan has been experiencing electricity shortage for a few decades now due to increasing urbanization and industrialization in the country. According to United Nation's estimates, Pakistan's population will increase by 45% in 2045 and with that, required services, infrastructure and energy demand will also increase. The demand-supply gap amounts to 5000 MW on average which reaches 7000 MW in the month of July when the energy demand is at peak. Multiple power plants in previous decade under China Pakistan Economic Corridor (CPEC) and other projects have been commissioned to fulfill this energy demand which has increased the installed capacity of country up to 37261 MW with a growth rate of 3.6% since year 2020 (GoP, 2021b). But to operate these plants, mostly imported fuels are used, as of June 2019, overall Generation mix consisted of 50.51% indigenous resources and 49.44% imported fuels (Government of Pakistan, 2021). They are imported in form of oil, coal and liquified natural gas which are a major source of carbon emissions. So, they are not just expensive for an economy like Pakistan but also fatal for the environment. Due to higher prices and environmental concerns, fossil fuels can no longer be relied on as a prime source of energy.

Pakistan has been one the most affected countries by climate change and though up until 2015 Pakistan's greenhouse gas emissions were about 405 Million tonne (Mt) CO_2, corresponding to only 0.93% of world's total GHG emissions. But the Coal Fired Power Plants commissioned under CPEC are likely to increase CO_2 emissions by 65% (14,500 Mt CO_2 in 2020) and push Pakistan from low contributor of CO_2 to being one of the major contributors (Ali et al., 2021). Limited share of renewable energy is one of the major causes of energy crisis in Pakistan along with circular debt, lack of effective energy policies and poor grid infrastructure (Rasheed et al., 2020). In the wake of the prevailing energy crisis, Pakistan needs to explore alternative clean, cheap, and sustainable resources of energy to keep the engine of economy running. Renewables other than hydel has only 2.23% share which corresponds to 2294 GWh in electricity generation while thermal has a huge share of 59.42% (GoP, 2021b). The contribution of renewables in energy mix in 2010 was less than 1% and Pakistan being signatory of Paris Agreement has set goals to increase her share of renewable energy up to 30% before 2030. The government has been developing plans and policies to develop its renewable energy sector as it would provide a sustainable and clean source of energy. The incentives offered, regulatory reforms and policies in favor of the investors has helped in the growth of renewable technologies in Pakistan during the recent years.

1.5 Biomass power generation in Pakistan

Pakistan has 47.1% of agricultural land which is cultivated every year for various crops including major food crops like wheat, rice, maize or cash crops like cotton and sugarcane or other vegetables and fruits (World Bank, 2018). Agriculture encapsulates huge potential to avert Pakistan’s energy woes. Pakistan can bring the agricultural residues to use for power generation which would reduce reliance on imported fuels. There are various power plants operating in country which generate electricity using processed agricultural waste. There is a potential of about 1844 MW of combined output capacity from 84 selected sugar mills (World Bank, 2016a). The currently operating power plants at the sugar mills contribute almost 364 MW out of total 37261 MW Fuel-wise installed capacity of Pakistan (GoP, 2021b). This is the only share of agricultural residue, or any type of biomass being used for power production currently in the country while other plentiful crop residue is being wasted.

1.6 Research objectives

This research was focused on conducting a comprehensive assessment of crop residue-based power generation in Pakistan. Statistical crop data at district level was used combined with relevant information consulted from literature to develop following objectives

i. To estimate and map the theoretical electricity generation of crop residues in Pakistan
ii. To spatially identify suitable sites for power plants
iii. Techno-economic assessment of selected crop residue-fueled power plants

1.7 Scope of research

This study, in the first part, maps the crop residue-based energy potential of Pakistan and uses the crop production data as starting point. However, for more accurate assessment of the crop residue available for this purpose, it incorporates the previously reported surveys about the crop residue left on field for open burning in different districts, stated as availability of crop residue along with other parameters from literature such as Grain to Straw Ratio, dry matter content etc. The estimated amount of available crop residue for each district is then equally divided into all pixels belonging to cropland class of the Land Use Land Cover (LULC) datasets within the same district to prepare 300m × 300m resolution crop residue availability map. Calorific value of each crop and efficiency of direct combustion power plant is used to estimate the electricity generation potential geographically. The second part of the study focuses on investigating the most suitable sites for crop residue based powerplant by systematic integration of other factors including road and electricity distribution networks etc. with the crop residue maps, using AHP.

In geospatial analysis for the powerplant site suitability analysis, previous studies divided the total crop residue generated in a particular area (e.g. district) to the pixels belonging to the agricultural land related classes of the land use. This type of crop residue availability maps tends to render unduly high importance to the agricultural land class in plant site selection, undermining the importance of other considered factors. For instance, a pixel may be geographically very close to road and electricity network and having high amounts of crop residue generated in its close vicinity, but because of not belonging to the agricultural crop land class, it would be having zero crop residue value assigned to it, thus making it less likely to be selected as a suitable location for plant site. However, to avoid assigning undue importance to the pixels/locations belonging to the cropland class, the basic crop residue maps are modified by changing the value of crop residue available within each pixel by the average value of all the pixels within its 50 km radius.

A thorough techno-economic analysis for a case study is also carried out under this study. The selection and potential estimation at the site were carried out as described in the first part and then required transportation distance and year-long storage for crop residue was optimized. Taking in consideration the technical parameters, required size and other raw materials, model for combustion power plant was built for electricity generation. The financial parameters were used to calculate the Net Present Value (NPV), Internal Rate of Return (IRR), payback period and return on investment.

CHAPTER 2

LITERATURE REVIEW

This chapter provides the relevant work previously conducted in the field of biomass energy assessment at regional or country level around the world and for Pakistan. Energy potential assessment of agricultural residue in link with the geospatial variables is discussed. A brief overview of the studies carried out on techno-economic analysis of biomass-based power plants is also presented.

2.1 History

Biomass has been an ancient renewable resource of energy generation. The use of biomass for energy dates to primitive times when wood was used to lit fire for the first time. By no means is biomass a new source of energy that has been discovered recently. Biomass existed on planet long before humans did, as more people lived on the planet, they began to use biomass as fuel. This indicates that the use of biomass predates the existence of humans. Utilizing fire is the initial method of using biomass as a source of energy. Humans employed biomass to produce heat and prepare meals since it is one of the simplest renewable energy sources of combustible carbon in the world. From that moment on, they became fascinated by what is now known as bioenergy. As of now, contemporary biomass energy generation is an important source of renewable energy.

2.2 Biomass to energy

There are several biomass-to-energy conversion processes including but not limited to biological, thermal, and chemical conversion which results in one or more than one product. Various techniques and technologies are used to convert biomass into a variety of useful forms of energy. Using the three primary process methods available—biochemical, thermochemical, and physiochemical—several processing stages are needed to transform raw biomass into usable energy.

Bio-chemical conversion encompasses two primary process options: anaerobic digestion (to biogas) and fermentation (to ethanol). Biomass feedstock materials are heated to high temperatures in sealed, pressure tanks called gasifiers during thermal decomposition operations. Even though the coal gasifiers' produced gas has been known to be put to use from as early as 1790s but biomass gasification has only been in use in late 1990s (Sikarwar et al., 2016). Fermentation was something that people were aware of and using long before societies were established. When humanity first began producing alcohol in the 12th century, ethanol was utilized for cooking and lighting right away (Seidel, 2021). Burning of woody biomass (forest biomass materials, wood pellets, etc.) continues to be the most common way we utilize this renewable energy resource.

For the thermo-chemical conversion routes, the four main process options are pyrolysis, gasification, combustion, and hydrothermal processing. Physio-chemical conversion consists principally of extraction (with esterification) where oilseeds are crushed to extract oil (Adams et al., 2018).

2.2.1 Biomass sources for energy

Biomass as an alternative energy source has been employed in developed countries in various forms; be it forest residues, agricultural residues, municipal waste, or special crops grown for energy generation. Some of the most frequently used biomass sources for energy generation are listed below:

i. Wood and wood processing wastes, including but not limited to firewood, wood pellets, and wood chips, as well as sawdust and trash from furniture and lumber mills and alcohol from pulp and paper mills

ii. Corn, soybeans, sugar cane, switchgrass, woody plants, algae, and crop and food processing wastes are examples of agricultural crops and waste materials that are typically used

iii. Biogenic materials in municipal solid waste, including food, yard and wood wastes, cotton, wool, and paper goods

iv. Human sewage and animal manure for biogas and sustainable natural gas generation

2.2.2 Biomass based electricity generation

Bio-power technologies use similar procedures to those used with fossil fuels to transform renewable biomass fuels into heat and electricity. The type, quantity, and qualities of the biomass feedstock, the end-use requirements, environmental legislation, economics, geography, and project-specific factors are some of the elements that influence the conversion process selection. The process path is determined by the form in which the energy is needed and the accessibility of the feedstock. The GHG emissions that could result from the utilization of biomass conversion technology will depend on how those technologies are put into use and run. Incineration of biomass remains the most common and mature technology in terms of development for biomass electricity generation.

2.2.3 Direct combustion

Direct combustion is the preferred choice for electricity generation as it does not require advanced technology and can easily be deployed with matured technology of existing thermal power generation system. All biomass types can be burned directly to heat facilities and water, supply process heat for industry, and produce electricity in steam turbines. In a boiler, biomass is burned to create high-pressure steam. These turbine blades rotate because of the steam flowing over them. A generator is powered by the turbine's rotation to create electricity. The general process of electricity generation using biomass is shown in Figure 4 (Lewis et al., 2018).

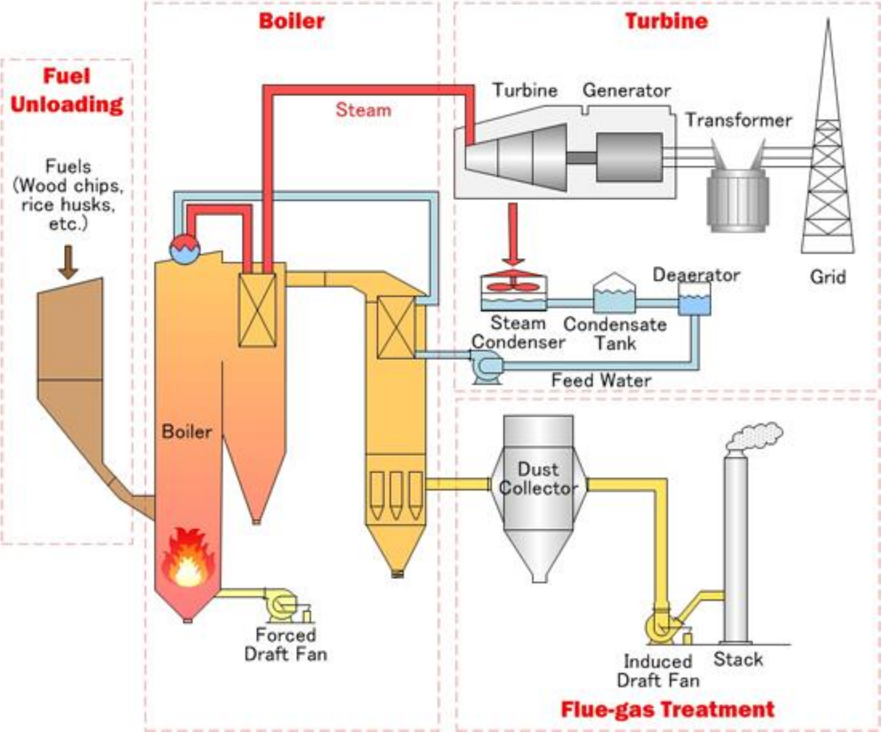


Figure 4 Biomass power generation process

2.3 Energy potential assessment of agricultural residue

There are multiple approaches used in previous works for calculating the theoretical and technical potential of agricultural residue. The most followed approach, with slight variation, is estimation of available residue for each residue by using following equation

$$R_i = P_i \times W_i \times A_i \times (1 - M_i) \qquad (1)$$

Where R_i is the amount of residue available of biomass *i* for energy exploitation, P_i is the yearly production, W_i is the ratio of residue to product, A_i is the percentage availability of the residue considering other uses and M_i is the moisture content of the residue *i*. The available residue quantity is further used for calculating the Electricity Generation Potential (EGP) using the equation (2) with little to no modification

$$EP = \sum_i (R_i \times LHV_i) \times 0.2778 \qquad (2)$$

Where LHV_i is the lower heating value for the residue of biomass *i* and 0.2778 is used for conversion from thermal energy to electrical energy.

Several studies have been conducted on estimation and assessment of agricultural residue at different locations using multiple methods and datasets, some relevant studies are tabulated below in Table 1

Table 1 Literature Review- Energy potential assessment of agricultural residue

Sr. No.	Methods	Results	Reference
1	Crop derived (lignocellulosic) and livestock derived (non-lignocellulosic) agricultural residues were used to assess the biogas production potential for Republic of Croatia	The technical potential of biogas production for lignocellulosic biomass was 6679 GWh and for non-lignocellulosic biomass, 3321 GWh	(Lovrak et al., 2020)
2	Energy crops cultivated on the marginal lands along with agroforestry residue were used for energy potential quantification in India	The agroforestry residues aggregated up to 457.02 Mt while the energy crops' total amount to be available was 1260 Mt, which corresponds to maximum energy potential of 7 EJ/year and 13.6 EJ/year, respectively.	(Usmani, 2020)
3	The residue generation and energy potential of arable field crops and horticulture crops in Turkey were explored for year 2015, using the grain to straw ratio, LHV, moisture content and dry matter content	Total amount of biomass calculated to be 59.4 Mt and 15.65 Mt for arable field crops and horticultural crops, respectively. The energy potential available from these residues were 298955 TJ for field crops and 65491 TJ for horticultural crops.	(Avcıoğlu et al., 2019)
4	Surplus biomass potential of forest and agricultural resources	A total of 235000 t/year of crop residue estimated for both	(Zyadin et al.,

	was assessed in Poland using crop production data with residue availability and forest cover data with type and availability of above-ground non-stem biomass for each type	provinces while the forest residue was limited reaching an estimated maximum of 1.4 t/ha	2018)
5	Spatial distribution and energy potential assessment of unused agricultural biomass with varying percentage availability for each residue type, carried out in Punjab, India	The total amount of unused agricultural biomass and its capacity to generate electricity was around 13.73 Mt/year and 900 MW, respectively	(Singh et al., 2008)

The studies carried out in Pakistan for crop residue-based power generation are presented in Table 2

Table 2 Literature Review- Energy potential assessment of agricultural residue power generation in Pakistan

Sr. No.	Methods	Results	Reference
1	An assumed residue availability of 50% was used to estimate residue generated from major crops, which was then in combination with waste to grain ratio and lower heating value, used to estimate the power production potential for year 2018.	The available crop residue was found out to be 40 Mt in year 2018 which could have power generation capacity of 11000 MW.	(Kashif et al., 2020)
2	Agricultural residue of 5 major crops in districts of Punjab,	An estimated 60 Mt of agricultural residue generated in	(Uzair et al., 2020)

	Pakistan was used to estimate total available residue for generating electricity and taking cost of residue in consideration, ideal districts identified for installation of power plants.	Punjab every year and it was found that central districts of Punjab with highest maize stalk generation are best suitable for building power plants with total capacity of 1700 MW.	
3	Bioenergy potential of agricultural side products was determined for time series of 2001-2010 and at spatial resolution of 1 km^2 using BETHY/DLR model while the potential power plant locations were identified using ASECO considering biomass availability and road network	The average sustainable bioenergy potential for years 2001-2010 was found to be 0.72 TJ/km^2-year with maximum of 10.8 TJ/km^2-year in year 2002. There were 5 optimal power plant location found, each in districts of Mardan, Jhang, Faisalabad, Mirpurkhas and Badin.	(Biberacher et al., 2015)
4	Lignocellulosic biomass generation and its ethanol production potential was estimated from the 5 major crops in Pakistan, for year 2013.	The theoretical residue potential amounts to 41.5×10^9 kg/year which can generate 13.45×10^9 L/year of ethanol.	(Bhutto et al., 2015)
5	Statistical data with relevant literature of crop residue, solid waste and animal dung was used for assessment of biomass-based electricity generation in Pakistan	Electricity generation potential of 2747 GWh from municipal solid waste, 5800 GWh from processed crop residue was estimated and power generation capacity ranging from 4.8 GW to 5.6 GW using animal dung.	(Irfan et al., 2015)

2.4 Geospatial site selection of biomass power plant

Besides residue availability and its power generation potential, multiple geospatial factors influencing the location of power producing facility have been reported in literature, which include road accessibility, proximity to electricity transmission network, availability of suitable land etc. so that it poses as least as possible social and economic burden. For cost affective utilization of the residues, incorporation of the spatial factors in site selection process for the power plant is critical.

Literature shows frequent use of cropland data layer with highways, railroads, gas pipelines, rivers and water bodies, urban area, and flooding area for optimal siting of crop residue-based plants. Proximity to road and electricity distribution network, water stress is important factor for site selection of power plant as significant amount of water is required for thermal power generation in the cooling towers, boilers and emission control equipment (Deshmukh et al., 2019). Similarly, proximity to the transmission lines or grid stations is also important factor as capital cost and line losses depend on the distance. Land with higher slope was excluded from the available land for power plant siting as steeper slope increases the construction cost (Morato et al., 2019). Previous studies recommend excluding land with slope >15% (Chukwuma et al., 2021)

Multi-criteria decision-making (MCDM) approach is usually used for assigning weightages when dealing with multiple factors to obtain one goal. Analytica Hierarchy Process (AHP) is the one of the MCDM tools widely used for decision making assigning in such scenarios. Several studies have used AHP to assign weightages and perform site suitability for biomass based energy facilities (Chukwuma et al., 2021; Waewsak et al., 2020). Relevant literature review for geo-spatial site suitability of biomass-based power plants is summarized in Table 3

Table 3 Literature Review- Geospatial analysis for biomass power plant site suitability

Sr. No.	Methods	Results	Reference
1	A multi criteria analysis was deployed with multiple social,	Initially 93 potential sites for biomass plants were identified.	(Ferrari et al., 2022)

	economic, and environmental constraints to identify potential sites for bioenergy plants. They were further put to 3 scenarios with road network, existing plants, and distribution network.	Under different scenarios, between 90-199 plants were found to having the biogas generation potential of 246.8 10^6 Nm^3 to 503.6 10^6 Nm^3	
2	Environmental and socio-economic criteria were employed as basis for site suitability using Geographic Information System (GIS) and AHP for Napier grass fueled power plants in Thailand	A total capacity of 420 MW can be achieved by building 5 power plants in abandoned areas, four plants with 90 MW capacity due to higher preference given to areas with high density of Napier grass	(Nantasaksiri et al., 2021)
3	Site suitability analysis for biogas power plant was carried out in Anambra state of Nigeria by giving varying weights to each geospatial thematic layer with biomass potential density	A total of 186 polygons were found to be most suitable location biowaste fueled plants	(Chukwuma et al., 2021)
4	Potential biorefinery sites were identified by using the service area, size of plant and available biomass as constraints in Canadian Prairies	A total of 12 plants were identified which would collectively have access to 25.39 dry Mt of biomass	(Zheng & Qiu, 2020)
5	Resource distribution of forest residue, crop straw and residential waste together with shortest path and transportation cost, the most economical locations for biomass power	Locations with maximum 22 km as the first level raw material collection and 63 km as second level raw material collection had the lowest transportation costs	(Cheng et al., 2020a)

	plant biomass collection points were determined in Shangzhi City, China		
6	Spatial biomass availability and road networks combined with location-allocation model were used to identify optimal locations for biomass energy plants in Queensland, Australia using forest and sugarcane residue	Optimally located plants had capacity ranging from 57 MW to 185 MW with average transportation distance from 27 km to 64 km	(Jayarathna et al., 2020)
7	GIS and AHP were used to locate para rubberwood based power plants of capacity 9.5 MW and design period of 20 years, where environmental and socio-economic constraints were used as influencing factors in Thailand	A total of 12 power plants with collective capacity of 114 MW could be installed in the most suitable locations identified. Total annual estimated electricity production was found to be 767 GWh	(Waewsak et al., 2020)
8	A GIS based analysis for biogas plant location was carried out using the heat map of citrus production along with citrus farm locations, road accessibility and collection area of 45 km in Catania, Italy	4 central locations for plants were identified with the shortest distance of 0.26 km to 7.83 km to nearby from citrus farms	(Valenti et al., 2018)
9	GIS-based inclusion-exclusion multi criteria analysis and location-allocation model were used for optimal siting of biogas plants in State of Ohio using	About 4-13 dry Tg of crop residue sustainably available to fuel 1-25 biogas plants from a transport radius of about 19-35 km	(Sahoo et al., 2018)

	corn stover and wheat straw		
10	An integrated GIS-fuzzy AHP approach was used to identify energy conversion facilities using crop residues of cocoa crops, using logistics, technical, geographical and transportation cost as selection criteria in Santander, Columbia.	12 ideal locations were identified to install bioenergy conversion plants of annual capacity ranging from 171 TJ to 479 TJ.	(Rodríguez et al., 2017)
11	GIS-MCE model developed to feasible site for biofuel production in US by performing spatial exclusion and preference analysis	Co-location with existing power plants and biorefineries reduced the ethanol production capacity by 15% of available capacity in US	(Sharma et al., 2017)

2.5 Techno-economic analysis

Abundance of biomass residue and identification of the most suitable location are not enough to recommend building of power plant. Techno-economic analysis for any suggested power plant would be needed to check its feasibility for commercial potential. Many tools have been developed to assess the technical and economic feasibility of renewable energy sources. Some of the tools found in literature consisted of engineering economics where simple equations were used for techno-economic analysis, multi-objective linear programming while some studies have used software which have all the technical and economic parameters in-built and programmed and only requires the user to put in the parameters according to their available climatic, technical, and economic conditions. RetScreen, SAM, Aspen HYSYS, HOMER etc. Previous studies found in literature for technical and economic feasibility of biomass power plants are summarized in Table 4

Table 4 Literature Review- Techno-economic analysis

Sr. No.	Methods	Results	Reference
1	Techno-economic analysis of a 10 MW plant fueled by forest biomass was carried out using RetScreen and impact of feedstock cost and electricity production cost was studied for financial viability	An NPV of 16.1 million USD with payback period of 5.6 years and benefit-to-cost ratio of 2.5 came out at 68.6 USD/tonne feedstock cost and 0.1621 USD/kWh electricity export tariff	(Prasad & Raturi, 2021)
2	Economic feasibility of biogas power plant assessed by using the financial model in SAM which calculates LCOE; mainly used as the financial assessment tool	LCOE found to be very sensitive to feedstock costs and the discount rate used in calculation	(Mana et al., 2021)
3	Cost of electricity generated from sugarcane straw from mills was calculated	Besides discount rate, fixed capital investment (FCI) and moisture content variation significantly impact the LCOE, plant has no viability for electricity price below 56 USD/MWh	(Cervi et al., 2020)
4	A spreadsheet techno-economic model for 11 MW biomass power plant for central Portugal was developed over 25 years of plant's lifetime	NPV of 2.367 M€ and IRR of 8.66% were found to be highly sensitive to the electricity production and selling price of electricity	(Cardoso et al., 2019)
5	Rice straw fueled power plants assessed using model simulation in SAM for LCOE calculation, further analysis was carried out	Average real and nominal LCOE came out to be 6.33 ₡/kWh and 10.55₡/kWh, respectively. Highly sensitive to cost of	(Abdelhady et al., 2018)

	evaluate its sensitivity to technical and economic parameters	feedstock and discount rate	

CHAPTER 3

DATA AND METHODS

This work entails the complete assessment needed for utilizing the crop residues for electricity generation from their collection on field and production of electricity. In first part, estimation and mapping of total available crop residue and its available potential is done for all the districts of Pakistan. Afterwards, these maps were used to identify the optimal locations for building power plants that would be fueled with these residues. At the end, a techno-economic analysis for a power plant at selected site with storage optimization was carried out. A framework of methodology followed in this study is given in figure 5.

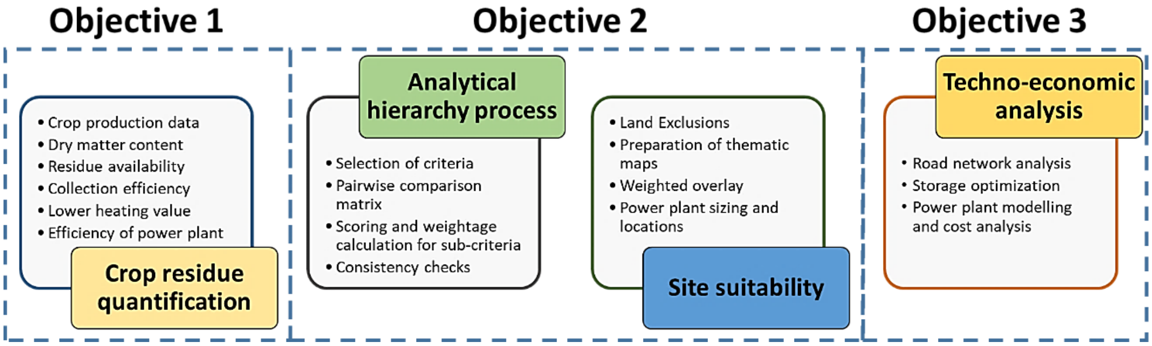
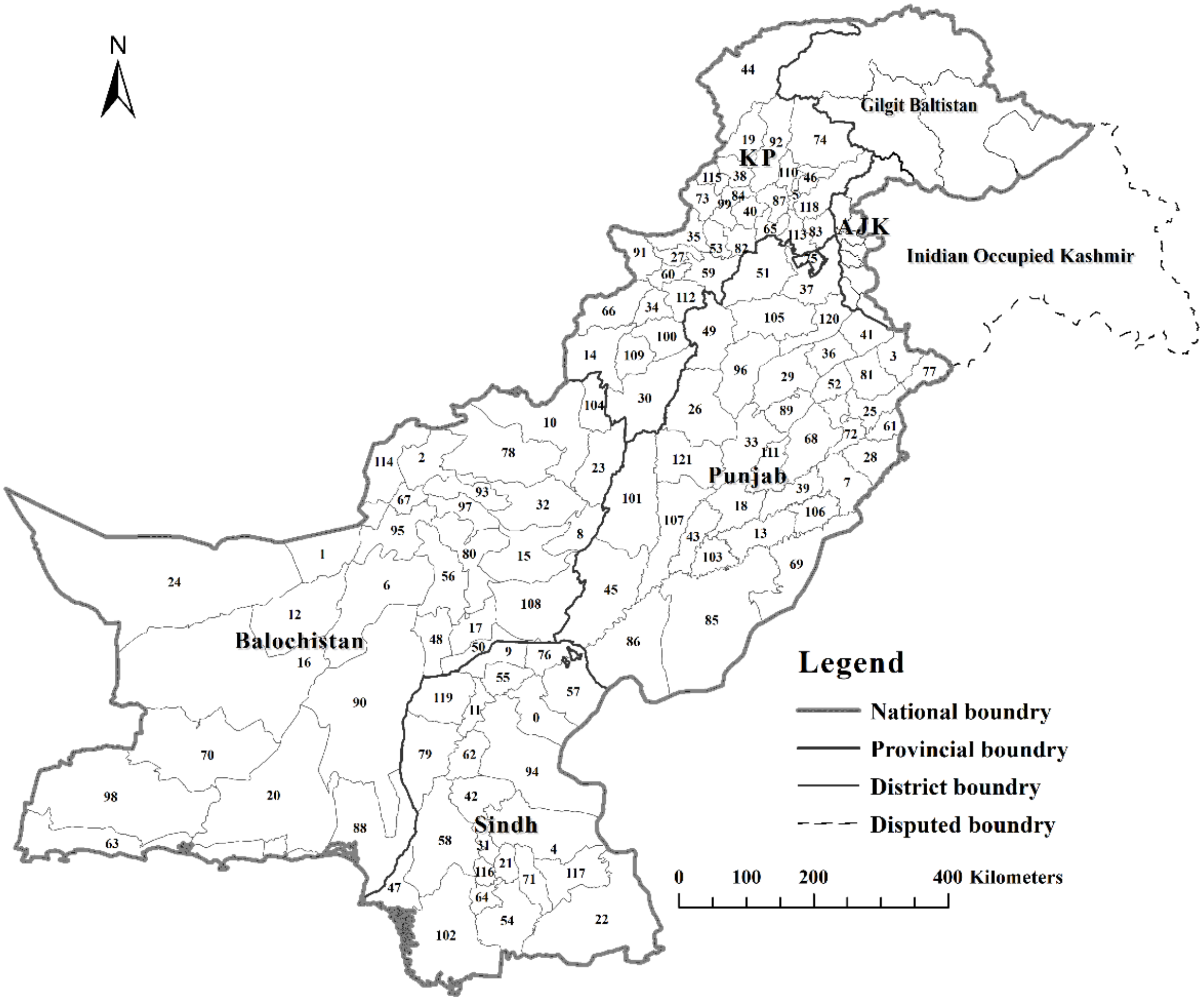


Figure 5 Methodology framework for site suitability of power plants fueled with crop residue

3.1 Study area

Pakistan is the fifth largest country according to UN’s World Population Prospects 2019 having a population of 225.2 million in 2021 and average annual growth rate of 2.4%. Pakistan lies in north-western part of Asia sharing border with India on eastern side, China on north-eastern side, Afghanistan on northern and western edge and Iran on the south-western border. Arabian sea is in south with a coastline of 1064 km bifurcated in two: Makran Coast and Sindh Coast. The country is composed of one federal and two autonomous territories and four provinces: the Islamabad Capital Territory, regions of Gilgit-Baltistan and Azad Jammu and Kashmir, and Punjab, Sindh, Khyber Pakhtunkhwa and Balochistan respectively. All the territories and provinces are divided into divisions which are further divided into districts, which are further subdivided into tehsils. A map of Pakistan showing details of the districts, is given in Figure 6.

Agriculture is one of the key sectors in Pakistan’s economy, contributing 19.2% to country’s GDP and is responsible for livelihood of about 70% population (GoP, 2021a). Wheat, cotton, sugarcane, maize, and rice are considered important crops and they collectively contribute 4.32% to Pakistan’s GDP. As of 2018 productions for these crops, Pakistan ranked 6th for cotton lint and sugarcane, 8th for wheat, 12th for rice and 20th for maize in world according to (*FAOSTAT*, 2018). Although these crop residues are produced in large quantities but most of these are burned on fields due to absence of a profitable use. This trend of residue burning in Pakistan has been causing critical environmental concerns regarding air pollution (T. Ahmed et al., 2015; W. Ahmed et al., 2019). We suggest utilizing this left-over residue for generation of renewable energy instead of burning on fields. It would rather mitigate the issue of GHG emissions that are dramatically increasing due to the practice of left-over residue burning on field.



0	Sukkur	25	Sheikhupura	50	Jaffarabad	75	Islamabad	100	Lakki Marwat
1	Nushki	26	Bhakkar	51	Attock	76	Kashmore	101	Dera Ghazi Khan
2	Pishin	27	Orakzai Agency	52	Hafizabad	77	Narowal	102	Thatta
3	Sialkot	28	Kasur	53	Peshawar	78	Killa Saifullah	103	Lodhran
4	Sanghar	29	Sargodha	54	Badin	79	Dadu	104	Sheerani
5	Tor Ghar	30	Dera Ismail Khan	55	Shikarpur	80	Sibi	105	Chakwal
6	Kalat	31	Matiari	56	Kachhi	81	Gujranwala	106	Pakpattan
7	Okara	32	Loralai	57	Ghotki	82	Nowshera	107	Muzaffargarh
8	Barkhan	33	Jhang	58	Jamshoro	83	Abbottabad	108	Dera Bugti
9	Jacobabad	34	Bannu	59	Kohat	84	Malakand	109	Tank
10	Zhob	35	Khyber Agency	60	Hangu	85	Bahawalpur	110	Shangla
11	Larkana	36	Mandi Bahauddin	61	Lahore	86	Rahim Yar Khan	111	Toba Tek Singh
12	Kharan	37	Rawalpindi	62	Naushahro Feroze	87	Buner	112	Karak
13	Vehari	38	Lower Dir	63	Gwadar	88	Las Bela	113	Haripur
14	South Waziristan Agency	39	Sahiwal	64	Tando Muhammad Khan	89	Chiniot	114	Killa Abdullah
15	Kohlu	40	Mardan	65	Swabi	90	Khuzdar	115	Bajaur Agency
16	Washuk	41	Gujrat	66	North Waziristan Agency	91	Kurram Agency	116	Hyderabad
17	Nasirabad	42	Shaheed Benazirabad	67	Quetta	92	Swat	117	Umerkot
18	Khanewal	43	Multan	68	Faisalabad	93	Ziarat	118	Mansehra
19	Upper Dir	44	Chitral	69	Bahawalnagar	94	Khairpur	119	Qambar Shahdadkot
20	Awaran	45	Rajanpur	70	Panjgur	95	Mastung	120	Jhelum
21	Tando Allah Yar	46	Batagram	71	Mirpur Khas	96	Khushab	121	Layyah
22	Tharparkar	47	Karachi City	72	Nankana Sahib	97	Harnai		
23	Musakhel	48	Jhal Magsi	73	Mohmand Agency	98	Kech		
24	Chagai	49	Mianwali	74	Kohistan	99	Charsadda		

Figure 6 Map of Pakistan with district names of 4 provinces under study

3.2 Data description

3.2.1 Crop production data on district level

Annual crop production data for wheat, cotton, sugarcane, rice, and maize for the year 2017-2018 was acquired from websites of provincial bureau of statistics for Punjab (P. Bureau of Statistics, 2019), Khyber Pakhtunkhwa (K. P. Bureau of Statistics, 2019), Sindh (S. Bureau of Statistics, 2019) and Balochistan (B. Bureau of Statistics, 2019).

Crop production, Grain to Straw Ratio (GSR), dry matter content and LHV is used to calculate the residue availability and its energy content. Values of these parameters for selected crops were taken from the previous studies conducted for the same region and are summarized in Table 5.

Table 5 Crop residue characteristics used for estimation of amount of crop residue available and its energy content

Crop residue	Dry matter content (Reference)	Grain to straw ratio (kg/kg) (Reference)	LHV (GJ/tonne) (Reference)
Wheat straw	0.83 (Streets et al., 2003)	1.75 (Streets et al., 2003)	17.15 (Jain, 1997)
Cotton stalk	0.80 (Kanabkaew & Oanh, 2011)	3 (Kanabkaew & Oanh, 2011)	17.40 (Jain, 1997)
Sugarcane trash	0.71 (Streets et al., 2003)	0.24 (Kanabkaew & Oanh, 2011)	20.0 (Jain, 1997)
Rice straw	0.85 (Streets et al., 2003)	1.5 (Irfan et al., 2015)	16.02 (Jain, 1997)
Maize stalk	0.40 (Streets et al., 2003)	2.0 (Streets et al., 2003)	16.67 (Jain, 1997)

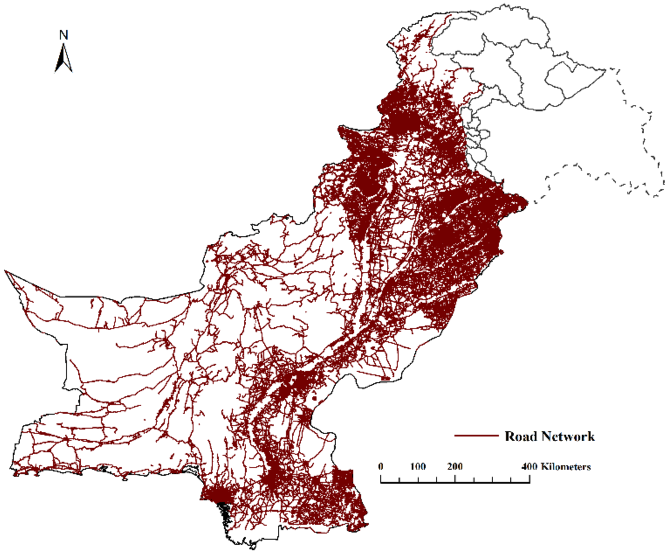
3.2.2 Geospatial data

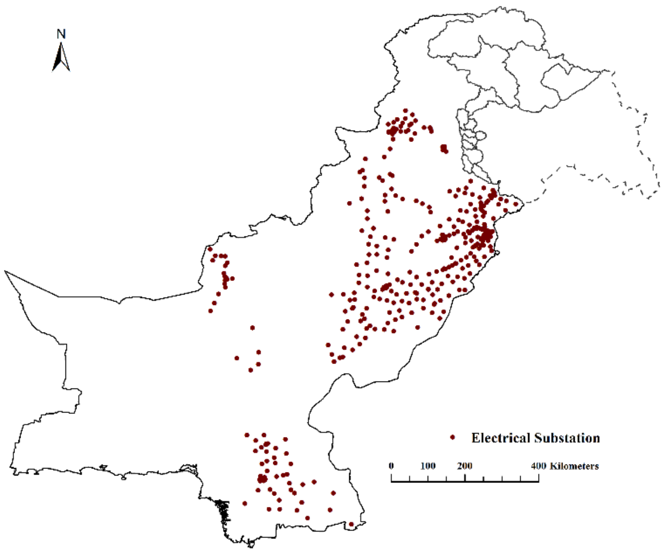
The maps of the geospatial data sets used in this study are presented in Figure 7 and their details with their respective sources are given in Table 6

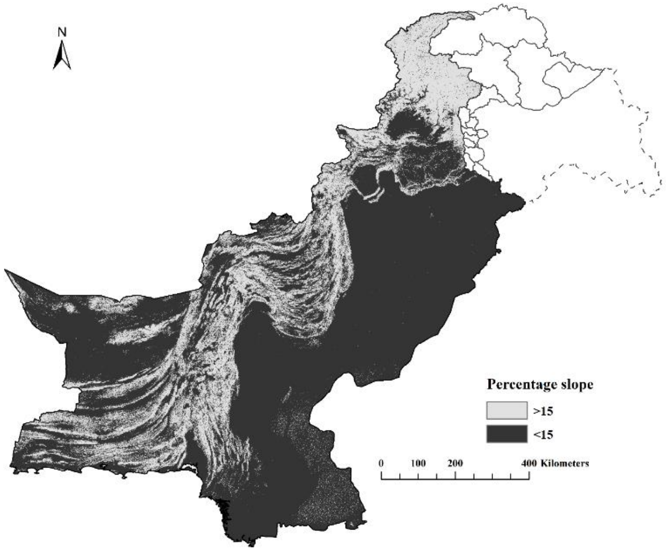
Table 6 Geospatial datasets used in the study

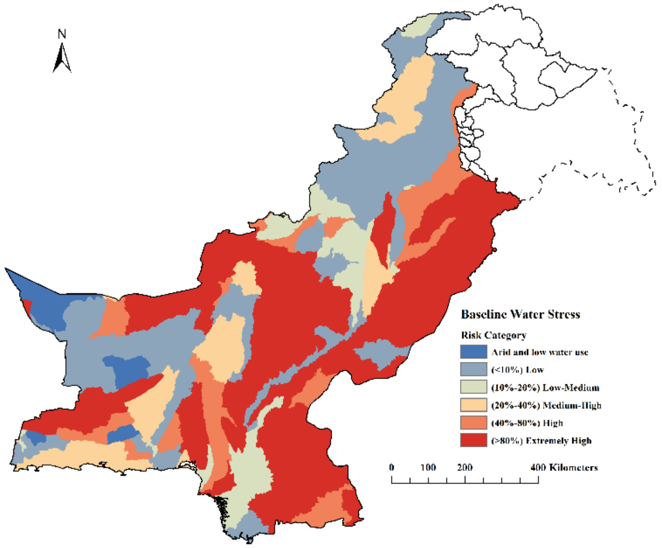
Data type	Data format	Spatial resolution[a]	Source
Road network	Polyline feature		(OpenStreetMap, 2021)
Grid stations	Point features		(World Bank, 2016b)
Slope (Digital surface model)	GeoTIFF	30m × 30m	(JAXA, 2021)
Water stress	Polygon features		(World Resource Institute, 2019)
Land cover	NetCDF	300m × 300m	(C3S-LC, 2021)
Protected areas	Polygon features		(UNEP-WCMC, 2021)
Water bodies	Raster	30m × 30m	(U.S. Geological Survey, 2020)
Population density	Raster	1km × 1km	(WorldPop and CIESIN, 2020)

[a] The vector layers (points, polylines and polygon features) were later converted to raster on the same resolution of LULC i.e. 300m x 300m


N
Road Network
0
100
200
400 Kilometers


N
Electrical Substation
0
100
200
400 Kilometers


N
Percentage slope
>15
<15
0
100
200
400 Kilometers


N
Baseline Water Stress
Risk Category
Arid and low water use
(<10%) Low
(10%-20%) Low-Medium
(20%-40%) Medium-High
(40%-80%) High
(>80%) Extremely High
0
100
200
400 Kilometers

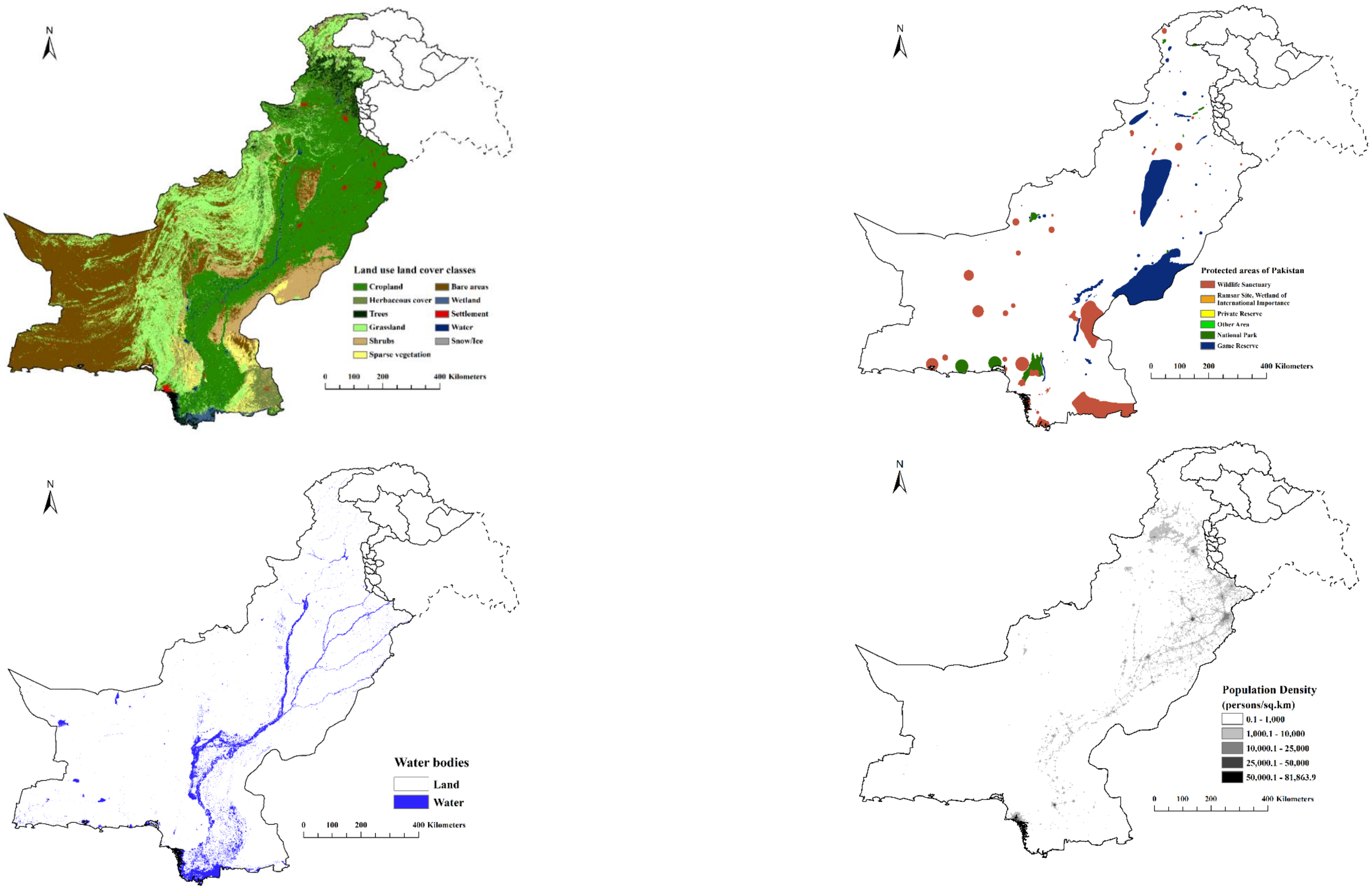


Figure 7 Maps of Land use data sets for Pakistan

Land cover data, provided by European Space Agency-Climate Change Initiative (ESA-CCI) for the year 2020, was taken which is at 0.002778° resolution (approximately 300m) and contained 22 classes. Reclassification of this data was done (C3S, 2021) to group various classes as given Table 7

Table 7 Reclassification of LULC for land suitability

	Class Name	**Class Description**
1	Cropland	Rainfed cropland, Irrigated cropland, Mosaic cropland (>50%)/ natural vegetation (tree, shrub, herbaceous cover) (<50%)
2	Shrub/Grass/Herbaceous	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (< 50%), Mosaic tree and shrub (>50%) / herbaceous cover (< 50%), Mosaic herbaceous cover (>50%) / tree and shrub (<50%), Shrubland, Grassland
3	Trees	Tree cover, broadleaved, evergreen, closed to open (>15%), Tree cover, broadleaved, deciduous, closed to open (> 15%), Tree cover, needle-leaved, evergreen, closed to open (>15%), Tree cover, needle-leaved, deciduous, closed to open (>15%), Tree cover, mixed leaf type (broad leaved and needle leaved), Tree cover, flooded, fresh or brackish water, Tree cover, flooded, saline water
4	Sparse vegetation	Sparse vegetation (tree, shrub, herbaceous cover), Lichens and mosses
5	Bare Areas	Bare areas
6	Wetland	Shrub or herbaceous cover, flooded, fresh-saline or brackish water
7	Settlement/Urban	Urban
8	Water	Water
9	Snow/ice	Permanent snow or ice

3.3 Energy potential assessment

3.3.1 Residue availability

The methodology for the estimation of available biomass in each district given by Azhar et al. (2019) is followed. Following equation was used to calculate the available biomass in each district.

$$C_{m,j} = P_{m,j} \times GSR_j \times D_j \times \frac{\omega_{m,j}}{100} \times \eta_c \tag{3}$$

Here, $C_{m,j}$ is the amount of residue (tonne/year) of crop type j available for collection in district m. $P_{m,j}$ represents the annual production (tonne/year) of crop j in district m. The GSR_j in Eq. (3) is the grain to straw ratio and Dj is the dry matter content for the crop j. η_c is collection efficiency taken as 0.85 (Hiloidhari & Baruah, 2014) which caters for the residue loss during collection, handling, and transportation. It is to be noted here that the amount of the crop residue left on field for collection depends on the method of harvesting (mechanical or manual). It is reported that higher amounts of crop residue is left on field after mechanized harvesting than manual harvesting (Li et al., 2016). To account for the difference in residue availability for each harvesting mode, ω_m was calculated by Eq. (4) as given below.

$$\omega_m = A_m \times \alpha_m + B_m(1 - \alpha_m) \tag{4}$$

Here ω_m is the percentage of crop residue available for collection in district m. A_m and B_m is the proportion of residue left on field after mechanical and manual harvesting respectively and α_m is proportion of crop harvested using machine in district m (so $1 - \alpha_m$ is the proportion harvested manually). The values of A_m, B_m and α_m were calculated from a survey (World Bank, 2016a), which was conducted in 44 districts of Pakistan. Values of these parameters for the surveyed districts were used and for remaining districts, known values of the nearest district were used as agricultural practices are deemed similar within neighboring areas.

3.3.2 Electricity generation potential

Theoretical thermal energy potential of the districts for individual crops residues was calculated by using Eq. (5), as given below.

$$TEP_{m,j} = C_{m,j} \times LHV_j \quad (5)$$

Here, $TEP_{m,j}$ is the theoretical thermal energy (GJ/year) potential of district m for crop j and LHVj is the lower heating value (GJ/tonne) of the crop j (Table 1). The total thermal energy potential of the district m (TEP_m) was calculated by adding the energy potential of all types of crop residues collected in the district *m*, as shown in the Eq. (6) below.

$$TEP_m = \sum_j TEP_{m,j} \quad (6)$$

Based on the thermal energy potential, the electrical energy potential, EEP_m (MWh) was calculated using Eq. (7) as given below.

$$EEP_m = TEP_m \times \eta_e \times 0.278 \quad (7)$$

Here, η_e is the efficiency of thermal power plant taken as 20% (Hiloidhari & Baruah, 2014) and 0.278 is the factor for unit conversion from GJ to MWh. Assuming the plant would work 8250 hours (355 days) a year (Waewsak et al., 2020), sizing of the thermal powerplant for district *m* was calculated by using Eq. (8) given below.

$$Electricity\ Generation\ (MW_m) = \frac{EEP_m}{8520h} \quad (8)$$

3.3.3 Resource mapping

Above mentioned calculations were performed using Microsoft Excel (2021) and were later incorporated into shapefile for administrative boundaries of districts in Pakistan prepared by Saif (2018) using ArcGIS 10.8 (ESRI, 2020) to prepare district-level maps of crop residue generation and electricity generation potential.

3.4 Site suitability

The geospatial site suitability for crop residue-based power plants is divided into following steps

i. Selection of factors to be incorporated in the analysis,
    a. Land suitability maps e.g. LULC, Slope etc.
    b. Other factors e.g. road and electricity supply network, water stress index etc.
ii. Processing data for site suitability by AHP
    a. Assigning priority and relative class weights to the selected parameters, and
    b. Using ArcGIS (weighted overlay) for generating suitability maps

These steps are discussed in detail in following sub-sections.

3.4.1 Preparation of thematic maps for site suitability

LULC maps were used to identify the croplands and then overlayed with biomass energy potential at district level (Lovrak et al., 2020). Total potential of each district (MWh), calculated using Eq. (7), was divided by the underlying area (ha) of croplands in that district as given in Eq. (9). This average energy availability per unit area (MWh/ha), to be referred as energy intensity from here on, was assigned to cropland pixels.

$$Energy\ Intensity\left({}^{MWh}/_{ha}\right) = \frac{\Sigma MWh_m}{A_{crop,m}} \tag{9}$$

Where, ΣMWh_m is the total energy potential in district m and $A_{crop,m}$ is the total area covered by crop fields in district *m*. Focal statistics tool in ArcGIS spatial analyst was used to further modify the energy intensity map. The feasible distance between power plants and biomass feedstock regions is reported to be 41-86 km, using trucks as means of transportation (Shu et al., 2017), 50 km as supply radius for biomass power plants is selected as reported in previous studies (Nantasaksiri et al., 2021; Sahoo et al., 2018). An average value was calculated for 50 km circular radius around each pixel and assigned to that pixel. This tool changed the nature of data from discrete to continuous, indicating the availability of residue potential in nearby places where croplands are not present, but residue is easily accessible. As energy intensity carries high weight in MCDM for powerplant location, without this modification in the map, only cropland pixels are expected to be candidate for plant site location.

Distance from road is taken as another main criterion because transportation of crop residue to plant site is an important factor that can impact the cost of power generation. The road network for Pakistan in the form of polylines was downloaded and multiple buffers of 1, 2, 3 and 5 km around the polylines (roads) were applied for weighted overlay analysis (Waewsak et al., 2020). These buffers represented the multiple levels of accessibility to the potential power plant. The residue collection from fields would be done through the same roads which connect the fields with the main roads network.

Land use type for site selection is another important factor. Wetlands, urban areas, water, and permanent snow/ice cover classes were excluded from the available land due to their unsuitability for plant construction. Remaining land use types were grouped in 5 classes namely crop land, shrub/grassland/herbaceous, trees, sparse vegetation, and bare areas.

Ideally, the plant should be sited near the existing grid station. Proximity to grid stations was implemented using buffers. Locations of existing grid stations were used in form of point features and multiple ring buffers were created at 3, 8, 50 and 80 km distances. A 100 meters buffer around each substation was excluded from analysis as a safety measure.

The Aqueduct water risk atlas was used to identify the most water stressed areas in country. The values of baseline water stress were in percentages and categorized in 5 classes, higher percentage values indicate competition among users and hence were given lesser preference.

3.4.2 Land use exclusions

Multiple factors were used for exclusion in LULC map because of their environmental importance. This included future expansion of urban areas, slope, surface water bodies and protected areas. Future urban area expansions were excluded from LULC map using the (Urban areas) Settlement class from ESA-CCI Land cover. Population density (WorldPop and CIESIN, 2020) was used to identify the underlying population in these urban settlements to estimate their expansion for accommodating the future population. Considering 25 years' service life of the plant, percentage increase in population was calculated using Eq. (10).

$$Percentage\ population\ increase = \frac{P_{2045} - P_{2020}}{P_{2020}} \tag{10}$$

Where P_{2020} and P_{2045} are total projected population of Pakistan for the year 2020 and year 2045 respectively (UN, DESA, 2019). It was then employed with the population of extracted major urban areas to render the expansion of respective urban settlements using QGIS plugin.

The class of surface water bodies in land cover map (C3S-LC, 2021) showed the presence of water on surface on annual average basis, ignoring the seasonal variation in the forms of the flooded banks of rivers in monsoon or expansion of lakes and ponds after rains. To resolve this, Landsat 8-OLI data (U.S. Geological Survey, 2020) for multiple days in 2020 was used to identify the surface water bodies. The classes of seasonal, permanent, and ephemeral water bodies were excluded except the permanently lost water bodies (M. Ahmad & Zeeshan, 2022).

Pakistan has a very diverse landscape, including mountain peaks, plateaus, and alluvial plains. Areas with slope>15% were excluded (Chukwuma et al., 2021), as construction becomes challenging and costly in those areas. The ALOS world 3D – 30m digital surface model data was used to determine slope across terrain of Pakistan).

Environmentally sensitive and other important places were excluded using World database on protected areas (UNEP-WCMC, 2021), which contained wildlife sanctuaries, national parks, game reserves and other protected areas.

3.4.3 AHP for site suitability

AHP is a technique used for decision making by identifying the relevant factors and quantifying their weights, in relation to each other. The detailed method for using AHP is given in literature (Saaty, 2008) and is briefly explained here. Firstly, the goal of AHP in our study, was defined as site suitability of residue-based power plants. Then selected criteria factors, discussed in section 3.4.1, were hierarchically established. A pair-wise comparison matrix of the selected factors was made for site suitability and is given as Table 8.

Table 8 Pair-wise comparison matrix of main criteria factors

Criteria factors	**Water stress**	**LULC available**	**Distance from grid station**	**Distance from road**	**Energy intensity**
Water stress	1.0	0.3	0.2	0.1	0.1
Distance from grid station	3.0	1.0	0.3	0.3	0.2
LULC available	5.0	3.0	1.0	1.0	0.3
Distance from road	7.0	3.0	1.0	1.0	1.0
Energy intensity	9.0	5.0	3.0	1.0	1.0

Relative weights were assigned to each criterion using a 1-to-9 scale, 1 being the least and 9 being the most important, as explained in Table 9

Table 9 AHP scale for criteria weighting

Intensity of weight	**Definition**
1	Equal importance

3	Weak/moderate importance
5	Essential or strong importance
7	Very strong or demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between two adjacent values

The input weights assigned to sub-criteria factors are presented in Table 10

Table 10 Input weights of sub-criteria used in AHP

Sr No.	Criteria	Unit	Sub-Criteria	Input Weights
1	Energy intensity	kWh/ha	<194	1
			195 - 550	5
			551 - 1003	7
			1004 - 2457	9
2	Distance from Road	km	0.1 to 1	9
			1 to 2	7
			2 to 3	5
			3 to 5	3
			> 5	1
3	Land Use		Bare Land	9
			Sparse vegetation	7
			Shrub/Grass/Herbaceous	5
			Trees	3
			Cropland	1
4	Distance from Grid Station	km	0.1 to 3	9
			3 to 8	7
			8 to 50	5
			50 to 80	3

			>80	1
5	Water Stress	%	Low (<10%)	9
			Low-Medium (10-20%)	7
			Medium-High (20-40%)	5
			High (40-80%)	3
			Extremely High (>80%)	1

The weights of criteria were then calculated as the eigenvector of pair-wise comparison matrix. To check the reliability of assigned and calculated weights, consistency checks were performed using following equations (Aly et al., 2017). Consistency Index (CI) is calculated using Eq. (11)

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{11}$$

Where n is the number of factors or size of matrix and λ_{max} is the maximum eigen value. This CI was then used to calculate the Consistency Ratio (CR) using Eq. (12).

$$CR = \frac{CI}{RI} \tag{12}$$

Where RI is random index, an average of CI values calculated for random matrices of same size, calculated and given by (Saaty, 2008)

3.4.4 Weighted overlay

Once the selection criteria were defined, respective data was downloaded to produce maps which were then edited, processed, and overlaid to perform AHP using weighted overlay tool in ESRI’s ArcGIS Desktop 10.8. For vector feature data like road network and location of substations, buffers were created for defined ranges of distance. These layers were then converted into raster layers because application of GIS for overlaying thematic layers requires all the layers to be in same data format and coordinate system. The raster layers prepared for AHP are processed using weighted overlay tool in ArcMap.

The final weightages in pair wise comparison matrix were assigned as the percentage influence and input weightages of sub-criteria were assigned under scale value. The overall influences should sum up to 100 and the resulting raster values range from 0-9 where 0 means least and 9, the most suitable. The resulting raster was reclassified based on equal interval, pixels of value 0 and 1, 2 and 3, 4 and 5, 6 and 7, and 8 and 9 were grouped as Least suitable, Slightly suitable, Moderately suitable, Highly suitable and Extremely suitable locations, respectively.

The” extremely” suitable locations were extracted and converted to polygon feature class to eliminate the competing locations. Focal statistics tool in spatial analyst was used on the energy intensity map to calculate sum of electricity potential in proximity of 50 km radius around each pixel. It was then used to identify the EGP in 50 km circular radius around each most suitable location using Zonal statistics tool. For each identified most suitable location, EGP was used for sizing the power plant at that site. A condition of area requirement was imposed in a study done by Hassaan et al. (2021) for siting solar power plants in Kuwait. As a biomass combustion CHP on average requires 3.5 acres/MW (1.42 ha/MW) of land (NREL, 2018), land parcels with an area less than this requirement were excluded from most suitable sites. One site from clusters of remaining suitable sites with highest underlying EGP was selected.

3.5 Techno- economic analysis; Case study of SEZ Faisalabad

There has been a plan to build 9 Special Economic Zones (SEZs) under the China-Pakistan Economic Corridor (CPEC), 4 of which are under construction at the locations mentioned in Table 11 below

Table 11 Special Economic Zones being constructed under CPEC

SEZ Name	Latitude	Longitude	Address
Rashakai Special Economic Zone	34.06575	72.14629	Nowshera KP
Dhabeji Special Economic Zone	24.79938	67.50621	Thatta Sindh
Allama Iqbal Industrial City	31.69362	73.21475	Faisalabad Punjab
Bostan Special Economic Zone	30.38912	67.01264	Pishin Balochistan

Residue availability in areas was calculated using crop production data for the year 2019-2020. The corresponding EGP was calculated following the method used in first objective of this study, overlaid with the croplands class of LULC map to determine the energy potential in 50 km radius of each SEZ, location with highest residue availability was selected for further analysis. After selecting the suitable site for power plant based on the biomass availability, for utility scale biomass power plant, site specific techno-economic analysis needs to be done in addition to previously adopted factors.

This analysis was divided into 3 steps as listed below

i. Road network analysis using network analyst
ii. Storage size optimization
iii. Technoeconomic analysis using SuperPro Designer

3.5.1 Road network analysis

Once the SEZ has been finalized with regards to availability of crop residue, further detailed analysis for transportation distance from fields to selected site was performed. The road network in form of polylines was used to practically estimate the distance for transportation of crop residue. The road network for 50 km radius area, around the selected SEZ, was used. The supply region falling under this radius was divided into 25 km × 25 km grid cells (Ma et al., 2022) and each cell center was assigned as the residue collection point for transportation vehicles. The network analyst tool in ArcGIS 10.8 was used to identify the shortest road distance from these collection points to the power plant site to estimate the cost of transportation more realistically. Cost and capacity of transporting straw in trucks was calculated based on the local practice of trucks carrying the straw in forms of small square bales. The total cost of 1 large truck carrying around 25 tonne of straw was used to calculate the transportation cost in PKR/tonne-km.

3.5.2 Storage optimization

After site selection and road analysis, storage optimization was done as storage plays a crucial part in economic feasibility of a biomass based power plant (Allen et al., 1998). Wheat Straw (WS) and Rice Straw (RS) being in abundance at selected location were chosen as fuel for power generation. The total collectable amount of WS and RS generated in a year was divided so as to utilize the available residue’s thermal energy potential to fullest and keep the size of storage as small as possible. The amount of straw previously received and currently present along with the quantity of straw burned each day are the chief factors that influence the size of storage. The width and height of the residue piles are also have significant impact on the required storage area (District, 2010).

The harvest season of wheat and rice lies at almost 6 months from each other, and WS and RS have similar bulk densities (Cheng et al., 2020b) which make them suitable for baling using the same equipment. A large rectangular bale which can be used to bale 500 kg of straw in bale of dimensions 1.6m×1.20m×1.25m and density of 208 kg/m^3, was used in the analysis. Assuming 6 bales (Sahoo & Mani, 2017) would be stacked at each other, at maximum, for smooth operation of moving bales from storage facility to the boiler. Heating value of WS and RS with bale size and density were used for estimating the required storage area for total exploitable straw in a year.

3.5.3 Techno-economic Analysis model

After the storage size and road network analysis, a biomass power plant direct combustion model was built in SuperPro Designer to assess the viability of power plant at selected site. The process flow diagram shown in Figure 8 presents all the operations involved in the process.

According to the equipment performance, individual unit processes are parameterized in the model. Energy and mass balances are computed for each process along with the economic performance to model the entire system. The technical parameters of main equipment used for operation with their cost and capacity are presented in Table 12 below

Table 12 Cost and capacity of main equipment at the power plant

Description	**Capacity**	**Unit Cost ($)**	**Cost ($)**
Steam turbine-generator	84.40 MW	11,885,000	11,885,000
Steam Generator	545.70 MT/h	4,248,000	4,248,000
Grinder	79.00 MT/h	473,000	473,000
Heat Exchanger	48.23 m^2	94,000	94,000

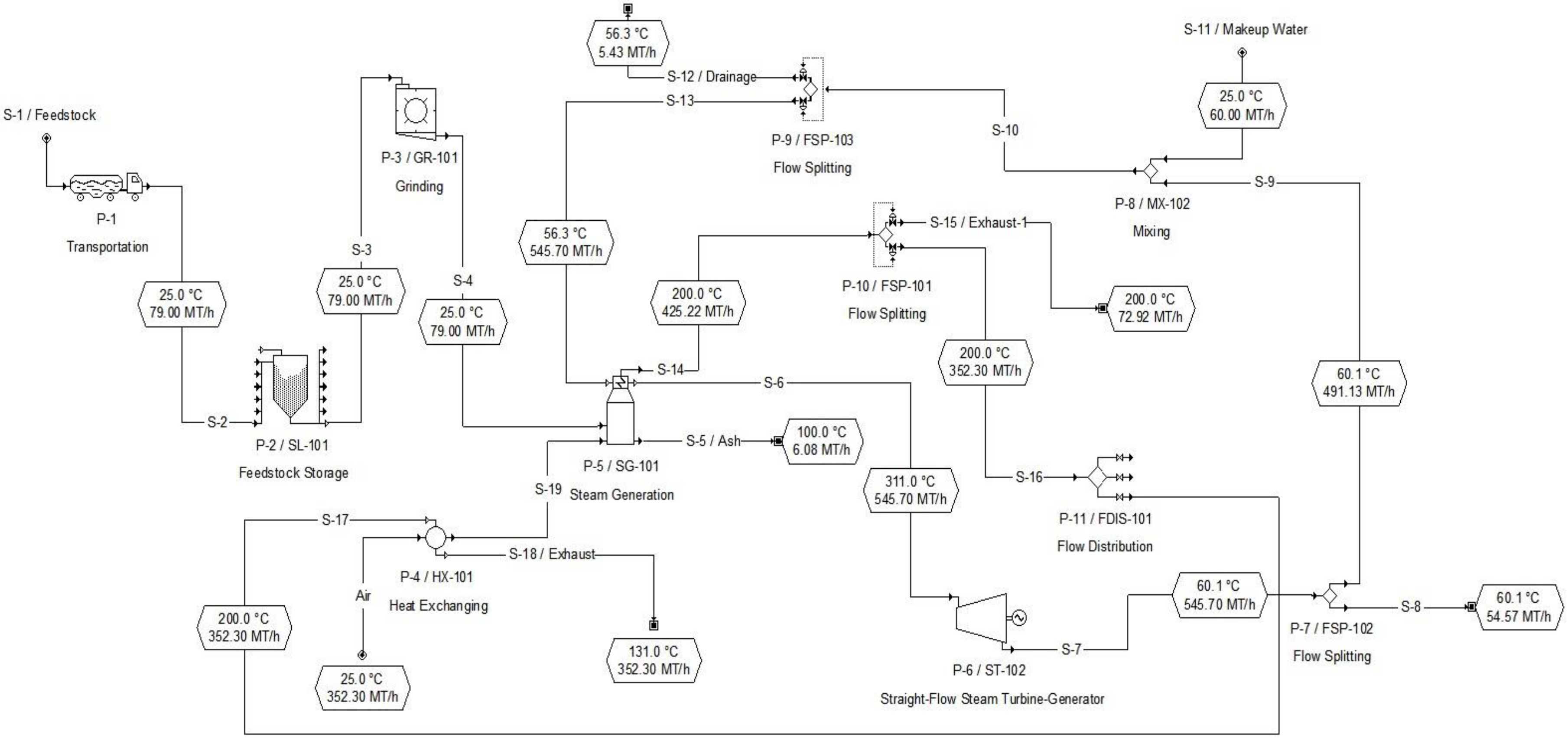


Figure 8 Process flow diagram of biomass power plant model in SuperPro Designer

The average annual inflation rate for the year 2022 was considered whereas the policy for interest rate for biomass combustion power plants given by National Electric Power Regulatory Authority (NEPRA) was used. The Karachi Inter Bank Offered Rate (KIBOR) is used for locally financed projects, State Bank of Pakistan is the issuing authority for KIBOR. The cost and financial parameters used for economic viability in this study are tabulated in Table 13.

Table 13 Input financial parameters and costs

Input parameter	Value	Unit	Source
Inflation rate	9.5	%	(WorldData.info, 2022)
Interest rate (NPV)	15	%	(*Trading Economics*, 2022)
KIBOR	15.74	%	(SBP, 2022)
Loan Interest (KIBOR+3%)	18.74	%	(NEPRA, 2021)
Feedstock cost[a]	51	$/MT	(NEPRA, 2021)
Cooling water	0.03	$/MT	(Kablouti, 2015)
Transportation	0.05	$/MT-km	Local transporters survey
Boiler feed water	8	$/ton	(WASA, 2019)
Electricity selling price	0.15	$/kWh	(FESCO, 2022)
Operator fee	0.465	$/hr	(WageIndicator, 2022)
Supervisor fee	0.93	$/hr	Assumed[b]
Project lifetime	30	years	(NEPRA, 2021)

[a] Biomass + Storage
[b] Twice the operator fee

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Residue availability

The amount of crop residue available for electricity generation was estimated to be 21.6 Mt, most of which was wheat straw (33%) followed by sugarcane trash (30%), rice straw (20%), cotton stalk (15%) and the maize stalk (3%). Relative amounts among the crops varied largely across districts due to the type of crops cultivated, mode of harvesting adopted and the alternative uses of the residues. District wise distribution of residue availability and EGP of each crop are presented in Figure 9 and Figure 10. The croplands extracted from LULC show that crops are produced throughout Punjab due to the extensive river and canal system in the province. In Sindh, most of agricultural fields are present along the Indus River. KPK comes 3rd in crop production due to less cropped areas, low production and yield. Blochistan has the least crop cultivation and production due to unavailability and poor management of water resources, arid conditions, and low quality inputs (Asian Development Bank, 2018).

4.2 Electricity generation potential

An estimated 21390 GWh of electricity can be generated annually, using residues from all 5 crops. This corresponds to a capacity of about 2500 MW which can significantly help in limiting the electricity shortfall of 5000 MW (Rafique & Rehman, 2017). As per Alternative and Renewable Energy Policy (AREP) 2019, formulated by Government of Pakistan, the goal has been set to increase the share of renewables up to 20% by year 2025 and 30% by year 2030 for electricity generation (AEDB, 2019). Pakistan's electricity demand is likely to reach 192640 GWh in 2025 (Tao et al., 2022), the estimated potential (21390 GWh) makes 11% of that demand, a significant contribution to achieve the AREP 2019 goal.

Total district wise EGP as shown in Figure 11, depicts electricity generation potential of 100 GWh or above for almost all the districts in Punjab and Sindh. Districts of Khairpur (94), Nausharo Feroze (62), Shaheed Benaziarabad (42), Sanghar (4), Badin (54) and Ghotki (57) in Sindh have potential ranging from 500 GWh to 1000

GWh. These six districts can collectively contribute 4674 GWh, approximately 2.4% of the estimated national electricity demand for year 2025. In Punjab, Rahim Yar Khan (86), Faisalabad (68), Gujranwala (81) and Sargodha (29) are the districts with highest potential providing a total of 4885 GWh, approximately 2.5% of electricity demand for 2025. It is to be noted that most of these districts have already developed industrial cities with high electricity demand. Building power plants at these locations would help in fulfilling their demand, increase production and job opportunities. Rahim Yar Khan (86) alone has a potential of 2810 GWh, greater than the total share of renewables (2294 GWh) to electricity generation in Pakistan (GoP, 2021b). The district wise mapping of crop residue-based electricity potential suggests a promising prospect for renewable power generation in Punjab and Sindh provinces.

4.2.1 Spatial variation in electricity generation potential

Figure 12 shows spatial variation in energy intensity at 100m × 100m resolution. The contrast in Figures 7 and 8 can be explained by the fact that Figure 7 shows the overall energy potential of each district, hence districts having larger areas, may show higher potential. But Figure 8 is obtained after dividing the total energy potential of each district to the pixels identified as its agricultural lands only. As a result, some bigger districts like Rahim Yar Khan (86), Matiari (31), Ghotki (57), Naushahro Feroze (62), and Bahawalnagar (69) show higher energy intensity in some areas only where crop fields are concentrated.

Besides varying crop production, variation in energy intensity can also be explained by alternate uses of residues. Particularly, in the areas with lesser crop production (e.g. north-western region), usually the crop residue is used by the farmers as animal feed, bedding etc. The south-eastern regions show highest electrical energy intensity up to 3800 kWh/ha. It can be explained by the fact that multiple residues are generated on the same crop fields along the year. For example, wheat is cultivated in upper Sindh during the November-May period and cotton from mid-May to end of October which results in two produces of residue from same piece of land in a year.

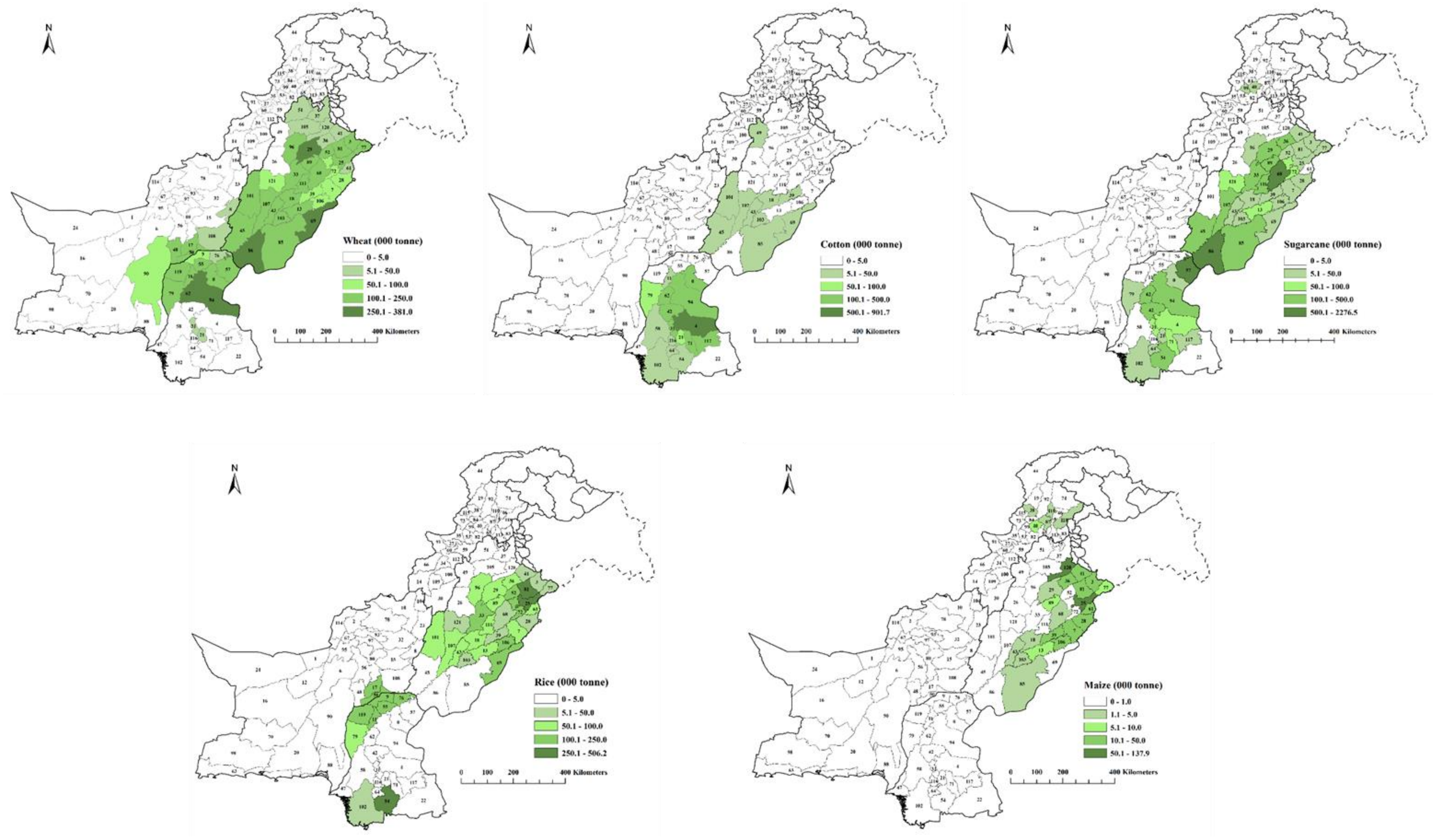


Figure 9 District wise residue generation for each crop

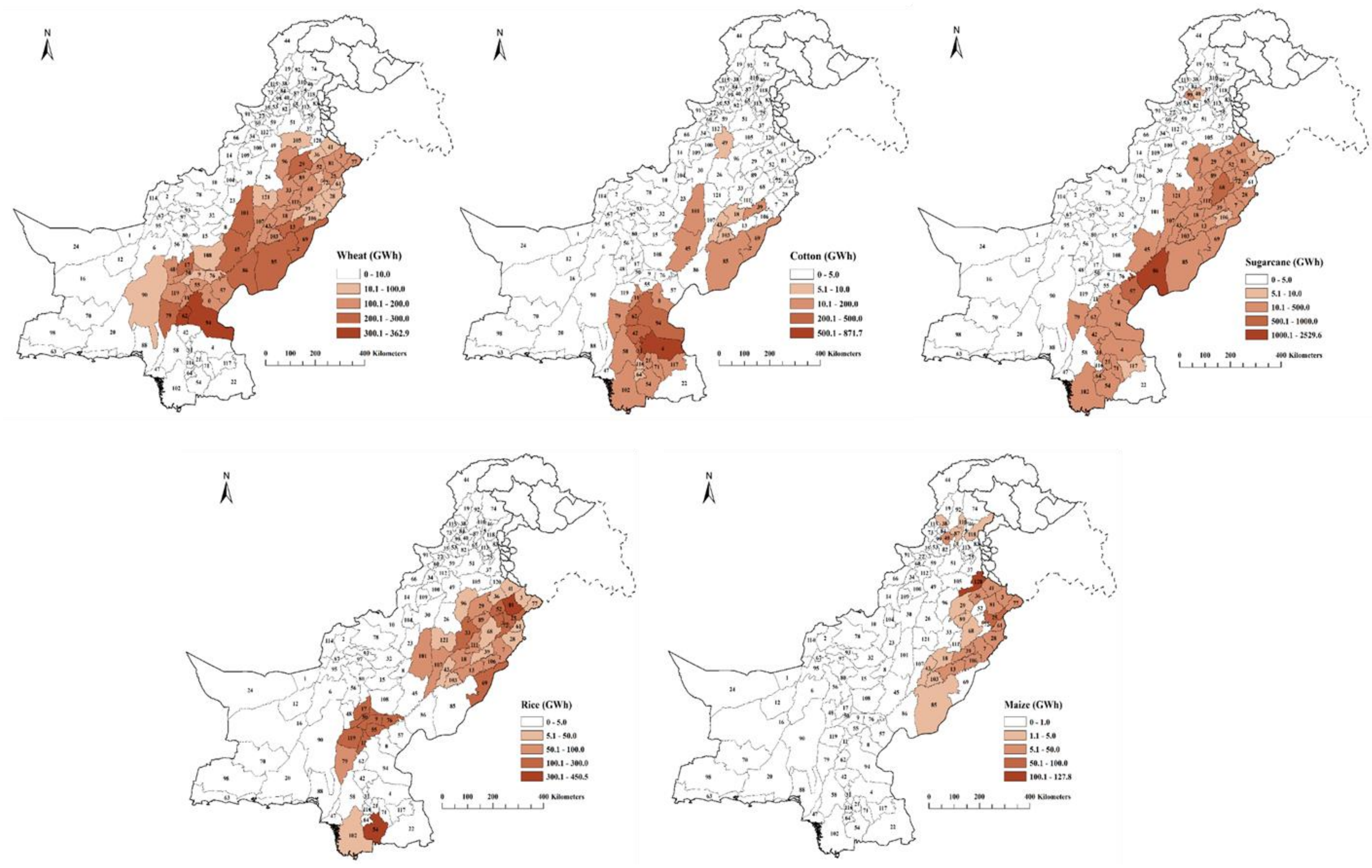


Figure 10 District wise electricity generation potential for each crop

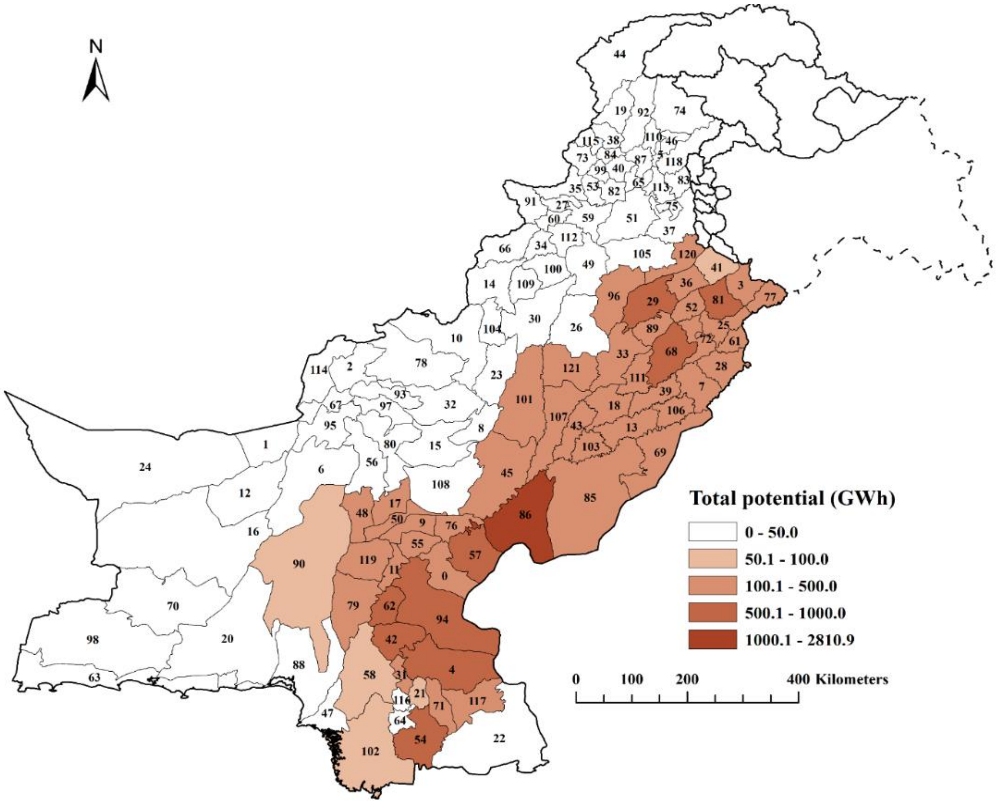


Figure 11 Total district wise energy potential for all crops

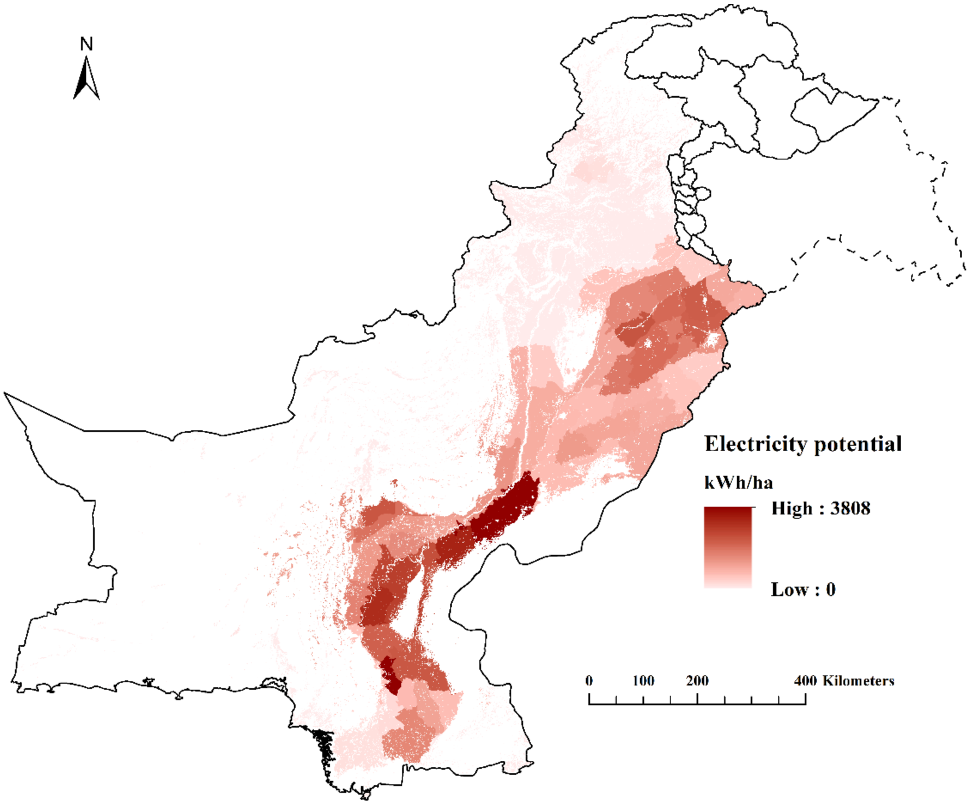


Figure 12 Energy intensity (electricity generation potential per unit area)

The modified energy intensity map, given in Figure 9, represents the average energy intensity for a neighborhood of 50 km circular radius. The resolution of this map is 100m × 100m which makes each pixel equal to that of 1 hectare in area. The spatial variation of energy intensity in Figure 13 is similar to that in Figure 12. But the higher range of last class here shows that a 2457 kWh potential is available in and around every pixel, within 50 km radius proximity. A power plant at this location would be able to generate about 1929 GWh of electricity in a year. This map redefines the spatial variation of electricity generation potential in terms of supply area.

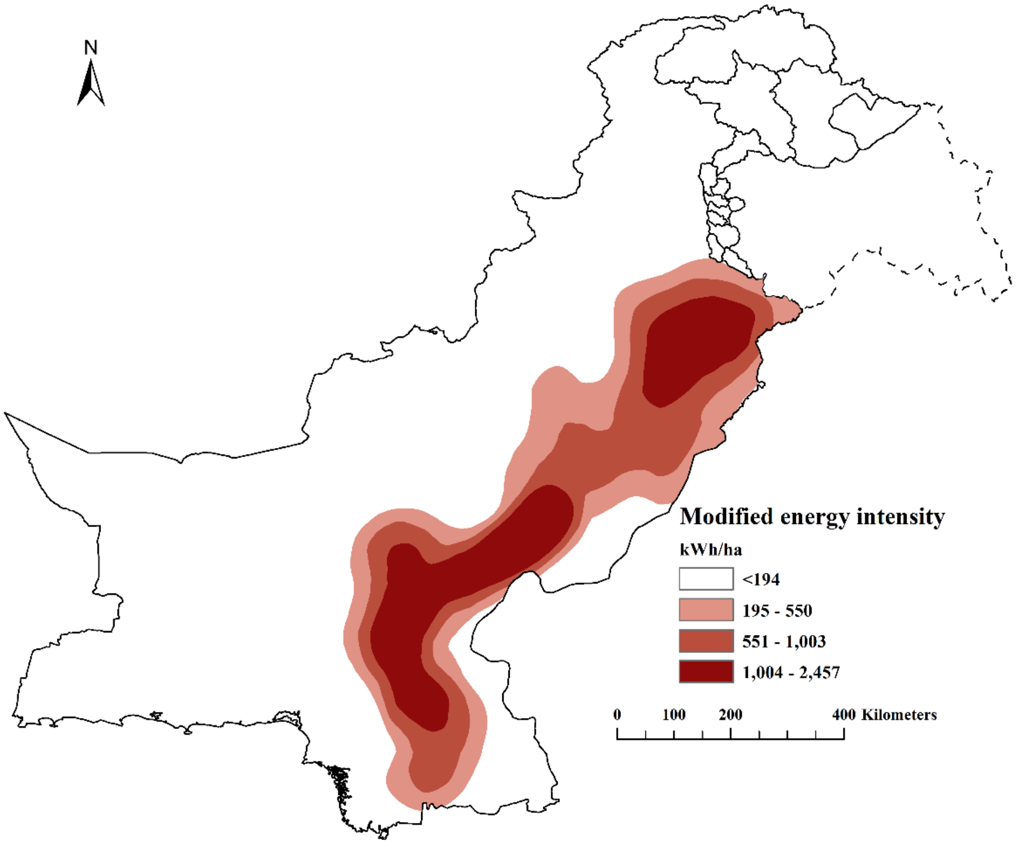


Figure 13 Modified energy intensity map (50 km radius)

4.3 Identification of suitable locations

4.3.1 AHP ranked criteria

The final weights of criteria and sub-criteria factors obtained after performing AHP are presented in Table 14.

Table 14 Final weights of criteria and sub-criteria factors used in AHP

Sr No.	**Main criteria**	**Unit**	**Final weights**	**Consistency ratio**	**Sub-criteria**	**Final weights**
1	Energy intensity	kWh/ha	0.395	0.025	<194	0.044
					195-550	0.200
					551-1003	0.223
					1004-2457	0.533
2	Distance from road	km	0.274	0.018	0.1 to 1	0.389
					1 to 2	0.334
					2 to 3	0.133
					3 to 5	0.107
					> 5	0.038
3	LULC available		0.208	0.022	Bare Land	0.472
					Sparse vegetation	0.211
					Shrub/Grass/Herbaceous	0.195
					Trees	0.085
					Cropland	0.037
4	Distance from grid station	km	0.087	0.028	0.1 to 3	0.389
					3 to 8	0.348
					8 to 50	0.154
					50 to 80	0.071
					>80	0.037
5	Water stress	%	0.037	0.021	Low (<10)	0.492
					Low-Medium (10-20)	0.205
					Medium-High (20-40)	0.189
					High (40-80)	0.077
					Extremely High (>80)	0.037
	Total		1.00			

The energy intensity criterion with highest weight (0.39) is the most essential regarding the final goal of this AHP which is in line with the previous studies (S. Ahmad & Tahar, 2014). The distance from road was assigned the second highest weight (0.27) as proximity to the existing roads means no or lesser cost requirement for road network enhancement for residue transportation from field to plant site. LULC availability for site selection had comparable weight (0.21) to distance from road (M. Ahmad & Zeeshan, 2022), as the land selected for power plant would have environmental impacts on its surrounding for its lifetime.

4.3.2 Geo-spatial suitability map

These weights were input to the weighted overlay tool along with the maps of other considered factors for site suitability analysis. The weighted overlay resulted as a raster map (100m × 100m resolution, resampled at 300m × 300m) with suitability classes ranging from 0 to 9, which was reclassified into 5 classes (Chukwuma et al., 2021), as depicted in Figure 10. Almost 52% of area was excluded under various environmental and economic constraints, mostly due to unavailability of residue followed by areas with higher slopes and presence of surface water bodies. The least and slightly suitable areas can be seen across the country, making about 14% of total area. Limited access to road and grid stations is major reason besides no or low energy intensity for these categories. About 32% of viable area is identified as "moderately" and "highly" suitable. Though easy access to infrastructure is there in these areas, the main limiting factor limited availability of residue.

Most of the "highly" and "extremely suitable" locations belonged to the districts Sukkar (0), Jamshoro (58), Ghotki (57), Jhal Magsi (48), Nasirabad (17), Rajanpur (45), Rahim Yar Khan (86), Bahawalpur (85) and Khushab (96). A few such locations also belonged to Multan (43), Muzaffargarh (107), Khairpur (94), Shaheed Benazirabad (42), Sanghar (4) and Okara (7). The "extremely" suitable class covered only about 130 km^2 which is less than 1% of total land area of the country.

4.3.3 Power plant locations

It is to be noted in Figure 10 that the suitable locations were clustered together in specific areas. It is not advisable to propose all potential sites within a cluster or even two potential sites closer to each other, as candidate sites for the power plant, as in that case the biomass collected in the vicinity, would be divided. In such cases, one site, having maximum biomass availability, was selected in an area of 50 km and all biomass available within this radius was dedicated to that site. In total, 10 sites were identified

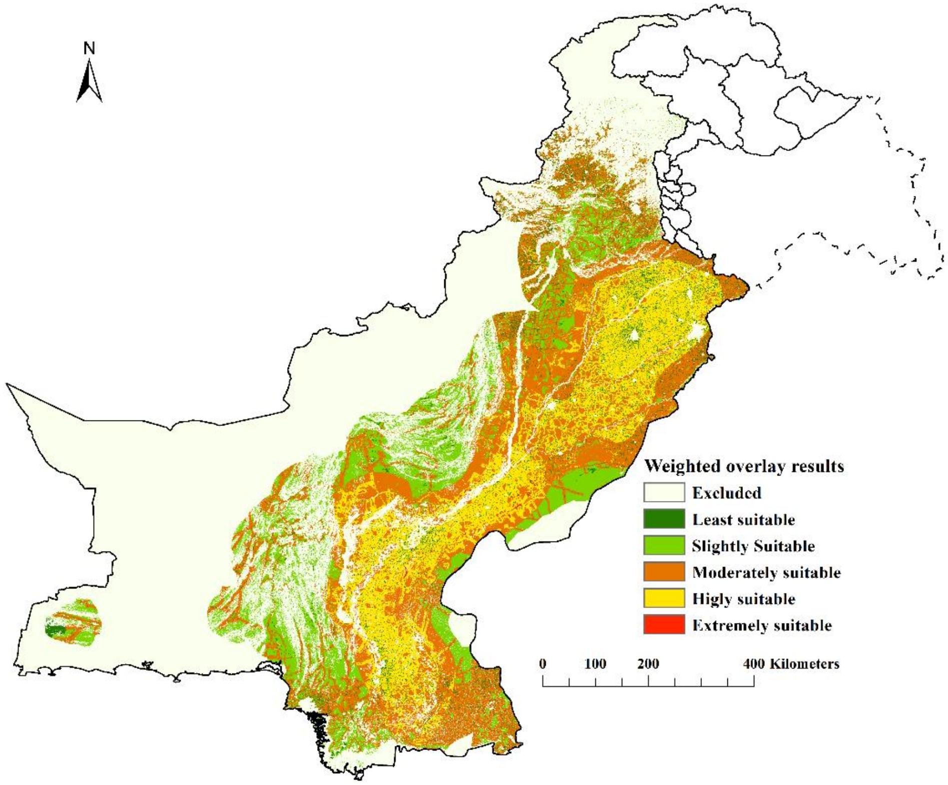


Figure 14 Site suitability map

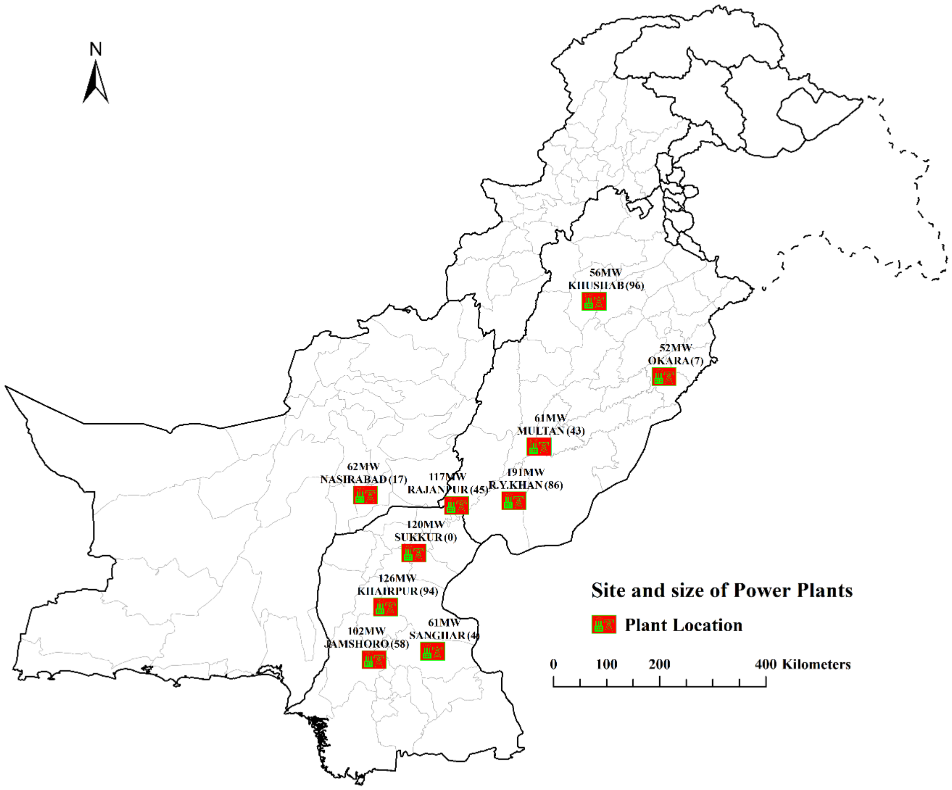


Figure 15 Final selected power plant locations

having annual electricity potential ranging from 443 GWh to 1625 GWh. The resultant map along with the estimated capacity of power plant for each site is shown in Figure 11.

The identified locations belonged to high crop production areas, having road and electricity transmission infrastructure in vicinity. Since water stress was given low importance in site selection process, most of these locations were identified in the areas having higher water risks except the 3 locations in districts of Jamshoro (58), Khushab (96) and Rajanpur (45). Since major water requirement in direct combustion power plant is that for the cooling to remove unusable heat from the systems, dry cooling systems are recommended to avoid further water stress.

All identified plant sites were located in rural areas of Sindh and Punjab except the one in Nasirabad (17). It is to note here that besides having high energy potential, the important factor here was presence of barren land which was given highest preference as sub-criterion of LULC available. Constructing these power plants would bring jobs and basic amenities to these localities. As electricity generation from biomass creates highest employment opportunities, about 36000 jobs per 500 MW (Asakereh et al., 2022), it would help curb the increasing unemployment rates in the country.

4.4 Road network and storage optimization for case study of Allama Iqbal Industrial City

The crop residue availability at 4 SEZs was calculated for the major 5 crops for the year 2019-2020. The resulting resource map is presented in Figure 16 which indicates the only SEZ with significant residue availability was Allama Iqbal Industrial City in Faisalabad. The total theoretical crop residue-based EGP in 50km radius around the Faisalabad SEZ came out to be 1051 MWh, considering the 20% plant efficiency and 15% collection efficiency.

4.4.1 Shortest road distance

This SEZ was further analyzed using network analysis to obtain real road distances for transporting the residue. Overlaying mesh grid of 25km by 25km resulted in 16 collection points, each located at the center of grid. The collection radius used was 50 km but the network analysis resulted in varying road distances for each collection point as shown in

Figure 17. The maximum road distance for the farthest collection point was 60.8km even though the collection radius was set to 50km, and the shortest path was 25.4km despite the selected straight-line distance of 25km. The reason for this huge difference is mainly the distribution of collection points and the fact that roads are typically build following the natural terrain and there are multiple obstacles like towns and populated areas which would result in increase in distance compared to the straight line.

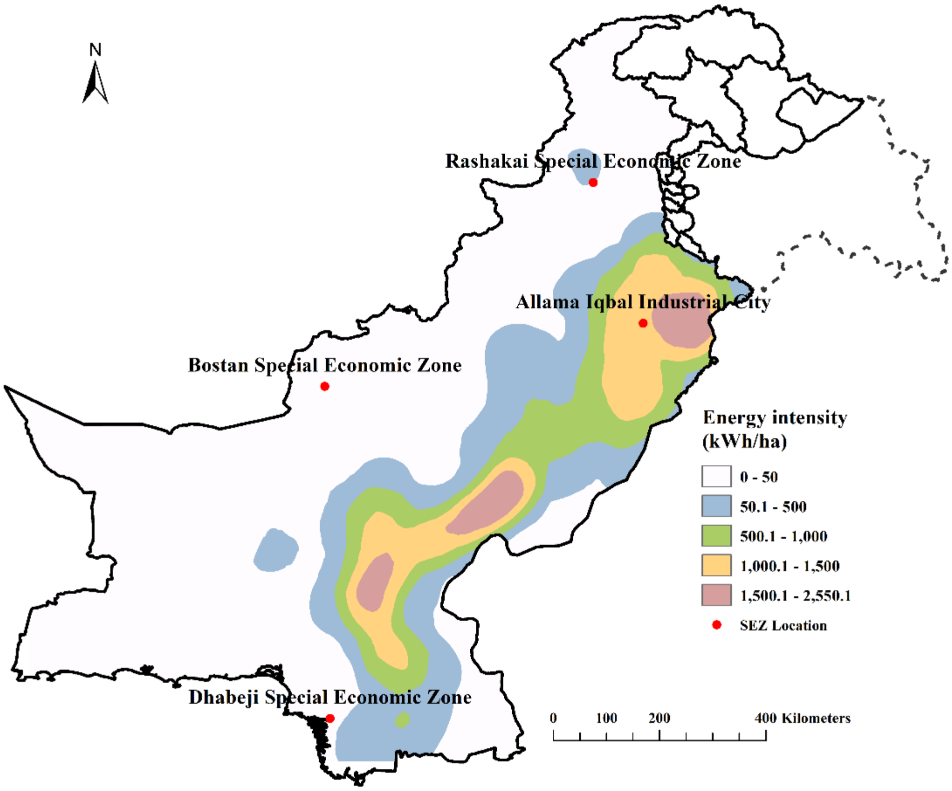


Figure 16 Total electricity generation potential of crop residue with SEZs

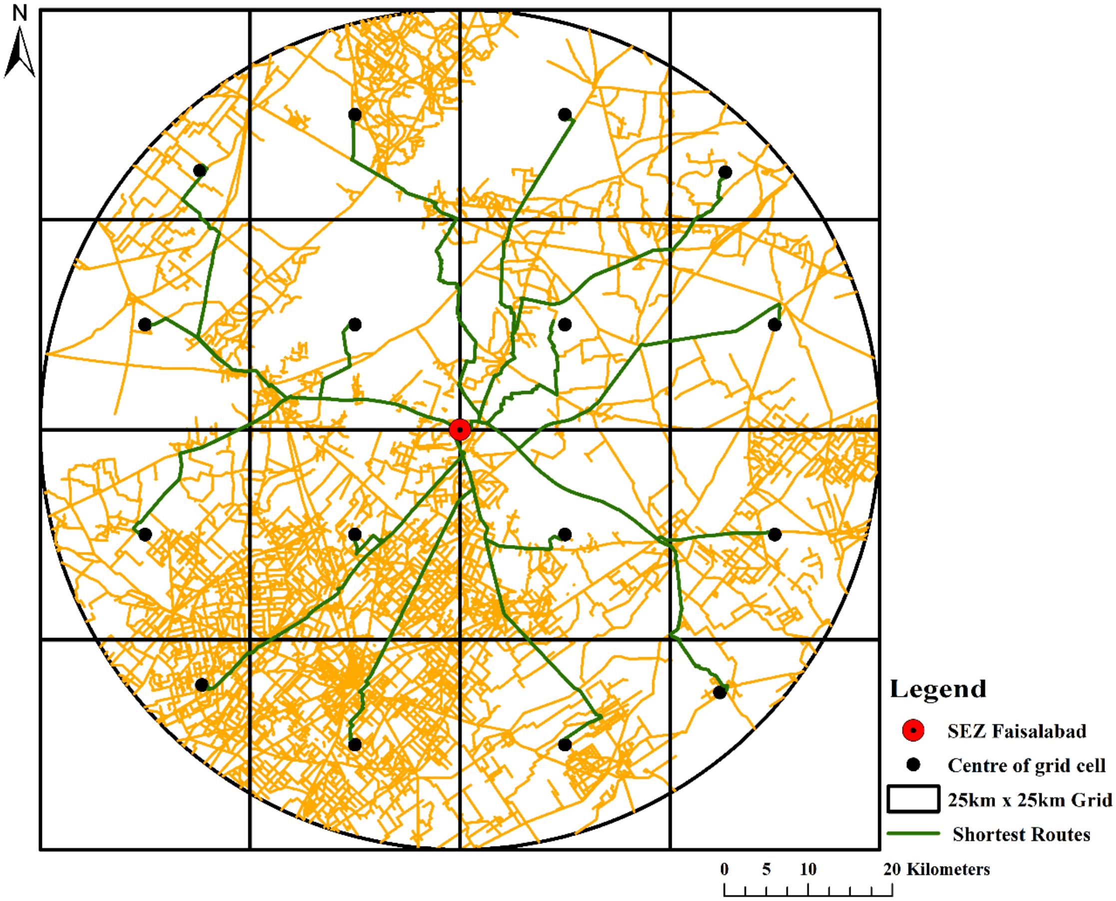


Figure 17 Network analysis to calculate shortest distance from collection points to plant site

The average distance for all 16 points was calculated, which was 43.7km and it was used in the technoeconomic analysis to get a realistic residue transportation cost.

4.4.2 Storage area calculation

Total WS and RS availability, their calorific value and total potential available at the selected SEZ was used to calculate the area required to store and smoothly operate the power plant avoiding shut down due to fuel unavailability. The horizontal area calculation was done based on weight and volume of 1 large rectangular bale with density of 208 kg/m^3, considering 6 bales would be stacked together. The simple calculations based on the total available RS and WS is given in table 15, considering the full year storage of residues.

Table 15 Simple area calculation based on residue availability, bale size and density

	Residue quantity (10^3 tonne)	Area ($m^{2)}$	Area (acres)
Wheat Straw	297	187633.5	46.3
Rice Straw	338	160924.1	39.76
Total	635	348557.7	86.06

Storage optimization however resulted in lesser storage area as we considered the collection of RS at the end of rice harvesting and WS collection when wheat harvested is completed. It can be seen from table 16 that RS and RS is brought to the storage facility at almost 6 months gap which significantly impacts the utilization and storage requirement (Jayarathna et al., 2020). A major influencing factor in storage optimization was the calorific values of each straw and consequently varying EGP using same volume of residue. A weekly breakdown of storage facility regarding incoming RS and WS and their corresponding occupied storage is presented in Table 16. It is assumed that it takes 2 weeks for all total straw in a season to reach storage facility, once crop harvesting is completed. The per week residue quantity for WS and RS i.e., 9400 tonne and 10900 tonne, respectively, corresponds to same amount of energy

Table 16 Storage optimization (weekly schedule for straw storage)

	Residue at storage (10^3 tonne)			**Area Occupied at the storage (m2)**		
	Incoming	Consumed	Remaining	Covered	Emptied	Remaining
week 1	140.5	9.4	140.5	93816.8	6294.2	93816.8
week 2	140.5	9.4	271.6	93816.8	6294.2	181339.4
week 3		9.4	262.1		6294.2	175045.2
week 4		9.4	252.7		6294.2	168751.1
week 5		9.4	243.3		6294.2	162456.9
week 6		9.4	233.9		6294.2	156162.8
week 7		9.4	224.4		6294.2	149868.6
week 8		9.4	215.0		6294.2	143574.5
week 9		9.4	205.6		6294.2	137280.3
week 10		9.4	196.2		6294.2	130986.2
week 11		9.4	186.7		6294.2	124692.0
week 12		9.4	177.3		6294.2	118397.9
week 13		9.4	167.9		6294.2	112103.7
week 14		9.4	158.5		6294.2	105809.6

week 15		9.4	149.0		6294.2	99515.4
week 16		9.4	139.6		6294.2	93221.3
week 17		9.4	130.2		6294.2	86927.1
week 18		9.4	120.8		6294.2	80632.9
week 19		9.4	111.3		6294.2	74338.8
week 20		9.4	101.9		6294.2	68044.6
week 21		9.4	92.5		6294.2	61750.5
week 22		9.4	83.1		6294.2	55456.3
week 23		9.4	73.6		6294.2	49162.2
week 24		9.4	64.2		6294.2	42868.0
week 25	120.5	9.4	54.8	80462.07265	7252.4	116077.7
week 26	120.5	9.4	45.3	80462.07265	7252.4	189287.5
week 27		9.4	35.9		7252.4	182035.1
week 28		9.4	26.5		7252.4	174782.8
week 29		9.4	17.1		7252.4	167530.4
week 30		9.4	7.6		7252.4	160278.1
week 31		10.9	107.9		7252.4	153025.7
week 32		10.9	217.5		7252.4	145773.3
week 33		10.9	206.6		7252.4	138521.0
week 34		10.9	195.8		7252.4	131268.6
week 35		10.9	184.9		7252.4	124016.3
week 36		10.9	174.0		7252.4	116763.9
week 37		10.9	163.2		7252.4	109511.6
week 38		10.9	152.3		7252.4	102259.2
week 39		10.9	141.5		7252.4	95006.9
week 40		10.9	130.6		7252.4	87754.5
week 41		10.9	119.7		7252.4	80502.2
week 42		10.9	108.9		7252.4	73249.8
week 43		10.9	98.0		7252.4	65997.5
week 44		10.9	87.2		7252.4	58745.1
week 45		10.9	76.3		7252.4	51492.7
week 46		10.9	65.4		7252.4	44240.4
week 47		10.9	54.6		7252.4	36988.0
week 48		10.9	43.7		7252.4	29735.7
week 49		10.9	32.9		7252.4	22483.3
week 50		10.9	22.0		7252.4	15231.0
week 51		10.9	11.1		7252.4	7978.6
week 52		10.9	0.3		7252.4	726.3

The WS comes in on week 1 starts on June 1st (Crop Reporting Service, 2021) with the end of wheat harvesting whereas the RS straws starts coming in on 25th week, that is when rice harvesting is completed. It can be seen from the table that although there is WS present at the storage area in 25th week when the RS starts to come in but there is enough free space to accommodate RS and the overlap of these residues is for only a few weeks. So, the storage is optimally utilized throughout the year without having to accommodate to different crop residues.

4.4.3 Techno-economic assessment

The results obtained from the techno-economic analysis performed for selected SEZ are presented in this section. The main results obtained from the technical and financial analysis of power plant are presented in Table 12. At available throughput of 80MT/h of straw into the boiler with excess fed air the electricity generation reaches up to 621 GWh/year. The steam generated had Capacity of the plant system reaches about 70 MW.

Table 17 Technical and financial parameters

Technical parameter	**Value**	**Unit**
Annual electricity generation	601,642	MWh/year
Biomass Feedstock	625680	Tonne/year
Boiler feedwater usage	523818	Tonne/year
Cooling water	440,285,559	Tonne/year
Capital cost	65,852,384	US$
Annual operating cost	76,206,388	$/year
NPV	11,153,993	$
Gross margin	15.56	%
Return on Investment	15.99	%
Payback Time	6.25	years
IRR (after tax)	19.47	%

The Net Present Value (NPV) is a metric used to assess the profitability of investment projects by adding up all cash inflows and expenditures throughout the course of the project. If the project's earnings exceed its anticipated expenses, as indicated by a positive NPV, the project is profitable; otherwise, it will experience a net loss. As evident from the results of economic evaluation, the NPV of the project is quite promising. The predicted return on the capital investment utilizing a proportional debt equity structure is shown by the equity-based

IRR throughout the course of the project. A project is often considered viable if the IRR is equal to or greater than the projected rate of return, which is frequently the discount rate employed in financial analysis. Because a high IRR suggests more profitability, it may be used as a benchmarking tool to compare various investment possibilities. The IRR obtained in this analysis is higher than the minimum IRR suggested by (NEPRA, 2021) for biomass based power plants in Pakistan which is 15%.

The selection of a project's techno-economic features may depend on the fiscal structure and available capital of the project. But a low payback period assures less risk and significant IRR signals better return on original investment, it is therefore advised to consider both characteristics to others for a full financial analysis.

4.4.3.1 Sensitivity analysis

According to earlier research, the economics of biopower is reliant on following input factors: feedstock cost, cost of electricity and discount rate (interest rate NPV) (Abdelhady et al., 2018; Cardoso et al., 2019). With a 10%, 20% in these and some other input variable, we further examined in this study how sensitive NPV, IRR and payback period are to these parameters.

Sensitivity analysis of NPV to different input values are shown in Figure 16, it is found to be highly sensitive to the per unit selling cost of electricity and feedstock cost (Mana et al., 2021). Increasing the per tonne feedstock cost of straw by only 10% would result in negative NPV, the selling cost of electricity however has a more sensitive association with NPV. To precisely determine if such biomass power plants are economically feasible, accurate data on feedstock price and actual discount rate must be gathered. When comparing the biomass power generation to other competing renewable power production sources, poor data would result in poor conclusions. Discount rate and interest rate also considerably affect the NPV estimated for the project.

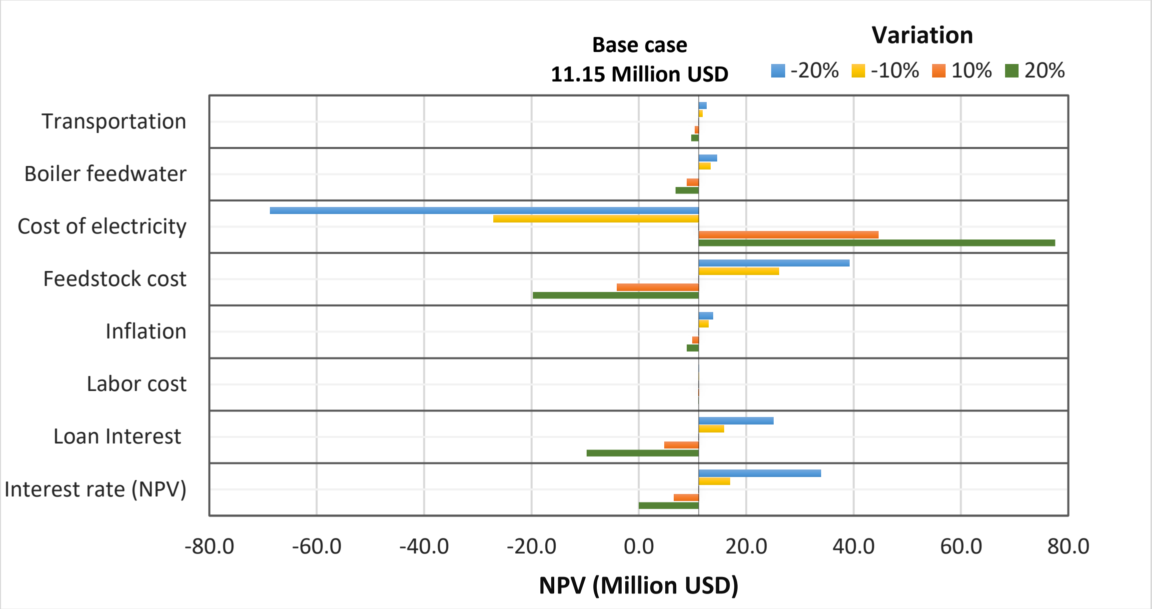


Figure 18 Sensitivity of NPV (Million USD) to various input variables

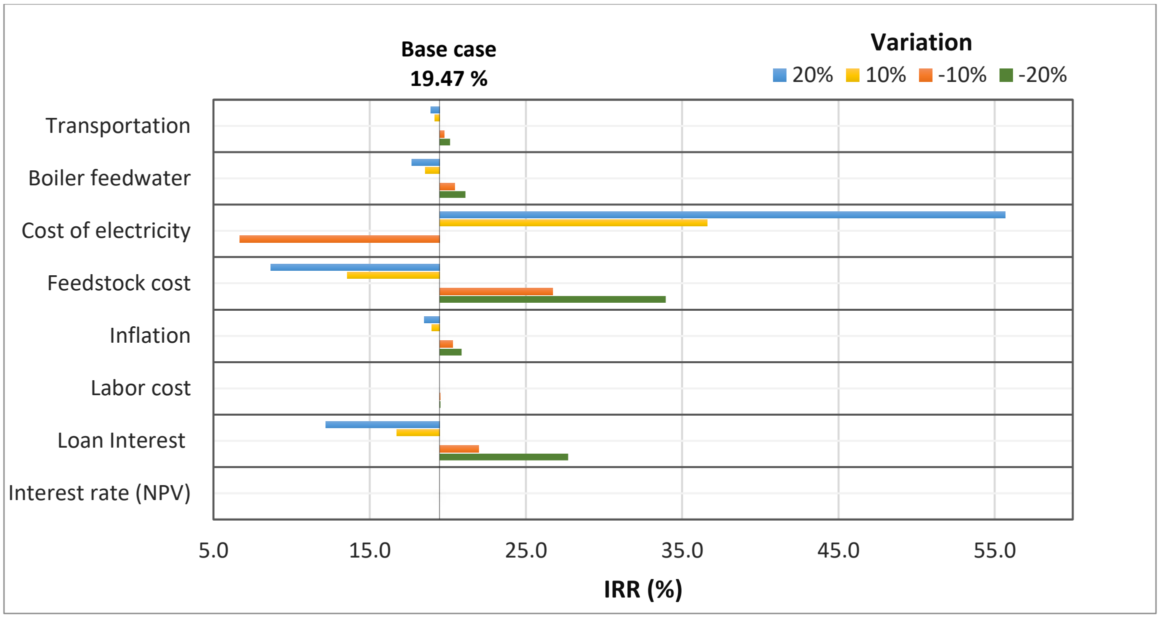


Figure 19 Sensitivity of IRR (%) to various input variables

Figure 17 shows the sensitivity of IRR (after tax) to selected input parameters, interest rate on loan is found to be of significant influence on IRR along with cost of electricity and discount rate.

Whereas payback time is only sensitive to electricity and feedstock cost as shown in Figure 18. The payback period has a direct relation with feedstock cost and an inverse relation with selling cost of electricity. However a 20% decrease in electricity cost reduced the payback period down to less than a year which suggests that electricity cost so low is practically not possible. The operating costs like transportation costs of feedstock, labor cost and cost of boiler feedwater have little to no impact on NPV, IRR and Payback period.

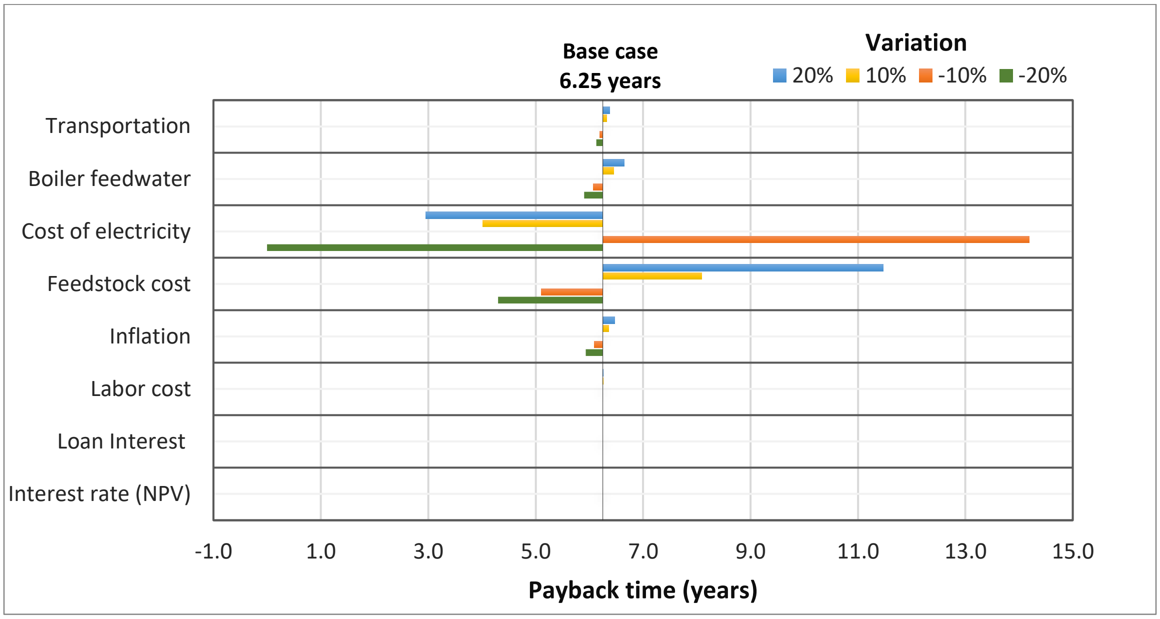


Figure 20 Sensitivity of Payback time (years) to various input variables

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In this study, a methodology was developed to identify suitable locations for crop residue-based power plants in Pakistan, by utilization of crop production data along with other geospatial datasets and integration of Analytical Hierarchy Process (AHP) and Geographical Information System (GIS) techniques. The study concludes that electricity generation potential of 5 major crops, estimated to be 21390 GWh is enough to reduce the electricity shortfall in the country by 50%. Six districts with high generation potential in Sindh province and 4 in Punjab, have collective annual potential of 4674 GWh and 4885 GWh, respectively. South-eastern region of Pakistan has highest values of EGP per unit area (up to 3800 kWh/ha) due to twice a year cultivation of same land.

The EGP is the most important factor in site suitability, followed by road accessibility and Land Use Land Cover (LULC) type available. About 52% of total landscape of country is excluded from analysis due to environmental and economic constraints. Only 130 km^2 (<1%) falls under extremely suitable areas, mostly in central and south Punjab and northern Sindh.

Besides optimally siting the power plant, the economic evaluation indicates that other parameters are quite significant as well. There has been much talk around the issue of transportation and storage of biomass when it comes to power generation but as seen from the results, they don’t have more influence on the economics than the cost and prevailing financial conditions of region under study.

5.2 Recommendations

- Based on the analysis carried out in this study, following recommendations are formed The feedstock availability is of vital importance in assessing the potential, detailed localized survey must be done for more accurate valorization for power generation
- More factors relating to social and economic prospects should be considered for power plant site suitability.

- Co-firing and replacement of fuel at coal power plants should be assessed using crop residue.
- Techno-economic analysis under varying financing schemes should be carried out.

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