An integrated Geographic Information System and Analytical Hierarchy Process based approach for site suitability analysis of on-grid hybrid concentrated solar-biomass powerplant.

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A thesis submitted in partial fulfillment of the requirement for the degree of Master of Science in Environmental Science

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Dedication

This research is dedicated to my loving and caring parents and my sisters Irum and Ateka as their efforts and sacrifices have made my dream of having this degree a reality. Words cannot adequately express my deep gratitude to them.

"O My Sustainer, bestow on my parents your mercy even as they cherished me in my childhood".

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LIST OF ABBREVIATIONS

GDP	Gross Domestic Product
IEA	International Energy Agency
SA	South Asia
SSA	Sub-Saharan Africa
SDG7	Sustainable Development Goal 7
CSP	concentrating solar power
DNI	Direct Normal Irradiance
DHI	Diffuse Horizontal Irradiance
PTC	Parabolic Trough Collectors
ST	Solar Towers
LFR	Linear Fresnel Reflectors
SPD	Solar Parabolic Dishes
HCSB	Hybrid Concentrated Solar Biomass
MCDM	Multi-Criteria Decision Making
AHP	Analytical Hierarchy Process
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
ANP	Analytic Network Process
GIS	Geographic Information System
IRENA	International Renewable Energy Agency
KPK	Khyber Pakhtunkhwa
AJK	Azad Jammu and Kashmir
GB	Gilgit Baltistan
CMSAF	The Satellite Application Facility on Climate Monitoring
C3S	Copernicus Climate Change Service
AMIS	Agriculture Marketing Information Service
UE_{2045}	Urban expansion by 2045 (km^2)
P_{2045}	Projected population of the polygon by 2045
A_{sp}	Specific area (km^2/person)
P_{2020}	Population of the polygon in year 2020
R	Projected rate of increase in population
A_{2020}	Area of the polygon in year 2020 (km^2)

PD_{2020}	Population density of the polygon in year 2020
IDW	Inverse Distance Weighting
BF_{mj}	Available amount of residue for crop j in district m (ton)
P_{mj}	Annual production of crop j in district m (ton)
G	Grain to straw ratio
ω	Portion of residue available
D	Dry matter content
η	Collection efficiency (%)
α_m	Portion of crop harvested mechanically in district m
$1- \alpha_m$	Portion of crop harvested manually
A_m	Portion of crop residues available for mechanical harvesting
B_m	Portion of crop residues available for manual harvesting
E_{mj}	Energy potential (kWh) of crop j for district m
LHV	Lower heating value (GJ/ton)
CF	Conversion factor (i.e., 1GJ = 277.8 kWh).
TE_m	Total bioenergy potential of district m
$\sum_{j=1}^{5} E_{mj}$	Summation of energy potential of five crops for district m
CI	Consistency Index
CR	Consistency Ratio

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ABSTRACT

For sustainable and resilient energy future, cost-efficient renewable energy technologies are critical. In this regard, hybridization of concentrated solar power with biomass is one of the most promising options for two major reasons (1) dispatchability; (2) low carbon emissions. This study aims to propose a methodological framework to identify suitable areas for deployment of Hybrid Concentrated Solar Biomass (HCSB) powerplants by using a combined Geographic Information System (GIS) – Analytical Hierarchy Process (AHP) approach. Moreover, Direct Normal Irradiance (DNI) and bioenergy resource potential in Pakistan is also evaluated and mapped. At first, different economical, technical and meteorological factors were selected after in-depth review of literature. High resolution criteria maps were developed for selected factors and unsuitable areas were excluded. Weights of selected factors were determined using AHP. Then a final suitability map, categorizing all non-excluded areas into five suitability classes was achieved. The results show that more than 80 % area of Pakistan (i.e., 684072.15 km^2) receives DNI > 1800 kWh/m^2.year, whereas 19 % of land (i.e., 153978.142 km^2) is found to have bioenergy potential greater than 45,000 kWh/m^2year. Moreover, approximately 37 % of land (i.e., 299,431.46 km^2) is identified as suitable for installation of HCSB projects. The district of Jamshoro (Sindh Province) is found out to be the most suitable location, whereas 36 districts lie in the “Highly suitable” class. Although, this study is focused on Pakistan, the approach applied informs decision makers, in realm of energy planning and development, on a regional level.

Keywords: Crop residue; Solar energy; solar-biomass hybrid energy; Site suitability; Powerplant location; Analytical Hierarchy Process

CHAPTER 1

INTRODUCTION

The energy demand is significantly rising across the globe due to increase in population and improving living standards. According to UN population projection, the current estimated global population of 7.7 billion, is expected to reach 9.7 billion in 2050 (*Population | United Nations*, n.d.). The global gross domestic product (GDP) has increased three times between 1978 and 2018, following an annual growth rate of 2.9 % from 26,301 billion US$ 2010 to 82,635 billion US$ 2010 (Kober et al., 2020), and is expected to increase at even higher rates with rapid socioeconomic development (*World Energy Scenarios: Composing Energy Futures to 2050 | World Energy Council*, n.d.). Although in year 2020, a decline of 4 % in global energy consumption was observed because of COVID 19 induced restrictions and lockdown measures(*World Energy Consumption Statistics | Enerdata*, n.d.), however, the energy demand is expected to rebound post-COVID (*Covid-19 Impact on Electricity – Analysis - IEA*, n.d.). According to International Energy Agency's (IEA) electricity market report 2022 (*Electricity Market Report - January 2022 – Analysis - IEA*, n.d.), global energy demand increased by 6 % in year 2021, which was the highest ever annual percentage increase in energy demand since recovery from 2010 financial crisis. Therefore, it is crucial to develop more energy resources to cater the increasing energy demands.

At present, the global energy supply heavily leans on nonrenewable fuel resources, as major share of global energy consumption is contributed by fossil fuels (Gouareh et al., 2021). For year 2020, coal, oil and natural gas continued to be the largest contributors in global energy mix with 31.2 %, 27.2 % and 24.7 % shares respectively (bp, n.d.). With intensifying climate change and air pollution issues, and depleting fossil reservoirs, global energy mix requires larger share of renewables. Climate change mitigation focused policies such as net zero emissions and carbon neutral targets have been adopted by different countries around the globe, consequently promoting the use of renewables and phasing out of fossil fuels. For instance, developed countries such as Austria, Hungary and United Kingdom have committed to achieve carbon neutral status by 2040-2050, while other Asian countries such as Japan, China and South Korea aim to achieve it by 2050-2060 (IEA et al., 2021).

Among renewables, solar and wind are the most extensively exploited resources for electricity production worldwide (*Renewables 2021 Global Status Report | UNEP - UN Environment Programme*, n.d.). At present, China leads the use of renewables (solar, biomass, wind) for electricity production, followed by USA, European Union and India (Energy Agency, 2021). A growth of 11 % for renewable resources in China's electricity production mix has been reported for year 2020 (B. Li & Haneklaus, 2021), where solar and wind were the key contributors. Significant development in use of renewables is also expected in USA in approaching years as a result of consistent support at the state and federal levels (Energy Agency, 2021). However, the situation is quite different in many developing and underdeveloped countries of South-Asia (SA) and Sub-Saharan Africa (SSA) regions. Despite significant potential of renewable resources (*Energy Trade in South Asia: Opportunities and Challenges | Asian Development Bank*, n.d.; Shukla et al., 2017), these regions are grappling with issues of energy inadequacy, financial instability and crippling economies (*Human Development Report 2011 - Sustainability and Equity: A Better Future for All - World | ReliefWeb*, n.d.), questioning their capacity to attain Sustainable Development Goal 7 (SDG7) i.e. "clean and affordable energy for all" (*Home - United Nations Sustainable Development*, n.d.). Widening gap between energy demand and supply in these regions, makes exploration and use of renewable resources for electricity generation indispensable. The focal point of current study is exploration of renewable resources, particularly concentrating solar power (CSP) and biomass in selected study area and to propose most feasible sites for installation of hybridized concentrated solar and biomass power plants.

Among solar energy harvesting technologies, global potential for CSP stands at 2.6 × 10^9 TWh/year (Köberle et al., 2015), with hotspots located in South Asia (H. L. Zhang et al., 2013). CSP technology differs from Photovoltaics (PV) in a manner that it makes use of Direct Normal Irradiance (DNI) exclusively to produce electricity whereas the latter works in the presence of both Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI) (Giamalaki & Tsoutsos, 2019; Gouareh et al., 2021). CSP technologies include Parabolic Trough Collectors (PTC), Solar Towers (ST), Linear Fresnel Reflectors (LFR) and Solar Parabolic Dishes (SPD). Previously, various studies have assessed the potential of standalone CSP plants for different regions (Islam et al., 2018a; Middelhoff et al., 2021; Tassoult & Haddad, 2019; Yushchenko et al., 2018). Significant potential for deployment of CSP projects has been reported for Tanzania (Aly et al., 2017), Morocco (Tazi et al., 2018), West Africa (Yushchenko et al., 2018), India (Purohit & Purohit, 2017) and Pakistan (Ahmad & Zeeshan, 2022). However, despite considerable potential, the global installed capacity for the technology grew by trifling 1.6 % in 2020 (*Renewables 2021 Global Status Report | UNEP - UN Environment Programme*, n.d.). Relatively high costs of CSP and consistent cost reductions for PV systems, have put immense pressure over the former in recent times. Conversion of 500 MWe Parabolic Trough plant (located in USA) to PV is the most evident example of existing competition between the two technologies(Juergen H. Peterseim, Herr, et al., 2014; *Whole 1 GW Blythe Project to Convert to PV – Pv Magazine International*, n.d.). Therefore, in order to expand CSP market and to remain competitive, the industry has to further signify advantages that arise from energy dispatchability, in addition to lower plant costs (Juergen H. Peterseim, Herr, et al., 2014). Hybridization of CSP systems with biomass, in this regard, is considered as a viable option (Juergen H. Peterseim, Herr, et al., 2014) and is endorsed worldwide (*Technology Roadmap - Concentrating Solar Power*, n.d.). Such hybridization systems, not only provide 100 % renewable energy (Herrera et al., 2020), round the clock, but also result in reduction of capital costs when compared to standalone CSP plants because of smaller solar field footprint(Middelhoff et al., 2021)

The hybridization of CSP with biomass combustion for electricity generation is known as Hybrid Concentrated Solar Biomass (HCSB) power plant (Middelhoff et al., 2021). One of the major advantages of hybridizing biomass with CSP technology is its dispatchability in terms of integration with Thermal Energy Storage (TES) which makes installations of these systems flexible and more operationally stable (Middelhoff et al., 2021). Moreover, electricity generation potential of biomass resource alone is underutilized on a global scale primarily because of high transportation costs and requirement of biomass storage in large amounts for continuous and smooth operation of power plant. Hence, hybridizing biomass with CSP technology is an efficient approach as it is not only reported to be economically viable and sustainable (Middelhoff, Madden, et al., 2022) but also better net energy efficiency has been observed for HCSB powerplants as compared to stand alone biomass power plants by (Middelhoff et al., 2021).

Termosolar Borges' plant, with nominal capacity of 22.5 MW, located in Spain, is considered as one of the oldest working examples of HCSB concept (*Termosolar Borges CSP-Biomass Power Plant - Power Technology*, n.d.). HCSB plants not only provide solutions to the problems associated with standalone CSP plants but such hybridizations also address the issues and constraints of biomass-only power plants (Mohaghegh et al., 2021). Simin et al., reported 31 % reduction in CO_2 emissions for HCSB plant when compared to standalone biomass powerplant (Anvari et al., 2019). Moreover, Peterseim et al., (Juergen H. Peterseim, White, et al., 2014) reported 4.8% reduction in CO_2 emissions while studying techno economic feasibility analysis of HCSB powerplants for Australia. Similarly, Jonathan et al., reported that by hybridizing CSP technology and biomass, dependency on land and biomass can be reduced up to 14 – 29 % (Nixon et al., 2012).

Several studies in literature (Milani et al., 2017; J. H. Peterseim et al., 2014; Juergen H. Peterseim, Tadros, et al., 2014; G. Zhang et al., 2016) have focused on the design and configuration of HCSB plants, while few others (Middelhoff et al., 2021; Middelhoff, Furtado, et al., 2022) have investigated their techno-economic feasibilities. The review of literature enlightens that number of studies focused on site suitability analysis for HCSB plants is insufficient. To the best of authors' knowledge, only three studies (Middelhoff, Madden, et al., 2022; Juergen H. Peterseim, Herr, et al., 2014; Thiam et al., 2017) till date have been published that investigated potential locations for installation of HCSB powerplants. These studies considered proximity to substations or access to transmission lines, in addition to resource availability, as the only identifying factors to locate most suitable areas. Only one study (Thiam et al., 2017), conducted in Sahel, Senegal, has been identified to include other factors such as water requirement, slope and land availability in their analysis. Nevertheless, the study lacked in proposing a structured methodology for the same for the process.

Selecting ideal locations for large scale powerplants, is considered to be an intricate process because of involvement of various meteorological, technical, economic and environmental factors (Gouareh et al., 2021). Multi-Criteria Decision Making (MCDM) methods, in this regard, are considered to be useful techniques to solve complex decision-making problems (Vassoney et al., 2021). Various previously published studies (Castro & Silv Parreiras, 2018; Kumar et al., 2017; Simsek et al., 2018) presented review of MCDM methods in domain of sustainable renewable energy development. Also, the application of these methods towards sustainable energy planning has been discussed in detail by Pohekar et al., (Pohekar & Ramachandran, 2004), where more than 90 published papers were reviewed. After exploring existing literature on MCDM, it is found out that over the years, several MCDM methods such as TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), AHP (Analytic Hierarchy Process), ANP (Analytic Network Process) and Fuzzy AHP have been considered by different researchers (Castro & Silv Parreiras, 2018; Kengpol et al., 2013; Pohekar & Ramachandran, 2004), in site selection domain. However, Analytical Hierarchy Process (AHP) has emerged out to be the most popular technique for solving complex decision-making problems, because of its flexibility and robustness (Kumar et al., 2017; Messaoudi et al., 2019). Recently, application of AHP coupled with Geographic Information System (GIS) has gained popularity among researchers and has been widely employed for site suitability analysis of large-scale renewable energy powerplants [7,27]. However, no study has been identified that employed integrated GIS-AHP approach for site suitability analysis of HCSB powerplants.

While using MCDM for site suitability analysis of large-scale renewable energy powerplants, previous studies observed that selection of criteria, sub-criteria and constraint sets for site suitability are arbitrary and may differ depending upon renewable technology and region/country. For instance, for CSP plants many researchers agree that lands with slope higher than 5 % are not feasible for installation (Aly et al., 2017; Yushchenko et al., 2018) whereas for PV powerplants, this limit is extended up to 11 % (Noorollahi et al., 2016).

Like many developing countries, Pakistan is undergoing industrialization and thus experiencing annual growth rate of 5 % in its energy demand, while facing severe multifaceted energy shortages (*Renewables Readiness Assessment: Pakistan*, n.d.). According to International Renewable Energy Agency (IRENA), more than 70 % of country's energy mix is acquired by fossil fuels with renewable resources holding share of less than 4 % (excluding hydropower), one of the lowest in the region (*ENERGY PROFILE*, n.d.). Although the Government of Pakistan introduced its renewable energy policy in 2006 and developed the road map to promote renewable resources, yet the focus has been on deployment of PV and wind power systems, with no development projects of CSP or hybrid technologies in pipeline. Several of the previous studies have assessed the potential of standalone CSP plants for Pakistan (Ahmad & Zeeshan, 2022; Farooq & Shakoor, 2013; Tahir et al., 2021) while few others have discussed the dynamics of bioenergy potential in the country (Azhar et al., 2019; Rehman Zia et al., 2020). However, no study has been identified that performed site suitability analysis for HCSB projects in the country.

The research gaps identified through the reviewed literature can be summarized as:

- Insufficient number of studies for site suitability analysis of large scale HCSB powerplants,
- Lack of comprehensive and well-defined framework for site suitability analysis of hybrid CSP/biomass projects,
- Non-incorporation of integrated GIS-AHP approach for assessment of suitable sites for HCSB powerplants.

1.1 Objectives

The objectives of current study are defined below:

- To develop annual bioenergy and DNI resource potential maps for of Pakistan.
- To locate suitable sites for installation of HCSB powerplants in Pakistan using an integrated GIS-AHP approach.

CHAPTER 2

LITERATURE REVIEW

Particularly when it comes to the power industry, renewable energy technologies have progressively increased their percentage in the world's energy mix. There are several factors contributing to this tendency, most of which are related to various global concerns. The need for alternate energy sources, climate change, and sustainable development are just a few of the issues that have prompted technical growth in the energy industry. However, these clean energy technical advancements must be hastened if climate change targets such as limiting global warming up to 2°C by 2050 are to be met (*Human Development Report 2011 - Sustainability and Equity: A Better Future for All - World | ReliefWeb*, n.d.).

Solar energy is a viable resource for the creation of clean energy. The amount of solar energy that reaches the surface of the globe each year (roughly 885 million TWh) makes it the most plentiful energy source on Earth (Kober et al., 2020). The yearly energy consumption of the whole human population, which is expected to be 104,426 TWh by 2012, may be more than covered by this quantity of energy. The fact that the distribution of solar radiation throughout the planet's surface is not uniform and is continually changing, however, poses a significant technological problem (H. L. Zhang et al., 2013). This is said to be one of the reasons why solar energy hasn't always been used to its full potential. The global solar radiation map is depicted in Figure 2.1. Solar Radiation in Figure 2.1 is calculated using average yearly global irradiance data. It has been demonstrated that certain places are better suited than others for the development of solar energy.

However, recent technological developments and price drops, driven by policies emphasizing the need to speed up the development of clean energy, have resulted in the profitable infiltration of solar power in suitable markets (e.g., South Africa) and other industrialized countries (such as Germany). (IEA et al., 2021). Photovoltaics (PV) solar power and concentrated solar power (CSP) are the only two primary forms of solar energy technologies that are currently extensively used and capable of harvesting this plentiful energy source. The focus of this chapter, along with biomass energy resource, is on the latter because it is the major topic of this thesis.

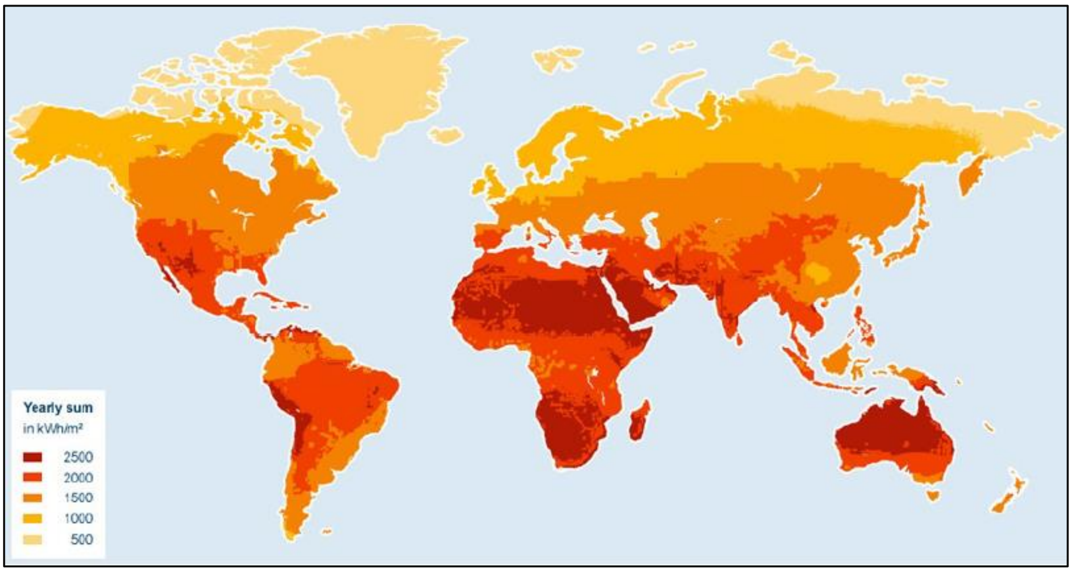


Figure 2.1: Map depicting global solar irradiance (Meteonorm Global Meteorological Database)

2.1 Concentrating Solar Power

Solar energy is captured and concentrated using the Concentrating Solar Power (CSP) technology to create a heat source with high temperature that may be utilized to generate electricity or heat (for example, for industrial operations). In a solar plant using CSP technology, specifically, the direct solar irradiation is concentrated using a solar collector field of mirrors, which concentrates the energy into a receiver. A source of high-temperature heat is created here through the absorption of energy (Kwak et al., 2021). By using this heat to run a typical power cycle, electricity may be produced. Because high-temperature heat is produced as an intermediary stage, CSP plants may add affordable thermal energy storage units (TES) technologies that are beneficial for storing energy later use. Like normal power generating cycles, the technology's coupling to them makes it adaptable enough to enable hybridization with different resources (Messaoudi et al., 2019). The flow chart given in Figure 2.2 serves as a general summary of this procedure.

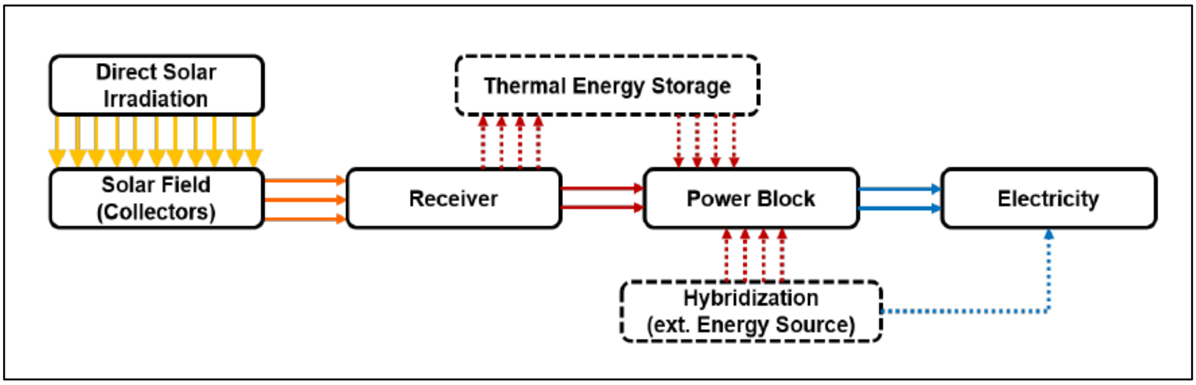


Figure 2.2: Flow chart depicting process flow in a CSP plant.

CSP plants are "dispatchable" since one of their main competitive advantages is their ability to supply regulated power on demand, either through TES integration or through hybridization. In reality, CSP and biomass are two of the few renewable dispatchable choices that have already gained traction in the market for large-scale power generation. Because of its dispatchability, a CSP plant may be created to perform a variety of functions within the energy system (Haddad et al., 2021).

2.2 Key Components of a CSP Plant

The three main components of a CSP plant are:

1. The Solar Field (including the receiver)
2. The Thermal Energy Storage (TES) system
3. The Power Block

The following sub sections provide detail understanding of the components of CSP plant.

2.2.1 The Solar Field

As a result of the solar field (SF) block's role in focusing solar energy, high temperatures are created. The heat transfer fluid (HTF), the receiver, and collector field are its three main components. The heat transfer fluid, or HTF, is a fluid that moves through the receiver and can carry energy. For categorization of solar field following two important criteria are considered:

1. Fixed or Mobile receiver type SFs.

2. Line or Point focus collection systems.

The receiver in a fixed type receiver SF is a stationary component that doesn't depend on the focusing collector, making it easier to transfer heat to the power block, which is also frequently stationary. On the other hand, a "mobile receiver type" travels with the collector, theoretically allowing it to increase optical efficiency and therefore capture more energy (Guedez et al., 2015).

Regarding second criterion, line focus SFs are made up of collectors that can only follow the position of the Sun along one axis, concentrating the energy on a linear receiver (such as a tubular one). In contrast, point focus SFs are made of mirrors that each include a two-axis tracking system that enables them to concentrate radiation at a single location. This improves optical efficiency and makes it possible to raise the temperature at the receiver. Next, a quick summary of the four primary SF technologies is given (R. Guédez et al., 2015a).

(a) Parabolic Trough Collectors

Mobile linear-focus collectors called Parabolic Trough (PT) collectors are made up of parabolic-shaped reflectors that concentrate light onto a tubular receiver. It accounts for over 85% of all CSP installations worldwide and is the most developed CSP technology available. In Figure 2.3, the technique is depicted both schematically (on the left) and in use (on the right). The HTF (often oil) is passed via the receiver in PT concentrators, which is typically made of a metal pipe that is encased in a vacuum tube (to reduce convection losses) (Juergen H. Peterseim, Tadros, et al., 2014). The maximum temperature for traditional systems is now 390 °C due to HTF property restrictions. The mirror area should be increased, and the HTF qualities should be improved, according to research. In a steam-cycle, for instance, the heat transported by the HTF is commonly employed to produce steam (Rafael Guédez et al., 2014).

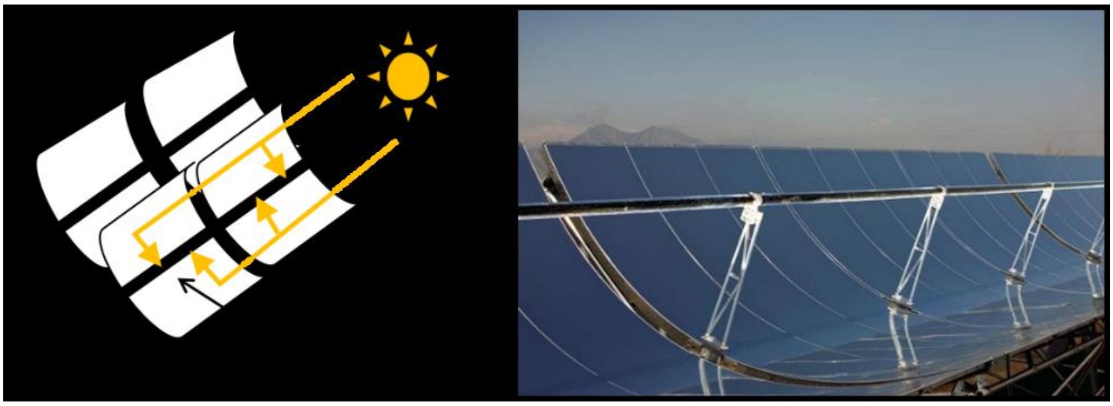


Figure 2.3: Parabolic Trough Collectors. Schematics (left) and real operation (right) (Source: Tamme et al., 2003)

(b) Linear Fresnel Technology

PT collectors are counterparts of linear Fresnel (LF) reflectors. As seen on the left side of Figure 2.4. The long row flat mirror segments that make up LF collectors are concentrated on a fixed linear receiver. The synchronous rotation of the flat mirrors keeps the receiver in focus while allowing for a lot of design flexibility. These systems, as opposed to PTs, offer the benefits of a low profile and a less complicated permanent structure, which might result in cheaper costs. These systems are still less common than PT collectors since the cheaper prices do not appear to make up for the lower efficiency (H. L. Zhang et al., 2013).

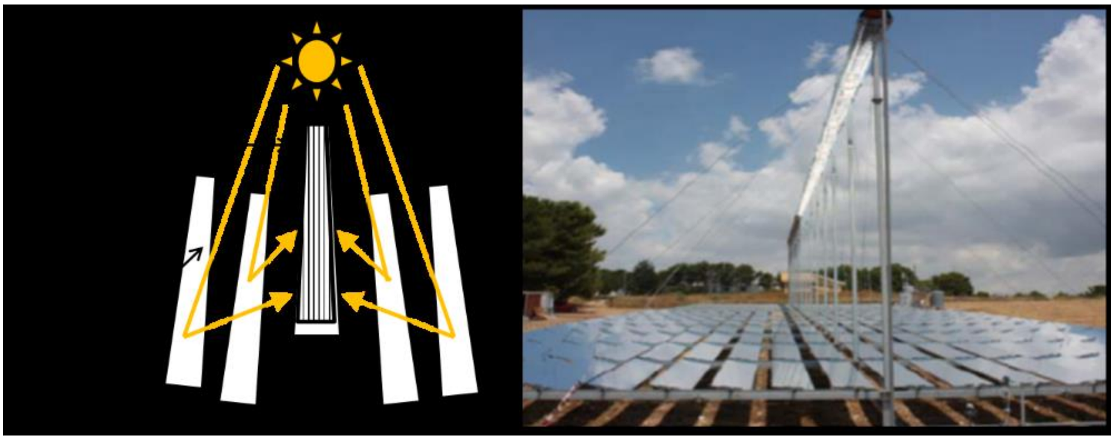


Figure 2.4: Linear Fresnel Collectors: Schematics (left) and real operation (Source: Zhu et al., 2014)

(c) Solar Tower Technology

A group of tracking mirrors, known as heliostats, are used in central receiver (CR) systems or solar tower systems to focus direct solar radiation onto a central receiver mounted at a certain height, sometimes referred to as the tower (Figure 2.5 left). Solar tower power plants (STPPs) is another name for these devices. So far, this technology has had the highest growth, making up around 14% of the installed CSP capacity (Soria et al., 2015). On the right side of Figure 2.5, an aerial shot of the Gemasolar solar tower power plant (STPP) located in southern Spain is shown.

Because the conversion processes of solar energy to heat and further heat to electricity take place in a small space, STPPs are easier to operate. Other benefits of such a technology include its ability to operate at greater temperatures than PTs, its ability to incorporate a number of commercially available TES systems, and its enormous potential for cost and efficiency savings considering that it is still a relatively new technology (Guedez et al., 2016).

The type of HTF and TES system taken into consideration affects the STPP designs. Currently, there are three HTF options: air, molten salts, and water/steam. Direct steam generation (DSG) systems are employed when water is used as heat transfer fluid in a CSP plant. Water is frequently used as the HTF in STPPs, commonly referred to as DSG-STPPs. The primary advantage of DSG systems is that they do not need intermediary heat carriers, which lowers system-wide conversion losses. However, a fundamental downside of DSG-STPPs is that there is now no TES system that is cost-effective for such a technology.

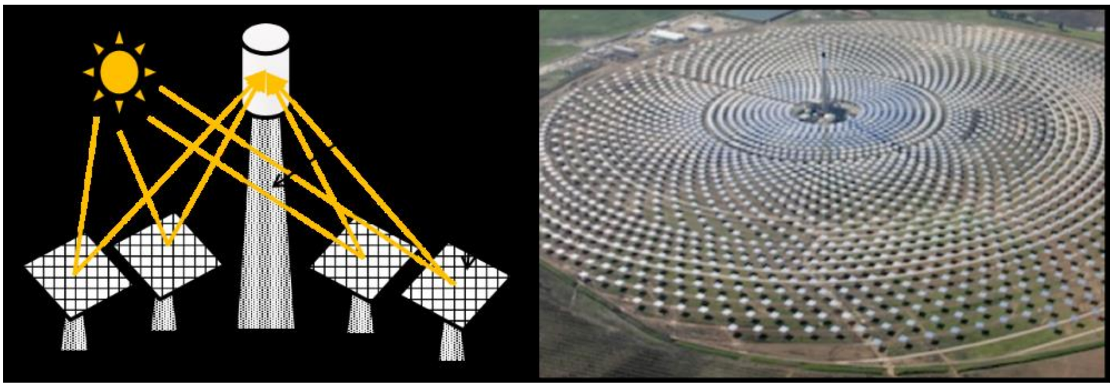


Figure 2.5: Solar Tower Plant: Schematics (left) and under real operation (right) (Source: Burgaleta, n.d.)

(d) Parabolic Dish Technology

Parabolic dish systems (PDs) are made up of several mirrors arranged to resemble a segment of a paraboloid. They direct the energy towards the focal point, which is home to a receiver. With the best optical efficiency of any commercial concentrator and the ability to operate at greater temperatures, PDs use a two-axis tracking mechanism. Either a local engine uses the heat gathered in the receiver, or it is sent to a plant on the ground. Based on the adoption of Stirling engines, this technology is being used the most frequently. PDs using Stirling engines have shown to have the greatest sun-to-electricity efficiency of any commercial solar applications (almost 30%) (Lovegrove & Stein, 2012). The versatility of a PD system is an additional benefit. The dish concentrator, receiver, and power block (the three main parts of a PD-CSP technology) are shown in Figure 2.6, which displays a straightforward schematic of the technology.

But even now, this technology is still being utilized for demonstrations. Its market acceptance has been hampered by costs and the lack of a workable commercial TES solution. However, there are a lot of chances for cost savings if the units are produced in large quantities. A TES system's possible integration is another factor that may be disruptive. The technique is still worth researching because of the potential for cost reduction and TES integration.

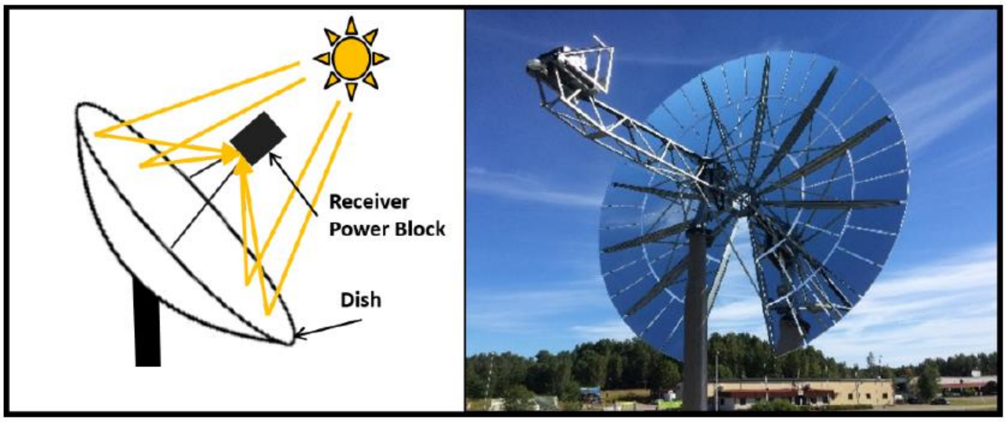


Figure 2.6: Parabolic Dish Systems: Schematics (left) and under real operation (Mohaghegh et al., 2021)

2.2.2 The Thermal Energy Storage System

Energy storage is the practice of conserving energy so that it may be used at a later time to complete useful tasks. (Gil et al., 2010). Heat is the usable energy that moves across the storage system in TES. Cost-effective TES systems may be integrated into CSP facilities to provide regulated power on demand. Compared to other renewable energy methods, this is a distinct benefit. Depending on the structure of the CSP plant, the necessary heat capacity and temperature, and most crucially, the intended operating strategy, a variety of TES designs and materials can be taken into consideration during the pre-design stage (Lovegrove & Stein, 2012).

Indeed, CSP plants with TES may perform a variety of distinct market functions depending on their design (layout, component size, and operation). CSP plants play a variety of important functions, according to the IEA Solar Technology Roadmap (*IEA, "Technology Roadmap: Solar Thermal Energy", Technical Report, IEA, Paris, 2014. - Google Search*, n.d.). The production of stable and dispatchable baseload and mid-merit electricity is one potential role in a future market with a high proportion of renewable energy sources, where CSP may act as the grid's skeleton. Second, the availability of quick-response peaking power to balance out fluctuations in other renewable energy technologies that are not dispatchable, such wind and solar PV. Depending on the specific CSP plant architecture and TES concept, several TES system sizes and operating methods may be employed (Islam et al., 2018a).

Thermal energy storage (TES) is classified based on two categories:

1. Storage media
2. Storage system

2.2.2.1 Commercially deployed TES systems for CSP plants

By combining various TES media and concepts, many TES systems may be constructed and ultimately integrated into a CSP plant. Many TES systems are now undergoing large-scale demonstrations, and others have already attained market maturity for CSP applications. This section's goal is to give a brief summary of the most cutting-edge TES systems that are now offered or almost ready to be made accessible for CSP applications.

(a) Two Tank Molten Salt Systems

Nowadays in CSP facilities, the most widely used technology is two-tank TES systems *(Gemasolar, the First Tower Thermosolar Commercial Plant with Molten Salt Storage*, n.d.). The bulk of the time, molten salts are used as the TES medium in two-tank TES systems, which are S-TES systems. As was already indicated, these systems fall under the category of active TES systems since, while being charged and discharged, the molten salt itself circulates via a heat exchanger. There are two types of molten salt systems used today: direct (such as MS-STPPs) and indirect (such as parabolic via CSP plants). Figure 2.7 shows two two-tank systems that are in use. On the left side, it is stated that the MS-STPP's two-tank system is operational. On the right, you can observe the "Andasol I" parabolic trough CSP plant's TES system (*The Andasol Solar Power Station Project - Power Technology*, n.d.).

Figure 2.7: Two tanks TES systems in Germasolar (left), and in Andasol I (right) (Source: *The Andasol Solar Power Station Project - Power Technology*, n.d.)

The two-tank TES system's key benefit is its simplicity in regulating the charging and discharging procedures (Koçak et al., 2020), which facilitates seamless integration with the other blocks of power plant (i.e., the power block and the solar field). Their biggest drawback, however, is that they need two huge, similarly insulated tanks to serve as buffers (Gil et al., 2010). Each tank in these systems can hold all of the TES media that is available in the plant. Large investments are needed for this. Additionally, the chosen TES medium of molten salts imposes a restriction on the system's operating temperature range. Modern industrial salts are distinguished by having a high freezing point of 250°C and a maximum working temperature of around 580°C, which is consistent with how industrial steam cycles operate. This final step increases the system's complexity by requiring extra preheating stages in the power block and the installation of electric heat-tracing devices along the TES system's pipes (Gil et al., 2010; Koçak et al., 2020).

(b) High temperature concrete storage systems

A possible cost-competitive TES system alternative has been use of materials that are concrete based for solar TES systems (Tamme et al., 2003). However, utilizing concrete raises questions about its durability (Gil et al., 2010) and makes it difficult to construct a precise heat exchanger (for example, in the form of embedded pipes). These two key factors have made it difficult to use TES technologies utilizing this medium in a significant CSP project.

In Figure 2.8, a commercially accessible concrete-based solution is seen being tested in the field. This is based on a design of a heat exchanger that was initially put out by (Tamme et al., 2003) and is covered by a storage insulating box. It is comparable to the one that is seen in the left of the picture. This concept's creators assert that it can operate cycle after cycle at temperatures ranging from 50°C to 565°C. Additionally, they guarantee that the concept is robust and scalable, making it ideal for meeting medium- to large-scale storage requirements (Gil et al., 2010). Additionally, they assert that these qualities apply for a variety of HTFs. Disruptive technology for integration in direct steam producing plants might potentially result from the introduction of such a water-steam idea as HTF. Currently, tests are being conducted utilizing oil as HTF (Koçak et al., 2020)

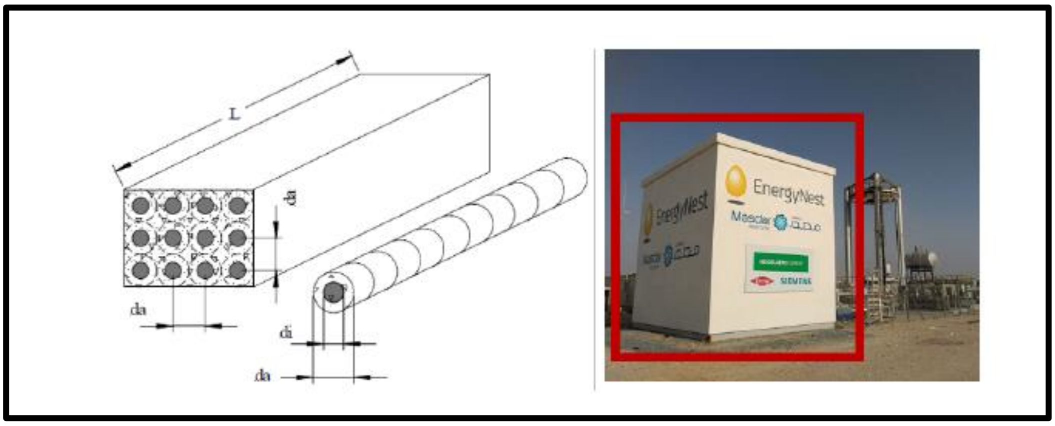


Figure 2.8: Schematics of concrete TES system (left) and real demonstration (right) (Source: Morisson et al., 2008)

2.2.3 The power block

In CSP facilities, energy may be produced using a variety of traditional thermodynamic power units. The temperature that can be reached in the receiver has a major role in the power block selection (J. D. Spelling, 2013). As a result, some power cycles are more suited than others for particular CSP systems. All CSP plants now employ industry-standard power block systems. The possible power cycles for CSP applications are summarized in Table 2, together with the applicable temperature ranges and their usual cycle efficiencies (J. D. Spelling, 2013).

Table 2.1: Typical power generation cycles for CSP applications

Power Cycle	Working Fluid	Temperature Range	Cycle Conversion Efficiency
Rankine	Organic Fluid	< 250°C	10 – 20 %
	Water / Steam	250 - 600°C	30 – 40 %
Stirling Engine	Helium	600 – 850°C	30 – 50 %
Brayton	Air	> 850°C	30 – 40 % (Simple Cycle) 45 – 60 % (Combined Cycle)

Table 2.1 suggests that one of the most promising possibilities for CSP to improve its competitiveness (J. D. Spelling, 2013) is the usage of simple or mixed cycle designs for high-efficiency Gas-Turbine (GT) cycles (Brayton) (J. Spelling et al., 2015) (with a bottoming Rankine steam-cycle (*Steam Turbine-Shandong Qingneng Steam Turbine Co.,Ltd.*, n.d.)). However, GT cycles can only run at high efficiency when temperatures above 1200°C are used. When considered for CSP applications, this offers new difficulties. The receiver side's material restrictions (maximum permitted temperature) and the absence of commercial TES (which is one of the key advantages of CSP plants) solutions for such high temperatures are two significant ones (R. Guédez et al., 2015b). In this sense, the use of GT for CSP applications is still a work in progress, and no significant system has been created to far.

2.3 Biomass energy potential in Pakistan

Biomass is employed extensively in industrialized nations despite a variety of difficulties and governmental regulations (Roni et al., 2017). According to Figure 2.9 the total amount of energy available worldwide in 2050 will be around 1041 Mto. By then, biomass will have the ability to produce around 1150 Mtoe of energy on its own, which may contribute significantly to the global energy mix. Globally, policymakers increasingly view bioenergy as the most significant renewable source, both now and in the long run (Welfle et al., 2014). Biomass is the fourth-largest source of energy, behind coal, oil, and gas. And unlike hydro, solar, and wind, it is available everywhere.

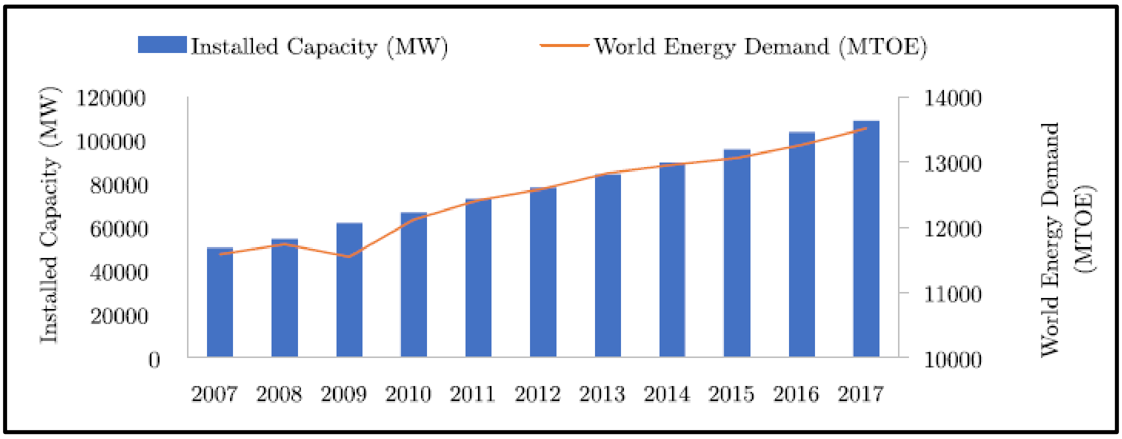


Figure 2.9: Trend of world's bioenergy installed capacity (IRENA)

And unlike hydro, solar, and wind, it is available everywhere. Only 5% (225 EJ) of the 4500 EJ of biomass produced worldwide can provide 50% of the world's current need for sustainable energy. However, instead of making up 50% of the overall land area, the land designated for energy crops makes up just 10% of the total area and 0.5–2% of the agricultural land. Therefore, the future seems bright, and although if its potential depends on local rules and incentives, investors still find it appealing because of its high availability and affordable fuel (Welfle et al., 2014).

It has been noted that a nation's agricultural productivity and technological uptake both play important roles in the economics of bioenergy. Due to a lack of available technology and a dysfunctional market, power costs are higher in emerging and underdeveloped nations. Similar to this, feedstock costs are relatively low in countries with an agricultural economy, which lowers overall costs. Because bioenergy's

Levelized Cost is at the low end of a wide range for economies based on agriculture, it is economically more viable than fossil fuels (Paolotti et al., 2017).

Biomass unquestionably offers a benefit, particularly for a nation like Pakistan that spent billions of dollars importing fossil fuels. The concentration of biomass leftovers in the vicinity of that plant is another aspect that affects it (Okeke & Mani, 2017). However, social benefits of biomass, such as the creation of jobs and supply networks for bioenergy, are also related to its economic benefits. Some users are even ready to pay more for power in exchange for the substitution's positive externalities. Consequential life-cycle assessment approaches (CCLA) (Gasol et al., 2011) have been used in several research to analyze the environment. This outlines the environmental effects brought on by the establishment of a new power plant across the board. Additionally, environmental effects limit the technological potential since a portion of the residue must stay on the site to control the ecosystem and allay worries about soil erosion and nutrient cycle (Naqvi et al., 2018).

A safe and ecologically beneficial method of power generation is biomass. Diverse biomass resources, such as agricultural wastes and animal wastes, offer the potential to produce bioenergy with lower greenhouse gas emissions. 130 GW of installed biomass energy capacity has been achieved globally. Given that 63% of Pakistan's population lives in rural regions, the home sector accounts for 76% of all biomass use (Irfan et al., 2020). Potential biomass resources utilised for energy production in Pakistan include animal waste, forest leftovers, agricultural residues, and city solid waste. All of these resources work together to produce 230 billion t of biomass annually. There is a potential for 652 M kg of manure, 230,000 t of agricultural residues, and 60,000 t of solid trash per day in the animal and agricultural waste resources. These biomass resources may be converted into worthwhile goods through effective biochemical and thermochemical processes. Due to its significant fuel product qualities, biomass is regarded as being highly appropriate for energy generation (Azhar et al., 2019; K Hossain & Badr, 2007).

When compared to fossil fuels, biomass resources often emit less carbon and other emissions, although this is not always the case and relies on a variety of factors, including the kind of biomass resources and how the fuel is generated and transported to the desired locations (Panepinto et al., 2015).

2.4 Hybridization Concepts of CSP and Bioenergy

Numerous HCSB plant design proposals have been put out in the literature (e.g., Termosolar Borges plant in Leida, Spain), but few have been implemented. A variety of power cycles, including as the Organic Rankine Cycle (ORC) and micro-gas turbines, have been examined in HCSB facilities. This section offers a brief assessment of HCSB plant concepts and prior deployments with the aim of identifying a highly effective and mature plant design for this case study (Juergen H. Peterseim, White, et al., 2014).

The most used HTF for parabolic trough collectors is thermal oil. Solar steam can only achieve a maximum temperature of around 400 C due to thermal oil, which is lower than the normal steam temperatures attained in bioenergy facilities, which range between 450 and 520 C depending on the feedstock. The use of thermal oil in a highly efficient HCSB plant restricts the Rankine cycle's feed-in points, including solar feedwater heating and extra steam production 'in-series' with the biomass boiler (Juergen H. Peterseim, Tadros, et al., 2014). The process by which saturated steam that leaves the solar system at a temperature of about 393 °C is superheated to temperatures between 450 and 520 °C by the biomass boiler before entering the high-pressure turbine is known as "in-series" generation, a solution that has also been chosen for the Termosolar Borges HCSB plant. At a maximum temperature of 450 °C, DSG generation may be used with both linear and parabolic trough collectors. This steam parameter enables the use of a biomass boiler in "in-parallel" with solar feed-in. In this mode of operation, both technologies simultaneously produce steam for the steam turbine. The "Scalable CSP Optimised Power Plant Engineered with Biomass Integrated Gasification" (SCOPEBIG) project, referenced by Soares, was started in 2015 in Barun, India, and it served as a test bed for this idea. Biomass combustion produces superheated steam for the high-pressure turbine in this 3 MWe parabolic trough HCSB power system, while CSP produces saturated steam through DSG for the low-pressure turbine. Molten salts and DSG are only two examples of the many HTF that CSP tower hybrids might deploy. A simple and direct integration of molten salt storage without the need for an extra heat exchanger is provided by the use of molten salts as HTF. Higher cycle efficiency is achieved by using DSG and molten salts, which may be used in thermal oil at temperatures and pressures greater than 500 °C and 100 bar, respectively. These steam parameters enable the operation of a biomass boiler in "parallel" with solar feed-in. To reduce high temperature corrosion and ash melt, steam temperatures in the CSP tower can be set based on the ideal combustion temperature for particular biomass feedstock types (Guedéz et al., 2016).

Several studies in literature (Milani et al., 2017; J. H. Peterseim et al., 2014; Juergen H. Peterseim, Tadros, et al., 2014; G. Zhang et al., 2016) have focused on the design and configuration of HCSB plants, while few others (Middelhoff et al., 2021; Middelhoff, Furtado, et al., 2022) have investigated their techno-economic feasibilities. Table 2.2 elaborates some of the recently published studies focused on CSP/biomass hybridization. The review of literature enlightens that number of studies focused on site suitability analysis for HCSB plants is insufficient. To the best of authors' knowledge, only three studies (Middelhoff, Madden, et al., 2022; Juergen H. Peterseim, Herr, et al., 2014; Thiam et al., 2017) till date have been published that investigated potential locations for installation of HCSB powerplants. These studies considered proximity to substations or access to transmission lines, in addition to resource availability, as the only identifying factors to locate most suitable areas. Only one study (Thiam et al., 2017), conducted in Sahel, Senegal, has been identified to include other factors such as water requirement, slope and land availability in their analysis. Nevertheless, the study lacked in proposing a structured methodology for the same for the process.

Table 2.2: Summary of previous studies related to Hybrid Concentrated Solar Biomass (HCSB) powerplants

Study area	Research domain	CSP technology	Biomass feedstock Type	Ref
Australia	Design, evaluation of technoeconomic analysis and environmental performance	ST	Rice straw	(Middelhoff et al., 2021)
Australia	Ideal areas for HCSB plants installation and annual electricity potential	ST, LFR	Forestry residues, Bagasse, urban wood waste, refuse derived fuels, stubble	(Juergen H. Peterseim, Herr, et al., 2014)
India	Feasibility of hybrid solar-biomass in India.	LFR	Rice husk, coconut shells, bio-bricks (composed of sawdust, ground	(Nixon et al., 2012)

Study area	Research domain	CSP technology	Biomass feedstock Type	Ref
			nut husk, coffee husk and tamarind husk)	
New South Wales (NSW), Australia	Assessment of electricity generation potential and identification of possible sites for HCSB plants	ST	Bagasse, stubble and forestry residues	(Middelhoff, Madden, et al., 2022)
Europe	Technological assessment of solar-biomass systems for power generation	ST, PTC, LFR	Agricultural residues, forestry residues, biomass from waste	(Hussain et al., 2017)
Brazil	Proposed and analyzed various options for HCSB plants	PTC	*Jurema-preta* wood	(Milani et al., 2017)
Australia	Enabling Cost effective strategies for HCSB plants	PTC	Agricultural regions	(Juergen H. Peterseim, White, et al., 2014)
Sahel, Senegal	Assessment of generation potential and identification of suitable areas for HCSB plants	Not defined	Animal waste, Typha Australys Plant	(Thiam et al., 2017)
Bahia, Brazil	Deployment of HCSB plants	PTC	*Jurema-preta* wood	(Soria et al., 2015)

From the above studies, it can be concluded that resource requirement for hybrid CSP/biomass projects is low as compared to standalone CSP and biomass powerplants. For instance, where standalone CSP plants require DNI > 2000 kWh/m^2.year (Aqachmar et al., 2019; Islam et al., 2018b), installation of HCSB projects is feasible on areas receiving DNI within the range of 1600 -1800 kWh/m^2.year (Middelhoff, Madden, et al., 2022; Thiam et al., 2017). Also, biomass feedstock requirement for HCSB plants is lower as compared to that for biomass only powerplant (Middelhoff, Madden, et al., 2022; Nixon et al., 2012) due to offset energy production from solar energy. This is highly beneficial because not only it results in reduced emissions (Middelhoff et al., 2021) but it also leads to the implementation of circular economy approach in agricultural sector (*Mission Possible | Energy Transitions Commission*, n.d.).

2.5 Multicriteria Decision Making (MCDM) Methods

Selecting ideal locations for large scale powerplants, is considered to be an intricate process because of involvement of various meteorological, technical, economic and environmental factors (Gouareh et al., 2021). Multi-Criteria Decision Making (MCDM) methods, in this regard, are considered to be useful techniques to solve complex decision-making problems (Vassoney et al., 2021). Various previously published studies (Castro & Silv Parreiras, 2018; Kumar et al., 2017; Simsek et al., 2018) presented review of MCDM methods in domain of sustainable renewable energy development. Also, the application of these methods towards sustainable energy planning has been discussed in detail by Pohekar et al., (Pohekar & Ramachandran, 2004), where more than 90 published papers were reviewed. After exploring existing literature on MCDM, it is found out that over the years, several MCDM methods such as TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), AHP (Analytic Hierarchy Process), ANP (Analytic Network Process) and Fuzzy AHP have been considered by different researchers (Castro & Silv Parreiras, 2018; Kengpol et al., 2013; Pohekar & Ramachandran, 2004), in site selection domain. However, Analytical Hierarchy Process (AHP) has emerged out to be the most popular technique for solving complex decision-making problems, because of its flexibility and robustness (Kumar et al., 2017; Messaoudi et al., 2019). Recently, application of AHP coupled with Geographic Information System (GIS) has gained popularity among researchers and has been widely employed for site suitability analysis of large-scale renewable energy powerplants [7,27]. However, no study has been identified that employed integrated GIS-AHP approach for site suitability analysis of HCSB powerplants.

While using MCDM for site suitability analysis of large-scale renewable energy powerplants, previous studies observed that selection of criteria, sub-criteria and constraint sets for site suitability are arbitrary and may differ depending upon renewable technology and region/country. For instance, for CSP plants many researchers agree that lands with slope higher than 5 % are not feasible for installation (Aly et al., 2017; Yushchenko et al., 2018) whereas for PV powerplants, this limit is extended up to 11 % (Noorollahi et al., 2016).

CHAPTER 3

MATERIAL AND METHODS

To select the most feasible sites for development of HCSB power projects in Pakistan, various meteorological, economical, technical, and environmental factors were selected. ArcMap was used for the development of raster maps of selected evaluation criteria. Afterwards, relative importance weight of each criterion was calculated using AHP, followed by reclassification of raster maps from 1 to 5 (1 being the least and 5 being the most suitable). Finally, weighted overlay was performed in ArcGIS (*ArcGIS Desktop | Desktop GIS Software Suite*, n.d.) and most suitable sites for HCSB projects in Pakistan were identified. The overall method followed in the study has been summarized in Figure 3.1 and is elaborated in the following subsections.

3.1 Study area

This study covers Pakistan, situated in South Asia, located between longitudes of 60° E - 76° E and latitudes of 23° N – 27° N. Pakistan is the sixth most populous country in the world with total population of 207.8 million (*Final Results (Census-2017) | Pakistan Bureau of Statistics*, n.d.). With an area of 796,096 km^2 (*Final Results (Census-2017) | Pakistan Bureau of Statistics*, n.d.), it ranks 36th in the list of largest countries. Pakistan has substantial potential of solar and biomass energy. More than 70% of the land receives solar radiations (i.e. DNI) greater than 1800 kWh/m^2.year (Ahmad & Zeeshan, 2022; Stökler et al., 2016), which makes it favorable for installation of CSP plants. Moreover, copious amounts of different crops (such as wheat, rice, sugarcane, maize and cotton) are harvested each year, resulting in large quantities of crop residue that can be used for power generation (Irfan et al., 2020; Naqvi et al., 2018). Annual crop production for the last five years of major crops in the country are shown in Figure 3.5. It is important to mention that study area includes four provinces of Pakistan i.e., Punjab, Sindh, Khyber Pakhtunkhwa (KPK), and Balochistan. Areas of Gilgit-Baltistan (GB) and Azad Jammu and Kashmir (AJK) have not been included due to lack of biomass data availability. Administrative map of Pakistan is given as Figure 3.2.

3.2 Datasets Description

Description of all the used datasets is summarized in Table 3.1. The datasets are further discussed in the following subsections:

Table 3.1: Description of datasets used and their sources.

Parameter	Spatial resolution	Temporal resolution	Source	Ref
DNI	0.05°	1996 - 2016	The Satellite Application Facility on Climate Monitoring (CMSAF)	(Amillo et al., 2014)
Biomass (Punjab)	-	2017 - 2018	Agriculture Marketing Information Service (AMIS)	(*Untitled Page*, n.d.)
Biomass (Sindh)	-	2017 - 2018	Sindh Bureau of Statistics	(*Development Statistics | Sindh Bureau of Statistics*, n.d.)
Biomass (KPK)	-	2017 - 2018	KPK Bureau of Statistics	(*Bureau of Statistics | Khyber Pakhtunkhwa*, n.d.)
Biomass (Balochistan)	-	2017 - 2018	Balochistan Bureau of Statistics	(*Bureau of Statistics – Government of Balochistan*, n.d.)
Water stressed areas	-	2019	Aqueduct 3.0: Updated Decision-Relevant Global Water Risk Indicators	(*Aqueduct 3.0: Updated Decision-Relevant Global Water Risk Indicators| World Resources Institute*, n.d.)
Land cover	300 m	2020	Copernicus	(*Land Cover*

Parameter	Spatial resolution	Temporal resolution	Source	Ref
			Climate Change Service (C3S)	*Classification Gridded Maps from 1992 to Present Derived from Satellite Observations*, n.d.)
Road network	-	2018	WFPGeoNode (Extracted from OpenStreetMap)	(*Pakistan Road Network (Main Roads) — WFP GeoNode*, n.d.)
Transmission network	-	2017	The World Map – Data Catalog (Extracted from OpenStreetMap)	(*Pakistan - Electricity Transmission Network | Data Catalog*, n.d.)
Elevation	30 m	2021	Advance Land Observing Satellite	(Tadono et al., 2014)
Slope	30 m	-	Derived from Elevation	-
Population density	1 km	2020	WorldPop Population Count Datasets	(*WorldPop :: Population Density*, n.d.)
Water bodies	30 m	1984 - 2020	Land Remote Sensing Satellite (LANDSAT)	(Pekel et al., 2016)

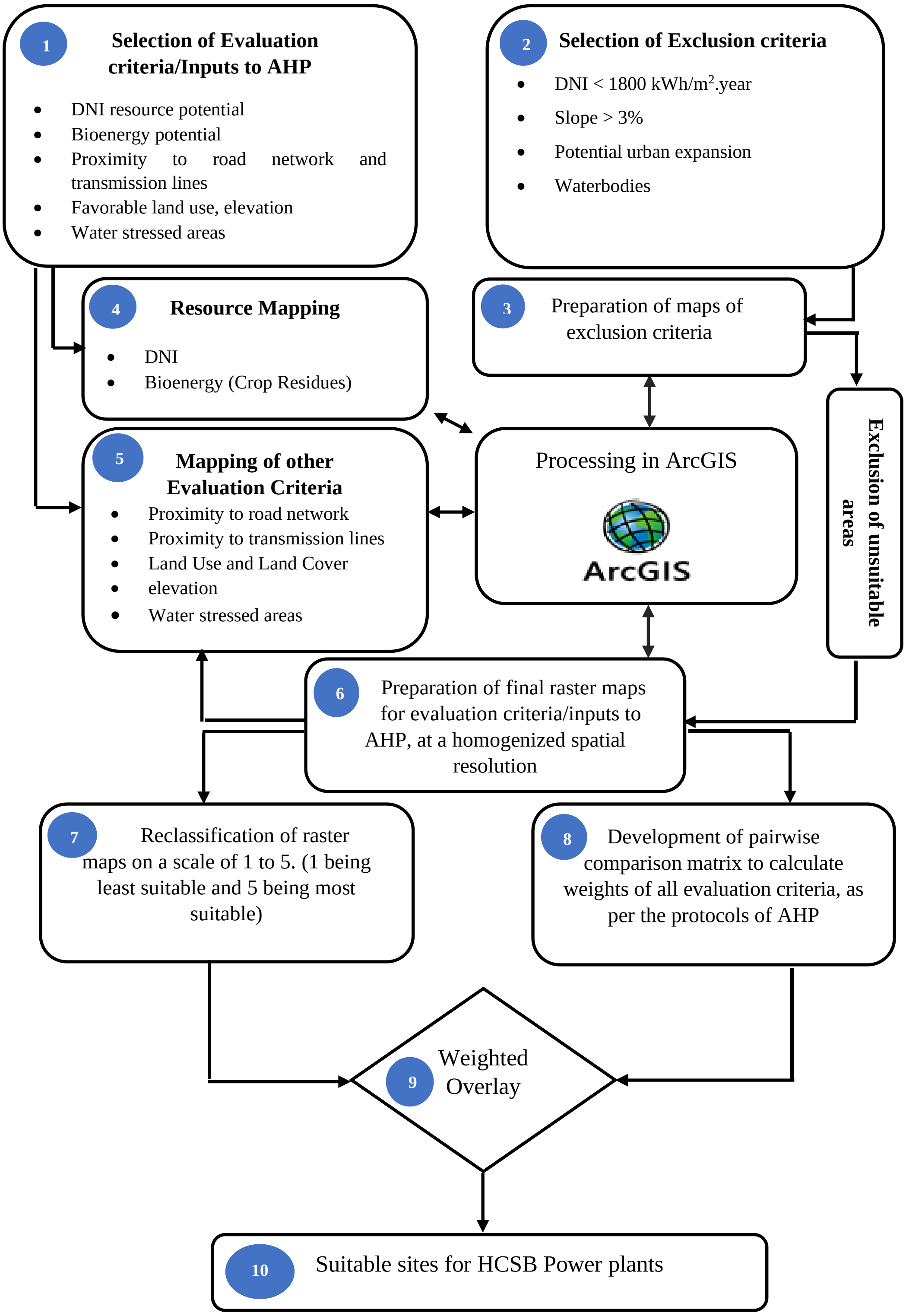
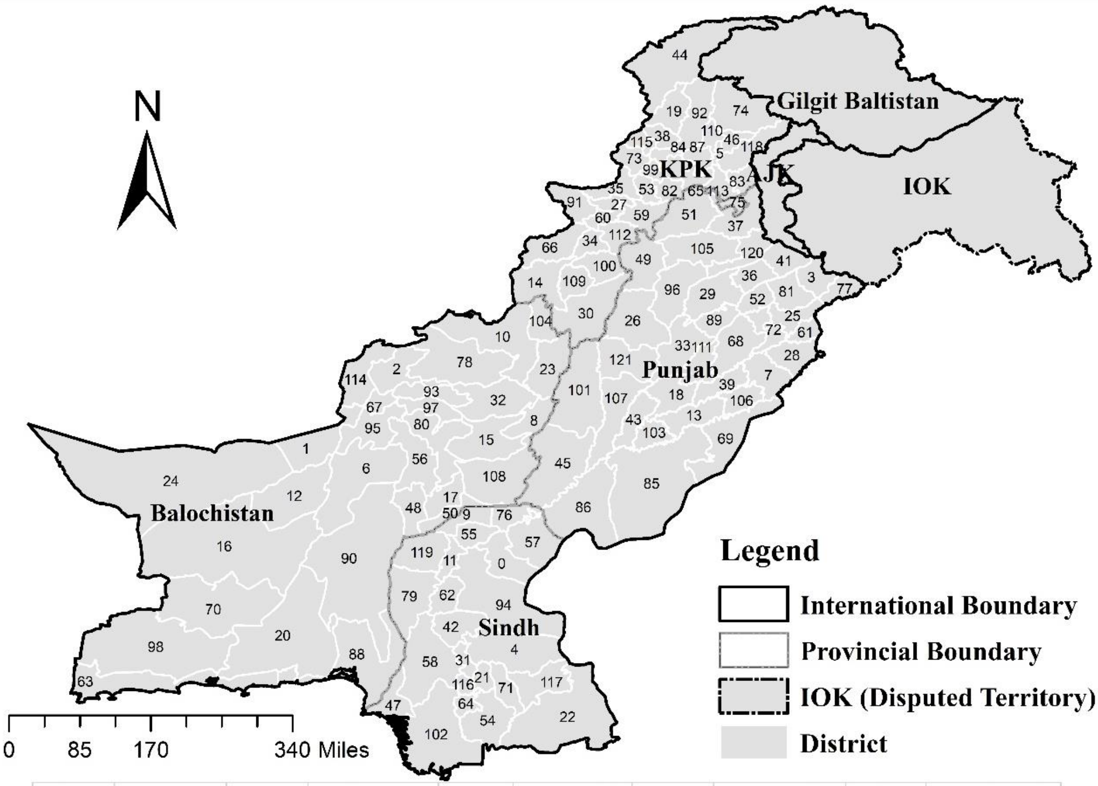


Figure 3.1: Framework of methodology adopted for site selection process of HCSB powerplants.



No.	DISTRICT	No.	DISTRICT	No.	DISTRICT	No.	DISTRICT	No.	DISTRICT
0	Sukkur	25	Sheikhupura	50	Jaffarabad	75	Islamabad	100	Lakki_Marwat
1	Nushki	26	Bhakkar	51	Attock	76	Kashmore	101	DG_Khan
2	Pishin	27	O_Agency	52	Hafizabad	77	Narowal	102	Thatta
3	Sialkot	28	Kasur	53	Peshawar	78	Killa_Saif	103	Lodhran
4	Sanghar	29	Sargodha	54	Badin	79	Dadu	104	Sheerani
5	Tor_Ghar	30	DI_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	M_Bahauddin	61	Lahore	86	RY_Khan	111	TT_Singh
12	Kharan	37	Rawalpindi	62	N_Feroze	87	Buner	112	Karak
13	Vehari	38	Lower_Dir	63	Gwadar	88	Las_Bela	113	Haripur
14	SW_Agency	39	Sahiwal	64	TM_Khan	89	Chiniot	114	Killa_Ab
15	Kohlu	40	Mardan	65	Swabi	90	Khuzdar	115	Bajaur_Agency
16	Washuk	41	Gujrat	66	NW_Agency	91	Kurram_Agency	116	Hyderabad
17	Nasirabad	42	S_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	Q_Shahdadkot
20	Awaran	45	Rajanpur	70	Panjgur	95	Mastung	120	Jhelum
21	TA_Yar	46	Batagram	71	Mirpur_Khas	96	Khushab	121	Layyah
22	Tharparkar	47	Karachi	72	Nankana_Sahib	97	Harnai		
23	Musakhel	48	Jhal_Magsi	73	M_Agency	98	Kech		
24	Chagai	49	Mianwali	74	Kohistan	99	Charsadda		

Figure 3.2: Map of Pakistan with district names

3.3 Data processing and mapping

Data processing and consequent map generation is explained in the following subsections.

3.3.1 Exclusion criteria maps

Considering the varying nature of the land or resource availability, some area was considered not suitable for the plant deployment and thus an exclusion criterion was applied to the total land. The factors considered in exclusion process are given as following.

(a) Urban expansion

Pakistan is rapidly undergoing urbanization with annual growth rate of 2.77 % (Fahad et al., 2021). It has been estimated that in coming 10 to 15 years, almost half of country's population will be residing in urban areas (Fahad et al., 2021), leading to significant alterations in its landcover (Shah et al., 2021). Rapid increase in country's population is considered to be one of the most important factors responsible for acceleration in urban sprawl (Fahad et al., 2021; Shah et al., 2021). Therefore, it is important to consider potential urban expansion, while investigating suitable sites for large scale power plants.

The potential expansion in urban area (km^2) by 2045 (considering service life of ~25 years for powerplant) was calculated by using Eq. (1) and resulting areas were excluded from land cover map.

$$UE_{2045} = P_{2045} \times A_{sp} \tag{1}$$

Here UE_{2045} denotes urban expansion by 2045 (km^2) for given polygon identified as urban area currently, P_{2045} denotes the projected population of the polygon by 2045 calculated by Eq. (2), as given below.

$$P_{2045} = P_{2020} + (P_{2020} \times R) \tag{2}$$

Here P_{2020} is the population of the polygon in year 2020, calculated by Eq. (3) and R is the projected rate of increase in population of Pakistan from 2020 to 2045 (*World Population Prospects - Population Division - United Nations*, n.d.) calculated by Eq. (4)

$$P_{2020} = A_{2020} \times PD_{2020} \tag{3}$$

$$R = \frac{(P_{2045} - P_{2020})}{P_{2020}} \times 100 \quad (4)$$

Here A_{2020} is the area of the polygon in year 2020 (km^2) and PD_{2020} is the population density of the polygon in year 2020. The A_{sp} in eq. 1 is the specific area (km^2/person), calculated by Eq. (5), given below.

$$A_{sp} = \frac{A_{2020}}{P_{2020}} \quad (5)$$

The excluded area due to urban expansion is indicated in Figure 3.3(a).

(b) Slope

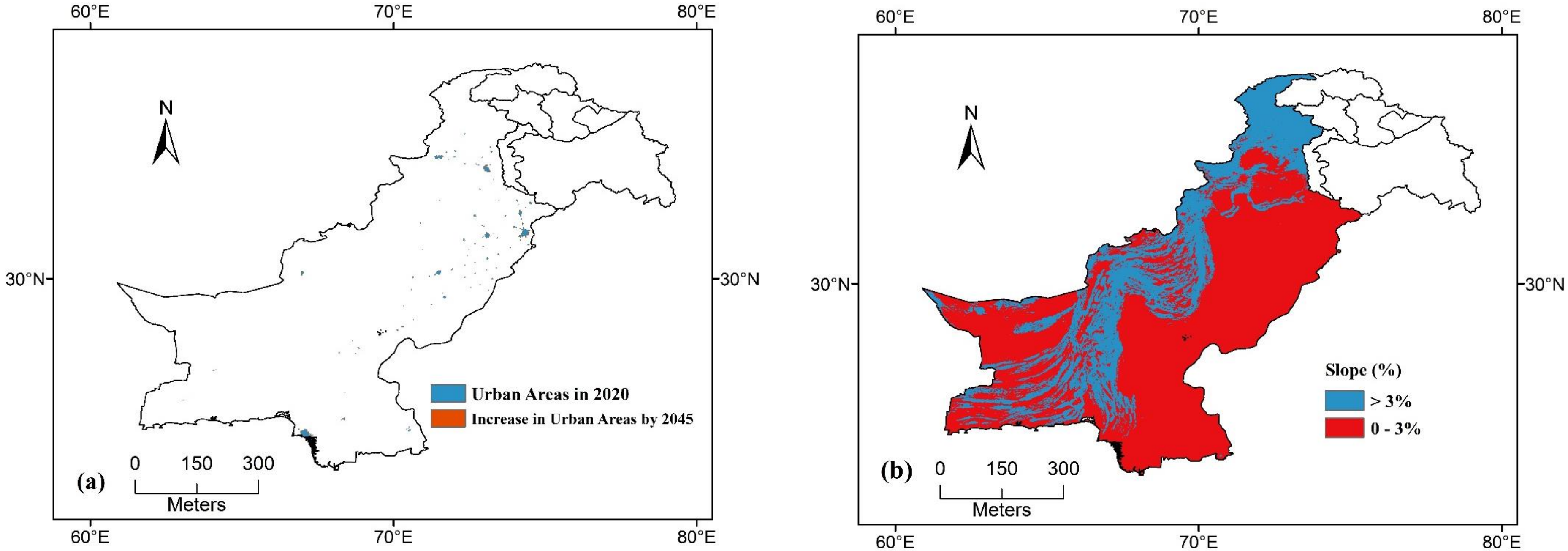
High slopes are considered as unsuitable for development of large-scale powerplants (Gašparović & Gašparović, 2019), because of high construction costs (Alami Merrouni et al., 2018; Gastli et al., 2010). For standalone CSP plants, studies suggest exclusion of areas with slope >3 % (Tlhalerwa & Mulalu, 2019; Ziuku et al., 2014). On the other hand, for standalone biomass powerplants, slope up to 15 % has been considered acceptable (Woo et al., 2018). Therefore, only areas with slope < 3 % were considered acceptable for installation of HCSB plants. The excluded area due to higher slope is indicated in Figure 3.3(b).

(c) Direct Normal Irradiance (DNI)

The amount of solar radiation received per unit area by a surface held normal to the radiation coming in a straight line from the sun at any given time is called Direct Normal Irradiation (DNI) (“Solar,” 2013). Various studies in literature such as (Middelhoff, Madden, et al., 2022; Juergen H. Peterseim, Herr, et al., 2014) suggest that for a site to be considered as a candidate for installation of HCSB power plants, DNI must be greater than 1800 kWh/m^2.year on an average. Therefore, all areas receiving lesser annual average DNI were excluded. The excluded area due to lesser DNI is indicated in Figure 3.3(c).

(d) Water bodies

All water bodies were considered as unavailable areas for plant deployment due to potential complexities in construction. The excluded area due to water bodies is given in Figure 3.3(d).


60°E
70°E
80°E
30°N
N
Urban Areas in 2020
Increase in Urban Areas by 2045
0 150 300
Meters
(a)
Slope (%)
> 3%
0 - 3%
(b)

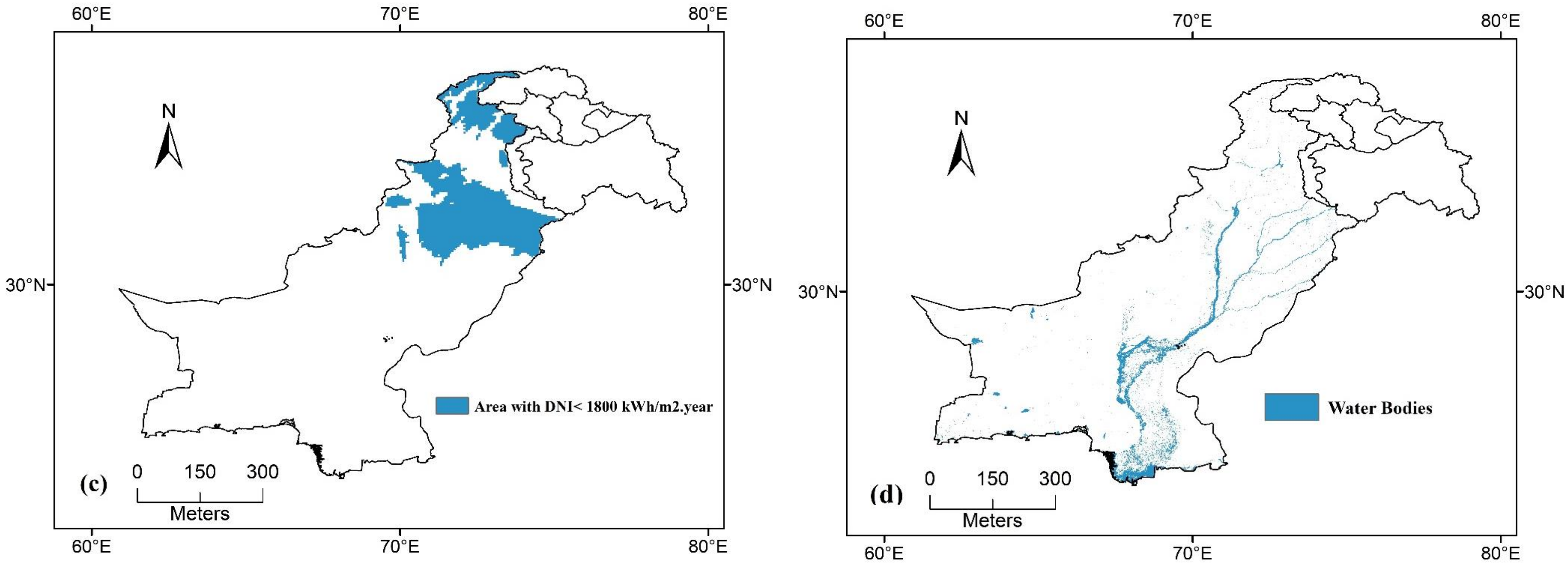


Figure 3.3: Maps of exclusion criteria considered in this study (a) urban expansion, (b) slope, (c) DNI, (d) water bodies.

3.3.2 Resource mapping

Mapping of DNI and bioenergy potential, being the two most important criteria, is explained below.

(a) Direct Normal Irradiance mapping

Previous studies (Middelhoff, Madden, et al., 2022; J. H. Peterseim et al., 2014) report that DNI is the most crucial factor in determining feasibility of HCSB powerplants, as it is considered primary resource. The framework adopted to develop DNI resource potential map is shown in Figure 3.4(a). Briefly, the daily mean DNI data for years 1999 – 2016 for area located between 60° – 81° longitude and 23.5°–37.5° latitude in NetCDF format was obtained from CMSAF website (Table 3.1). The daily files were processed using MATLAB algorithm to obtain annual average value for 18 years. An excel file containing DNI data was prepared and inputted in ArcGIS. Afterwards, the data was interpolated using inverse distance weighting (IDW) method in ArcMap. The extract tool was used to mask study area, and all pixels outside the boundary of study area were removed. At this point, areas with insufficient resource availability (as described in previous Section) were excluded and final DNI resource potential map for Pakistan was obtained.

(b) Bioenergy potential map

Residues of five major crops (i.e., wheat, rice, maize, cotton, and sugarcane) were considered. According to field surveys conducted by World Bank (*Biomass Resource Mapping in Pakistan : Final Report on Biomass Atlas*, n.d.), agricultural residues are used for various purposes such as animal fodder, domestic burning and as a fertilizer. A portion of generated residue is sold to industries and biomass suppliers while the remaining portion is left on the field for burning (as the farmers need to vacate the land for next crop harvesting). The targeted biomass for current study, is the part left on the field for burning. Figure 3.4(b) illustrates framework of methodology adopted to develop bioenergy potential map of Pakistan. In the first step, quantification of available amount of all five types of biomass feedstock considered, was performed by using Eq. (6) (Azhar et al., 2019; J. Li et al., 2016)

$$BF_{mj} = P_{mj} \times G \times \omega \times D \times \eta \quad (6)$$

Where: BF_{mj} denotes the available amount of residue for crop *j* in district *m* (ton), P_{mj} denotes the annual production of crop *j* in district *m* (ton, Table 3.1), *G* represents grain to straw ratio, ω signifies portion of residue available, D is dry matter content and η is collection efficiency (%). Values for G and D were obtained from literature as described in Table 3.2. Collection efficiency (η) of 90 % was considered for all residues, where the remaining 10 % was assumed to be lost due to collection inefficiency (Hiloidhari & Baruah, 2014). Available amount of crop residues for all five crops considered in this study are given in Figure 3.5.

Table 3.2: Values of parameters used in calculations and their sources.

Crop	**Grain to straw ratio**	**Dry matter content (%)**	**LHV (GJ/ton) (K Hossain & Badr, 2007)**
Wheat straw	1.75 (Azhar et al., 2019)	0.83 (Azhar et al., 2019)	15.76
Rice straw	1.5 (Azhar et al., 2019)	0.85 (Azhar et al., 2019)	16.3
Maize stalk	2.0 (Butt et al., 2013; K Hossain & Badr, 2007)	0.88 (K Hossain & Badr, 2007)	14.70
Cotton stalk	2.755 (Butt et al., 2013; K Hossain & Badr, 2007)	0.88 (K Hossain & Badr, 2007)	16.4
Sugarcane leaves	0.24 (Azhar et al., 2019)	0.71 (Azhar et al., 2019)	15.81

Of particular interest here is ω, the portion of crop residues available. It is to be noted that the amount of residue generated during harvesting process depends on whether harvesting is carried out manually or by machines, besides other factors. Since, in Pakistan, both harvesting modes are used, the value of ω was determined by using Eq. (7) (Azhar et al., 2019)

$$\omega_m = A_m \times \alpha_m + B_m \times (1 - \alpha_m) \tag{7}$$

Here, α_m is the portion of crop harvested mechanically in district m (consequently, $1-\alpha_m$ is the manually harvested portion), while A_m and B_m are the portions of crop residues available, after some parts of residues were used for other purposes, for mechanical and manual harvesting respectively. Values for α_m, A_m and B_m were obtained from field surveys conducted by World Bank earlier (*Biomass Resource Mapping in Pakistan : Final Report on Biomass Atlas*, n.d.), for 44 districts of Pakistan. Districts that were not incorporated in survey, were assigned values of the nearest district included in the report (Azhar et al., 2019). The biomass energy potential for the 5 crops was determined by using Eq. (8)

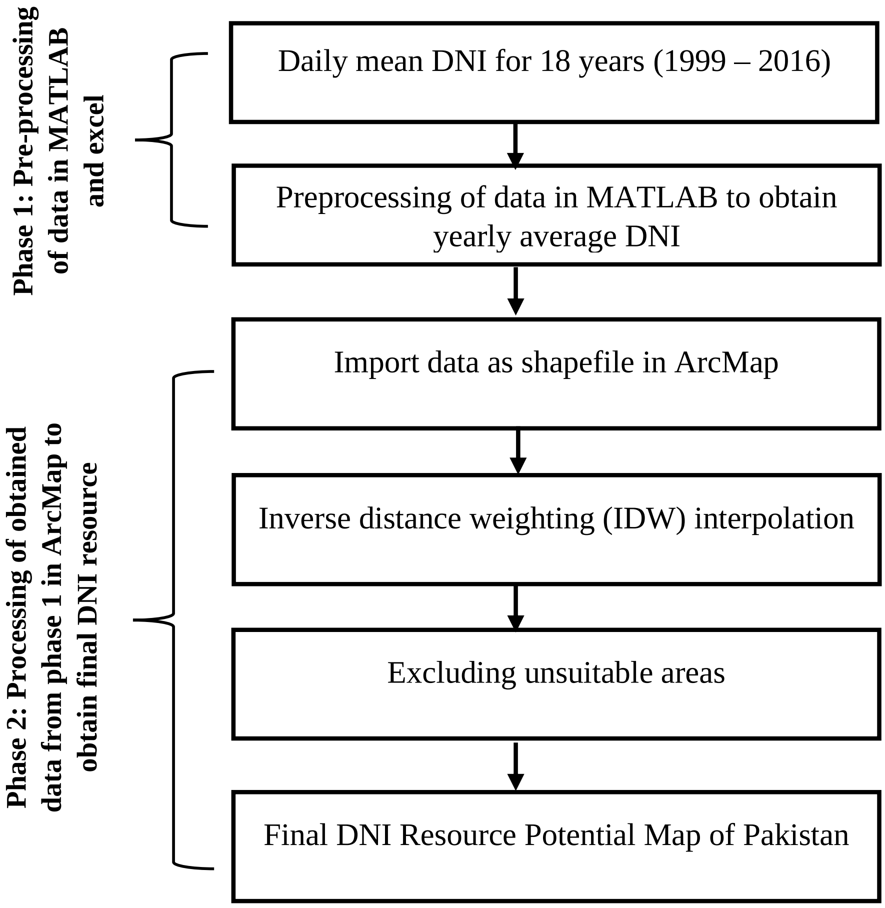
$$E_{mj} = BF_{mj} \times LHV \times CF \quad (8)$$

Where: E_{mj} signifies energy potential (kWh) of crop *j* for district *m*, BF_{mj} represents available residue (ton) calculated by using Eq. (6), *LHV* is lower heating value for crop *j* (GJ/ton), and *CF* is the conversion factor (i.e. 1GJ = 277.8 kWh). The *LHV* in Eq. (8) were obtained from literature (Table 3). Eventually, the total crop residue energy potential for each district was determined by Eq. (9)

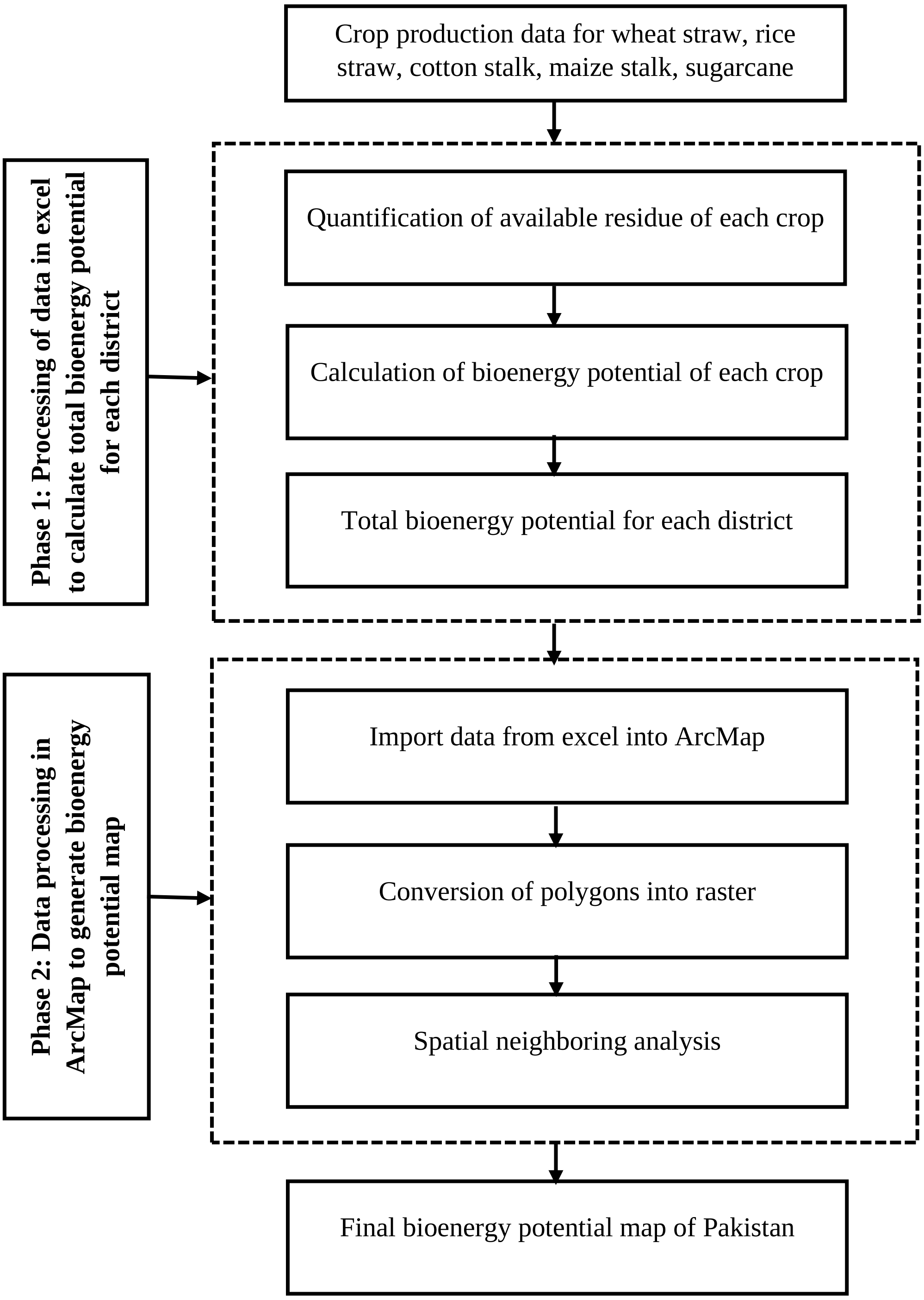
$$TE_m = \sum_{j=1}^{5} E_{mj} \quad (9)$$

Where: TE_m signifies total bioenergy potential of district *m*.

The data was then transferred from excel files to ArcGIS and together with landcover data (Table 3.1), bioenergy potential of each district was equally divided among the agricultural pixels within district to obtain the bioenergy potential map. However, this map was further processed by performing spatial neighboring analysis, using focal statistics tool in ArcMap, to assign each pixel the average value of the energy potential in all pixels within its 50 km radius. This modification in bioenergy potential map was done to avoid assigning of unduly high importance in the AHP process, to the pixels belonging to croplands in comparison to their neighboring pixels belonging to other land use classes.

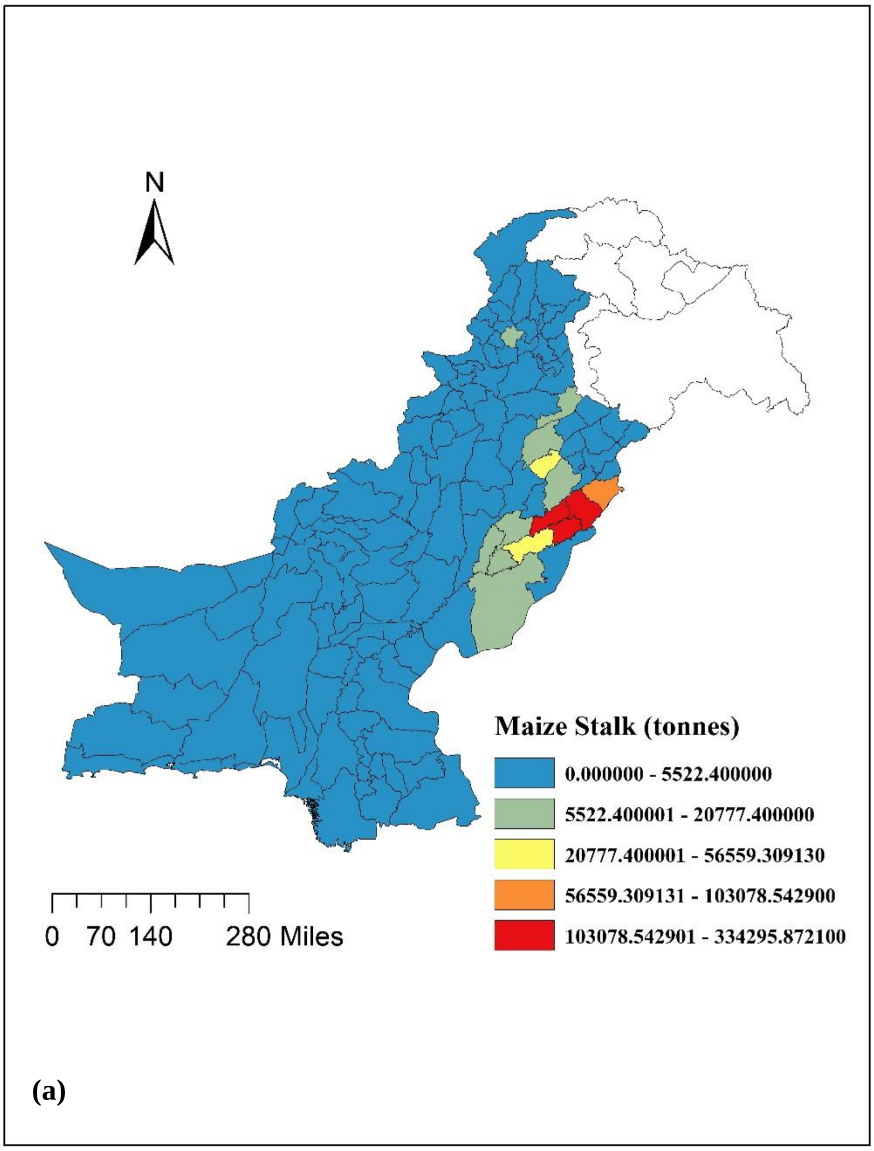

Phase 1: Pre-processing of data in MATLAB and excel
Daily mean DNI for 18 years (1999 – 2016)
Preprocessing of data in MATLAB to obtain yearly average DNI
Phase 2: Processing of obtained data from phase 1 in ArcMap to obtain final DNI resource
Import data as shapefile in ArcMap
Inverse distance weighting (IDW) interpolation
Excluding unsuitable areas
Final DNI Resource Potential Map of Pakistan

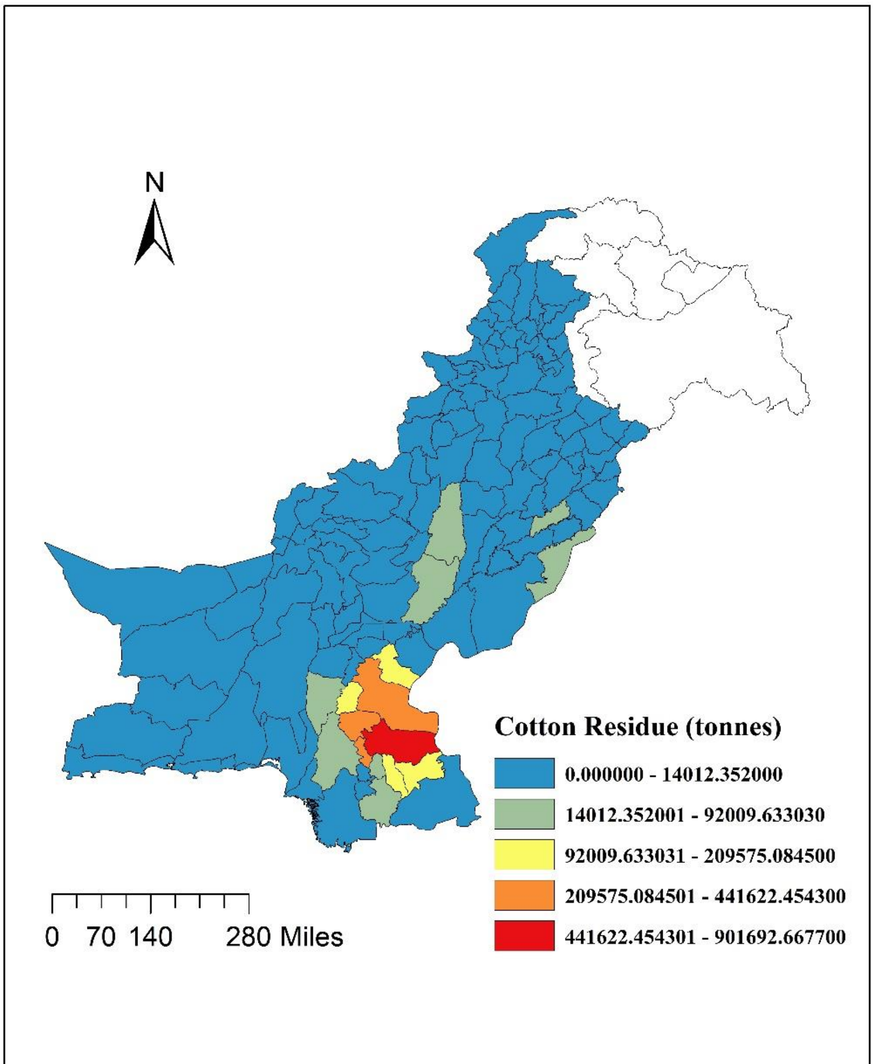
(a)



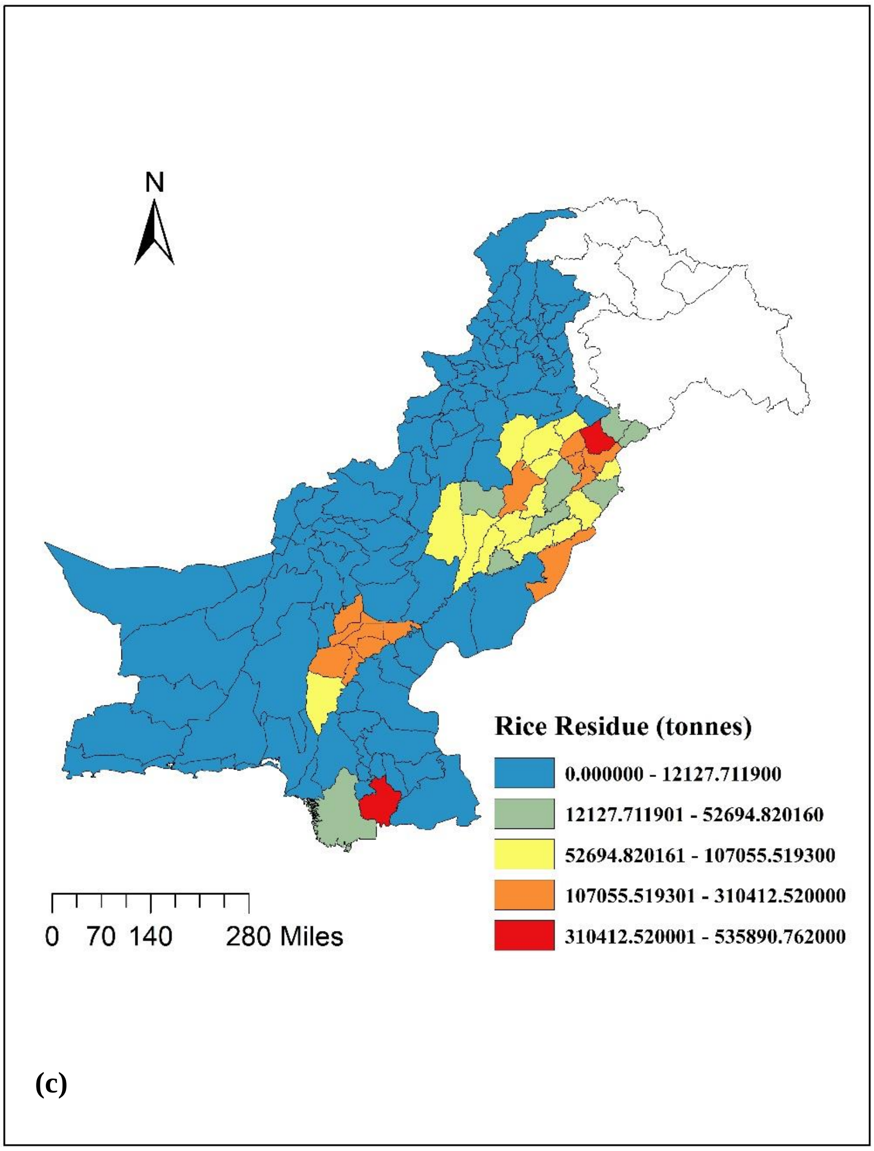
(b)

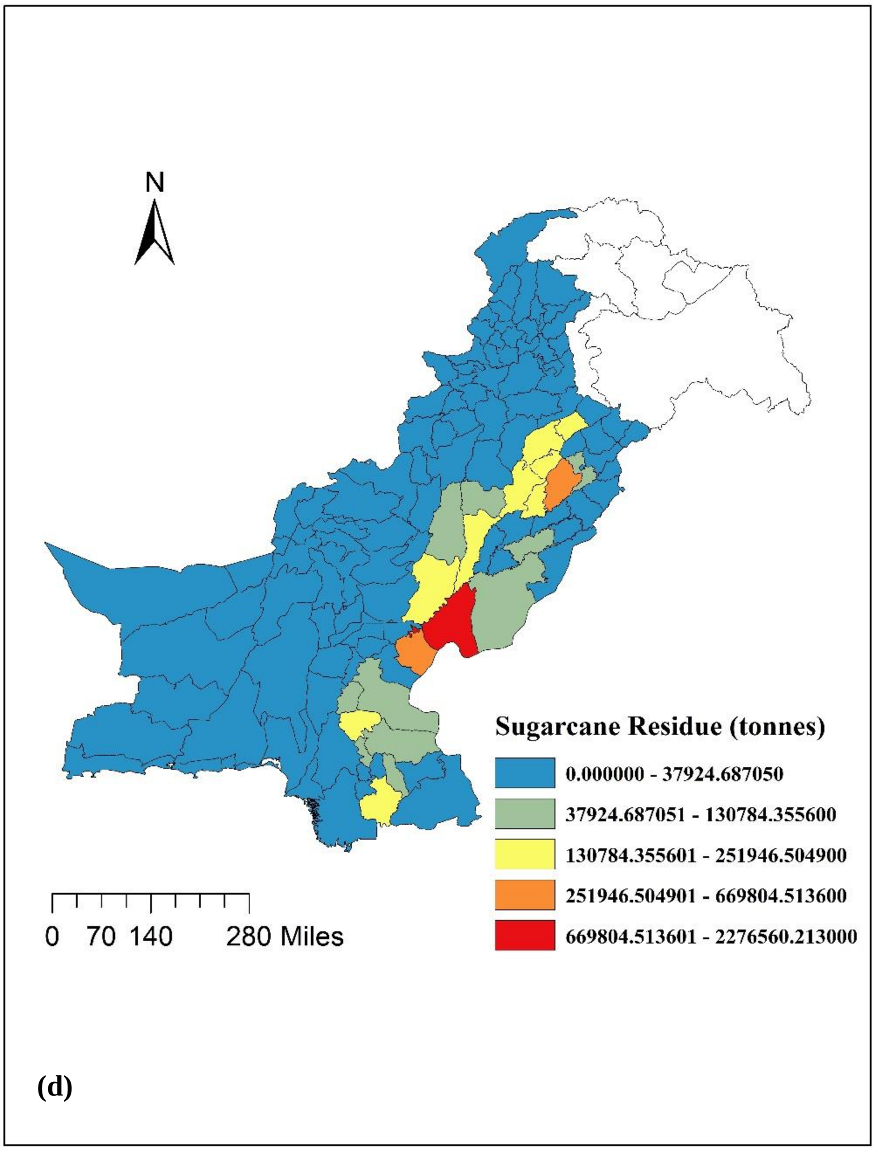
Figure 3.4: (a) Framework illustrating development process of DNI resource potential l map, (b) framework illustrating bioenergy potential map generation.


N
Maize Stalk (tonnes)
0.000000 - 5522.400000
5522.400001 - 20777.400000
20777.400001 - 56559.309130
56559.309131 - 103078.542900
103078.542901 - 334295.872100
0 70 140 280 Miles
(a)


N
Cotton Residue (tonnes)
0.000000 - 14012.352000
14012.352001 - 92009.633030
92009.633031 - 209575.084500
209575.084501 - 441622.454300
441622.454301 - 901692.667700
0 70 140 280 Miles

(b)


N
Rice Residue (tonnes)
0.000000 - 12127.711900
12127.711901 - 52694.820160
52694.820161 - 107055.519300
107055.519301 - 310412.520000
310412.520001 - 535890.762000
0 70 140 280 Miles
(c)


N
Sugarcane Residue (tonnes)
0.000000 - 37924.687050
37924.687051 - 130784.355600
130784.355601 - 251946.504900
251946.504901 - 669804.513600
669804.513601 - 2276560.213000
0 70 140 280 Miles
(d)

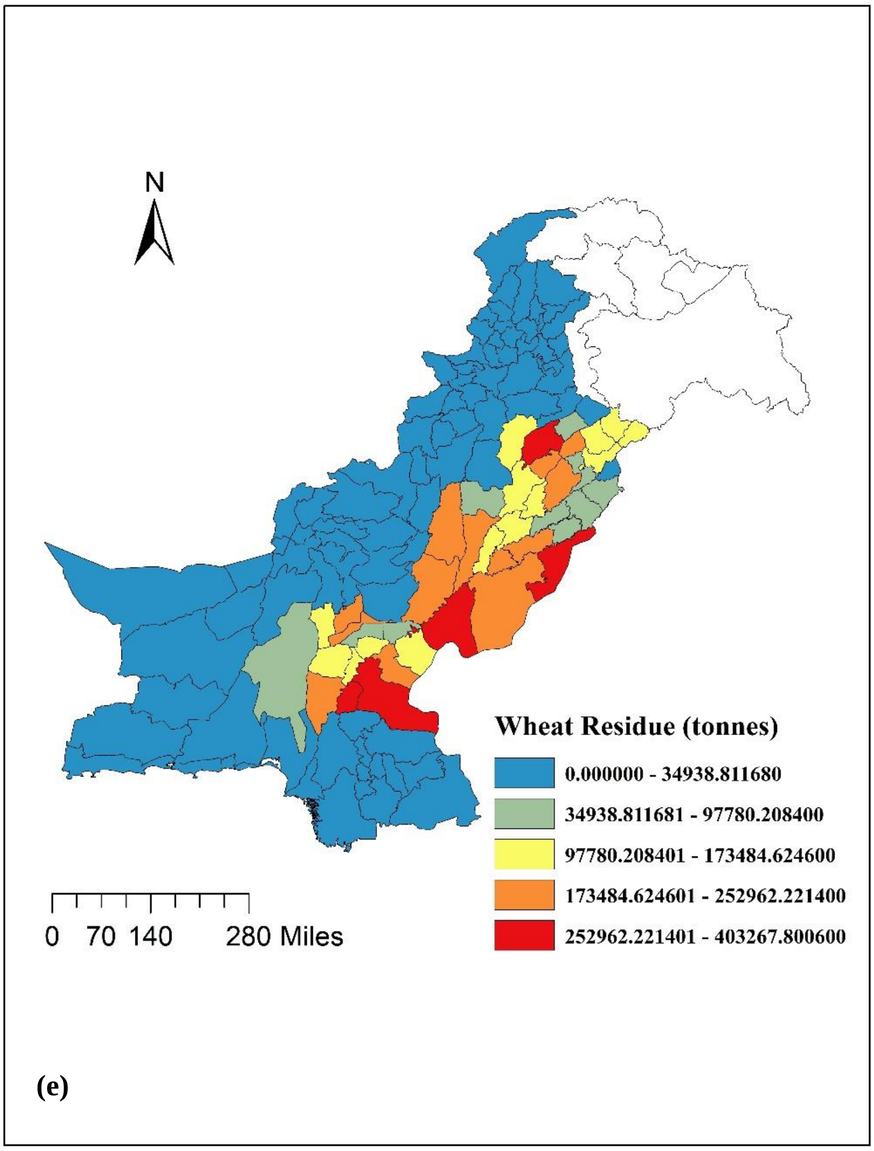


Figure 3.5: Maps depicting available quantity of crop residues (a) maize, (b) cotton, (c) rice, (d) sugarcane, (e) wheat.

3.3.3 Other Evaluation Criteria Maps

Besides the resource potential maps, multiple other criteria were used as input to analysis, which are briefly described in following subsections.

(a) Proximity to transmission network

Due to high costs associated with development of new power infrastructure, it is preferred to consider using existing transmission networks instead of developing new ones (Mohammadi & Khorasanizadeh, 2019; Singh Doorga et al., 2019). Previous studies considered proximity of potential renewable energy plant site to transmission network as an important factor (Ghasemi et al., 2019; Gouareh et al., 2021) Hence, map for existing transmission lines was obtained (Table 3.1) and buffers of 5, 15, 30 and 50 km were applied. Afterwards, the map was converted into raster image and resultant map is shown in Figure 3.6(a). The area within 5 km radius of transmission network were considered to be highly suitable for installation of HCSB plant, whereas beyond 50 km, areas were considered as least suitable.

(b) Proximity to road network

Proximity to road network is a crucial factor to be considered, as it highly influences the economics of power plant (Azouzoute et al., 2020; Uyan, 2013). Vehicular access to the plant's installation site is important in terms of its construction, maintenance and operations (Tlhalerwa & Mulalu, 2019), as easy access to road network reduces transportation cost of crop residue. Therefore, map of existing road network was obtained (Table 3.1) and the buffers of 5, 15, 30 and 50 km were applied in ArcMap. Afterwards, it was converted to raster image and resultant map is shown in Figure 3.6(b).

(c) Land cover

Land cover is one of the important parameters to be assessed for site selection of large scale powerplants. This may vary depending upon the policies of the country where deployment is being considered. For instance, Dejan et al., excluded croplands while siting ideal locations for construction of PV plants in Serbia (Doljak & Stanojević, 2017), while others such as Momina et al., included croplands while selecting suitable sites for construction of large scale CSP powerplants in Pakistan (Ahmad & Zeeshan, 2022). For this study, Land cover map of Pakistan was obtained from C3S (Table 3.1), which was reclassified into five categories: bare areas (28.5%), sparse vegetation (3.6%), shrub land (33.1%), crop land (32.1%) and tree cover (2.53%). Land cover classification followed in this study was informed by the previous studies e.g., (Ahmad & Zeeshan, 2022). Bare areas were highly preferred, followed by sparse vegetation and shrub land, whereas tree cover was least preferred. Crop land was also considered acceptable, but with less preference, from an energy-food-environment viewpoint (Ahmad & Zeeshan, 2022). The resultant map, input to AHP process, is given in Figure 3.6(c).

(d) Water stressed areas

Water requirement for HCSB powerplant may vary depending upon the CSP technology being deployed. Majority of designs presented in literature for HCSB powerplants are based on Rankine cycle (steam generators), which require large quantity of water for cooling of steam cycle and also for mirror washing (Thiam et al., 2017). Out of total water required for these powerplants, 90 % goes into cooling of steam cycle and remaining 10 % is required for mirror washing and other uses (Poullikkas et al., 2013). For reduction in water requirement for large scale powerplants, various researchers recommend use of dry cooling systems (Ahmad & Zeeshan, 2022; Alami Merrouni et al., 2018). Since water scarcity is a serious issue in Pakistan, criteria map for water stressed areas was also incorporated in AHP. Extreme water stressed areas were least preferred, whereas high preference was given to low water stressed areas. The water stress map input to AHP process is given in Figure 3.6(d).

(e) Elevation

High elevation lands are suggested not to be considered for development of large scale powerplants primarily because of high construction and installation costs [7,24]. Moreover, construction of powerplants on high altitudes can also affect transmission facilities (Guaita-Pradas et al., 2019). Therefore, areas less than 440 m in elevation were considered most preferred. Since areas with slope >3 % were already excluded from study area, therefore no exclusion was done based on elevation. The elevation map used in AHP is shown in Figure 3.6(e).

3.4 Analytical hierarchy process (AHP)

The AHP is a mathematical technique, in which pair-wise comparison matrix is used to calculate criteria weights (Vargas, 1990). The details of AHP process can be found in previous studies (Ishizaka & Labib, 2011; Saaty, 1990), however, the process is briefly described as following :

Step 1: Identify the problem and build a hierarchical structure of all the criteria or factors that are expected to have influence on the identified problem and are representative of decision-maker's interest.

Step 2: Construct a pairwise comparison matrix $A_{(n \times n)} = [C_{ij}]$ for selected n criteria that are regarded as influential, on the basis of Saaty's fundamental scale (Singh Doorga et al., 2019) as given in Table S1, SI.

The pairwise comparison matrix (also known as judgment matrix) is representative of how much one criterion is preferred on the other as per the expert's decisions, which will consequently affect the placement of suitable sites. An example pairwise comparison matrix is shown in Eq. (6) for n number of selected criteria, where C_{12} signifies relative importance of criterion C_1 over criterion C_2 (Giamalaki & Tsoutsos, 2019). It is important to mention here that for pairwise comparison matrix $C_{ii} = 1$, $C_{ji} = 1/C_{ij}$ and $C_{ij} \neq 0$ (Gouareh et al., 2021). Higher weight of one criterion corresponds to its higher importance in site selection process (Ghasemi et al., 2019).

$$A = \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1(n-1)} & C_{1n} \\ C_{21} & C_{22} & \dots & C_{2(n-1)} & C_{2n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ C_{n1} & C_{n2} & \cdots & C_{n(n-1)} & C_{nn} \end{bmatrix} \quad (6)$$

The relative weights of all criteria $C_1, C_2, \dots, C_n$ can be computed by normalizing matrix A into a new matrix, where each element of a new matrix is derived by dividing all the elements of matrix A by the sum of their respective columns. The criteria weights are then determined by averaging the rows of normalized matrix. One of the major advantages of AHP is that it allows to check the consistency of the judgments made by the comparison matrix. For a judgment to be consistent, Eq. (7) must hold true (Giamalaki & Tsoutsos, 2019).

$$C_{ij} = C_{ik} \times C_{kj} \quad \forall\ i, j, k \quad (7)$$

Step 3: To determine the degree of inconsistency of judgment matrices and to avoid consistency error, Saaty suggested measure of two important parameters called as Consistency Index (CI) and Consistency Ratio (CR) (Franek & Kresta, 2014).

The pairwise comparison matrix constructed to compute criteria weights for all evaluation criteria is illustrated in Table 3.3. Similar matrices were also developed for each parameter's sub-criteria. Weights allotted to sub-criteria are tabulated in Table S2, SI. One of the major requirements for the setting of renewable energy projects is sufficient resource availability, to make installation both economically and technologically viable. Therefore, the highest weightages were fixed for DNI and bioenergy potential. To further enhance the economic feasibility of power plant in terms of cutting down on direct capital cost and power losses, proximity to transmission network was the next highest weighted factor. Moreover, with their weights in descending order, proximity to road network, land cover, water stressed areas and elevation were also incorporated in AHP as criteria factors.

3.5 Reclassification and weighted overlay

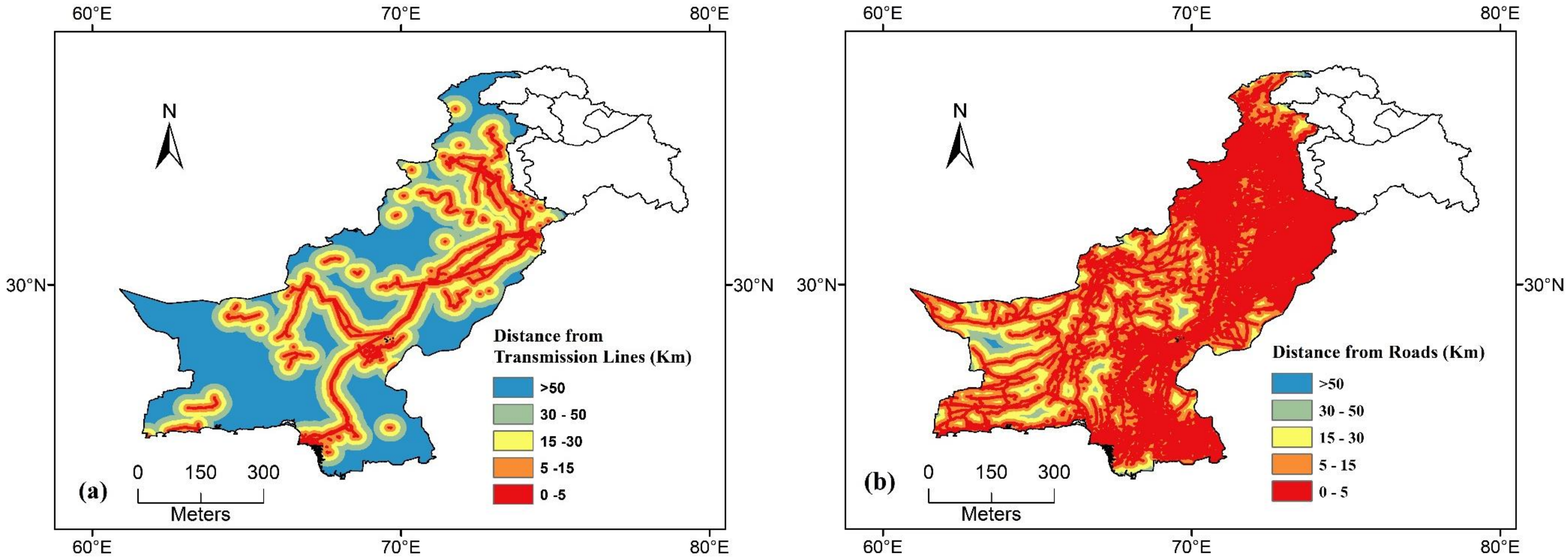
Raster maps for all input criteria were reclassified on a scale of 1 to 5, where 1 represents the least suitable class and 5 denotes most suitable class. Afterwards, weighted overlay was performed in ArcGIS to identify most suitable sites using Eq. (10).

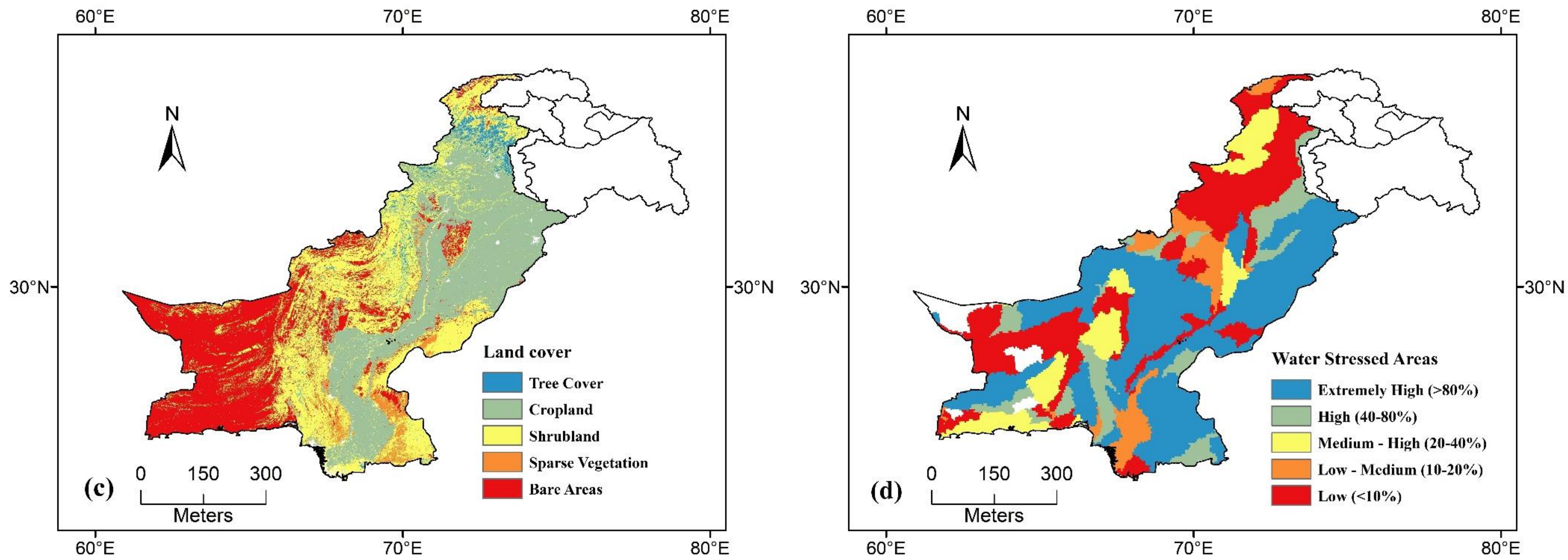
$$s = \sum_{i=1}^{n}(CW_i \times SV_i) \quad (10)$$

where, *s* represents suitability score assigned to each pixel, CW_i is the criteria weight (i.e., % influence) of raster *i* and SV_i denotes scale value of raster *i* for that particular pixel. Eventually 5 suitability classes were obtained.

Table 3.3: Pairwise comparison matrix depicting relative importance of considered factors.

Criteria	DNI	Biomass	Land cover	Proximity to roads	Proximity to transmission network	Water stressed areas	Elevation
DNI	1	1	5	5	1	7	9
Biomass	1	1	5	3	1	7	9
Land cover	0.2	0.2	1	0.3	0.3	3	5
Proximity to roads	0.2	1	3	1	0.3	3	5
Proximity to transmission network	1	1	3	3	1	3	5
Water stressed areas	0.14	0.14	0.3	0.3	0.3	1	3
Elevation	0.11	0.11	0.2	0.2	0.2	0.3	1


60°E
70°E
80°E
30°N
N
Distance from Transmission Lines (Km)
>50
30 - 50
15 -30
5 -15
0 -5
0 150 300
Meters
(a)
Distance from Roads (Km)
>50
30 - 50
15 - 30
5 - 15
0 - 5
0 150 300
Meters
(b)


60°E
70°E
80°E
30°N
N
Land cover
Tree Cover
Cropland
Shrubland
Sparse Vegetation
Bare Areas
(c)
0 150 300
Meters
Water Stressed Areas
Extremely High (>80%)
High (40-80%)
Medium - High (20-40%)
Low - Medium (10-20%)
Low (<10%)
(d)

s

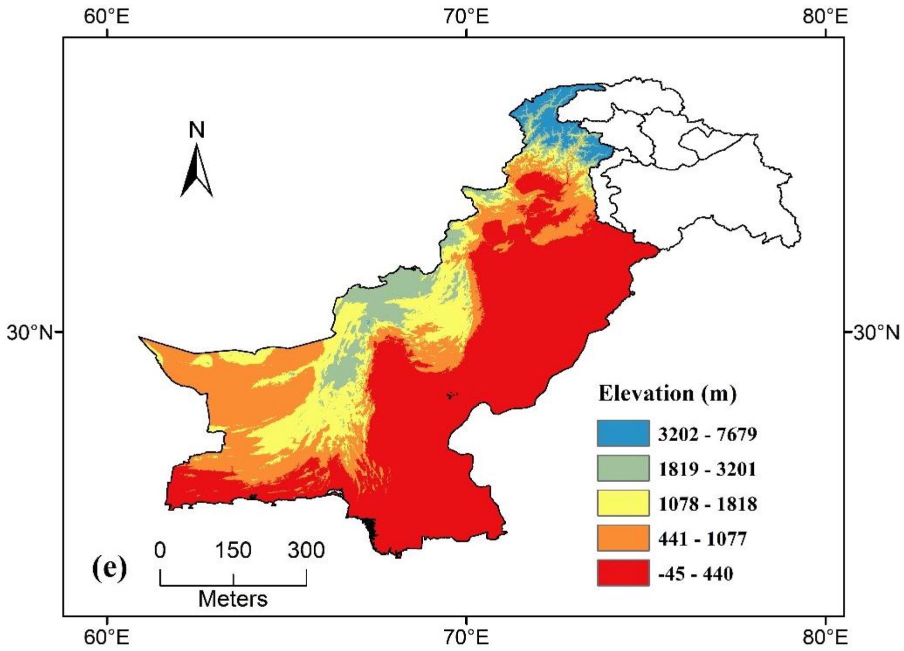


Figure 3.6: Criteria maps of parameters used in HCSB site suitability analysis using AHP (a) transmission network, (b) road network, (c) land cover, (d) water stressed areas, (e) elevation.

CHAPTER 4

RESULTS AND DISCUSSION

Results and detailed discussion are given in the following subsections.

4.1 Resource mapping

4.1.1 DNI resource potential

Figure 4.1 (a) shows spatial distribution of annual average DNI over the period of 18 years (1999 – 2016) for Pakistan. Around 30 % of the area (i.e., 203697.07 km^2) receives DNI within the range of 2400 – 2650 kWh/m^2.year, which is amongst the highest in the world (Prăvălie et al., 2019), including majority of the districts located in southwestern parts of Pakistan. Furthermore, around 42 % of study area (i.e., 340643 km^2) receives DNI ranging between 2000 – 2400 kWh/m^2.year, covering most of the south-eastern region of the country. Minimum values for DNI (i.e., <1800 kWh/m^2.year) are found in north-western and north-eastern parts of Pakistan, with exception of few anomalies that exist on account of high elevation. Overall, more than 80% of study area (i.e., 684072.15 km^2) receives DNI > 1800 kWh/m^2.year, presenting high possibility for installation of HCSB plants in Pakistan. Similar results for potential of DNI resource in Pakistan were reported by Steffen et al, (Stökler et al., 2016) and Momina et al,(Ahmad & Zeeshan, 2022).

4.1.2 Bioenergy potential

Figure 4.1 (b) illustrates annual bioenergy potential map of Pakistan. The highest values for bioenergy potential are found for districts located in provinces of Punjab and Sindh (Irfan et al., 2020). This is reasonable as both the provinces share maximum portion of agricultural land in the country (Uzair et al., 2020). Around 19 % of area (i.e., 153978.142 km^2) is found to have bioenergy potential greater than 45,000 kWh/m^2year, presenting high possibility for installation of HCSB powerplants

(Juergen H. Peterseim, Herr, et al., 2014), as DNI potential in these areas is also in the acceptable range (Middelhoff et al., 2021) (also see Figure 4.1 (a)). Minimum potential values (i.e., below 10,000 kWh/m^2.year) are found in north-western and south-western regions of the country, incorporating approximately 53.9 % of land. The reason for low bioenergy potential in these regions is minimum crop production.

4.1.3 Weights of criteria factors

The final weights of evaluation criteria along with their consistency indices are given in Table 4.1. The pair wise comparison matrix was assessed on the basis of three parameters i.e., CR, CI and principal Eigenvalue, for which obtained values are 0.057, 0.075 and 7.45 respectively. DNI, biomass and proximity to transmission network are the most preferred.

Table 4.1: Final weights of parameters and sub parameters

Main criteria	**Final Weight (%)**	**Consistency Index (%)**	**Sub-criteria**	**Final Weight (%)**
DNI (kWh)	32	6.06	1800 -1950	1.28
			1950 – 2100	2.24
			2100 – 2250	4.16
			2250 – 2400	8.32
			2400 – 2600	16
Biomass(kWh)	30	6.06	0 – 10,000	1.2
			10,000 – 25,000	2.1
			25,000 – 45,000	3.9
			45,000 – 70,000	7.8
			70,000 – 135,953	15
Land Use Land Cover	7	6.06	Barren Land	3.5
			Sparse	1.82
			Vegetation	0.91
			Shrub Land	0.49
			Crop Land	0.28
			Tree Cover	
Proximity to Transmission Network (km)	15	6.06	0 – 5	7.5
			5 – 15	3.9
			15 -30	1.95
			30 – 50	1.05
			>50	0.6
Proximity to Roads (km)	10	6.06	0 – 5	5
			5 – 15	2.6
			15 – 30	1.3
			30 – 50	0.7
			>50	0.4
Water Stressed Areas	4	6.06	Low (<10%)	2
			Low – Medium (10 – 20%)	1.04
			Medium – High (20 – 40%)	0.52
			High (40 -80%)	0.28
			Extremely High (>80%)	0.16
Elevation (m)	2	6.06	-45 to 440	1
			441 – 1077	0.52
			1078 - 1818	0.26
			1819 – 3201	0.14
			3202 - 7679	0.08

4.2 Site suitability classification

The results on assessment of most suitable sites for installation of HCSB projects in Pakistan are shown in Figure 4.2. Approximately, 63 % of land is excluded based on criteria discussed previously and is labelled as unsuitable for HCSB powerplants. The remaining 37 % of land, which accounts for total area of 299,431.46 km^2, has been classified into five categories: most suitable, highly suitable, moderately suitable, marginally suitable and least suitable.

As shown in Figure 4.2, upper areas of Punjab province (more than 10 districts) are considered as unsuitable for installation of HCSB projects, despite having acceptably good access to transmission and road networks, along with availability of high bioenergy resource potential. Primary reason for exclusion of these areas is lower DNI. On the other hand, various regions of KPK and Balochistan provinces, along with some areas of Sindh are also excluded, mostly because of high slope. Exclusion on the basis of urban expansion has been specific to densely populated areas in the country. Around 1244.5 km^2 increase in urban areas has been estimated by 2045 and overall, 4102.35 km^2 of urban land has been excluded and labelled as unsuitable for installation of HCSB projects.

Around 20 % of available areas (i.e., 58220.7 km^2) lie in and below "Marginally suitable" class. Majority of these areas are in upper half of the country i.e., in KPK and Punjab provinces. Insufficient availability of renewable resources (i.e., DNI and bioenergy potential) make these regions least suitable. Moreover, approximately 62 % of viable areas lie in "Moderately suitable" class, mainly because of presence of croplands, categorically in areas located in Punjab and Sindh, even though resource potential for both renewable technologies in these provinces is in acceptable limits along with good infrastructure. However, in Balochistan, this categorization is mainly because of low bioenergy potential and proximity to existing transmission network.

On the other hand, the "Most suitable" and "Highly suitable" classes acquire share of about 19 % of total possible areas, out of which 238.2 km^2 is regarded as most suitable for installation of HCSB plants. Only one district i.e., Jamshoro located in the province of Sindh lies in "Most suitable" class whereas 36 districts, located largely in southern region of the country, are designated as "Highly suitable". High resource availability, low slope along with good infrastructure makes these areas highly feasible for installation of HCSB plants. On this account, these districts, in particular, (58), (79) (57), (76), (0), (86), (45), (62), (11), (9), (50), (31), (116), (4), (55), (17), (94) are estimated to be most feasible for future planning of large scale HCSB powerplants in the country.

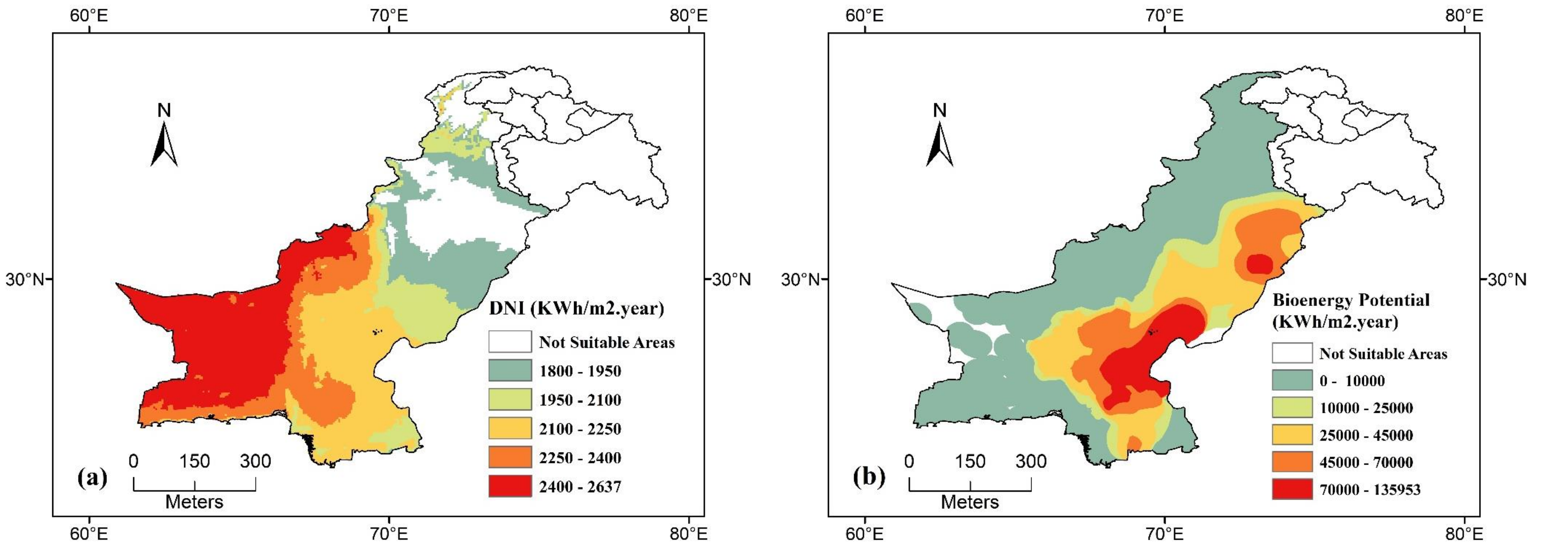


Fig. 4.1: (a) Annual DNI potential map of Pakistan, (b) annual bioenergy potential map of Pakistan

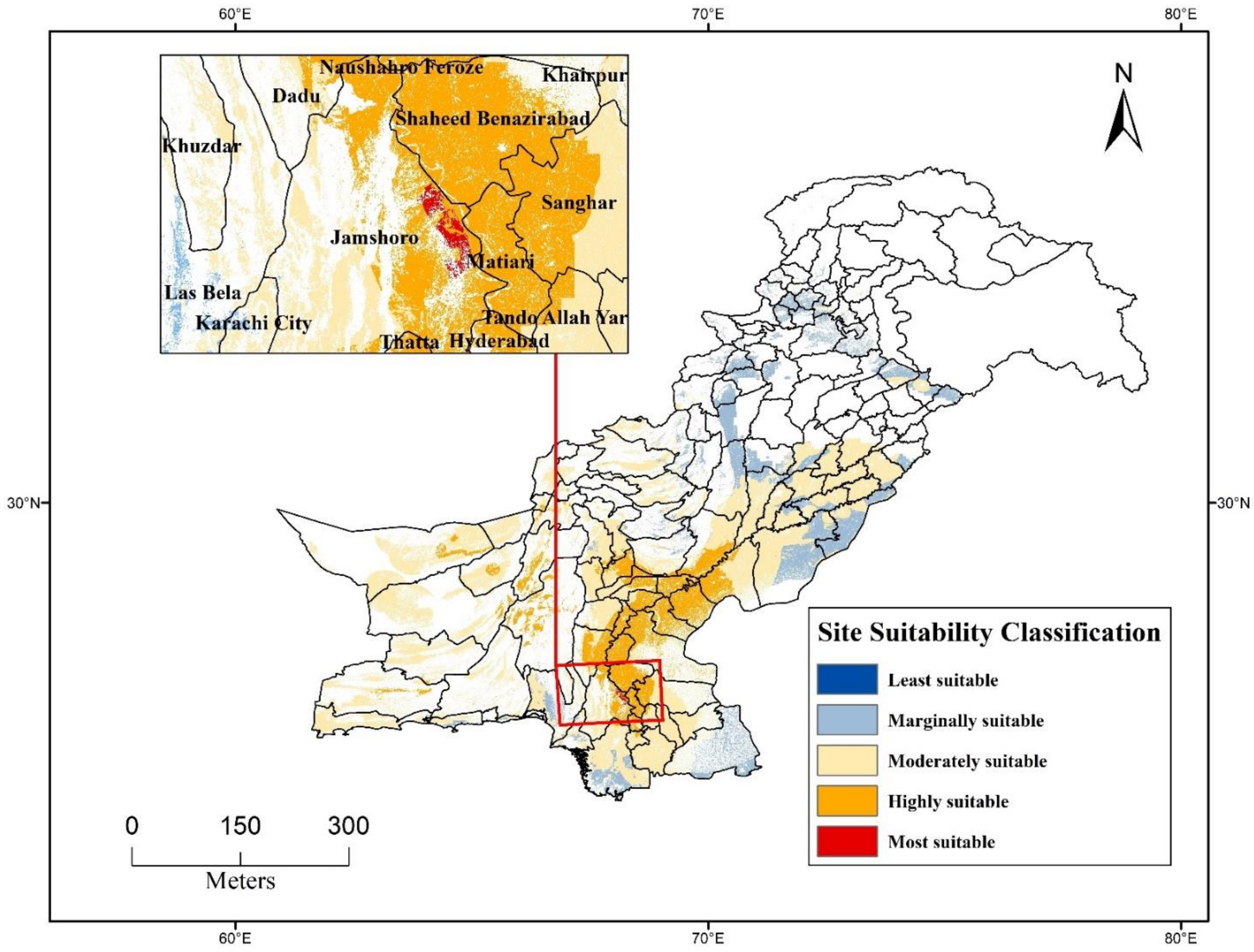


Fig. 4.2: Site suitability classification for installation of HCSB powerplants in Pakistan

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The aim of this study was to identify feasible locations to site utility scale on grid Hybrid Concentrated Solar Biomass (HCSB) powerplants in Pakistan. Simultaneously, a detailed methodology based on integrated Geographic Information System (GIS)-Multicriteria Decision Making (MCDM) approach was developed for site selection process of hybrid systems. Firstly, previous studies from literature related to siting of large scale powerplants were reviewed and important factors affecting placement of hybrid powerplants were identified. Resource potential maps for DNI and bioenergy were developed, along with criteria maps of other selected parameters including proximity to transmission network, land cover, proximity to road network, water stressed areas and elevation. Moreover, unsuitable sites from study area were removed. AHP was used to calculate criteria weights of all parameters. Finally, weighted overlay was performed in ArcMap to identify most ideal locations. Following conclusions can be drawn from the present study:

- The results of AHP scenario show that DNI, bioenergy and proximity to transmission network together account for more than 50 % of total criteria weight.
- More than 80 % of total land area receives DNI > 1800 kWh/m^2.year.
- Around 19 % of total land area is found to have bioenergy potential > 45,000 kWh/m^2year.
- Southern region of the country is highly suitable for installation of HCSB powerplants, on the basis of high resource potential, low slope and good infrastructure.

- District of Jamshoro stands out as extremely viable for installation of HCSB powerplants.
- Around 238.2 km^2 of land is found out to be most suitable, whereas 55691.67 km^2 is designated as highly suitable.
- Out of four provinces, Sindh presents maximum possibility of development of large-scale grid connected HCSB powerplants.

Although, current study gives defined methodology for site suitability analysis of HCSB powerplants, however, an important aspect that needs to be explored is the impact of electricity demand on site selection process along with its spatial variability. Moreover, biomass resources other than crop residues must be considered for development of bioenergy potential map for future work. Further, a detailed techno economic feasibility analysis of suitable sites along with sustainability assessment in terms of socio-environmental impacts of large scale HCSB installations is also recommended for future research.

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