Biomass Resource Mapping in Pakistan

FINAL REPORT ON BIOMASS ATLAS

June 2016

This report was prepared by Full Advantage Co. Ltd [Lead Consultant], Simosol Oy, VTT Technical Research Center of Finland and PITCO (Private) Ltd., under contract to The World Bank.

This is the final output from the Biomass Resource Mapping component of the activity "Renewable Energy Resource Mapping and Geospatial Planning – Pakistan" [Project ID: P146140]. This activity is funded and supported by the Energy Sector Management Assistance Program (ESMAP), a multi-donor trust fund administered by The World Bank, under a global initiative on Renewable Energy Resource Mapping. Further details on the initiative can be obtained from the ESMAP website.

The **Final Report** on Biomass Atlas for Pakistan summarizes the achievements of the study and presents the Biomass Atlas for Pakistan as its final product. The **Biomass Atlas** is a final output, and it has been **validated** through field-based surveys and **peer-reviewed.** It will be published via The World Bank's main website and listed on the ESMAP website along with the other project outputs – please refer to the corresponding country page.

RENEWABLE ENERGY RESOURCE MAPPING:
BIOMASS [PHASES 1-3] - PAKISTAN

FINAL REPORT
ON BIOMASS ATLAS FOR PAKISTAN

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LIST OF ACRONYMS

AEDB	Alternative Energy Development Board (Pakistan)
APTMA	All Pakistan Textile Mills Association
ESMAP	Energy Sector Management Assistance Program
FA	Full Advantage Co., Ltd. (Thailand)
GIZ	Gesellschaft fur Internationale Zusammenarbeit (Germany)
GIS	Geographic Information System
GoP	Government of Pakistan
IST	Institute of Space Technology (Pakistan)
LHV	Lower Heating Value
M&E	Monitoring and Evaluation
MHG	MHG Systems Oy Ltd. (Finland)
MSW	Municipal Solid Waste
NEPRA	National Electric Power Regulatory Authority (Pakistan)
NUST	National University of Sciences and Technology (Pakistan)
PCF	Plant Capacity Factor
PITCO	PITCO Private Limited (Pakistan)
PSMA	Pakistan Sugar Mills Association
REAP	Renewable and Alternative Energy Association of Pakistan
RE	Renewable Energy
SUPARCO	Space and Upper Atmosphere Research Commission (Pakistan)
TOR	Terms of Reference
WB	World Bank
WMC	Waste Management Company

UNITS

MW	Megawatt
GW	Gigawatt
MWh	Megawatt-hour
GWh	Gigawatt-hour
MJ	Megajoule
GJ	Gigajoule
TJ	Terajoule
MWh_{th}	Megawatt-hour thermal
GWh_{th}	Gigawatt-hour thermal
kg	kilogram
m	meter
km	kilometer
ha	hectare

1. EXECUTIVE SUMMARY

The present report is the Final Report on the Biomass Resource Assessment Study for Pakistan. The report summaries the achievements of the study and presents the Biomass Atlas for Pakistan as its final product.

Overall Achievements of the Study	All the expected outputs of the study were achieved as per the TOR. The outputs/deliverables of the project can be accessed at *https://esmap.org/RE_Mapping_Pakistan*.
Biomass Atlas for Pakistan	The Biomass Atlas consists of raw survey data, the atlas datasets and the maps. The Biomass Atlas contains two sections: the first one related to biomass feedstock availability and the second one related to the potential use of the biomass feedstock for energy. The residues of five major crops (i.e. wheat, cotton, rice, sugarcane and maize) were included in the Biomass Atlas. The crop residues are divided into two categories: crop harvesting residues and crop processing residues. Crop harvesting residues are generated in the field during crop harvesting activities while crop processing residues are produced during crop processing operations at agro-industrial sites. Both theoretical and technical potentials of crop residues were assessed. The theoretical feedstock potential was estimated at about 25.3 million tonnes/year with an energy potential of 222,620 TJ/year (61,838 GWh_{th}/year) for crop processing residues and 114 million tonnes/year with an energy potential of 1,616,362 TJ/year (448,990 GWh_{th}/year) for crop harvesting residues. Based on the existing uses of the residues, the technical potential of crop harvesting residues was estimated at about 25.1 million tonnes/year with an energy potential of 342,236 TJ/year (95,065 GWh_{th}/year). If the farmers' willingness to sell their biomass residues is taken into consideration, the technical potential of crop harvesting residues decreases to about 20.5 million tonnes/year with an energy potential of 280,177 TJ/year (77,828 GWh_{th}/year). The analysis shows that bagasse offers the highest potential via their use as fuel in cogeneration plants. The total installed power capacity of the cogeneration plants using bagasse generated from the 84 existing sugar mills in Pakistan is estimated at about 1,844 MW. Municipal Solid Wastes (MSW) can also be used in large-scale grid-connected power plants with a combined installed power capacity of 360 MW. However, rice husk and cattle manure seem to offer a limited energy potential which is limited to captive power plants that generate electricity to cover the power requirements of the rice mills or livestock farms. It should be noted that the analysis does not include all the existing MSW landfills, rice mills and livestock farms in

	Pakistan due to the lack of data. The potential for greenfield power plants using crop harvesting residues was assessed based on their site suitability indicators. This site suitability indicator takes into account the feedstock sourcing area size, the road network density in the region, and the distance to a grid. A high site suitability value indicates a good site for a potential power plant, whereas a low value indicates a poor location. The site suitability maps were produced for 21 different combinations of energy conversion technologies and power plant capacities.
Information Dissemination and Capacity Building	During the process of the study, several seminars, workshops and trainings were conducted to present the study objectives or to disseminate the study results to the local stakeholders and to build their capacity in usage and maintenance of the Biomass Atlas. Nine (9) multi-stakeholder seminars and workshops were conducted. These events attracted a total of 295 participants. In addition, several individual meetings with local institutions and companies were organized during the missions of the consultants to Pakistan.
Key Lessons Learned	The key lessons learned can be summarized as follows: • The field survey and collection of the data is a hard, time-consuming exercise. It requires good planning and excellent coordination; • The use of NUST and its university network was key to the success of the field survey; • The involvement of local agriculture officers in the field surveys was important to facilitate the contact with farmers; • Good knowledge of the biomass producers and consumers by PITCO facilitated the industrial surveys; • A well-designed and continuous data validation process helped the international consultants (Simosol and FA) and the local consultants/enumerators (NUST and PITCO) to immediately check and correct any erroneous data; • The whole data collection exercise required some flexibility to cope with unexpected problems (e.g., security issues) during field surveys; • The strong support and guidance of the WB and AEDB as well as the feedback and specific advice from the local stakeholders were essential for a smooth implementation of the project and to the achievement of its objectives, especially the production of a most appropriate Biomass Atlas for Pakistan.

2. INTRODUCTION

Pakistan is facing a large deficit in electricity supply. A report published by the Government of Pakistan (GoP) in 2013[1] showed that the electricity supply-demand gap has continuously grown over the past five years and has reached 4,500 to 5,500 MW in 2013. Such an enormous gap has led to load-shedding of 12-16 hours a day across the country.

GoP has set a target to reduce the electricity supply-demand gap to zero by 2017. In order to attain such ambitious target, the GoP has been endeavoring to exploit various options to meet the current and future anticipated electricity needs of the country. Conventional power generation has been the focus of the power master plan that includes large hydropower and fossil fuel-based thermal power projects. As Pakistan has a huge potential of renewable energy resources, the GoP is also promoting the use of renewable energies to increase their shares in total electricity mix of the country.

In order to support the GoP, the World Bank (WB) has been providing assistance towards continued development of renewable power (RE) generation (hydro, biomass, solar and wind). Therefore, the energy sector meets electricity demand in an efficient, affordable and environmentally sustainable manner. One of these assistances is to develop RE resource maps for Pakistan. This project is being implemented by the World Bank in Pakistan in close coordination with the Alternative Energy Development Board (AEDB), a government agency of Pakistan. The project is funded by the Energy Sector Management Assistance Program (ESMAP), a global knowledge and technical assistance program administered by the WB and supported by 11 bilateral donors. It is part of a major ESMAP initiative in support of renewable energy resource mapping and geospatial planning across multiple countries.

Biomass resource mapping is one of component of the ongoing renewable energy resource mapping project in Pakistan. The objective of this biomass mapping component is to support the sustainable expansion of electricity generation from biomass. This is fulfilled by providing the national government and provincial authorities in Pakistan, and commercial project developers, with an improved understanding of the location and potential of biomass resources.

For this purpose, the World Bank has assigned a consulting Consortium, including Full Advantage Co., Ltd. (Thailand) as a lead consultant, Simosol Oy (Finland), VTT Technical Research Center of Finland, and PITCO Private Limited (local consultant) to develop a Biomass Atlas for Pakistan with a focus on Punjab and Sindh provinces as the starting points. NUST was contracted to conduct the field survey and data collection on crop biomass residues.

The biomass resource mapping project consisted of three phases:

- Phase 1: Project inception, team building, data source identification and implementation planning;
- Phase 2: Data collection/analysis and creation of draft biomass resource maps;
- Phase 3: Production and publication of a validated biomass resource atlas.

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[1] *National Power Policy, Government of Pakistan, 2013.*

The main activities implemented during these three phases were as follows:

Phase 1:

- Conduct of inception meetings;
- Identification and assessment of existing data sources needed for the project;
- Conduct of team building;
- Development of an Implementation Plan for Phase 2.

Phase 2:

- Conduct of remote data collection and analysis;
- Preparation for field survey and data collection;
- Conduct of field survey and data collection;
- Conduct of data analysis and development of draft biomass atlas;
- Conduct of stakeholder data validation workshop.

Phase 3:

- Production of final Biomass Atlas for Pakistan;
- Conduct of seminars to disseminate the Biomass Atlas;
- Conduct of trainings for local stakeholders in using and updating the Biomass Atlas.

3. PROJECT SCOPE

3.1 Expected Outputs of the Project

According to the Terms of Reference (TOR), the expected outputs/deliverables of the project include:

Phase 1:

- Execution of the inception meetings in Pakistan;
- Inception report;
- Implementation plan for Phase 2.

Phase 2:

- Creation of a comprehensive database for biomass resource mapping, including raw data files;
- Production of draft biomass resource maps;
- Organization of a stakeholder data validation workshop.

Phase 3:

- Production of final Biomass Atlas including associated GIS files and datasets;
- Conduct of a one-day biomass atlas dissemination workshop;
- Conduct of a two-day training on using and updating of Biomass Atlas.

3.2 Summary of Achievements vs Expected Outputs

The expected outputs and the summary of achievements of the project are presented in Table 1.

Table 1: Summary of Achievements vs Expected Outputs

Activity	Expected outputs	Achievements
PHASE 1:		
Conduct of inception meetings	• Inception meetings conducted • Inception Report prepared and submitted	• Three inception meetings were conducted in Islamabad (21 Nov 2014), Lahore (24 Nov 2014) and Karachi (26 Nov 2014). A total of 74 participants (29 in Islamabad, 20 in Lahore and 25 in Karachi) attended the meetings. • The Inception Report was developed and submitted on 5 December 2014.
Identification and assessment of existing data sources needed for the project	• Existing data sources identified and assessed	• Several local stakeholders (NUST, SUPARCO, IST, REAP, PSMA, etc.) were contacted to obtain existing information on the biomass mapping exercises in Pakistan. • Ten existing studies and publications were obtained and reviewed. The reviews were reported in the Inception Report
Conduct of team building	• Local counterparts identified and their capacity assessed	• Meetings with NUST, SUPARCO and IST were conducted to assess their capability in executing field surveys and data collection for Phase 2 of the project.
Development of an Implementation Plan for Phase 2	• Implementation Plan prepared and submitted	• Implementation Plan for Phase 2 was developed and submitted on 12 March 2015. • Contract with NUST for field surveys and data collection was signed on 30 March 2015.
PHASE 2:		
Conduct of remote data collection and analysis	• Remote data collected and analyzed	• Satellite images were acquired from Landsat 8 and were analyzed to produce the raw biomass cluster images for field observation and inspection. • A field inventory plan was developed.
Preparation for field survey and data collection	• Training on field survey and data collection conducted	• Field survey forms for MHG Biomass Manager[2] were developed. • Required smartphone applications for navigation, data entry and data transfers were acquired. • A training on field survey and data collection was conducted on 7-9 April 2015. A total of 59 participants from 3 universities attended the training.
Conduct of field survey and data collection	• Field surveys conducted and data collected	• Field surveys were conducted and the data on crop biomass residues were collected in 166 tehsils of 44 districts in Punjab, Sindh, KPK and Baluchistan (12,450 farmers interviewed). • Field surveys were conducted and the data on industrial biomass residues were collected (178

[2] *http://www.mhgsystems.com/services/mhg-biomass-manager/*

		sites). • GIS data of other driving components (road network, power T&D network, etc.) were acquired.
Conduct of data analysis and development of draft biomass atlas	• A comprehensive database necessary for biomass resource mapping, including raw data files elaborated • Draft biomass resource maps developed	• The collected data were processed and integrated into a comprehensive database. • Draft biomass resource maps were produced.
Conduct of stakeholder data validation workshop	• A stakeholder data validation workshop conducted	• A stakeholder data validation workshop was conducted on 26 November 2015. Forty-five (45) participants attended the workshop.
PHASE 3:		
Production of final Biomass Atlas for Pakistan	• Final Biomass Atlas including associated GIS files and datasets produced	• The final Biomass Atlas including associated GIS files and datasets was produced.
Conduct of seminars to disseminate the Biomass Atlas	• A one-day dissemination workshop conducted	• Three one-day Biomass Atlas Dissemination Seminars and Usage Training Workshops were conducted in Islamabad (15 Feb 2016), Lahore (17 Feb 2016) and Karachi (18 Feb 2016). A total of 86 participants (42 in Islamabad, 20 in Lahore and 24 in Karachi) attended the seminars and workshops.
Conduct of trainings for local stakeholders in using and updating the Biomass Atlas	• A two-day training on using and updating of Biomass Atlas conducted	• A one-day Biomass Atlas Maintenance Training Workshop was conducted at NUST campus, Islamabad on 16 Feb 2016. Thirty-one (31) trainees from AEDB, IST, SUPARCO, Elan Partners and NUST attended the training workshop.

4. BIOMASS ATLAS FOR PAKISTAN

Based on the Implementation Plan approved by the WB in March 2015, five types of biomass resources are included in the Biomass Atlas for Pakistan:

- Crop harvesting residues;
- Crop processing residues;
- Livestock residue;
- Municipal Solid Waste; and
- Forest harvesting and wood processing residues

The Biomass Atlas for Pakistan has two main components: the maps and datasets. The maps are derived from the atlas datasets and each visually illustrates one specific aspect of the biomass-based energy production potential in Pakistan. The datasets contain the full results of the mapping project, and can be used in numerical analysis with a GIS program. It should be noted that the Biomass Atlas and its associated datasets provide information on the feasibility of biomass-based power generation in Pakistan from the technical feedstock availability and from an infrastructure point of view. For each concrete project to be developed in the future, its economic and financial viability as well as an optimal biomass supply chain should be assessed during the project feasibility study.

The mapping methodology is described in Annex 1. The maps and main datasets are introduced in the following sections, and the full set of datasets is provided in Annex 2.

Training materials directed to familiarize novice GIS users with the use and update of the Biomass Atlas data using GIS software is included in Annex 3.

4.1 Crop Biomass Feedstock Potential

The *theoretical crop biomass feedstock potential* is based on the total amount of crop production. The crop residues are divided into two categories: crop harvesting residues and crop processing residues. Crop harvesting residues are generated in the field during crop harvesting activities while crop processing residues are produced during crop processing operations at agro-industrial sites.

For Pakistan, the crop residues of five major crops (i.e. wheat, cotton, rice, sugarcane and maize) were included in the Biomass Atlas. The amount of crop production was estimated using two main information sources: the land use classification based on the Landsat 8 satellite images, and the district level crop yields based on the field survey. The land use classification was done for each of the 30 m x 30 m pixel covering Pakistan in the Landsat 8 images. The crop harvesting residues were aggregated for the atlas to 990 m x 990 m pixels based on cropping season information in the 30 m x 30 m land use classification.

The annual production of the crop type *j* in the land pixel *i* is calculated using the formula:

$$P_{ij} = A_{ij} \times CY_{ij} \qquad [1]$$

Where:

P_{ij}	= annual production of the crop type *j* in the land pixel *i*, in tonnes/year
A_{ij}	= combined cultivation area of the crop type *j* in the land pixel *j* (990 m x 990 m) over the two yearly cropping seasons, in ha
CY_{ij}	= crop yield of the crop type *j* in the land pixel *i*, in tonnes/ha/cropping season

The district-level crop yields based on the field survey executed within the project are used for calculating the crop production. For the 44 districts covered by the survey, the district-average values of surveyed crop yields were used, while the province-average values were used for the remaining districts.

The crop production was converted to crop residues by using the conversion factors (residue-to-crop ratios) and the formula:

$$CR_{ijk} = P_{ij} \text{ x } RCR_k \qquad [2]$$

Where:

CR_{ijk}	= annual amount of crop residue type *k* produced from the crop type *j* in the land pixel *i*, in tonnes/year
RCR_k	= residue-to-crop ratio of the crop residue type *k*

The annual theoretical production of the crop residue type *k* from the crop type *j* for the whole country (CR_{jk}) is calculated using the formula:

$$CR_{jk} = \sum_i^n P_{ij} \text{ x } RCR_k \qquad [3]$$

The theoretical energy potential of the crop residue type *k* can be calculated by multiplying the annual production of the crop residue by its lower heating value (LHV).

The type of crops, the type of crop residues and their RCR and LHVs are provided in Table 2 and Table 3.

Table 2: Residue to crop ratios used for the atlas

Type of crop *j*	Type of crop residue *k*	RCR, average	RCR, min	RCR, max
Cotton	Cotton stalks	3,40	2,76	4,25
Wheat	Wheat straw	1,00	0,50	1,30
Rice	Rice straw	1,00	0,42	1,30
Rice	Rice husk	0,20	0,15	0,36
Sugarcane	Sugarcane trash	0,12	0,10	0,20
Sugarcane	Bagasse	0,30	0,26	0,32
Maize	Maize stalk	1,25	1,00	2,25
Maize	Maize husk	0,22	0,20	0,30
Maize	Maize cob	0,33	0,20	0,86

The RCRs are country-specific values for Pakistan which were obtained from the field surveys as well as from studies conducted by various institutions in Pakistan (GIZ, UNIDO, PITCO and NUST).

It should be noted that, for all residue types, the range of RCR values used in this study fall within the range of values used in FAO's Bioenergy and Food Security (BEFS) Rapid Appraisal Tool for crop residues assessment.

Table 3: Lower heating values of different biomass residues

Type of crop *j*	Type of crop residue *k*	Moisture content of residues (%)	LHV (MJ/kg)
Cotton	Cotton stalk	12.5	15.0
Wheat	Wheat straw	10.0	14.4
Rice	Rice straw	10.5	12.5
Rice	Rice husk	11.5	13.5
Sugarcane	Sugarcane trash	24.0	12.6
Sugarcane	Bagasse	50.0	7.5
Maize	Maize stalk	16.0	13.0
Maize	Maize husk	11.9	11.6
Maize	Maize cob	17.6	14.0

The moisture content of "as-received" crop residues was obtained from the report on "Development of market-based approach for utilization of biomass in industrial power generation" published by APTMA (All Pakistan Textile Mills Association) and GIZ Pakistan in 2013. The LHVs used in this study were calculated based on LHVs of moisture-free crop residues and moisture content of as-received biomass residues.

The annual calculated theoretical potentials of crop processing residues and crop harvesting residues are presented in Table 4 and Table 5, respectively.

Table 4: Country-level annual theoretical potential of crop processing residues

Type of crop *j*	Type of residues *k*	Annual production of residues (1000' tonnes)	Energy potential of residues	
			TJ/year	GWh_{th}/year
Sugarcane	Bagasse	19,577	146,828	40,785
Rice	Rice husk	3,351	45,239	12,566
Maize	Maize cob	1,406	19,684	5,468
Maize	Maize husk	937	10,869	3,019
Total		**25,271**	**222,620**	**61,838**

Table 5: Country-level annual theoretical potential of crop harvesting residues

Type of crop *j*	Type of residues *k*	Annual production of residues (1000' tonnes)	Energy potential of residues	
			TJ/year	GWh_{th}/year
Cotton	Cotton stalk	49,405	741,075	205,854
Wheat	Wheat straw	34,581	497,966	138,324
Rice	Rice straw	16,754	209,425	58,174
Sugarcane	Sugarcane trash	7,831	98,671	27,409
Maize	Maize stalk	5,325	69,225	19,229
Total		**113,896**	**1,616,362**	**448,990**

Figure 1 illustrates the theoretical feedstock potential of crop harvesting residues over the map of Pakistan. While this map shows the potential for the total amount of generated biomass residues, the Biomass Atlas's GIS datasets contain a more detailed description of the potential, broken down by the type of the crop harvesting residue and crop season, as well as the location down to the 990 m x 990 m resolution.

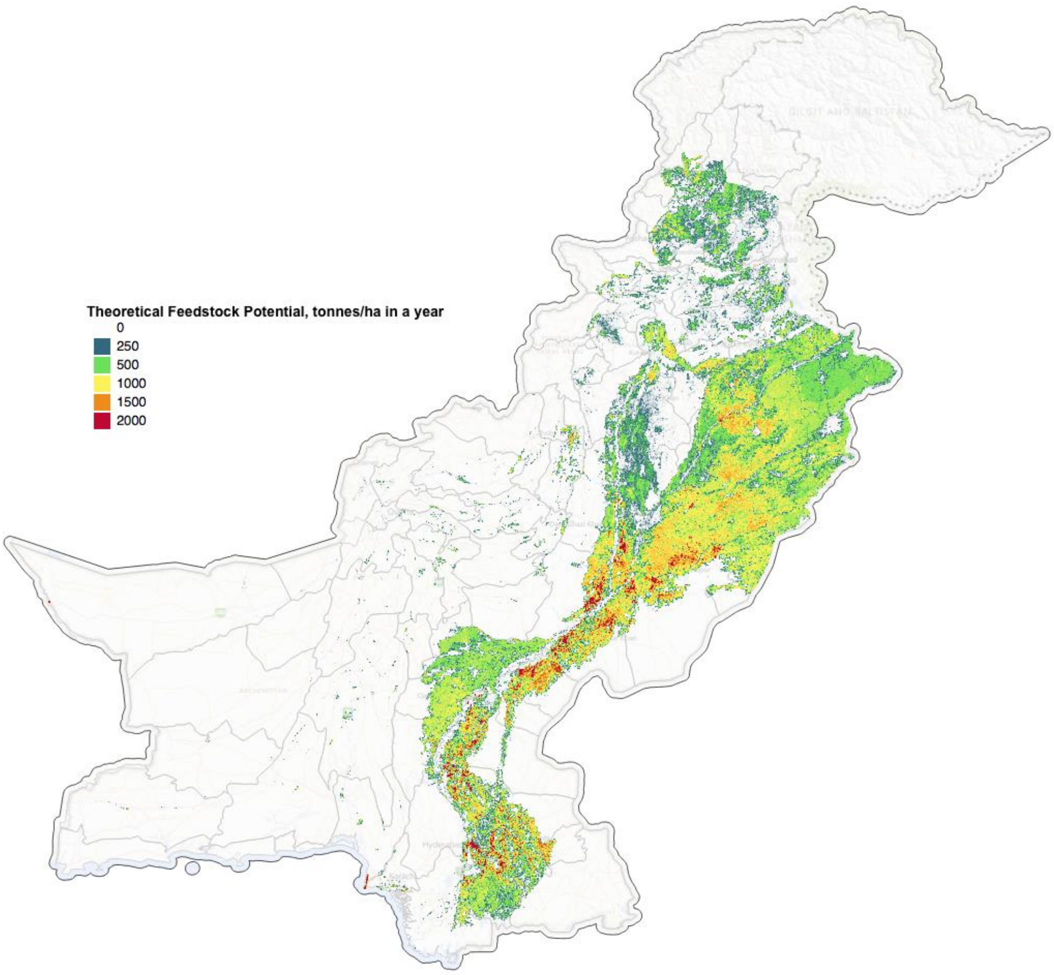

Figure 1: Theoretical potential of crop harvesting residues
[Background map: Microsoft® Bing™ Maps]

The links to access the Biomass Atlas map and GIS datasets for the theoretical potential of crop harvesting residues are provided in Table 6.

Table 6: Links for accessing the maps and datasets for the theoretical potential of crop harvesting residues

Atlas data	Can be accessed at:
Map	http://irena.masdar.ac.ae/?map=2636
GIS datasets:	https://energydata.info/dataset/pakistan-biomass-gis-atlas
Theoretical feedstock potential	files: feedstock\theoretical_feedstock_per_pixel_FALL.tif feedstock\theoretical_feedstock_per_pixel_SPRING.tif feedstock\theoretical_feedstock_per_pixel_WHOLE_YEAR.tif file content description: feedstock\metadata\feedstock.txt
District level crop residue yields	file: feedstock\districts\district.shp file content description: feedstock\metadata\district.txt
Land use GIS datasets:	https://energydata.info/dataset/pakistan-biomass-gis-atlas
Land use classification	file: pakistan_land_use.ers file content description: metadata\land_use.txt
Other datasets:	
Crop yield data from the survey aggregated to the district level (min, mean, max yield)	file: feedstock\crop_yield.xlsx

The technical crop feedstock potential of the crop harvesting residues was derived from the theoretical feedstock potential by excluding the existing use of the residues based on the field survey results. During the field survey, the following uses of crop harvesting residues were recorded: animal fodder, domestic burning (cooking), selling to biomass supplier, selling to industry, organic fertilizer or open field burning. Only the crop harvesting residues that would have been burning at the fields were included in the technical feedstock potential. Table 7 and

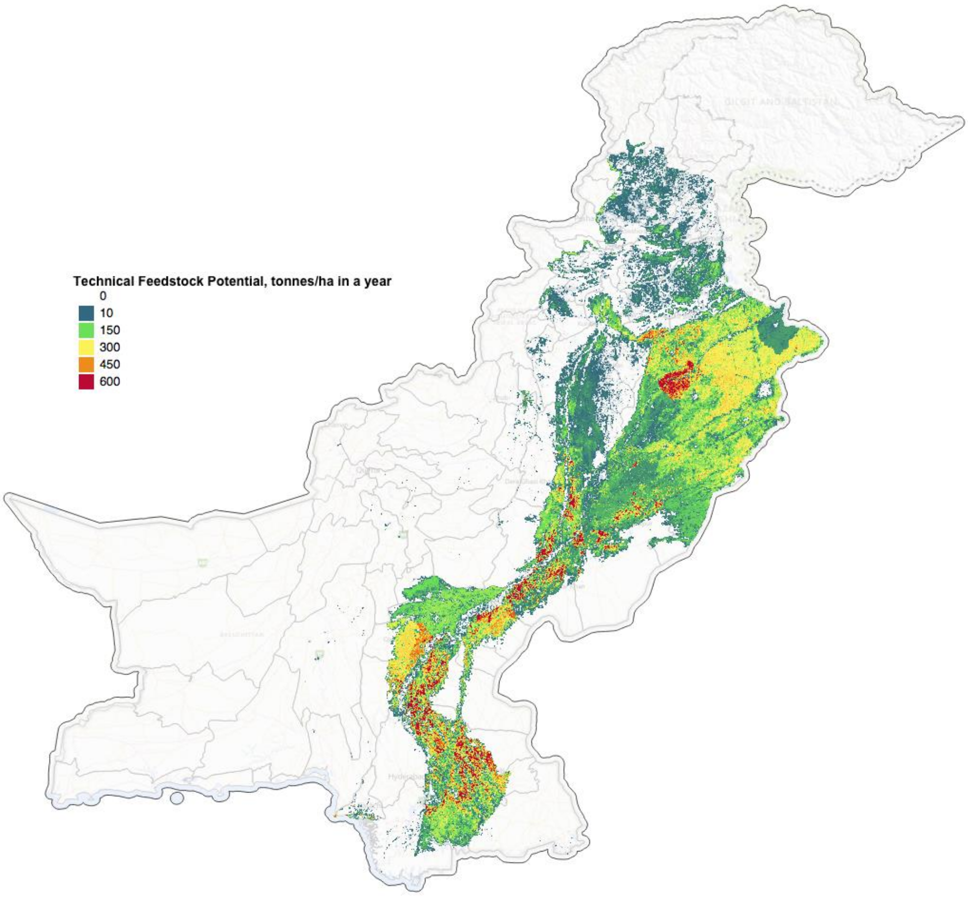

Figure 2 present the technical potential of the crop harvesting residues based on their existing uses.

Table 7: Technical potential of crop harvesting residues based on their existing uses

Type of crop *j*	Type of residues *k*	Annual technical potential of residues (1000' tonnes)	Energy potential of residues	
			TJ/year	GWh_{th}/year
Cotton	Cotton stalk	6,013	90,195	25,054
Wheat	Wheat straw	6,488	93,427	25,952
Rice	Rice straw	8,314	103,925	28,868
Sugarcane	Sugarcane trash	3,516	44,302	12,306
Maize	Maize stalk	799	10,387	2,885
Total **25,130**	**342,236**		**95,065**	

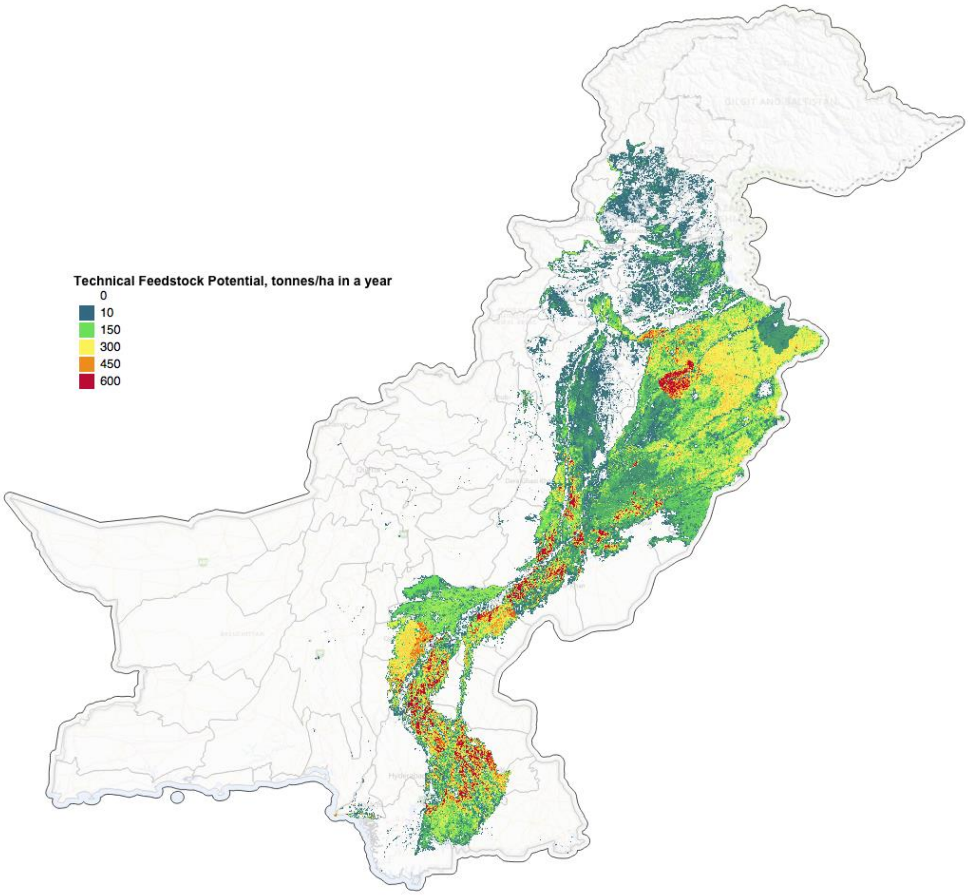

Figure 2: Technical potential of crop harvesting residues based on their existing uses
Note: the color scale was changed compared to the theoretical potential map
[Background map: Microsoft® Bing™ Maps]

Another aspect affecting the availability of the crop harvesting residues for power generation is the willingness of the farmers to participate in the biomass feedstock supply chain (i.e. to sell their biomass residues to the market). This aspect was also covered in the survey, and was aggregated to the district level from the individual surveys by weighing the farmer responses. Table 8 and Figure 3 present the technical feedstock potential of the crop harvesting residues based on their existing uses and the farmers' willingness to sell their biomass residues.

Table 8: Technical potential of crop harvesting residues based on their existing uses and farmers' willingness to sell

Type of crop *j*	Type of residues *k*	Annual technical potential of residues (1000' tonnes)	Energy potential of residues	
			TJ/year	GWh_{th}/year
Cotton	Cotton stalk	5,039	75,585	20,996
Wheat	Wheat straw	5,689	81,922	22,756
Rice	Rice straw	6,534	81,675	22,688
Sugarcane	Sugarcane trash	2,552	32,155	8,932
Maize	Maize stalk	680	8,840	2,456
Total		**20,494**	**280,177**	**77,828**

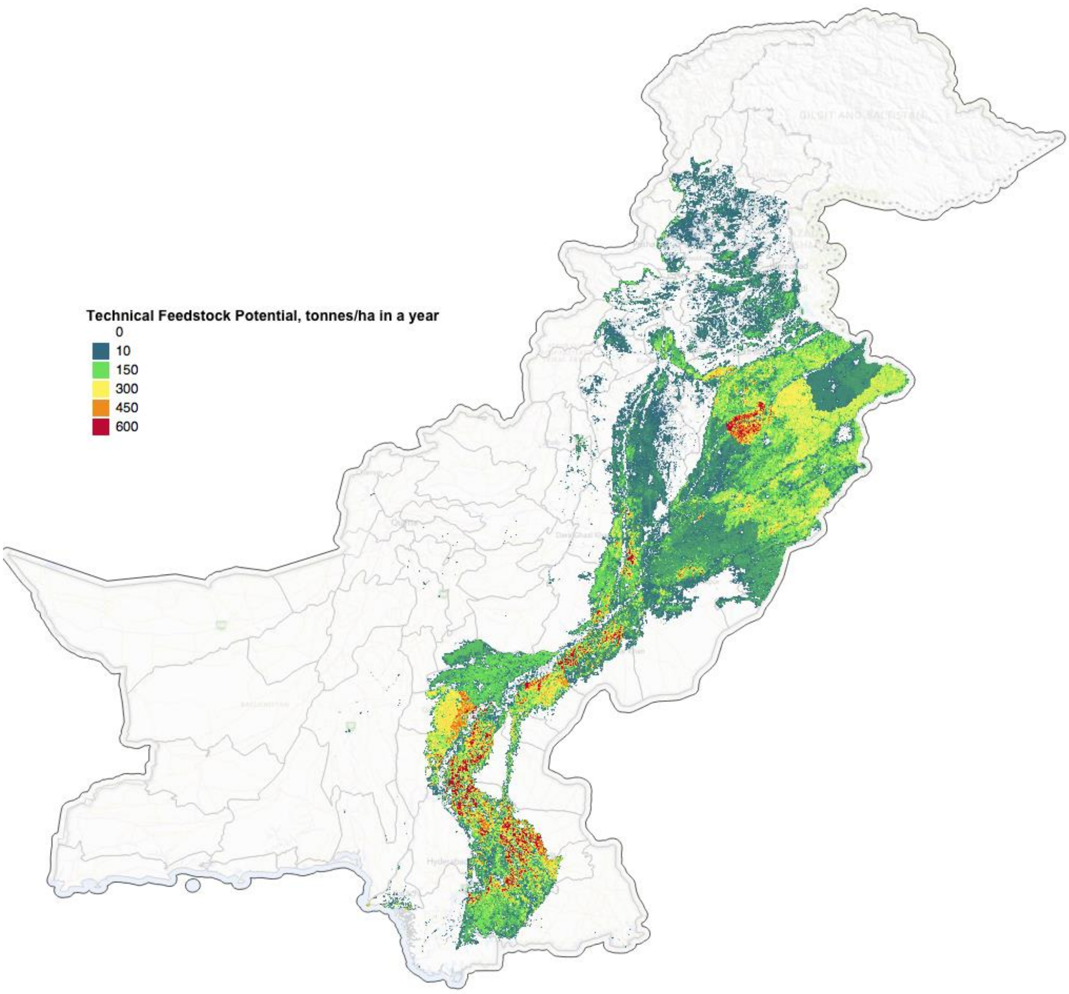

Figure 3: Technical potential of crop harvesting residues based on their existing uses and farmers' willingness to sell

Note: the color scale was changed compared to the theoretical potential map

[Background map: Microsoft® Bing™ Maps]

The links for access to the Biomass Atlas map and GIS datasets for the technical potential of crop harvesting residues are provided in Table 9.

Table 9: Links for access to the maps and datasets of the technical potential of crop harvesting residues

Atlas data	Can be accessed at:
GIS datasets:	https://energydata.info/dataset/pakistan-biomass-gis-atlas
Technical feedstock potential, based on existing use only	files: feedstock\technical_feedstock_per_pixel_FALL_residue.tif feedstock\technical_feedstock_per_pixel_SPRING_residue.tif feedstock\technical_feedstock_per_pixel_WHOLE_YEAR_residue.tif file content description: feedstock\metadata\feedstock.txt
Technical feedstock potential, based on existing use and farmers' willingness to sell	files: feedstock\technical_feedstock_per_pixel_FALL_willing.tif feedstock\technical_feedstock_per_pixel_SPRING_willing.tif feedstock\technical_feedstock_per_pixel_WHOLE_YEAR_willing.tif file content description: feedstock\metadata\feedstock.txt
District level data on existing use and willingness to sell biomass	file: feedstock\districts\district.shp file content description: feedstock\metadata\district.txt

residues	
Other datasets:	
Feedstock summary by country and by district, including sampled district confidence intervals for yearly feedstock amounts	file: feedstock\feedstock.xlsx

The crop processing residues are not included in the maps of feedstock potential presented in Figures 1 to 3 above, as they are generated at the agro-industrial sites, but not in the field. The field survey did not provide the data for assessing their technical potential. However, for the two most important crop processing residues, bagasse and rice husk, their technical potential for energy generation at the agro-industrial sites, i.e., sugar and rice mills, is analyzed and presented in section 4.2.

Table 10 contains the confidence intervals for the yearly production of different crop residues based on the 44 surveyed districts. It should be noted that these figures cover only the parts of the country shown in Figure 4, not the whole country. However, the upper and lower confidence interval bounds can be used to get an indication of same bounds for the whole country.

Table 10. The mean annual potential with 95% confidence interval for different types of crop residues for the sampled 42 districts

Type of residues	Feedstock type	Mean annual potential with a 95% confidence interval (1000' tonnes/yr)
Bagasse	Theoretical	11,790 ±844
	Technical, based on residue use	4,224 ±1,396
	Technical, based on residue use and farmers' willingness to sell	2,954 ±1,152
Rice husk	Theoretical	1,288 ±114
	Technical, based on residue use	557 ±161
	Technical, based on residue use and farmers' willingness to sell	398 ±154
Maize cob	Theoretical	599 ±36
	Technical, based on residue use	67 ±35
	Technical, based on residue use and farmers' willingness to sell	61 ±34
Maize husk	Theoretical	400 ±24
	Technical, based on residue use	45 ±24
	Technical, based on residue use and farmers' willingness to sell	41 ±23
Cotton stalk	Theoretical	25,865 ±2,087
	Technical, based on residue use	2,764 ±737
	Technical, based on residue use and farmers' willingness to sell	2,225 ±702
Wheat straw	Theoretical	16,323 ±505
	Technical, based on residue use	2,604 ±767
	Technical, based on residue use and farmers' willingness to sell	2,144 ±709
Rice straw	Theoretical	6,438 ±571
	Technical, based on residue use	2,784 ±806
	Technical, based on residue use and farmers' willingness to sell	1,989 ±772
Sugarcane trash	Theoretical	4,716 ±338
	Technical, based on residue use	1,690 ±558
	Technical, based on residue use and farmers' willingness to sell	1,182 ±461
Maize stalk	Theoretical	2,270 ±136
	Technical, based on residue use	256 ±134
	Technical, based on residue use and farmers' willingness to sell	233 ±129

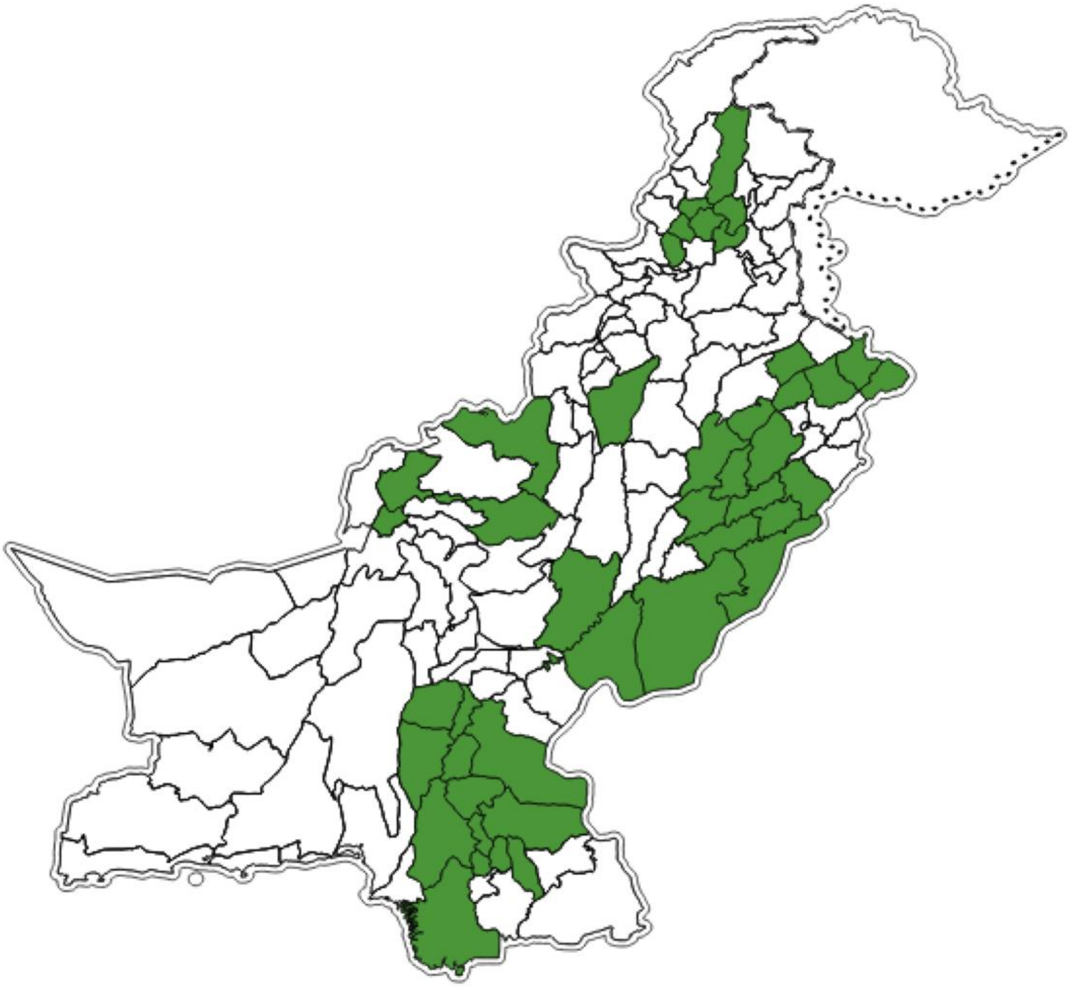

Figure 4. Distribution of the 44 districts targeted by the field survey (shown in green on the map)

4.2 Power Plant Potential at Biomass Producing Sites

An analysis of agro-industrial sites covered by the industrial survey (see Annex 1) was conducted with the aim of evaluating the potential of each site for implementing a biomass-based power or cogeneration plant.

4.2.1 Sugar Mills

Based on the industrial survey, a total of 17.1 million tonnes/year of bagasse is generated in 84 existing sugar mills in Pakistan. Around 90% of this amount of bagasse are used as fuel in cogeneration plants to produce electricity and low pressure steam for covering the energy demand of the sugar mills. Most existing cogeneration plants are equipped with low pressure steam boilers and back-pressure steam turbines working at 21-25 bar. Only two of them already installed high pressure (66 bar) steam boilers. The total installed power capacity for all 84 existing cogeneration plants is estimated at 830 MW. Around 10% of the total bagasse availability (i.e., 1.7 million tonnes/year) constitute a surplus which is sold to other consumers.

There is a large potential for implementing new high-pressure cogeneration plants using bagasse generated at the sugar mills. The potential is calculated based on the assumption that all existing low pressure back-pressure steam turbine-based cogeneration systems will be converted to high pressure system using extraction condensing steam turbines. It should be noted that the use of new extraction condensing steam turbine allows the high pressure cogeneration system to run during the off-milling season by utilizing all the bagasse generated at the sugar mill as well as additional biomass feedstock sourced from the vicinity of the sugar mill. Although the investment costs to convert the existing low pressure to high pressure cogeneration systems are high[3], the implementation of high pressure cogeneration systems is a priority for AEDB in order to optimize the use of bagasse for power generation. Sticking to old, inefficient and polluting low pressure systems is not an option anymore.

The process of analysis of new high pressure cogeneration systems at sugar mills is as follows:

(1) *Calculating the energy input from bagasse (GWh_{th}/year):* For each sugar mill, the energy input from bagasse to the new high-pressure cogeneration plant is calculated based on the annual amount of bagasse generated at the sugar mill and the LHV of bagasse (7.5 MJ/kg). The data on bagasse generation was obtained from the industrial survey.

(2) *Calculating the total energy output from a cogeneration plant:* An overall cogeneration efficiency of 75% was conservatively assumed for the cogeneration system at each sugar mill. Based on this assumption and the energy input from bagasse, the total energy output (i.e., steam thermal energy for process and electricity generation) from a cogeneration plant can be calculated.

(3) *Calculating the process steam consumed by the sugar mill (GWh_{th}/year):* In order to calculate the process steam consumption (in thermal energy unit) of the sugar mill, it was assumed that 450 kg of low pressure steam (at 2.5 bar and 130°C) is consumed for processing one tonne of sugarcane.

(4) *Sizing the cogeneration plant:* The gross electricity generation of the cogeneration plant is calculated by subtracting the thermal energy of process steam consumed by the sugar mill from its total energy output. Then, the rated gross power capacity is defined based on the plant capacity factor (PCF) of the cogeneration plant. According to NEPRA's regulation promulgated in 2013, a PCF of 45% was approved for newly-established cogeneration plants running on bagasse only, based on 180 days of operation (120 days milling season and 60 days off-milling season) and a plant availability factor of 92%.

(5) *Calculating the net electricity output (GWh/year):* This value is calculated from the gross electricity generation and an assumed parasitic load (electricity own-consumption) of the cogeneration plant. Based on NEPRA's regulation, an average value of 8.5% is used for parasitic load.

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[3] Based on the Consultant's experience in the region, the investment costs are USD 0.9 - 1.2 million/MW of installed power capacity for the capacity range of 15 - 35 MW. For the small-scale systems (<10 MW), the investment costs may reach USD 1.5 million/MW.

(6) *Calculating electricity export to the grid (GWh/year) in case only bagasse is used:* The amount of electricity exported to the grid is calculated by subtracting the electricity consumed by the sugar mill from the net electricity output of the cogeneration plant. The electricity consumption of the sugar mill is calculated based on the assumption that 30 kWh of electricity is required for processing one tonne of sugarcane.

(7) *Calculating the energy input from additional biomass feedstock (GWh_{th}/year) for year-round operation of the cogeneration plant:* Assuming that the annual PCF of the cogeneration plant increases to 85%, the annual PCF of the cogeneration plant running on additional biomass feedstock during off-milling season is calculated at 40%. Based on this PCF value and the rated gross power capacity defined in step (4), the gross electricity generation of the cogeneration plant running on additional feedstock can be calculated. Then, the amount of energy input from additional biomass feedstock is calculated using an assumed value of 25% for electrical efficiency of the cogeneration plant running in pure-power generation mode. For the additional biomass feedstock, the fuel deterioration during storage for a period of six months was taken into account.

(8) *Calculating the total electricity export to the grid (GWh/year):* The net electricity output of the cogeneration plant running on additional biomass feedstock is calculated from the gross electricity generation defined in step (7) and the plant parasitic load.

(9) *Calculating the amount of additional biomass feedstock (tonnes/year) and its sourcing area (km^2/GWh):* This is done based on the amount of energy input calculated in step (7) and the map of technical potential of crop harvesting residues provided in Figure 3. In other words, the sourcing area for additional biomass feedstock takes into account the real distribution of the crop fields and crop residues within the vicinity of the mill.

The additional biomass feedstock sourcing area matches the best-case scenario, which is able to source all of the technically available crop harvesting residues suitable for the cogeneration plant from the immediate neighborhood of the sugar mill. Therefore, it helps ranking the sugar mills in terms of the ease of sourcing the additional biomass feedstock.

The results of the sugar mills analysis show that the new high-pressure cogeneration plants at 84 sugar mills could have a combined power capacity output of 1,844 MW which is 2.2 times higher than the total power capacity of all existing low pressure cogeneration plants. It was assumed that the whole amount of generated bagasse, i.e. 17.1 million tonnes/year are used. In order to run these cogeneration plants at an annual PCF of 85%, around 12.9 million tonnes/year of additional biomass feedstock are needed. A total amount of about 4,944 GWh/year of electricity could be exported to the grid if only bagasse is used or 10,759 GWh/year if both bagasse and additional biomass feedstock are used as fuels for the cogeneration plants.

Table 11 presents the key results of analyzing 25 sugar mills with the highest power capacity potential (≥ 25 MW). The map of potential cogeneration plants at all existing sugar mills in Pakistan is shown in Figure 5.

Table 11: List of 25 sugar mills with highest potential for cogeneration plants

Province	District	Sugar mill	Bagasse production (tonne/yr)	Gross power capacity output (MW)	Electricity export (use of bagasse only) (GWh/yr)	Electricity export (use of bagasse and additional feedstock) (GWh/yr)	Additional feedstock sourced (tonne/yr)	Feedstock sourcing area (km^2/GWh)
Punjab	Rahim Yar Khan	Hamza Sugar Mills Ltd.	1,127,487	122	327	711	1,287,559	0.19
Punjab	Rahim Yar Khan	JDW Sugar Mills Ltd.	859,989	93	249	542	887,492	0.19
Punjab	Toba Tek Singh	Kamalia Sugar Mills Limited	495,000	53	143	312	419,163	0.26
Sindh	Ghotki	J.D.W Sugar Mills Ltd (Unit IV) - Dehrki	477,284	52	138	301	347,969	0.20
Sindh	Ghotki	J.D.W Sugar Mills Ltd (Unit III) - Ghotki	451,430	49	131	285	303,121	0.14
Punjab	Muzaffargarh	Shaikhoo Sugar Mills Limited	442,446	48	128	279	368,632	0.37
Punjab	Rahim Yar Khan	Etihad Sugar Mills Ltd.	420,302	45	122	265	352,526	0.30
Sindh	Shaheed Benazirabad	Al Noor Sugar Mills Ltd.	387,978	42	112	245	293,258	0.24
Punjab	Rahim Yar Khan	RYK Sugar Mills Ltd.	378,329	41	110	238	276,127	0.34
Punjab	Faisalabad	Tandlianwala Sugar Mills Ltd. (II)	376,187	41	109	237	295,626	0.25
Punjab	Rahim Yar Khan	JDW Sugar Mills Limited (Unit II)	355,881	38	103	224	243,689	0.26
Punjab	Layyah	Layah Sugar Mills Limited	345,863	37	100	218	303,420	0.48
Punjab	Bahawalpur	Ashraf Sugar Mills Limited	345,000	37	100	217	276,544	0.27
Sindh	Tando Allah Yar	Mehran Sugar Mills Limited	341,920	37	99	216	232,503	0.27
Sindh	Shaheed Benazirabad	Habib Sugar Mills Ltd.	334,966	36	97	211	206,850	0.19
Punjab	Muzaffargarh	Fatima Sugar Mills Ltd.	326,940	35	95	206	256,527	0.39
Sindh	Tando Muhammad Khan	Faran Sugar Mills Limited	274,488	30	80	173	172,477	0.24
Punjab	Mandi Bahauddin	Colony Sugar Mills Ltd-I, Bahauddin	252,000	27	73	159	175,657	0.26
Punjab	Jhang	Shakarganj Mills Limited-I, Jhang	249,225	27	72	157	198,425	0.51
Punjab	Nankana Sahib	Haseeb Waqas Sugar Mills Limited	246,600	27	71	155	178,795	0.26
KPK	Dera Ismail Khan	Chashma Sugar Mills Limited Unit-I	242,406	26	70	153	206,923	0.68
KPK	Dera Ismail Khan	Almoiz Sugar Mills Ltd.	238,909	26	69	151	228,571	0.88
Punjab	Mandi Bahauddin	Shahtaj Sugar Mills Limited	235,104	25	68	148	188,747	0.40
Punjab	Jhang	Kashmir Sugar Mills Ltd.	231,747	25	67	146	186,024	0.55
Punjab	Kasur	Chaudhry Sugar Mills Ltd.	230,511	25	67	145	161,473	0.28
Total			**9,667,993**	**1,044**	**2,801**	**6,094**	**8,048,098**	

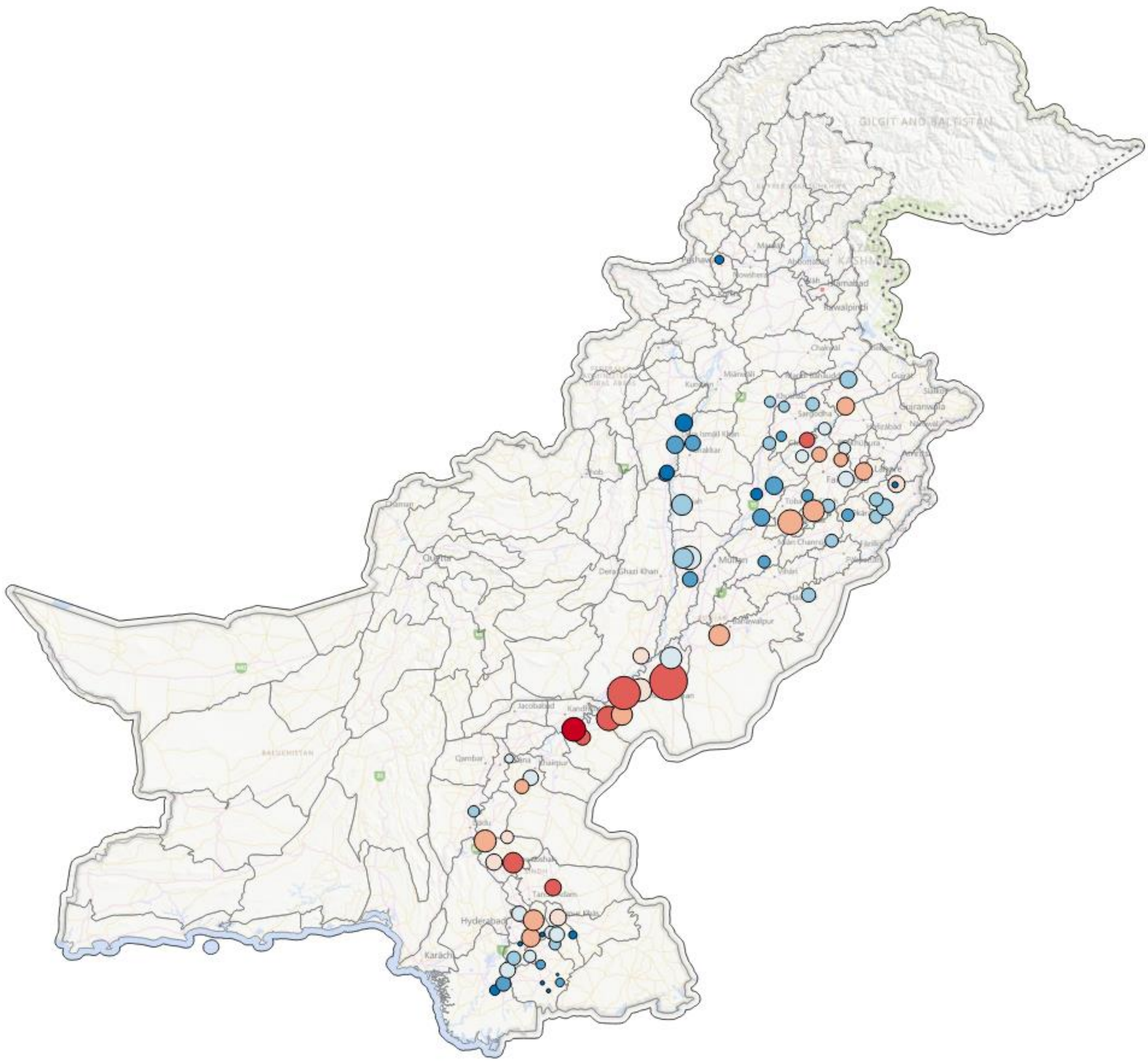

Figure 5: Sugar mill analysis results

Note: The area of the circle denotes the power plant capacity, and the color the relative ranking of sourcing area for additional feedstock: blue hues–larger sourcing area per GWh, red hues–smaller sourcing area per GWh [Background map: Microsoft® Bing™ Maps]

Table 12 provides the links for access to the survey results, the map and datasets for the sugar mills analysis.

Table 12: Links for access to the survey results, the maps and datasets of sugar mills analysis

Atlas data	Can be accessed at:
GIS and other datasets:	https://energydata.info/dataset/pakistan-biomass-gis-atlas
Sugar mill analysis	file: industrial\sugar_mills\sugar_mills.shp file content description: industrial\metadata\sugar_mill.txt
Crop harvesting residue availability (for this analysis the technical availability is based on current residue use only)	files: feedstock\technical_feedstock_per_pixel_FALL_residue.tif feedstock\technical_feedstock_per_pixel_SPRING_residue.tif feedstock\technical_feedstock_per_pixel_WHOLE_YEAR_residue.tif file content description: industrial\metadata\feedstock.txt
Other datasets:	
Mill analysis results without the	file: industrial\Mills.xlsx

map data	
Cogeneration model the analysis results are based on, feedstock to conversion technology suitability mapping	file: industrial\Power_plant_model.xlsx
Survey results	file: industrial\Industrial_survey.xlsx

4.2.2 Rice Mills

It must be mentioned that only 54 rice mills provided adequate data during the industrial survey (see Annex 1). Based on a total national rice production of around 7 million tonnes during 2014-2015 season[4], the total amount of rice husk generated is estimated at 1.75 million tonnes/year[5]. With a LHV of rice husk of 13.5 MJ/kg, this amount of rice husk has an energy potential of 23,625 TJ/year (6,563 GWh_{th}/year). If 100% of this amount of rice husk is used for power generation, the potential power capacity output would be about 200 MW, based on an average electrical efficiency of 22.5% and annual PCF of 85%.

The milling capacity of the 54 surveyed rice mills is rather low, with a combined amount of generated rice husk of about 140,000 tonnes/year. This amount can support 16 MW of power capacity only, i.e. an average of around 300 kW per mill. For this power capacity range, rice husk gasification-based power systems can be used to generate electricity for covering the power demand of these rice mills.

As this potential is too low to attract investors, the use of additional biomass feedstock was considered in the analysis of the power generation potential in order to increase the capacity of each power plant to be able to connect to the grid. It was assumed that the power plant would be run with a fuel mixture of rice husk and of locally sourced crop harvesting residues. The minimum fixed power plant capacity of 3 MW is assumed for all 54 surveyed rice mills. The additional biomass feedstock was calculated in order to assure an annual plant capacity factor of 85% for all power plants. As for the sugar mills, the analysis results for each rice mill contain the sourcing area (km^2/GWh) for the additional biomass feedstock needed to operate the power plant, with the sourcing area matching the best-case sourcing scenario.

The process of analysis of potential power plants at rice mills is as follows:

(1) *Calculating the gross electricity output of the power plant:* The gross electricity output of a 3 MW power plant running at 85% annual PCF is calculated at 22,338 MWh/year.

(2) *Calculating electricity export:* For a 3 MW power plant, the parasitic load (own consumption) is assumed at 15% of the gross electricity output. The net electricity output or electricity export is calculated at 18,987 MWh/year.

(3) *Calculating the energy input from biomass fuel required for a 3 MW power plant:* For a 3 MW power plant, a medium pressure (40-50 bar) grate steam boiler with a fully condensing

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[4] *Source: Pakistan Economic Survey 2014-2015. Available at http://www.finance.gov.pk/survey/chapters_15/Highlights.pdf*

[5] *Based on a rice husk to milled rice ratio of 25%*

steam turbine can be used. With these assumptions, the gross electrical efficiency of the power plant will be 20.8%. The energy input from biomass fuel is calculated at 107,394 MWh_{th}/year.

(4) *Calculating the energy input from rice husk (MWh_{th}/year):* The energy input from rice husk is calculated based on the rice husk production of each rice mill (obtained from the industrial survey) and its LHV of 13.5 MJ/kg. This value varies between rice mills.

(5) *Calculating the energy input from additional biomass feedstock (MWh_{th}/year):* Energy input from additional feedstock is calculated by subtracting the amount of energy input from rice husk from the total amount of energy input required for the power plant defined in step (3). For the additional feedstock, the effect of fuel deterioration during the storage period of six months was taken into account.

(6) *Calculating the amount of additional biomass feedstock (tonnes/year) and its sourcing area (km^2/GWh):* This is done based on the amount of energy input calculated in step (5) and the map of technical potential of crop harvesting residues provided in Figure 3. It takes into account the real distribution of fields and crops, but assuming 100% sourcing ability of the available feedstock.

As mentioned above, the potential of rice husk utilization for power generation at each of 54 surveyed rice mills are small (around 300 kW per mill in average). These are commonly used as captive power plants for supplying the power demand of the rice mills. In order to connect these power plant to the grid, their capacity should be increased to a minimum of 3 MW, and additional biomass feedstock should be used.

The results of the rice mills analysis show that, for a combined power capacity output of 162 MW of the potential power plants at 54 rice mills, a calculated amount of biomass fuel of 1.86 million tonnes/year is required of which 0.14 million tonnes/year come from rice husk and 1.72 million tonnes/year from other additional biomass feedstock. These potential power plants could export about 1,026 GWh/year of electricity to the grid. Table 13 lists the 25 rice mills with the lowest sourcing area ($\leq$ 0.43 km^2/GWh) for additional biomass feedstock. The map showing these rice mills is provided in Figure 6.

Table 13: List of 3 MW rice husk-based power plants with lowest sourcing area for additional feedstock

Province	District	Rice mill	Rice husk production (tonne/yr)	Electricity export (GWh/yr)	Additional feedstock sourced (tonne/yr)	Feedstock sourcing area (km^2/GWh)
Punjab	Gujranwala	Al-Hameed Rice Mills	81	19.0	34,278	0.40
Sindh	Larkana	Abadghar Rice Mill Larkano.	560	19.0	30,058	0.40
Sindh	Qambar Shahdadkot	Memon Rice Mill Kamber.	760	19.0	31,591	0.41
Sindh	Qambar Shahdadkot	Muzamil Rice Mill Mirokhan.	800	19.0	33,582	0.41
Sindh	Larkana	Dastagheer Rice Mill Badah.	800	19.0	31,946	0.41
Sindh	Qambar Shahdadkot	Hamid Rice Mill Wagan.	800	19.0	32,680	0.41
Sindh	Qambar Shahdadkot	Tunio Rice Mill Mirokhan.	800	19.0	33,582	0.41
Sindh	Larkana	Kashtkar Rice Mill Larkano.	800	19.0	29,569	0.41
Sindh	Qambar Shahdadkot	Mughari Rice Mill Kamber.	800	19.0	32,103	0.41
Sindh	Larkana	Amaanullah Rice Mill Larkano.	900	19.0	28,315	0.41
Sindh	Qambar Shahdadkot	Bismilah Rice Mill Nasiradad.	960	19.0	32,886	0.41
Punjab	Nankana Sahib	Amin Ittefaq Rice Mills	1,000	19.0	33,340	0.41
Sindh	Qambar Shahdadkot	Faiz Masan Rice Mill Nasiradad.	1,120	19.0	32,734	0.41
Sindh	Qambar Shahdadkot	Mohammadi Rice Mill Nasiradad.	1,120	19.0	32,732	0.41
Sindh	Larkana	Jawed Rice Mill Larkano.	1,200	19.0	28,498	0.41
Sindh	Qambar Shahdadkot	Ubaidullah Rice Mill Kamber.	1,200	19.0	31,092	0.41
Sindh	Qambar Shahdadkot	Aziz Rice Mill Wagan.	1,200	19.0	32,211	0.41
Sindh	Qambar Shahdadkot	Abdullah Rice Mill Mirokhan.	1,200	19.0	33,099	0.41
Sindh	Qambar Shahdadkot	Madina Rice Mill Mirokhan.	1,200	19.0	33,099	0.41
Sindh	Larkana	Bismillah Rice Mill Ratodero.	1,440	19.0	30,970	0.42
Sindh	Larkana	Masha Allah Rice Mill Ratodero.	1,600	19.0	29,097	0.42
Sindh	Qambar Shahdadkot	Aaquib Rice Mill Kamber.	1,600	19.0	30,664	0.42
Punjab	Chiniot	Iqbal Rice Mills	2,008	19.0	31,978	0.42
Punjab	Gujranwala	Kashif Rice Mills	2,190	19.0	30,812	0.43
Sindh	Larkana	Husnain Rice Mill Ratodero.	2,400	19.0	29,054	0.43
Total			**28,539**	**475**	**789,971**	

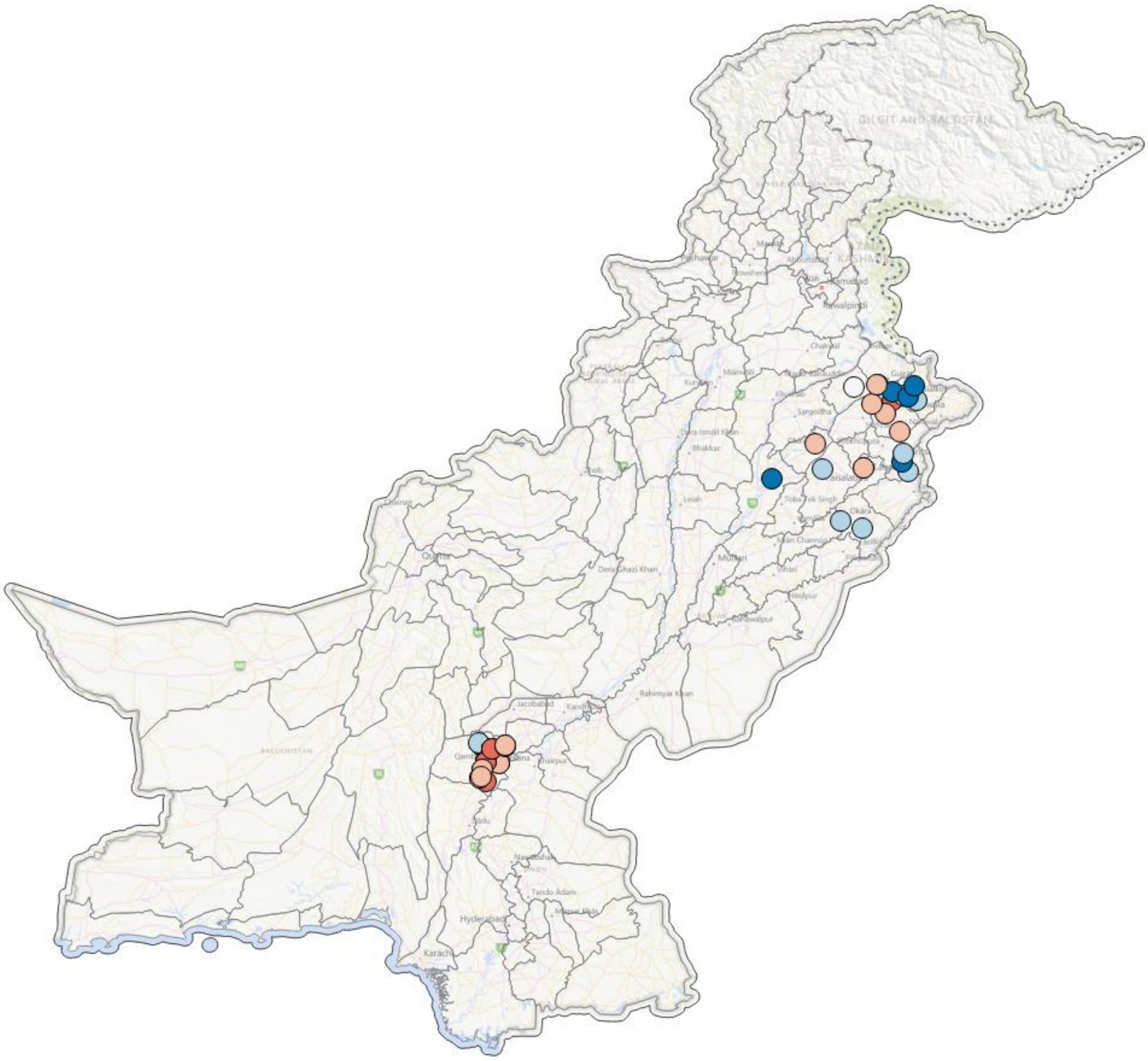

Figure 6: Rice mill analysis results

Note: All power plants have 3 MW capacity. The color indicates the ranking of the sourcing area for additional feedstock: blue hues – larger sourcing area per GWh, red hues – smaller sourcing area, white – in between [Background map: Microsoft® Bing™ Maps]

The links for access to the survey results, the map and datasets for the rice mills analysis are showed in Table 14.

Table 14: Links for access to the survey results, the map and datasets of rice mills analysis

Atlas data	Can be accessed at:
GIS datasets:	https://energydata.info/dataset/pakistan-biomass-gis-atlas
Rice mill analysis	file: industrial\rice_mills\rice_mills.shp file content description: industrial\metadata\rice_mill.txt
Crop harvesting residue availability (for this analysis the technical availability is based on current residue use only)	files: feedstock\technical_feedstock_per_pixel_FALL_residue.tif feedstock\technical_feedstock_per_pixel_SPRING_residue.tif feedstock\technical_feedstock_per_pixel_WHOLE_YEAR_residue.tif file content description: feedstock\metadata\feedstock.txt

Other datasets:	
Mill analysis results without the map data	file: industrial\Mills.xlsx
Cogeneration model the analysis results are based on, feedstock to conversion technology suitability mapping	file: industrial\Power_plant_model.xlsx
Survey results	file: industrial\Industrial_survey.xlsx

4.2.3 MSW Landfills

There is a potential use of MSW for energy generation at the landfills in Pakistan. Two technologies which are most frequently used for generating electricity and/or heat from MSW include:

- direct combustion of organic materials of MSW in an incinerator/steam boiler to produce high pressure steam. Then, this steam is used in a steam turbo-generator to generate electricity or both electricity and heat;
- anaerobic digestion of biodegradable fraction of MSW to produce biogas which is used in a gas engine/turbine system to generate electricity or both electricity and heat.

The method of using incinerator/steam boiler to convert MSW to energy is a relatively old method. The electrical efficiency of this technology is low (typically, 14-28%) due to the low efficiency of the incinerator/steam boiler burning MSW with high moisture content and low LHV. Another problem associated with direct combustion of MSW to generate electricity is the potential for pollutants (such as nitrogen oxides, sulphur dioxide, heavy metals and dioxins) to enter the atmosphere with the flue gases from the incinerator/boiler. In this study, the anaerobic digestion of MSW is proposed as it has a higher electrical efficiency and a lower environmental impact than the direct combustion technology.

The following steps were used for analyzing the potential power plants installed at the landfills based on anaerobic digester combined with gas engine/turbine systems:

(1) *Calculating the annual biogas production for each landfill (m^3/year):* Based on the amount of MSW disposed at each landfill (obtained from the industrial survey), the annual biogas production is calculated by using an average biogas production rate of 120 m^3/tonne of MSW as-received basis.

(2) *Calculating the energy input from biogas to the gas engine/turbine (GWh_{th}/year):* This value is calculated based on the annual biogas production and biogas LHV. Assuming that biogas produced from MSW consists of 60% of methane, the biogas LHV was calculated at 21.54 MJ/m^3.

(3) *Calculating the gross electricity output from the power plant (GWh/year):* The gross electricity output was calculated based on an assumed gross electrical efficiency of 40% for biogas engine-based technology and 30% for biogas turbine-based technology.

(4) *Calculating the rated gross power capacity (MW):* The rated gross power capacity of each power plant was calculated based on its gross electricity output and an annual PCF of 90%.

(5) *Calculating the electricity export (GWh/year):* The amount of electricity export was calculated based on an average parasitic load of 5% assumed for all power plants.

The industrial survey covered 16 landfills in the major cities of Pakistan. However, only 12 landfills provided adequate data for the analysis. The combined amount of MSW collected at these landfills is around 29,000 tonnes per day. However, some amount of MSW is being sold out for fertilizer production, and the remaining amount of around 27,000 tonnes a day is currently dumped at the 12 landfills. This amount of MSW could generate around 360 MW of gross power capacity in the anaerobic digester-based power plants. The MSW-based power generation potential of the 12 surveyed landfills is presented in Table 15 and illustrated in Figure 7.

Table 15: Potential power plants installed at the landfills

No.	Name of Landfill (Waste Management Company)	MSW dumped (tonne/day on wet basis)	Annual biogas production (Million m^3/year)	Gross electricity output (GWh/year)	Rated gross power capacity (MW)	Electricity export to the grid (GWh/year)
1.	Gondpass (Sindh Solid Waste Management Board)	6,000	262.8	629.0	79.8	597.5
2.	Jam Chakro (Sindh Solid Waste Management Board)	6,000	262.8	629.0	79.8	597.5
3.	Bhakkay Wala (Gujranwala WMC)	6,000	262.8	629.0	79.8	597.5
4.	Mehmood Booti (Lahore WMC)	3,500	153.3	366.9	46.5	348.6
5.	Lossar (Rawalpindi WMC)	1,200	52.6	125.8	16.0	119.5
6.	Makkuana Site I (Faisalabad WMC)	1,100	48.2	115.3	14.6	109.6
7.	Ring Road (Water and Sanitation Services Peshawar)	850	37.2	89.1	11.3	84.7
8.	Gondlanwala (Gujranwala WMC)	850	37.2	89.1	11.3	84.7
9.	Sector I-12 (Capital Development Authority)	700	30.7	73.4	9.3	69.7
10.	Eastern Pass (Quetta Municipality)	375	16.4	39.3	5.0	37.3
11.	Tiba Badarshar (Bahawalpur WMC)	225	9.9	23.6	3.0	22.4
12.	Ratta Village (Sialkot WMC)	185	8.1	19.4	2.5	18.4
	Total	**26,985**	**1,182**	**2,829**	**359**	**2,687**

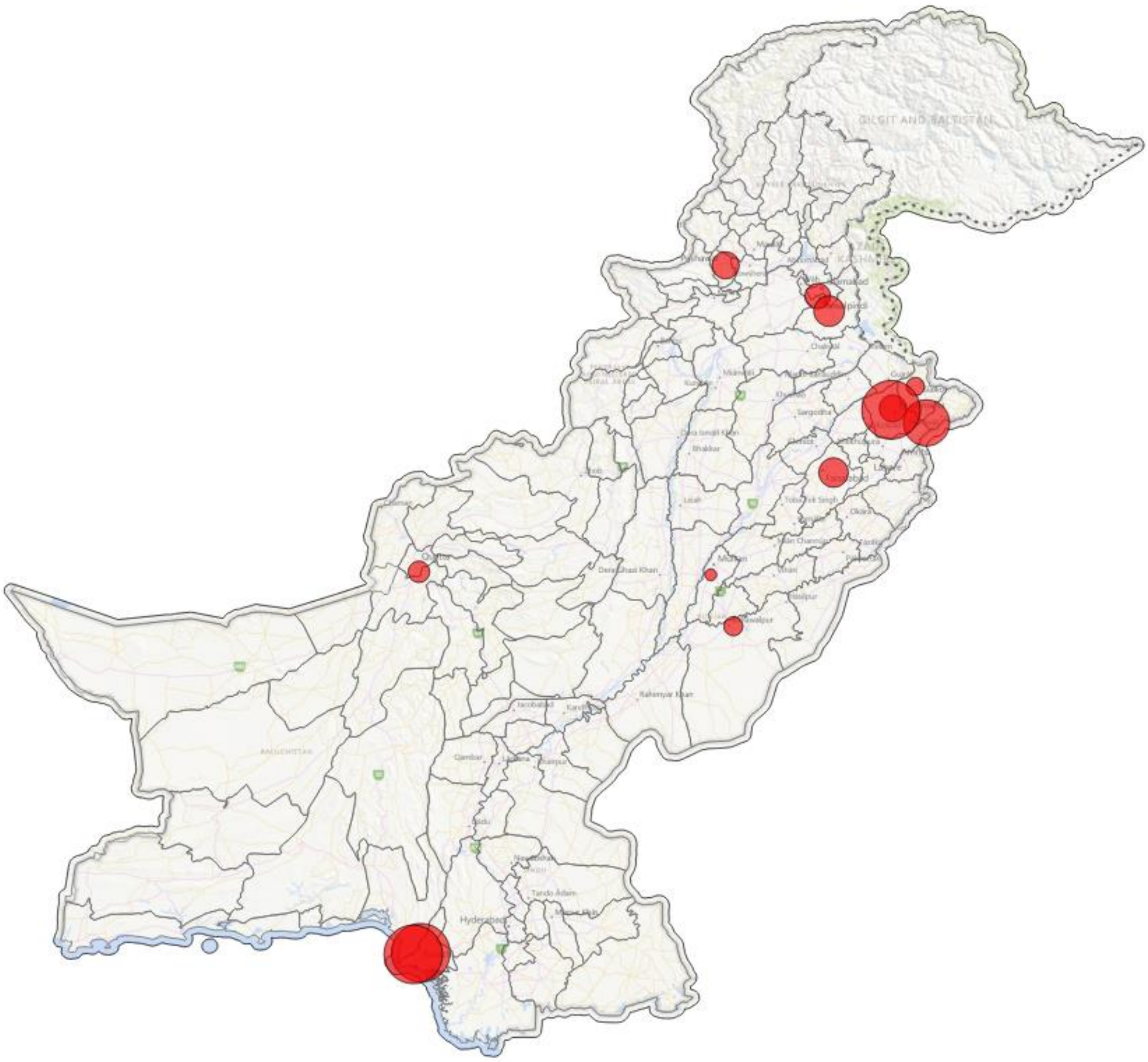

Figure 7: Ranking of the MSW landfills based their power generation potential
Note: Bigger area of the circle denotes higher capacity [Background map: Microsoft® Bing™ Maps]

The links for access to the survey results, the map and datasets for MSW landfills analysis are provided in Table 16.

Table 16: Links for access to the survey results, the map and datasets of MSW landfills analysis

Atlas data	Can be accessed at:
GIS datasets:	https://energydata.info/dataset/pakistan-biomass-gis-atlas
MSW landfill analysis	file: industrial \MSW\MSW.shp file content description: industrial\metadata\MSW.txt
Other datasets:	
Survey results	file: industrial\Industrial_survey.xlsx

4.2.4 Livestock Farms

The industrial survey covered the large-scale livestock farms with a minimum of 1,000 cattle heads. This led to the survey of five dairy farms. Only three of them provided the required information on their GPS coordinates and the production of livestock manure. The combined manure production of these farms is 100 tonnes per day. This amount could support 0.36 MW of gross power capacity for anaerobic digester-based power plants with mono-digestion of manure.

The methodology used for analyzing the potential of biogas-based power plants at the dairy farms is similar to that used for the case of MSW. However, for the case of dairy farms, the average biogas production rate was assumed to be 32 m^3/tonne of manure.

The power generation potential of three surveyed dairy farms are presented in Table 17 and illustrated in Figure 8.

Table 17: Potential power plants installed at the dairy farms

No.	Name of Dairy Farm	Manure collected (tonne/day on as-received basis)	Annual biogas production (m^3/year)	Gross electricity output (GWh/year)	Rated gross power capacity (MW)	Electricity export to the grid (GWh/year)
1.	Engro Dairy Farm Nara	64	747,520	1.79	0.23	1.70
2.	JK Dairies Pvt. Limited	30	350,400	0.84	0.11	0.80
3.	Sarsaabz Dairy Farm Nestle	6	70,080	0.17	0.02	0.16
	Total	**100**	**1,168,000**	**2.80**	**0.36**	**2.66**

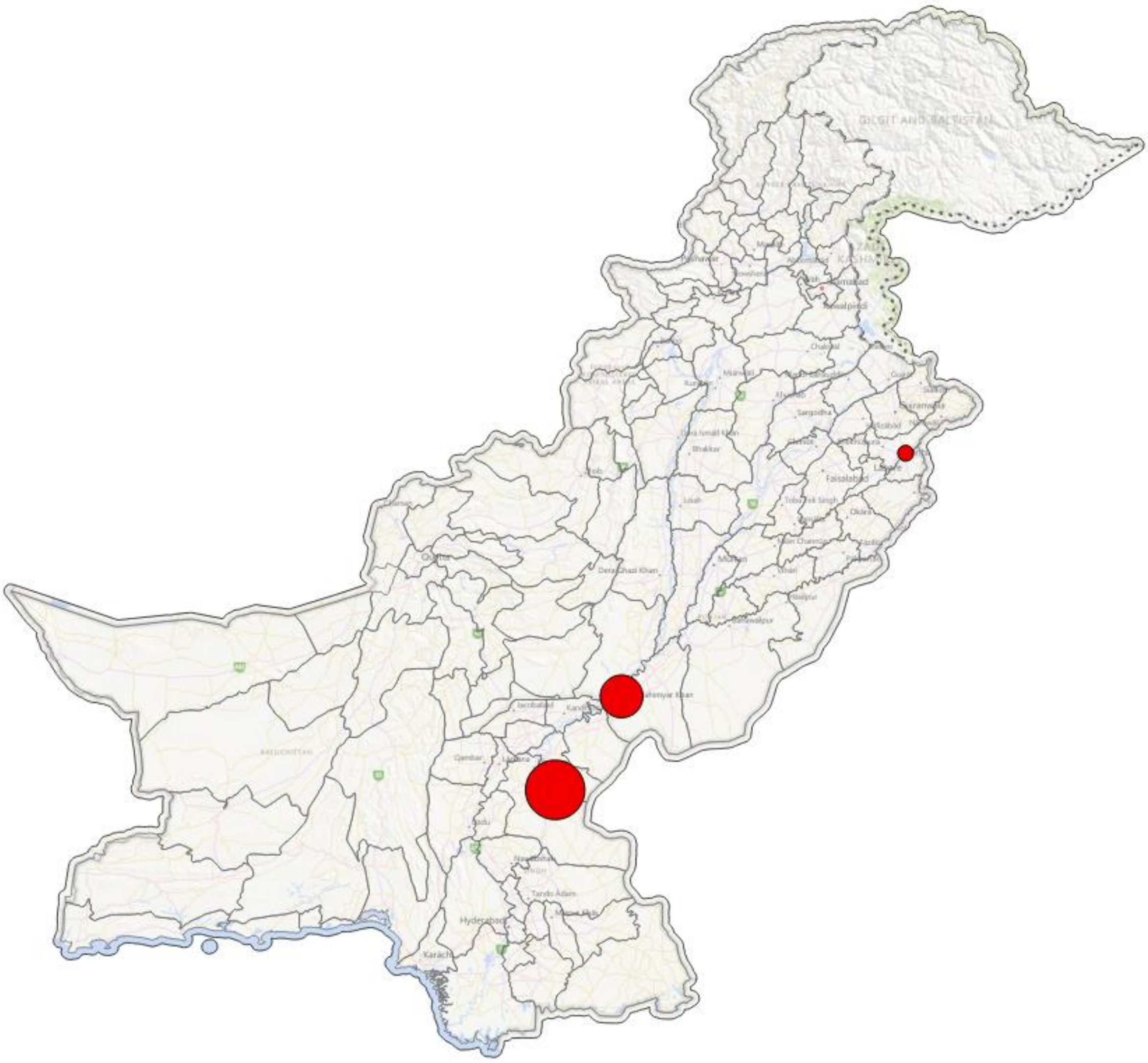

Figure 8: Ranking of the dairy farms based on their power generation potential
[Background map: Microsoft® Bing™ Maps]

The links for access to the survey results, the map and the datasets for dairy farms analysis are provided in Table 18.

Table 18: Links for access to the survey results, the map and datasets of dairy farms analysis

Atlas data	Can be accessed at:
GIS datasets:	https://energydata.info/dataset/pakistan-biomass-gis-atlas
Dairy farm analysis	file: industrial\dairy_farms\dairy.shp file content description: industrial\metadata\dairy_farm.txt
Other datasets:	
Survey results	file: industrial\Industrial_survey.xlsx

4.2.5 Forest harvesting and wood processing residues

During the inception phase of the project, the Consultant has conducted interviews with the Forestry Departments of Punjab, Sindh, and Khyber Pakhtunkhwa (KPK) provinces. All three departments stated that they have no available data on forestry sector. They also stated that almost all the forest residues generated are collected by the local people for domestic uses (e.g., for cooking). Hence, there is no surplus of forest residues that can be used for power generation. As a consequence, the assessment of forest biomass residues was excluded from the scope of this study.

4.3 Greenfield Power Plant Potential

This part of the Biomass Atlas consists of site suitability indicator maps for greenfield power plants using crop harvesting residue feedstock. A high site suitability value indicates a good site for a potential power plant, whereas a low value indicates a poor location.

This site suitability indicator takes into account the feedstock sourcing area size, the road network density in the region, and the distance to a grid power station. The first two factors serve as proxies for site-dependent operational costs, and the third one as site dependent investment cost proxy.

The site suitability indicator map can be used by the potential project developers/investors for initially screening the locations for greenfield biomass-based power plant. In order to select the best site, more detailed investigation and assessment of biomass residues availability and their supply chains should be conducted during the project feasibility study phase.

Each of the indicator components get values between 0 and 100, scaled linearly between the worst and best values for the component in the dataset. This means that a component gets value 100 for smallest sourcing area, shortest direct distance to a grid power station and the highest road network density in the whole dataset, and vice versa for value 0. The three components are then combined so that the site suitability indicator also gets values between 0 and 100, where 100 indicate a site where all the three factors are optimal. The weights used in combining the components were 0.6 for feedstock sourcing area, 0.3 for grid power station distance and 0.1 for road network density.

The maximum direct sourcing distance allowed was 50 km. The maximum feedstock sourcing area, and hence distance, is determined by both the power plant capacity and the technology used. The power plant modeling includes a compatibility matrix between different crop residues and technology & capacity combinations. Other factors included in the model are feedstock pre-processing and storage.

The site suitability indicator value was computed for 21 different combinations of energy conversion technologies and power plant capacities as shown in Table 19.

Table 19: Analyzed combinations of power plant technologies and capacities

Technology	Power plant capacity (MW)
Horizontal grate combustion steam boiler + steam turbine	3, 8 and 15
Inclined grate combustion steam boiler + steam turbine	3, 8 and 15
Bubbling fluidized bed combustion steam boiler + steam turbine	8, 15, 25, 50 and 100
Circulating fluidized bed combustion steam boiler + steam turbine	15, 25, 50 and 100
Gasifier + syngas engine/turbine	0.5 and 1.5
Anaerobic digester + biogas engine/turbine	0.5,1.5, 3 and 8

Each combination can be illustrated with a map. Figure 9 illustrates the site suitability for the 15 MW power plants with inclined grate combustion steam boiler and steam turbine.

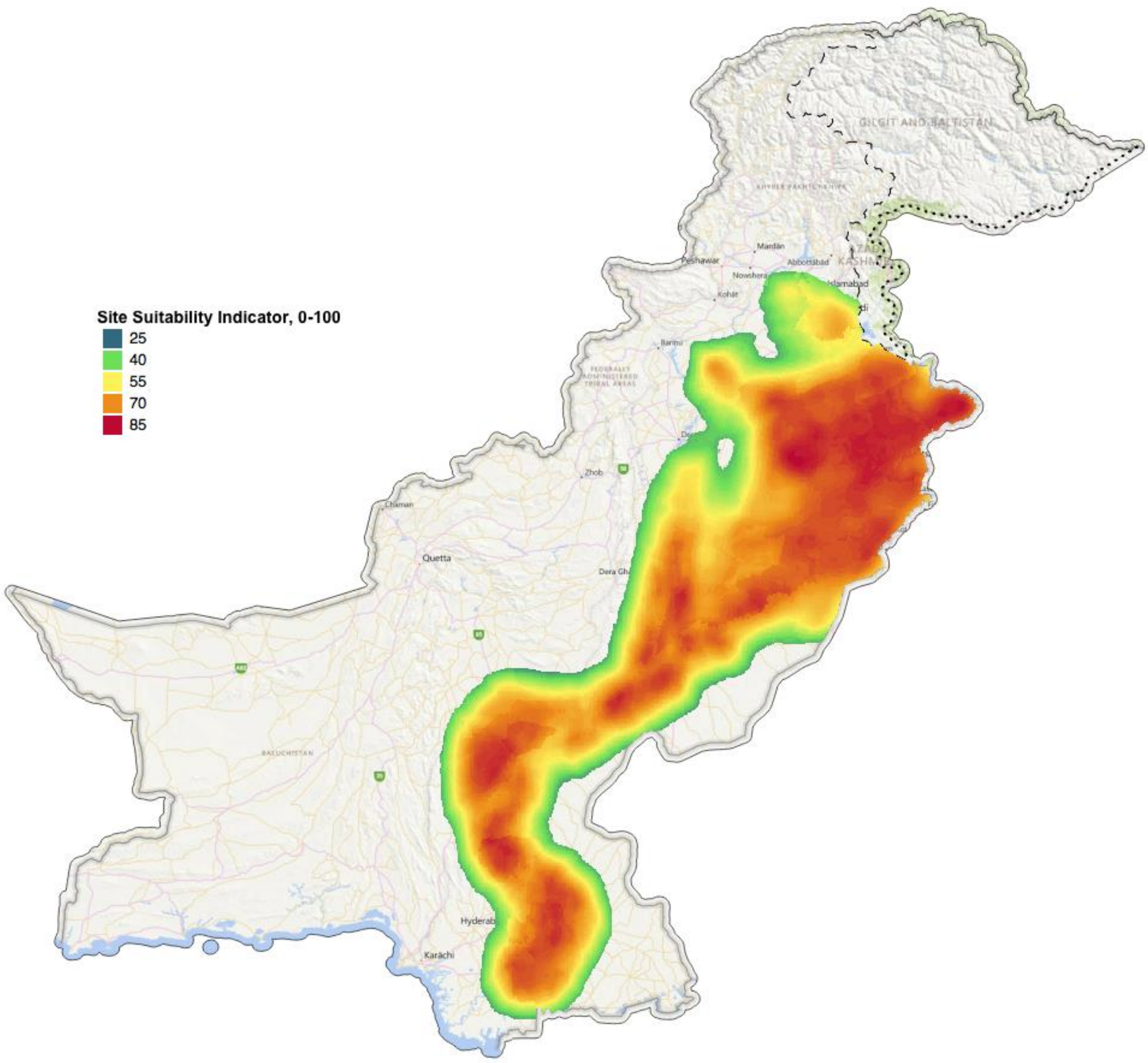

Figure 9: Site suitability indicator map for 15 MW power plants with inclined grate steam boiler
Note: Red color indicating high potential and blue color potential approaching zero
[Background map: Microsoft® Bing™ Maps]

The links for access to the results of site suitability analysis are provided in Table 20.

Table 20: Links for access to the results of site suitability analysis

Atlas data	Can be accessed at:
GIS & other datasets:	https://energydata.info/dataset/pakistan-biomass-gis-atlas
Site suitability indicator	files: site_suitability\heatmap_combined_MIXED.tif site_suitability\heatmap_combined_SINGLE.tif site_suitability\heatmap_gs_distance.tif site_suitability\heatmap_r_mixed.tif site_suitability\heatmap_r_single.tif site_suitability\heatmap_rn_density.tif file descriptions: site_suitability\metadata\site_suitability.txt
Grid power station data	file: grid_station\Gridstation.shp
Road network density	Original data downloaded from: https://www.humanitarianresponse.info/operations/pakistan/

	Data aggregated to districts: file: feedstock\districts\district.shp file content description: feedstock\metadata\district.txt
Other datasets:	
Energy conversion model the analysis results are based on	file: Power_plant_model.xlsx

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This report presents the final product of the assignment, i.e. the Biomass Atlas for Pakistan. More details on interim outputs as well as the detailed approach and methodology used for developing the Biomass Atlas for Pakistan can be found in separate reports, which are available at *https://esmap.org/RE_Mapping_Pakistan*. They are:

- the Inception Report;
- the Implementation Plan;
- the Implementation Report; and
- the Report on Final Biomass Atlas Dissemination Seminars and Training Workshops.

The Biomass Atlas presents both theoretical and technical potentials of crop residues. Crop residues of five major crops (i.e. wheat, cotton, rice, sugarcane and maize) were included in the Biomass Atlas.

The theoretical generation potential of crop processing residues was estimated at 25.3 million tonnes/year with an equivalent energy potential of 222,620 TJ/year (61,838 GWh_{th}/year). Bagasse accounts for 66.0% of this energy potential, followed by rice husk with 20.3%, maize cobs with 8.8% and maize husk with 4.9%.

The theoretical potential of crop harvesting residues was estimated at around 114 million tonnes/year with an equivalent energy potential of 1,616,362 TJ/year (448,990 GWh_{th}/year). 45.8% of the total energy potential come from cotton stalk, 30.8% from wheat straw, 13.0% from rice straw, 6.1% from sugarcane trash, and 4.3% from maize stalks.

Based on the existing uses of the residues by the farmers, the technical potential of crop harvesting residues was estimated at about 25.1 million tonnes/year with an equivalent energy potential of 342,236 TJ/year (95,065 GWh_{th}/year). Rice straw accounts for 30.4% of this energy potential, followed by wheat straw with 27.3%, cotton stalk with 26.4%, sugarcane trash with 12.9% and maize stalks with 3.0%. It can be seen from these percentages that large amounts of cotton stalk and wheat straw are being used by the farmers (in forms of cooking fuel, animal fodder and fertilizer) or sold to industries.

In case the farmers' willingness to sell their biomass residues is taken into account, the technical potential of crop harvesting residues decreases to about 20.5 million tonnes/year with an equivalent energy potential of 280,177 TJ/year (77,828 GWh_{th}/year). Rice straw and wheat straw account for a majority of this energy potential with 29.2% each, followed by cotton stalk with 27.0%, sugarcane trash with 11.5% and maize stalk with 3.2%.

The Biomass Atlas for Pakistan also presents the potential for implementing power plants at the biomass producing sites (such as sugar mills, rice mills, MSW landfills and dairy farms) as well as the potential for greenfield power plants using crop harvesting residue feedstock.

The analysis showed that bagasse offers the highest potential as fuel for cogeneration plants at the existing sugar mills of Pakistan. The results of sugar mills analysis show that the new high-pressure cogeneration plants at 84 sugar mills could have a combined power capacity output of 1,844 MW based on a total amount of generated bagasse of about 17.1 million tonnes/year. These potential cogeneration plants could export about 4,944 GWh/year if only bagasse is used or 10,759 GWh/year if an additional biomass feedstock of around 12.9 million tonnes/year are used as fuel for the cogeneration plants.

MSW can also be used for large-scale grid-connected power plants. With a total MSW amount of around 27,000 tonnes/day generated at 12 surveyed landfills, around 360 MW of gross power capacity could be generated based on the anaerobic digester-based power generating technology. These potential MSW-based power plants could export about 2,687 GWh/year to the grid.

However, rice husk and cattle manure seem to offer a limited energy potential which limited to captive power plants which can generate electricity for covering the power requirements of the rice mills or livestock farms.

It should be noted that the analysis does not include all the existing MSW landfills, rice mills and livestock farms in Pakistan due to the lack of data.

The potential for greenfield power plants using crop harvesting residues was assessed based on their site suitability indicators. This site suitability indicator takes into account the feedstock sourcing area size, the road network density in the region, and the distance to the grid. A high site suitability value indicates a good site for a potential power plant, whereas a low value indicates a poor location. The site suitability maps were produced for 21 different combinations of energy conversion technologies and power plant capacities.

5.2 Recommendations

Freely available, but with relatively low spatial resolution, Landsat 8 images were used for land use mapping. The crop-level accuracy of the land use classification needs to be taken into account when evaluating single site feasibility.

There is a lack of data on industrial sites. It is recommended that an additional industrial survey is conducted to complete the database for the key industrial sectors with high potential of biomass residues. These sectors include rice mills, wood processing mills, MSW landfills and livestock farms.

The Biomass Atlas for Pakistan shall be broadly disseminated via WB, AEDB and other channels.

The stakeholders who have participated in the training on Biomass Atlas usage and maintenance shall share their knowledge and skills with other local stakeholders.

Plans shall be made to secure funds for a regular updating of the Biomass Atlas by the persons who have been trained.

NUST and other universities shall use the project study methodologies and outputs as training materials for building the capacity of their students.

6. ANNEXES

Annex 1: Biomass Resource Mapping Methodology

1.1 End User Interaction

During the process of project implementation, the consulting consortium maintained a close interaction with the key local stakeholders who are the potential end-users of the Biomass Atlas of Pakistan. This interaction helped the consulting consortium not only to update the local stakeholders on the progress of the project implementation, but also to receive their feedback on the project.

Nine (9) multi-stakeholder seminars and workshops were conducted. These events attracted a total of 295 participants (see Table 21). In addition, several individual meetings with local institutions and companies were also organized during the missions of the consultants to Pakistan.

The details of these seminars, workshops and meetings were reported in separate reports which are available at *https://esmap.org/RE_Mapping_Pakistan*.

Table 21: List of seminars and workshops conducted

No.	Name of event	Location	Date/Time	No. of Participants
1.	Inception Meeting	Islamabad	21 Nov 2014	29
2.	Inception Meeting	Lahore	24 Nov 2014	20
3.	Inception Meeting	Karachi	26 Nov 2014	25
4.	Training Workshop on Field Survey and Data Collection	Islamabad (NUST campus)	7-9 Apr 2015	59
5.	Stakeholder Data Validation Workshop	Islamabad	26 Nov 2015	45
6.	Final Biomass Atlas Dissemination Seminar and Usage Training Workshop	Islamabad	15 Feb 2016	42
7.	Final Biomass Atlas Maintenance Training Workshop	Islamabad (NUST campus)	16 Feb 2016	31
8.	Final Biomass Atlas Dissemination Seminar and Usage Training Workshop	Lahore	17 Feb 2016	20
9.	Final Biomass Atlas Dissemination Seminar and Usage Training Workshop	Karachi	18 Feb 2016	24
	Total			**295**

1.2 Mapping Methodology

The mapping methodology for the Biomass Atlas consisted of four distinct components: crop biomass field survey, industrial survey, satellite image analysis and bioenergy potential modeling. Each of these components is described in the following sections.

1.3 Crop biomass field survey

The National University of Sciences and Technology (NUST) of Pakistan was contracted to carry out the crop biomass field survey and data collection. NUST engaged six other universities to provide their students for conducting the survey. All nominated students were trained on how to conduct field survey.

The survey was performed as a person-to-person interview of the farmers by the survey team using smartphones as survey tools. The surveyors used the Android applications that can record the responses of the farmers, indicate the location of the interview and attach a geographically tagged photograph of a reference field of the farm to be used in land use classification of satellite images.

All the collected data were transferred to Simosol in real time. After being validated, the data were sent back by Simosol to NUST for correction of any errors and for completion of any missing information on the second or third day of the survey. The survey monitors/supervisors from NUST assisted in verifying the data. The validated and verified data were eventually sent back to Simosol. That procedure continued until data were finally accepted by Simosol (see Figure 10).

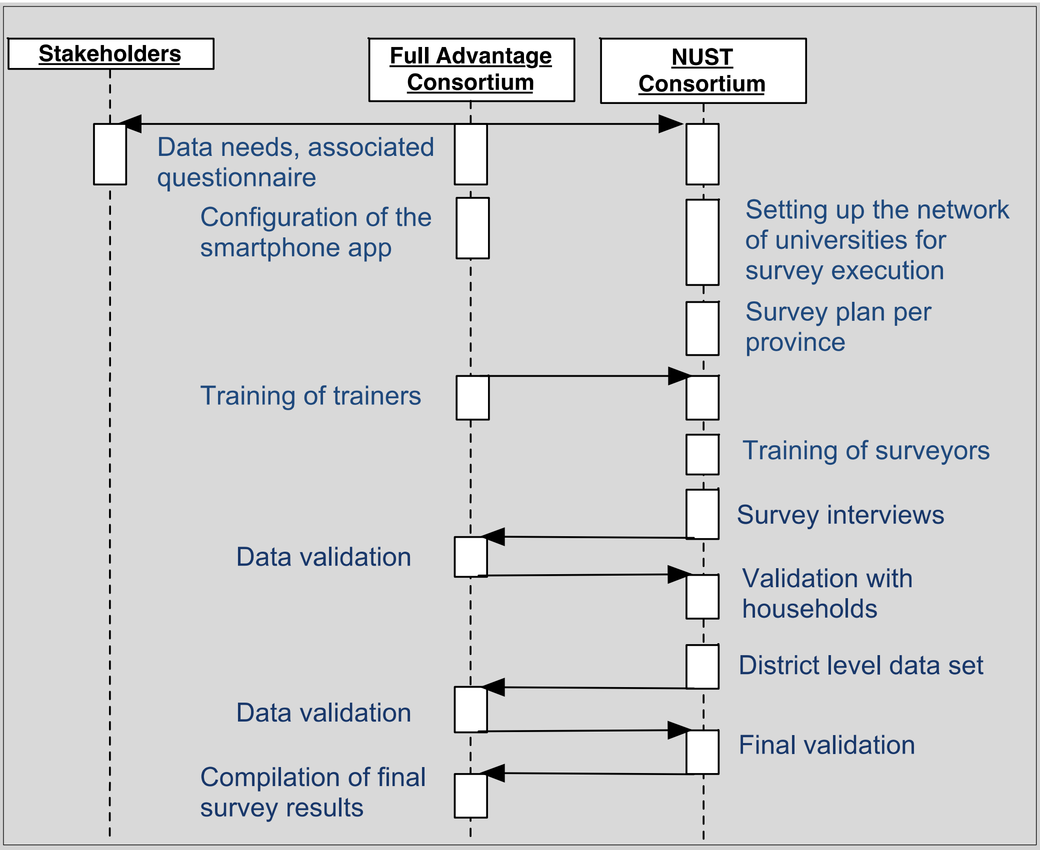

Figure 10: Procedure for data validation and verification

In addition, PITCO was assigned to be responsible for the monitoring, evaluation and verification of the surveys carried out by NUST. PITCO systematically reviewed the consolidated field survey data collected by NUST and counterchecked them through telephone calls to surveyed farmers. A report on monitoring and evaluation (M&E) of crop biomass survey was developed by PITCO.

A total of 12,450 farmers in 166 tehsils of 44 districts were interviewed on their cropping patterns, obtained yields, crop residue utilization patterns, and attitudes towards commercial crop residue supply chains. The sample size of 44 districts out of 123 districts was selected based on secondary data from the agriculture department for crop rich areas in rain fed and canal irrigated regions. The farmers were questioned about cultivated crops in the year of 2014-2015. Small holders were not surveyed in this study; all of the farmers interviewed were cultivating on commercial scale, representing both farmers with under 25 acres and over 25 acres of land. The number of surveyed districts and tehsils and the number of farmers interviewed in each province are presented in Table 22.

Table 22: Number of districts, tehsils and farmers surveyed

Name of province	Number of districts surveyed	Number of tehsils surveyed	Number of farmers interviewed
Punjab	18	62	4,650
Sindh	13	67	5,025
KPK	9	26	1,950
Baluchistan	4	11	825
Total	**44**	**166**	**12,450**

The detailed results of the crop biomass field survey and its M&E report were presented in the Implementation Report which is available at *https://esmap.org/RE_Mapping_Pakistan*.

1.4 Industrial survey

PITCO was assigned to carry out the industrial biomass survey (including MSW landfills, dairy farms, and power plants). The purpose of this activity was to survey industrial sites producing biomass residues (such as sugar mills, rice mills, wood processing factories, dairy farms and MSW landfills) or utilizing biomass feedstock for energy generation (such as textile mills, cement factories, pulp and paper mills, etc.)

The industrial biomass survey and data collection were conducted through various means:

- Survey questionnaires sent via emails, followed up by phone calls;
- Site visits; and
- Internet research on publicly available information.

A total of 587 industries and associations were contacted; however, only 178 datasets (around 30%) were collected through emails (8), follow-up phone calls (71), site visits (91) and from publicly available data sources (8). Table 23 summarizes the number of datasets collected from each industry and their sources.

Table 23: Summary of data collection sources

Industry	Total datasets collected	Sources of data			
		Emails	Follow-up calls	Site visits	Publicly available information
Textile	21	1	9	8	3
Rice mills	66	1	31	34	0
Cement	6	3	0	1	2
MSW landfills	11	0	1	10	0
Power plants	12	0	0	10	2

Sugar mills	35	0	26	9	0
Dairy farms	5	2	1	2	0
Food processing	3	0	0	3	0
Paper and pulp	4	1	0	2	1
Wood processing	3	0	1	2	0
Associations	12	0	2	10	0
Total	**178**	**8**	**71**	**91**	**8**

The obtained data were processed and validated with the persons who provided the data. A database consisting of validated datasets was created for mapping purpose. It contains:

- All 84 sugar mills in Pakistan (in addition to 35 surveyed sugar mills, the datasets for the remaining 49 sugar mills were created by interpolating the data of these 35 sugar mills and based on the list of sugar mills with their milling capacities provided by PSMA);
- 54 rice mills (the datasets of the remaining 12 surveyed rice mills were incomplete, especially the information on the estimation of rice husk production);
- 12 MSW landfills (in addition to 11 landfills included in the industrial survey, PITCO collected the data for 5 more landfills in the major cities of Pakistan. However, only 12 of 16 these landfills provided adequate data for the analysis);
- 3 dairy farms (the datasets of the remaining 2 surveyed dairy farms were incomplete, i.e., no information on the amount of manure collected).

The detailed results of the industrial biomass survey were reported in the Implementation Report which is available at *https://esmap.org/RE_Mapping_Pakistan*.

1.5 Satellite image analysis

The purpose of the satellite image analysis was to produce a land use classification for the whole country. Together with the crop yield and residue information collected during the field survey, the land use classification forms the basis for estimating the localized biomass feedstock potential.

The first step in the satellite image analysis was gathering the satellite images. The images used were Landsat 8 images with 30 m x 30 m ground resolution. In order to be able to do a per cropping season crop level classification, seven image datasets covering the area to be analyzed within Pakistan and distributed over one year were used. Figure 11 shows the coverage of the analyzed 43 Landsat 8 image tiles over the map of Pakistan. Table 17 lists the different image sets covering the Kharif and Rabi cropping seasons in Pakistan for one year. As a rule, images presenting the least cloud cover within the specified time frame were selected for analysis, however for each Landsat path, the images taken during the same day were used. In total 301 Landsat 8 images were used in the crop level land use classification.

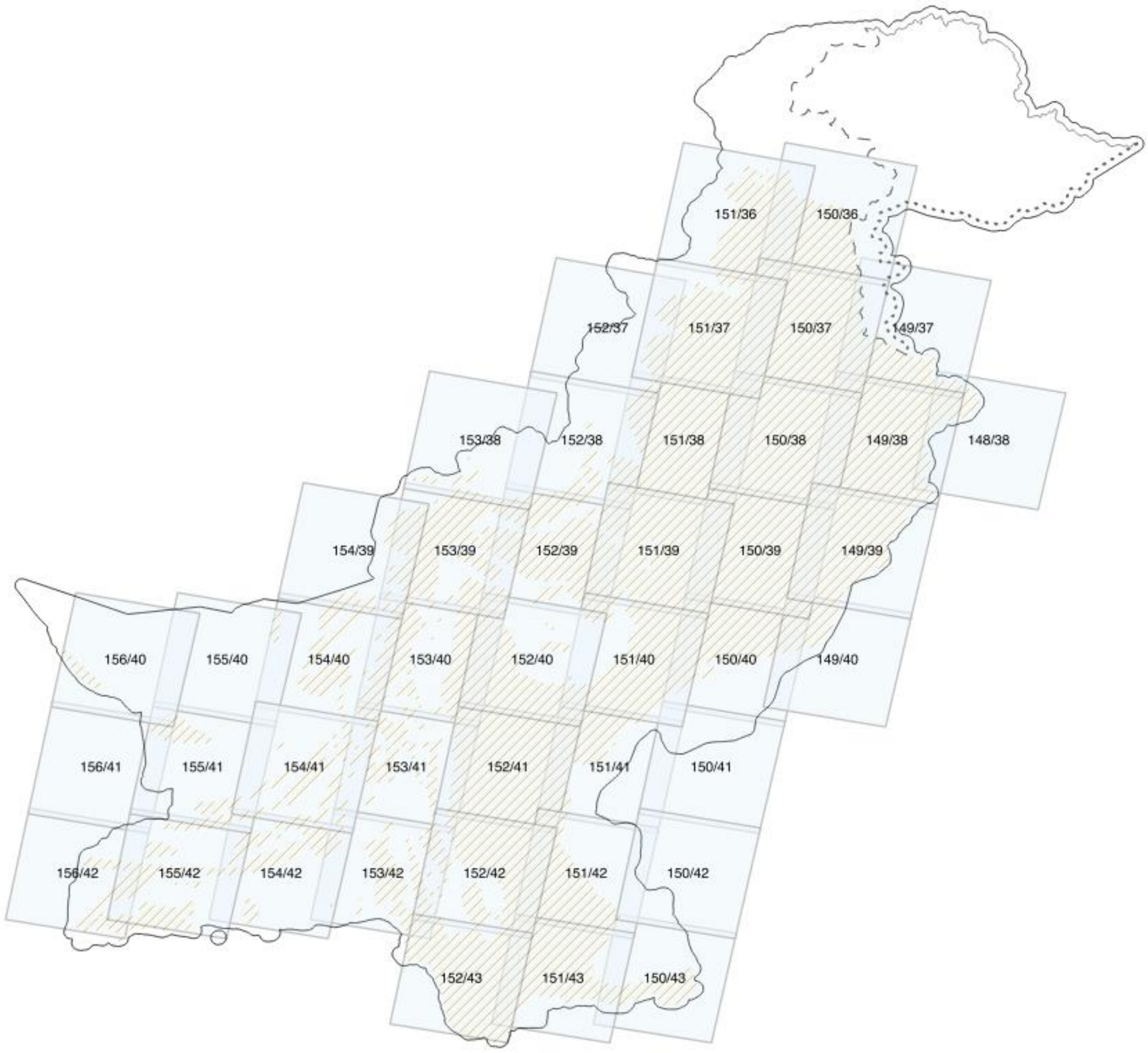

Figure 11: Landsat 8 image tiles used in the analysis

Note: The numbering relates to the global path and row grid of the Landsat data. Orange line hatching indicates the analysis area for land use classification

Table 24: The date ranges for Landsat 8 image sets used in land use classification

Set 1	2014-04-01	2014-05-06
Set 2	2014-05-14	2014-06-02
Set 3	2014-06-04	2014-06-29
Set 4	2014-09-08	2014-09-29
Set 5	2014-10-03	2014-10-22
Set 6	2014-11-11	2014-11-25
Set 7	2015-03-08	2015-04-22

The satellite image processing consisted of 9 stages described below.

1. ***Image unpacking:*** the unpacking stage extracts the satellite image data and its metadata from the distribution archive downloaded from USGS Earth Explorer. This was executed with the pre-processing software Envimon by VTT Technical Research Centre of Finland.

2. ***Cloud masking:*** a cloud mask for each of the satellite images was created by combining the cloud mask produced with the Fmask software with manual delineation of clouds, cloud shadows

and haze. Usually the Fmask produced mask was augmented with the manual mask, but in some cases the quality of the automatically created mask was so poor that it was replaced completely with the mask created with visual analysis of the images.

3. ***Analysis area masking:*** To allow better classification accuracy for agricultural land use an analysis area mask was created based on visual interpretation of the satellite images. The purpose of this mask is to target the land cover classification to the areas that are of interest to the task at hand, i.e. to the areas used for agricultural production. This mask is also shown in Figure 11.

4. ***Radiometric correction:*** images taken at different times are taken under different optical conditions. Therefore, their radiometry, i.e. how the reflectance of sun radiation at different wavelengths is recorded by the sensors in the satellite must be calibrated so that similar pieces of land have similar reflectance values on different images. This radiometric correction was done in two steps. First, a "within path calibration" was done by selecting a reference image for each Landsat path (see Figure 11 for LS8 path/row numbering) for each image set, and calibrating other images to it based on common pixels, not covered by the cloud mask, between image pairs. In the second step, after within path calibration, neighboring image paths were again calibrated with each other using common pixels.

5. ***Image and mask mosaicking:*** Once the radiometry of all individual images was calibrated, the images were mosaicked, i.e. "stitched" together into a one seamless image covering the whole analysis area. The same procedure was executed for the cloud and analysis masks, so that at the end a single mask showed areas that had clear pixels on the area of interest.

6. ***Ground reference data processing:*** Individual field observations recorded with the MHG Mobile software during the field survey (see above) were processed into "per cropping season reference observations" (geographic coordinates for the observation, cultivated crop). A separate quality control was executed at this stage selecting only those samples that clearly represented a field pixel. This brought the field reference sample size to 3,161 out of which 80% were used for classification, and 20% for the classification result validation. Additionally, 2,705 reference samples for the other than agricultural land use classes were generated using very high resolution imagery available online. Random image samples, covering roughly 300 m x 300 m at 50 cm pixel resolution, were generated. On each of these, a clear sample of one of the other land use classes; natural vegetation, urban area, road, water; was assigned to a point location using visual interpretation of the image content.

7. ***Pixel to effective field area sampling:*** At 30 m spatial resolution, many of the Landsat image pixels are "mixels", i.e. pixels that actually cover several land use classes on the ground. To estimate the effect this has on the final field area results, 49 random sample images were generated using the same very high resolution visual imagery as in the previous step. The Landsat pixel borders were then imposed on these sample images, and the fields digitized as polygon geometries. By comparing the digitized field area in the sample images and the field area based on classified Landsat pixels, a conversion factor 0.9 was defined to derive the real field area from the classification result. This conversion factor assumes a perfect classification, i.e. all pixels covered by more than 50% of field are classified as field pixels. An example of this process is given in Figure 12.

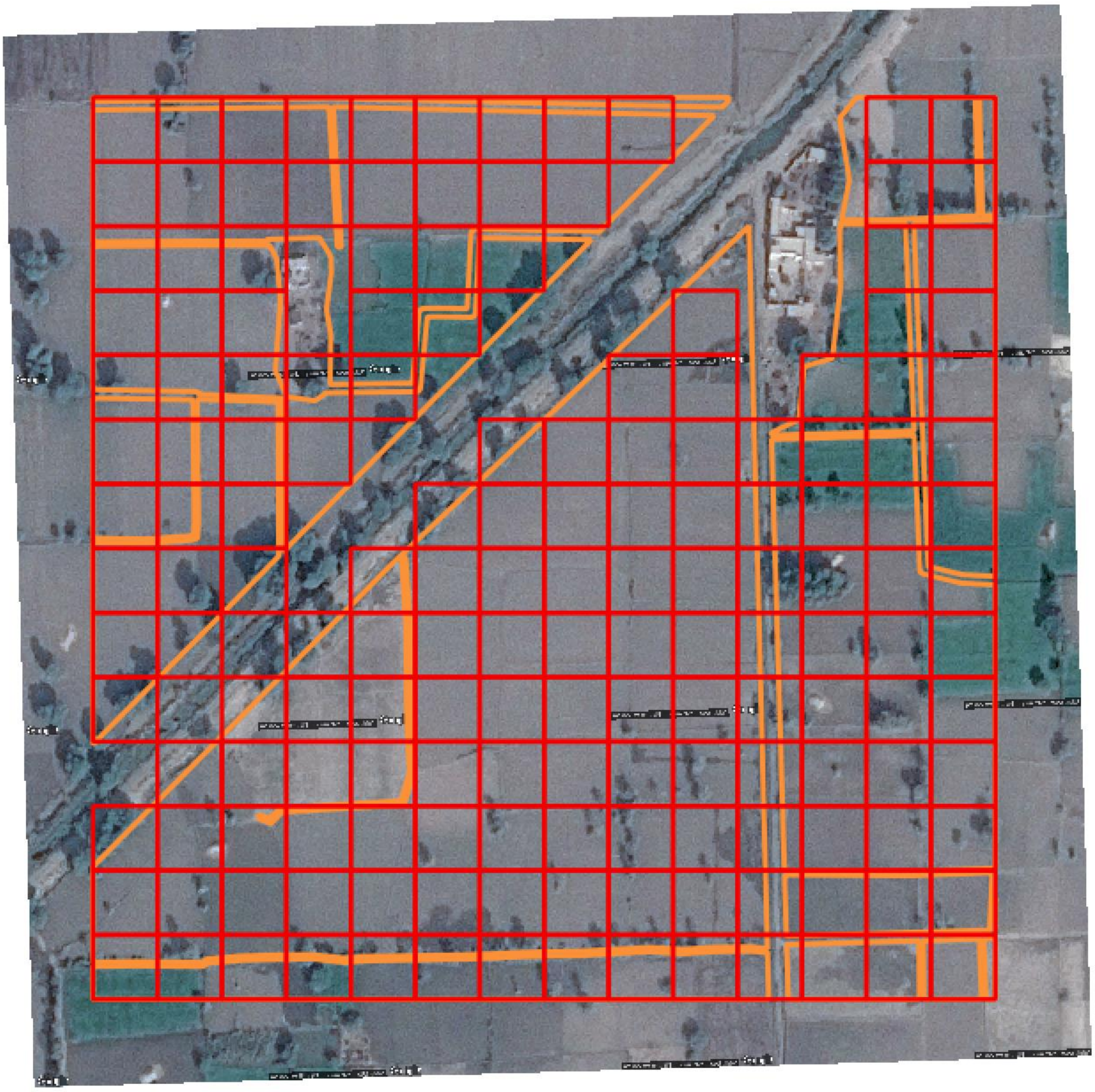

Figure 12: Effective field area sample

(Note: red cells are the perfectly classified Landsat image field pixels, and the polygons with orange borders are the fields digitized on this sample)

8. ***Agricultural statistics data collection:*** two sources were used to collect crop production statistics at district level; the "Crops Area and Production (By Districts) (1981-82 to 2008-09), Volume I, Food and Cash Crops" publication by Government of Pakistan Statistics Division Federal Bureau of Statistics (Economic Wing) Islamabad, and an online source http://www.amis.pk/Agristatistics/DistrictWise/2010-2012/2010-2012.aspx. The latter one, having more recent data, was used to compile the total cultivated area in each district and the share of each crop of the cultivated area.

9. ***Land cover classification:*** The seven-time series image mosaics were combined into a single layered mosaic. Blue, green, red, near-infrared and short wave infrared bands were used in this mosaic for the final land use classification. The spectral information was combined with the ground reference data using a Random Forest classifier. The land cover classes used in the classification were derived from the field survey information by analyzing existing pairs of Kharif-Rabi crops. These, along with the non-agricultural classes used are listed in Table 25.

Table 25: The land use classes used in the classification

Field classes (Kharif-Rabi)	Other classes
cotton-maize	bare area
cotton-other crop	low biomass
cotton-rice	medium biomass
cotton-sugarcane	high biomass
cotton-wheat	road
maize-maize	urban
maize-rice	water
maize-sugarcane	
maize-wheat	
other crop-other crop	
rice-rice	
rice-sugarcane	
rice-wheat	
sugarcane-sugarcane	
sugarcane-wheat	
wheat-wheat	

The Random Forest classification produced 23 probabilities, matching the land use classes above, for each pixel in the analysis area. By default, the land use class having the highest probability was assigned for each pixel, leading to land use classification confusion matrix show on Figure 13. The confusion matrix is created with the 20% of field samples reserved for classification validation. The y-axis is for the real land use classes for the field samples, and x-axis is for the land use classes predicted using the satellite images. Each cell on a grid row shows the share of that "true" class being classified as the "predicted" class indicated by the grid cell column. Thus, if the classification were 100% accurate, there would be just a dark blue diagonal line in the confusion matrix, with 1.0 share of all class observations, and overall accuracy score of 1.0. All misclassifications add blue hues to the off-diagonal cells in the confusion matrix.

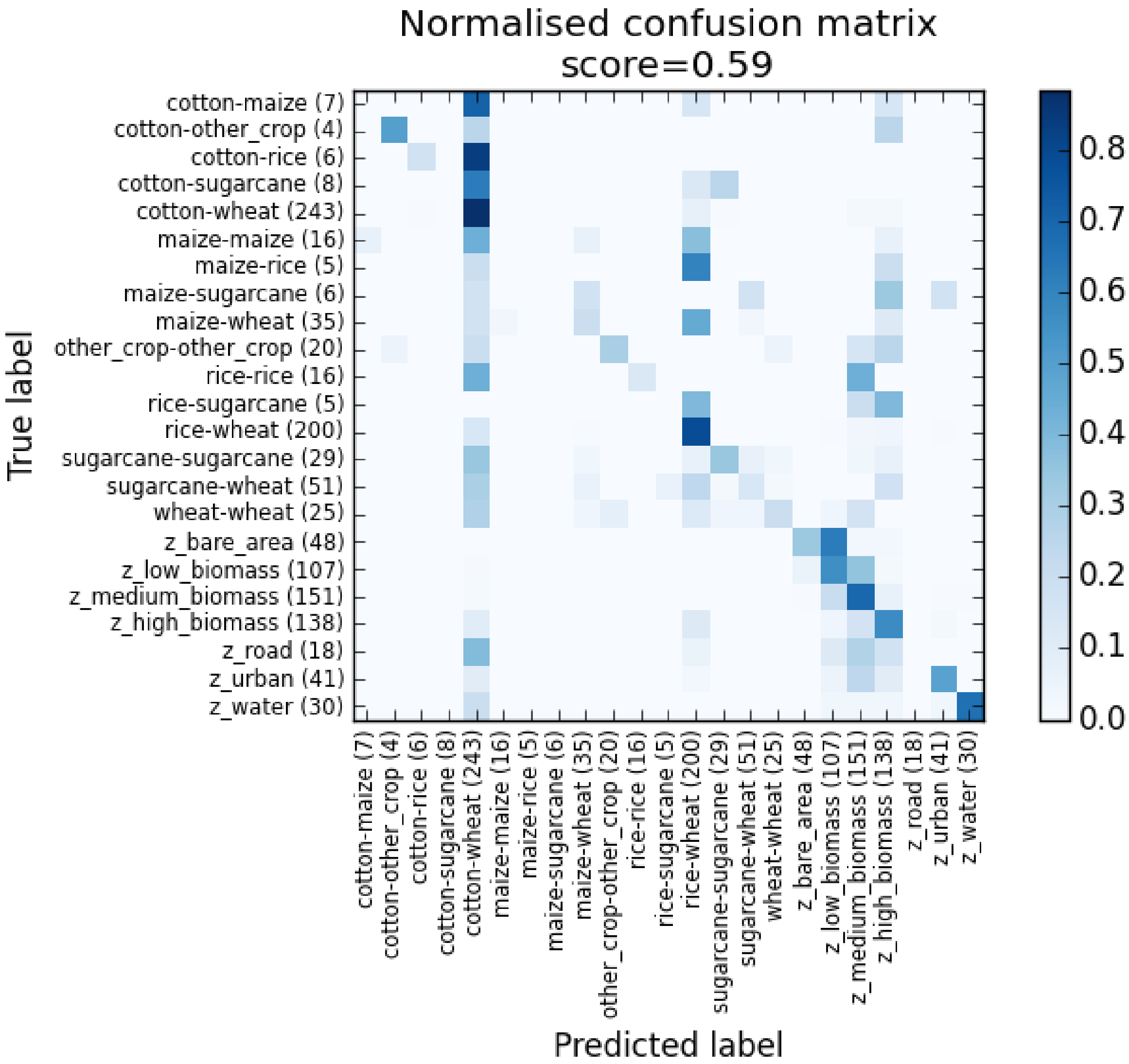

Figure 13: Land use classification confusion matrix based on satellite image information only

Overall the classification based on assigning the land use class having the highest probability for each pixel in the satellite image mosaic covering Pakistan works well in separating agricultural land and other land uses. There is a considerable amount of crop misclassification for the agricultural land (Figure 14). The most dominant crop classes are over-presented in the land use predictions, and the more infrequent classes are un-presented. This is a common feature in satellite image based classification.

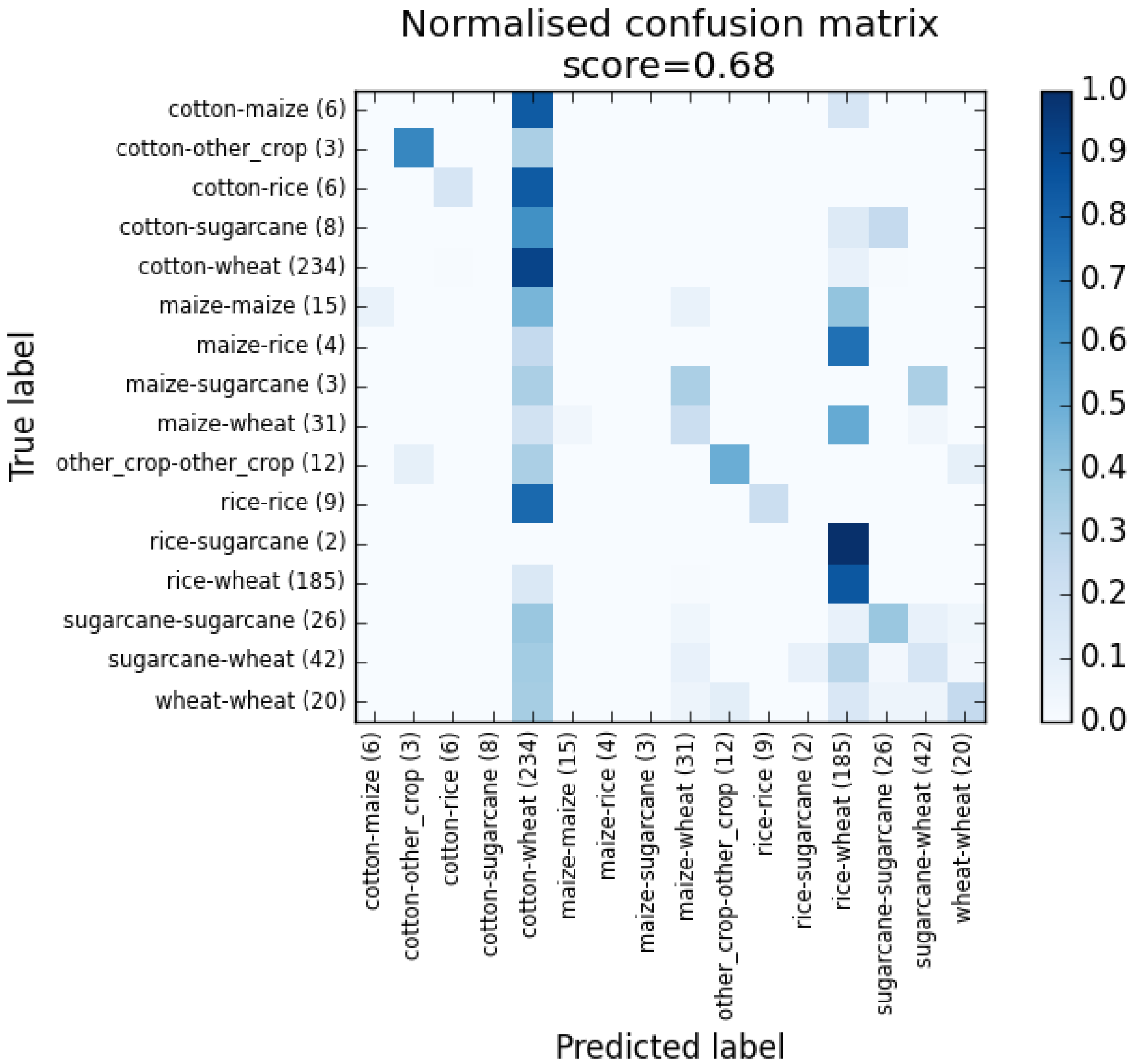

Figure 14: Land use classification confusion matrix for crop classes only, taking only the satellite image information into account

While the confusion matrix indicates good accuracy for agricultural - other use classification, comparison to agricultural statistics shows a discrepancy of having considerably higher amount of agricultural land for the whole country than what is reported in the statistics. Due to this and the "between crops" mixing the classification result was further modified from the "highest probability" result based on the agricultural statistics at district level. For each district, reallocation from field to other land use, or vice versa, was done based on the class probability distribution for the pixel and its neighborhood values. The direction and maximum extent of this reallocation was determined by the relationship between the highest probability classification result and the statistics for the district. In other words, if the statistics indicated less agricultural area for the district, and there were pixels classified as fields, but surrounded by other land use classes, and the second most probable class for the pixel was one of the other land use classes, the pixel classification was changed from the most likely to the second most probable class.

The statistics were also used in the second step of reallocation of land use classes for the pixels. This step used the share of cultivated area for each crop for the district. The land use classification based on the most probable classes was converged towards the crop shares in the statistics by reallocating one of the second to fourth probable classes to a pixel if it changed the crop shares towards the statistics.

The reallocation was done in the "most probable misclassifications first" order. The pixels that in the Random Forest results had several highly probable classes; i.e. the probabilities between the classes were close to each other; were the first candidates for the class reallocation. A minimum class probability of 10% was also used to allow a switch from the most probable class to a less probable class.

The resulting confusion matrix from this land use class reallocation based on the agricultural statistics is shown on Figure 15. There is a notable increase in field to other biomass class misclassification. The low, medium and high biomass classes (in the figure having a z_-prefix) represent either natural vegetation or woody biomass cultivation areas (orchards and tree plantations) in the reference data used for validation. Therefore, it seems there is a clear discrepancy between the satellite image information and the statistics agricultural area information. However, since the validation data was collected using the same method as the actual classification modeling data, it is possible that there is bias in the confusion matrix results. This could be the case if the field reference data fails to cover the full land use class variation in Pakistan.

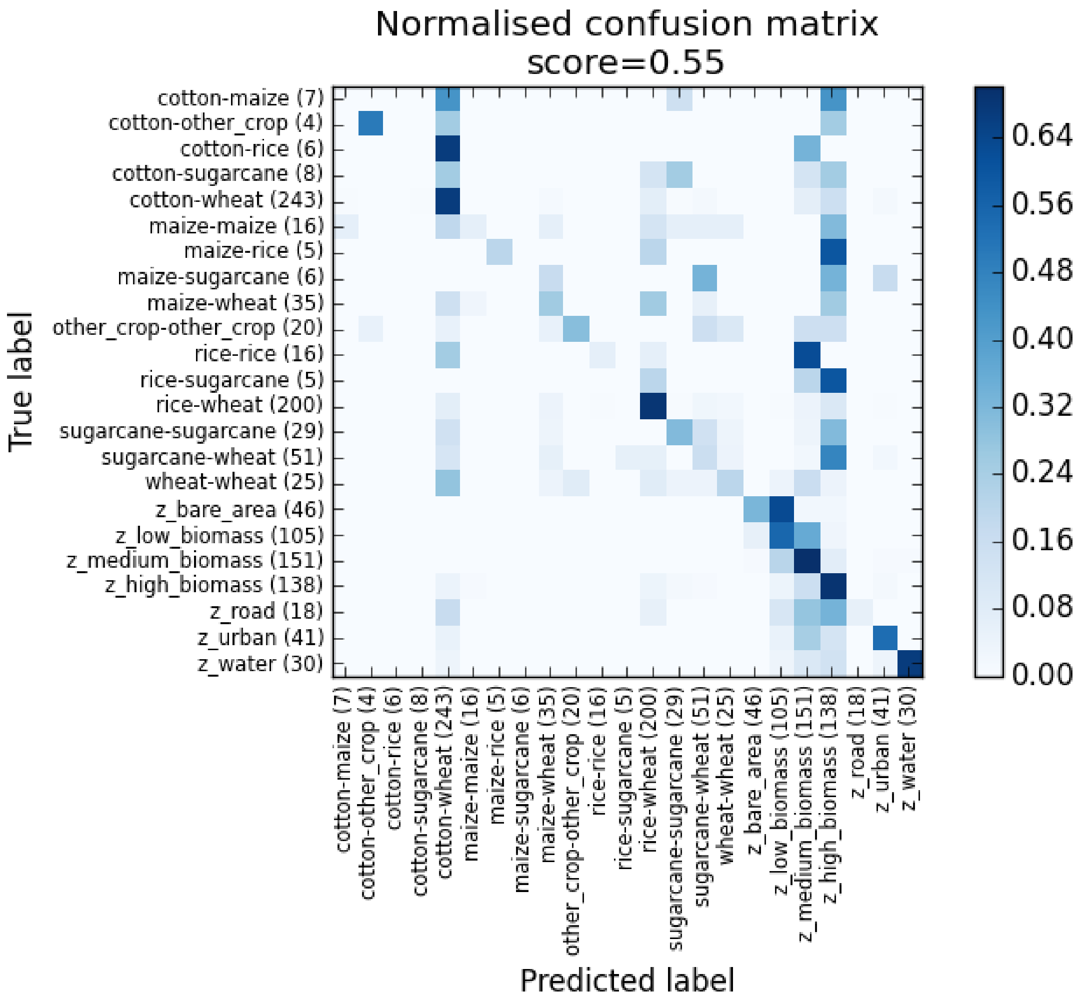

Figure 15: Land use classification confusion matrix taking agricultural statistics data into account

The classification accuracy within the crop classes only is shown in Figure 16. While the overall accuracy score is the same with and without introducing the district level crop shares from the statistics, the classification accuracy has improved for the non-dominant classes (especially maize) at single pixel level.

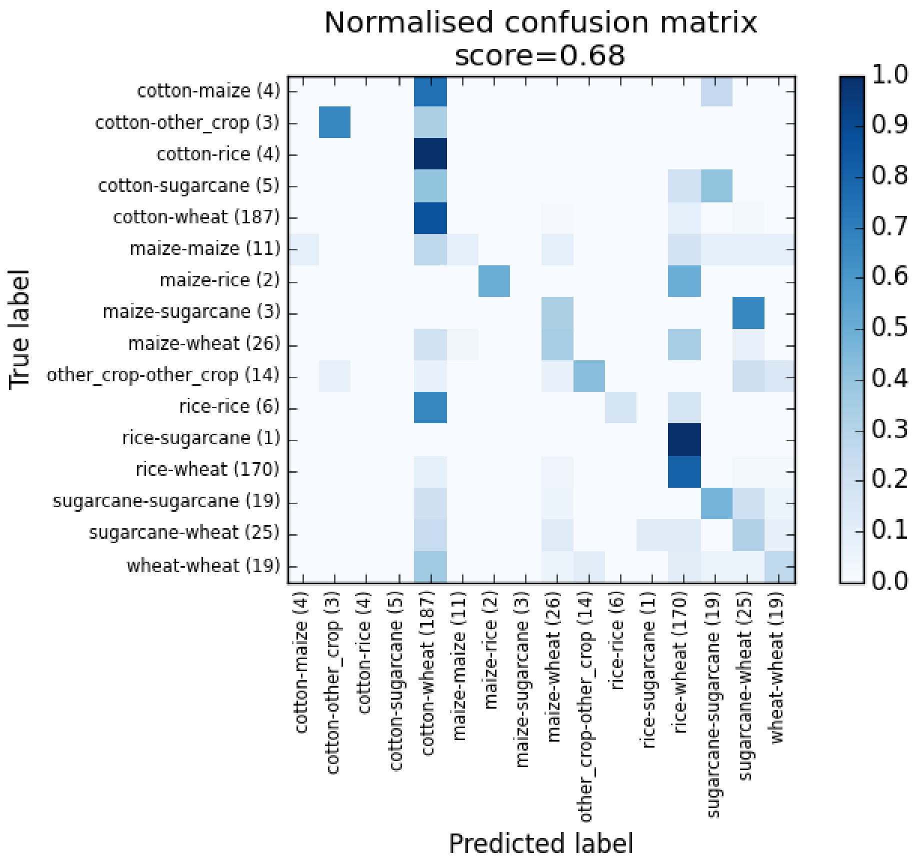

Figure 16: Land use classification confusion matrix for crop classes only, taking both satellite image information and agricultural statistics into account

The final results are based on the land use classification that takes the agricultural statistics information into account. It should also be noted that a feature of satellite image classification is that the accuracy of the results improves when the pixel level results are aggregated into larger units. In this project the 30 m x 30 m classification result was not used directly but was rather aggregated to 990 m x 990 m level first.

1.6 Biomass feedstock potential modeling of the Biomass Atlas

The first step in modeling the biomass feedstock potential was the processing of field survey data into district-level average crop yields and availability values per each feedstock class. This processing included the calculation of district-level averages of crop yields from the field survey and generation of the maps for feedstock average yields and feedstock availability using the district polygons. As part of the districts had missing values for some of the feedstock classes, the missing values were substituted with province-level averages. The RCRs (Residue to Crop Ratios) from Table 2[6] were used for calculating the theoretical potential of the crop residues from the crop production figures. As described in chapter 4, the technical potential of the crop residues was estimated based on the field residue utilization data from the survey as well as the farmers' willingness to participate in a feedstock supply chain.

In the second step, the district-level average yield and availability information was combined with the land use raster to get a feedstock availability raster. The satellite image analysis yielded a 30 m x 30 m land use class map for the analyzed areas in Pakistan. For practical purposes this is at too high detail level and therefore the land use classification was aggregated to 990 m x 990 m pixel size. At the same time a reclassification was made. In the aggregated classification only the crop classes are used and the classification is split into Kharif and Rabi classifications; i.e. each class in the two resulting datasets represent just one crop. The aggregation from the 30 x 30 land use raster to the 990 x 990 aggregated feedstock raster was done in a following way for each feedstock class:

1. Get the average yield and availability (tons per ha) for the feedstock class inside the current 990 m x 990 m window.
2. Get the number of 30 m x 30 m cells that represent the current feedstock class and calculate the total amount of available feedstock inside the window (tons).
3. Store that value to the correct feedstock band in the aggregated feedstock raster.

The third step consisted of preprocessing road network line geometries into district-level road network density values and calculation of whole country-level distance raster to the nearest grid power station using the grid station point geometries.

The fourth step consisted of computing sourcing distance raster for the different combinations of power plant technologies and capacities. The sourcing distance raster was computed using the aggregated feedstock availability raster as input. The sourcing distance raster was generated for each power plant technology and capacity combination separately. For each raster cell (x, y) in the sourcing distance raster, the minimum sourcing area that can provide enough biomass feedstock for running the power plant was computed. The algorithm calculated the available feedstock amount inside a window with radius r around each raster cell x, y. The sourcing radius was computed iteratively by incrementing the radius r until the required feedstock amount was achieved, or until r exceeded maximum sourcing distance limit.

In the fifth, and final step, the sourcing distance raster was combined with the road network average density raster and the distance to nearest grid power station raster in order to produce a bioenergy site suitability indicator map for different types of power plant technology and capacity combinations. Each of the components of the model (sourcing distance raster, road network density and distance to nearest grid power station) was given weights and the resulting raster was scaled to [0, 100] where 0 value indicates no potential for a biomass-based energy generating plant and 100 indicates high potential. The weights used were 60 % for feedstock procurement distance, 30 % for grid power station distance, and 10 % for road network density. These were based on the feedback at the Validation Workshop organized in Islamabad in Nov 2015.

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[6] *Source 1: GIZ 2013, Report on Biomass Potential Resource Assessment and Feedstock Preparation, prepared by the Alternative Energy Solution Providers (Pakistan)*

Each step in the process of generating the site suitability maps was parameterized so that the model could be run with alternative parameters, such as different weights for the site suitability components. The processing workflow used for generation the Biomass Atlas datasets is illustrated in Figure 17. The Biomass Atlas Model was implemented with Python programming language, and is available as part of the Atlas (see Annex 3 for the instructions on using and updating of the Biomass Atlas).

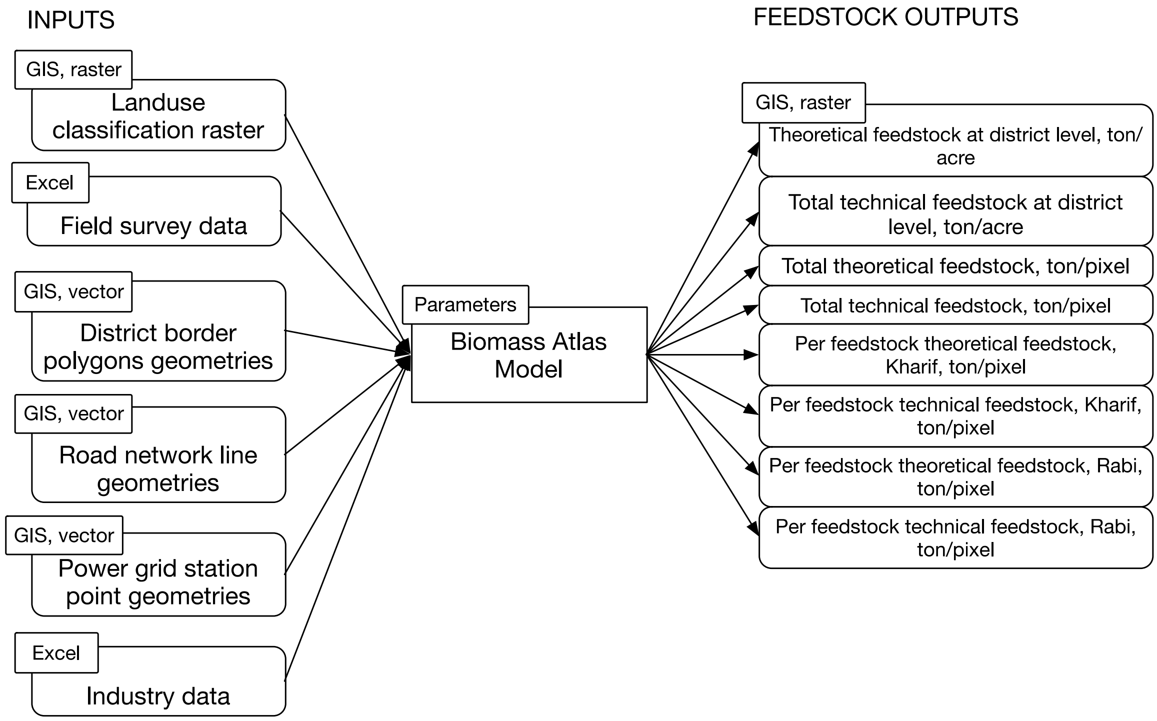


Figure 17: The processing workflow used for generating the Biomass Atlas datasets

Annex 2: Biomass Atlas Components

The Biomass Atlas consists of various maps and datasets. The links for access to these maps and datasets are provided in Tables 26 to 31.

2.1 Survey Data

Table 26: Links for access to the results of survey data

Atlas data	Can be accessed at:
GIS & other datasets:	https://energydata.info/dataset/pakistan-biomass-gis-atlas
Grid power station data	file: survey\grid_station\Gridstation.shp
Road network density	Original data downloaded from: https://www.humanitarianresponse.info/operations/pakistan/ Data aggregated to districts: file: feedstock\districts\district.shp file content description: feedstock\metadata\district.txt
District level aggregates of the field survey data	file: feedstock\districts\district.shp file content description: feedstock\metadata\district.txt
Other datasets:	
Field survey interview data	files: survey\field\

2.2 Land Use Classification

Table 27: Links for access to the results of land use classification

Atlas data	Can be accessed at:
GIS & other datasets:	https://energydata.info/dataset/pakistan-biomass-gis-atlas
Site suitability indicator	files: pakistan_land_use.ers file descriptions: metadata\land_use.txt

2.3 Biomass Feedstock Data

Table 28: Links for access to the feedstock data

Atlas data	Can be accessed at:
Map, theoretical feedstock potential	http://irena.masdar.ac.ae/?map=2636
GIS & other datasets:	https://energydata.info/dataset/pakistan-biomass-gis-atlas
Theoretical feedstock potential	files: feedstock\theoretical_feedstock_per_pixel_FALL.tif feedstock\theoretical_feedstock_per_pixel_SPRING.tif feedstock\theoretical_feedstock_per_pixel_WHOLE_YEAR.tif file content description: feedstock\metadata\feedstock.txt
Technical feedstock potential, based on existing use only	files: feedstock\technical_feedstock_per_pixel_FALL_residue.tif feedstock\technical_feedstock_per_pixel_SPRING_residue.tif feedstock\technical_feedstock_per_pixel_WHOLE_YEAR_residue.tif file content description: feedstock\metadata\feedstock.txt
Technical feedstock potential, based on existing use and farmers' willingness to sell	files: feedstock\technical_feedstock_per_pixel_FALL_willing.tif feedstock\technical_feedstock_per_pixel_SPRING_willing.tif feedstock\technical_feedstock_per_pixel_WHOLE_YEAR_willing.tif file content description: feedstock\metadata\feedstock.txt

2.4 Power Plant Analysis Data

Table 29: Links for access to the power plant analysis data

Atlas data	Can be accessed at:
GIS & other datasets:	https://energydata.info/dataset/pakistan-biomass-gis-atlas
Sugar mill analysis	file: industrial\sugar_mills\sugar_mills.shp file content description: industrial\metadata\sugar_mill.txt
Rice mill analysis	file: industrial\rice_mills\rice_mills.shp file content description: industrial\metadata\rice_mill.txt
Other datasets:	
Mill analysis results without the map data	file: industrial\Mills.xlsx
Cogeneration model the analysis results are based on, feedstock to conversion technology suitability mapping	file: industrial\Power_plant_model.xlsx

2.5 Greenfield site suitability analysis data

Table 30: Links for access to the site suitability analysis data

Atlas data	Can be accessed at:
GIS & other datasets:	https://energydata.info/dataset/pakistan-biomass-gis-atlas
Site suitability indicator	files: site_suitability\heatmap_combined_MIXED.tif site_suitability\heatmap_combined_SINGLE.tif site_suitability\heatmap_gs_distance.tif site_suitability\heatmap_r_mixed.tif site_suitability\heatmap_r_single.tif site_suitability\heatmap_rn_density.tif file descriptions: site_suitability\metadata\site_suitability.txt

2.6 Biomass Atlas model and training data

Table 31: Links for access to the Biomass Atlas training data

Atlas data	Can be accessed at:
GIS & other datasets:	https://energydata.info/dataset/pakistan-biomass-gis-atlas
Training dataset	files: training\
Biomass atlas model code	files: atlas_model\

Annex 3: Using and Updating of the Biomass Atlas

3.1 Using of the Biomass Atlas Data

<u>Set-up</u>

For these instructions you need two things, the QGIS software, and the training dataset:

Table 32: Biomass Atlas training requirements.

Requirement	Can be accessed at
QGIS	https://www.qgis.org
Training dataset	https://energydata.info/dataset/pakistan-biomass-gis-atlas in training-folder

After downloading the training dataset zip-file, unzip it and make a note of the folder where you unzipped it. This is the folder you will find the exercise data referred to below.

<u>Task 1: Power Plant Investment Feasibility for a Sugar Mill</u>

Your task is to evaluate the feasibility of switching a sugar mill's power plant into year round operation using a mixed feedstock from the current status of operating it only during the milling season, and two months after the milling season.

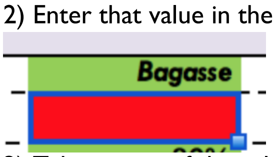
For this evaluation, you need to figure out from how far from the sugar mill you would need to source the additional feedstock for the off-season operation of the power plant.

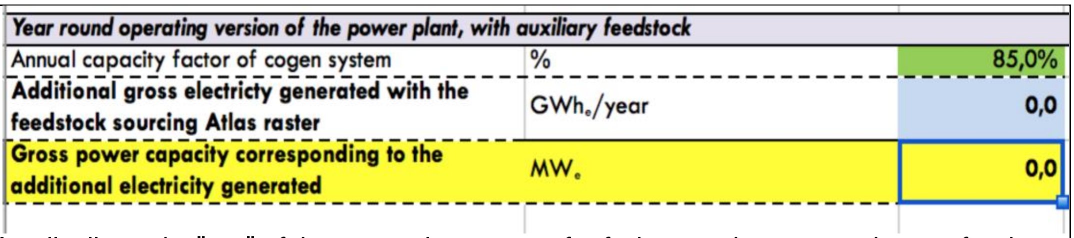
Let's use the Kohinoor Sugar Mills Ltd. as an example.

To answer this question, you need to

1. ***Find out the steam turbine size the mill can have to run it on bagasse for the milling season plus two months.***

Throughout this workshop manual, steps needed to take are documented in the tables like the one below, please follow the instructions in the tables step by step, and keep coming back to this manual for the instructions.

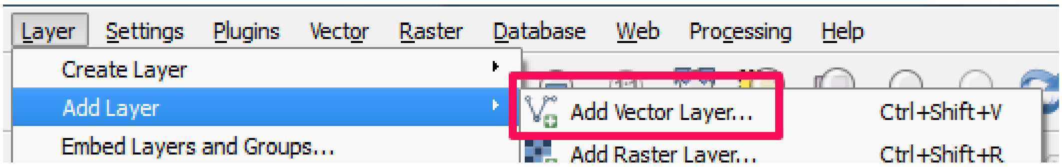
Files needed	power_plant_model.xlsx
In Excel/ OpenOffice	1) With Excel, open power_plant_model.xlsx. It is located in the folder where unzipped the workshop.zip file you downloaded above. The file is withing the workshop folder. 2) Go to the the "sugarmills" sheet. Find the yearly bagasse production for the Kohinoor Sugar Mills Ltd. mill. 2) Enter that value in the red cell in the "MW Cogen-Sugar" sheet:  3) Take a note of the value at the yellow cell at the bottom of the sheet



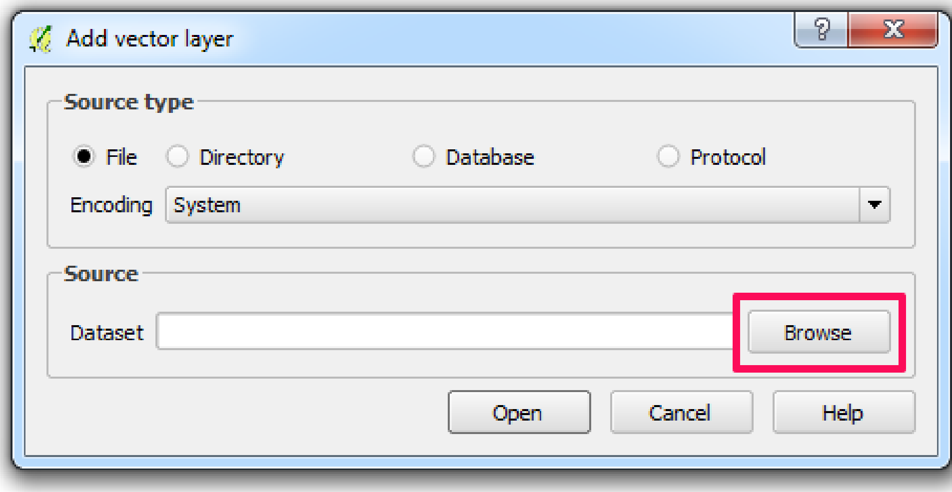
It will tell you the "size" of the power plant you use for finding out the sourcing distance for the additional feedstock needed to extend the operation of the power plant year round.

2. ***Now you need to find the Kohinoor Sugar Mill from the Atlas maps. You start by putting the sugar mills on the map in QGIS. Open up QGIS, and then:***

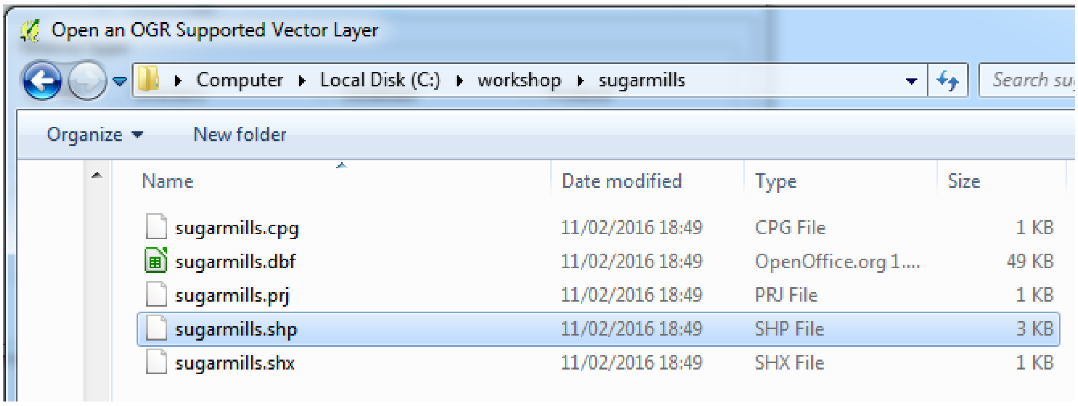
Files needed	sugarmills\sugarmills.shp districts\districts.shp
QGIS tools needed	1) Add the sugar mills as a new vector layer to QGIS Note: As the screenshots were taken on OS X, they will look different to what you see on Windows.



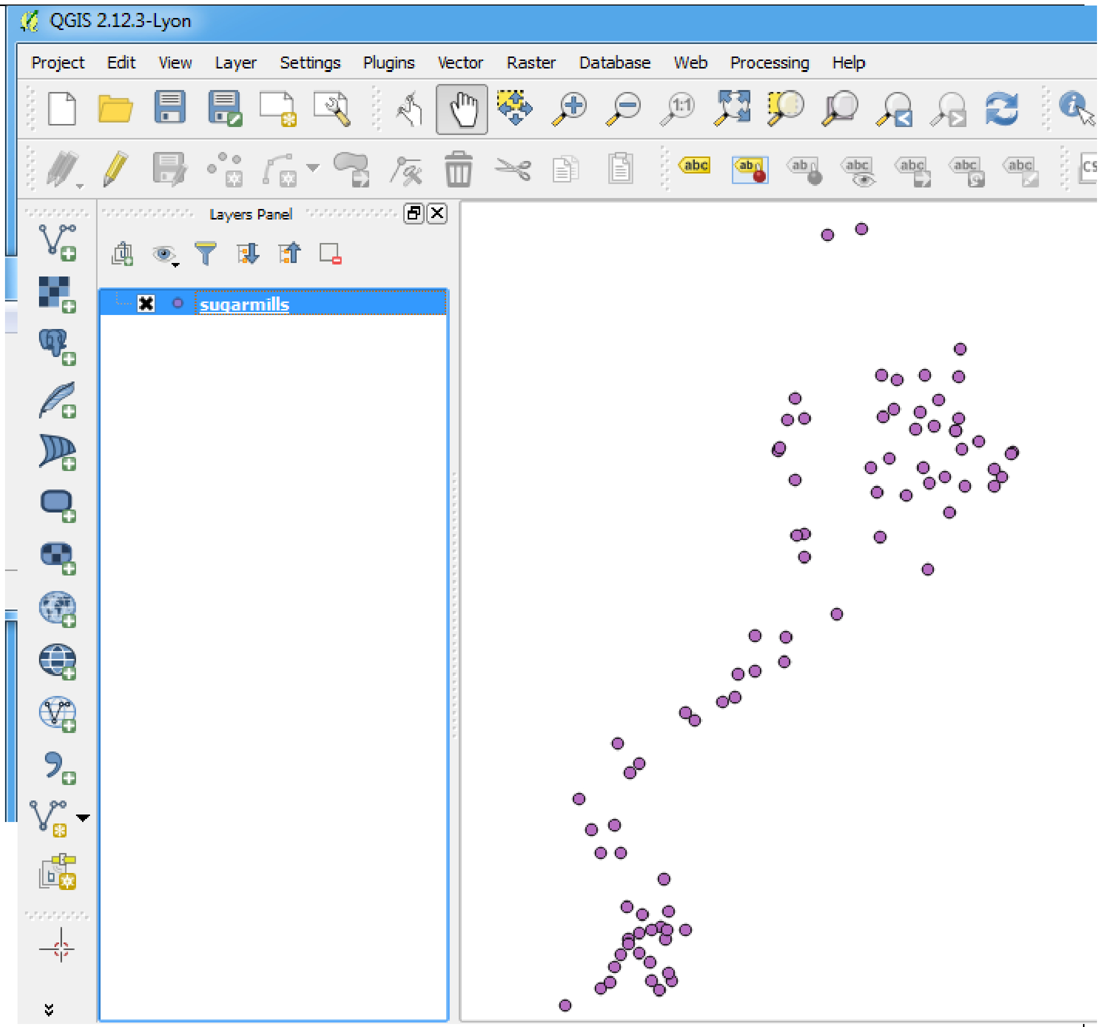
=>



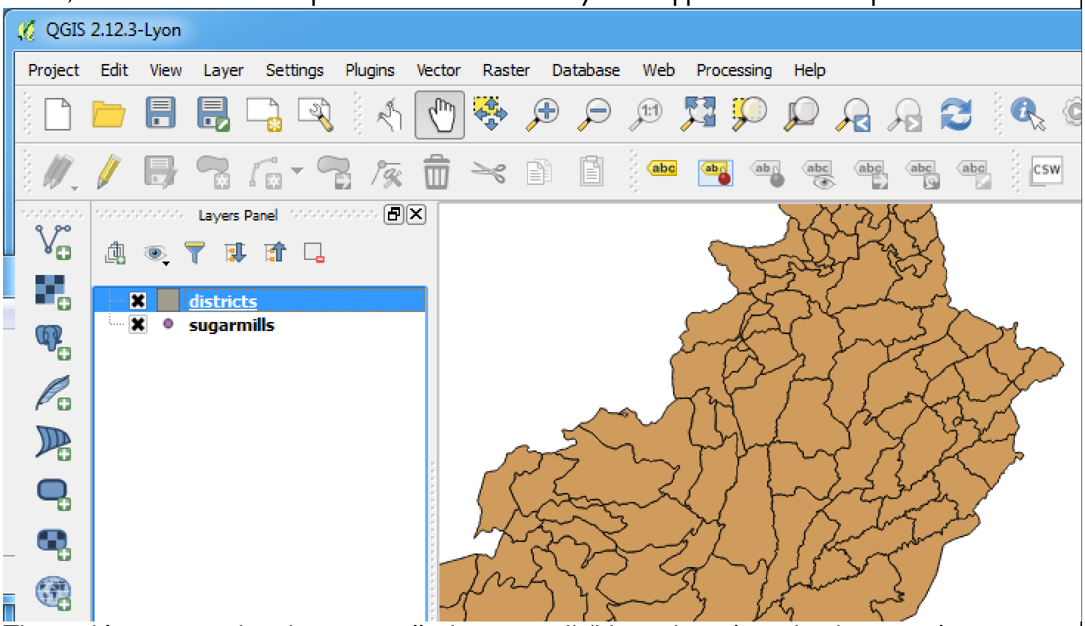
=>



=>

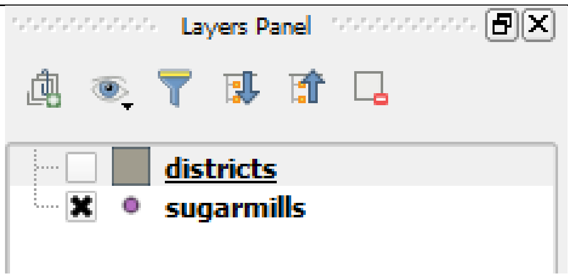


2) To add some context to the map, add another new vector layer to QGIS. Repeat the steps above, and select districts.shp from the folder where you unzipped the workshop data.

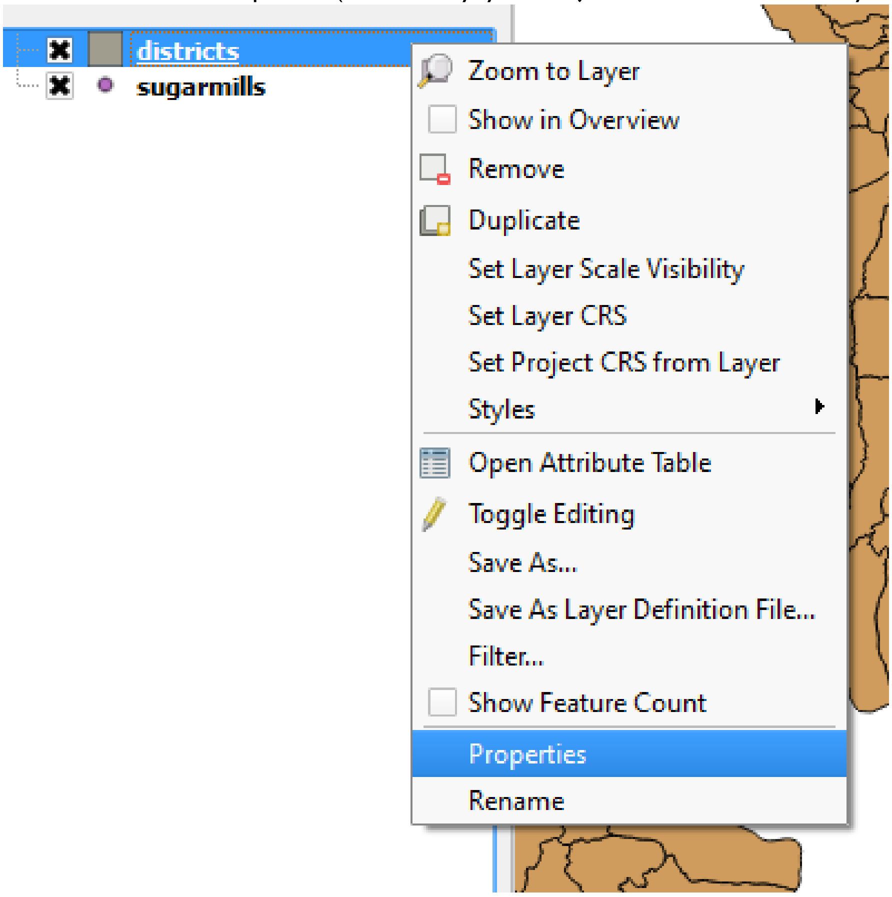


The problem now is that the sugar mills disappeared! (Note: the colour the district polygons have, will be random)

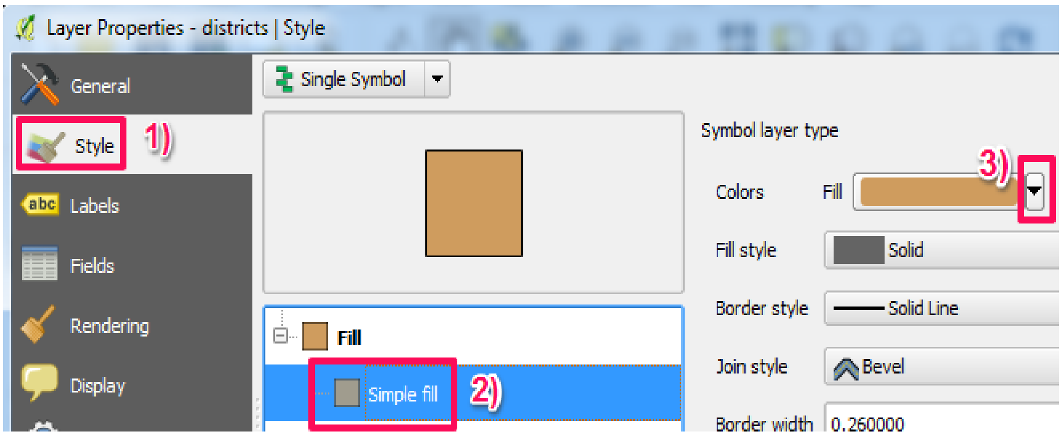
You can make the districts disappear too, by unchecking the checkbox in front of them in the "Layers Panel" list:



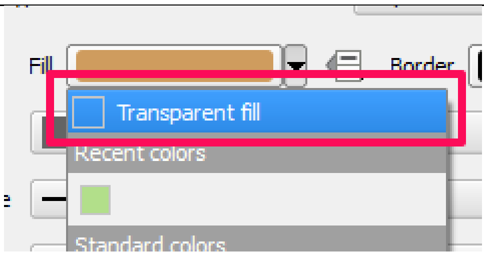
3) But let's make the district polygons transparent, so that we can see both the location of the sugar mills and the district borders on the map. Right-click on the districts layer in the "Layer Panel", and choose Properties (alternatively, you can just double click on the layer name)

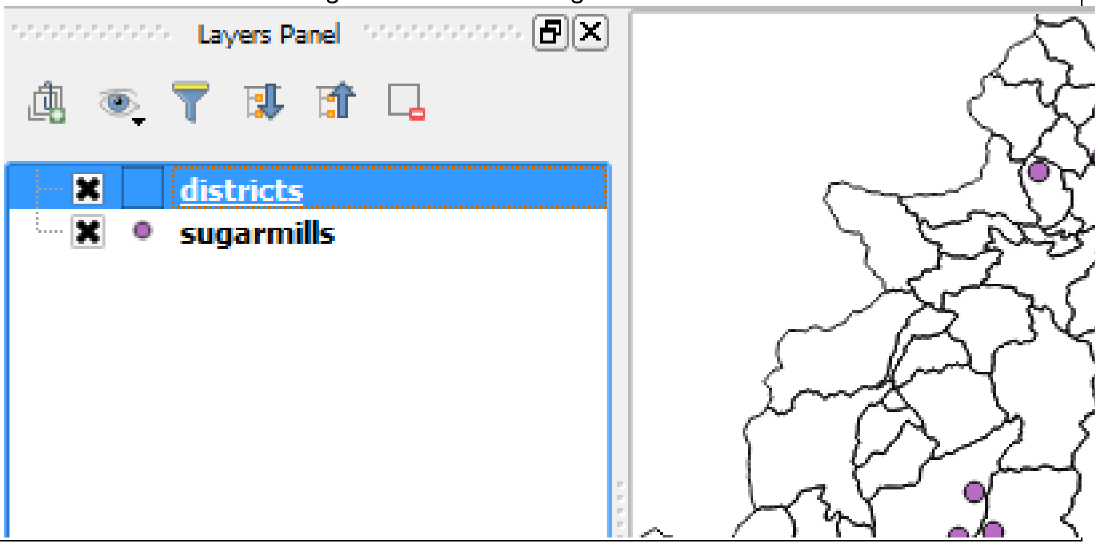


=>

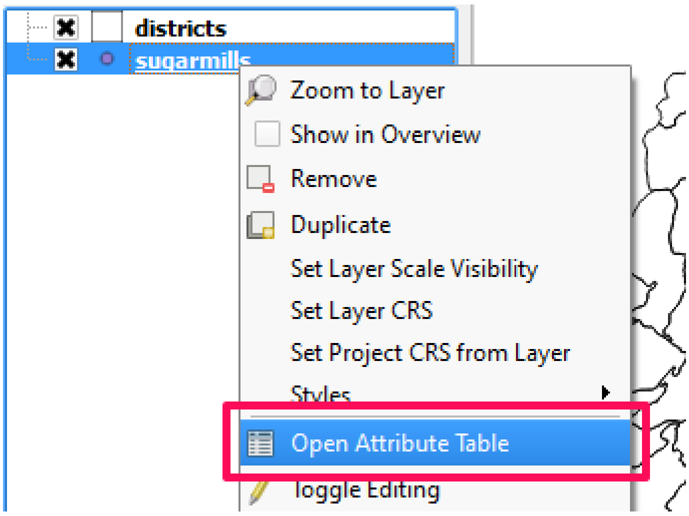


=>

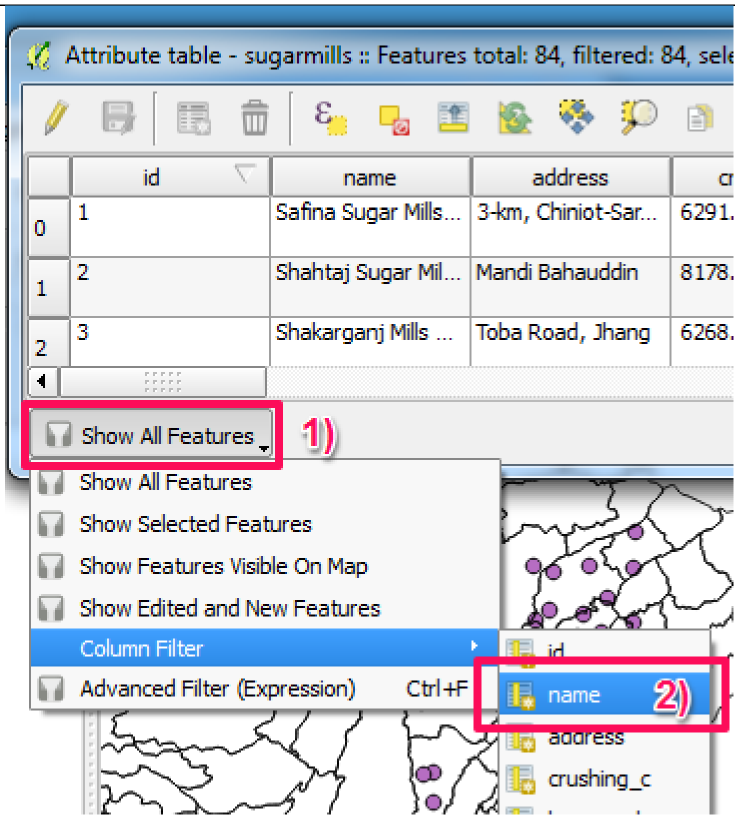
<table>
<tr><td></td><td>

=> Click OK at the bottom right corner of the dialog

</td></tr>
</table>

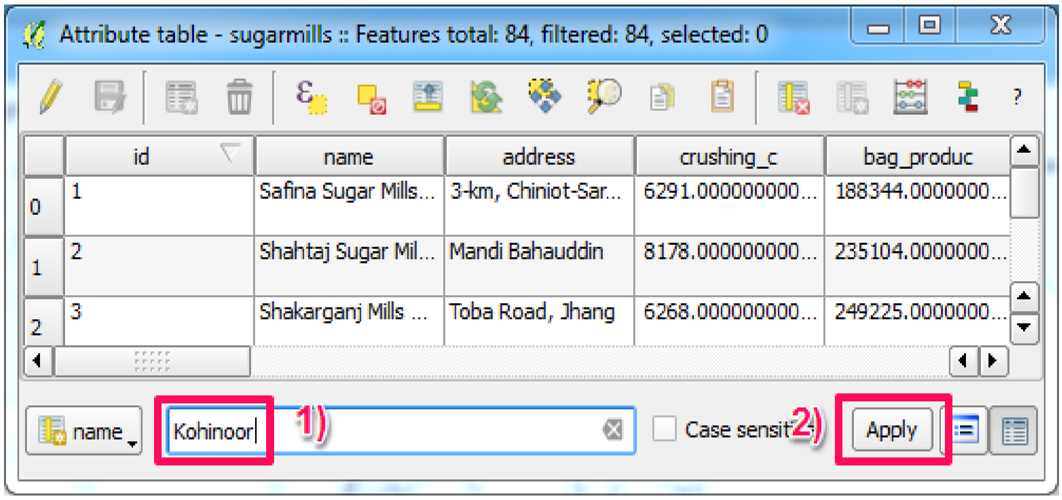
3. *Find the Kohinoor Sugar Mills site in QGIS.*

<table>
<tr><td>QGIS tools needed</td><td>1) Open up the attribute table for the sugarmills layer. Right click on the layer name in the Layer Panel:


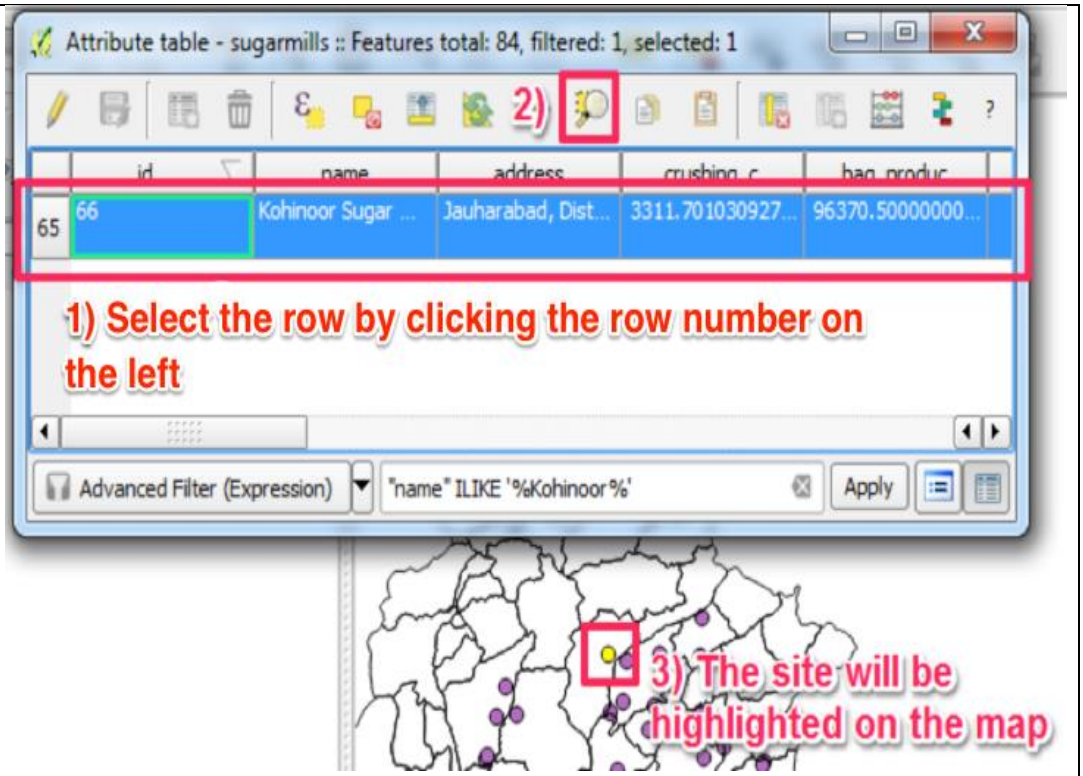
=></td></tr>
</table>


Attribute table - sugarmills :: Features total: 84, filtered: 84, sele
id
name
address
1
Safina Sugar Mills...
3-km, Chiniot-Sar...
6291.
2
Shahtaj Sugar Mil...
Mandi Bahauddin
8178.
3
Shakarganj Mills ...
Toba Road, Jhang
6268.
Show All Features
1)
Show All Features
Show Selected Features
Show Features Visible On Map
Show Edited and New Features
Column Filter
Advanced Filter (Expression)
Ctrl+F
id
name
2)
address
crushing_c

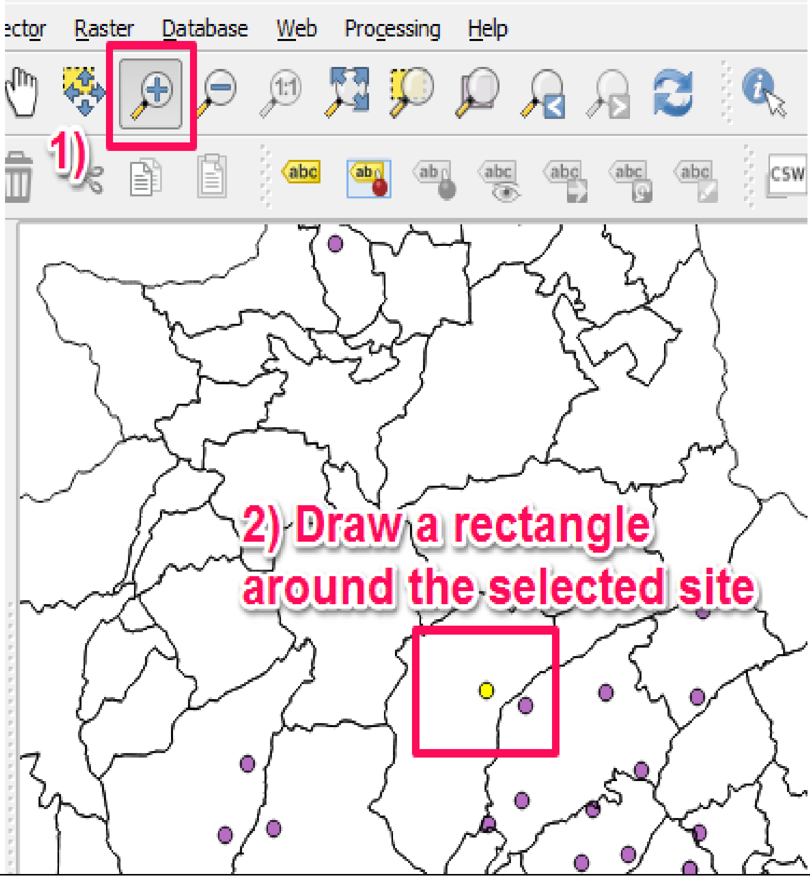
=>


Attribute table - sugarmills :: Features total: 84, filtered: 84, selected: 0
id
name
address
crushing_c
bag_produc
1
Safina Sugar Mills...
3-km, Chiniot-Sar...
6291.000000000...
188344.0000000...
2
Shahtaj Sugar Mil...
Mandi Bahauddin
8178.000000000...
235104.0000000...
3
Shakarganj Mills ...
Toba Road, Jhang
6268.000000000...
249225.0000000...
name
Kohinoor
1)
Case sensit
2)
Apply

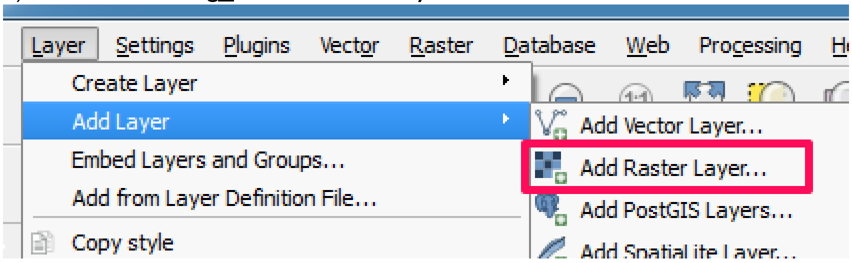
=>

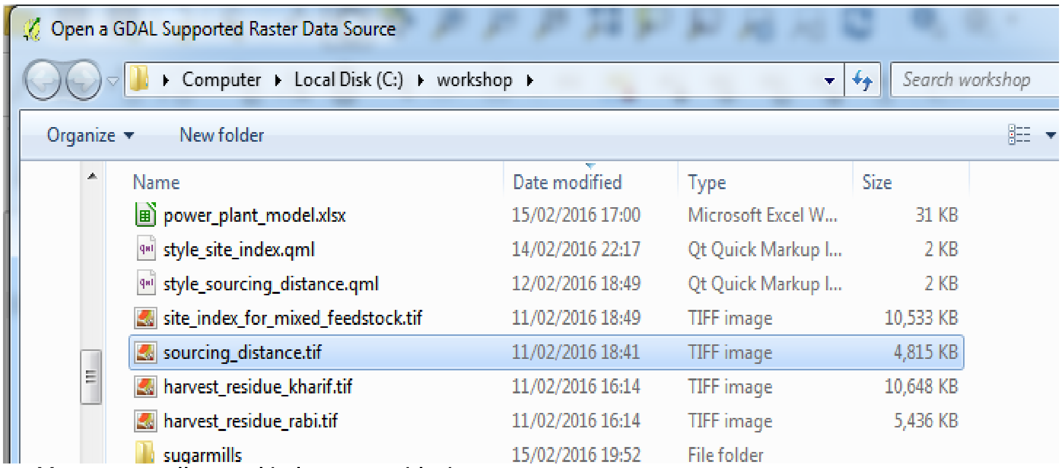


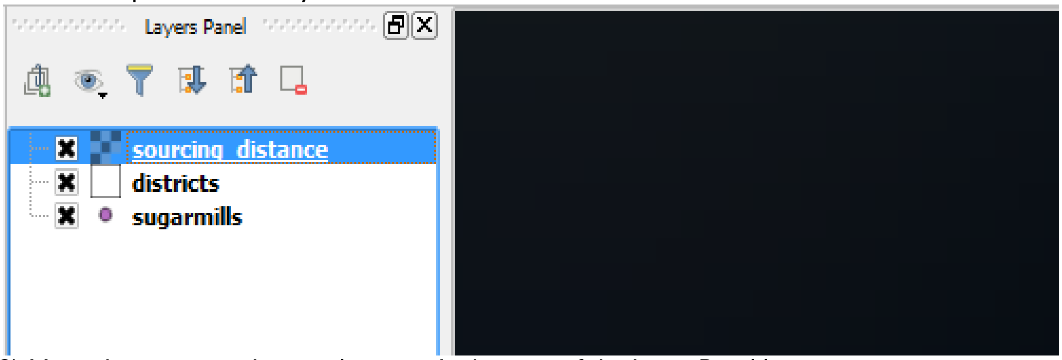
You can close the Attribute table - sugarmills window now.
2) Zoom the map closer to the Kohinoor Sugar Mill site

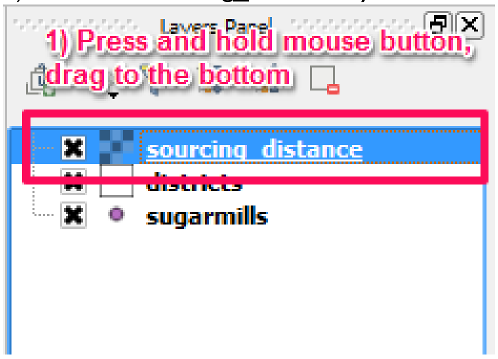


4. ***Find the sourcing distance for the additional feedstock needed for the Kohinoor site location.***

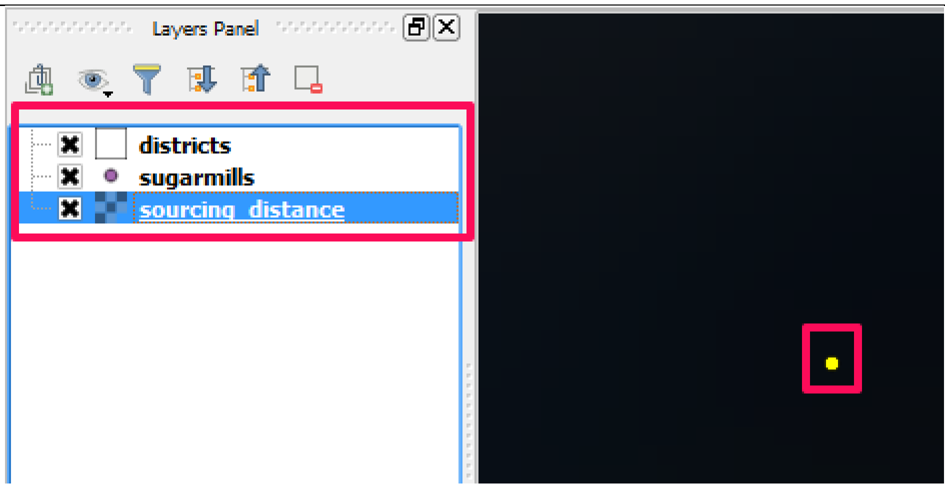
<table>
<tr><td>Files needed</td><td>sourcing_distance.tif</td></tr>
<tr><td>QGIS tools needed</td><td>1) Add the sourcing_distance raster layer to QGIS


=>


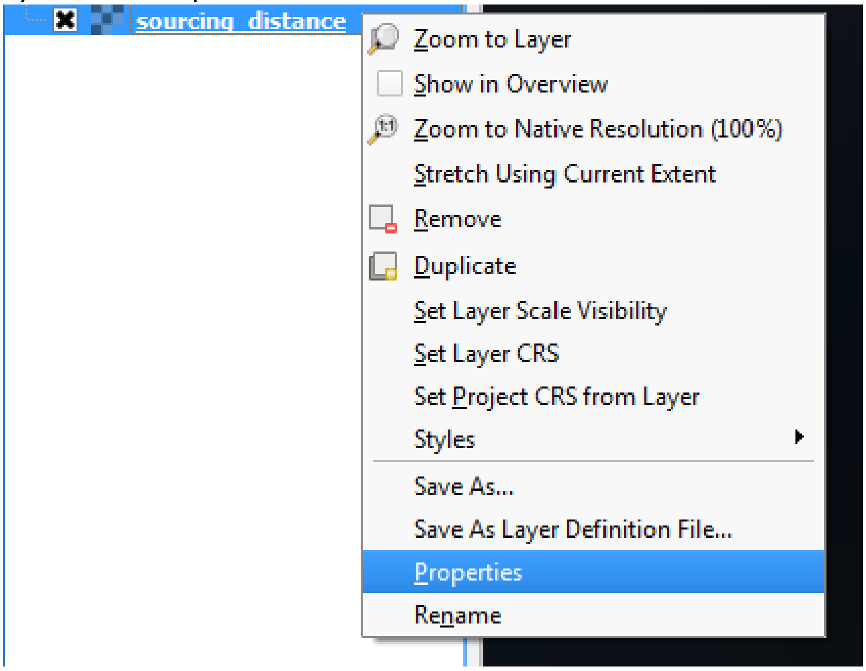
=> Your map will most likely turn to black


2) Move the sourcing_distance layer to the bottom of the Layer Panel list


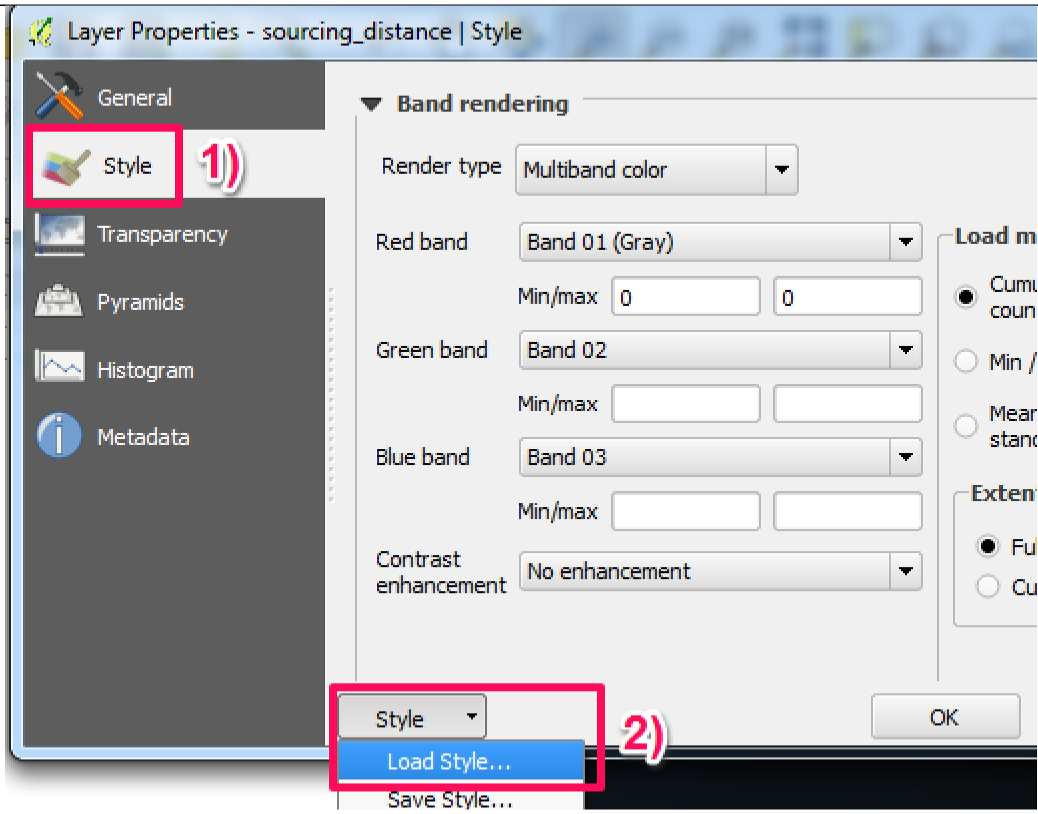
=> You should now see the yellow dot for the Kohinoor site:</td></tr>
</table>



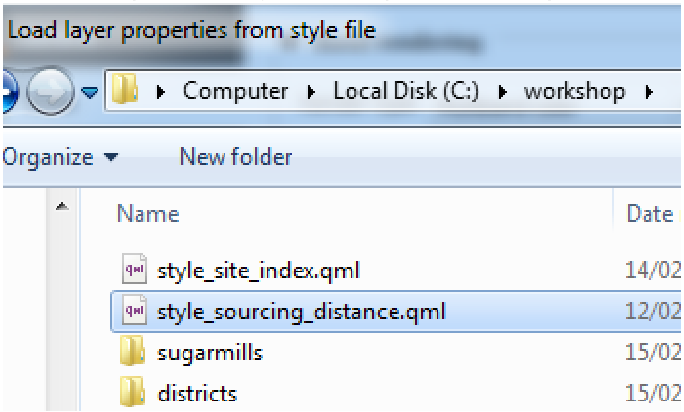
3) Let's make the sourcing_distance raster look a bit nicer. Right-click the sourcing_distance layer, choose Properties



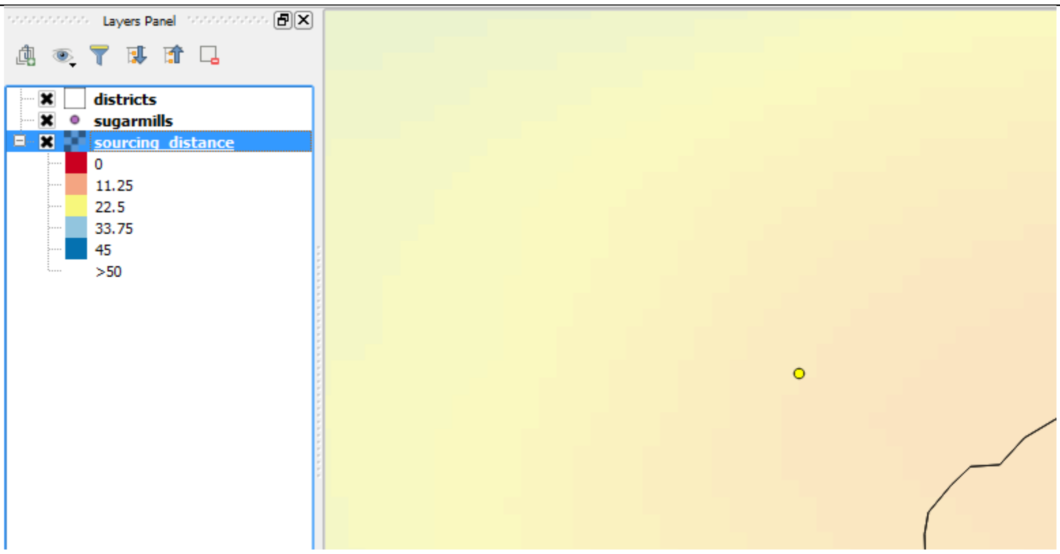
=>



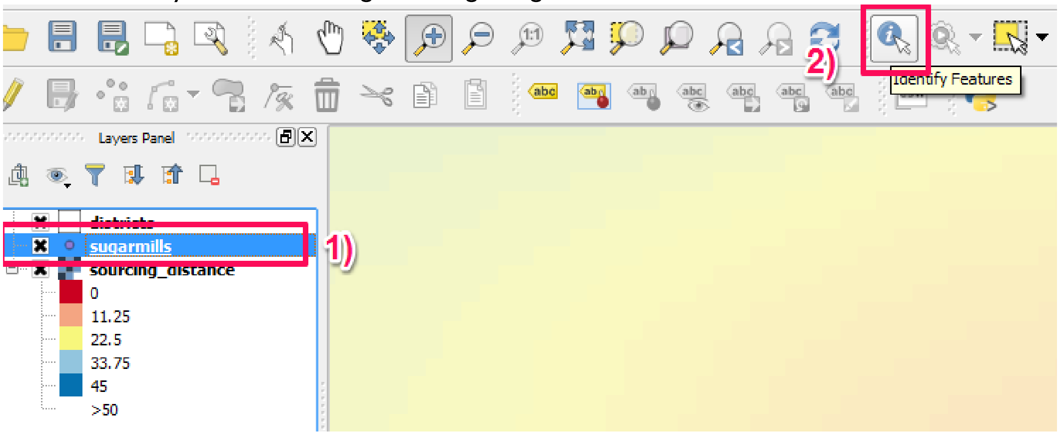
=> Select style_sourcing_distance.qml and click Open



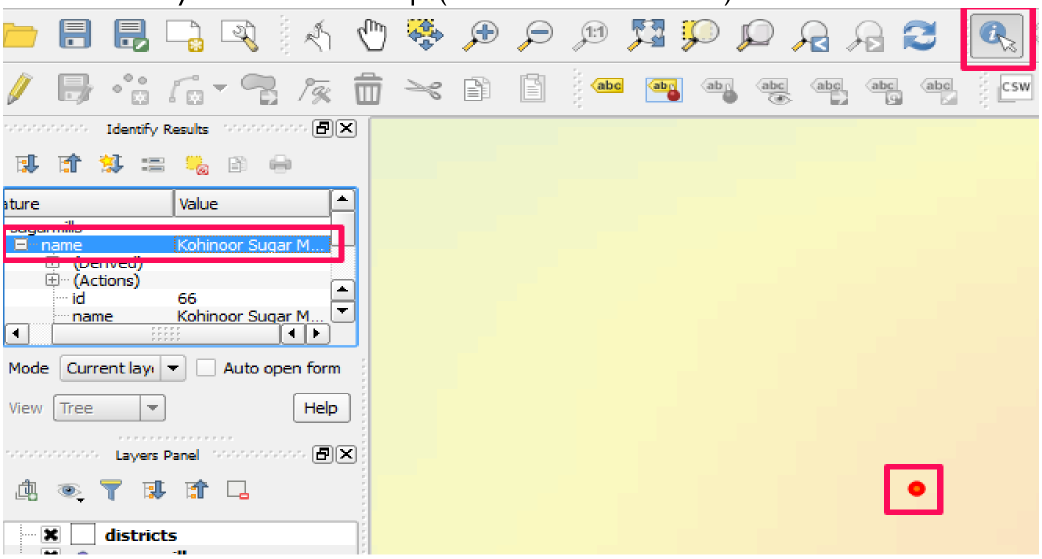
=> Click OK to close the Layer Properties dialogue



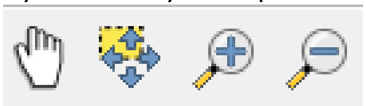
4) Find the exact sourcing distance value for the Kohinoor site
First make sure you're still looking at the right sugar mill



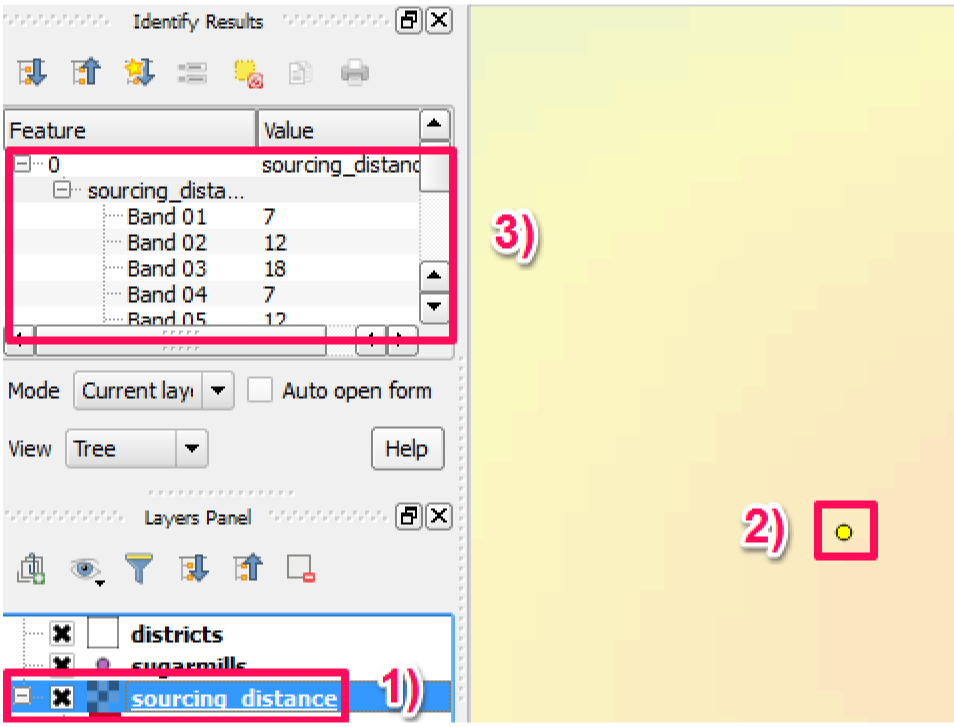
=> Click on the yellow dot on the map (which then turns into red)



If you need to, you can pan and zoom the map with these tools:



=> Now change the active layer to the sourcing distance layer, and again click on the Kohinoor site dot



=> In the Identify Results panel you now have the sourcing distances for different types and size categories of power plants given as the **sourcing area radius in km**. The radius is the direct "as crow flies" distance, not the road transport distance.

The band number interpretations are:

Band	Power plant
	Horizontal grate combustion steam boiler + steam turbine
1	3 MW
2	8 MW
3	15 MW
	Incline grate combustion steam boiler + steam turbine
4	3 MW
5	8 MW
6	15 MW
	Bubbling fluidized bed combustion steam boiler + steam turbine
7	8 MW
8	15 MW
9	25 MW
10	50 MW
11	100 MW
	Circulating fluidized bed combustion steam boiler + steam turbine
12	15 MW
13	25 MW
14	50 MW
15	100 MW
	Gasifier + syngas engine/turbine
16	0.5 MW
17	1.5 MW
	Anaerobic digester + biogas engine/turbine
18	0.5 MW
19	1.5 MW
20	3 MW
21	8 MW

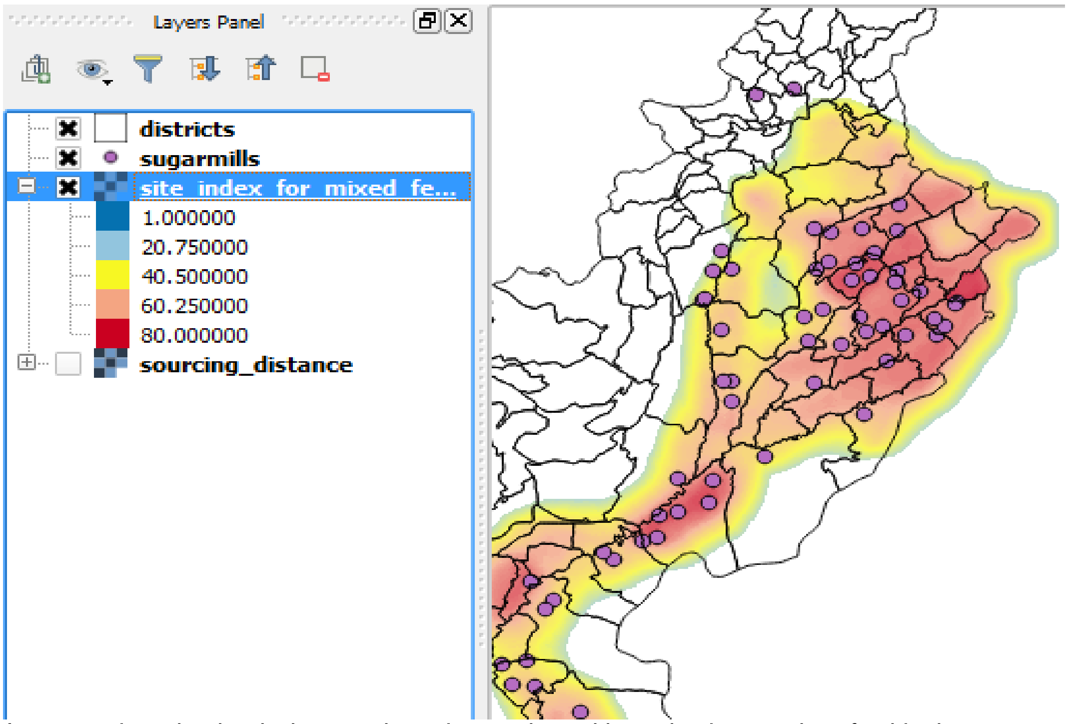
	Pick the values closest to the capacity you defined at the beginning with the Excel sheet (the yellow cell on the sheet). Extrapolate or interpolate the sourcing distance value for the capacity you got from Excel. This number will tell you from how far from the sugar mill you'd need to purchase all the available field harvest residue to run the power plant all year. "All available" is here defined to mean harvest residue currently being burned on the fields by the farmers that are willing to participate in a commercial supply chain for power generation.

<u>Task 2: Identifying and Evaluating a Greenfield Investment Opportunity</u>

Your task is to find a potential site for a power plant that uses harvest residues collected from fields, and evaluate how much harvest residue, and of what kind is available within a 15 km radius from that site.

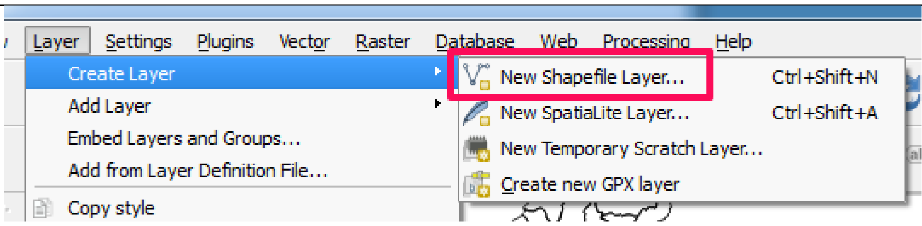
To answer the question, you need to

1. Open the site index raster that is part of the Atlas, and decide on the site you want to analyse

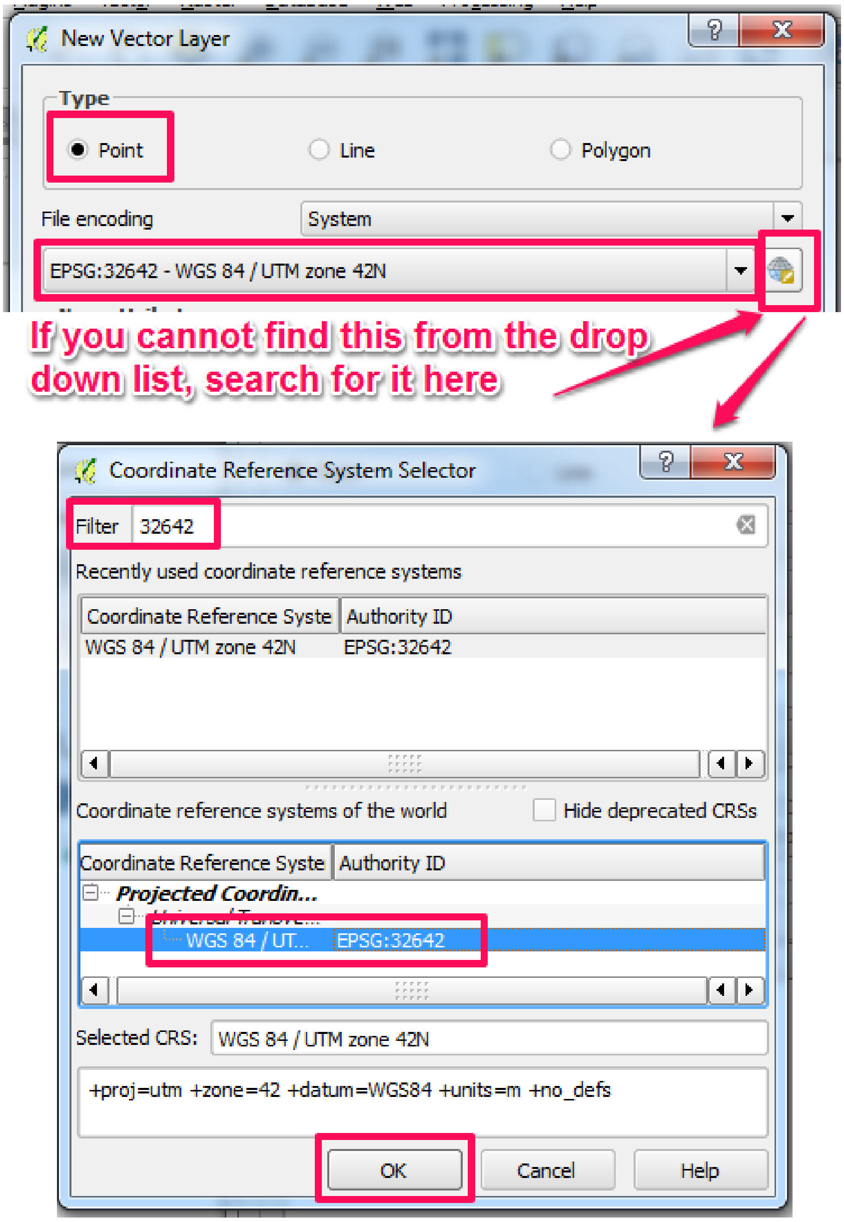
Files needed	site_index_for_mixed_feedstock.tif
QGIS tools needed	1) Open the site_index_for_mixed_feedstock.tif raster in QGIS the same way you opened sourcing_distance.tif in the previous exercise, see step 4 above. Apply the style style_site_index.qml on the layer, again see step 4 for instructions The end result should look like this:  Locate a place that has high site index values, indicated by red colour, and preferably does not have sugar mills right next to it (to avoid competition for harvest residues).

2. Next we mark that location with a point on the map, and create the 15 km radius sourcing area around it.

QGIS tools needed	1) Create a new vector layer on the map

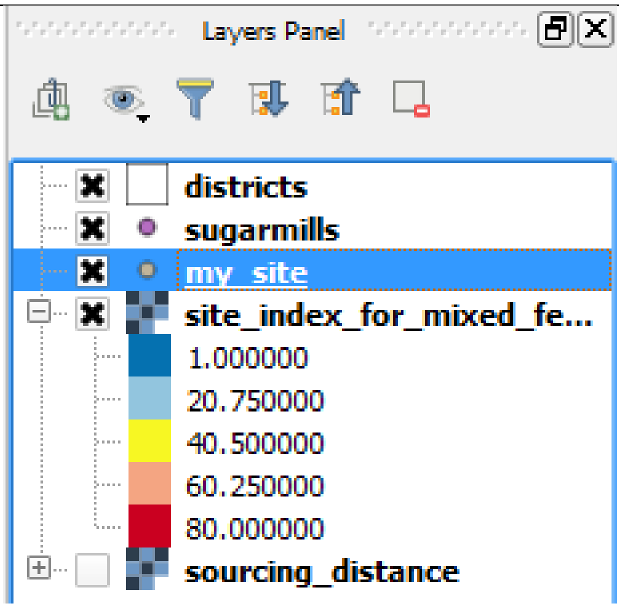


=>

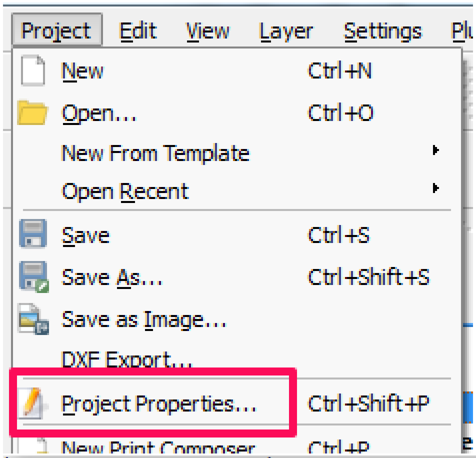


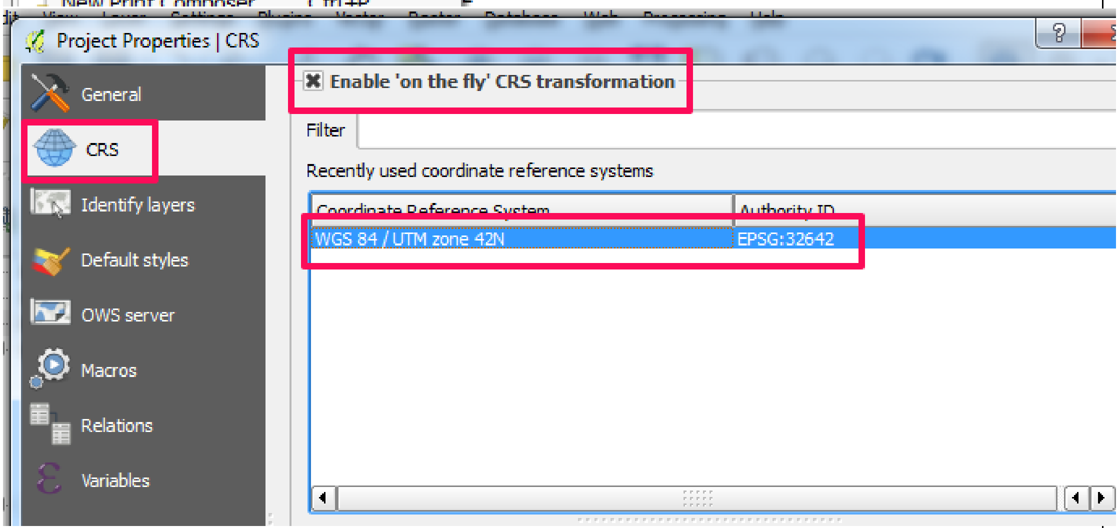
=> give the new layer a name, and save it

=> You will have a new layer on the Layers Panel

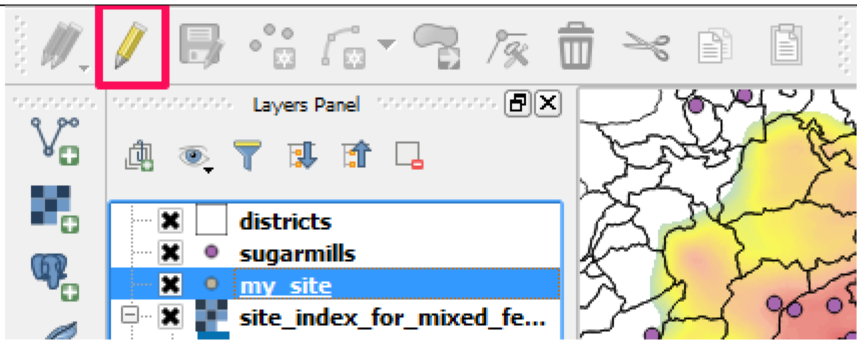


=>
Check that also the QGIS project you're working with has the same coordinate system as the newly added layer:

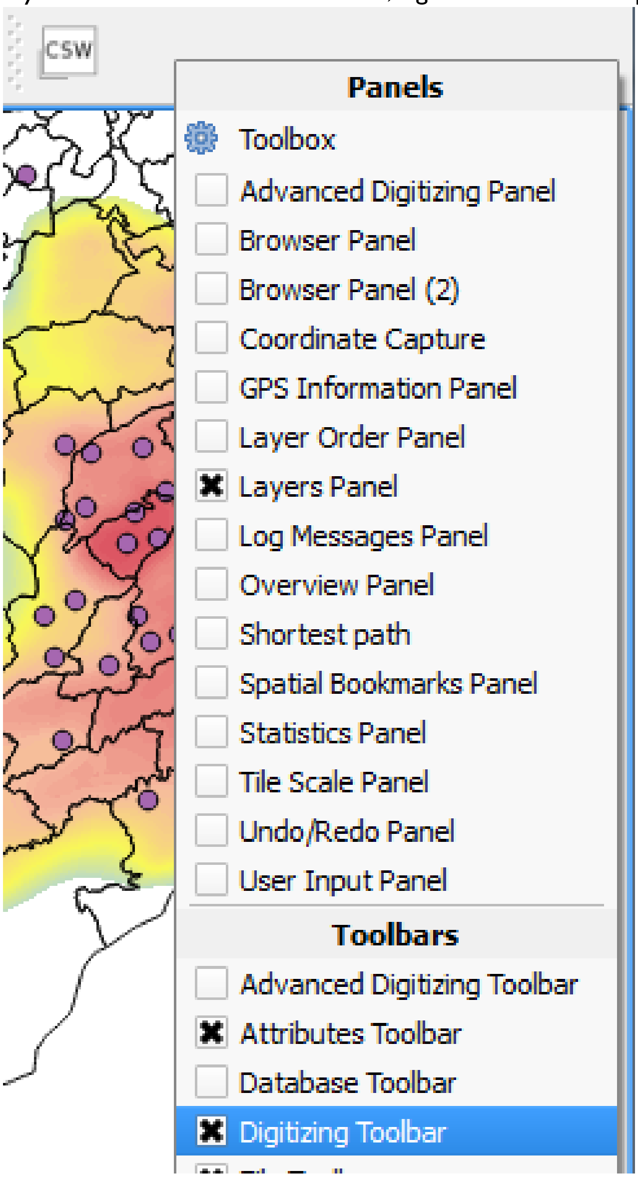




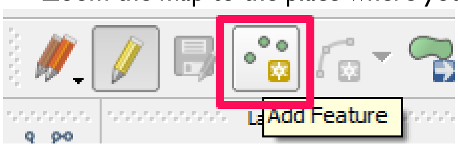
2) Add a new point to the new layer to the place you picked for analysis
While your new layer is highlighted on the Layer's Panel, click here



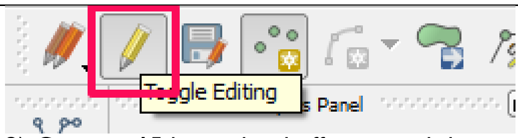
If you don't see that toolbar button, right click over an empty spot on the toolbar, and select:



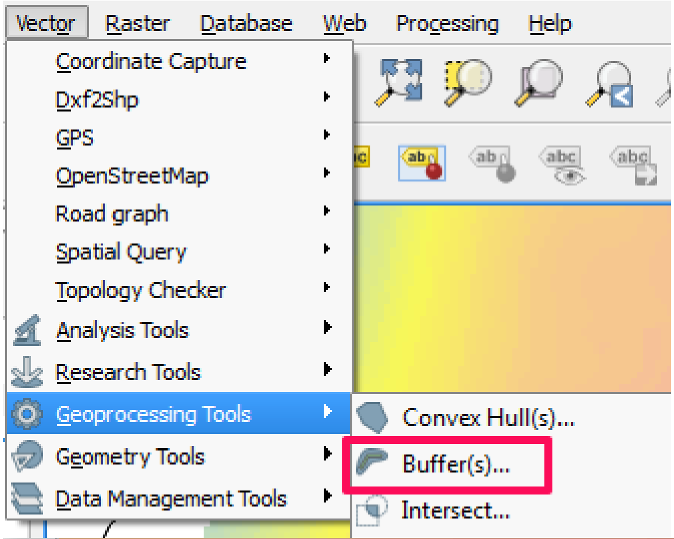
=> Zoom the map to the place where you want to add the point, and then:

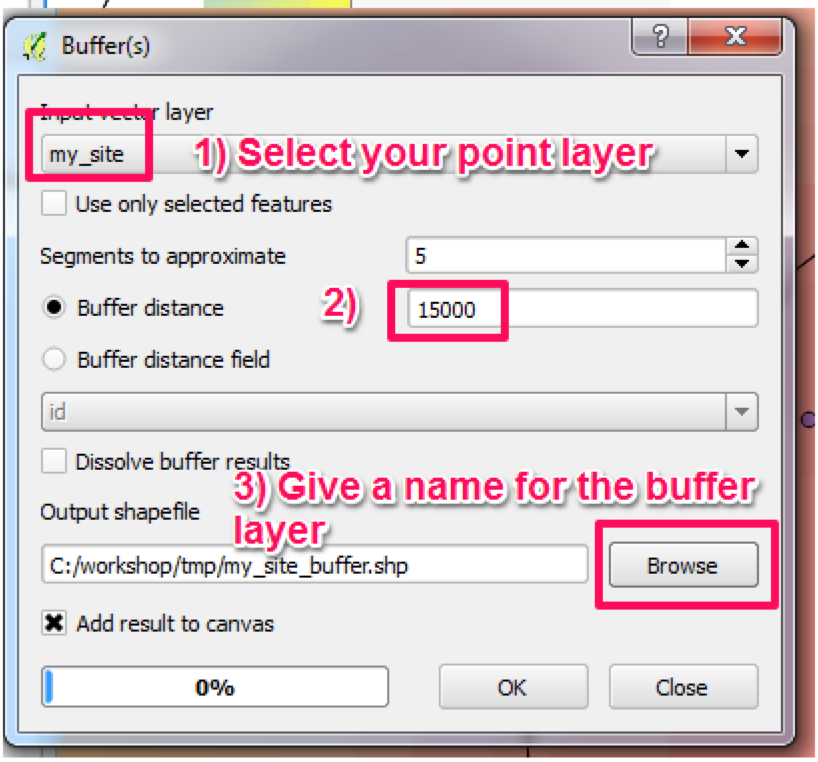


=> click on the place on the map you selected for analysis, give an id for the new point (e.g. 1) and then, click here again, and save the changes when prompted:

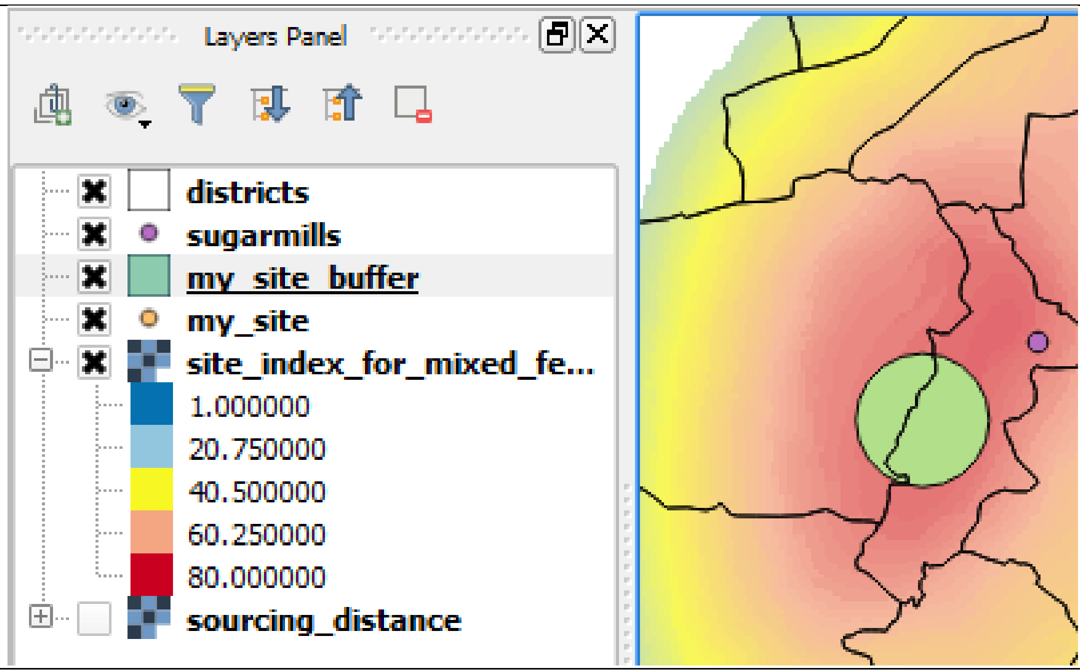


3) Create a 15 km radius buffer around the site marked with the point

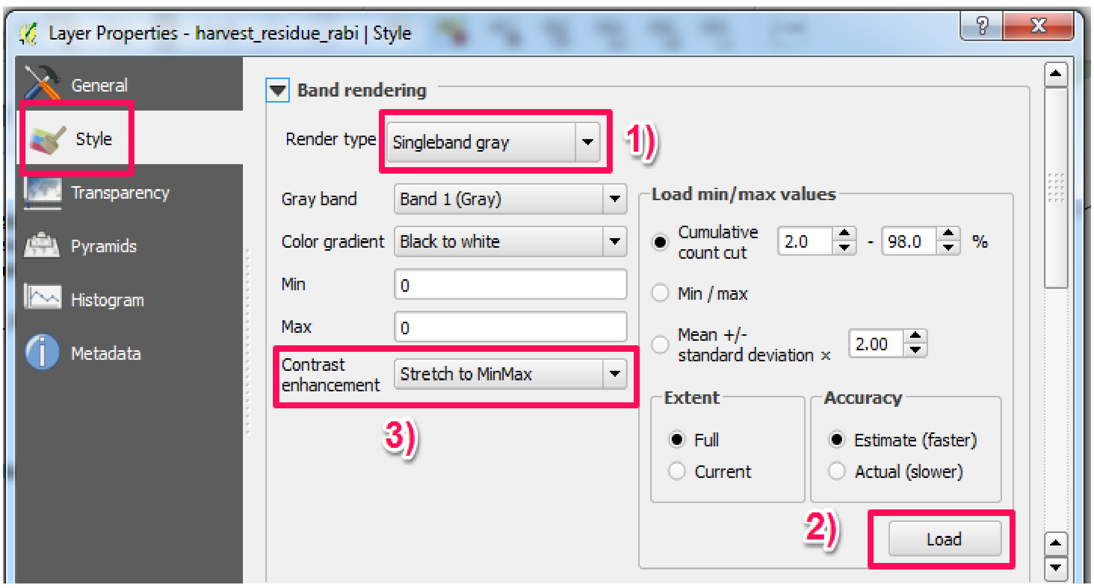




=>

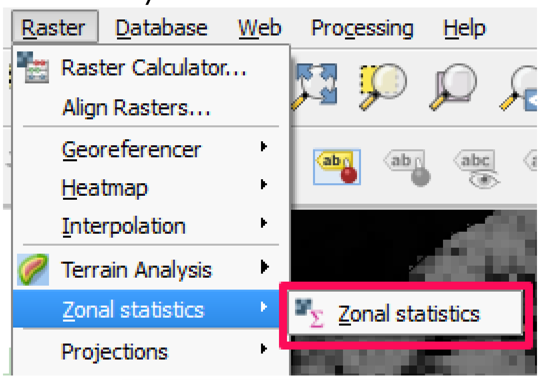
3. *Next you calculate how much and what type of harvest residue is available from that 15 km radius circle.*

Files needed	harvest_residue_rabi.tif harvest_residue_kharif.tif power_plant_model.xlsx
QGIS tools needed	1) Add the rasters harvest_residue_kharif.tif and harvest_residue_rabi.tif to your map. See instructions for step 4 for the previous exercise for adding raster layers to the map. Note: since these rasters are 9 band rasters, each band containing the available biomass for each pixel, there is no obvious way of styling the layer for display. If you want, you can show the values for a single band (i.e. single harvest residue) for example by right clicking the layer name in the Layers Panel, and then:  2) For each band that has the biomass for a field based harvest residue, calculate the total amount within the 15 km radius circle. The bands in the raster are:

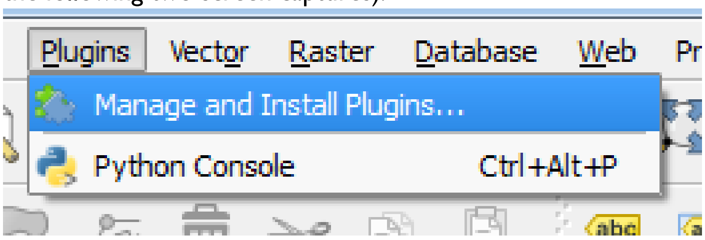
Band	Feedstock
1	Wheat straw
2	Cotton stalk
3	Rice straw
4	Rice husk
5	Maize stalk
6	Maize cob
7	Maize husk
8	Sugarcane trash
9	Bagasse

Since we're interested in field harvest residue only, you should only include bands 1, 2, 3, 5 and 8 in the analysis.

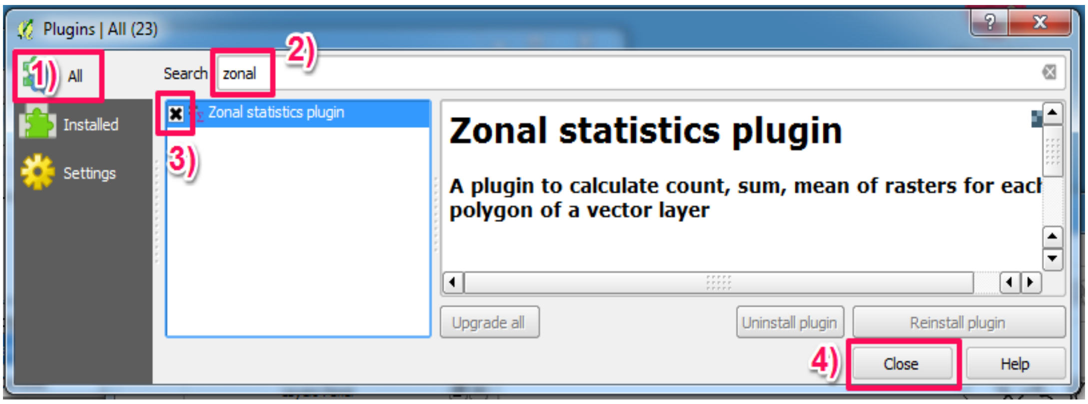
For this task you will use the Zonal statistics tool of QGIS:



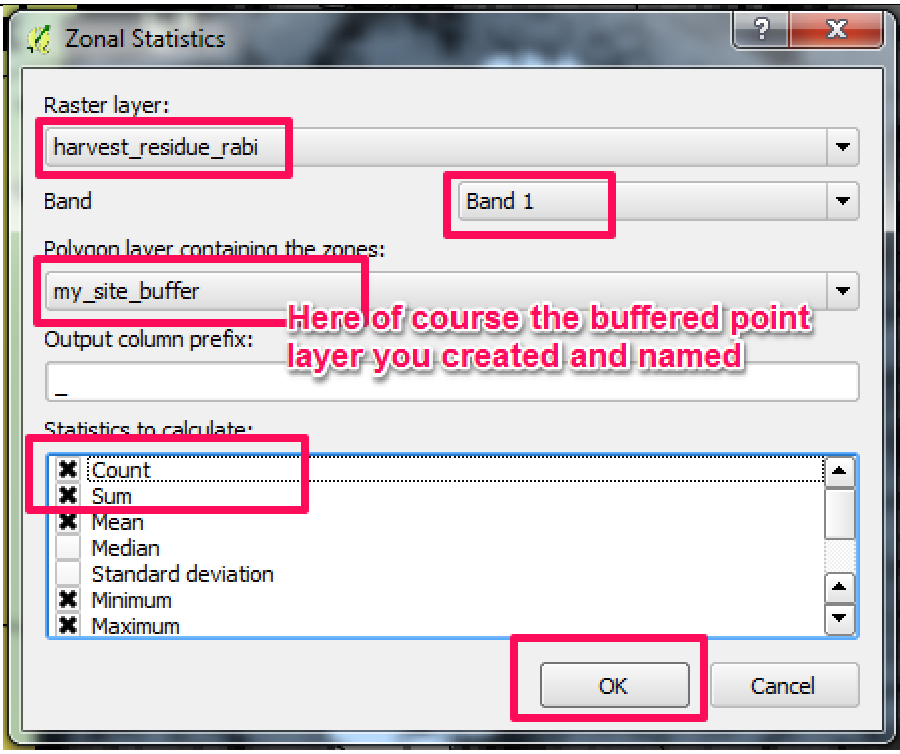
If Zonal statistic s is not visible in the Raster menu, you will need to enable it (otherwise, skip the following two screen captures):



=>

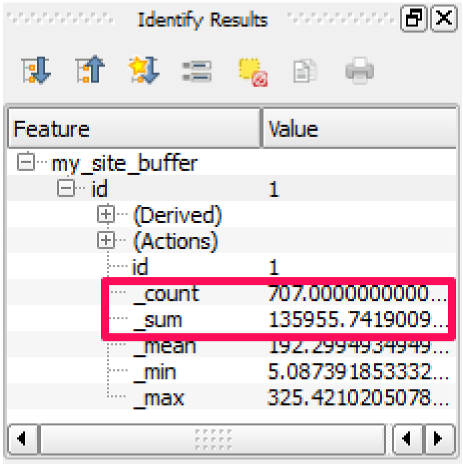


=>



=> After running the Zonal Statistics like this, you will have the raster statistics in the buffered point layer attributes. You can use the Identify features-tool to have a look at the numbers.

Select the Identify Features tool  and while the Zonal statistics layer is selected in the Layers Panel, click on the 15 km circle. The Identify Results panel will show statistics for that area based on the harvest_residue_rabi raster:



You will want the _sum and _count values; _sum is the sum of pixel values for band 1 for the raster, i.e. tonnes of wheat straw available. The _count value is the number of pixels from which this amount comes from. The size of a single pixel is 990 m x 990 m. You can check that value to validate that the sum is for the area under the circle.

Write down the sum in the appropriate yellow cell in the "MW Power" sheet of the power_plant_model.xlsx

Biomass fuels used	Low Heating Value (LHV) (3)		Amounts of biomass fuels used
	MJ/kg	MWh/t	t/yr
Wheat straw	14.40	4.00	136,000
Cotton stalks	15.00	4.17	0
Rice straw	12.50	3.47	0
Maize stalks	16.30	4.53	0
Sunflower stalks	19.90	5.53	0
Sugarcane trash	13.70	3.81	0
Lentil stalks/pods	10.50	2.92	0

Repeat this step for all the relevant bands (see above), and for the harvest_residue_kharif raster as well. After that you have the your power plant model primed with feedstock data, and can see for example the gross power capacity of the power plant:

Calculation results:		
Rated gross power capacity output:	15.68	MWe
Gross electricity output:	109,888.0	MWh/yr
Electricity own-consumption by the power plant(4)	15.0%	% of gross electricity output
Net electricity output	93,404.8	MWh/yr

Of course it's not realistic to assume that you can source 100% of the available feedstock, but now you have the baseline, and can start playing with the sourcing assumptions.

3.2 Updating of the Biomass Atlas Data

The purpose of this chapter is to introduce the structure and the parameterization of the Biomass Atlas Model so that in the event of updates to some of the input data for the Biomass Atlas, new versions of the Atlas datasets can be generated.

The exercises in this chapter rely on a sample of the original Atlas data to keep the runtime for the exercises at a reasonable level.

Set-up

The Biomass Atlas model, used to generate the Biomass Atlas datasets, is implemented with the Python programming language. It also relies on several Python modules that need to be installed together with Python. Table 337 lists the required modules, and the easiest way to get them installed on Linux and OS X environments. On Windows, a good source for installation files of the needed modules is http://www.lfd.uci.edu/~gohlke/pythonlibs/

Table 33: The requirements for generating the Biomass Atlas data with the Biomass Atlas model

Requirement	Can be accessed at
Python 2.7	https://www.python.org/downloads/
pip	https://pip.pypa.io/en/stable/installing/
Python modules, installed with pip:	Execute on command line
rasterio	pip install rasterio
shapely	pip install shapely
fiona	pip install fiona
xlrd	pip install xlrd
xlsxwriter	pip install xlsxwriter

rtree	pip install rtree
numpy	pip install numpy
pyproj	pip install pyproj
affine	pip install affine
scipy	pip install scipy
Biomass Atlas Model	https://energydata.info/dataset/pakistan-biomass-gis-atlas in atlas_model folder
Training dataset	https://energydata.info/dataset/pakistan-biomass-gis-atlas in training folder

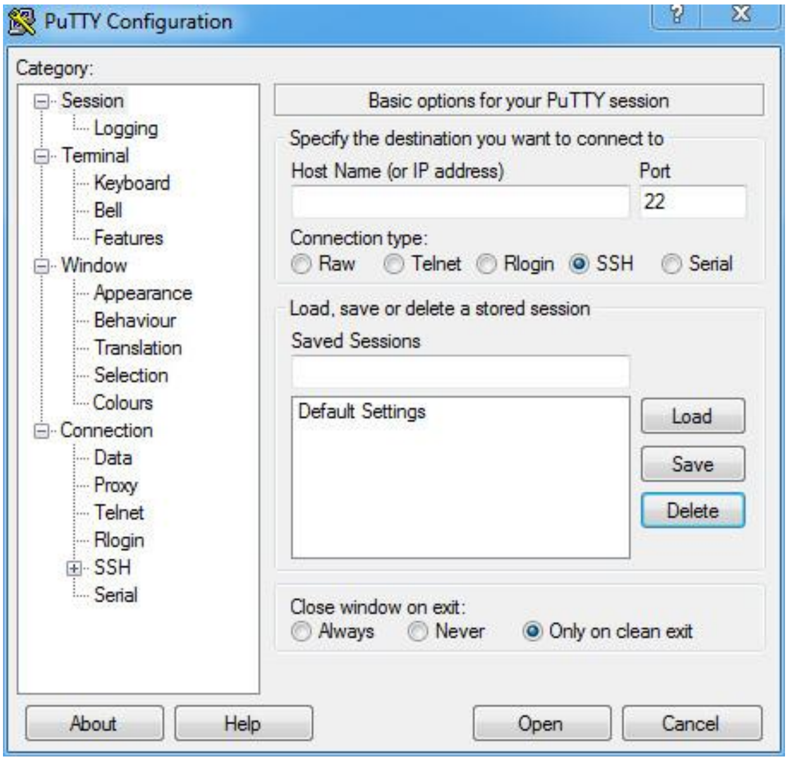
After downloading the Biomass Atlas Model and the training dataset zip-file, unzip them and make a note of the folder where you did the unzipping. This is the folder you will find the model and the exercise data referred to below.

Accessing Biomass Atlas tools remotely using SSH client (PuTTy)

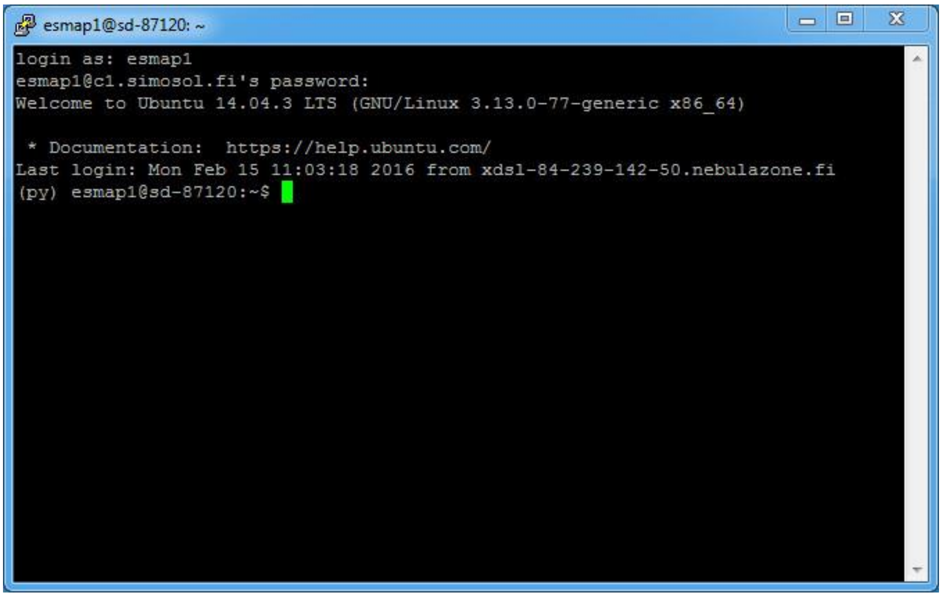
These instructions have been written from the point of view that the Biomass Atlas model is executed on a remote Linux server, accessed using an SSH client on a Windows desktop. If you're running the whole exercise locally on a Windows desktop, you can skip the remote access and data download sections in the instructions.

In order to install PuTTy, go to http://www.putty.org and follow the "Download PuTTy link" and from there, download the "putty.exe" to your computer. A detailed PuTTy documentation can be found from http://the.earth.li/~sgtatham/putty/0.66/htmldoc/

To sign in to the remote server, write the server address in the text field under "Host Name (or IP address). Click "Open". The first time you log on the server you are shown a pop-up "PuTTY Security Alert"; click "Yes". More detailed instructions on logging in to remote server using PuTTY can be found here: http://the.earth.li/~sgtatham/putty/0.66/htmldoc/Chapter2.html#gs



Type in the user name when prompted followed by the password. After a successful login, the windows should look something like this:



Task 1: Changing How the Atlas Is Generated

Overview of the Biomass Atlas model

The Biomass Atlas Model consists of two main scripts: feedstock.py module and heatmap.py module (located in <*unzipping location*>/atlas_model/src directory). Both of the modules are controlled by a number of settings in constants.py file, which is located in <*unzipping location*>/atlas_model/src/utils directory. The steps in running the whole Biomass Atlas model are:

1. Set the run parameters by editing the constants.py file
2. Run the feedstock.py module
3. Run the heatmap.py module

Detailed instructions for doing this are below.

Before running the Biomass Atlas, you must change current working directory to the Biomass Atlas main directory, by running a command:

```
$ cd <unzipping location>/atlas_model
```

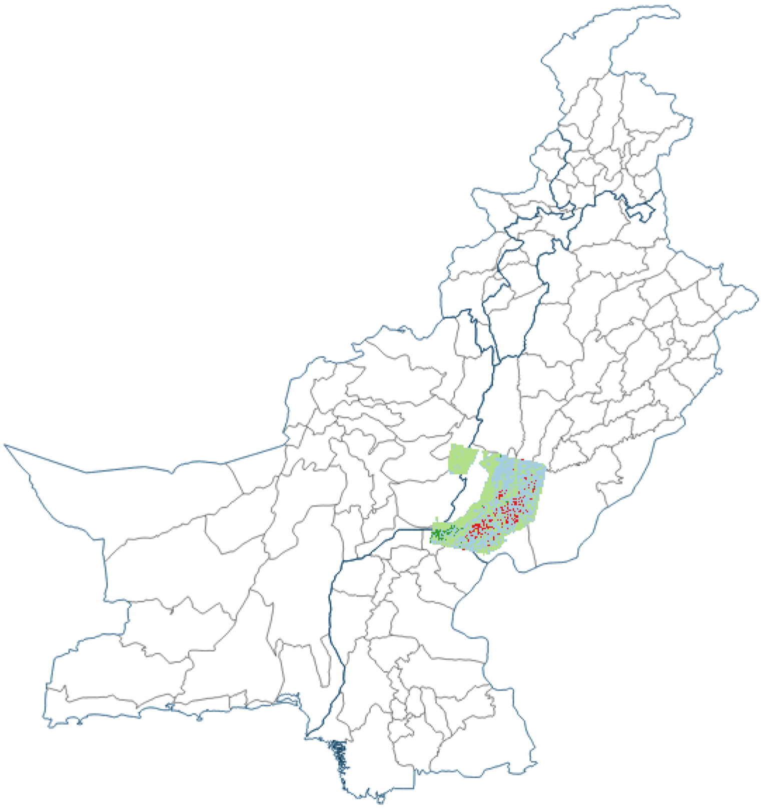
Here <*unzipping location*> is the folder in which you unzipped the model and training data. Note that these instructions are written for Linux, so you need to adapt them for Windows (e.g. \ instead of / as the directory separator in path names).

Above the "$" marks the "command prompt" in your PuTTy window, i.e. you're meant to type the text following the $-sign and press Enter/Return key. On Windows this would be your Command Line window.

Modifying Biomass Atlas settings in the constants.py
You need to modify the file paths in

```
# PATHS TO MODEL INPUTS
```

part of constants.py file. Constants.py contains the documentation of the purpose of each file path setting; here we give instructions about changing the land use classification file path. In this example we will be running the Biomass Atlas model for only a small subset of the whole country, as running the model for the whole of Pakistan would take a considerable time. So the instructions assume that you have at hand land use classification for a single Landsat image, named p151r40.ers. First we need to set the model land use classification input to this single Landsat image classification by modifying the constants.py file. The area covered by this Landsat image used to create these instructions is shown in the following image as the colored area in central Pakistan.



Note that this is also how you would assign a completely new land use classification to the Atlas.

The constants.py module can be modified using nano editor by running the following command (here we assume that you successfully changed your working directory to workspace/pakistan/atlas in the previous step above):

```
$ nano src/utils/constants.py
```

(on Windows, use e.g. Notepad to open the file)

After starting the nano editor, your screen should look like this:

```
GNU nano 2.2.6                  File: src/utils/constants.py                  Modified

'''
Created on Nov 5, 2015

@author: antti
'''

import os


# ----------------------------------------------------------------------------
# PROCESSING PARAMETERS
#
# General processing parameters
PIXEL_SIZE = 990  # Land use classification raster pixel size in meters

# Settings for running the different subtasks in the feedstock analysis
FEEDSTOCK_RUN_SURVEY_ANALYSIS = True  # Process the field survey data?
FEEDSTOCK_RUN_FEEDSTOCK_MAPS = True  # Generate the feedstock maps?
FEEDSTOCK_RUN_DISTRICT_LANDUSE = True  # Run district-level landuse analysis

# Settings for running the different subtasks in the heatmap analysis
HEATMAP_RUN_PROCUREMENT_DISTANCE = True
HEATMAP_RUN_GRID_STATION_DISTANCE = True
HEATMAP_RUN_ROAD_NETWORK_DENSITY = True
HEATMAP_RUN_COGEN_ANALYSIS = True
HEATMAP_RUN_IN_DEBUG_MODE = False
HEATMAP_SUBTASK_SIZE = 5  # n for n x n window in concurrent processing
```

Subtask 1.1: Changing the model inputs - land use classification file

Using the nano editor, find a row that contains a text *LANDUSE_CLASSIFICATION*. You can do this either by moving down using arrows, or by searching for the text using "Where Is" command (press ctrl + w). After finding the correct row, change the row contents into the following:

LANDUSE_CLASSIFICATION = os.path.join('<unzipping location>, 'data', 'p151r40.ers')
After the change, the constants.py should look like this in nano editor.

NB: the screenshots originate from a training workshop organized in Islamabad on February 16, 2016, so the paths are specific to that event, and do not always match the text of this document.

```
# ----------------------------------------------------------------------------
# PATHS TO MODEL INPUTS
#
# Land use classification
LANDUSE_CLASSIFICATION = os.path.join('/home', 'simo', 'workspace', 'pakistan', 'pred', 'p151r40.ers')
```

After saving this edit (press ctrl + o) the land use classification will be read from a single Landsat image named p151r40.ers instead of the mosaic that combines a large number of Landsat images and covers the whole Pakistan.

Subtask 1.2: Changing the model parameters - maximum biomass sourcing distance

Before running the Biomass Atlas model, we should still edit some of the input parameters of the Biomass Atlas model. In this example we will modify the maximum biomass sourcing distance. By default, the maximum sourcing distance is 50 km, but you should change it to 25 km. This means that the maximum allowed distance, from which biomass can be transported to a power plant, will be 25 km.

To modify the maximum sourcing distance, search for the text *MAX_DISTANCE* from the constants.py using the nano editor and change its value to 25. After the edit, the constants.py should look like this.

```
# -----------------------------------------------------------------------
# PARAMETERS RELATED TO FEEDSTOCK PROCUREMENT, PROCESSING AND STORAGE
#
# Maximum feedstock procurement distance (km)
MAX_DISTANCE = 25
```

Subtask 1.3: Changing the model outputs - result heatmap file names

Another thing we want to change, are the names of the output files that will be generated when running the Biomass Atlas model. The names of the output files, and other model outputs are also defined in the constants.py file. The Biomass Atlas model will generate a number of raster files during the processing, but the most relevant outputs are the so called *combined heatmaps*, which represent the potential for biomass based power plants of different types and capacities.

In order to compare model outputs with different input parameters, we want to save the outputs from separate model runs with separate names. Using the nano editor, search for the text *PATH_TO_COMBINED_HM_SINGLE* from the constants.py file. Change the name of the file to heatmap_combined_SINGLE_run1.tif. Do the same for the *PATH_TO_COMBINED_HM_MIXED* and change the output file name to heatmap_combined_MIXED_run1.tif.

The "SINGLE" refers to heatmap for a single fuel power plant and "MIXED" refers to a heatmap for a mixed fuel power plant.

After these changes, the constants.py file should look like this:

```
  GNU nano 2.2.6                File: src/utils/constants.py                        Modified

PATH_TO_ROAD_NETWORK_HM = os.path.join(OUTPUT_DIR, 'heatmap_rn_density.tif')

# Combined heatmaps, both for single fuel and mixed fuel cases
# 16 channels, one per each power plant type and capacity class combination.
# These classes are defined in constants.TECHNOLOGY_TYPES
# Unit: "goodness" index, 0..100
PATH_TO_COMBINED_HM_SINGLE = os.path.join(OUTPUT_DIR,
                                          'heatmap_combined_SINGLE_run1.tif')
PATH_TO_COMBINED_HM_MIXED = os.path.join(OUTPUT_DIR,
                                         'heatmap_combined_MIXED_run1.tif')
```

Now, make sure you save your edits (ctrl + o), exit the nano editor (ctrl + x) and we're ready to run the model!

Subtask 1.4: Running the Biomass Atlas model

The Biomass Atlas model should be run in two steps: first the feedstock.py module and then heatmap.py module.

Run the feedstock.py module with the following command:

```
$ python src/feedstock.py
```

The server logs will show messages about the execution of the model, and in case anything goes wrong, the error messages. If you did the edits in the previous steps following the instructions, then there should be no error messages.

After the feedstock.py module has been run successfully, the next step is to run the heatmap.py module. This is done with the following command:

```
$ python src/heatmap.py
```

Running the heatmap.py module will take a while, as it will run a spatial analysis for the biomass potential for 19 power plant type and capacity combinations. The heatmap.py module will generate the power plant potential heatmaps and after the model run has ended, we're ready to analyse the results.

Subtask 1.5: Re-running the Biomass Atlas model with alternative parameters

In this example, we want to run the model twice with different parameters in order to see how the parameters affect the model outputs.

In subtask 1.2 we changed the maximum sourcing distance to 25 km. Now, edit the constants.py and change the maximum sourcing distance back to 50 km.

In subtask 1.3 we change the output filenames by adding "_run1" to the end of the output heatmap file names. For the model re-run we want to change the output file names so that we will have two alternative sets of result files to compare. Follow the instructions of subtask 1.3, but now the filenames so that you change the "_run1" into "_run2".

After finishing the above edits, save your changes (ctrl + o) and exit nano editor (ctrl + x). Then, re-run the heatmap.py model. Notice that you don't need to re-run the feedstock.py again as you didn't change any parameters that affect the feedstock.py module.

<u>Task 2: Checking the Results with QGIS, Did the Atlas Change?</u>

Subtask 2.1: Loading the results from remote server to desktop computer

In order to view the Biomass Atlas model results, you need to first load the model outputs (the raster files) from the remote server to your desktop computer.
You can download files from the server using a program called PSCP, which you can download from the same web page as PuTTy.

PSCP download: http://www.chiark.greenend.org.uk/~sgtatham/putty/download.html

Copy the downloaded pscp.exe to the folder of where you want to copy the files. For these instructions, we assume the desired location for downloading the heatmaps is "C:\Atlas", so the pscp.exe should be saved to the folder "C:\Atlas".

PSCP is a command-line tool and should be run from the command-line prompt. To start the prompt, click the Windows icon at the bottom of the screen, and type "cmd" and press Enter in the "Search for programs and files" text box at the bottom of the menu.

In the prompt, change to the folder by typing

C: (and Enter)

followed by

cd \Atlas

Again, assuming that you want to work in the C:\Atlas folder. Change this according to the folder in which you want to have the data.

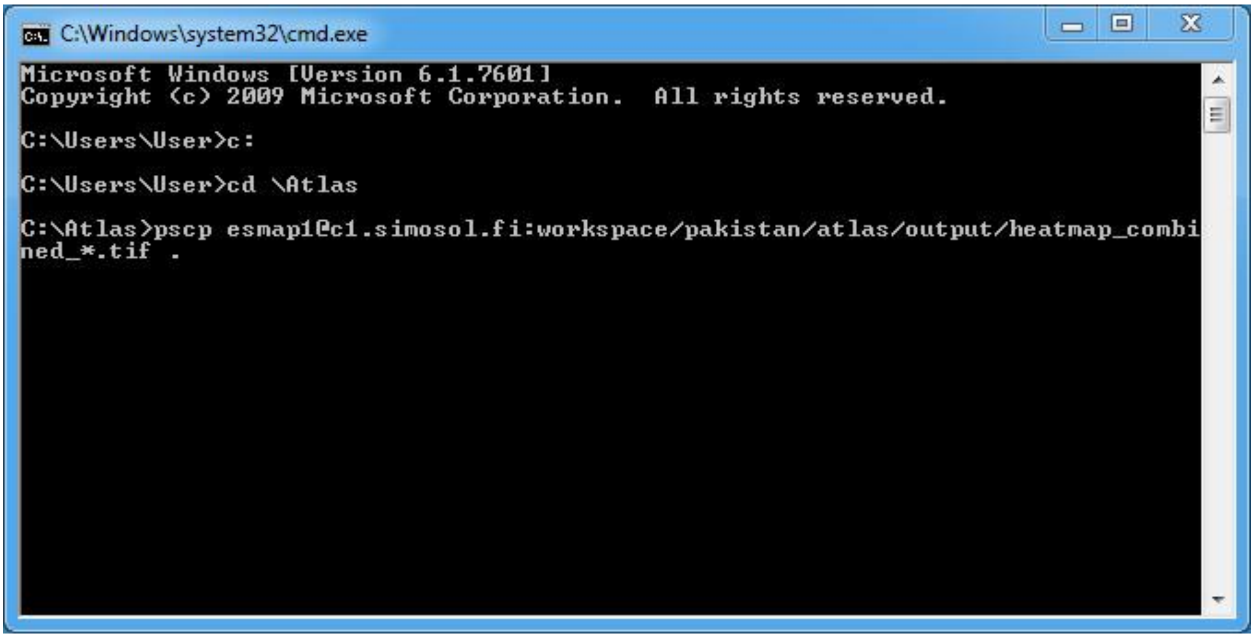
To copy the output files to C:\Atlas use the following command, but replace the user name esmap1 and the server name c1.simosol.fi with those you used when logging on with PuTTY to run Atlas:

pscp <username>@<your server>:<unzipping folder>/atlas_model/output/heatmap_combined_*.tif

.

Make sure to include the last point in the command.

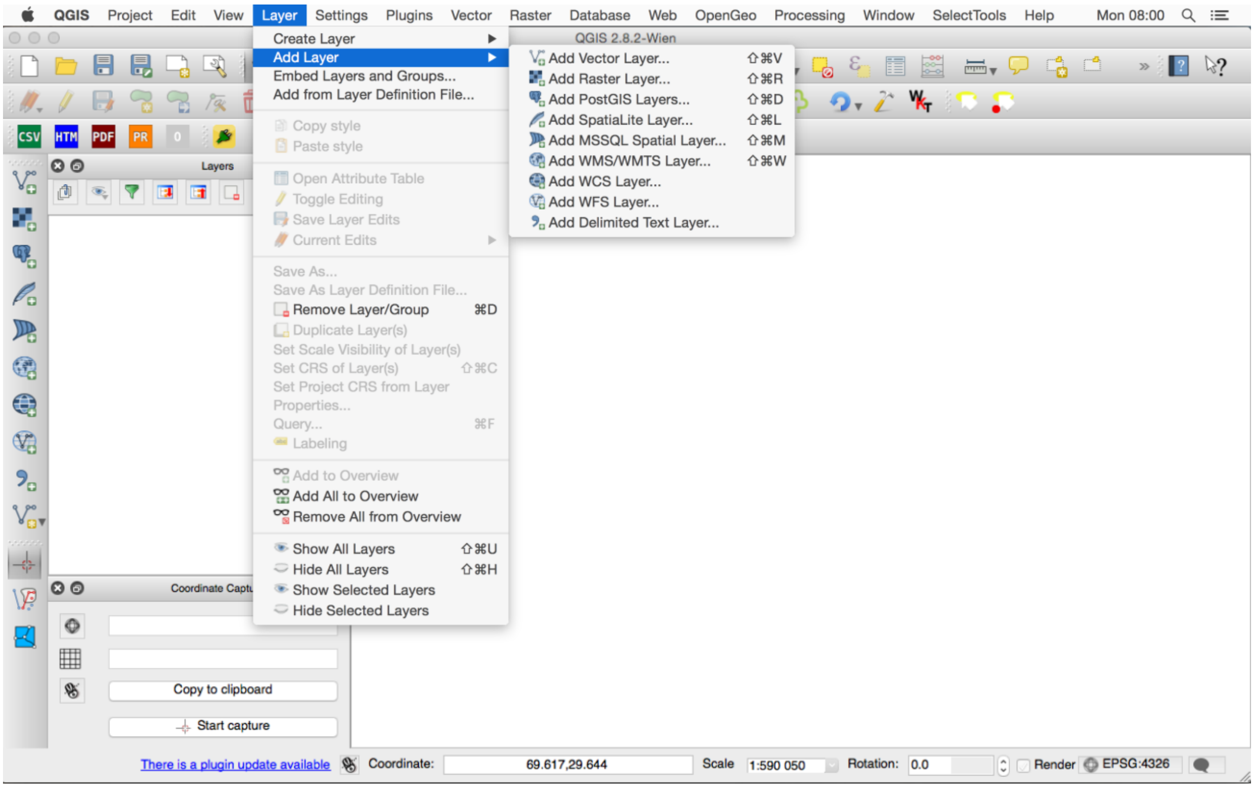
After pressing Enter, the program will ask for the same password it did when logging in with PuTTY.



If everything worked OK, you should have now downloaded all four combined heatmaps you just generated in the two model runs.
heatmap_combined_SINGLE_run1.tif
heatmap_combined_MIXED_run1.tif
heatmap_combined_SINGLE_run2.tif
heatmap_combined_MIXED_run2.tif
To copy only one single file, replace “heatmap_combined_*.tif” with the name of the desired file.

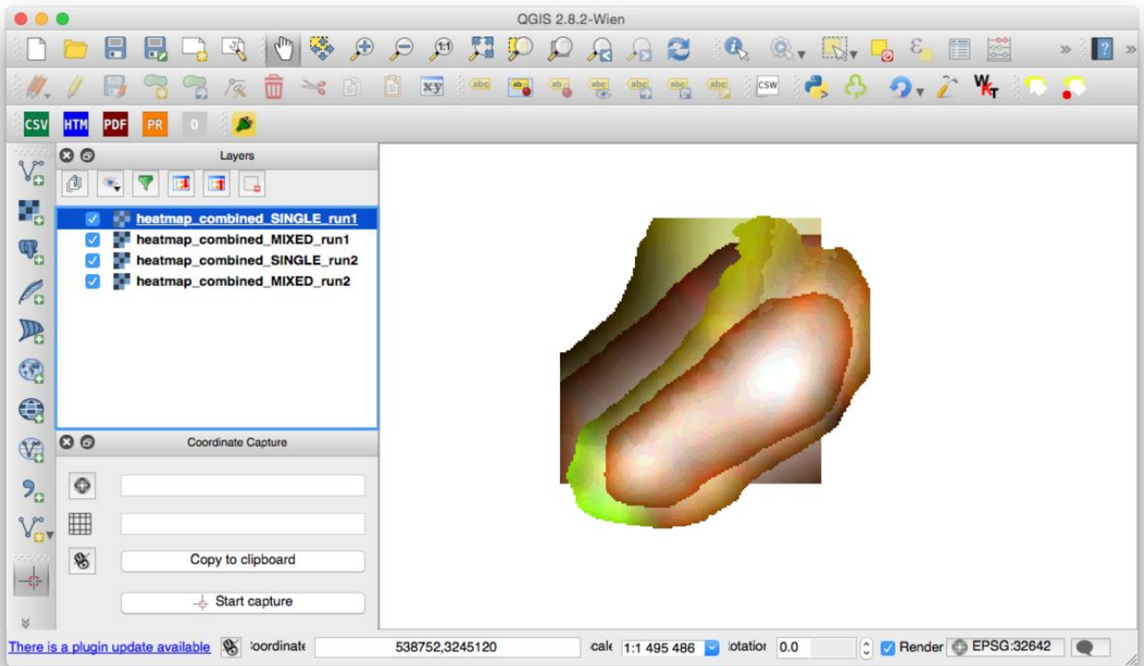
Subtask 2.2: Loading the heatmaps into QGIS

After downloading the generated heatmaps to your desktop computer, you can view them in QGIS. To do this, first start QGIS and create a new project. Next, add the rasters to QGIS by selecting "Layer" from the top menu, select "Add Layer" and finally "Add Raster Layer...".



From the file selector, select the four combined heatmaps you generated and downloaded from the server: heatmap_combined_SINGLE_run1.tif, heatmap_combined_MIXED_run1.tif, heatmap_combined_SINGLE_run2.tif and heatmap_combined_MIXED_run2.tif.

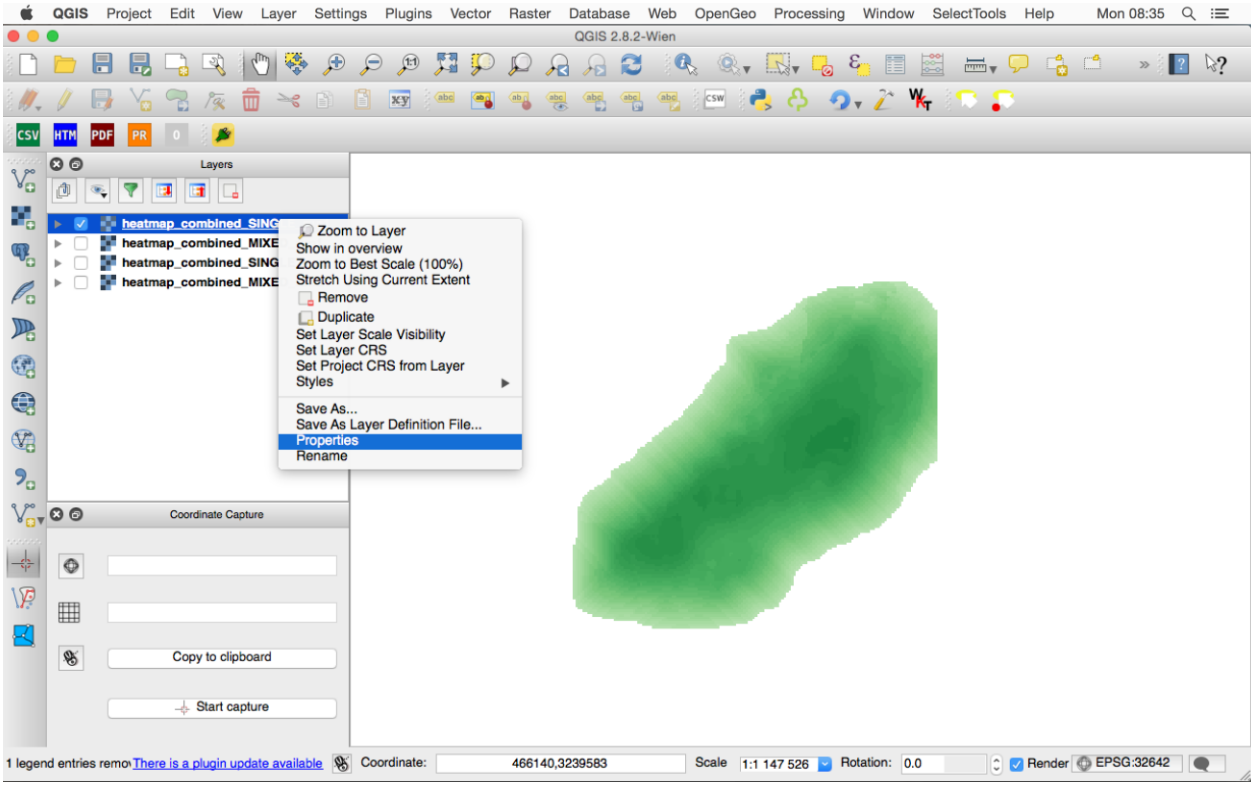
After loading the heatmaps to QGIS, each of the heatmaps should show as a separate *layer* in the layer listing on the left side of your QGIS application (see the following image).



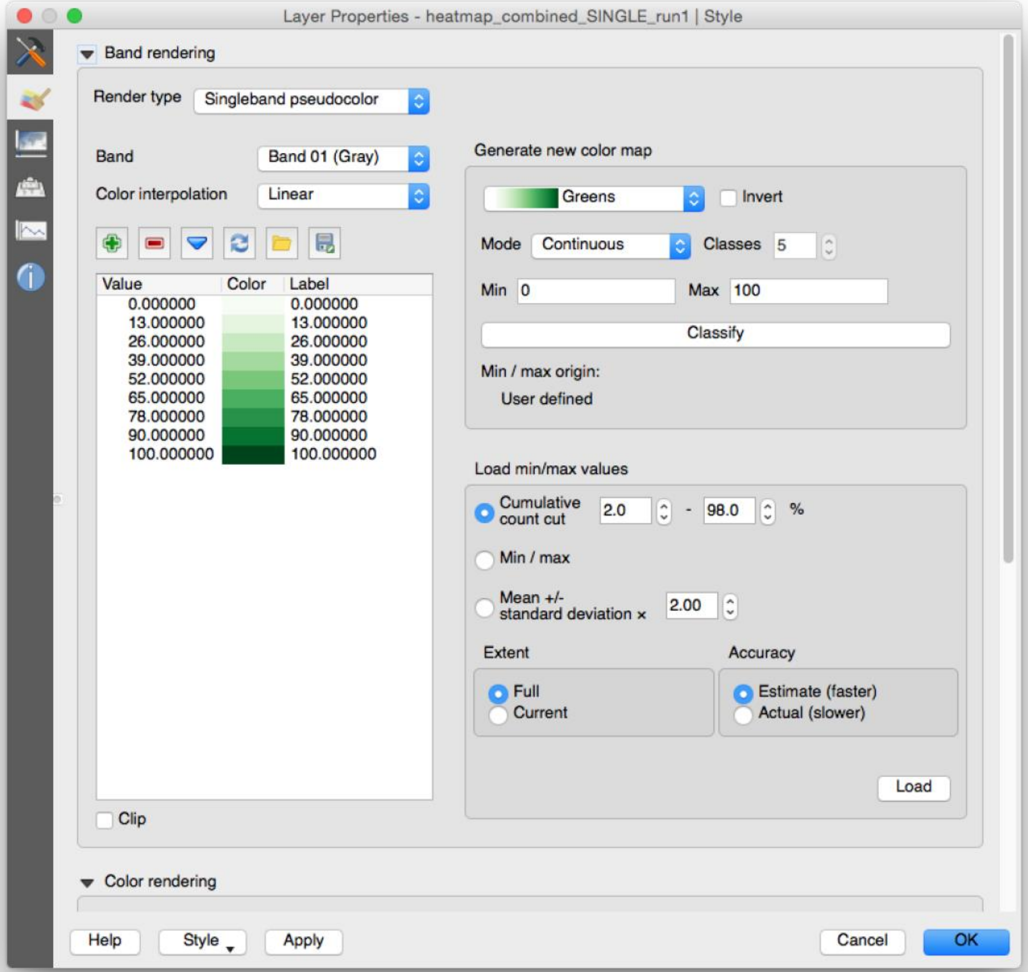
Subtask 2.3: Setting the layer style of the heatmaps in QGIS

The visual representation of the layers in QGIS are controlled by layer *style*. In order to compare the alternative heatmaps, we want to set their visual properties to represent the potential for biomass based power plants.

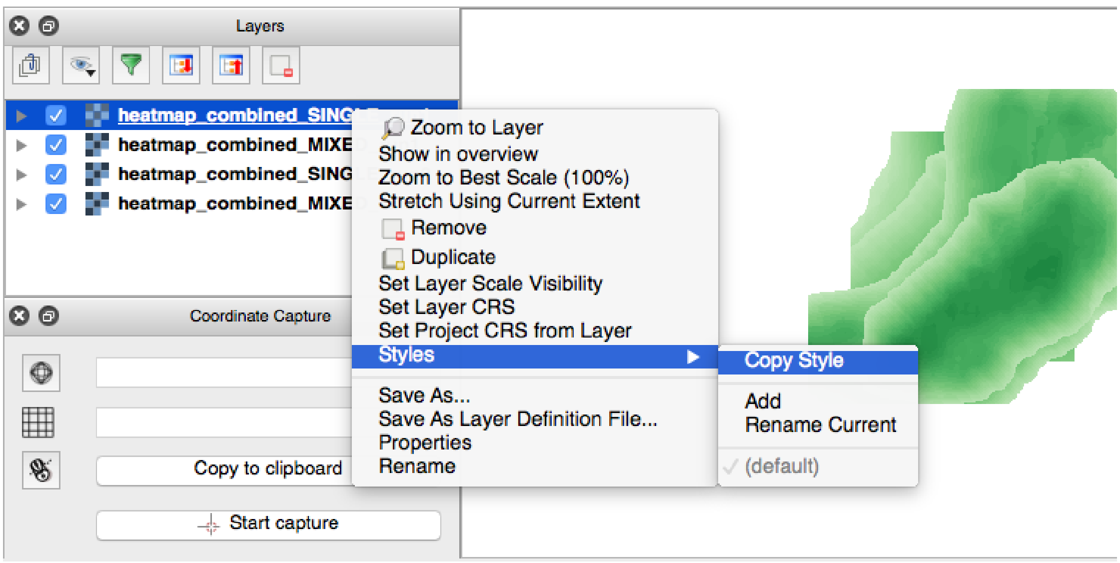
To do this, first select the heatmap_combined_SINGLE_run1 layer, press the right button of your mouse and select "Properties" from the pop up menu (see the following image).



In the layer properties, select "Style", from there set Render type as "Singleband pseudocolor", set the Band as "Band 01", select green color map, set minimum value to 0 and maximum to 100 and click "Classify" button. After this, the layer style settings should look similar to the following image. Make sure that your layer style settings are ok, then click "Apply" and "OK".



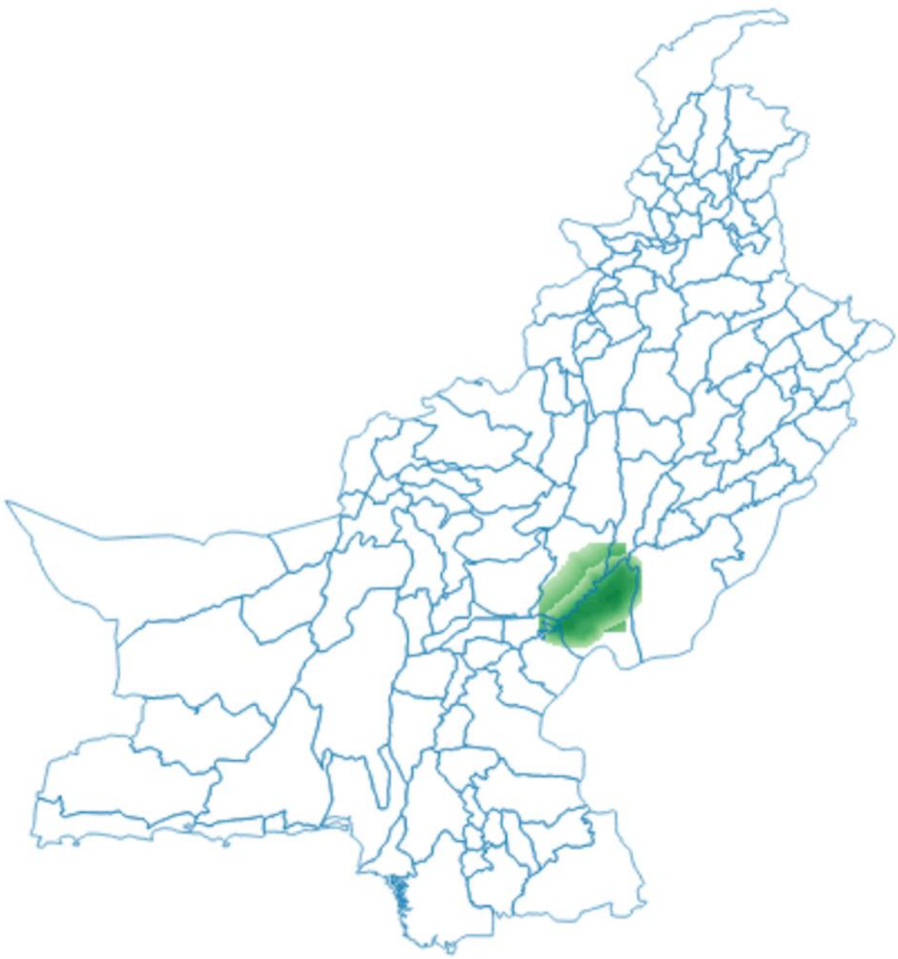
The above steps changed the style of one of the four layers. Next, you should copy the same style for the other three layers. This can be done by selecting the layer that you just modified, opening the pop up menu by right clicking, and selecting "Style" and "Copy style". Then, select one of the other three layers and do the same steps, except that in the end, select "Paste style".



Subtask 2.4: Comparing the layers from alternative runs

After setting the styles of all four layers, you can start comparing the heatmaps from the alternative model runs.

In the following image you can see the heatmaps for single stock power plants from runs 1 and 2 (25 km and 50 km maximum sourcing distance). The raster band 1 is for 3 MW HGC power plant so in the current settings, the raster displays the potential, or goodness, of each 1 x 1 km cell for a 3 MW HGC power plant, so that dark green means high potential and light green low potential. The white areas are outside the maximum sourcing distance.



Task 3: Changing the weights of different factors affecting the heatmap

Besides the maximum sourcing distance, there are also other factors that affect what the site suitability index heatmaps end up looking like. These are "nearest grid station distance factor" and "road network density factor". Find out where these are in **constants.py**, change them so that the weight of the sourcing distance is 80%, the weight for the grid station distance is 20%, and the road network distance has no weight at all (0%).

Rename the output rasters from having the "_run2" to have "_run3" ending.

Compare the results of this model run to the previous ones in QGIS.