Implications of Scale and Water-Energy-Food Nexus Interactions on Crop Residue Energy Potential in Pakistan

Emma C. Anderson

Under the Supervision of Dr. Jan Adamowski
Department of Bioresource Engineering
McGill University
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Email correspondence: emma.anderson2@mail.mcgill.ca

Abstract

Biomass-based energy production from crop residues is a proposed solution to Pakistan's persistent energy crisis. However, current estimates of residue energy potential vary widely due to differences in scales and assumptions. Furthermore, despite significant interdependencies between residue-based energy and agriculture and water systems, quantitative analyses of the implications of the water-energy-food (WEF) nexus on residue energy potential are unexamined in the literature. A failure to consider the impacts of scale, assumptions and factors related to the WEF nexus, such as competitive uses, water availability and management, climate change, soil quality and farming practices, can lead to overestimations in residue energy potential, hindering implementation. This is important in Pakistan, as successfully implementing energy projects is vital to ameliorating the current energy crisis and supporting sustainable development.

This research applies two methodologies to address these overlooked aspects of crop residue energy potential estimation. Method one calculates residue energy potential for the province of Punjab under different data aggregation scales (district, administrative division, and province) and assumptions of residue availability and feedstock collection radius. Alternatively, method two applies a case study in an agricultural region of the Rechna Doab, Punjab, through the novel application of a coupled human-water model (the P-GBSDM) to examine the implications of the WEF nexus on crop residue-based. The P-GBSDM, which captures the spatially explicit socioeconomic and environmental feedbacks related to agricultural productivity and hydrological parameters in the study area, was modified to include crop residue energy and associated income and costs feedbacks. The impacts of the WEF nexus on the viability of residue-based energy were explored by simulating different stakeholder-suggested water and soil salinity management strategies, competitive residue uses, and climate change scenarios. The method one results demonstrate the importance of using high resolution (e.g., district level) crop yield and competitive residue use data when estimating bioenergy potential as low-resolution data can cause overestimations when competitive uses are not considered and underestimations when they are considered. Alternatively, the results of method two highlight the value of integrated analysis of the WEF nexus, suggesting that farm-level synergies exist between residue energy income and the implementation of water management practices, though trade-offs can exist in the presence of temporal delays. Both methods stress the importance of sub-national and local level analysis for strategic residue energy planning.

Résumé

La production d'énergie à partir de la biomasse et des résidus de culture est une solution proposée à la crise énergétique persistante du Pakistan. Cependant, les estimations actuelles du potentiel énergétique des résidus varient considérablement en raison des différences d'échelles et d'hypothèses. En outre, malgré les interdépendances significatives entre l'énergie basée sur les résidus et les systèmes agricoles et hydriques, les analyses quantitatives des implications du lien eau-énergie-alimentation (EEA) sur le potentiel énergétique des résidus sont inexistantes dans la littérature. L'absence de prise en compte des effets d'échelle, des hypothèses et des facteurs liés au lien EEA, tels que les utilisations concurrentielles, la disponibilité et la gestion de l'eau, le changement climatique, la qualité des sols et les pratiques agricoles, peuvent conduire à des surestimations du potentiel énergétique des résidus, ce qui entrave la mise en œuvre. Ceci est important au Pakistan, car la mise en œuvre réussie de projets énergétiques est vitale pour améliorer la crise énergétique actuelle et soutenir le développement durable.

Cette recherche applique deux méthodologies pour aborder ces aspects négligés de l'estimation du potentiel énergétique des résidus de culture. La première méthode consiste à calculer le potentiel énergétique des résidus pour la province du Punjab en fonction de différentes échelles d'agrégation des données (district, division administrative et province) et d'hypothèses sur la disponibilité des résidus et le rayon de collecte des matières premières. La deuxième méthode consiste en une étude de cas dans une région agricole du Rechna Doab, au Pendjab, par l'application novatrice d'un modèle couplé homme-eau (le P-GBSDM) pour examiner les implications du lien EEA sur les résidus de culture. Le P-GBSDM, qui saisit les rétroactions socio-économiques et environnementales spatialement explicites liées à la productivité agricole et aux paramètres hydrologiques dans la zone d'étude, a été modifié pour inclure l'énergie des résidus de culture et les rétroactions associées sur les revenus et les coûts. Les impacts du lien EEA sur la viabilité de l'énergie basée sur les résidus ont été explorés en simulant différentes stratégies de gestion de la salinité de l'eau et du sol suggérées par les parties prenantes, des utilisations compétitives des résidus et des scénarios de changement climatique. Les résultats de la première méthode démontrent l'importance d'utiliser des données à haute résolution (par exemple, au niveau du district) sur le rendement des cultures et l'utilisation concurrentielle des résidus lors de l'estimation du potentiel bioénergétique, car les données à faible résolution peuvent entraîner des surestimations lorsque les utilisations concurrentielles ne sont pas prises en compte et des sous-

estimations lorsqu'elles le sont. Alternativement, les résultats de la deuxième méthode soulignent la valeur de l'analyse intégrée du lien EEA, suggérant que des synergies au niveau de l'exploitation existent entre le revenu énergétique des résidus et la mise en œuvre de pratiques de gestion de l'eau, bien que des compromis puissent exister en présence de délais temporels. Les deux méthodes soulignent l'importance de l'analyse au niveau sous-national et local pour la planification stratégique de l'énergie résiduelle.

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Contribution of authors

The author of this thesis developed the literature review, methodology, data extraction and processing codes and analyzed the data. Dr. Jan Adamowski, Dr. Azhar Inam, Reza Alizadeh, Jessica Bou Nassar, and Julien Malard provided feedback on the concept and methodology. Reza Alizadeh assisted in preparing data input files and installing Tinamit. Dr. Azhar Inam Baig developed the original P-GBSDM, helped with parametrization for this research, and obtained necessary data from the Pakistan crop reporting service. Julien Malard developed Tinamit.

Publications and presentations

1. **Anderson**, **E.C.,** A. Inam, M.R. Alizadeh, J. F. F. Adamowski, and J.B. Nassar. Identification of Trade-offs and Synergies Between Crop Residue Based Energy and Water Management in Pakistan. Oral presentation at the *Delft International Conference on Sociohydrology*, online, 6 Sept 2021.
2. **Anderson**, **E.C.,** M.R. Alizadeh, J. F. Adamowski, J. Malard, and A. Inam. Use of Coupled Human-Water Model for Evaluating the Impacts of the WEF Nexus on the Energy Potential of Crop Residues in Pakistan. Oral presentation at the *EGU General Assembly 2021*, online, 28 Apr 2021, https://doi.org/10.5194/egusphere-egu21-6568.

3. **Anderson, E.C.** and J. F. Adamowski. Water-Energy-Food Nexus Considerations in Residue-Based Energy in Pakistan. Poster presented at the *McGill Sustainability Research Symposium*, online, 25-27 Jan 2021.
4. **Anderson**, **E.C.,** A. Inam, M.R. Alizadeh, J. F. F. Adamowski, and J.B. Nassar. Assumptions Matter: Analyzing the Impacts of Aggregation Scale and Residue Use Assumptions on Estimates of Residue Energy Potential in Pakistan (*To be submitted).*
5. **Anderson**, **E.C.,** A. Inam, M.R. Alizadeh, J. F. F. Adamowski, and J.B. Nassar. Application of a Coupled-Human Water Model to Explore the Impacts of the Water-Energy-Food Nexus on Bioenergy in Pakistan (*To be submitted)*.

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Chapter 1: Introduction

While Pakistan is rich in energy-producing resources, the current power infrastructure is underdeveloped, leading to average energy deficits of 3,000 MW (Irfan et al., 2020). Correspondingly, power authorities have had to employ load-shedding, causing outages of 7-10 h and 15-20 h per day in urban and rural areas, respectively (Rauf et al., 2015). The unreliable electricity supply has hampered industrial and economic growth (Kessides, 2013), slowed the adoption of alternatives to fossil-fuel-based technologies (Erenstein, 2009), and reduced GDP growth by 4% (Rehman Zia et al., 2020).

Pakistan's economic growth will continue to be constrained if its reliance on energy imports is not reduced (Rosbach & Aleksanyan, 2019). Pakistan relies on imported furnace oil and natural gas for most of its energy needs, reducing the energy system's resiliency and threatening the national security (Chu & Majumdar, 2012). As such, the Government of Pakistan aims to exploit indigenous resources to improve Pakistan's energy supply (Zafar et al., 2018; *Pakistan Economic Survey 2019-20*, 2020). Simultaneously, the Government of Pakistan is committed to an energy supply transition to support climate change mitigation and adaptation, with an ambitious target of increasing non-hydro renewable energy from ~4% today to 30% of total electricity supply by 2030 (Pakistan Ministry of Energy, 2019).

Bioenergy is increasingly being considered alongside solar and wind to support this energy transition. Agriculture is a pillar of Pakistan's economy, accounting for over 20% of GDP and 40% of the workforce (*Pakistan Economic Survey 2019-20*, 2020). However, land for agricultural expansion is limited due to population growth, land degradation, water availability and competition with non-agricultural sectors (Aggarwal et al., 2004; Kamal, 2009), restricting opportunities for bioenergy crops due to food security concerns (Naqvi et al., 2018; Rehman Zia et al., 2020). Correspondingly, crop residues are seen as a viable, readily available, and low-cost feedstock for biomass-based energy and various estimates of its energy potential in Pakistan have been made under different scales and assumptions (Iqbal et al., 2018; Irfan et al., 2020; Kashif et al., 2020; Naqvi et al., 2018; Tareen et al., 2019). As a result, estimates of the energy potential of crop residues in Pakistan have varied widely. For example, the annual residue energy potential in the province of Punjab has been estimated as 1700 MW/year (Uzair et al., 2020) and 7100 MW/year (Kashif et al., 2020). A better understanding of these significant discrepancies is needed to support strategic bioenergy planning. This is important as Pakistan's precarious economic situation has led many ongoing renewable energy projects to fail or underperform expectations (Irfan et al., 2019; Maqbool et al., 2020). Overestimates in residue-based energy potential can lead to infrastructure development with energy generation capacities that exceed the energy potential of available feedstocks, creating financial risks due to revenue inadequacy (Kessides, 2013).

Transitions towards sustainable production and consumption systems are theorized as complex, dynamic and political processes that involve change and interactions in and between multiple systems (Van Den Bergh et al., 2011). Residue-based energy is attractive as it may have Water-Energy-Food (WEF) nexus synergies since the same land and water inputs are used to produce food and energy feedstock (Carriquiry et al., 2011; Creutzig et al., 2015). This is in contrast to traditional "first-generation" bioenergy crops, which either displace food production (Hasegawa et al., 2015) or cause an increase in cultivated areas, threatening biodiversity (Evans et al., 2015) and straining water and land resources (Popp et al., 2014; Tapia et al., 2019). However, the implications of the water-energy-food nexus on residue-based energy are under-examined in the literature, both globally and in Pakistan. For example, residue bioenergy potential can be overestimated without considering local factors, including water availability and management, climate change, soil quality, farming practices, harvest capacity, and competitive uses. Understanding the linkages, feedbacks, and trade-offs between different systems and impacts is key to understanding what affects biomass supply (and demand) (Wicke et al., 2015).

Furthermore, as crop residues are low-density lignocellulosic feedstocks, the viable feedstock sourcing area, based on the transportation distance between the feedstock source and power plant, is economically constrained by transportation costs (Chu & Majumdar, 2012). Therefore, due to spatial variability in crop and residue yields, it is necessary to consider the spatially explicit impacts of the water-energy-food nexus on net energy yield per area over time for bioenergy site selection. This is especially relevant in Pakistan as soil salinity impacts 35% of areas equipped for irrigation, groundwater levels are declining (FAO, 2020), and the region is highly vulnerable to climate change (Khan et al., 2016). Furthermore, many residues have well-established competitive uses, including fodder, traditional fuel (domestic fuel), sale to industries, sale to biomass providers and fertilizer (Rehman Zia et al., 2020), further limiting residues available for energy generation. Therefore, a nexus approach to resource management is vital in countries like Pakistan, as water and food availability is directly affected by growing energy costs and electricity shortages, given the relatively high (and increasing) energy intensity of the agricultural production systems (Siddiqi & Wescoat, 2013).

As such, this research intends to fill gaps in knowledge about the diverse factors impacting the viability of crop residue-based energy in Pakistan and beyond to support strategic bioenergy implementation. Correspondingly, this thesis has two broad aims:

1. investigate how assumptions and scale impact residue-based energy potential estimates and,
2. explore the implications of interactions between the water-energy-food nexus and residue-based energy in Pakistan.

Aim one is achieved by calculating crop residue energy potential for the province of Punjab under different assumptions and scales of data aggregations (method one). Alternatively, aim two is accomplished through a case study in the Rechna Doab region through the application of a coupled human-water model (Inam et al., 2015; Inam, Adamowski, Prasher, & Albano, 2017; Inam, Adamowski, Prasher, Halbe, et al., 2017) of the local agricultural system (method two). The coupled-human water model (the P-GBSDM) captures the spatially explicit socioeconomic and environmental feedbacks related to agricultural productivity, hydrological parameters, and farmer livelihood indicators. Scenario analysis is used to explore how factors related to the WEF systems impact the viability of residue-based energy by simulating the effect of stakeholder-selected water management strategies, competitive residue uses, climate change and added farm income and cost feedbacks over time. The residue use scenarios explored include none, competitive residue use and ecological residue uses, while the water management scenarios include status quo, canal lining, irrigation improvement, rainwater harvesting, and vertical drainage. All possible combinations of residue use and water management scenarios were simulated under current climatic conditions from 2005 to 2030. Furthermore, to understand the potential impacts of climate change on local residue energy potential, the combinations were simulated through two climate change scenarios, representing current radiative forcing and the radiative forcing of Representative Concentration Pathways (RCPs) RCP 4.5 and RCP 8.5 in 2100. Risks and opportunities for residue-based energy were identified while considering farmer livelihoods and WEF nexus trade-offs and synergies arising from system feedbacks. Through analysis and summary of the results of both methods, recommendations were made for bioenergy planning and optimized management of WEF systems in Pakistan.

1.1 Objectives

To achieve the aims outlined above, this thesis has six specific objectives. Objectives one and two relate to aim one, whereas objectives three to five relate to aim two. Objective six relates to the broader intent of this thesis to support strategic bioenergy planning and implementation. The objectives are as follows:

1. Collect and critically analyze existing estimates of crop residue-based energy potential in Pakistan (chapter 2, section 2.4)
2. Estimate residue-based energy potential at three spatial scales: the province of Punjab, its administrative divisions, and its districts, and under various competitive use and collection radius assumptions, to delineate the impacts of scale and assumptions on crop residue-based energy estimations (chapter 5).
3. Develop and apply a methodology to estimate crop residue-based energy potential and associated feedbacks related to added farm income and costs within the P-GBSDM (chapters 4 and 6).
4. Develop and simulate scenarios to explore how factors related to the WEF systems impact the viability of residue-based energy, including stakeholder-approved water management strategies and soil salinity, competitive residue uses and climate change (chapters 4 and 6).
5. Perform trade-off analysis on simulation results of variables of interest related to residue based-energy, water availability, soil salinity, and farmer livelihood indicators to identify trade-offs and synergies. Explore the impact of scale on residue-based energy estimates by comparing the residue energy density of the case study area to that of Punjab, its administrative divisions, and its district (chapter 6).
6. Identify residue energy and agricultural production risks and synthesize recommendations to support strategic and integrated bioenergy planning (chapter 7).

1.2 Thesis structure

The thesis is structured as follows: Chapter 2 provides a literature review on residue energy assessments globally and in Pakistan, exploring how methodological approaches and assumptions impact estimations. Chapter 2 also includes information about the conceptual and methodological framework applied in method two, explaining the water-energy-food nexus as a conceptual framework and rationalizing the case study and simulation methodology. Chapter 3 provides an overview of the study area. Chapter 4 outlines the methods of methods one and two. Chapter 5 provides the results and discussion from method one, while chapter 6 provides the results and discussion from method two. Chapter 7 concludes the thesis, highlighting the implications of the results from both methods for bioenergy planning and implementation in Pakistan and beyond.

Chapter 2: Literature review

2.1 Estimating residue energy potential

Crop residue energy is energy produced from the by-product material of food or feed crop production (Rahman & Paatero, 2012). Residues can be divided into field residues, such as wheat straw or cotton stocks, which are left in the field after harvest and processes residues, which are removed from the grain during post-harvest processing.

Several metrics are used to estimate the potential of biomass-based energy, including theoretical, technical, eco-technical, economic, and implementation potential (Vis and Berg, 2010). As demonstrated in Figure 1, starting at theoretical potential, each subsequent type represents a fraction of the previous. The theoretical potential refers to the maximum residues available for bioenergy production given biophysical limits (Gonzalez-Salazar et al., 2014). The technical potential is the share of theoretical potential residues available for the given socio-technical system, considering harvesting techniques and processing technical constraints (Gonzalez-Salazar et al., 2016). Estimates of technical potential sometimes also include sustainability; therefore, the eco-technical (ecological technical) potential is the amount that can be sustainably removed from a field to maintain ecological integrity and function (e.g., soil carbon, erosion prevention) given technological constraints (Thorenz et al., 2018).

The economic potential is the fraction of the technical potential (or eco technical potential if sustainability is considered) which meets economic profitability criteria of farmers and energy producers. Economic evaluations vary, with some authors focusing on calculating the localized cost of electricity for electricity produced by residues (Rehman Zia et al., 2020), with other authors concentrate on the economic availability of residues given existing competing uses (Hanssen et al., 2020; Hoogwijk et al., 2003; Thorenz et al., 2018). The latter approach, which considers competitive uses, has been termed the bioeconomic potential (Thorenz et al., 2018). Estimates of economic potential that consider sustainability can be termed eco-economic.

Some estimates of residue energy economic potential also take into account residue-energy densities and corresponding collection radii, as transportation costs of feedstocks can constrain the economic viability (Kashif et al., 2020; Monforti et al., 2015); for this thesis, this approach can be termed logistical potential. Finally, the implementation potential is the share of the economic potential that can be implemented under current or future socio-political conditions (considering economic, institutional, and social constraints and policy incentives). Studies of implementation potential often consider how socio-technical system change impacts bioeconomic or economic potential, for example, by considering how the shared-socioeconomic pathways drive and constrain future global economic (residue energy) potential by affecting competitive uses (Daioglou et al., 2016). While this paper briefly touches on local-level implementation potential by exploring how human-environmental system functioning impacts local residue energy potential, the focus is more on the technical, bioeconomic, eco-economic and logistical potential of bioenergy in Pakistan. The calculation of theoretical, technical, eco-technical, bioeconomic and logistical potential are described below.

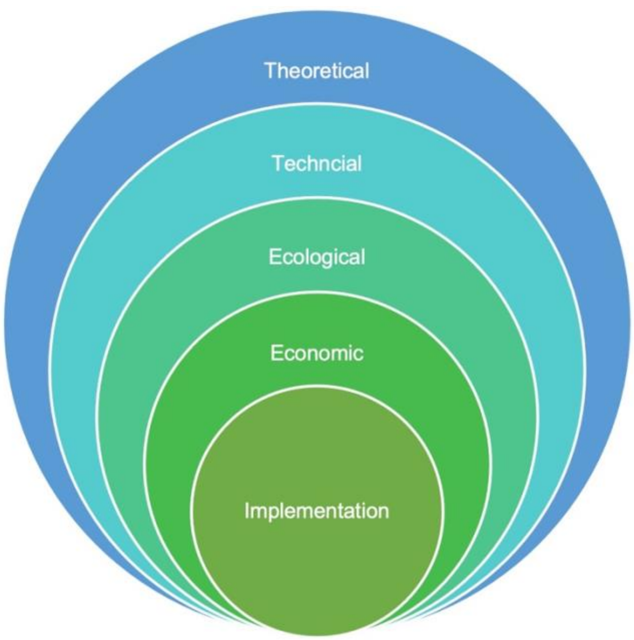


Figure 1 Hierarchy of biomass energy potential estimations.

2.2 Calculating crop residue-based energy potential

In general, the energy potential of residue-based energy is calculated as:

$$Ep = \sum (RA^{f}_{c,i} * LHV^{f}_{c} \quad + RA^{p}_{c,i} * LHV^{p}_{c}) \qquad \forall\, c \cup i \qquad (1)$$

where $Ep\ \left(\frac{\text{MJ}}{\text{yr}}\right)$ is energy potential, $RA_{c,i}^{f}$ and $RA_{c,i}^{p}\ \left(\frac{\text{tonne}}{\text{yr}}\right)$ are the residue availabilities of field (f) and process (p) residues for crop (c) in an area (i), and LHV_c^f and $LHV_c^p\ \left(\frac{\text{tonne}}{\text{yr}}\right)$ are the lower heating values of the field (f) and process (p) residues of crop (c). The lower heating value of a substance represents the thermal energy produced by the combustion of that substance while considering energy losses, for example, due to the energy needed to vaporize water.

Estimates of theoretical, technical, eco-technical, and bioeconomic energy potential vary in how residue availability is determined, as shown below. Conversely, the logistical potential goes further to consider how the density of available residues in each area impacts energy generation feasibility given a set maximum collection radius.

The theoretical residue availability of either process (p) or field (f) residues, which represents the maximum residue available given biophysical constraints, is calculated as (Gonzalez-Salazar et al., 2014):

$$theoretical\ RA_{c,i}^{f\ or\ p} = CY_{c,i} * RPR_c^{f\ or\ p} \tag{2}$$

where $CY_{c,i}\left(\frac{\text{tonne}}{\text{yr}}\right)$ is the crop (grain) yield for crop (c) in an geographical area (i) and $RPR_c^{f\ or\ p}(\frac{\text{tonne}}{\text{tonne}})$ is the residue to product ratio, which represents the ratio of either process(p) or field (f) residue yields to grain yields for a particular crop (c).

Alternatively, technical residue availability or either process (p) or field (f) residues, which represents the share of theoretical potential biomass that is available given farm-level and processing-level technical constraints, including harvesting and processing techniques, is calculated as (Kashif et al., 2020):

$$technical\ RA_{c,i}^{f\ or\ p} = CY_{c,i} * RPR_c^{f\ or\ p} * RRF_c^{f\ or\ p} \tag{3}$$

where $RRF_c^{f\ or\ p}$ (%), the residue removal factor, is the portion of either process (p) or field (f) residues for a particular crop (c) in an area (i) that is recoverable given technological constraints. In general, the $RRF_c^{p} \approx 1$, as process residues are the by-products of post-harvest processing.

If sustainability is considered, the eco-technical residue availability of field (f) residues is calculated using equation four (Daioglou et al., 2016). The eco-technical residue availability of process residues is equal to the technical availability, as these are inevitably removed from the field during crop harvest.

$$eco - technical\ RA_{c,i}^{f} = CY_{c,i} * RPR_c^f * ERRF_c^f \tag{4}$$

where $ERRF_c^f$ (%), the ecological residue removal factor, is the portion of field (f) residues for a particular crop (c) that is recoverable given technological and sustainability constraints in an area (i).

The bioeconomic residue availability, which considers the surplus residues available given competitive uses such as food, fibre or fuel, is calculated as (Thorenz et al., 2018):

$$bioeconomic\ RA_{c,i}^{f\ or\ p} = CY_{c,i} * RPR_c^{f\ or\ p} * RRF_c^{f\ or\ p} * SAF_{c,i}^{f\ or\ p} \tag{5}$$

where $SAF_{c,i}^{f\ or\ p}$(%), the surplus availability factor, is the surplus process (p) or field (f) residues of crop (c) that are available for energy production given competitive uses in an area (i). If sustainability is considered, then the eco-economic energy potential can be calculated by replacing RRF_c^f with $ERRF_c^f$.

The logistical potential of residue energy can then be further defined by considering (1) the number of power plants (N) that can be supported given the energy potential (equation six), (2) the equivalent collection radius (ECR) of residues for an area (i) and (3) a maximum collection radius, as determined by transportation logistics (Kashif et al., 2020).

$$N_i = round(\frac{Ep_i}{RE}) \tag{6}$$

where N_i is the number of potential power plants and Ep_i is the energy potential per year in an area (i). RE is the required energy per year for each power plant. Both residue energy potential and required energy must be in the same energy/time units (e.g., MW or KJ/year). N_i is rounded down.

The equivalent collection radius (ECR), which represents the maximum radial distance for the collection of crop residues based on the geographical area and number of potential power plants, is calculated as:

$$ECR_i = \sqrt{\frac{A_i}{N_i * \pi}} \tag{7}$$

where ECR_i (km) is the equivalent collection radius and A_i (km^2) is the area of the geographical area (i).

Given a maximum feasible collection radius (CR_{max}), the logistical energy potential is calculated as:

$$Ep_i = \begin{cases} N_i * RE, & ECR_i \leq CR_{max} \\ 0, & ECR_i > CR_{max} \end{cases} \tag{8}$$

$$logistical\ Ep = \sum_{i=1}^{n} Ep_i \tag{9}$$

where Ep_i is the logistical energy potential of a given area (i), given a maximum collection radius, CR_{max} (km).

2.3 Agricultural residue-based bioenergy: Global outlooks to local implementation

Globally, the technical potential of residue-based bioenergy is much lower than the theoretical potential due to functional land and material uses. Multiple studies of the global prospects of residue-based energy have been performed (Cornelissen et al., 2012; Daioglou et al., 2016; Fischer & Schrattenholzer, 2001; Gregg & Smith, 2010; Haberl et al., 2010, 2011; Hakala et al., 2009; Hoogwijk et al., 2003; Searle & Malins, 2015; Smeets et al., 2007), with global primary energy estimations of agricultural residues ranging from 10-55 EJ/year in 2050 (Hanssen et al., 2020). Studies employing a top-down approach based on macro-economic drivers had a higher average residue-based energy potential than bottom-up studies, which estimate residue availability based on trends in population, diet, consumption patterns, and ultimately agricultural and forestry production. However, with both approaches, large variabilities exist between individual studies based on whether ecological (e.g., soil quality, biodiversity and/or carbon capture) or economic constraints (e.g., competitive uses) were considered, along with other assumptions (e.g., about cropping intensity, yield improvements, as well as the economics of harvesting, aggregating and transporting residues) (Hanssen et al., 2020). The extensive range in estimates suggests that a better understanding of the drivers of residue availability is needed, including a comprehensive evaluation of residue generation and alternatives (Daioglou et al., 2016). However, many drivers or residue generation and availability occur at sub-regional scales and cannot be incorporated into global estimates due to a deficiency in fine-scale datasets and associated computational costs.

As a result, while global estimates help determine the feasibility of residue-based bioenergy, they overestimate economic and implementation potential as this is highly dependent on local circumstances (Hanssen et al., 2020). This is especially relevant when considering supply chain logistics, as most estimates consider all residues usable, regardless of spatial origin. However, residue density (residue availability per unit area) is highly important, as the low-energy density of lignocellulosic feedstocks creates higher transportation costs, limiting the viable collection radius (Chu & Majumdar, 2012; Kashif et al., 2020; Monforti et al., 2015). Furthermore, significant opportunity costs may be associated with diverting residues to other sectors, leading to cascading impacts or unintended consequences (Carriquiry et al., 2011). Therefore, global studies should not be relied on alone for estimates of bioenergy potential that aim to support implementation at a national or sub-national scale. Instead, their insights can be augmented with methods that allow for the physical representation of residue productivity, ecological functions, and alternative use at the sub-national scale.

2.4 Bioenergy in Pakistan: Current estimates

Correspondingly, several studies have quantified the energy potential of residue-based bioenergy in Pakistan (Iqbal et al., 2018; Irfan et al., 2020; Kashif et al., 2020; Naqvi et al., 2018; Uzair et al., 2020). However, estimates have ranged widely due to differences in assumptions and data scale. Table 1 shows a comparison in residue estimates and methodological choices.

Table 1 Estimates of crop residue-based energy in Pakistan and corresponding assumptions.

Source	Annual Energy Potential	Aggregation Scale	Values
Khasif et al. (2020)	11,000 MW	Administrative Division	RRF = 50% SAF= n.a. Cr = 50 km
Uzair et al. (2020)	10,331 MW assuming SAF=1 3100 MW considering competitive uses	Administrative Division	RRF = 0.35-1 SAF= 0.2-1 Cr= n.a.
Farooq et al. (2013)	1,744 MW technical potential * Does not consider bagasse or wheat due to competitive uses	Country	RRF=0.35, SAF= n.a., Cr= n.a.
Iqbal et al. (2017)	58,313 MW	Country	RRF= n.a., SAF= n.a., Cr = n.a.
Irfan et al. (2020)	90,223 MW	Country	RRF= n.a. SAF=n.a., Cr = n.a.

While these studies provide a good indication of the feasibility of residue-based energy in Pakistan, there are several limitations and methodological differences that reduce their applicability for the implementation of bioenergy projects. Climate change is only considered by Kashif et al. (2020), who they assume it will improve crop yield due to carbon enrichment of the atmosphere. However, due to the projected impacts of climate change on water resources and temperatures, agricultural yields may be negatively impacted by increased heat and water stress, negating any beneficial impacts of the atmospheric carbon enrichment (Aggarwal et al., 2004). For example, projections for South Asia predict a -8% change in yields across all crop types by 2050 due to increased temperatures and erratic water availability (Knox et al., 2012). More specifically, in Pakistan, estimates have shown that a 1°C increase in temperatures can result in a decrease of 194741, 351234, 387812, 349128 and 5519 tonnes in rice, wheat, maize, sugarcane and cotton yields, respectively (Ali & Erenstein, 2017; Gul et al., 2021).

Likewise, the scale of analysis ranged considerably, deriving estimates from yield data at the district to country-wide scale. All scales considered were greater than the feasible collection radius, which is the radius in which transportation of residues to a power plant is possible given economic constraints. Therefore, the impact of heterogeneous yields (and residue density) on the feasibility of residue-based bioenergy was not considered. Likewise, factors contributing to heterogenous yields, including soil salinity, water stress and different cropping patterns were not considered. Furthermore, the maximum viable collection radius of 50 km used in Kahsif et al. (2020) was based on Monforti et al. (2015), who calculated the number based on a maximum transportation distance of 70 km and a road deviousness factor of 1.4 (70km/1.5 = 50 km radius). However, this road deviousness factor is based on the European Union, with Circuity factors in developing countries ranging between 1.4-2.0 (Ballou et al., 2002). Other research assumes an even smaller maximum viable collection distance of 10-40 km (Höhn et al., 2014).

Similarly, the temporal impacts of management strategies were not considered. Residue yields can be impacted by management practices that aim to remediate soil salinity or fertility or reduce water usage in the short and long term. For example, some water management strategies may decrease crop yields in the short-term in order to improve soil salinity and overall result in the long-term (Inam, Adamowski, Prasher, Halbe, et al., 2017), causing decreased residue feedstocks for bioenergy implementation. Similarly, system feedbacks related to management practices, income and production costs may have unintended consequences on yields due to nexus interactions. For example, since irrigation from tubewells is often limited by farmer income in Pakistan (Qureshi, 2020), increased revenue from residue sales could lead to an increase in groundwater use. Increased groundwater use could improve crop yields in the short term due to decreased water stress. However, in the long-term, increased groundwater use could exacerbate groundwater drawdown, leading to greater salinization of groundwater and thus soil, and increased pumping costs since costs are related to groundwater depth (Qureshi et al., 2003).

As outlined in section 2.2, the net supply of residues is calculated through the product of grain yield and a residue-to-product ratio (also known as harvest index or residue-to-grain ratio). In all the studies listed above, these values are fixed, despite considerable evidence that residue yields vary with grain yields (Daioglou et al., 2016b).

One of the most important constraints impacting residue bioenergy potential is competitive uses. Multiple alternative uses exist already for residues in Pakistan, including fodder, traditional fuel (domestic fuel), sale to industries, sale to biomass providers and fertilizer (The World Bank, 2016). The remaining crop residues are burnt in the field. Irfan et al. (2020) and Naqvi et al. (2018) use competitive use data from Bangladesh, which is not necessarily representative of the situation in Pakistan. Alternatively, Kashif et al. (2020) did not consider competitive uses, instead assuming that 50% of yields are available for use. Pakistan-specific data should be applied to get an accurate picture of the impact of competitive uses on residue availability. For example, in (Farooq & Kumar, 2013), bagasse and wheat straw are not considered in calculations of residue-based energy because they both have well-established competitive uses in Pakistan. Specifically, wheat straw is often used for animal feed and fodder. In contrast, bagasse, the leftover material from sugar cane processing, is used by sugar mills to create energy to power their facilities (Farooq & Kumar, 2013). As will be elaborated on later, due to local economies the use of these residues varies by district and crop type.

Finally, the impact of ecological constraints on residue yields were poorly defined. Residue removal rates must not deplete soil organic carbon stocks otherwise crop yield may be reduced, reducing energy potential and farm income, or increasing fertilizer inputs needed to sustain yields, which increases environmental impacts associated with carbon emissions from fertilizers and nutrient runoff and rising costs of production (Warren Raffa et al., 2015). Alternatively, a reduction in residue burning could lead to decreased air pollution since open field burning leads to increased atmospheric pollution from aerosols, particulate matter, and trace gasses, (Tariq et al., 2015), which would offset the carbon footprint associated with this practice (Benbi, 2018).

The numerous factors impacting residue availability and viability as an energy source in Pakistan must be better understood. Therefore, this research applies two methods to improve this understanding; (1) method one, which compares residue-based energy potential estimations for the province of Punjab using different assumptions and aggregation scales and (2) method two, which applies the Water-Energy-Food nexus as a conceptual framework to understand how interactions between these systems impact residue energy potential. Exploratory scenario analysis is applied using a participatory-built coupled human-water model to capture these interactions. The rationale behind using the WEF nexus and the coupled-human water model is explained briefly below.

2.4 Conceptual framework

2.4.1 Water-energy-food nexus

The WEF nexus is a conceptual approach broadly used to consider interdependencies and integration of key production and consumption systems for sustainable resource management (Albrecht et al., 2018; Pahl-Wostl, 2019; Wolfe et al., 2016). By considering interrelationships and feedbacks, synergies (mutually beneficial outcomes) and trade-offs (non-optimal outcomes) of potential resource management solutions can be understood, which allows for the internalization of social and environmental impacts (Kurian, 2017). As opposed to a single-sectoral approach, the WEF nexus aims to avoid externalities related to siloed management (Albrecht et al., 2018; Biggs et al., 2015). Examples of applications of system dynamics in WEF research include (Burhanudin et al., 2021; Kotir et al., 2016; Tong & Dong, 2007; Yang et al., 2019; Yung et al., 2019; Zhang et al., 2018).

WEF systems are socio-technical systems that support the provision of societal functions, such as sanitation services, food, fuel, and fibre, and consist of a combination of technology, norms, practices, infrastructure, and institutions. These systems reinforce incumbent structures (Brauch et al., 2016). Transformational failure and externalities can occur when the reinforcing structure of incumbent socio-technical systems is not considered in the planning and implementation of sustainability transitions. For successful residue-based bioenergy development, relevant feedbacks between these systems should be considered.

As stated above, in the case of residue-based energy, the current analysis overlooks feedbacks related to the WEF nexus that impact residue-based energy or the agricultural system. This is despite residue-based energy having significant WEF dependencies. As an agricultural by-product, residues are constrained by crop yields (food), which are directly dependent on irrigation (water) of adequate quality and quantity and acceptable inputs (fertilizer, labour/machinery), both of which are dependent on sufficient energy inputs (Zhang et al., 2018). Given these complex interlinkages, failures, or deficiencies of one sector, e.g., water depletion or energy crisis, may have cascading impacts on the other systems (e.g., food and energy production). Beyond climate change and energy security, knowledge of how interactions between the WEF nexus may impact crop residue-based energy is essential to optimizing implementation and avoiding tensions (Bazilian et al., 2011).

2.4.2 Modelling framework

To explore the localized impacts of the WEF nexus on residue-based energy in Pakistan, it was necessary to apply an appropriate modelling framework. The desired framework must be able to simultaneously and accurately represent physical processes related to crop yields and water systems and socioeconomic factors related to farmer behaviour and management, as well the human-environmental feedbacks linking them. Therefore, this research applied a coupled human-water systems model (described in section 4.2.1) of an agricultural region in Pakistan (described in chapter 3). The modelling frameworks applied, including system dynamics modelling, coupled participatory modelling and exploratory scenario analysis, are described below.

2.4.2.1System dynamics modelling

System dynamics, founded by Forrester, (1961) is an object-oriented modelling approach which is based on the idea that real world system behaviour is the result of feedbacks and interactions between system components. Systems dynamics models are highly suited to studying transitions and the WEF nexus because they allow for the conceptualization of problems in terms of feedbacks affecting them, time delays, and complex and non-linear relationships (Raven & Walrave, 2020; Sterman, 2000). There are numerous examples of the application of system dynamics to studying the WEF nexus (Yung et al., 2019; Zhang et al., 2018) (e.g., Burhanudin et al., 2021; Kotir et al., 2016; Tong & Dong, 2007; Yang et al., 2019).

The creation of system dynamics models, especially in a participatory setting, is usually facilitated through the creation of causal loop diagrams (mental models), in which system variables are linked with positive or negative polarities, creating feedback loops that show how actions or changes in variables impact the problem variable (Bala et al., 2017). The polarity of the casual links that join variables indicates whether the independent variables have a direct or inverse effect on the dependent variables. A positive polarity suggests a direct effect; an increase in the independent variable increases the dependent variable. A negative polarity indicates an inverse effect; an increase in the independent variable decreases the value of the independent variable. The succussive linking of variables can lead to feedback loops, representing the qualitative behaviour of a system. There are two types of feedback loops, reinforcing and balancing. Reinforcing loops create an exponential or amplifying impact on the process of interest, whereas balancing loops equilibrate the system's state, counteracting the process. CLDs are then quantified by creating stock and flow diagrams, where the causal links between variables are represented through mathematical equations. This process was undergone in a participatory process used to develop the model applied in the research (as outlined in (Inam et al., 2015)).

2.4.2.2 Coupled participatory modelling

Increasingly, however, to overcome challenges related to the representation of physical processes using system dynamics models, integrated modelling, which couple system dynamics models with other modelling frameworks, such as physically based models, are used to improve the representation of physically-based processes (Basco-Carrera et al., 2017; Kotir et al., 2016). As pointed out by Liu et al. (2017), data and representation also remain critical challenges in analyzing the WEF nexus. Conventional modelling techniques often either (1) do not consider critical socioeconomic feedbacks or (2) consider them exogenously (outside the system boundary), which can narrow model boundaries and limit the ability of the model to capture human-environmental dynamics (Baig, 2017). Additionally, statistical and process-based models can require large amounts of data.

In a data-scarce environment, participatory-built models can help capture important interactions between human and environmental factors, which are paramount to resource management (Bou Nassar et al., 2021; Halbe et al., 2018; Inam et al., 2015). However, as stakeholders build participatory-built models, they can include simplified versions of physical phenomena. As human development and societal changes co-occur through interactions between human and environmental systems, the practice of coupling socioeconomic models with physically-based environmental models can strengthen the representation of physical processes and thus the interactions between socio-technical and environmental systems (Inam, Adamowski, Prasher, & Albano, 2017; Inam, Adamowski, Prasher, Halbe, et al., 2017; Malard et al., 2017). Therefore, coupled participatory-built models provide avenues for exploring underexamined factors impacting residue-based energy. Beyond accurate representation of the system, participatory modelling engages stakeholders, which is critical for sustained environmental management and decision-making (R. Biggs et al., 2007; Bou Nassar et al., 2021). Stakeholder involvement in the modelling and policy selection processes may also improve the quality and inclusiveness of policy solutions and their broader acceptability (Butler and Adamowski, 2015).

2.4.2.3 Exploratory scenario analysis

Scenario analysis is commonly applied in research related to environmental management (Tourki et al., 2013). Scenarios are used to explore plausible stories of how futures unfold when factors affecting the future are uncontrollable or uncertain (Albrecht et al., 2018; Biggs et al., 2007). Scenarios are constructed using quantitative or qualitative models based on current and past conditions modelling. Scenarios that are developed in participatory processes can be powerful tools to improve knowledge-sharing, collective understanding and communication among stakeholders (Bou Nassar et al., 2021).

Scenario analysis does not aim to predict a single accurate outcome (Biggs et al., 2007). Instead, scenario analysis can be used to help decision-makers identify policies that are robust over a wide range of possible futures or promote a desired outcome, such as the sustainable development goals. As both methods aim to explore trends in system behaviour, rather than predict point values, scenarios analysis is often performed using system dynamics modelling (e.g., (Burhanudin et al., 2021; Kotir et al., 2016; Tong & Dong, 2007; Yang et al., 2019)) and coupled physical-based and system dynamics models (e.g., (Qin et al., 2019)). Scenarios are often applied to understand the interactions between socioeconomic factors and agricultural and water systems (e.g., Kotir et al., 2016).

In general, scenario analysis is seen as a valuable tool for linking pathways of environmental development and management and human well-being, such as in socio-ecological systems (Carpenter et al., 2006) and human-water systems (e.g., (Burhanudin et al., 2021; Kotir et al., 2016; Tong & Dong, 2007; Yang et al., 2019)). Several authors have applied scenario analysis in exploring the implications of the WEF nexus (Albrecht et al., 2018; Kulat et al., 2019; Lee et al., 2020; Wen et al., 2022; Wu et al., 2021; Yung et al., 2019; Zuo et al., 2021).

The scale of scenario analysis exercises ranges from global to local villages depending on the intent of the exercise and the methods used (e.g., (Carpenter et al., 2005; Alcamo et al., 2006)). However, global, regional or even national level scenario storylines related to development pathways are often too spatially coarse to adequately capture impacts, vulnerability and adaptive capacity of systems to environmental or policy change, which are often place-based phenomena (Kriegler et al., 2012). Most applications of scenario analysis for analyzing the impacts of changing conditions and policies on crop residue-based energy have focused on the national (e.g., in Denmark (Hansen et al., 2020), Hungary (Soha et al., 2021) and Nigeria (Iye & Bilsborrow, 2013)), regional (e.g., for Europe (Monforti et al., 2015)) or global scales (e.g., (Daioglou et al., 2016; Hanssen et al., 2020). Notably, local-scaled crop residue energy potential scenarios are missing, especially those exploring the impact of various policies, environmental conditions, and farmer behaviour and residue availability. Therefore, to reap the benefits of assessments at multiple scales, this research applies both residue-energy estimates at a regional scale (Punjab) and exploratory scenario analysis and simulation at a local scale (750 km^2). Below the study area is described, followed by the methodology section.

Chapter 3: Study Area

This research explores factors impacting residue-based energy in Pakistan, to support strategic bioenergy implementation to ameliorate the current energy crisis and support a clean energy transition. To do so, two methods are applied at different scales: the Provincial and sub-district scales.

The study area for method one, which estimates the provincial residue potential energy under different use assumptions and data aggregation scales, is the province of Punjab (figure 2). Punjab is the second largest province in Pakistan and an industrial and agricultural powerhouse, accounting for 83% of cotton, 80% of wheat, 97% of aromatic rice, 63% of sugarcane and 51% of maize production in the country (Agricultural Statistics of Pakistan, 2012). Over three-quarters of the total geographic area is cultivated. Punjab consists of 9 administrative divisions and 36 districts, as shown in figure 2. Of the cropped area, around 88% is irrigated with either canals or surface water (Agricultural Statistics of Pakistan, 2012). While crop productivity in the province has been improving, it still lags behind international peers by as much as 60% (Gul et al., 2021b)

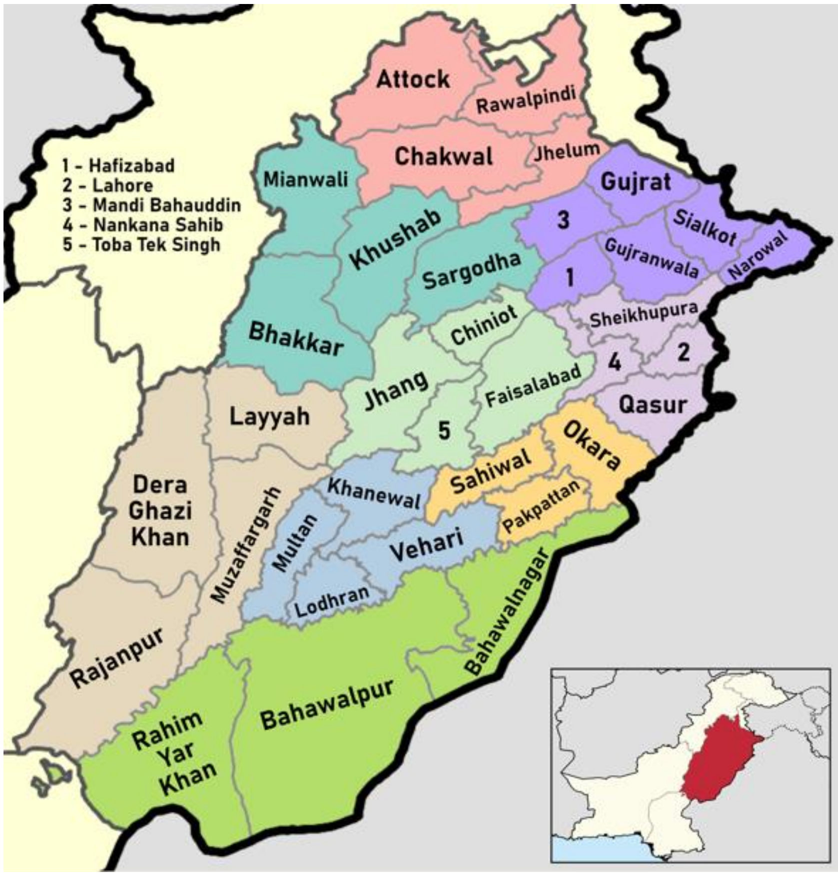


Figure 2 A map of the districts of Punjab, Pakistan, with each district's name in English. Colours correspond to Divisions (Abdullah Ali Abbasi, CC BY-SA 4.0, Wikimedia Commons).

To explore the implications of the WEF nexus on crop residue-based energy in Pakistan, method two applies a case study in the lower Rechna Doab by applying a coupled human-water model. The Rechna Doab is wholly located within the province of Punjab, and the study area (figure 3) is the region bound by the Chenab and Ravi rivers and the Haveli canal. The region is mainly within the Jhang district of the Faisalabad administrative division, with a small portion in both the Khanewal district of the Multan division and the Toba Tek Singh District of the Faisalabad division. Uzair et al. (2020) identified the Jhang district as having a high electricity generation potential, while Toba Tek Singh had an average potential. Kashif et al. (2020) identified both the Faisalabad and Multan administrative divisions as having high residue-based energy potentials.

The lower Rechna Doab is an agricultural region reliant on irrigation, where rice-wheat rotations dominate, but cotton-berseem rotations are also prevalent (Inam et al., 2015). Irrigation water is provided through surface water supplies from canals and groundwater from tubewells. As with most irrigated areas in Pakistan, deficit irrigation is common due to water availability and tubewell operation costs (Erenstein, 2009; Qureshi et al., 2003; Wescoat et al., 2018). Up to 30% of the area is fallow due to soil salinity, a widespread issue throughout Pakistan.

Figure 3 Study Area of Method Two: the lower Rechna Doab (produced using Google Maps).

Chapter 4: Methodology

This research applies two methods to estimate residue-based energy potential in Pakistan at two different scales. For both methods, the residues of Pakistan's five important crops are considered: wheat, rice, maize, cotton, and sugarcane (Government of Pakistan (Planning Commission, Ministry of Planning, 2020). Crop residues are divided into two categories: field residues and process residues. Field residues include wheat and rice straws, sugarcane tops, cotton stalks and maize stalks. Process residues include rice husks, bagasse, and maize cobs and husks.

4.1 Overview of the two methods

As stated above, this research uses a combination of methods to estimate crop-residue energy, allowing for the exploration of the impacts of multiple factors, such as scale, water management policies, alternative residue uses and climate change. The details and differences between method one and method two are shown in table 2.

	Method one: standard method	Method two: P-GBSDM
Scale of Energy Potential Estimate	Province of Punjab	The lower Rechna Doab (sub-district: 750 km^2)
Temporality	3 years: 2010, 2015, 2020	2005-2030: 25 years (50 seasons)
Crop Yield Data Source	Crop reporting service of Punjab	Computed through simulation of the P-GBSDM model
Scenario Components	• 100% and 50% residue use • Competitive and ecological use • Spatial aggregation levels of yield data (district, administrative division, and provincial level) • Maximum collection radius (35 versus 50 km).	• Competitive and ecological residue use • Water management policies (canal lining, rainwater harvesting, vertical drainage, and irrigation improvement)
Energy Variables of Interest	• Residue availability • Residue energy density • Energy potential • Equivalent collection radius	• Residue availability • Residue energy density • Energy potential
Water, Food and Livelihood Variables of Interest	• n/a	• Water availability, groundwater depth and soil salinity • Crop yield • Farmer net income • Water policy indicators

Table 2 Methods applied in this research to calculate residue potential energy.

4.2 Method one

Method one aimed to investigate the impact of aggregation scale and residue use assumptions on estimates of residue potential energy for the province of Punjab. Under different residue use assumptions, residue energy potential was calculated based on crop yields reported by the Government of Pakistan's Crop Reporting Service (http://www.crs.agripunjab.gov.pk/reports). The theoretical, technical, bioeconomic and eco-economic energy potential estimates for the province of Punjab were calculated using data aggregated at three scales (from finest to coarsest): the 36 districts of Punjab, the nine administrative divisions and the province and assuming three potential maximum collection radii (maximum CR=None, maximum CR=50 km and maximum CR=35 km). Due to economies of scale, there is a significant reduction in specific investment costs ($/KW) when building a 100 MW versus a 10 MW power plant, resulting in a lower and more competitive Levelized Cost of Electricity (COE) (Uzair et al., 2020). Therefore, to better understand the economic potential of the residue-based energy for a given area, this study calculates the Equivalent Collection Radius (ECR) for 100 MW power plants (Kashif et al., 2020).

The energy potential, when CR=None, was calculated using equation 1 in section 2.2. The lower-heating values used for the specific residues are shown in table 3. When considering the maximum collection radii, the equivalent collection radius was first calculated for the spatial aggregation scale using equation 7 (section 2.2). Considering the maximum collection radius, the energy potential was then calculated using equations 8 and 9 (section 2.2). For the different residue use scenarios, the calculations varied based on how residue availability was calculated, however, the same residue-to-product ratio equations (or values) were used for all scenarios. While other estimates of field residue energy production use a fixed RPR, this study uses the correlation equations adapted from (Daioglou et al., 2016). The use of the correlation is more accurate, as the literature shows that the RPR is impacted by crop yield. These values are shown in Table 1. Fixed RPR values are used for process residues. These values are shown in table 3.

For the theoretical potential (100% residue use), residue availability was calculated using equation 2 (section 2.2). For the technical potential (50% residue use), the residue availability was calculated using equation 3 (section 2.2) with RRF=0.5.

For the bioeconomic potential, residue availability was calculated using equation 5 (section 2.2), the RRF values shown in table 3, and surplus availability factors (SAF) for the aggregation scale. The SAF factors were calculated using equation 10 with the survey results of the Pakistan Biomass Atlas, created through the World Bank's Energy Sector Management Assistance Program (ESMAP) (The World Bank, 2016). SAF was calculated as:

$$SAF_{c,i} = 1 - AF_{c,i} - DF_{c,i} - SI_{c,i} - SB_{c,i} - FF^{*}_{c,i} \tag{10}$$

Where for a given crop (c) in a given area (i), $SAF_{c,i}$ is the surplus availability factor, $AF_{c,i}$ is the fraction of residue used for animal fodder, $DF_{c,i}$ is the fraction of residue used for domestic fuel, $SI_{c,i}$ is the fraction of residue sold to industry, $SB_{c,i}$is the fraction of residue sold to biomass and $FF^{*}_{c,i}$= modified fraction of residue retained as fertilizer. FF* is calculated as:

$$FF^{*}_{c,i} = \begin{cases} 0, & FF < 0.1 \\ FF - 0.1, & FF \geq 0.1 \end{cases} \tag{11}$$

Where FF= fraction of residues retained as fertilizer. The modified fraction is used in the SAF calculation to account for the assumption that 10% of the field residues are not harvestable given technological constraints.

For each calculation of residue availability, the SAF value was calculated using data at the corresponding spatial level. Division level SAFs were calculated by averaging the SAFs for each administration division's constituent districts. The provincial SAF was calculated by averaging the value for all districts. If district-level data was not available, average values were used.

Finally, for the eco-economic scenario, equation 5 was used, however the RRF values were substituted for the E-RRF values found in table 3. The E-RRF is the fraction of residues that must be retained in the field to mitigate soil and nutrient loss (Gregg & Smith, 2010). In general, this value is a function of soil type, carbon stocks, topography, climate and soil management practices (Gregg & Izaurralde, 2010). However, given the complexity of obtaining this value, general crop-specific values of residue retention per unit area can be used (Gregg & Smith, 2010). The ecological RRFs are based on the E-RRF values of 0.7 (Mg/Mg) for corn and wheat (Graham et al., 2007; Wilhelm et al., 2007), 0.25 for rice and sugarcane (Gregg & Smith, 2010) and 0.4 for cotton.

All calculations were performed using python. A link to the codes is available in Appendix A. Figure 4 shows the general workflow for method one.

Table 3 Parameters used in the calculation of crop energy potential in methods one and two.

Crop	Residue to Product Ratio (RPR) (Mg/Mg)[a]	Residue Removal Factor (RRF) (Mg/Mg)	Ecological Residue Removal Factor (E-RRF) (Mg/Mg)	LHV (MJ/kg)[c]
Field Residues				
Wheat Straw	$-0.266 \times Ln(\text{Yield}) + 3.108$	0.9	0.3	13.9
Sugarcane Trash	$-0.018 \times \text{Ln}(\text{Yield}) + 1.4289$	0.9	0.75	15.21
Rice Straw	$-0.925 \times \text{Ln}(\text{Yield}) + 7.371$	0.9	0.75	13.8
Maize Stalk	$-0.138 \times \text{Ln}(\text{Yield}) + 1.8681$	0.9	0.3	17.2
Cotton Stalk[b]	2.75	0.9	0.6	14.65
Process Residues				

Sugarcane Bagasse	0.25	na	na	8.57
Rice Husk	0.267	na	na	13.48
Maize Cob	0.27	na	na	16.28
Maize husks	0.2	na	na	11.6

[a] Values for field residues are from (Daioglou et al., 2016), process-based values are from (Rahman & Paatero, 2012)
[b] no correlation equation could be found for cotton, therefore a fixed value was obtained from (Terai et al., 2006)
[c] These LHV values consider moisture content "as-received" for each biomass residue. Values were obtained from (Rahman & Paatero, 2012) and (Uzair et al., 2020)

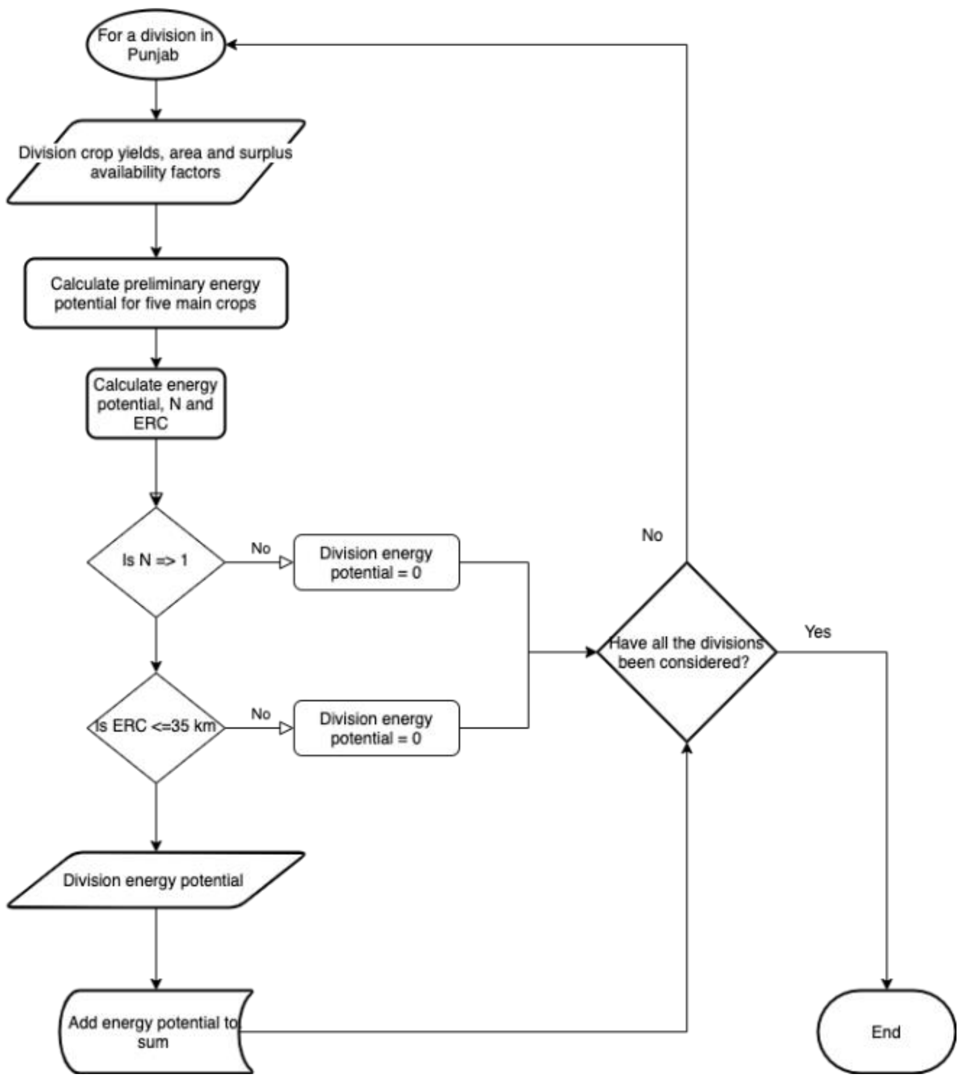


Figure 4 Example of the workflow for method one with the maximum collection radius of 35 km.

4.3 Method two

Method two aimed to explore the impacts of interactions between the WEF on crop residue energy potential estimations through the application of exploratory scenario analysis using a coupled human-water model. As described in chapter 3, the modelled area is the lower Rechna Doab region of Pakistan, a sub-district area located within the province of Punjab. The model is described below, followed by the method steps.

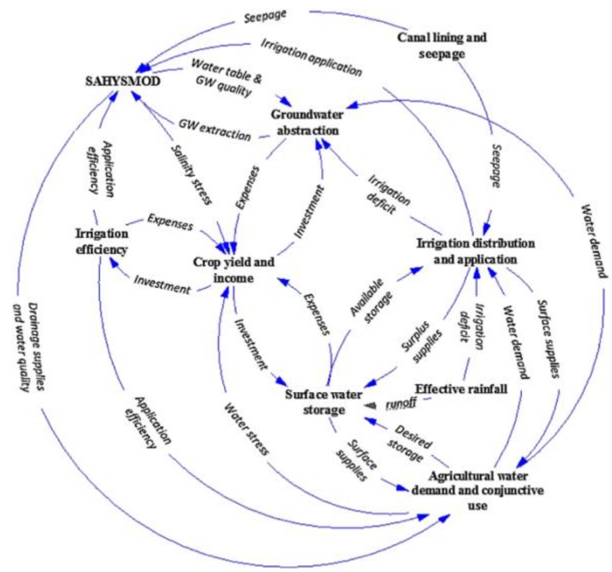
4.3.1 Coupled human-water model description

The human-water model used in this research is a coupled Physical-Group-Built System Dynamics Model (P-GBSDM) of the study region developed in (Inam, Adamowski, Prasher, & Albano, 2017; Inam, Adamowski, Prasher, Halbe, et al., 2017). The P-GBSDM integrates a Physically-based (P) agro-hydro-soil-salinity model (SahysMod), simulating the hydrological parameters of the agricultural system, with a participatory, group-built system dynamics model (GBSDM), which captures the socioeconomic and managerial system components. SahysMod is a spatially distributed, physically-based watershed scale model that simulates soil salinity and ground and surface water dynamics under agricultural conditions. SahysMod has been widely applied in arid regions (Akram et al., 2009; Desta, 2009; Kaledhonkar & Keshari, 2007; Liaghat & Mashal, 2010; Singh & Panda, 2012).

The original model contains five submodules representing the agricultural, economic, water, and farm management components of the system, which are linked by feedbacks (see Figure 5). The model is deterministic and has a simulated time-step of six months (one season). The model is also spatially explicit, dividing the 750 km^2 study area into 215 distinct polygons. (See Figure 6).

The GBSDM was created through a participatory model-building process that facilitated the creation of stakeholder-built casual-loop diagrams (CLDs). Individual stakeholder CLDs were merged and digitized in Vensim to create the final GBSDM, thereby representing the views of multiple stakeholders in the region, including local farmers, NGOs and government agencies. Details are provided in Inam et al. (2015). The GBSDM model was then coupled with the physically-based (P) model, SahysMod, using the programming interface Tinamit (developed in Malard et al. (2017)), which allows the integrated models to exchange data at runtime. Quantification of the physical-based model (SahysMod) is described in (Inam, Adamowski, Prasher, & Albano, 2017). Coupling of the P-GBSDM, validation and application for testing stakeholder-suggested salinity management strategies are outlined in (Inam, Adamowski, Prasher, Halbe, et al., 2017). A behaviour pattern-based sensitivity analysis of the P-GBSDM was also performed (see Peng et al., 2020).

Figure 5 Integrated model feedback structure. Note: variables in bold represent sub-modules of the integrated model. Reproduced with permission from (Inam, Adamowski, Prasher, Halbe, et al., 2017).



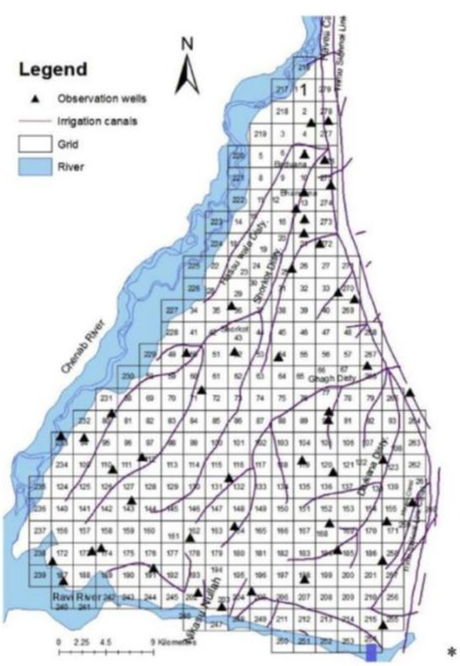


Figure 6 Nodal network polygonal configuration of the Rechna Doab watershed with observation wells, canal network, and grid (reproduced with permission from (Inam, Adamowski, Prasher, Halbe, et al., 2017).

4.3.2 Method two steps

The steps of method two are as follows:

1. **Model modification and validation**: modify the P-GBSDM to incorporate residue-based energy calculations and income/cost feedbacks and validate changes.
2. **Scenario development:** Develop scenarios and corresponding policy and runtime python codes.
3. **Simulation and data extraction:** run model with Tinamit over 25 years (2005-2030) with a 50 season timestep and extract variables of interest for each polygon for each scenario from model output.
4. **Data aggregation and extraction**: extract and aggregate variables of interest.
5. **Data analysis**: plot data and calculate percent differences between scenarios.

4.3.3 Model modification and validation

4.3.3.1 Incorporation of crop residue energy

To incorporate residue-based energy into the P-GBSDM, equation 1, the energy potential equation and equation 5, the bioeconomic residue availability equation, were incorporated into the system dynamics portion of the model using the parameters outlined in table 3. A link to the model, which includes the added equations, is available in Appendix A. The surplus availability factors (SAFs) (Table 4) for the main crops grown in the study area (wheat, cotton and rice) were calculated using equations 10 and 11 using the average values for the Jhang, Toba Tek Singh and Khanewal districts (The World Bank, 2016) as the modelled area is partially in each of these districts. The SAF values are shown in table 4. The crop yield was estimated endogenously by the P-GBSDM and is impacted by multiple feedbacks related to soil salinity (salt stress), water stress and heat stress.

Income and cost feedbacks were also added to the model. The income from selling each residue was calculated by calculating residue yield by the average residue price, derived from (Bhawan, 2016). Residue income was added to the GBSDM, which contributed to the income rate variable which is an inflow into the (net) Farm Income stock. The values used for residue price and harvest cost are shown in table 4.

Similarly, the surplus residue harvest costs were added to the model and to the farm expenditure rate variable, which represents the outflow of the (net) Farm Income stock. The standard surplus residue harvest cost was calculated by multiplying the full residue harvest costs with the SAF for each field residue. In the ecological scenario, expenses were further reduced due to use of the E-RRF. As with other monetary components, these values were transformed into their present value for the simulation year using inflation.

Table 4 Model specific values to calculate residue availability and energy potential.

	Residue SAF for study area (Mg/Mg)	Residue price (2015) (Rs/Mg)[a]	Full Residue Harvest cost (2015) (Rs/Acres)[b]
Rice	Straw: 0.92 Husk: 0.7[c]	Straw: 6,710 Husk: 9,093	1162
Cotton	0.26	6,703	1500
Wheat	0.10	6,905	1162

[a]Bhawan (2016)
[b] Derived from (Ahmed et al., 2015) and the Agricultural Marketing Information Service (http://www.amis.pk/surveys.aspx). No value was found for wheat however given similarities in harvesting procedures for straw-grain crops, the same value is used for rice and wheat.
[c] Obtained from Mohiuddin et al. (2016)

4.3.3.2 Model extension

While the P-GBSDM was created with the possibility of simulating into the future, the original simulation period was between 1990-2010 (Inam, Adamowski, Prasher, Halbe, et al., 2017). In this study, insight into short-medium term potential and risks of residue-based energy was deemed desirable, necessitating simulation beyond the present (2021+). While the real values of many model variables are not impacted by future simulation windows, others, including monetary and climate variables, as well as policies, are time dependent. While extrapolation methods of forecasting can be accurate, uncertainty in forecasted values increases as the number of forecasted periods increase (Armstrong, 2001). An underlying assumption when using historical data to forecast future data is that past trends will continue. However, this assumption can be incorrect due to unforeseen structural changes (e.g., new policies, socio-technical changes) over the forecast horizon (Armstrong, 2001). Therefore, risk and uncertainty in the P-GBSDM can increase as future periods increase.

To balance the value of gaining future insight into residue-based energy with the risks of using uncertain long-term input variables, a study period of 2005-2030 was chosen, requiring only medium-term forecasts (10 years) for input variables. To cover the study period, data was collected from the same sources used in (Inam, Adamowski, Prasher, & Albano, 2017; Inam, Adamowski, Prasher, Halbe, et al., 2017) to cover 2010-2021, then the appropriate techniques were used based on variable type to obtain data for 2021-2030. The different methods are explained below.

Extrapolating monetary variables with inflation

Certain monetary variables within the P-GBSDM can be indexed accurately with inflation. Therefore, as was done in (Inam, Adamowski, Prasher, Halbe, et al., 2017), these variables are calculated with the inflation rate in reference to a base year. In the original P-GBSDM, 2003 was used a base year for most monetary variables. For simplicity, these values were retained in the current study. However, the new monetary variables associated with the added residue-based energy module were calculated from a base year of 2015 due to data availability of residue harvest costs and prices. As will be discussed below, for each year values were either inflated or deflated from the base year to represent the present value for that year.

These variables include:

- Lining cost (Rupees/m) in 2003 for channel carrying 8.5 m^3 /second discharge
- Tubewell installation cost in terms of water table depth (Rupees/m) < 6 m in 2003
- Tubewell operating cost (Rupees year/m) in 2003
- Tubewell maintenance cost (Rupees year/m) in 2003
- Irrigation improvement cost (Rupees/year) in 2003
- Pond cost (Rupees/ m^3 *season) in 2003
- Diesel cost (Rupees/season) in 2003
- Crop production costs (Rupees/season) in 2015
- Crop harvesting costs (Rupees/season) in 2015

As well as added variables:

- Residue harvest costs (Rupees/season/m^2) in 2015
- Residue price (Rupees/season*m^2) in 2015

Selecting a future inflation rate

The choice of inflation rate varies in farm-level simulation studies, some authors choose a fixed rate, which is commonly done when simulating into the future (e.g., (McDonald et al., 2013; Rahman & Paatero, 2012)). Alternatively, forecasted inflation rates are also applied when reliable forecasts are available (Kuhns et al., 2015). Modelling studies that cover past-present timeframes usually use the historical inflation rate, which is calculated with either the Consumer Price Index

(CPI) (e.g., (Dashora et al., 2019)) or the Wholesale/Producer Price Index (WPI or PPI) (e.g., (Lange & Mahumani, 2013)). However, in general, in developing countries it is more common to use CPI (as in this study) unless dealing with large scale commercial operations (Meemken & Bellemare, 2020).

In this study, the historical and forecasted inflation rate in Pakistan was obtained from the International Monetary Fund (IMF) (https://www.imf.org/en/Countries/PAK). The historical inflation rate (based on CPI) is used from 2000-2020, whereas IMF forecast values are used from 2021-2026. The IMF predicts that Pakistan's inflation rate will plateau at around 6.5% in 2026, therefore a fixed value of 6.5% is used for 2026-2030.

From the inflation rate, an inflation factor for each base year (2003 or 2015) is calculated for each year in the simulation period (2005-2030). This is done through use of the Future Value equation (Ardalan, 1999):

$$FV = PV * (1 + i)^n \tag{12}$$

Were FV=future value, PV= present value, i= interest rate and n=number of periods. Similarly, the Past Values are calculated as:

$$HV = PV * (1 - i)^n \tag{13}$$

Where HV=historical (past) value.

Based on these equations, the inflation factor (IFs) for base years 2003 and 2015 are calculated iteratively using the inflation rates for each year by making PV ($IF_{\text{base year}}$) =1 during the base year and sequentially calculated the FV for each year before and after the base year. For example, for a specific base year, the inflation factor for any year can be calculated as:

$$IF(t) = \begin{cases} IF_{BY} * (1 - i_{BY-1}) * (1 - i_{BY-2}) * \dots (1 - i_{t+1}) * (1 - i_t)\,, & t < BY \\ 1 & t = BY \\ IF_{BY} * (1 + i_{BY}) * (1 + i_{BY+1}) * \dots (1 + i_{t-1}) * (1 + i_t), & t > BY \end{cases}$$

Where IF_t is the inflation factor for year t based on base year (BY).

From this, the value of any monetary variable x(t) is calculated from the base year as:

$$x(t) = IF(t) * x_{BY} \tag{14}$$

Where x_{BY} is the price of that variable at the base year.

4.3.3.3Model validation

Given that modifications had to be made to the P-GBSDM in this research, the model's structure had to be revalidated prior to simulation. Model testing and validation is important to determine a model's acceptability for its intended use. While the performance of conventional modelling techniques (mechanistic, stochastic and empirical models) is tested using statistical methods (e.g., RSME, R^2, MAPE, etc.), these methods are not suited to the GBSDM because system dynamics models; a) are meant to predict patterns and trends in system behaviour over time, rather than point values and b) often include noise that is not normally distributed due to auto-correlated and nonstationary variables (Barlas, 1989).

Alternatively, the SDM model validation process is done through two stages: (1) testing model structure (structural validation) and (2) testing model behaviour (Qudrat-Ullah & Seong, 2010; Schwaninger & Groesser, 2020). The validation procedures used when creating and testing the original P-GBSDM, as outlined in (Baig, 2017), were repeated here to confirm the validity of the model after modifications. For brevity, these are briefly described below. For full details, please refer to Baig (2017).

Structural validity tests

In structural validity tests, the structure and equations in the system dynamics model are compared with theory (Qudrat-Ullah & Seong, 2010). This research modified the structure of the system dynamics (Vensim DSS) portion of the P-GBSDM (the GBSDM) through the addition of the crop residue income module and the crop production cost module, both of which impacted the existing farm income module. As these modules were implemented into the GBSDM, their structure was iteratively refined to ensure the model passed all validity tests. The validity tests applied included (1) boundary adequacy tests, (2) structural verification, (3) dimensional consistency, and (4) extreme conditions tests.

Boundary Adequacy

As outlined by (Baig, 2017), ensuring the boundary adequacy of a model means that processes necessary for addressing the utility of a policy are endogenous. For example, for policies to ameliorate water stress, processes such as water demand and use, crop stress, surface and groundwater balances, evapotranspiration, and salinization must be internal to simulate the impact of policy options such as rainwater harvesting, improved irrigation methods or canal lining. While processes related to water management, crop yields and crop income were already endogenous to the model, residue use, and corresponding income and cost feedbacks were not. Therefore, for the purposes of this research, these processes were added endogenously to the model, as shown in bold in Table 5. Uncontrolled parameters related to residue energy were also added to the model exogenously, such as residue price and harvest costs.

Endogenous	**Economic prices and costs** • Crop market prices • Cost of water management strategies • Cost of crop production and residue harvest • **Residue market price**	**Water inflow and Climate** • Rainfall • Canal discharge • Temperature	**Salt inflow** • Irrigation water quality
	Agriculture • Crop rotation • Crop yield • Cropped area • Crop water demand • **Residue availability**	**Groundwater** • Tubewell growth and depreciation • Utilization	**Irrigation** • Water distribution • Losses • Water availability
	Farm Income • Irrigation expenditure • Crop income • Soft government loans • **Residue income and expenditure** • **Crop production expenditures**	**Water storage** • Storage capacity and utilization • Water availability and outflow control	**Water management** • Management scenarios • Costs of implementing • Efficiency
Exogenous	**Residue Energy** • **Residue energy potential** • **Residue energy density** • **Residue use scenarios**	**Structure depreciation and construction delays**	

Table 5 Endogenous and exogenous processes of the P-GBSDM (adapted from Baig, 2017 and modified). Bold values represent processes added during this research.

Structural verification

Structural verification involves testing the model output against available data and information. Specific data on residue energy potential is not available for this region. However, since energy potential is directly proportional to crop yields, structural verification of the model with the added modules was done by repeating the structural verification tests for the original P-GBSDM (Baig, 2017).

Dimensional consistency

The dimensional consistency of each added equation and variable was checked by making sure the right-hand side and left-hand side equations had the same dimensions. Checking dimensional consistency is important to ensure proper model formation.

Structurally oriented behaviour tests

Structurally oriented behaviour tests involve simulating the model in a variety of conditions to determine the acceptability of model behaviour (Qudrat-Ullah & Seong, 2010). A variety of extreme condition tests were simulated to ensure that the model behaved as expected. For example, extreme water scarcity was simulated with the crop residue energy switch activated by setting canal supplies to 0, this resulted in a huge spike in groundwater abstraction and tubewell growth, as would be expected. Furthermore, the residue energy switch was tested to ensure when it was not activated that the residue income and energy potential were zero. When the switch was activated, the values of farm income and expenditures were also monitored to ensure they were consistent with reality. The built-in function in Vensim called reality check was also used to make sure that the system functioned as anticipated. Reality checks were used to test for unrealistic behaviour as well as conservation of mass. The five reality tests outlined in (Baig, 2017) were repeated and all 215 polygons passed successfully. These checks are as follows, equations can be found in (Baig, 2017):

- **Unrealistic behaviour check:** measures of farm (crop and residue) income, soil salinity, water and salinity stress, water in storage, crop water demand, cropped area, available water, and residue availability should never be negative under any scenario.
- **Conservation of mass tests:** the sum of canal supplies and losses in a particular canal should be equal to the amount of water diverted from the main canal. For the second conservation of mass test, the water table depth must be constant if there are no tubewells in the system and zero recharge and discharge from sources or sinks.

- **Constrained behaviour test:** if farm income is insufficient to cover the costs of policy implementation, then farm management measures, such as canal lining, surface water storage and groundwater extraction are zero and irrigation efficiency is minimum (0.6).
- **Unrealistic positive behaviour test:** if there is no surface storage capacity in the system then supplies, operation and maintenance expenditures, seepage, and evaporation, as well as inflows into surface storage are zero.

4.3.4 Scenario development

Scenarios can be useful to explore uncertainties, uncover future issues and optimize management. Here scenarios were used to identify synergies and trade-offs between residue-based energy and water management strategies under different competitive uses and climate change.

This research is an example of exploratory scenario analysis, which aims to answer the question "what may happen" (Börjeson et al., 2006). This is because there is both a high degree of uncertainty within the future energy and agricultural development pathways of the region, along with drivers impacting them and local livelihoods.

Residue-based energy (E)	**Water management (W)**
NU: Without crop residue energy	NW: No water policies/status quo
CU: With crop residue energy and competitive residue use	CL: Canal lining
EU: With crop residue energy and ecological residue use	RH: Rainwater harvesting
	II: Irrigation improvement
	VD: Vertical Drainage

Table 6 Scenario components of method 2.

Given the scenario components shown in table 6, a total of 15 scenario were simulated per climate scenario (45 in total), representing a combination of residue use scenarios (NU, CU, and EU) and water management policies (NW, CL, RH, II and VD).

The water management policies represent stakeholder-suggested solutions (i.e., local farmers, academic experts, government officials, NGOs, management institutes, etc.) to address soil salinity and water scarcity in the region (Inam et al., 2015). NW represents no water policies, or the status quo, which is the case where no extra actions are taken to improve soil salinity and or water availability. CL, canal lining, is a government-supported policy to reduce conveyance losses of surface water supplies by up to 80% (Arshad, 2004) thereby increasing downstream canal supplies, improving water availability and potentially reducing reliance on marginal groundwater irrigation which causes secondary soil salinization. While effective, canal lining is associated with considerable costs, leading to economic and environmental trade-offs (Inam, Adamowski, Prasher, Halbe, et al., 2017). In the model, when the canal lining policy was activated, the desired canal lining goal was determined through a lookup function (created based on stakeholder interviews), whereas a goal seeking function was used to estimate the incremental length lined. Due to high costs, the government covers 75% of implementation costs, while 25% of implementation costs are borne by the beneficiaries (Baig, 2017).

RH, rainwater harvesting, involves construction of rainwater harvesting ponds on fallow lands to increase surface water supplies. Based on recommendations by local stakeholders, the model assumes that individual farmers will only use up to 10% of their land for constructing rainwater harvesting ponds. If this capacity is reached, further construction is limited (Baig, 2017). In terms of construction costs, again it is typical for 75% to be covered by the government and 25% of costs to be covered by beneficiaries. The operation expenditure is calculated based the water harvesting share of farmers. As ponds become silted overtime, maintenance costs for rainwater harvesting ponds are dependent on farmer perception of the siltation. Based on stakeholder input, maintenance costs for silt removal were activated when 25% or more of the constructed capacity was silted (Baig, 2017; Inam, Adamowski, Prasher, Halbe, et al., 2017).

II, irrigation improvement, involve implementation of a pressurized irrigation method (PIM) which increases irrigation efficiency from 60% to 90% over time through gradual implementation of pressurized drip irrigation systems that reduce return flow. Due to the high investment costs in irrigation system improvements, only 20% of the cost of installation is borne by the farmer and 80% of the costs are subsidized by the Government of Pakistan (see details in (Inam et al., 2015)). Finally, VD involves pumping water out groundwater to reduce water logging and control primary salinization. To reiterate, these policies were chosen because they were suggested by local stakeholders (e.g., farmers, NGOs, government) and encompass the wide variety of strategies that are being implemented in Pakistan to combat water stress and soil salinity. Full details of the policies and related equations are outlined in (Baig, 2017; Inam et al., 2015; Inam, Adamowski, Prasher, Halbe, et al., 2017).

NU represents no residue-based energy. This scenario is used as a reference point to investigate the impact of added residue incomes and costs on the system. CU is the bioeconomic energy potential scenario, where competitive uses of residues are considered when calculating residue availability. Alternatively, EU represents the eco-economic energy potential scenario, where both competitive and ecological residue uses are considered (equation 5 with E-RRF). To facilitate the CU and EU scenarios, a switch was built into the GBSDM model to turn on and off residue-based energy calculations and corresponding income and cost feedbacks.

Beyond the current climate, the model was also simulated under two climate change scenarios which applied two Representative Concentration Pathways (RCPs) for carbon emissions. C1 is RCP 4.5, which represents the moderate-low emissions scenario and C2 is RCP 8.5, which represents a high emission scenario. The region is highly susceptible to climate change, which may impact the viability of residue-based energy. Application of these RCPs to the study area have shown minimum temperatures are likely to increase from baseline temperatures (1980-2011) by 5.1% in 2025 and 9.0% in 2050 under RCP 4.5 and 5.8% in 2025 and 12.0% in 2050 under RCP 8.5 (Amin et al., 2018). Maximum temperatures are expected to increase from the baseline by 2.7% and 4.7% in 2025 and 3.0% and 6.4% in 2050 for RCP 4.5 and 8.5, respectively. To explore the impacts of intense climate change, downscaled climate datasets representing the radiative forcing levels of Representative Concentration Pathways (RCP) RCP 4.5 (mid-low emissions) and RCP 8.5 (high emissions) during 2100 were obtained from http://www.ccafs-climate.org/ and used as model inputs for these scenarios. A python code (Appendix A) was written to facilitate simulation of the different scenario combinations.

4.3.5 Simulation

The coupled model simulation was performed using the python program Tinamit (Malard et al., 2017). Each scenario was simulated for 50 cropping seasons, representing 25 years between 2005-2030. Tinamit is a python program used to couple socioeconomic and physically-based models. It acts as a wrapper, exchanging information dynamically between the two models at run-time. Tinamit is available free at: https://pypi.org/project/tinamit/. The specific codes used to run the P-GBSDM with Tinamit for this research are provided in Appendix A.

4.3.6 Data extraction and aggregation

Simulation of the P-GBSDM generates a large amount of data, with over 200 variables simulated for 215 polygons for 50 seasons (25 years). The simulation results for each scenario are outputted in CSV form. To perform analysis, variables of interest had to be extracted, and for some purposes, aggregated spatially and/or temporally. The extraction and aggregation processes are here forth referred to as data processing. To compare between scenarios, variables of interest from each scenario file were extracted and combined into a single data file. Several python codes were developed to automate the data extraction and aggregation processes.

Value Aggregation

An aggregated value representing the system state over a single year was needed to simplify the analysis. Therefore, the variables had to be aggregated over two dimensions, spatially (over the 215 polygons) and temporally (over the two seasons). The aggregation method differed depending on the variable, as shown in table 7. For example, to get the yearly residue energy potential of the study area, the energy potential of each polygon (KJ $Polygon^{-1}$ $Season^{-1}$) had to be summed, then the energy potential of the winter and summer seasons (KJ $Season^{-1}$) had to be summed. This resulted in a unitary conversion from KJ $Polygon^{-1}$ $Season^{-1}$ to KJ $Year^{-1}$. This is because residue energy potential is an auxiliary model variable; its value is independent to its value at previous timesteps.

Conversely, net farm income is a stock or level variable, meaning that its value at a given timestep is dependent on the value at the previous time step. Any income left over after all expenditures and household income is accounted for may be available to cover expenditures in the following years. Given this relationship, it is not appropriate to temporally aggregate level variables based on summation. Therefore, averaging is used to determine yearly values. However, as level variables still only represent that variable level for each polygon, they can be spatially aggregated through summation (if appropriate). The saline polygons and moderately saline polygon variables, conversely, which are binary variable with a value of 1 is the polygon is saline (or moderately or highly saline, respectively) and 0 if it is not, are summed spatially, representing the number of saline polygons per season. However, the spatial aggregates are averaged to get a yearly value, as summing would double count the same polygon.

For other variables, specifically those with a denominator other than polygon or season, such as soil salinity (dS m^{-1}) or Salinity Stress Yield Reduction (%), summation is not appropriate. For these variables, averaging over both the temporal and spatial dimensions is used, representing the yearly average value of the variable of interest for the study area. Residue energy density is the only variable that is summed temporally and averaged spatially. This is because the yearly residue energy potential results from available residues from both seasons.

Table 7 Spatiotemporal aggregation methods for data processing of variables of interest.

		Spatial aggregation Method	
		Sum	**Average**
Temporal aggregation method	**Sum**	• Residue energy potential • Canal lining • Constructed capacity	• Residue energy density
	Average	• Water availability • Farm income • Saline polygons • Moderately saline polygons • Highly saline polygons	• Water table depth • Irrigation efficiency • Salinity stress yield reduction • Water stress yield reduction • Soil salinity

4.3.7 Data Analysis

The percent difference between each scenario and the base case scenario (NU NW) was calculated for 2005, 2010, 2015, 2020, 2025 and 2030 to facilitate data analysis. The base case scenario (NU NW) represents no residue-based energy and no (status-quo) water management. Furthermore, to delineate the impact of residue-based energy, the percent difference between the NU case for each water management scenario and the CU and EU cases were also calculated, as shown with equation 14 (e.g., the difference between NU CL and CU CL and EU CL).

$$Percent\ Change\ (\%) = \frac{\sum_{1}^{n=215} Variable\ of\ Interest_{Scenario} - \sum_{1}^{n=215} Variable\ of\ Interest_{Base\ case}}{\sum_{1}^{n=215} Variable\ of\ Interest_{Scenario}} \quad (14)$$

For each variable with a non-negligible percent change due to residue-based energy, there are four options depending on whether residue-based energy reinforces or balances the impact of the scenario components without residue-based energy, as shown in table 8. These results were used to interpret the impact of the residue-based energy scenarios. The residue energy density of the study area under the simulated scenarios was compared with the residue energy density of its districts, as calculated in method one. For example, imagine the percent change between the NU

CL scenario (no residue energy and canal lining) and the base case (NU NW) scenario (no residue energy and no canal lining) is positive for a variable, such as water availability. If the percent difference between the NU CL and CU CL (residue energy and canal lining) is also positive, this means that the addition of residue-based energy had a reinforcing impact on the effect of canal lining on water availability. However, if the percent change between NU CL and CU CL is negative, then crop residue energy would have a balancing impact on the effect of canal lining on water availability. If there is no difference between NU CL and CU CL, this means residue-based energy had no impact on the performance of that policy for the specific variable of interest.

Percent change (%) between base case (NU NW) and scenario (NU**)	Positive	Positive	Negative	Negative
Percent change (%) between NU** and CU** (or EU**)	Positive	Negative	Negative	Positive
Impact of residue-based energy	Reinforcing	Balancing	Reinforcing	Balancing

*Table 8 Interpretation of the impact of residue-based energy on scenarios.** represent a water management policy (CL, II, RH or VD)*

Chapter 5: Results and discussion of method one

The aim of method one was to explore the impact of scale and calculation assumptions on estimations of crop residue-based energy. Within this aim, there were two broad objectives, (1) to collect and critically analyze existing estimates of crop residue-based energy potential in Pakistan (performed in section 2.2 of the literature review) and (2) to delineate the impacts of scale and assumptions on residue energy potential estimations. To achieve objective two, the residue energy potential of the province of Punjab for its five major crops (wheat, rice, cotton, maize and sugarcane) was calculated for three years (2010, 2015, and 2020) using data aggregated at three spatial scales and various competitive use and collection radius assumptions.

The residue use scenarios included 100%, 50%, competitive, and ecological residue use (ecological also considered competitive residue uses), corresponding to theoretical, technical, bioeconomic and eco-technical energy potential estimations, respectively. The maximum feedstock collection radii to power a 100 MW power plant included none, 35 km, and 50 km to consider transportation logistics. The total residue energy potential of the province of Punjab was calculated using data aggregated, from finest to coarsest, at the district, administrative division, and provincial scale. For the administrative division and provincial scales, district-level data for competitive uses and corresponding surplus availability factors were aggregated from district-level data by averaging. For example, the surplus availability factor for the Faisalabad Division was equal to the average of the surplus availability factors of its constituent districts, Faisalabad, Chiniot, Toba Tek Singh, and Jhang. Correspondingly, crop yield and area of each division (and province) were the summation of the yields and areas of each constituent district.

This research was motivated by the wide variability of existing energy potential estimates in Pakistan. For example, the energy potential of residues in Punjab has been estimated at 1700 MW (Uzair et al., 2020) and 7100 MW (Kashif et al., 2020). In both cases, the data were aggregated at the administrative division scale. However, assumptions of residue availability varied widely. For Kashif et al. (2020), 50% of residues were seen as recoverable and available for energy production; however, the maximum collection radius was set at 50 km which was based on European estimates. Alternatively, Uzair et al. (2020) did not consider a maximum collection radius but did consider surplus availability factors based on competitive uses and variable residue recovery factors, which contributed to the lower estimations. Overall, furthering understanding how assumptions and data aggregation scales impact residue-based energy estimations is important for strategic planning and implementation. Method one also aimed to provide data on residue energy density for the districts containing the study area of method two (Jhang, Toba Tek Singh and Khanewal). This data was used for comparison purposes to further highlight the impact of scale and heterogeneity on bioeconomic and eco-economic residue energy potential.

As shown in Table 9 and Figure 8, this research demonstrated that data aggregation scale, competitive use assumptions and maximum collection radius all impact energy potential estimations. As shown in figure 8, results were similar across all years. As such, table 9 displays values for 2015 only. As shown, in 2015, estimations of residue energy potential ranged from 0 to 53345 MW, depending on the assumptions made. The largest estimation, at 53345 MW, came from calculating the theoretical energy potential (100% residue use and no maximum collection radius) at the provincial scale, which only considers biophysical limits. The lowest estimate of energy potential, at 0 MW, came from provincially aggregated bioeconomic energy potential with a maximum CR=35 km and the divisionally and provincially aggregated eco-economic energy potential estimations when CR=50 and CR=35. Both the bioeconomic and eco-economic scenarios considered current competitive uses, whereas the eco-economic scenario also considered sustainable residue harvest levels. However, when aggregated at the district level, all scenarios resulted in a nonzero energy potential across all years. The sources and implications of temporal, spatial and scenario-level variation in energy potential estimates are discussed below.

Table 9 Method one results- energy potential of Punjab (MW) under different data aggregation scales and assumptions of residue use and maximum collection radius.

		Spatial Aggregation Scale		
Residue use scenario	**Maximum collection radius**	**District**	**Division**	**Province**
Theoretical energy potential: 100% residue use	None	49063	52907	53345
	50 km	20800	22600	22800
	35 km	20300	22300	22800
Technical energy potential: 50% residue use	None	24122	26456	26674
	50 km	10100	11100	11400
	35 km	9200	11100	11400
Bioeconomic energy potential: competitive residue use	None	10074	8847	8829
	50 km	3800	3400	3800
	35 km	3000	1800	0
Eco-economic energy potential: competitive and ecological residue use	None	5389	3587	3749
	50 km	1800	0	0
	35 km	700	0	0
Average		13196	13675	13733

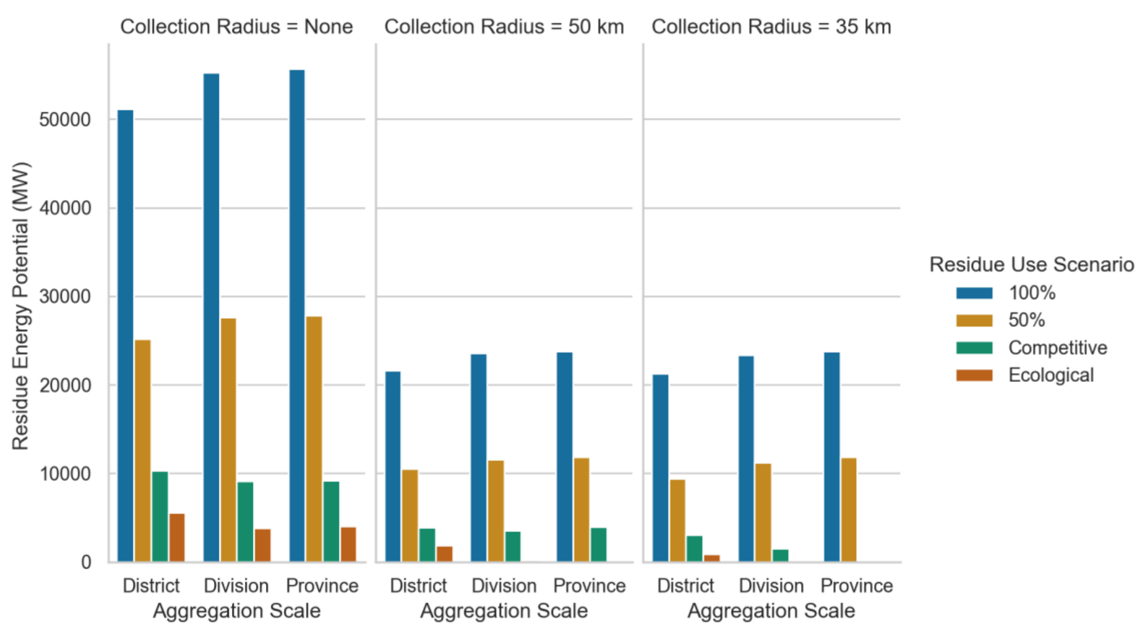
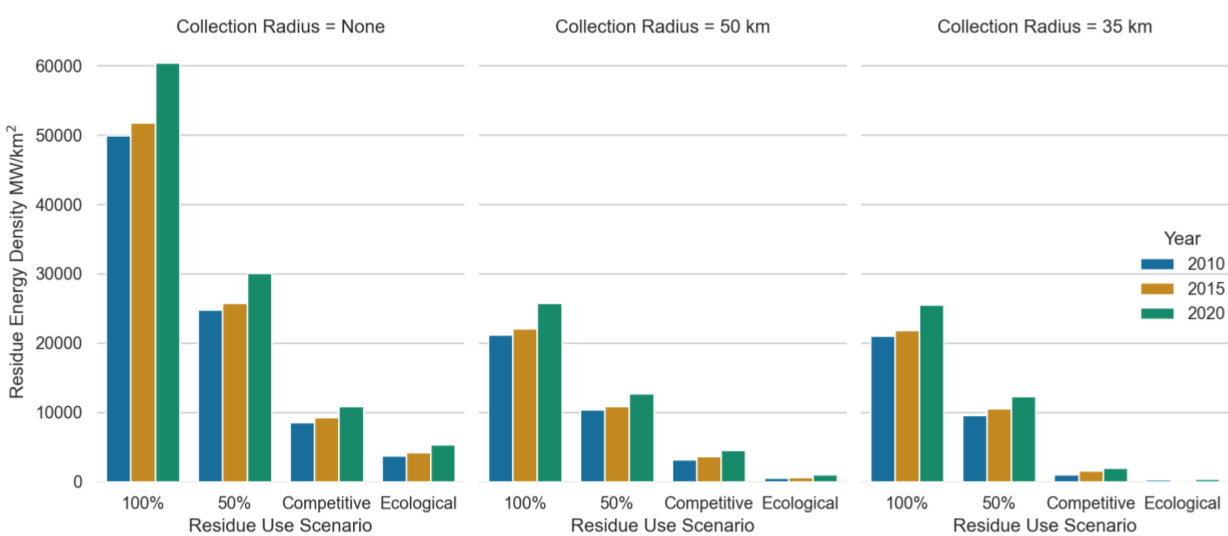


Figure 7 Variation of residue energy potential (MW) across scenarios and spatial aggregation levels in 2015.

5.1 Temporal variation in energy potential estimations

As shown in Figure 8, regardless of maximum collection radius, scenario or spatial aggregation scale, crop residue energy potential estimates increased from 2010 to 2020. The direct reason, as apparent in Figure 9, is an increase in total crop production in the province, from 70.831 Mt to 91.673 Mt. Interestingly, however, the total production area remained roughly the same, between 29.22 million acres and 30.18 million acres, though the portion of the area cropped by individual crops changed, representing shifts in farmer cropping behaviour. With regards to individual crops, only maize, rice and sugarcane saw increases in crop productivity (yield/cropped area), while wheat and cotton crop productivity decreased. While crop productivity increased for some crops, changes to agricultural patterns may have also contributed to higher total yields, as crop (and residue) yields are heterogenous amongst crop types.

Figure 8 Temporal variation of energy potential estimations.



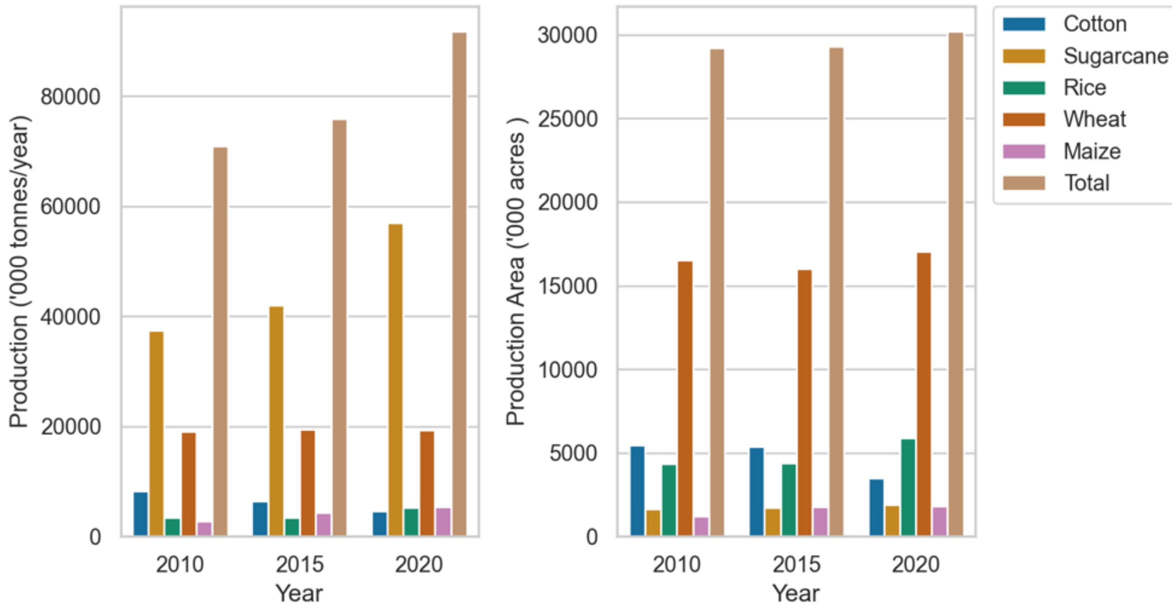


Figure 9 Crop yields in Punjab in 2010, 2015 and 2020.

Crop productivity has been incrementally increasing in Pakistan over the past decades (Rehman et al., 2015), due to increasing agricultural inputs and policies aimed at supporting farmers through credit, yet it still remains far under international averages (Aslam, 2016). While improvements in crop productivity can be expected, changes in cropping patterns and shifts away from cash crops could reduce regional crop yields of wheat, corn, maize, sugarcane, and cotton, necessitating long-term flexibility in bioenergy feedstock planning. Furthermore, Pakistan is one of the most vulnerable regions in the world to climate change, and various estimates have shown that Pakistan will undergo high agricultural productivity losses due to increasing heat and water stress, as well as extreme events (Gul et al., 2021b; Rehman et al., 2021).

5.2 Variation in estimations due to spatial aggregation

The residue energy potential estimations for each scenario varied depending on the spatial aggregation level (district, administrative division, or province). There are numerous sources of this variation, some of which apply to all scenarios and others which apply only to the scenarios considering competitive uses. Several key trends were evident. Overall, regardless of the maximum collection radius, the theoretical energy potential (100% residue use) and the technical energy potential (50% residue use) increased with aggregation level, with the highest estimates being obtained at provincial level aggregation and the lowest at the district level. As discussed below, this trend is attributed to differences in the calculation of the residue-to-product ratio across aggregation levels.

For the bioeconomic (competitive residue use) and eco-economic (ecological and competitive residue use) scenarios, the impact of spatial aggregation was reversed, with the highest estimates occurring with district-level aggregation and the lowest occurring at the provincial level. This is due to the dilution of the residue energy density at higher aggregation levels, as will be discussed further below.

Residue to Product Ratio (RPR)

The impact of spatial aggregation on the residue-to-product ratio was especially evident in the calculation of the theoretical energy potential (100% residue use and CR=none). As can be seen in the first row of table 9 and the first panel of Figure 7, the theoretical energy potential in 2015 varied between 49063 MW under district-level aggregation and 53345 MW under provincial-level aggregation, even though competitive uses and maximum collection radii were not being considered. Even though the province's total crop yields (tonnes) are the same under each aggregation scale, the average crop yield per area is not. This is important as RPR, which is the ratio of residue yield (tonne) to grain/product yield (tonne), is dependent on average yields, as shown in Figure 10, with higher residue yields resulting from lower product yields (and vice versa) (Daioglou et al., 2016). Whereas at the district level, a district-level RPR is calculated using district crop yield densities, at the administrative division and provincial levels, the RPR is calculated using division and province crop yield densities, respectively.

As can be seen in Table 11, while the average RPRs are similar across aggregation scales, the district scale results in a lower maximum RPR than the division scale for rice, maize, and sugarcane, as well as a lower minimum RPR for wheat, rice, and maize. This discrepancy led to an overestimation of theoretical (RU=100%, CR=none) and technical (RU=100%, CR=none) energy potential by approximately 4,000 MW for the provincial aggregation level and 3000 MW for the division aggregation level data.

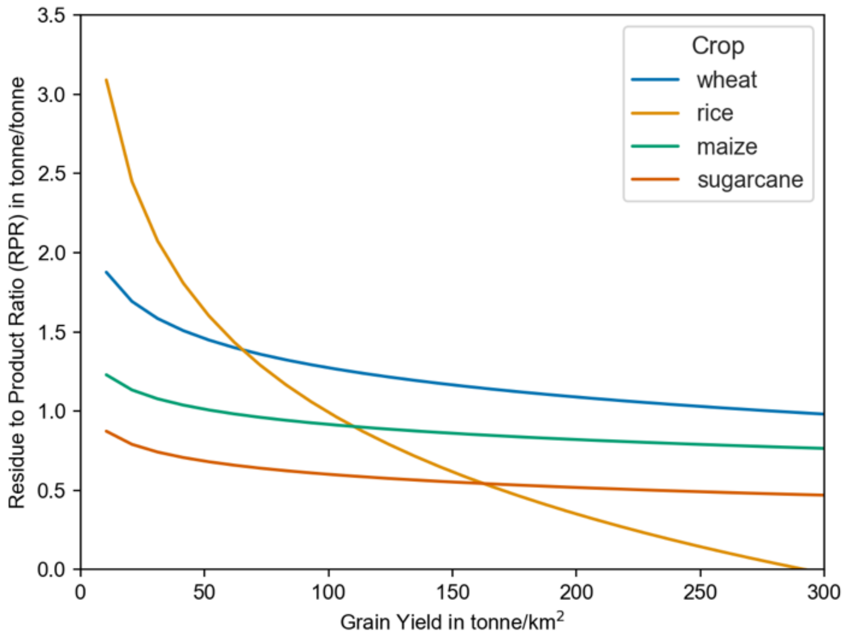


Figure 10 Residue to product ratio.

		WHEAT	RICE	MAIZE	SUGARCANE
AVERAGE RPR	**Province**	1.60	2.55	1.04	1.28
	Division	1.60	2.61	1.05	1.28
	District	1.60	2.60	1.05	1.28
MAX RPR	**Division**	1.70	3.83	1.17	1.30
	District	1.76	2.57	1.19	1.28
MIN RPR	**Division**	1.55	2.35	0.95	1.27
	District	1.51	2.15	0.92	1.27

Table 10 Average, maximum, and minimum RPR values at three different aggregation scales.

Spatial aggregation and surplus availability factor (SAF)

Spatial aggregation also led to differences under the considered competitive residue use (bio-economic and eco-economic) scenarios. Within Pakistan, residue usage for domestic fuel and animal feed and fodder is widespread, representing a significant constraint on current residue availabilities, as discussed further below (IRENA, 2018; Tareen et al., 2019; Uzair et al., 2020). However, given the presence of local economies, residue usage is heterogeneous across both crop types and districts. This is illustrated by the average district SAFs for each crop and maximum and minimum district SAFs shown in table 10.

Table 11 Average, maximum and minimum crop SAFs over the districts of Punjab.

SAF	COTTON	MAIZE	RICE	SUGARCANE	WHEAT	AVERAGE
AVERAGE	0.18	0.31	0.48	0.48	0.15	0.32
MAXIMUM	0.47	0.96	1.00	1.00	0.28	0.52
MINIMUM	0.00	0.00	0.00	0.04	0.00	0.16

As can be seen, the average SAFs range between crops, with higher values for sugarcane, rice, and corn, than for wheat and cotton. SAFs also vary between districts. For example, for rice, the minimum district SAF is 0 and the maximum is 1, meaning that there are districts where all residues and no residues are available. In general, the SAF is lower for wheat and cotton due to widespread established uses; cotton sticks are a common domestic fuel used for cooking and household heating (Rahut et al., 2020), whereas wheat straw is a common animal bedding (Farooq et al., 2013). Therefore the range of values for wheat (0, 0.28) and cotton (0 to 0.47) are smaller than for the other three crops. The average SAF across all districts and crops is 0.32, much less than the 50% assumed in other estimates of residue energy potential (e.g., (Kashif et al., 2020)).

As will be discussed further below, the consideration of competitive residue uses greatly decreases the energy potential estimations. However, spatial aggregation of surplus availability factors also impacts energy potential estimations. When competitive uses are considered (under bioeconomic and eco-economic scenarios, the residue energy density of Punjab (CR=none) is higher when aggregated by district than at the division or provincial level, as shown in Figure 12. This trend is visable over all three years. This suggests that important information about the surplus available residues is lost when applying aggregated SAFs.

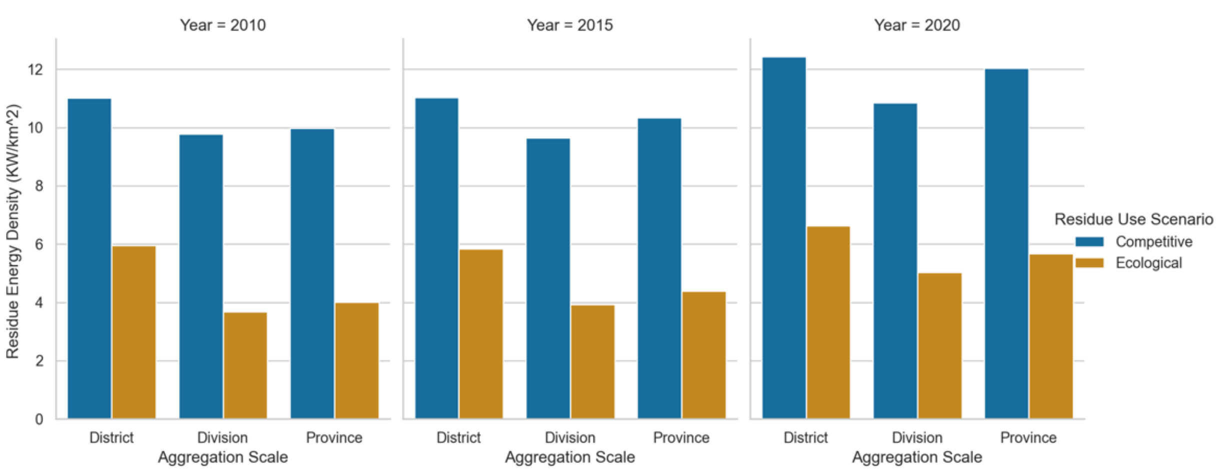


Figure 11 Results of the bioeconomic and ecological use scenarios across aggregation levels

The impact of SAF aggregation on the residue availability (and subsequent energy density) is apparent when comparing the residue energy densities in Figure 13, where the districts are shown on the top and the divisions are on the bottom. For multiple districts, such as Rahim Yar Kahn and Rajanpur, the residue energy density under the bioeconomic and eco-economic scenarios is approaching the 50% residue use scenario, indicating that a) this region has higher than average SAFs (the average is 0.32) and b) this region grows a large proportion of crops with higher SAFs (e.g., rice). Alternatively, for a district like Pakpattan, where the residue energy density under competitive and ecological residue use is 0, it is apparent that the SAFs of residues in this region are approaching zero. In the case of the divisional aggregation, none of the districts achieved a residue energy density under the competitive and ecological scenarios that approached the 50% scenario. Though the residue energy densities for the division level are more moderate (containing fewer highs and lows), it is apparent in Table 9 that the application of aggregated SAFs over larger areas creates a dilution in residue energy density (KW km^{-2}) as the spatial aggregation level increases. This has implications for considering the logistical energy potential.

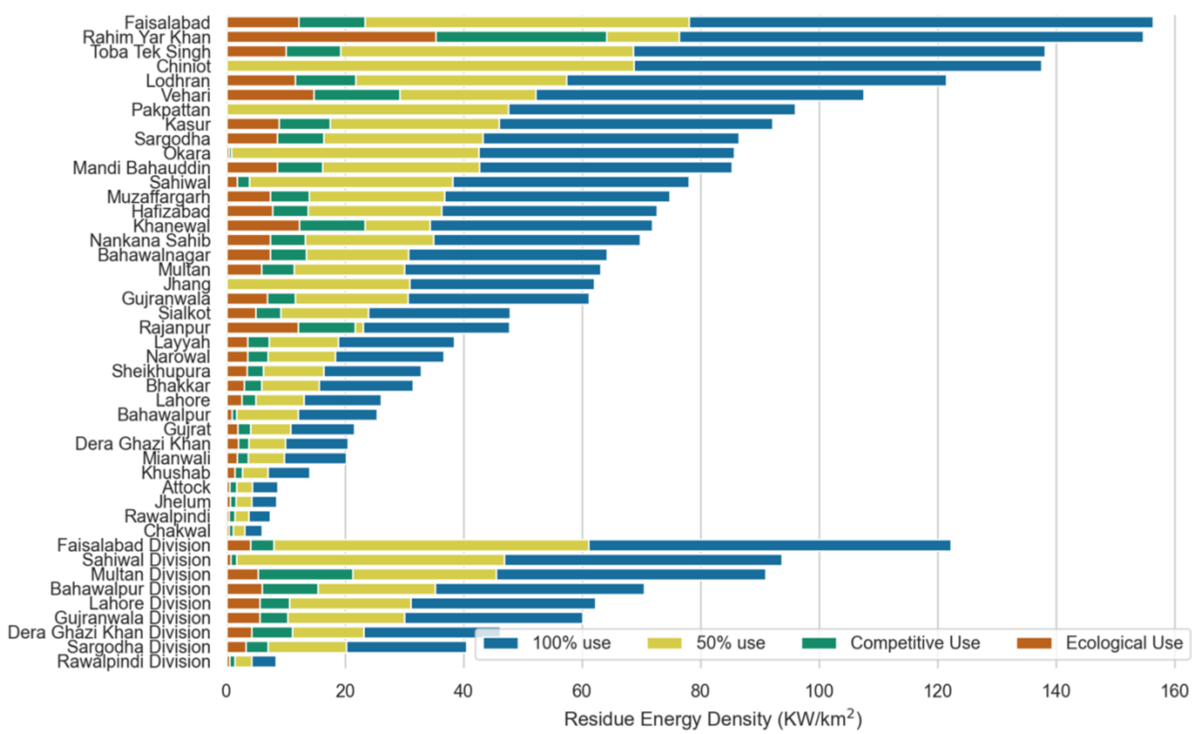


Figure 12 Residue energy densities of the districts and divisions of Punjab in 2015.

Spatial aggregation: Maximum collection radius and logistical energy potential

The maximum collection radius is a way to consider logistical residue energy potential. As low-density feedstocks, agricultural residues are economically constrained by transportation distance (Chu & Majumdar, 2012; Kashif et al., 2020; Monforti et al., 2015). However, estimates of the maximum economically-feasible transportation distance vary, with no studies focusing on Pakistan. Studies that have applied the concept to Pakistan have used a maximum collection radius of 50 km (Kahsif et al., 2020) which was based on a maximum transportation distance of 70 km and a road deviousness factor of 1.4 (70km/1.5 = 50 km radius) (Monforti et al., 2015). However, this road deviousness factor is based on the European Union, with road deviousness factors in developing countries ranging between 1.4 and 2.0 (Ballou et al., 2002). Therefore, this research looked at two maximum collection radii, assuming a powerplant size of 100 MW, of 50 km (70 km/1.4) and 35 km (70 km/2.0).

As can be seen in Figure 14, considering a maximum collection radius had a large implication on the residue energy potential. In all scenarios and under all aggregation levels, the residue potential energy with a 50 or 35 km maximum collection radius was under half that with no collection radius. Moving from 100% to ecological residue use, the gap in residue energy potential between CR=none and CR=50 and between CR=50 and CR=35, widened. The residue energy potential for the competitive (bioeconomic) and ecological (eco-economic) use scenarios also decreased when moving from district-level aggregation to provincial-level aggregation. At the provincial-level aggregation and division, both the bioeconomic and eco-economic scenarios resulted in energy potentials of 0 km with CR =35 km, while the eco-economic also had 0 MW at CR=50 km. As shown at the bottom of Figure 14, the ECR under the ecological use scenario is never under 35 or 50 km for any administrative divisions, which is why the eco-economic energy potential estimates at the division-aggregation level are 0 for CR=35 and CR=50. Conversely, the ECR under the eco-economic scenario (ecological use) is under 35 for two individual districts (Rahim Yar Khan and Vehari).

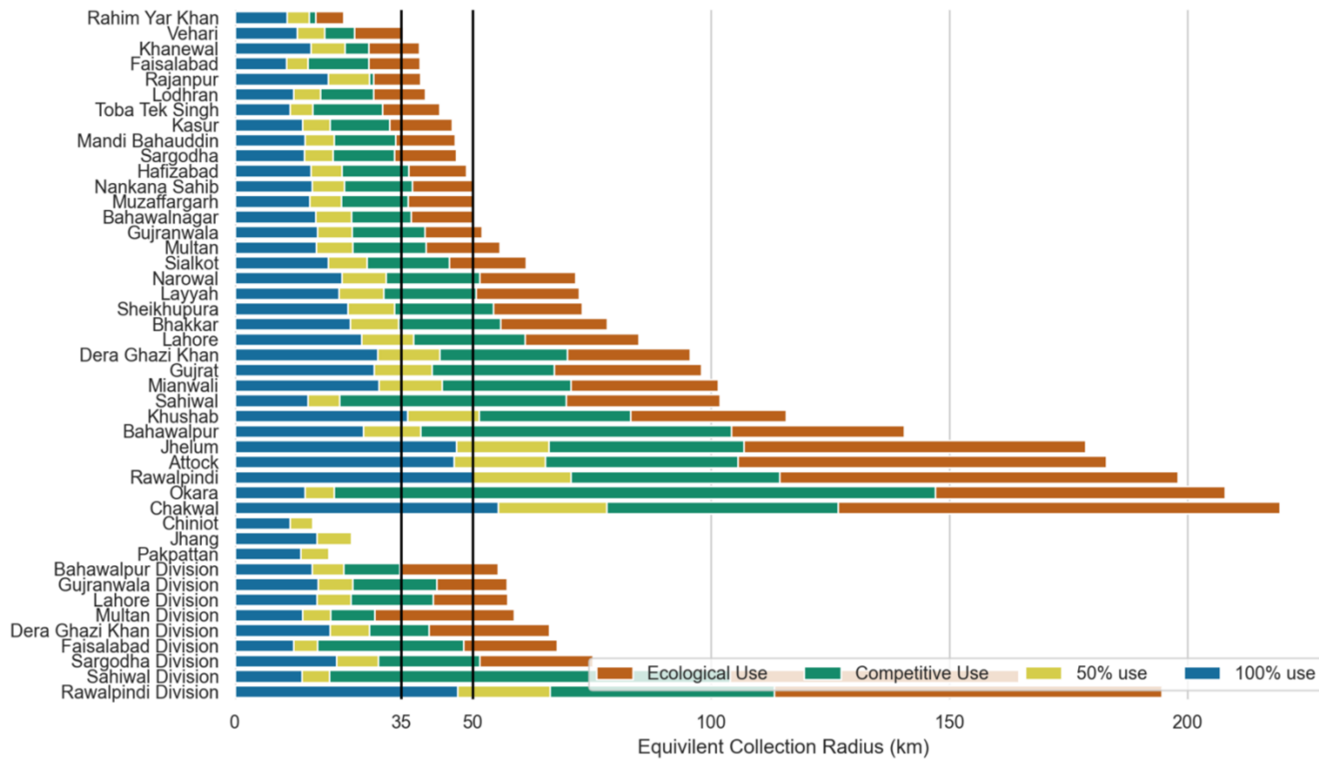


Figure 13 Equivalent collection radii of the districts and divisions of Punjab.

Expanding on the district level aggregation, as this is the most accurate, the lowest energy potential estimation for Punjab, of 700 MW, occurred in the eco-economic scenario under 35 km. However, at 50 km, the residue energy potential of the eco-economic scenario more than doubled to 1800 MW, which is similar to the estimation of Uzair et al. (2020). In the bioeconomic scenario (under district-level aggregation), the potential energy ranged from 3000 MW (CR= 35 km) to 3800 (CR=50 km). At the same time, the technical energy potential (50% residue use) ranged from 9200 (CR=35 km) to 10100 (CR=50 km). As demonstrated in Figure 13, the equivalent collection radii vary across districts due to a) the density of crop production within the district and b) the surplus availabilities of residues under the scenario assumptions. A smaller ECR under the 100% and 50% residue use scenarios indicates higher crop density, whereas a relatively small ECR under competitive and ecological use scenarios indicates high SAFs. Since the graph is sorted by ECR under the ecological scenario, the districts at the top of the graph, such as Rahim Yar Khan and Vehari, represent districts with a high density of available residues. Conversely, the districts at the bottom, Chiniot, Jhang and Pakpattan, despite low ECRs under the 100% and 50% residue use scenarios, indicating high residue density, have no ECRs under the competitive and ecological use scenarios since there are no surplus available residues. Conversely, for districts such as Chawal, the apparent issue is a low density of crop production, as the ECR is over 50 for all scenarios.

The results show that when considering the maximum collection radius, it is important to choose the highest resolution data possible. Estimates are likely to underestimate residue energy potential when considering competitive uses at lower resolutions (or higher aggregation scales). Furthermore, the choice of maximum collection radius has a significant impact. With no maximum collection radius, energy potential is likely to be overestimated; at the same time, too low of a maximum collection radius may lead to underestimating the bioeconomic or eco-economic energy potential.

5.3 Variation due to scenarios

As evident in Figure 7, the residue use scenario had the most significant impact on residue energy potential. Consideration of competitive and ecological residue uses are vital to conservative estimates of residue potential energy. As mentioned above, there are several well-established competitive uses for residues in Pakistan, including fodder, traditional fuel (domestic fuel), sale to industries, sale to biomass providers and fertilizer (The World Bank, 2016). It is unrealistic to assume that farmers will divert residues from current competitive uses toward residue-based energy without adequate incentives or logistical support. Considering only the district-level data, the energy estimates with CR=none for the bioeconomic (considering competitive residue use) were 79% less than the theoretical energy potential (100% residue use) and 58% less than the technical energy potential (50% residue use). When considering maximum collection radii, the bioeconomic energy potential was 81% (CR=50 km) and 85% (CR=35 km) less than the theoretical energy potential and 62% (CR=50 km) and 65% (CR=35 km) less than the technical energy potential.

The eco-economic residue energy potential further constrained energy potential. To maintain soil functioning, a portion of residues must be retained to prevent soil erosion and corresponding soil carbon and nutrient losses (Ranaivoson et al., 2017). The eco-economic scenario (competitive and ecological residue use) decreased the energy potential estimates by 89% (CR=None), 91% (CR=50 km) and 97% (CR=35 km) relative to the theoretical scenario (100% residue use). Relative to the technical scenario (50% residue use), the eco-economic scenario decreased energy potential estimates by 78% (CR=None), 82% (CR=50 km) and 92% (CR=35 km). Finally, even though both considered competitive uses, the eco-economic scenario reduced energy potential by 47% (CR=None), 53% (CR=50 km) and 77% (CR=35 km) relative to the bioeconomic (competitive residue use) scenario.

As can be seen, considering of ecological residue use under current patterns of competitive uses greatly decreases the potential for residue bioenergy to ameliorate Pakistan's energy crisis. High residue removal rates can have unintended impacts, leading to soil organic carbon depletion and erosion, potentially reducing crop yield, increasing surface water pollution, and increasing the need for agricultural inputs, which increases environmental impacts associated with carbon emissions from fertilizers and nutrient runoff and increasing costs of production (Warren Raffa et al., 2015). At the same time, despite potential negative impacts, the dominant residue management practices in Pakistan do not consider residue retention for sustainability; the majority of residues are removed or burned in the field (Ahmed et al., 2015; Benbi, 2018; The World Bank, 2016). Therefore, it is unrealistic to assume that farmers will adopt sustainable residue retention rates without increased education and incentives regarding residue retention. However, even if ecological residue retention is not applied, the implementation of crop residue-based energy may help reduce the harmful practice of open-field burning, which is a significant regional source of NO_X, CO and CH_4 (Yevich & Logan, 2003). Full residue removal is around 34% costlier than full-field residue burning; however, as shown in method 2, these costs can be outweighed by the added income from residue energy (Ahmed et al., 2015). Based on these findings, the bioeconomic energy potential (considering competitive uses), aggregated at the district level and under CR=50 km or CR=35 km, provides the most realistic estimation of the energy potential now and into the near future.

5.4 Implications of method one

Based on the results and discussion presented above, the following implications can be derived:

1. Aggregation scale and assumptions related to residue use and availability significantly impact estimations of crop residue-based energy potential.
2. The use of low-resolution data causes overestimations of theoretical and technical energy potential (100% and 50% residue use) and underestimations of bioeconomic (competitive residue use) and eco-economic (competitive and ecological residue use) energy potential due to heterogeneity in crop productivity, production area density, cropping patterns and competitive uses.

3. The highest resolution data about crop yields and competitive uses should be used to estimate crop residue-based energy to obtain accurate estimates. If possible, at least district-level data should be used.
4. Studies are needed to determine Pakistan's maximum economically feasible collection radius based on transportation costs and road circuity.
5. In terms of implementation:
    a. Rahim Yar Khan and Vehari represent ideal districts residue-based energy implementation as the ECR <35 for both bioeconomic and eco-economic scenarios.
    b. Khanewal, Faisalabad, Rajanpur, Lodhran, Toba Tek Singh, Kasur, Mandi Bahauddin, and Sargodha are good for residue-based energy, as they have an ECR < 35 for the bioeconomic scenario and an ECR<50 for the eco-economic scenario.
    c. Hafizabad, Nankana Sahib, Muzaffargarh, Bahawalnagar, Gujranwala, Multan and Sailkot (50 km) are acceptable as they have an ECR <50 km for the bio-economic scenario, however, under the eco-economic scenario, the ECR is over 50 km.
    d. Narowal, Layyah, Sheikhupura, Bhakkar, Lahore, Dera Ghazi Khan, Gujrat, Mianwali, Sahiwal, Khushab, Bahawalpur, Jhelum, Attock, Rawalpindi, Okara and Chakwal are not recommended due to low residue energy densities.
    e. Conversely, Chakwal, Chiniot, Jhang and Pakpattan are not recommended due to low surplus availabilities.

Chapter 6: Method two results and discussion

Together, methods one and two aimed to fill gaps in knowledge about the diverse factors impacting residue-based energy in Pakistan to support strategic bioenergy planning and implementation. In comparison to method one, which looked at the role of scale and residue use assumptions on energy potential, the broad aim of method two was to gain insights into how feedbacks in the WEF nexus impact residue-based energy potential at a sub-district scale. In general, the impacts of the WEF nexus on residue energy potential are underexamined in the literature, both in Pakistan and beyond. This is even though numerous factors related to the WEF nexus, including water and salinity management, competitive uses for feed, fuel and fibre, agricultural practices and climate change, can impact residue-based energy potential locally and globally. This is especially relevant in Pakistan, as soil salinity impacts a third of areas equipped for irrigation, water scarcity is prevalent

(FAO, 2020), residues have well-established competitive uses (Rehman Zia et al., 2020), and the region is vulnerable to climate change (Khan et al., 2016)

To achieve the aim of method two, a spatially explicit coupled human-water model (the P-GBSDM), described in Section 5.2.1, of the local agricultural system in the Rechna Doab was applied to simulate the impacts of various water management and competitive use scenarios on the energy potential of the region over time. The P-GBSDM dynamically couples a physically-based agro-hydro-salinity model (SahysMod) with a participatory-built system dynamics model that captures the socioeconomic and managerial aspects of the systems. For this research, a crop residue-based energy module was added to the model (described in Section 5.2.1). Following modification, two stages of validation were performed: (1) testing model structure (structural validation) and (2) testing model behaviour, as discussed in section 5.2.4.

Like many areas of Pakistan, the study area simulated in the P-GBSDM has portions impacted by water stress and soil salinity. Therefore, its application towards residue-based energy potential estimations allows for exploring of how marginal production conditions impact residue energy potential and density over time, further shedding light on the impact of spatial and temporal scale on residue-based energy. Furthermore, the estimation of energy potential under various stakeholder-selected water management scenarios allows for identifying optimal solutions for the co-management of water, residue energy and agricultural production (food systems). Furthermore, the ability of the P-GBSDM to capture income and cost feedbacks also allows for the exploration of the impact of residue-based energy on the agricultural system, allowing for the identification of trade-offs and synergies. Finally, the ability to simulate extreme climate change impacts on residue-based energy sheds light on future risks.

Therefore, this research simulated residue energy potential under four stakeholder selected water management scenarios and two residue use scenarios. The water management scenarios, which were suggested by local stakeholders during the participatory model building exercises (Inam et al., 2015) aimed to ameliorate water supply and soil salinity issues in the area. These included none (NW), canal lining (CL), rainwater harvesting (RH), irrigation improvement (II) and vertical drainage (VD). The residue uses for energy scenarios included none (NU), competitive use (CU), and ecological residue (EU) use which considered competitive residue uses and ecological and competitive residue uses, respectively. In addition, three climate scenarios were considered, the base case (historical climate extended with no added radiative forcing) and two future climate scenarios representing the radiative forcing of RCP 4.5 and RCP 8.5 in 2100. The model was simulated for 25 years (52 seasons, inclusive), from 2005 to 2025. As model outputs resulted in many variables, only variables of interest related to residue-based energy, water management and availability, soil salinity, crop yields and farm income are presented. The results under the current climate will be discussed first, followed by a brief discussion of the results under future climate change. The results for the percent difference calculations for variables of interest for the current climate are shown in Appendix B.

6.1 Residue energy potential across scenarios

Under the current climatic conditions, as shown in Figure 15, the residue energy potential of the study area varied both temporally and spatially between scenarios. In general, scenarios followed the same temporal variation due to variation in seasonal climatic factors, such as maximum and minimum temperature and rainfall. The maximum energy potential value, at 24 MW, occurred under the CU VD scenario (competitive residue use with vertical drainage) during 2006, with a similar spike being seen in the EU VD scenario. However, this maximum was short-lived, with the CU CL (competitive use with canal lining) achieving the highest residue potential energy for all years after 2008. Conversely, the minimum value of approximately 7.5 MW occurred under the EU NW (ecological residue use with no water management) and EU RH (ecological residue use with rainwater harvesting) scenarios during 2020. These scenarios achieved the lowest energy potential during the total study period of 25 years.

As expected, the competitive residue use (CU) scenarios achieved a more significant energy potential than the ecological residue use (EU) scenarios since the ecological residue use scenario considered both competitive uses and ecological residue retention. The different water management scenarios created similar trends between competitive and ecological residue use scenarios. However, the difference in energy potential between the no water management scenario and canal lining, rainwater harvesting and vertical drainage, respectively, was more significant under competitive residue use than under ecological residue use, likely due to the impact of higher residue income, as will be discussed further below.

The canal lining policy generally led to the highest residue energy potential under both residue use scenarios, surpassing the next best policy by an average of 2 MW under competitive use and 1 MW under ecological use. On average, canal lining under the competitive use scenario led to an increase in the residue energy potential of 12% with respect to the CU NW (competitive uses with no water management) scenario (Appendix B). In contrast, the EU CL scenario outperformed the EU NW (ecological uses with no water management) scenario by 9%. The second-best policy with regards to residue energy potential was vertical drainage; however, it performed closer to the base case than canal lining under both residue use scenarios; the residue energy potential was only increased by an average of 4% under competitive residue use and 2.5% under ecological residue use. Rainwater harvesting slightly increased (1%) residue energy potential relative to the CU NW scenario, but none under the EU scenario. Irrigation improvements were ineffective at improving residue energy potential relative to no water management. The mechanisms contributing to these impacts, as related to water, salinity stress and farm income, are described below.

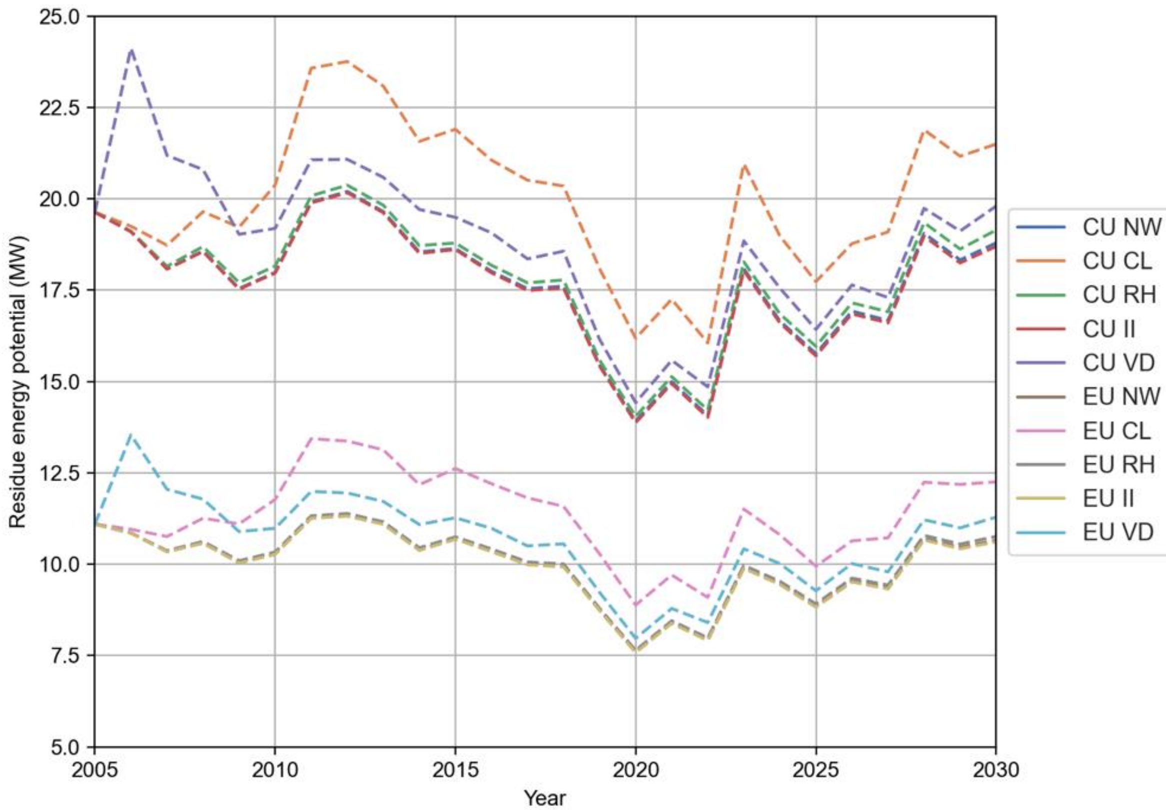


Figure 14 Simulated residue energy potential (MW) of the Rechna Doab under different competitive use and water management scenarios.

6.2 Salinity across scenarios

Overall, soil salinity increased under all scenarios. As evident in Figure 16, the residue use scenarios (NU, CU and EU) had little impact on soil salinity. Conversely, as shown in Figures 16 and 17, all water management scenarios, including no water management, led to an increase in soil salinity over the study period. There was a negligible difference between the polygon salinity under rainwater harvesting and no water management. Similarly, irrigation improvements only led to an average of 0.19% increase in polygon salinity over the study period, differing from the NW scenario by 0.5% during 2030.

Conversely, both canal lining and vertical drainage led to increases in soil salinity relative to the NW scenario. Vertical drainage caused soil salinity to increase by an average of 23% (to an average of 9 ds/m), while canal lining caused an increase of 5.8% (to an average of 7.75 dS/m), relative to no water management. Correspondingly, salinity stress under those scenarios increased by an average of 57 % (VD) and 10% (CL). Under the VD scenario, the number of moderately saline polygons (EC = 8-16 dS/m) increased by an average of 153%, and CL increased by an average of 20%, with respect to NW. The causes of these increases will be discussed below in conjecture with the discussion on water table depth.

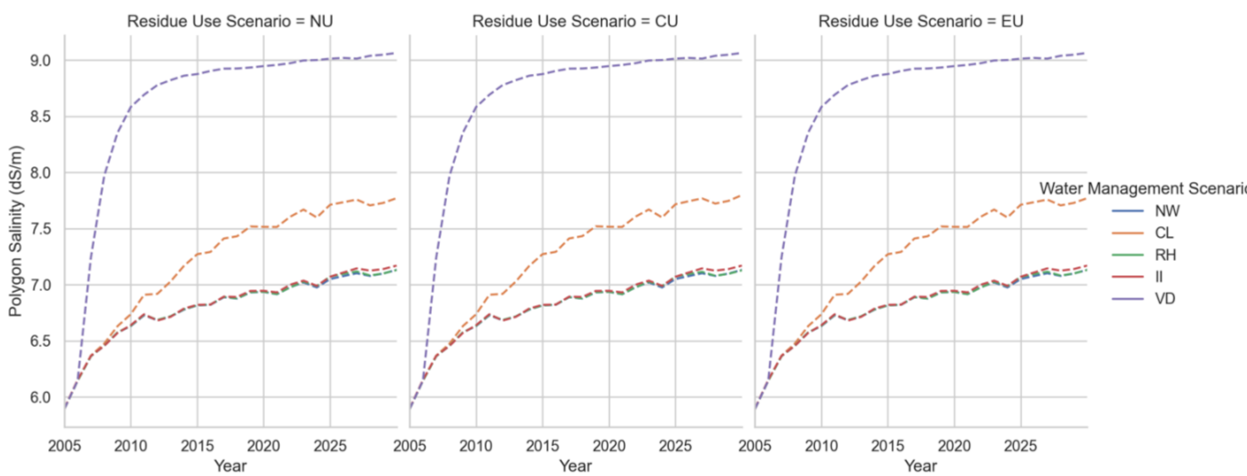


Figure 15 Polygon salinity across scenarios.

As mentioned, the residue use scenarios had negligible impact on soil salinity. One minor exception was noted. In the case of canal lining, the number of moderately saline polygons increased by 2.3% and 2.4% in 2025 and 2030 under the competitive use scenario with respect to the no residue use. However, this only corresponded with an increase in average polygon salinity and salinity stress across the study area of 0.35% and 0.7% in 2030. No difference was noted between the ecological residue use scenario. As will be discussed further below, the implementation of water management scenarios and groundwater pumping for tubewell irrigation is constrained by farm income. In the case of canal lining, an expensive water management policy, the added income from crop residues creates conditions in some polygons (where income is sufficient) to increase tubewell irrigation along with canal lining implementation. In turn, the application of marginal tubewell water onto the polygon increases soil salinity, creating a balancing effect on residue income and potential investments.

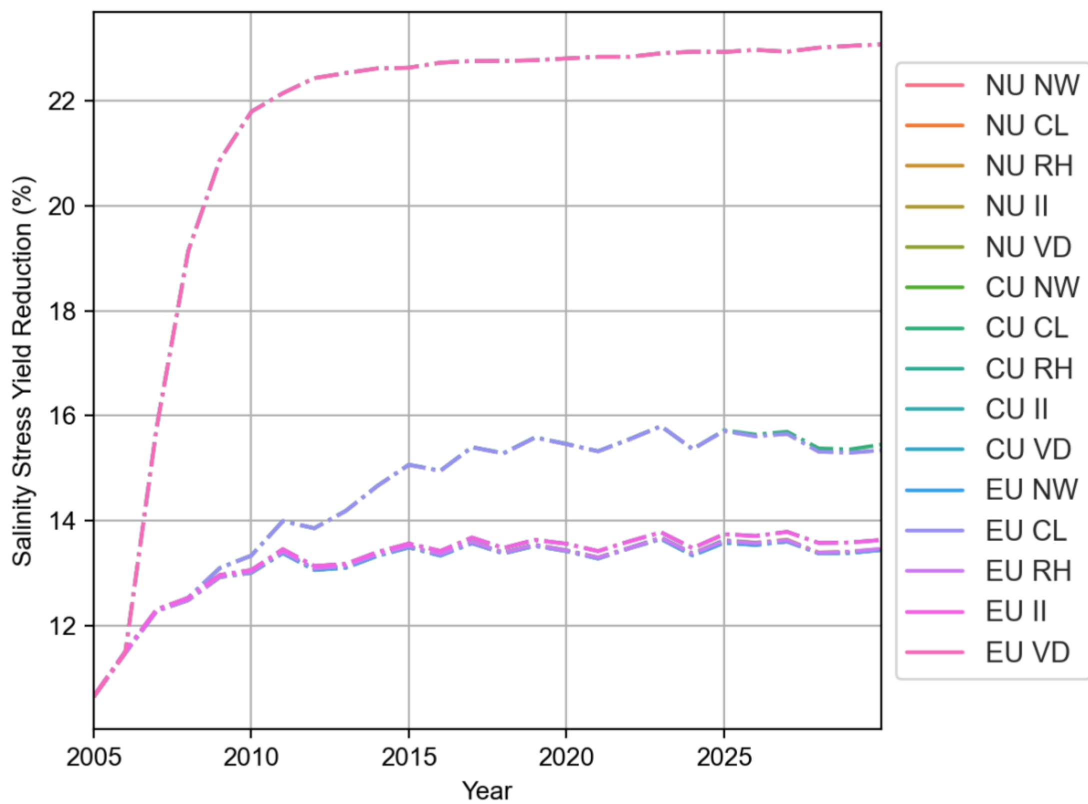


Figure 16 Crop yield reduction (%) due to salinity stress across scenarios.

6.3 Water table depth and irrigation water quality

Similar to the trends identified above, the residue use scenarios had little impact on the water table depth, though some water management policies did, namely vertical drainage and canal lining, as shown in Figure 18. Overall, the irrigation efficiency and rainwater harvesting policies had a negligible impact on the water table depth relative to no water management. Under each of these scenarios, the water table depth remained relatively constant over the study period. While improved irrigation efficiency reduces deep percolation and thus recharge of groundwater, the water conveyance losses in unlined canals are much greater in magnitude, limiting the realized impact of irrigation improvements on groundwater table depth. Conversely, the vertical drainage policy led to an increase in water table depth of approximately 50% (to an average depth of 4 m) in comparison to no water management. The water table depth in the canal lining scenario increased by an average of 5%, relative to the no water management policy. In both cases, this contributed to increases in soil salinity, but through different mechanisms.

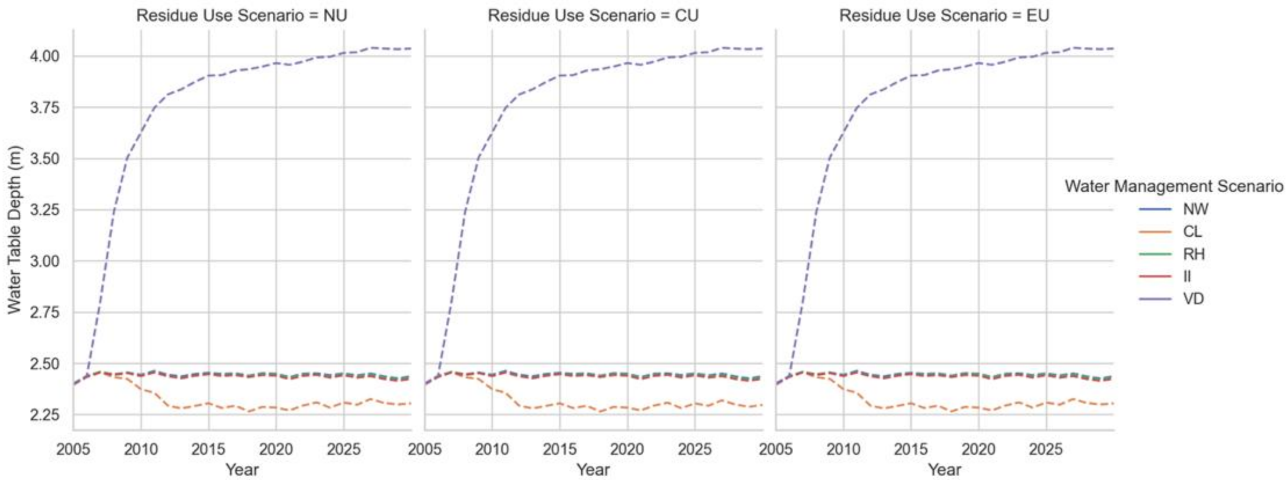


Figure 17 Water table depth across scenarios.

For canal lining, increases in water supply (Figure 20) and corresponding irrigation water application and subsequent root zone seepage, combined with decreased groundwater abstraction, caused an increase in water table depth which increased primary salinization through the capillary rise of saline groundwater, even though canal lining decreased the salinity of irrigation water (Figure 19).

Alternatively, in the case of vertical draining, the policy caused excessive groundwater pumping and over-abstraction, which depletes fresh zone layers in the aquifer, deteriorating the quality of applied irrigation water. As shown in Figure 19, while the electrical conductivity of irrigation water did not vary between residue use scenarios, it did vary between water management scenarios. In the case of vertical drainage, the electrical conductivity of the irrigation water increased by around 6.27% relative to no water management policies. Alternatively, canal lining caused a decrease in the electrical conductivity (-6.13%) of irrigation water due the dilution of the saline aquifer with fresh water.

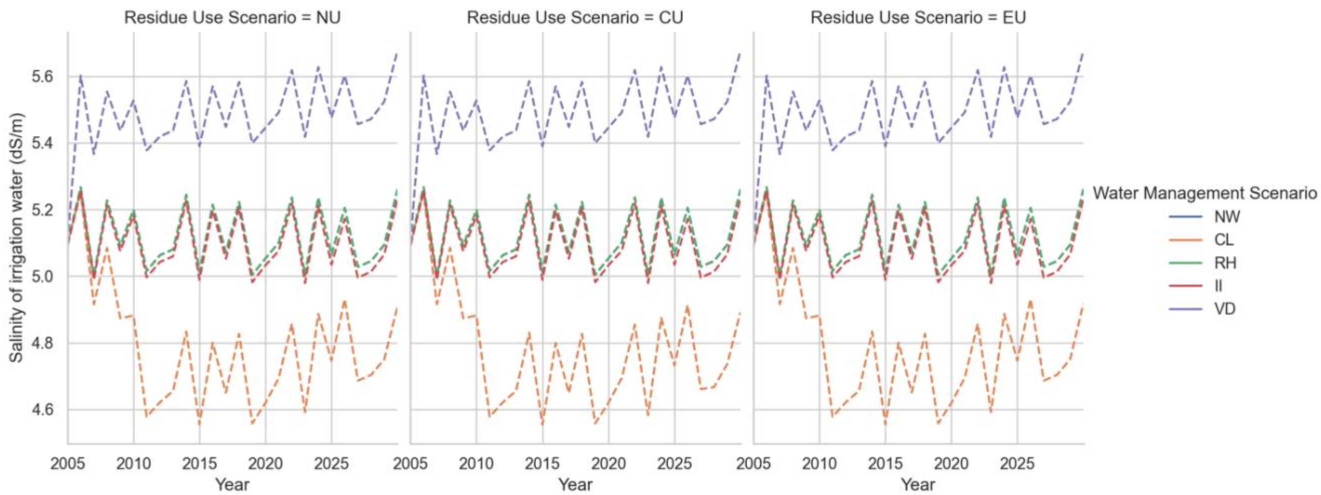


Figure 18 Salinity of irrigation water across scenarios.

6.4 Total water supply and water stress

Despite increasing soil salinity, both canal lining and vertical drainage improved crop yields and, correspondingly, the residue energy potential of the study area in comparison to the other water management scenarios. In both cases, this was caused by improved total crop water supply (Figure 20), as well as corresponding decreases in crop water stress (Figure 21). Overall, vertical drainage improved total crop water supply the most, increasing water supply by 23% in comparison to no drainage. Canal lining led to comparable increases in water supply over time but had a delayed response time of around five years. On average, canal lining increased total water supply by 20% above no water management. Rainwater harvesting had a marginal impact, increasing the total water supply by around 1%, whereas irrigation improvements were ineffective. While the impact of residue energy use was minimal, canal supplies were 1% greater under the competitive use scenario than under the no residue and ecological use scenarios due to increased implementation of canal lining, as will be shown below.

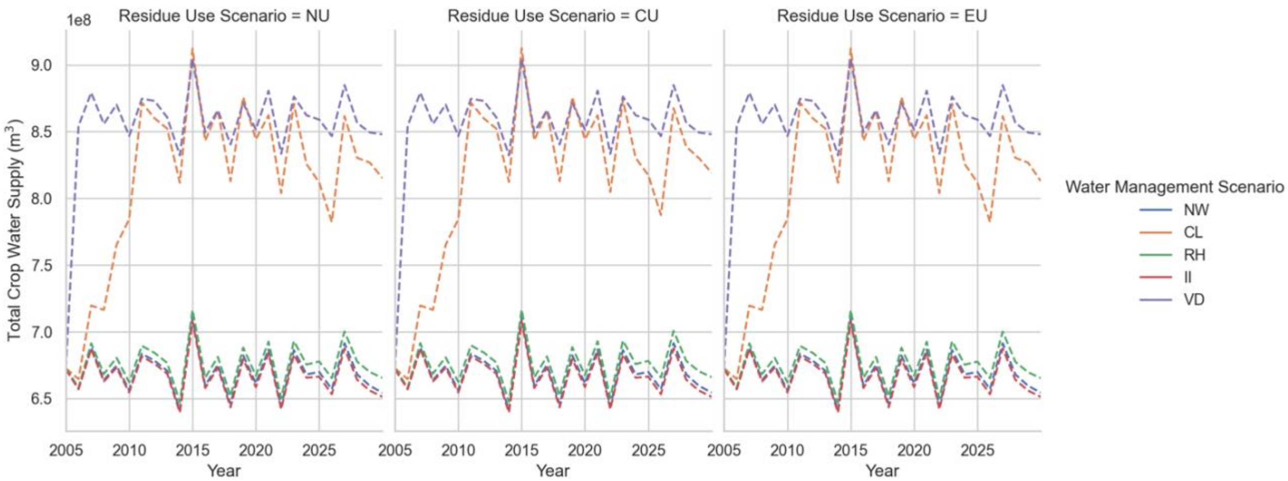


Figure 19 Total crop water supply (m^3) across scenarios.

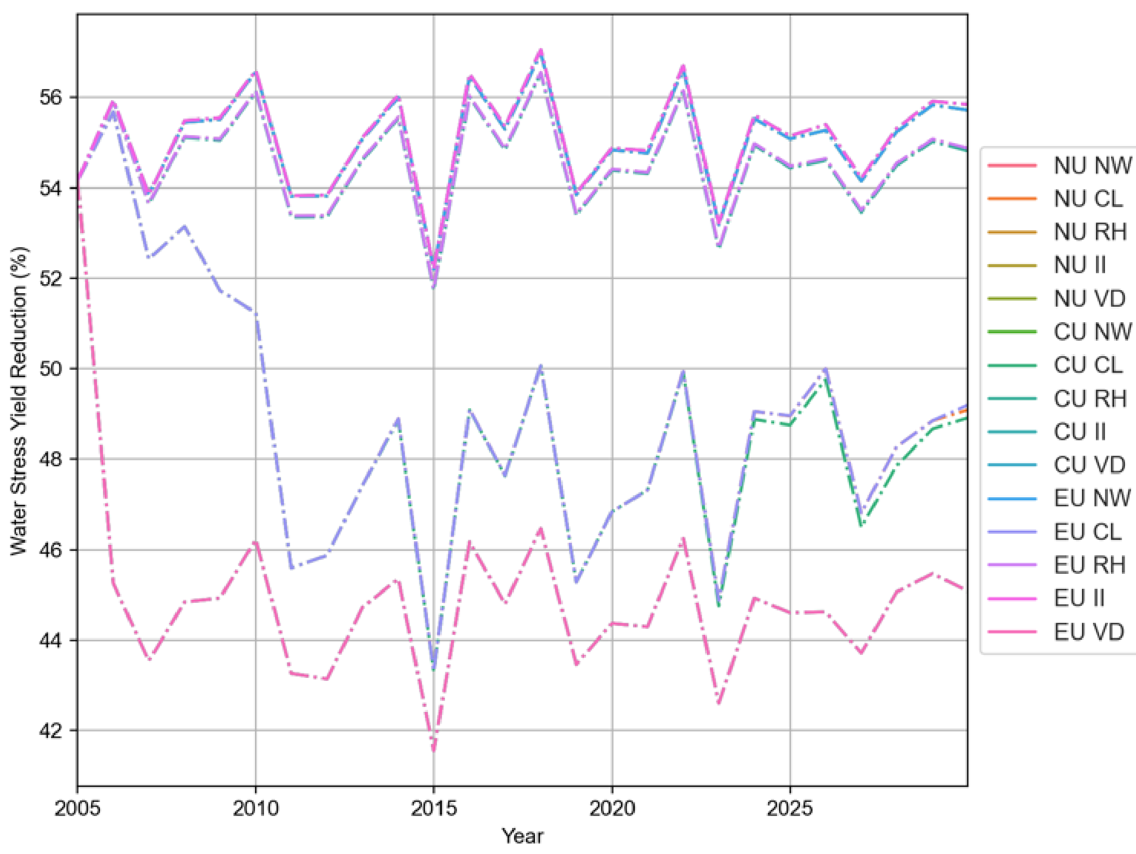


Figure 20 Crop yield reduction (%) due to water stress across scenarios.

Due to improvements in total water supply under vertical drainage and canal lining, water stress was also reduced under these policies. Vertical drainage and canal lining led to average decreases in water stress of 16% and 11%, respectively, compared to no water management. However, the decreases in water stress under canal lining showed an upward trend, growing from approximately 9% in 2010 to 12% in 2030, whereas the impact of vertical drainage remained constant. Overall, though vertical drainage improved total crop water supply the most, it also led to large increases in salinity stress, which partially negated the reduction in water stress. Therefore, canal lining performed the best in reducing combined crop stress and improving yields and residue energy potential.

6.5 Farm income and expenditure

Both residue energy use and water management policies impacted net farm income over the study period, as shown in Figure 22. For brevity, this section will only focus on the impacts of canal lining and vertical drainage in comparison to no water management scenario, as the other two water policies (rainwater harvesting and irrigation improvements) had negligible impacts on crop and residue yields. Overall, under no water management scenarios, competitive residue use improved farm income on average by 4.3%; however, this grew from 1.6 to 6.29% between 2005 and 2030. Alternatively, ecological residue uses did not significantly impact farm income, as added income from negligible harvest did not counteract added harvesting costs. Under no residue use, canal lining led to an average decrease of net farm income, relative to no water management strategies, of %16 due to the high expenditures for policy implementation (Figure 23). Alternatively, vertical drainage positively impacted net income, increasing it by an average of 2.8%. The effect of canal lining increased over time, causing a 14% reduction in net income in 2010 and a 27% reduction in 2030. Alternatively, the impact of vertical drainage showed a downward trend.

Overall, the added income from competitive residue uses helped counteract a portion of the income loss under the NU CL scenario. Conversely, the farm income under the CU CL scenario was, on average, 5.58% higher than under the NU CL, meaning that the overall farm income CU CL scenario was only 11% less than in NU NW (rather than 16% less). The same impact was noticed with the vertical drainage policy. The farm income under the CU VD scenario was 4.38% higher than the NU VD scenario, meaning that overall farm income under the CU VD scenario increased by 7.3% relative to no water management.

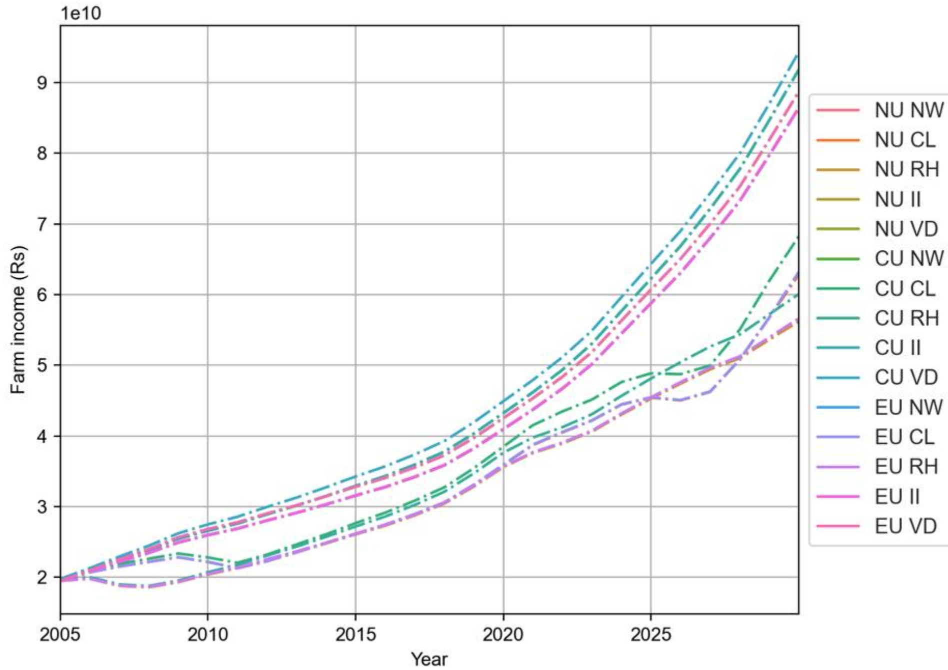


Figure 21 Farm income (Rs) across scenarios.

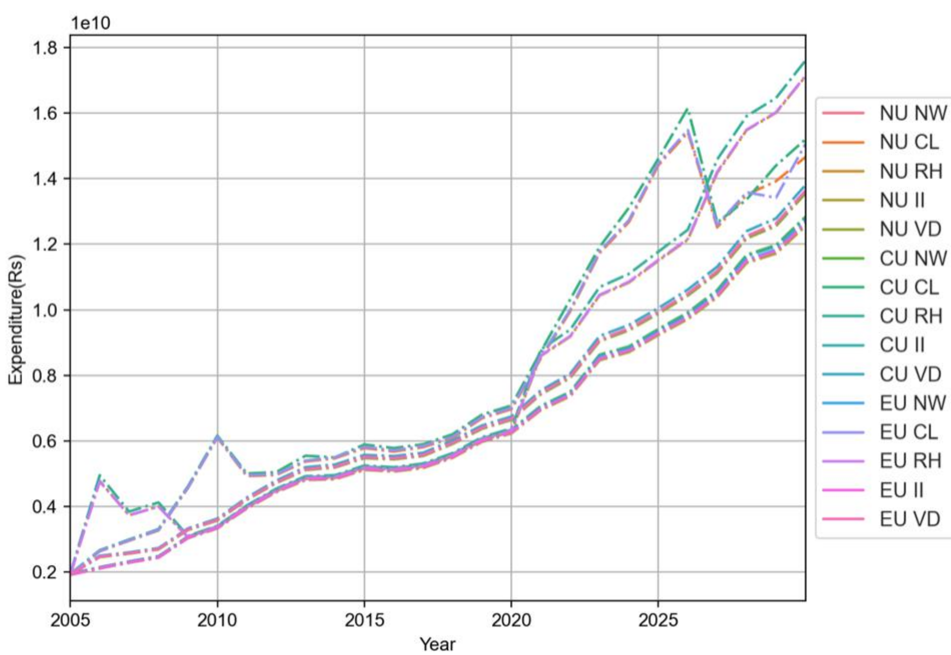


Figure 22 Expenditure (Rs) across scenarios.

6.6 Policy implementation

As shown below, the increase in farm income under the CU scenario had a positive impact on the implementation of two expensive policies, rainwater harvesting and canal lining. Generally, investments in water management policies are constrained by net farm income. Net farm income is a stock variable, meaning it accumulates profits over time and is impacted by income flows in (from crops, residues, and loans) and expenditure flows out (from crop production costs, harvest costs, irrigation costs, water management policies, debt repayment, and interest). As discovered through stakeholder interviews in (Inam et al., 2015), farmers only invest in water management policies if the costs per season are less than 20% of net farm income. If costs are more than 20% per season, the farmer will forgo implementation until income is sufficient. Therefore, there is a balancing effect between water policy expenditure and farm income to ensure it does not exceed an acceptable threshold.

Near the end of the study period, the additional income from the competitive use scenario caused an increase in canal lining with respect to no residue and ecological residue use scenarios (Figure 24). Overall, the CU scenario led to an increase in canals lined of 3.8% in 2025 and 4.2% in 2030, as shown in Appendix B. The increase in canal lining under the CU CL scenario directly led to an increase of approximately 1% in total water supply in 2025 and 0.5% in 2030 compared to NU CL and a slight decrease in water stress of 0.4% in both years. The observed decrease in lined canals is due to canal decay, which occurs roughly every five years (Baig, 2017).

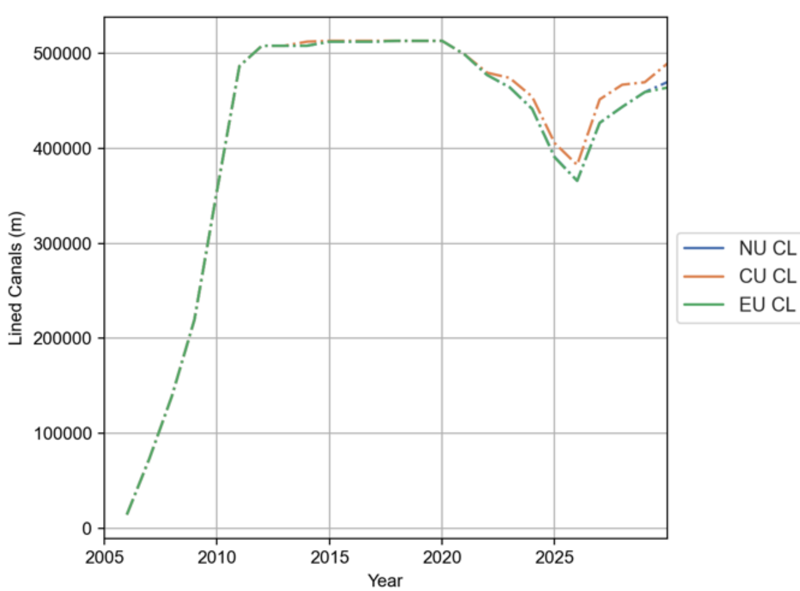


Figure 23 Impact of residue uses on length of lined canals (m).

A similar effect occurred with rainwater harvesting. Over the study period, the percent of constructed ponds increased by 5% in the CU RH scenario as opposed to no residue use (NU RH). However, as this had a negligible impact on residue-based energy and water and salinity stress and was associated with significant expenses, this policy is not recommended, despite synergies in its implementation under competitive residue use.

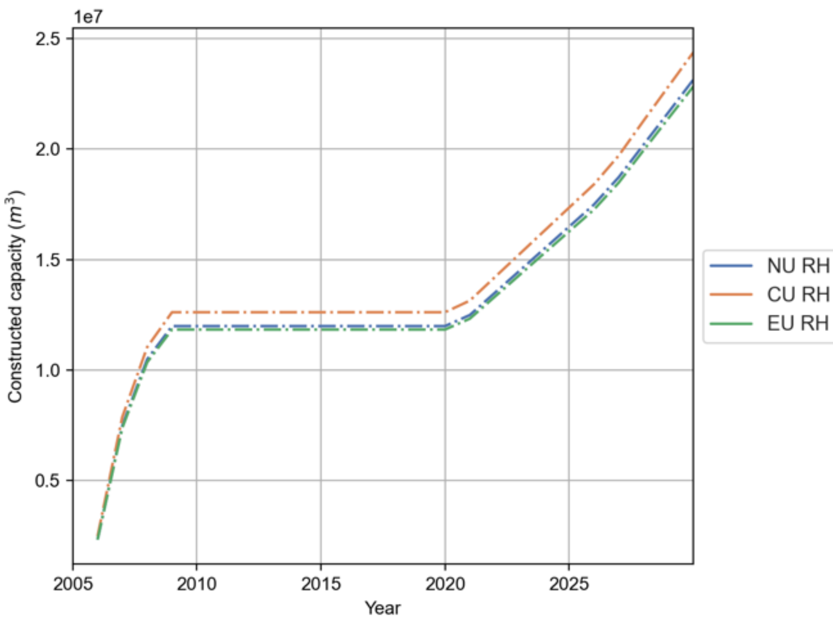


Figure 24 Impact of residue use on the constructed capacity of rainwater harvesting ponds (m^3).

6.7 Impacts of climate change on residue energy potential

As shown above, current climate variability and conditions of water stress and soil salinity in the study area already create significant variation in the crop residue-based energy potential of the study area. However, the climate scenarios applied in this study were meant to be purely exploratory; therefore, the results will only be discussed in terms of the general trends rather than in detail as was done above. As the climate scenarios used represent radiative forcing values of 2100, the system configuration could change considerably by that time. Therefore, the output of the P-GBSDM under these climate scenarios should not be taken as a predictive; rather, it indicates how the system may react under future climate change.

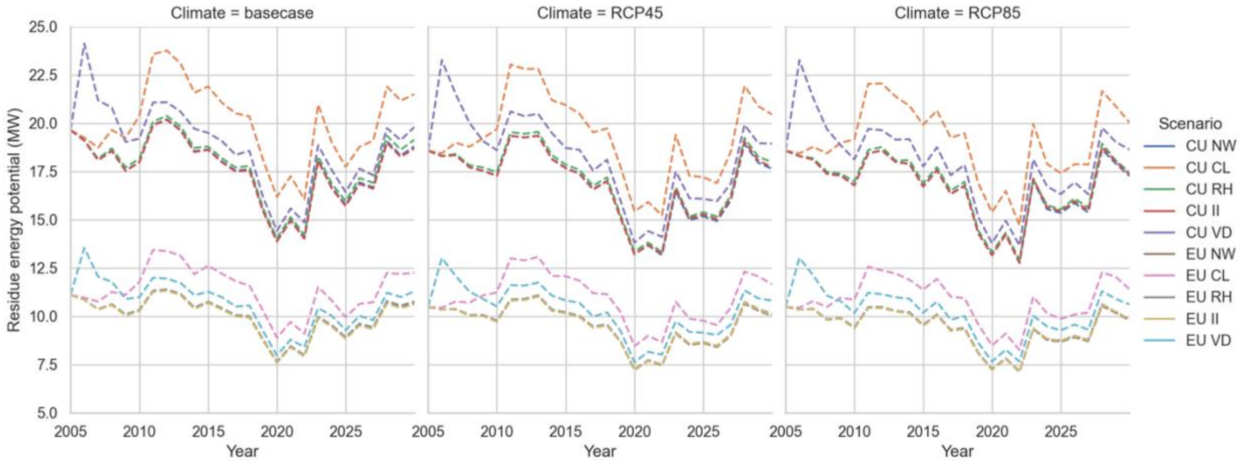


Figure 25 Residue energy potential of the study area under RCP 4.5 and RCP 8.5.

Overall, as shown in Figure 26, both RCP 4.5 and RCP 8.5 reduced the residue energy potential of the region. On average, across all residue use and water management scenarios, the climate scenarios reduced the residue energy potential of the region by 4% (RCP 4.5) and 5% (RCP 8.5). However, given Pakistan's vulnerability to climate change (Aggarwal et al., 2004), especially to climate extremes such as flooding and droughts (flooding is not simulated in the P-GBSDM), under current system configurations, it is likely that these reductions are underestimated.

The climate scenarios, on average across all management scenarios, increased water stress by 3% and 4%, for RCP 4.5 and RCP 8.5, respectively, as well heat stress. However, as shown in Figure 27, the benefits of canal lining and vertical drainage can help mitigate large losses in water availability, providing added adaptive capacity to the region with regard to water stress. Overall, more research is needed to understand the impact of climate change on residue-based energy potential in Pakistan.

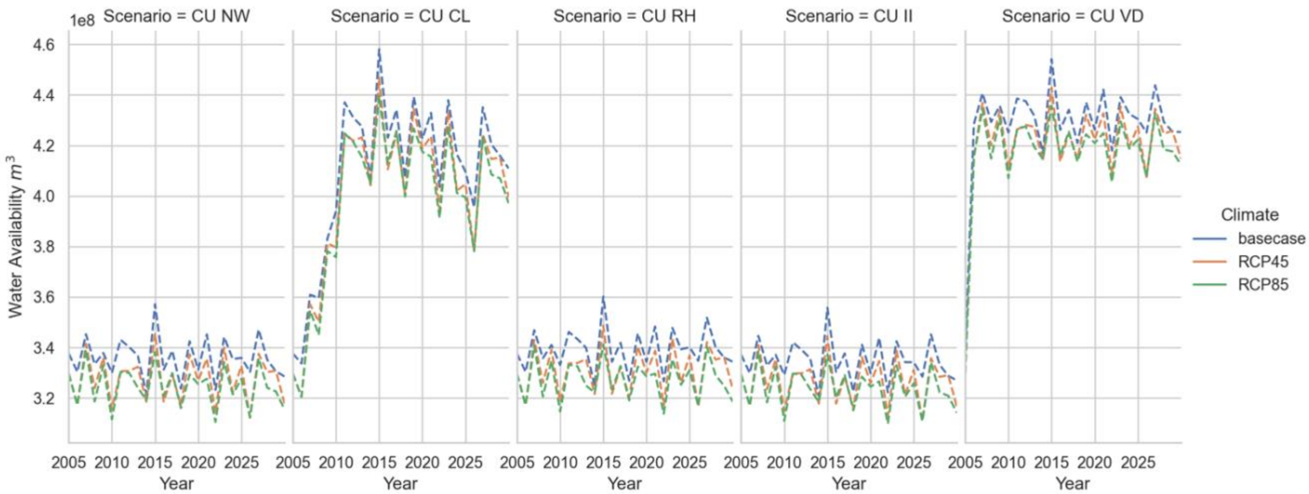


Figure 26 Water availability under climate change.

6.8 Comparison between methods one and two

To better understand the potential of the lower Rechna Doab for residue-based energy and to aid the interpretation of energy density results, the average residue energy densities for each water management scenario under the CU and EU residue scenarios were obtained (table 11) and compared to the results of method one (table 12). Despite being impacted by soil salinity and water stress, the study area achieved an average bioeconomic (CU) residue energy density of 19.5 KW/km^2 over the water management scenarios, ranging from 18.6 KW/km^2 under irrigation improvement and 21.1 KW/km^2 under canal lining. In comparison, the study area's districts achieved an average bioeconomic residue energy density of 15.4 KW/km^2; however, this was primarily due to Jhang having zero surplus residues (and thus 0 residue energy density). Compared to the other districts, Khanewal (26.2 KW/km^2) and Toba Tek Singh (20 KW/km^2), the average simulated bioeconomic residue energy density was less than in both districts than the bioeconomic residue energy density under all scenarios except canal lining. However, only by around 1 to 1.5 KW/km^2. Both Khanewal and Toba Tek Singh were found to be good candidates for crop residue bioenergy, as they both had ECRs of less than 35 km for the bioeconomic scenario and less than 50 km for the eco-economic scenario. Therefore, these results suggest that this area could be promising for residue-based bioenergy implementation.

Results for the simulated eco-economic energy potential across all scenarios were similar to Toba Tek Singh, indicating residue-based energy may even be feasible in the Rechna Doab if ecological residues are retained, highlighting a potential avenue for synchronous improvements in both energy and agricultural sustainability. At the same time, given current patterns of residue uses, capacity gaps would need to be addressed.

Table 12 Average simulated bioeconomic (CU) and eco-economic (EU) residue energy densities across water management policies.

	Bioeconomic residue energy density (KW/km^2)	**Eco-economic residue energy density (KW/km^2)**
NW	18.7	10.5
CL	**21.1**	12.0
RH	18.8	10.6
II	18.6	10.5
VD	19.9	11.3
Average	19.4	11.0

Table 13 Bioeconomic and eco-economic residue energy densities in the Jhang, Khanewal and Toba Tek Singh in 2010, 2015 and 2020.

Bioeconomic residue energy density (KW/km^2)				
District	2010	2015	2020	Average
Jhang	0	0	0	0
Khanewal	30.3	23.4	24.9	26.2
Toba Tek Singh	20.3	19.2	20.6	20.0
Average	16.9	14.2	15.2	15.4
Eco-economic residue energy density (KW/km^2)				
Jhang	0	0	0	0
Khanewal	17.0	12.3	12.7	14.0
Toba Tek Singh	10.7	10.0	10.8	10.5
Average	9.2	7.4	7.8	8.2

6.9 Implications of method two

Method two looked at how dynamic WEF interactions impact crop residue potential energy at an agricultural system scale. Overall, the results showed that water management can have a synergistic relationship with residue-based energy if the water management policies are appropriately selected. In the simulated area, the application of canal lining reinforced the bioeconomic energy potential of the region, increasing it by an average of 12% in comparison to no water management practices (CU NW). Congruently, the added income from the sale of residues under the CU scenario helped to reduce the drop in net farm income observed in the NU CL scenario from -16% to -11%. By offsetting some of the costs from canal lining, the competitive use scenario reduced financial barriers to policy implementation, increasing canals lined under the CU CL scenario relative to NU CL and EU CL. A similar reinforcing relationship was seen between residue-based energy and the constructed capacity of rainwater harvested ponds. However, as the rainfall is low in the study area, the ponds had a negligible impact on crop yields, and thus feedback was not observed.

Despite the dynamic synergy observed between canal lining and residue-based energy, significant trade-offs exist between canal lining and farm income, with may create barriers to implementation. Despite the added income from crop residues, canal lining still resulted in an average decrease in net farm income of 11% due to high installation and maintenance costs. Alternatively, vertical drainage had a positive but diminishing impact on farm income throughout the simulation period while also achieving higher energy yields than in the CU NW case. However, despite benefits in terms of income, water availability and residue energy potential under vertical drainage, a significant temporal trade-off exists, as the policy threatens long-term system sustainability by causing excessive groundwater drawdown and secondary salinization. This highlights the importance of considering the temporal and lagged effects of policy options as they pertain to optimal outcomes.

Both cases highlight the importance of integrated water, energy, and food systems management. In the case of residue energy, where the same land, water and farm inputs are used to produce both food and energy, residue-based energy can cause farm-level feedback. Identification and consideration of these feedbacks can help to optimize system management and improve sustainability, as well as avoid unintended outcomes. In this regard, participatory modelling can help to identify relevant socioeconomic factors of the target system, such as farmers' behaviours, whereas coupling between participatory system dynamics models and physically-based models can help improve the representation of the physical (environmental) side of the coupled human-environmental system.

Chapter 7: Conclusion

Given the importance of agriculture to Pakistan's economy, residue-based energy may be a viable solution to improve electricity supply and help reach the government's goal of increasing non-hydro renewable energy from ~4% to 30% of total electricity supply by 2030 (Pakistan Ministry of Energy, 2019). However, estimates of the residue potential energy in Pakistan vary widely, sometimes by thousands of MW, due to differing assumptions and estimation procedures. Furthermore, despite the numerous important interdependencies between water, energy and food systems in Pakistan (Siddiqi & Wescoat, 2013), the nexus implications of residue energy are unexamined in the literature. Therefore, to fill these gaps in knowledge, this research investigated these two overlooked aspects of residue energy potential estimations to support strategic bioenergy in Pakistan. This research thus had two broad aims, (1) to investigate how assumptions and scale impact residue-based energy potential estimates and (2) to explore the implications of interactions between the water-energy-food nexus and residue-based energy in Pakistan.

Aim one was achieved by critically analyzing the current literature on residue energy potential in Pakistan (section 2.3), finding that differences in assumptions of residue use and retention factors and scale were major sources of variation in current estimates. To further explore the implications of these assumptions, the theoretical (100% residue use), technical (50% residue use), bioeconomic (competitive residue use) and eco-economic (competitive and ecological residue use) energy potential of the Province of Punjab were calculated at three data aggregation scales (district, administrative division, and province) under three maximum collection radii (none, 35 km, and 50 km) (chapter 4). The results showed that aggregation scale and assumptions related to residue use and availability significantly impact estimations, with values ranging from 0-53345 MW. Overall, to obtain accurate estimations of energy potential, it is important to use the highest resolution data possible regarding crop yields and competitive uses. On the other hand, the use of low-resolution data causes distortions in potential energy estimations; Due to heterogeneity in crop yield, production density, and surplus availability factors, values are overestimated under theoretical and technical energy potential estimations but underestimated when considering competitive uses under bioeconomic and eco-economic scenarios. The results of this study echoed (Soha et al., 2021), who found that heterogeneity of agricultural supply of residues impacts the logistical viability of biogas plants in Hungary. To improve future estimates, this thesis recommends that further research be done with regard to transportation logistics to determine the

Pakistan-specific maximum collection radius. However, for residue-based energy implementation in the short term, the Rahim Yar Khan and Vehari represent ideal districts for implementation as they had an ECR over under 35 km for both bioeconomic and eco-economic scenarios.

To meet the second aim of this thesis, to explore the implications of the water-energy-food nexus on residue-based energy, a case study was performed in the Rechna Doab region through the application of a coupled-human water model (the P-GBSDM). The P-GBSDM, which couples a participatory built system dynamics model with the physically-based model SahysMod, was modified to calculate crop residue-based energy, corresponding income and cost feedbacks and validated structurally and behaviorally. Scenario analysis was used to explore how factors related to the WEF systems impact the viability of residue-based energy by simulating combinations of stakeholder-selected water management policies (none, canal lining, irrigation improvement, rainwater harvesting and vertical drainage) with residue energy scenarios (none, bioeconomic residue uses and eco-economic residue uses) over 25 years under current climate conditions and future climate change (radiative forcing values for RCP 4.5 and RCP 8.5 in 2100).

The results showed that aspects of soil and water scarcity could cause significant temporal variation in residue energy potential, and climate change could reduce long-term energy potential, highlighting the need for prudent estimations. At the same time, due to system feedbacks, significant synergies can exist between crop residue-based energy and appropriate water management strategies. This study observed a synergistic relationship between residue energy and canal lining, with canal lining improving residue energy potential and income. The added income, in turn, increased the implementation of canal lining and buffering against its associated high expenditures. At the same time, due to time delays, some scenarios which represented initial synergies led to long-term trade-offs. In the case of vertical drainage, increased water supply in the short-term improved energy potential and farm income; however, it led to unsustainable groundwater extraction and secondary salinization in the long term. Both examples show the importance and value of identifying and understanding WEF nexus feedbacks to optimize management and reduce unintended outcomes. As demonstrated in thesis research, participatory coupled models are useful tools for asking these types of what-if questions.

In terms of short-term implementation, the results of both methods suggest that the bioeconomic residue use scenario may have more short-term benefits in terms of increasing non-fossil fuel renewables and creating synergies in the WEFs. Nonetheless, for long-term planning

(2050+), it may be more prudent to apply the eco-economic scenario to account for shifts towards more sustainable residue management practices. At the same time, estimates in this range can also consider projected changes in competitive uses. For example, increased electrification of rural areas and improved consistency in supply is likely to increase the use of electric heating and cooking, increasing surplus residues (Rahut et al., 2020). In addition, cropping practices may also change, impacting theoretical residue availability.

This thesis demonstrates the importance of local-level analysis for bioenergy planning. At provincial, national, and global scales, information vital to the implementation of bioenergy projects, such as temporal and spatial yield heterogeneity and variability, local economies and actor behaviour, is lost. Therefore, a place-based approach, which considers assumptions and human-environmental interactions, is vital to successful residue-based energy planning and sustainable implementation.

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Appendix A: Code and Model

The model, codes and associated supplementary materials can be found here: https://mcgill-my.sharepoint.com/:f:/g/personal/emma_anderson2_mail_mcgill_ca/EuelDkqlv0NCmK1hEAdZXcsBScjv-ZB3KFMZQ6X0yLn_Qw?email=eammcooperanderson%40gmail.com&e=wLeyOT

Correspondence available at emma.anderson2@mail.mcgill.ca

Appendix B: Percent Difference Charts

Change in the electrical conductivity of applied irrigation water (%)

Energy Scenario	Water Scenario	2005	2010	2015	2020	2025	2030	Average
No residue use for energy (NU)	**No water management (NW) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	-6.1	-9.1	-8.6	-6.3	-6.69	-6.13
	Rainwater harvesting (RH)	0.0	0.0	0.0	0.0	0.0	-0.01	0.00
	Irrigation Improvement (II)	-0.2	-0.3	-0.5	-0.4	-0.6	-0.54	-0.42
	Vertical Drainage (VD)	0.0	6.3	7.5	7.8	8.1	7.90	6.27
Residue energy with competitive use (CU)	**No water management (NW)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	-6.1	-9.2	-8.6	-6.6	-7.02	-6.24
	Rainwater harvesting (RH)	0.0	0.0	0.0	0.0	0.0	0.01	0.00
	Irrigation Improvement (II)	-0.2	-0.3	-0.5	-0.4	-0.6	-0.54	-0.42
	Vertical Drainage (VD)	0.0	6.3	7.5	7.8	8.1	7.90	6.27
Residue energy with ecological use (EU)	**No water management (NW)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	-6.1	-9.1	-8.6	-6.3	-6.53	-6.11
	Rainwater harvesting (RH)	0.0	0.0	0.0	0.0	0.0	-0.01	0.00
	Irrigation Improvement (II)	-0.2	-0.3	-0.5	-0.4	-0.6	-0.54	-0.42
	Vertical Drainage (VD)	0.0	6.3	7.5	7.8	8.1	7.90	6.27

Change in Farm Expenditure (%)								
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
No residue use for energy (NU)	**No water management (NW) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	82.9	12.8	11.6	55.7	16.36	29.88
	Rainwater harvesting (RH)	0.0	0.6	0.6	0.6	24.2	35.87	10.30
	Irrigation Improvement (II)	-0.1	-0.1	-0.2	-0.2	-0.3	-0.35	-0.20
	Vertical Drainage (VD)	0.0	7.1	6.8	6.4	6.8	7.55	5.77
Residue energy with competitive use (CU)	**No water management (NW)**	1.6	1.6	1.8	1.6	1.7	1.88	1.67
	Canal lining (CL)	1.6	84.6	14.9	13.4	57.9	20.64	32.17
	Rainwater harvesting (RH)	1.6	2.2	2.4	2.2	27.2	39.73	12.54
	Irrigation Improvement (II)	1.5	1.5	1.6	1.3	1.4	1.53	1.48
	Vertical Drainage (VD)	1.6	8.8	8.7	8.0	8.6	9.57	7.54
Residue energy with ecological use (EU)	**No water management (NW)**	0.5	0.5	0.6	0.5	0.6	0.62	0.56
	Canal lining (CL)	0.5	83.5	13.5	12.2	56.3	19.52	30.92
	Rainwater harvesting (RH)	0.5	1.1	1.2	1.1	24.5	36.00	10.72
	Irrigation Improvement (II)	0.4	0.4	0.5	0.3	0.3	0.27	0.36
	Vertical Drainage (VD)	0.5	7.7	7.5	6.9	7.4	8.24	6.38

Change in Farm Income (%)								
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
	No water management (NW) (base case)	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	-14.6	-17.1	-12.3	-22.7	-27.30	-15.68
	Rainwater harvesting (RH)	0.0	-21.5	-17.3	-13.0	-22.9	-34.94	-18.29
	Irrigation Improvement (II)	0.0	0.0	0.0	0.1	0.0	0.02	0.03
No residue use for energy (NU)	**Vertical Drainage (VD)**	0.0	3.2	4.0	3.8	3.3	2.64	2.83
	No water management (NW)	1.3	2.4	4.4	5.6	6.0	6.29	4.31
	Canal lining (CL)	1.3	-12.2	-12.3	-6.0	-16.9	-21.00	-11.17
	Rainwater harvesting (RH)	1.3	-20.2	-13.8	-8.0	-18.1	-30.46	-14.90
	Irrigation Improvement (II)	1.3	2.4	4.4	5.7	6.0	6.28	4.33
Residue energy with competitive use (CU)	**Vertical Drainage (VD)**	1.3	5.8	8.6	9.8	9.5	9.17	7.35
	No water management (NW)	0.0	0.0	0.1	0.1	0.1	0.06	0.06
	Canal lining (CL)	0.0	-14.6	-17.0	-12.2	-22.6	-26.84	-15.53
	Rainwater harvesting (RH)	0.0	-21.2	-17.0	-12.8	-22.6	-34.43	-18.01
	Irrigation Improvement (II)	0.0	0.0	0.1	0.2	0.1	0.08	0.09
Residue energy with ecological use (EU)	**Vertical Drainage (VD)**	0.0	3.3	4.1	4.0	3.4	2.74	2.90

Change in the Number of Moderately Saline Polygons (%)								
Energy Scenario	Water Scenario	2005	2010	2015	2020	2025	2030	Average
No residue use for energy (NU)	No water management (NW) (base case)	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	5.6	25.0	33.3	29.4	24.24	19.59
	Rainwater harvesting (RH)	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Irrigation Improvement (II)	0.0	0.0	0.0	0.0	0.0	3.03	0.51
	Vertical Drainage (VD)	0.0	141.7	177.8	203.0	197.1	203.03	153.76
Residue energy with competitive use (CU)	No water management (NW)	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	5.6	25.0	33.3	32.4	27.27	20.59
	Rainwater harvesting (RH)	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Irrigation Improvement (II)	0.0	0.0	0.0	0.0	0.0	3.03	0.51
	Vertical Drainage (VD)	0.0	141.7	177.8	203.0	197.1	203.03	153.76
Residue energy with ecological use (EU)	No water management (NW)	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	5.6	25.0	33.3	29.4	24.24	19.59
	Rainwater harvesting (RH)	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Irrigation Improvement (II)	0.0	0.0	0.0	0.0	0.0	3.03	0.51
	Vertical Drainage (VD)	0.0	141.7	177.8	203.0	197.1	203.03	153.76

Change in Polygon Salinity (%)								
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
No residue use for energy (NU)	**No water management (NW) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	1.6	6.7	8.4	9.4	8.94	5.82
	Rainwater harvesting (RH)	0.0	0.1	0.0	0.0	0.3	-0.02	0.06
	Irrigation Improvement (II)	0.0	0.1	0.1	0.1	0.3	0.52	0.19
	Vertical Drainage (VD)	0.0	29.4	30.2	29.0	27.8	27.07	23.91
Residue energy with competitive use (CU)	**No water management (NW)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	1.6	6.7	8.4	9.4	9.32	5.90
	Rainwater harvesting (RH)	0.0	0.1	0.0	0.0	0.3	-0.06	0.05
	Irrigation Improvement (II)	0.0	0.1	0.1	0.1	0.3	0.52	0.19
	Vertical Drainage (VD)	0.0	29.4	30.2	29.0	27.8	27.07	23.91
Residue energy with ecological use (EU)	**No water management (NW)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	1.6	6.7	8.4	9.4	8.94	5.82
	Rainwater harvesting (RH)	0.0	0.1	0.0	0.0	0.3	-0.02	0.05
	Irrigation Improvement (II)	0.0	0.1	0.1	0.1	0.3	0.52	0.19
	Vertical Drainage (VD)	0.0	29.4	30.2	29.0	27.8	27.07	23.91

Change in Salinity Stress (%)								
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
No residue use for energy (NU)	**No water management (NW) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	2.5	11.6	15.2	15.7	14.08	9.85
	Rainwater harvesting (RH)	0.0	0.1	0.2	0.1	0.4	0.10	0.14
	Irrigation Improvement (II)	0.1	0.4	0.5	1.0	1.2	1.38	0.77
	Vertical Drainage (VD)	0.0	67.4	67.7	69.9	68.8	71.54	57.55
Residue energy with competitive use (CU)	**No water management (NW)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	2.5	11.7	15.2	15.8	14.89	10.00
	Rainwater harvesting (RH)	0.0	0.1	0.1	0.1	0.3	-0.02	0.11
	Irrigation Improvement (II)	0.1	0.4	0.5	1.0	1.2	1.38	0.77
	Vertical Drainage (VD)	0.0	67.4	67.7	69.9	68.8	71.54	57.55
Residue energy with ecological use (EU)	**No water management (NW)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	2.5	11.6	15.2	15.7	14.08	9.85
	Rainwater harvesting (RH)	0.0	0.1	0.1	0.1	0.3	0.13	0.12
	Irrigation Improvement (II)	0.1	0.4	0.5	1.0	1.2	1.38	0.77
	Vertical Drainage (VD)	0.0	67.4	67.7	69.9	68.8	71.54	57.55

Change in Water Consumption (%)								
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
	No water management (NW) (base case)	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	19.4	28.2	27.6	21.1	24.44	20.14
	Rainwater harvesting (RH)	0.0	0.9	0.8	0.9	1.2	1.68	0.91
	Irrigation Improvement (II)	-0.1	-0.3	-0.4	-0.4	-0.5	-0.48	-0.36
No residue use for energy (NU)	**Vertical Drainage (VD)**	0.0	28.9	27.2	28.7	28.1	29.46	23.72
	No water management (NW)	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	19.4	28.3	27.6	21.9	25.06	20.38
	Rainwater harvesting (RH)	0.0	1.0	0.9	0.9	1.2	1.77	0.96
	Irrigation Improvement (II)	-0.1	-0.3	-0.4	-0.4	-0.5	-0.48	-0.36
Residue energy with competitive use (CU)	**Vertical Drainage (VD)**	0.0	28.9	27.2	28.7	28.1	29.46	23.72
	No water management (NW)	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	19.4	28.2	27.6	21.1	24.13	20.08
	Rainwater harvesting (RH)	0.0	0.9	0.8	0.9	1.2	1.66	0.90
	Irrigation Improvement (II)	-0.1	-0.3	-0.4	-0.4	-0.5	-0.48	-0.36
Residue energy with ecological use (EU)	**Vertical Drainage (VD)**	0.0	28.9	27.2	28.7	28.1	29.46	23.72

Change in Total Water Supply (%)								
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
No residue use for energy (NU)	**No water management (NW) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	19.5	28.4	27.7	21.2	24.54	20.21
	Rainwater harvesting (RH)	0.0	0.9	0.8	0.9	1.2	1.69	0.91
	Irrigation Improvement (II)	-0.1	-0.3	-0.4	-0.4	-0.5	-0.48	-0.36
	Vertical Drainage (VD)	0.0	29.0	27.3	28.7	28.2	29.57	23.81
Residue energy with competitive use (CU)	**No water management (NW)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	19.5	28.4	27.7	22.0	25.16	20.46
	Rainwater harvesting (RH)	0.0	1.0	0.9	0.9	1.2	1.77	0.96
	Irrigation Improvement (II)	-0.1	-0.3	-0.4	-0.4	-0.5	-0.48	-0.36
	Vertical Drainage (VD)	0.0	29.0	27.3	28.7	28.2	29.57	23.81
Residue energy with ecological use (EU)	**No water management (NW)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	19.5	28.4	27.7	21.2	24.23	20.16
	Rainwater harvesting (RH)	0.0	0.9	0.8	0.9	1.2	1.66	0.90
	Irrigation Improvement (II)	-0.1	-0.3	-0.4	-0.4	-0.5	-0.48	-0.36
	Vertical Drainage (VD)	0.0	29.0	27.3	28.7	28.2	29.57	23.81

Change in Water table Depth (%)								
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
No residue use for energy (NU)	**No water management (NW) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	-2.8	-6.1	-6.8	-5.8	-5.44	-4.48
	Rainwater harvesting (RH)	0.0	-0.2	-0.2	-0.1	-0.1	-0.16	-0.11
	Irrigation Improvement (II)	-0.2	-0.2	-0.3	-0.4	-0.4	-0.52	-0.33
	Vertical Drainage (VD)	0.0	48.4	59.1	61.9	63.8	65.63	49.80
Residue energy with competitive use (CU)	**No water management (NW)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	-2.8	-6.1	-6.8	-6.0	-5.72	-4.56
	Rainwater harvesting (RH)	0.0	-0.2	-0.2	-0.1	-0.1	-0.18	-0.12
	Irrigation Improvement (II)	-0.2	-0.2	-0.3	-0.4	-0.4	-0.52	-0.33
	Vertical Drainage (VD)	0.0	48.4	59.1	61.9	63.8	65.63	49.80
Residue energy with ecological use (EU)	**No water management (NW)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	-2.8	-6.1	-6.8	-5.8	-5.44	-4.48
	Rainwater harvesting (RH)	0.0	-0.2	-0.1	-0.1	-0.1	-0.15	-0.11
	Irrigation Improvement (II)	-0.2	-0.2	-0.3	-0.4	-0.4	-0.52	-0.33
	Vertical Drainage (VD)	0.0	48.4	59.1	61.9	63.8	65.63	49.80

Change in Water Stress (%)								
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
No residue use for energy (NU)	**No water management (NW) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	-9.4	-17.0	-14.6	-11.1	-11.88	-10.67
	Rainwater harvesting (RH)	0.0	-0.8	-0.8	-0.8	-1.1	-1.51	-0.83
	Irrigation Improvement (II)	0.0	0.1	0.0	0.1	0.1	0.23	0.09
	Vertical Drainage (VD)	0.0	-18.3	-20.4	-19.1	-19.0	-19.09	-15.98
Residue energy with competitive use (CU)	**No water management (NW)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	-9.4	-17.0	-14.6	-11.5	-12.21	-10.79
	Rainwater harvesting (RH)	0.0	-0.8	-0.9	-0.8	-1.2	-1.61	-0.88
	Irrigation Improvement (II)	0.0	0.1	0.0	0.1	0.1	0.23	0.09
	Vertical Drainage (VD)	0.0	-18.3	-20.4	-19.1	-19.0	-19.09	-15.98
Residue energy with ecological use (EU)	**No water management (NW)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	-9.4	-17.0	-14.6	-11.1	-11.69	-10.64
	Rainwater harvesting (RH)	0.0	-0.8	-0.8	-0.8	-1.1	-1.50	-0.82
	Irrigation Improvement (II)	0.0	0.1	0.0	0.1	0.1	0.23	0.09
	Vertical Drainage (VD)	0.0	-18.3	-20.4	-19.1	-19.0	-19.09	-15.98

Change in Residue Energy Density (%)								
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
Residue energy with competitive use (CU)	**No water management (NW) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	13.3	17.5	16.3	12.5	14.39	12.34
	Rainwater harvesting (RH)	0.0	1.0	0.8	0.9	1.3	1.87	0.98
	Irrigation Improvement (II)	0.0	-0.1	-0.2	-0.3	-0.4	-0.50	-0.25
	Vertical Drainage (VD)	0.0	6.7	4.6	3.6	4.2	5.36	4.09
Residue energy with ecological use (EU)	**No water management (NW)**	-43.5	-42.9	-42.6	-45.4	-43.9	-43.32	-43.58
	Canal lining (CL)	-43.5	-34.6	-32.3	-36.2	-36.9	-34.80	-36.37
	Rainwater harvesting (RH)	-43.5	-42.6	-42.3	-45.1	-43.5	-42.75	-43.28
	Irrigation Improvement (II)	-43.5	-42.9	-42.7	-45.5	-44.0	-43.54	-43.70
	Vertical Drainage (VD)	-43.5	-38.9	-39.5	-42.7	-41.2	-39.94	-40.97

Change in Residue Energy Potential (%)								
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
Residue energy with competitive use (CU)	**No water management (NW) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
	Canal lining (CL)	0.0	13.3	17.5	16.3	12.5	14.39	12.34
	Rainwater harvesting (RH)	0.0	1.0	0.8	0.9	1.3	1.87	0.98
	Irrigation Improvement (II)	0.0	-0.1	-0.2	-0.3	-0.4	-0.50	-0.25
	Vertical Drainage (VD)	0.0	6.7	4.6	3.6	4.2	5.36	4.09
Residue energy with ecological use (EU)	**No water management (NW)**	-43.5	-42.9	-42.6	-45.4	-43.9	-43.32	-43.58
	Canal lining (CL)	-43.5	-34.6	-32.3	-36.2	-36.9	-34.80	-36.37
	Rainwater harvesting (RH)	-43.5	-42.6	-42.3	-45.1	-43.5	-42.75	-43.28
	Irrigation Improvement (II)	-43.5	-42.9	-42.7	-45.5	-44.0	-43.54	-43.70
	Vertical Drainage (VD)	-43.5	-38.9	-39.5	-42.7	-41.2	-39.94	-40.97

Change in Moderately Saline Polygons (%)								
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
No residue use for energy (NU)	**Canal lining(CL) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
Residue energy with competitive use (CU)	**Canal lining (CL)**	0.0	0.0	0.0	0.0	2.3	2.44	0.79
Residue energy with ecological use (EU)	**Canal lining (CL)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00

Change in Polygon Salinity (%)								
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
No residue use for energy (NU)	**Canal lining(CL) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
Residue energy with competitive use (CU)	**Canal lining (CL)**	0.0	0.0	0.0	0.0	0.1	0.35	0.07
Residue energy with ecological use (EU)	**Canal lining (CL)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00

Change in Salinity Stress (%)								
No residue use for energy (NU)	**Canal lining(CL) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
Residue energy with competitive use (CU)	**Canal lining (CL)**	0.0	0.0	0.0	0.0	0.1	0.70	0.14
Residue energy with ecological use (EU)	**Canal lining (CL)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00

Change in Water Stress (%)								
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
No residue use for energy (NU)	**Canal lining(CL) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00

Residue energy with competitive use (CU)	**Canal lining (CL)**	0.0	0.0	0.0	0.0	-0.4	-0.37	-0.14
Residue energy with ecological use (EU)	**Canal lining (CL)**	0.0	0.0	0.0	0.0	0.0	0.22	0.04
Change in Total Water Supply (%)								
No residue use for energy (NU)	**Canal lining(CL) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
Residue energy with competitive use (CU)	**Canal lining (CL)**	0.0	0.0	0.0	0.0	0.7	0.50	0.20
Residue energy with ecological use (EU)	**Canal lining (CL)**	0.0	0.0	0.0	0.0	0.0	-0.25	-0.04
Change in Canals Lined (%)								
No residue use for energy (NU)	**Canal lining(CL) (base case)**		0.0	0.0	0.0	0.0	0.00	0.00
Residue energy with competitive use (CU)	**Canal lining (CL)**		0.0	0.2	0.0	3.8	4.15	1.62
Residue energy with ecological use (EU)	**Canal lining (CL)**		0.0	0.0	0.0	-0.1	-1.23	-0.27
Change in Consumption (%)								
No residue use for energy (NU)	**Canal lining(CL) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
Residue energy with competitive use (CU)	**Canal lining (CL)**	0.0	0.0	0.0	0.0	0.7	0.50	0.20
Residue energy with ecological use (EU)	**Canal lining (CL)**	0.0	0.0	0.0	0.0	0.0	-0.25	-0.04

Change in Water Stress (%)								
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
No residue use for energy (NU)	**Irrigation Improvement (II) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
Residue energy with competitive use (CU)	**Irrigation Improvement (II)**	1.3	2.4	4.4	5.6	5.9	6.27	4.30
Residue energy with ecological use (EU)	**Irrigation Improvement (II)**	0.0	0.0	0.1	0.1	0.1	0.06	0.06

Change in Constructed Capacity of Rainwater Harvesting Ponds (%)								
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
No residue use for energy (NU)	**Rainwater Harvesting (RH) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
Residue energy with competitive use (CU)	**Rainwater Harvesting (RH)**	0.0	5.2	5.2	5.2	5.2	5.34	4.38
Residue energy with ecological use (EU)	**Rainwater Harvesting (RH)**	0.0	-1.3	-1.3	-1.3	-1.3	-1.33	-1.10

Change in Canals Lined (%)								
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
No residue use for energy (NU)	**Canal lining(CL) (base case)**	0	0.0	0.0	0.0	0.0	0.00	0.00
Residue energy with competitive use (CU)	**Canal lining (CL)**	0	0.0	0.2	0.0	3.8	4.15	1.62
Residue energy with ecological use (EU)	**Canal lining (CL)**	0	0.0	0.0	0.0	-0.1	-1.23	-0.27

Change in Expenditure(%)								
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
No residue use for energy (NU)	**Vertical Drainage (VD) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
Residue energy with competitive use (CU)	**Vertical Drainage (VD)**	1.6	1.6	1.8	1.6	1.7	1.88	1.67
Residue energy with ecological use (EU)	**Vertical Drainage (VD)**	0.5	0.6	0.6	0.5	0.6	0.64	0.58
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
No residue use for energy (NU)	**Irrigation Improvement (II) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
Residue energy with competitive use (CU)	**Irrigation Improvement (II)**	1.6	1.6	1.8	1.6	1.7	1.88	1.67
Residue energy with ecological use (EU)	**Irrigation Improvement (II)**	0.5	0.5	0.6	0.5	0.6	0.62	0.56
No residue use for energy (NU)	**Rainwater Harvesting (RH) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
Residue energy with competitive use (CU)	**Rainwater Harvesting (RH)**	1.6	1.6	1.8	1.6	2.4	2.84	1.97
Residue energy with ecological use (EU)	**Rainwater Harvesting (RH)**	0.5	0.5	0.6	0.5	0.2	0.10	0.41
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
No residue use for energy (NU)	**Canal lining(CL) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
Residue energy with competitive use (CU)	**Canal lining (CL)**	1.6	1.0	1.9	1.6	1.4	3.68	1.85
Residue energy with ecological use (EU)	**Canal lining (CL)**	0.5	0.3	0.6	0.5	0.4	2.71	0.86

Change in Farm Income (%)								
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
No residue use for energy (NU)	**Vertical Drainage (VD) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
Residue energy with competitive use (CU)	**Vertical Drainage (VD)**	1.3	2.5	4.5	5.7	6.0	6.36	4.38
Residue energy with ecological use (EU)	**Vertical Drainage (VD)**	0.0	0.0	0.1	0.2	0.1	0.10	0.07
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
No residue use for energy (NU)	**Irrigation Improvement (II) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
Residue energy with competitive use (CU)	**Irrigation Improvement (II)**	1.3	2.4	4.4	5.6	5.9	6.27	4.30
Residue energy with ecological use (EU)	**Irrigation Improvement (II)**	0.0	0.0	0.1	0.1	0.1	0.06	0.06
No residue use for energy (NU)	**Rainwater Harvesting (RH) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
Residue energy with competitive use (CU)	**Rainwater Harvesting (RH)**	1.3	1.6	4.2	5.8	6.3	6.89	4.34
Residue energy with ecological use (EU)	**Rainwater Harvesting (RH)**	0.0	0.4	0.4	0.3	0.4	0.79	0.38
Energy Scenario	**Water Scenario**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**Average**
No residue use for energy (NU)	**Canal lining(CL) (base case)**	0.0	0.0	0.0	0.0	0.0	0.00	0.00
Residue energy with competitive use (CU)	**Canal lining (CL)**	1.3	2.9	5.8	7.3	7.6	8.67	5.58
Residue energy with ecological use (EU)	**Canal lining (CL)**	0.0	0.1	0.1	0.2	0.2	0.64	0.20