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Integrated production of food, energy, fuels and chemicals from rice crops: Multi-objective optimisation for efficient and sustainable value chains

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Abstract

Rice crops, which currently feed more than half of the world's population, is crucial in global food systems. Creating more efficient and sustainable rice value chains can facilitate the realisation of United Nations' Sustainable Development Goal of achieving zero hunger by 2050. Rice farming and milling suffer from interrelated techno-economic, policy and environmental constraints, whereas inefficient transport hamper rice distribution. Systematic and data-driven decision-making tools can help in understanding the complexity and in the formulation of effective strategies of national-level rice provision. For the first time, a multi-objective spatio-temporal mixed-integer linear programming model, based on the Value Web Model, was developed for rice value chains. The model can simultaneously optimise the value chains' planning, design and operation for efficient and sustainable food provision with integrated production of energy, fuels and chemicals. It considers various impacts, such as costs and greenhouse gas (GHG) emissions, in order to quantify their trade-offs and identify synergies between food and energy sectors. The model was applied to the Philippines in order to determine rice value chains that will result in lowest cost and GHG emissions. Streamlining value chains can prompt the country to be 100% rice self-sufficient without additional farmlands expansion and potentially reduce retail prices. Integrating energy and food production can result in increased total farm productivity and reductions in GHG emissions by 25% and 24%, respectively, with minimal land expansion required. However, careful and strategic planning is required when implementing multi-product rice value chains as integrated production of food, energy, fuels and chemicals could require 70% more farmlands and generate twice more GHG emissions relative to the food production only scenarios.

Keywords: rice value chains; rice self-sufficiency; integrated multi-product value chains; multi-objective optimisation; sustainable food and energy systems; Value Web Model.

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Abbreviations

CCGT	Combined cycle gas turbine	NPV	Net present value
EFEW	Environment-food-energy-water	PhP	Philippine Peso
FT	Fischer Tropsch	RVC	Rice value chain
GHG	Greenhouse gas	SDG	Sustainable Development Goal
MILP	Mixed integer linear programming	USD	United States Dollar

1. Introduction

Rice is integral to global food security with more than fifty percent of the world population consuming this crop. Rising population and booming economies are attributed to the growing demand (Bandumula, 2018). While it can survive as a perennial crop in the tropics (RiceIPM, 2003), rice is normally cultivated annually covering a total harvested area of 198 million hectares in more than a hundred nations (FAO, 2020). In order to secure sufficient supply, many of these countries increased production partly by enhancing productivity through Green Revolution technologies and significantly by expanding the use of land, water and other natural resources (FAO, 2017). The growth of farmlands is highest in Asia, which constitute 90% of global rice production and consumption, over the last thirty years (Bandumula, 2018). The 2008 rice crisis spurred recent expansions many importing regions, such as West Africa, in order to augment their self-sufficiency (Adjao and Staatz, 2015). Despite technology enhancements and scarce resources, rice farming remains highly land-, water-, and energy-intensive (Sims et al., 2015). Recent climate change-related extreme weather events have also resulted in agricultural damages and economic losses to most vulnerable nations in South Asia, South East Asia and sub-Saharan Africa (Baldos and Hertel, 2014). Dismally, rice production accounts for 10% and 1.5% of total agricultural and global anthropogenic greenhouse gas (GHG) emissions, respectively, due to persistent fossil energy dependence and unsustainable farming practices (Maraseni et al., 2018). These interrelated and competing issues on the environment, food, energy and water systems, which support and interact with a rice value chain (RVC), require a “nexus thinking” approach for their analyses (Wallington and Cai, 2017). In doing so, thorough understanding and evidence-based strategies can be acquired from the systematic and data-driven planning, design and operation of RVCs such that provision of food and interactions with the environment-food-energy-water (EFEW) nexus are efficient and sustainable (Samsatli et al., 2020).

1.1. Efficiency and sustainability of rice value chains

Many of the world’s food value chains have been dramatically increasing in length due to the growing physical distance from production to consumption (FAO, 2018). In the case of RVCs, the geographic length expanded to sufficiently supply the demand in heavily populated countries and burgeoning cities in Asia (Reardon et al., 2014) and increasing consumers in Africa and South America (Muthayya et al., 2014). In 2018, East, South and South East Asian regions are the main consumers of rice at 85% of the global consumption (Figure 1). These regions are also the main producers of rice at 90% of the global production (Figure 1). While majority of rice produced is consumed domestically, several countries in these regions are involved in the global rice trade. India, Vietnam and Thailand are leading exporters to many rice-importing countries (Bandumula,

2018), such as in West Africa, East Africa, Latin America and even neighbouring Asian nations, in order to meet their food security targets (Muthayya et al., 2014).

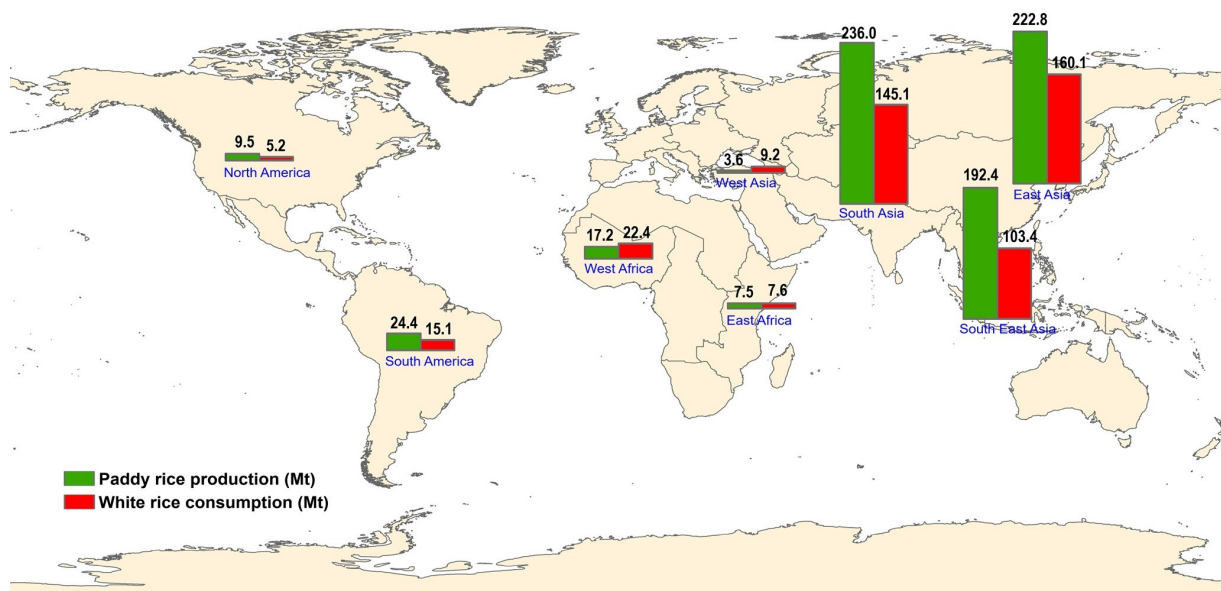


Figure 1: World paddy rice production and white rice consumption in 2018. (Plotted using data from World Rice Statistics (IRRI, 2018).)

The world rice market is known to be 'thin' and segmented, which result in highly volatile prices (Muthayya et al., 2014). Surging price hikes from 2007 to 2008 motivated many rice-importing countries to seek rice self-sufficiency¹. In response, rice production has expanded to sub-Saharan Africa but the cost-competitiveness of these RVCs are yet to be on a par with Asian counterparts. Enhancement of farm-level productivity and reduction of per-unit costs across all value chain components are key to the future success of African RVCs (Adjao and Staatz, 2015). Concurrently, RVCs of major rice-exporting Asian countries are also transforming that can significantly impact global food security. Growing trends at the farm level are the shift from subsistence farming to small commercial farming, fragmentation of farmlands and capital-intensive use of fertilisers and pesticides. At the midstream and downstream components (e.g. milling, trading, retailing), emerging trends are the upscaling and upgrading of milling facilities, urban wholesalers favouring medium-to-large mills over small mills, establishment of vertical coordination, branding of rice products, and rise of supermarkets. These transformations have led to lower retail prices, better quality and wider product diversity, all of which seem to improve the food security in urban centres (Reardon et al., 2014). However, there is still a need for RVCs to improve overall coordination of its components and ensure weaker segments are able to obtain the benefits of integrating agricultural sectors into broader markets (FAO, 2018). These transformations are mostly being led by the private sector. While most governments are relying on market forces, its role is crucial in providing infrastructural developments that could significantly reduce energy and transport costs of midstream and downstream components. Provision of modern rice mills can improve efficiency and reduce costs (Alavi et al., 2012). Investment on reliable transport infrastructures can reduce post-harvest losses and enhance distribution (Mopera, 2016). About 43% of the total value added in rice is

¹Ratio of supply to demand

due to midstream and downstream components but most of the effort in lowering the total cost of rice has been only focused on the farm level (Reardon et al., 2014). Thus, the food security debate must examine the planning, design and operation of the entire RVC in order to improve its efficiency and reduce food losses (FAO, 2018).

At the other end of the food security debate is the sustainability of RVCs. High economic growth and urbanisation are expected to diversify Asian national diets that could lower rice consumption per capita. However, global rice consumption will continue to increase due to growing world population (Dawe et al., 2014). Meeting this long-term demand via Asian rice production may become unsustainable due to the region's declining annual overall rice productivity in the past decade (Adjao and Staatz, 2015). Water shortages aggravated by climate change, limited new water sources for irrigation, and water-use competition with urban, industry and environment demands are current constraints (Hazell, 2010). Decreasing available land, due to competing production for high value-crops and biofuels, constraints rice production. Expansion to African and South American wetlands may be attractive but at the expense of severe social and environmental impacts (Pandey et al., 2010). High fertiliser cost along with its inefficient use and soaring energy prices are additional constraining factors (Adjao and Staatz, 2015). Rice production is also constrained by its significant contribution to global GHG emissions. Pumping of water for irrigation and production of fertiliser and pesticides rely on fossil fuels that result in indirect GHG emissions. Agricultural machinery for many rice farming activities also operate on fossil fuels, which results in direct GHG emissions (Zhang et al., 2018). Methane from rice paddies, which is produced from anaerobic conditions of continuously flooded soil, is a major source of GHG emissions. Hence, rice production must adopt practices that use less land, water and energy resources in order to reduce its carbon footprint (Maraseni et al., 2018). Moreover, the full range of costs, both economic and environmental, from production to consumption must be accounted in the price of rice, which could limit production inputs and reduce overall demand and wastage (FAO, 2017).

Future RVCs must operate both efficiently and sustainably while contributing to global food security. Transforming rice provision in such a way can contribute to food systems that are compliant to the United Nations' Sustainable Development Goals (SDG) for food and agriculture of 2050 and beyond (UNDESA, 2019). Food provision must use natural resources that maintain healthy ecosystem services for present and future generations. Food provision must also accommodate growing demands of agricultural products with non-food purposes, e.g. biofuels, bioenergy, etc. (FAO, 2018). Rice crop, both grains and residues, can potentially contribute to a bioeconomy that not only provides food but also a wide range of non-food commodities, such as energy, fuels and chemicals (Doliente and Samsatli, 2019). As with any biomass, many activities across existing and future RVCs can negatively impact environment, food, energy and water systems (Martinez-Hernandez and Samsatli, 2017). Many biomass value chains in both the developed and developing world are still rudimentary, which must be designed to maximise benefits from synergistic interactions and minimise impacts of non-cooperative interactions with the EFEW nexus (Tapia et al., 2019).

1.2. Current status of the Philippine rice value chains

The Philippines is among the top rice producers in the world. With 19.6 Mt paddy rice produced in 2018, the country ranked 8th in the world and contributed to 3% of the global production (IRRI, 2018). Despite being a world top producer, much of the grains produced is consumed domestically and additional grains has to be imported in order to meet the country's high demands (Muthayya et al., 2014). In 2018, the country

consumed 13.4 Mt milled rice, which 8.2% or 1.1 Mt was imported. The Philippines ranked 10th among the top rice-importing countries (IRRI, 2018). As the main staple food, rice is important to the average daily Filipino diet (37%). Rice consumption per capita income has also been rising in the last decade (OECD, 2017). Hence, a sufficient and secure supply of rice for the present and future generations of the Philippines is critical.

Due to the Green Revolution of the 1970s, Philippine rice production has been increasing (Bandumula, 2018), with an average growth of 0.3 Mt/yr from 1970 to 2014 (Ponce and Inocencio, 2017). However, the average rice self-sufficiency has only been 92% over the last 30 years with record lows of 72% during the severe drought brought by El Niño (an extreme warm climate phenomenon) of 1998 and 81% during the world food crisis of 2008. The sufficiency gap has been also historically increasing at 0.3% per year. The Philippine government has been consistent in pursuing rice self-sufficiency with high budgets for the rice sector but at the expense of high-value crop sectors. The policy is directed at expansion of rice production, reduction of post-harvest losses and diversification to other staples (Ponce and Inocencio, 2017). However, these strategies failed in alleviating high production and marketing costs (Briones, 2014), which caused a large and ever-increasing gap between domestic and world rice prices over the last three decades (Ponce and Inocencio, 2017). The government’s fixation in achieving rice self-sufficiency did not also improve the income of rice farmers due to mismatched policies and lack of infrastructures (Briones, 2014).

A schematic of conventional RVCs in the Philippines is illustrated in Figure 2. Food production (solid lines with arrows) is a fully-established value chain pathway (Muthayya et al., 2014). Harvested paddy rice (unpolished grains) from rice farms is delivered by either truck or barge for processing in rice mills. White rice (polished grains) is produced in rice mills and then transported by truck and barge to consumers (Alavi et al., 2012). Most of the crop residues, rice straw and husk, are disposed of by post-harvest burning (Mendoza, 2015). Rice bran, also a by-product of rice milling, which is produced at lower quantities than rice husk and excluded in the scope of this work, is usually utilised as animal feed or disposed of as a waste in developing countries (Sharif et al., 2014). Given the good energy content (Mofijur et al., 2019) and high accessibility (Lim et al., 2012) of rice husk, an emerging value chain pathway for bio-electricity production from it is a growing trend in rice growing countries (Chakma et al., 2016). However, the high ash content of rice husk may present some technical challenges on combustion systems (that may be remedied by co-firing with anthracite and other additives) and its solid waste disposal – more details can be found in the Supplementary Material.

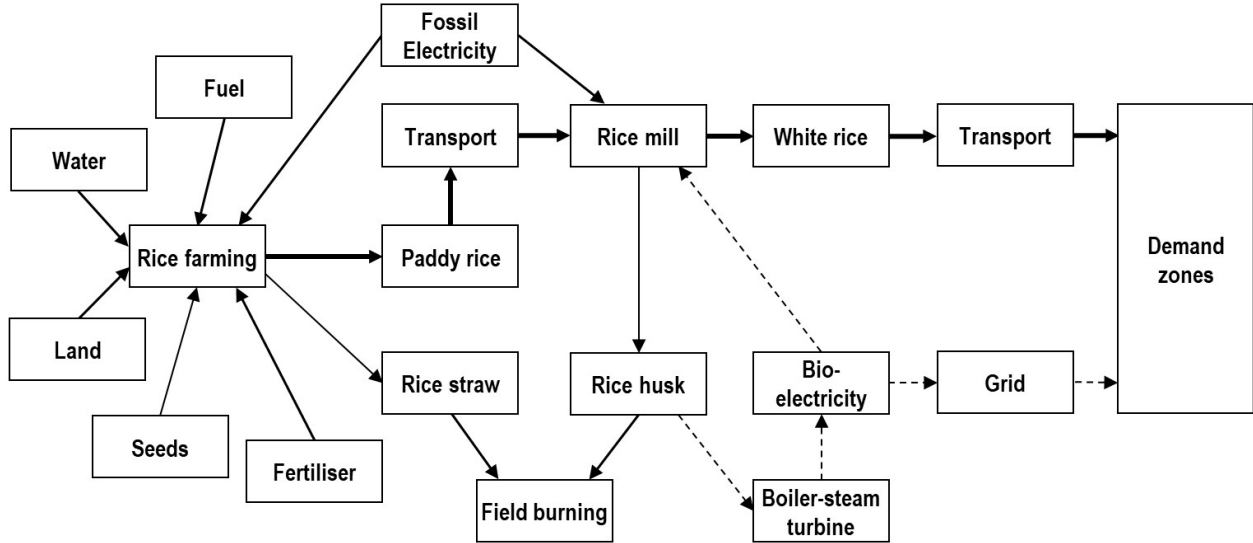


Figure 2: Schematic of conventional rice value chains. The solid lines represent established value chains while the broken lines represent emerging value chains. (Drawn using data from Sims et al. (2015).)

1.3. Sources of inefficiency in the Philippine rice industry

Analysing RVCs can help identify constraints and opportunities in the process of value creation along its chain of activities (Briones, 2014). The streamlined operation of RVCs is critical in providing sufficient supply of rice at the most affordable prices (FAO, 2018). However, the Philippine RVCs are operating inefficiently, which can be attributed to the following:

1. Due to disproportionate policies, rice has to be farmed throughout the Philippines even though not all locations are optimal.
 - Under the National Rice Programme, a ‘full’ rice self-sufficiency has remained the sole objective over the last 30 years, which turned into a protectionist policy for a rice-biased agricultural industry. Rice-bias is evident on large allocations by the government which ranged from 60% to 73% of the total agriculture budget in 1995 to 2015, and more was allocated to low rice yielding provinces from 2012 to 2015 (Ponce and Inocencio, 2017). This favouritism has resulted in the lack of opportunities for farmers to cultivate other important and/or high-value crops (OECD, 2017). The focus on rice self-sufficiency also resulted in high cost of rice farming (Bordey et al., 2016) and low farm gate price ceilings (Ponce and Inocencio, 2017).
 - In 1988, the Comprehensive Agrarian Reform Law was enacted to “improve equity and productivity in the agriculture sector by establishing owner-cultivatorship of economic-sized farms to landless farmers, farm workers and tenants”. Subsequent land reform laws over the next two decades were enacted in continuing and improving land acquisition and distribution and support services and credit access for farmers. Several socio-political issues and insufficient government funding hindered their successful implementation. Hence, there is a growing fragmentation of farmlands operated for subsistence farming by single families (Aquino et al., 2013). These fragmented farmlands are further becoming smaller due to low returns from rice farming and unregulated land-use conversion (Ponce and Inocencio, 2017).

- The Agriculture and Fisheries Modernisation Act was a landmark law passed in 1997 in order to accelerate needed developments through the provision of advanced production systems, marketing services, infrastructures and facilities. The policy is also rice-biased as evident with yearly budget allocations for irrigation services at 30% that grew to 50% by 2013 (Aquino et al., 2013). Accounting to only 2% of the total production cost, irrigation subsidies do not improve farm income and productivity as compared to public spending on infrastructures, such as roads and ports (Briones, 2013). This lack of transporting infrastructures stifles efficient product distribution results post-harvest losses (Mopera, 2016). Hence, more farmlands must be cultivated than needed in order to compensate for these losses.
2. The logistics infrastructure and transport system that support RVCs are under-performing.
 - Together with the lack of transporting infrastructure is the poor performance of existing ones. The Philippines scored 2.90 for its Logistic Performance Index (LPI), which is scored from 1 as least performing to 5 as best performing (The World Bank, 2018). The logistical infrastructures for both rice and corn in the country also rated from poor to fair quality (Alavi et al., 2012). Since quality and capacity of logistical infrastructures greatly affect supply chain efficiency; so a constrained Philippine transport system is the main impediment for efficient movement of grains (Alavi et al., 2012).
 3. Single-pass and two-pass rice mills still dominate multi-pass rice mills.
 - Modern rice mills are multi-pass systems with white rice recovery of 63-65% (maximum recovery² is 70%) (Tangpinijk, 2010). Manual mills, locally known as *kiskisan*, and compact electricity-powered rice mills, both of which are single pass-systems, have lower white rice recoveries of 50-55% and 60-63%, respectively (Umali and Santiago, 2015). The continued use of less efficient rice mills results in greater post-harvest losses, which eventually adds up to the overall inefficiency of existing RVCs.
 4. Lack of mechanisation among the many agricultural activities of the country.
 - Investment in large-scale machinery becomes economically infeasible in fragmented farmlands. Hence, rice farming or paddy rice production remains a labour-intensive activity, especially during crop management and harvesting (Bordey et al., 2016). Labour contributes the highest portion in the total cost of rice farming (Ponce and Inocencio, 2017). The share of labour to the total cost is also three times greater than that for highly mechanised rice-producing countries. Mechanisation can potentially decrease production costs by 35%, significantly reduce harvest and post-harvest losses and improve global competitiveness of the Philippine rice industry (Bordey et al., 2016).

1.4. Challenges to sustainable rice industry of the Philippines

Improving sustainability of conventional RVCs is critical due to their many impacts on the EFEW nexus of the country (Tapia et al., 2019). The area harvested for rice has been growing at 30 kha/yr in the last three decades. Because of the scarcity of agricultural lands in the country (Doliente and Samsatli, 2020), expansion to forest lands has further aggravated deforestation with about 70% lost since the 1900s (OECD,

²Recovery is mass of white rice divided by mass of paddy rice

2017). Driven by high economic growth, agricultural lands are also under threat to rapid urban development that adds pressure to expand to upland forests (OECD, 2017). Due to poor farming practices, excessive use of fertilisers and pesticides have resulted in water pollution and land degradation (Pandey et al., 2010). Most rice farms are continuously irrigated, which compete with many uses of the country’s limited freshwater resources such as household consumption, fish farming and hydropower (Llanto, 2015). Continuous irrigation is not only wasteful of water resources but also a source of GHG emissions (Maraseni et al., 2018).

Rice cultivation is a major source of GHG emissions for the Philippines: second to fossil-based power of the electricity sector (USAID, 2016) and first in the agricultural industry (Arnaoudov et al., 2015). Together with methane emissions from rice paddies, prevalent post-harvest burning practice of most rice straw and rice husk releases more GHGs (Lim et al., 2012). Open burning of crop residues must be banned in the Philippines and other rice-producing countries (Mofijur et al., 2019), in order that the carbon footprint of rice crops can be curtailed (Zhang et al., 2017). Banning open burning of crop residues would also prevent the release of toxic gases due to incomplete combustion, such as carbon monoxide, nitrogen oxides, sulphur dioxides, polycyclic aromatic hydrocarbon, polychlorinated dibenzo-p-dioxins, and polychlorinated dibenzofurans that have harmful health and environmental impacts (Kesari and Jamal, 2017). When residues of rice crops are also left in the field and mills, their gradual degradation also releases methane and nitrous oxide that contribute to GHG emissions from rice farming (Maraseni et al., 2018). Hence, these underutilised carbon-rich resources are potentially a missed opportunity to improve the economic and environmental sustainability of Philippine RVCs. By utilising crop residues, circular economies within food value chains can develop that can lead to more sustainable agri-food systems (Sharma et al., 2019). They can be converted to a variety of high value products, such as power, fuels, materials and chemicals, through various bio-chemical or thermo-chemical pathways (Doliente et al., 2020).

Despite long-standing renewable energy policies, rice husk-based biomass power has only begun a growing trend in the country’s electricity sector in the last decade (ADB, 2018), which contributes to a meagre 1% of the national supply (PH DOE, 2016). The food crop-based Philippine biofuels programme, which is constrained by feedstock availability (Corpuz, 2018), also needs to expand towards vastly available second-generation feedstocks like crop and forestry residues in order to satisfy growing domestic demand (Go et al., 2019). However, biomass utilisation in the country has not been yet fully realised due to regulatory barriers and lack of locally developed technologies (Brahim, 2014). Like in many developing countries, most Philippine biomass value chains also need planning, development and management (Raychaudhuri and Ghosh, 2016), such that resource efficiency and sustainability with the EFEW nexus are addressed together (Tapia et al., 2019).

1.5. Contributions of this work

The main objective of this work is to develop a multi-objective spatio-temporal mixed-integer linear programming model (MILP) to simultaneously determine the optimal planning, design and operation of more efficient and sustainable RVCs. To date, there has been no multi-objective and spatio-temporal optimisation model developed for RVCs at the national level as shown in Table 1. Lim et al. (2013) presented an optimisation model for production and utility planning of integrated resource-efficient rice mills in Northern Malaysia but it is limited to rice mills and maximisation of profit. Cheraghalipour et al. (2019) developed a bi-level programming model for planning and design of Iranian rice supply chains, which can determine the

minimum total cost with respect to hierarchical objectives of two decision-makers, but it cannot deal with spatial dimension, and sustainability of RVCs. [Jifroudi et al. \(2020\)](#) proposed a MILP model for planning and designing of rice supply chains in Iran, which aims to maximise profit across through best selection of farmlands, milling facilities, transportation and distribution, but it does not account for temporal aspect and environmental impacts. [Sahirman et al. \(2019\)](#) presented a transportation model based on linear programming in order to minimise cost but is limited to the paddy rice distribution from farmlands to milling facilities. [Kumar et al. \(2016\)](#) developed a two-echelon integrated procurement production model in a fuzzy stochastic framework for single-manufacturer and single-buyer rice supply chain, which serves as an inventory system in response to demand uncertainties. Other rice supply chains models are also concerned on inventory monitoring, which were formulated through max-plus algebra and system dynamics, but are solely single resource-single product (e.g. grains) – see Table 1. There are also stand-alone rice straw supply chain models for bio-ethanol provision in Indonesia (techno-economic optimisation with life-cycle analysis by [Kristianto and Gunasekaran \(2018\)](#)) and thermo-chemical production in Thailand (a hybrid Monte Carlo simulation and stochastic programming by [Diehlmann et al. \(2019\)](#)). Hence, there is a need for a RVC model that provides a holistic view of its various features when it either operates for production of food only or for integrated production of food and non-food products.

The contributions of this paper are the first multi-objective spatio-temporal optimisation of RVCs and the collated data, developed scenarios and drawn insights of its first application to national-level rice provision of the Philippines. The grains (paddy rice and white rice), crop residues (rice straw and rice husk), and a variety of products (food, energy, fuels and chemicals) can be considered within the framework of RVCs. Both space and time are embedded in the model, e.g. the variability of any resource supply and demand with respect to its location and period. A network design of processing technologies (rice mills and biomass conversion facilities) and transporting technologies (including its corresponding infrastructures) can be determined by the model. Moreover, it can recommend the location and size of rice farms, a crucial element not present in RVC models that were reviewed. The model is expressed as a multi-objective optimisation problem that can be set to minimise economic cost, environmental cost, or a combination of both. By doing so, the efficient provision of food with or without integrating non-food production by RVCs can be tied with its corresponding socio-economic impact (in terms of cost) and environmental sustainability (in terms of GHG emissions), which is a research gap in optimisation objectives. This work also fills the research gap on integrated food and non-food production, which could facilitate the needed development of circular economies and achievement of UN Sustainable Development Goals for food systems. While the insights gained are from the optimisation of Philippine RVCs, these are general and applicable to other rice-producing countries.

The rest of the paper is structured as follows. Section 2 outlines the problem statement. The components of the model and input data are discussed in Section 3. In Section 4, the network superstructure describes the various pathways to produce energy, fuels and chemicals when integrated conventional RVCs. Section 5 presents the mathematical formulation of the rice value chain model. Its applicability is demonstrated for the Philippines in Section 6 through three case studies: food production only, integrated food-energy production and integrated food-energy-fuels-chemicals production. Each case study presents two optimal scenarios along with their corresponding insights and implications. Section 7 provides the conclusions and recommendations from this work.

Table 1: Comparison of previous rice value chain models to this present work.

Author (Year)	Model	Scale(s) considered	Objective(s)	Raw material(s)	Product(s)	Region
Thongrattana and Robertson (2008)	System dynamics	Temporal	Inventory scheduling	Rice (unspecified)	Rice (unspecified)	Northeast Thailand
Lim et al. (2013)	MILP	Temporal	Maximise profit	Paddy rice	White rice, rice husk, rice bran, rice husk ash, rice bran oil, vermicelli	Northern Malaysia
Kumar et al. (2016)	Two-echelon fuzzy stochastic	Temporal	Minimise cost	Paddy rice	White rice	-
Chung (2018)	System dynamics	Temporal	Inventory control	Paddy rice	White rice	Malaysia
Cheraghalipour et al. (2019)	Bi-level programming	Temporal	Minimise cost	Paddy rice	White rice, rice bran	Mazandaran province, Iran
Cuellar-Molina et al. (2019)	System dynamics	Temporal	Improve profitability of farmer	Paddy rice	White rice	Plateau of Ibagué, Colombia
Putra (2019)	Max-plus algebra	Temporal	Optimise schedule	Rice (unspecified)	Rice (unspecified)	Yogyakarta, Indonesia
Sahirman et al. (2019)	Linear programming	Spatial	Minimise cost	Paddy rice	White rice	Merauke district, Papua, Indonesia
Jifroudi et al. (2020)	MILP	Spatial	Maximise profit	Paddy rice	White rice, rice husk, rice bran	Gilan, Iran
This work	MILP	Spatio-temporal	Multi-objective (e.g. Minimise cost, minimise GHG emissions)	Paddy rice, rice straw	White rice, bio-electricity, bioethanol, bio-FT diesel, bio-FT jet, bio-naphtha	Philippines

2. Problem statement

The RVC problem can be defined as follows:

Given:

- Available area of farmlands;
- Yield potential of primary resources such as of paddy rice and straw, which is space- and time-dependent;
- Demands for food, energy, fuels and chemicals, which are space- and time-dependent;
- Unit economic and environmental impacts of paddy rice production;
- Characteristics of processing technologies such as conversion factors, maximum production capacity, unit capital, operating & maintenance impacts and operating lifetime; and
- Properties of different transportation modes and their infrastructures for transporting grains and crop residues, such as their maximum capacity, unit capital and operating & maintenance impacts.

Determine:

- The design of the RVCs, in terms of
 - Location and allocated area for paddy rice production;
 - Investments in processing technologies, their location and capacity;
 - Structure of the transporting infrastructure network; and
 - Interconnections between resources, technologies and networks.
- The operation of the RVCs, in terms of
 - Combination and quantity of resources utilised;
 - Types and amount of food and non-food products generated;
 - Production rates of processing technologies; and
 - Transportation modes used and rates of resources transported.

In order to:

- Maximise net present value or NPV (a measure of economic performance);
- Minimise GHG emissions (a measure of environmental performance); and
- Combination of both economic and environmental performance.

Subject to:

- Satisfying completely the demand for food (e.g. white rice);
- Satisfying a portion of the demand for non-food products (e.g. bio-electricity, biofuels, etc.);
- Potentially and practically available farmlands;
- Local and national policies on available farmlands; and
- Availability, maximum capacities and build rates of the technologies.

3. Components of the model

An overview of the components of the RVC model is provided below. See Supplementary Material for additional details, assumptions and data of each component.

3.1. Space and time

The spatial representation of the Philippines is shown in Figure 3 by dividing the country into 81 zones corresponding to its provinces. Each zone, $z \in \mathbb{Z}$, contains the necessary data on the farmland available for paddy rice production, yield potential of paddy rice, unit impacts of paddy rice production, existing processing technologies, if any, and existing transporting infrastructures, if any. For time, a planning horizon of 32 years, from 2018 to 2050, is considered. These consisted of multiple timescales: planning periods $y \in \mathbb{Y}$, seasonal time steps $t \in \mathbb{T}$, type of day of the week $d \in \mathbb{D}$ and hourly intervals $h \in \mathbb{H}$.

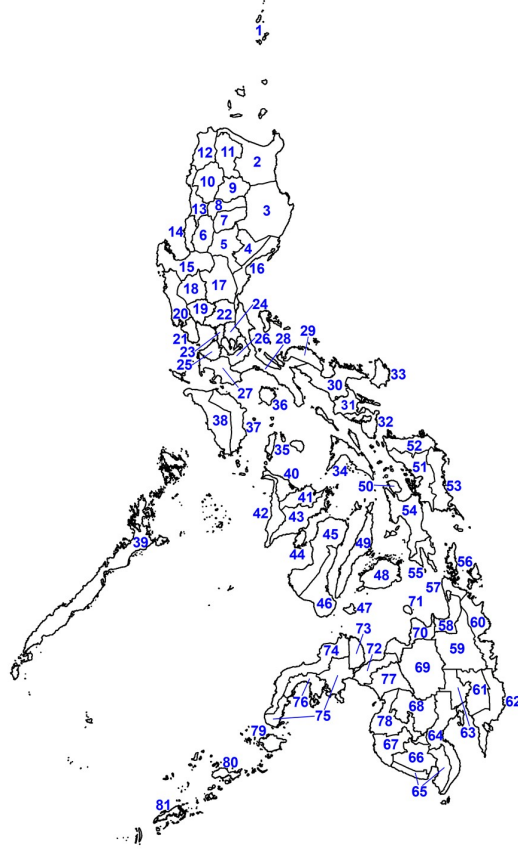


Figure 3: Representation of space for the Philippines in the model.

3.2. Resources

3.2.1. Farmland characteristics of the Philippines

Figure 4a shows the maximum available area of existing farmlands (or arable lands) per province in the Philippines. The total area is 8.23 Mha, which is 24% of the country's total land area. Figure 4b shows the yield potential of paddy rice (odt/ha/yr) per province. Figures 4c and 4d show the unit cost and unit GHG emissions of paddy rice production in each province of the Philippines. Since rice crop is replanted each year within the planning period, so these impacts are accounted per replanting.

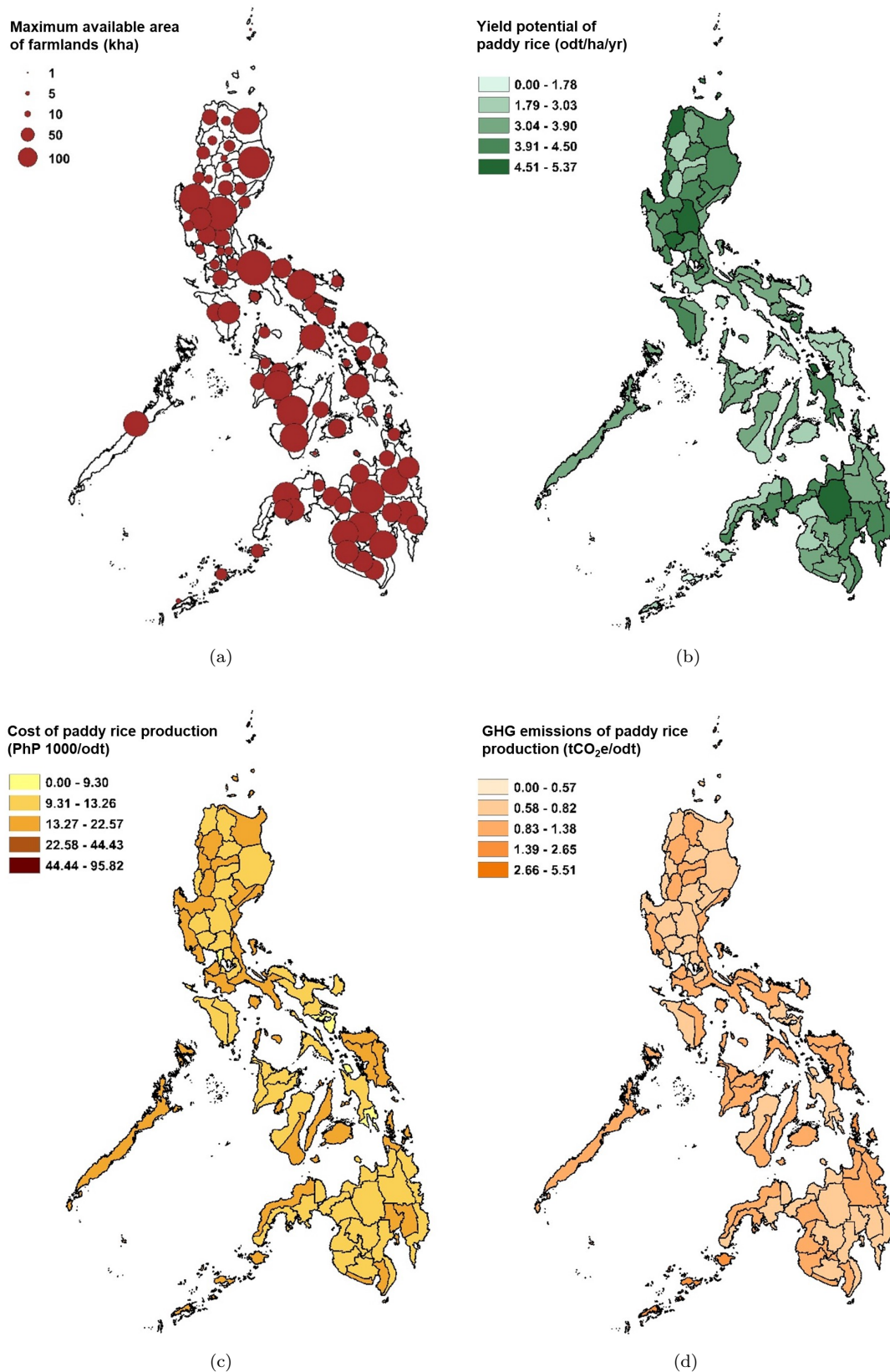


Figure 4: Farmland characteristics per province in the Philippines: (a) Maximum available area; (b) Yield potential of paddy rice; (c) Unit cost of paddy rice production; and (d) Unit GHG emissions of paddy rice production. See Figure 3 for zone numbers.

3.2.2. Demands for white rice, energy, fuels and chemicals

To estimate average hourly food (white rice) demand data per zone, consumption of white rice per individual per province per year was multiplied by total individuals per province and then divided by total hours per year. Considering available data on each non-food commodity (grid electricity, biofuels, and naphtha) is country total consumption per year, these values were divided by the total population first, then multiplied by total individuals per province, and finally divided by total hours per year. These derived hourly demand data for food and non-food products served as inputs to the case studies.

3.2.3. Types of resources

Resources are classified into six types: primary resources; intermediates; food products; energy and fuel products; chemical products; and by-products and wastes.

3.3. Processing technologies

The processing technologies are rice mill, pelletiser, gasification, FT jet synthesis, anaerobic digestion, pyrolysis, grain fermentation, lignocellulosic fermentation, and boiler-steam turbine. The conversion factors, maximum production rate, unit capital impacts, unit fixed operating & maintenance (O&M) impacts, and technical life per technology were estimated from various sources.

3.4. Transporting technologies and their infrastructures

The transporting technologies considered are barge and truck, which are the primary modes of transporting tangible goods in the Philippines ([Arnold and Villareal, 2002](#)). Paddy rice, white rice, rice straw, rice husk and pelletised crop residues can be transported by these transporting technologies.

4. Rice value web network superstructure

Figure 5 shows the potential value webs in two typical zones z and z' . Shown are transporting technologies (in hexagons), which can transport resources (in ovals): paddy rice, white rice, rice straw, rice husk and pellets, between zones. Each transporting technology is distinct and can, of course, operate between any two zones that are connected by a transporting infrastructure (e.g. road or suitable waterway).

Each zone starts with two raw materials for the value web: paddy rice and rice straw, both of which are harvested from the rice farm (or rice paddy). Paddy rice can be milled to produce rice husk and white rice, which is both a food source and a feed to grain fermentation technology. Grain fermentation produces bio-ethanol, as does lignocellulosic fermentation that may take rice straw or rice husk as feedstocks.

Rice straw and rice husk may both be used as feedstocks to a number of different processing technologies (in rectangles, including rice mill): pyrolysis, lignocellulosic fermentation, gasification, anaerobic digestion and pelletiser to produce various non-food products (also in ovals). Pyrolysis produces pyrolysis oil, which can be upgraded to UPO (upgraded pyrolysis oil), which is a substitute for marine fuel. Gasification produces syngas and anaerobic digestion produces biogas. Pelletiser produces pellets that are a densified form of rice straw and rice husk.

In addition to providing cheaper and cleaner transport, pellets can be gasified, to produce syngas, and combusted in boiler-steam turbine to produce bio-electricity. Boiler-steam turbine may also take rice straw and rice husk as feedstocks. The syngas produced can be used in FT jet synthesis to produce a number of fuels: bio-FT jet, bio-FT diesel and bio-naphtha. Syngas can also be fed to combined-cycle gas turbine (CCGT) technology to produce bio-electricity. Biogas, produced by anaerobic digestion of rice straw and rice husk, can be combusted in the CCGT technology to produce bio-electricity.

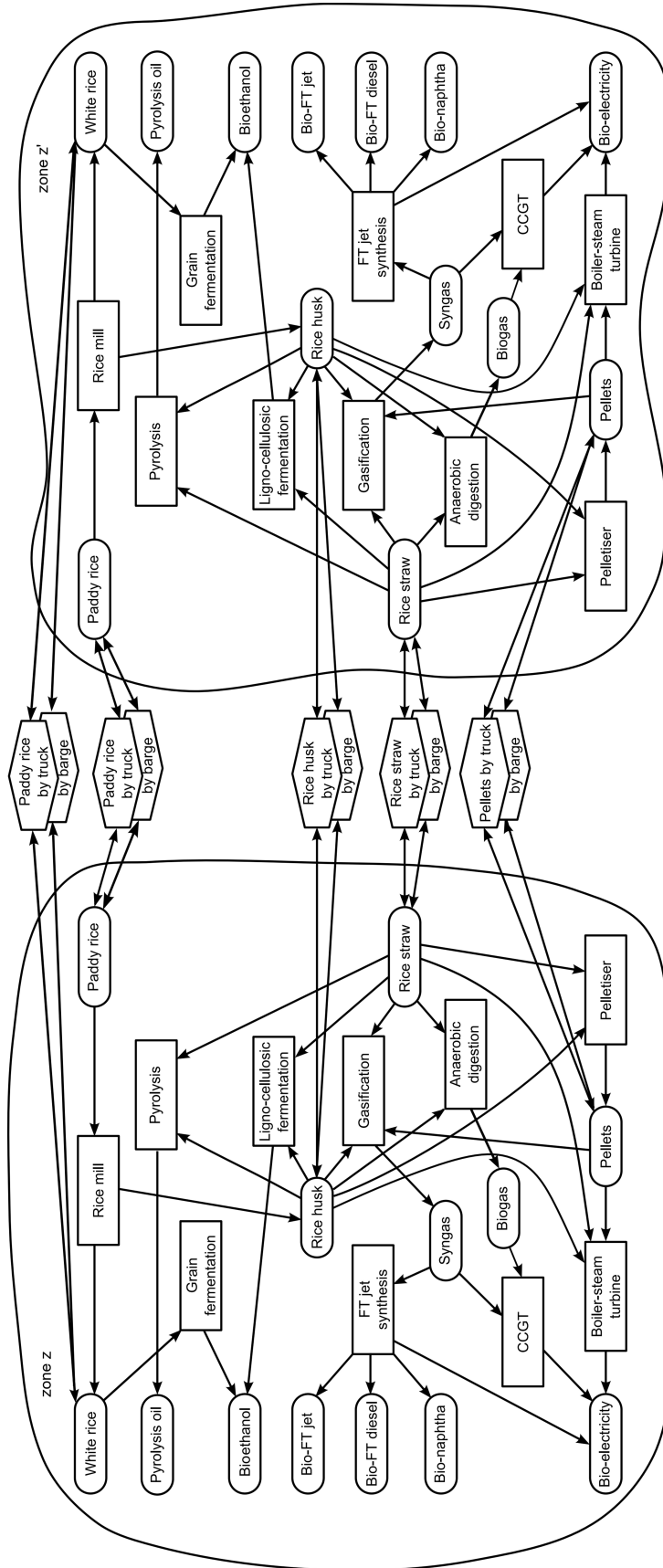


Figure 5: Value web superstructure for the integrated food-energy-fuels-chemicals rice value chain of the Philippines.

5. Mathematical formulation of the model

The mathematical formulation of the Value Web Model (VWM) has been developed by S. Samsatli and N.J. Samsatli and applied to energy systems in cities (Samsatli and Samsatli, 2018a), integrated energy value chains for the United Kingdom (Samsatli and Samsatli, 2018b), and hydrogen value chains (Samsatli and Samsatli, 2019). In this paper, the VWM was developed to model and optimise rice value chain scenarios for the Philippines. The definitions of the indices, sets, parameters, positive variables, free variables and integer variables of the model are found in the [Nomenclature](#). See Supplementary Material for further details of the mathematical formulation. The model is implemented in AIMMS and solved using the CPLEX solver.

5.1. Multi-objective optimisation

The model is expressed as a multi-objective optimisation problem in order to evaluate the trade-offs between several conflicting objectives. Using different combination of weighing factors w_i , which can assume values between 0 and 1 (with $\sum w_i = 1$), it is transformed into a single-objective optimisation problem (Ang et al., 2010), the minimisation of Z (Eq. 1). In this study, the performance metrics, denoted by the index i , are the economic impact and the environmental impact, i.e. $i = \{\text{Cost(PhP)}, \text{GHG emissions (kgCO}_2\text{e)}\}$.

$$Z = \sum_{iy} w_i (\mathcal{J}_{iy}^P + \mathcal{J}_{iy}^Q + \mathcal{J}_{iy}^{\text{fp}} + \mathcal{J}_{iy}^{\text{fq}} + \mathcal{J}_{iy}^{\text{vp}} + \mathcal{J}_{iy}^{\text{vq}} + \mathcal{J}_{iy}^{\text{m}} + \mathcal{J}_{iy}^{\text{x}} + \mathcal{J}_{iy}^{\text{U}} - \mathcal{J}_{iy}^{\text{Rev}}) \quad (1)$$

If the weighting factors are $w_i = \{1, 0\}$, the problem is maximisation of NPV and the solution represents the maximum economic benefit the rice value chain can provide regardless of the environmental impact. On the other hand, if the weighting factors are $w_i = \{0, 1\}$, the problem is the minimisation of GHG emissions, and the solution represents the minimum negative environmental impact the rice value chain can incur regardless of the economic impact. Each of the impacts summed within the parentheses are defined in Section S1 of the Supplementary Material.

5.2. Utilising resources

Equation 2 is the governing expression for the resource balance

$$U_{rzhdy} + M_{rzhdy} + P_{rzhdy} + Q_{rzhdy} \geq D_{rzhdy}^{\text{comp}} + D_{rzhdy}^{\text{sat}} + X_{rzhdy} \\ \forall r \in \mathbb{R} - \mathbb{C}, z \in \mathbb{Z}, h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \quad (2)$$

The resource balance ensures that the sum of the rate of utilising a resource r in zone z during hour h type of day d season t and planning period y or U_{rzhdy} ; the rate of importing a resource r in zone z during hour h type of day d season t and planning period y or M_{rzhdy} ; the net rate of producing a resource r in zone z during hour h type of day d season t and planning period y or P_{rzhdy} ; and the net rate of transporting a

resource r in zone z (from all other zones) during hour h type of day d season t and planning period y or $Q_{rzhdt y}$ must not be exceeded by the sum of the compulsory demands of a resource r in zone z during hour h type of day d season t and planning period y or $D_{rzhdt y}^{\text{comp}}$; the optionally satisfied demands of a resource r in zone z during hour h type of day d season t and planning period y or $D_{rzhdt y}^{\text{sat}}$; and the rate of exporting a resource r in zone z during hour h type of day d season t and planning period y or $X_{rzhdt y}$.

The maximum availability of a resource r must not be exceeded by the rate of utilising the resource:

$$U_{rzhdt y} \leq u_{rzhdt y}^{\max} \quad \forall r \in \mathbb{R}, z \in \mathbb{Z}, h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \quad (3)$$

For biomass, such as paddy rice and rice straw, their maximum available quantities are both space- and time-dependent, which is the product of the allocated area and yield potential in the province. Hence, the maximum seasonal availability of a biomass c must not be exceeded by the rate of utilising the biomass:

$$\sum_{hd} U_{czhdt y} n_h^{\text{hd}} n_d^{\text{dw}} n_t^{\text{wt}} \leq A_{czy}^{\text{Bio}} Y_{czy}^{\text{Bio}} \quad \forall c \in \mathbb{C}, z \in \mathbb{Z}, t \in \mathbb{T}, y \in \mathbb{Y} \quad (4)$$

In cultivating paddy rice, land footprint constraints can be set to comply to local and/or national policies on land-use and other agricultural and forestry activities. Eq. 5 constraints the allocated area of farmlands to the portion that is available in each province. Eq. 6 constraints the total allocated area of farmlands to the allowable portion at the national level.

$$\sum_c A_{czy}^{\text{Bio}} \leq f_{zy}^{\text{loc}} A_{zy}^{\text{Bio}, \max} \quad \forall z \in \mathbb{Z}, y \in \mathbb{Y} \quad (5)$$

$$\sum_{cz} A_{czy}^{\text{Bio}} \leq f_y^{\text{nat}} \sum_z A_{zy}^{\text{Bio}, \max} \quad \forall y \in \mathbb{Y} \quad (6)$$

To conveniently conduct case studies between food production only and integrated production of food and non-food products, the demands of resources can be delegated into two types: those that must always be satisfied or $D_{rzhdt y}^{\text{comp}}$ and those that may be optionally satisfied or $D_{rzhdt y}^{\text{opt}}$. Since food demand must always be satisfied and some demands of non-food products are optionally satisfied for RVCs with integrated food and non-food production; so the goal of the optimisation for a particular performance metric is to make food demand a priority while choosing the demands of non-food products that can be best satisfied. The model decides how much each of the demands is satisfied subject to:

$$D_{rzhdt y}^{\text{sat}} \leq D_{rzhdt y}^{\text{opt}} \quad \forall r \in \mathbb{R}, z \in \mathbb{Z}, h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \quad (7)$$

5.3. Processing resources

The net rate of producing (or consuming) resource r is defined by Eq. 8:

$$P_{rzhdy} = \sum_p \mathcal{P}_{pzhdy} \alpha_{rpy} \quad \forall r \in \mathbb{R}, z \in \mathbb{Z}, h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \quad (8)$$

The operation rate of a single processing technology at the industrial-scale $p \in \mathbb{P}^C$ must be within its minimum and maximum capacities:

$$p_p^{\min} N_{pzy}^{\text{PC}} \leq \mathcal{P}_{pzhdy} \leq p_p^{\max} N_{pzy}^{\text{PC}} \\ \forall p \in \mathbb{P}^C, z \in \mathbb{Z}, h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \quad (9)$$

The total quantity of processing technologies at the industrial-scale $p \in \mathbb{P}^C$ that can be installed in planning period y must not exceed the build rate:

$$\sum_z N I_{pzy}^{\text{PC}} \leq B R_{py} \quad \forall p \in \mathbb{P}^C, y \in \mathbb{Y} \quad (10)$$

5.4. Transporting resources

The net rate of transporting resource r into zone z from all other zones (Eq. 11) is the difference between the incoming and outgoing flow rates:

$$Q_{rzhdy} = \sum_{z' | \nu_{z'z}=1} \sum_{l \in \mathbb{L}} [(\bar{\tau}_{lr,dst,y} + \hat{\tau}_{lr,dst,y} d_{zz'}) \mathcal{Q}_{l z' zhdy}] + \\ \sum_{z' | \nu_{zz'}=1} \sum_{l \in \mathbb{L}} [(\bar{\tau}_{lr,src,y} + \hat{\tau}_{lr,src,y} d_{zz'}) \mathcal{Q}_{l zz' hdy}] \\ \forall r \in \mathbb{R}, z \in \mathbb{Z}, h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \quad (11)$$

The distance between the demand centres of two zones is:

$$d_{zz'} = \sqrt{(x_z - x_{z'})^2 + (y_z - y_{z'})^2} \quad \forall z, z' \in \mathbb{Z} \quad (12)$$

The maximum rate of a transporting technology l must not be exceeded by its operating rate:

$$\mathcal{Q}_{lzz' hdy} \leq \sum_{b \in \mathbb{B}} q_l^{\max} N_{bzz'y}^{\text{B}} |_{LB_{lb}=1 \wedge \nu_{zz'}=1} \quad \forall l \in \mathbb{L}, z, z' \in \mathbb{Z}, h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \quad (13)$$

The total rate of operation of all transporting technologies l must not exceed the maximum capacity of the transporting infrastructure b being utilised by these technologies:

$$\sum_{l \in \mathbb{L}} \mathcal{Q}_{lzz'hdy} \leq b_b^{\max} N_{bzz'y}^{\mathbb{B}} \quad \forall b \in \mathbb{B}, z, z' \in \mathbb{Z}, h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \quad (14)$$

5.5. Importing and exporting resources

The rate of importing and exporting resource r in and out of a zone z must not exceed the maximum rates, respectively:

$$M_{rzhdy} \leq m_{rzhdy}^{\max} \quad \forall r \in \mathbb{R}, z \in \mathbb{Z}, h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \quad (15)$$

$$X_{rzhdy} \leq \chi_{rzhdy}^{\max} \quad \forall r \in \mathbb{R}, z \in \mathbb{Z}, h \in \mathbb{H}, d \in \mathbb{D}, t \in \mathbb{T}, y \in \mathbb{Y} \quad (16)$$

6. Results and discussion

Using the model described above, three case studies, each with two scenarios, were developed for the Philippines: 1) food production only, 2) integrated food-energy production; and 3) integrated food-energy-fuels-chemicals production. See Supplementary Material for additional description, assumptions, optimisation results and implications of each case study.

6.1. Optimal scenarios for food production only

Figure 6a shows the Pareto set generated depicting the trade-offs between the two objectives: maximise NPV and minimise GHG emissions. The highest and lowest points represent optimal solutions of the two objectives; while points in between represent solutions of compromise between the two objectives. These results show the potential for existing Philippine RVCs to decarbonise without losing profit. These results also confirm the country's capacity to be 'fully' or 100% rice self-sufficient regardless of these objectives being prioritised. Moreover, an optimal design and operation of Philippine RVCs could potentially reduce by a factor of 6 times the retail price of white rice, which could be PhP 5.82/kg and PhP 6.22/kg in the maximise NPV scenario and the minimise GHG emissions scenario, respectively (Figure 6b). However, these calculations did not yet consider marketing gross margins and other market intermediary costs prevalent in the Philippine rice industry, which are highest among Southeast Asian nations (Bordey et al., 2016).

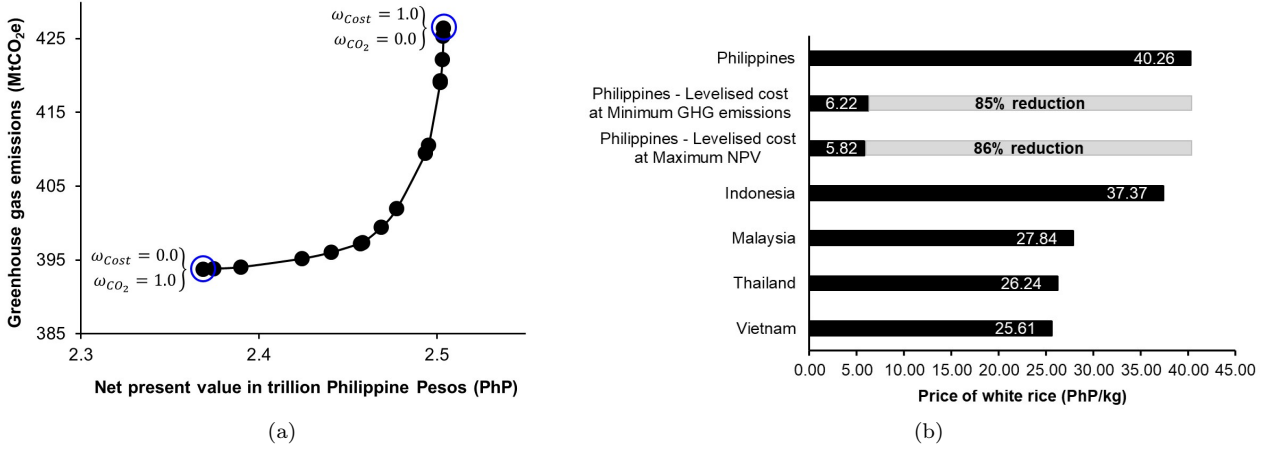
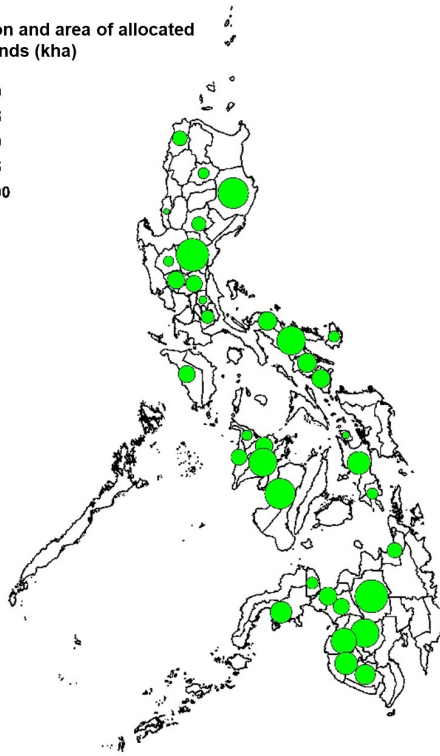


Figure 6: Optimal results for food production only: (a) Pareto set for Case 1 representing the trade-offs between profit and decarbonisation of Philippine rice value chains; and (b) Calculated levelised cost of white rice in the Philippines using the model against retail prices in the country and amongst Southeast Asian countries from the data of [Hoang and Meyers \(2015\)](#).

Figures 7 and 8 show the optimal location of rice farms, location and number of rice mill facilities, and operation of transport in the maximise NPV scenario (NPV of PhP 2.50 tn or USD 40.60 bn and GHG emissions of 426 MtCO₂e) and the minimise GHG emissions scenario (NPV of PhP 2.37 tn or USD 37.74 bn and GHG emissions of 394 MtCO₂e), respectively. NPVs indicate the potential of existing RVCs to become more profitable through effective management and efficient operation. In contrast to rice farming be widespread all over the country in order to achieve rice self-sufficiency, less than half of the Philippines' provinces are recommended as optimal locations: 35 in the maximise NPV scenario and 34 in the minimise GHG emissions scenario. Tables S1 and S2 present the provinces determined optimal for paddy rice production in the maximise NPV scenario and the minimise GHG emissions scenario, respectively. To maximise NPV, provinces with high yield potential but low cost of paddy rice production were chosen (Figure 7a); while to minimise GHG emissions, provinces with high yield potential but low GHG emissions were selected (Figure 8a). These optimal locations were not just determined through best yield/cost or best yield/GHG emissions ratios as several interrelated decisions must also be considered. Current rice farming takes up about 55% of total area available, but only 50% (4.11 Mha) and 46% (3.78 Mha) were required to meet the food demand in the maximise NPV scenario and the minimise GHG emissions scenario, respectively. Through a systematic and holistic analysis of RVCs, the Philippines is revealed to have more than enough area of farmlands in order to achieve 100% rice self-sufficiency; thus, further land expansion is not required. Rice farming in optimal locations would also allow farmers to use their farmlands in cultivating other valuable and/or more profitable crops.

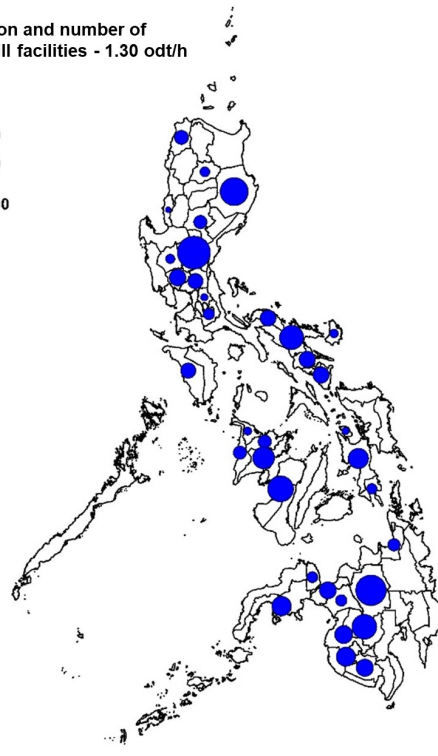
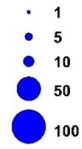
Provinces where rice farms are optimally located must have dedicated rice mill facilities as shown in Figures 7b and 8b in the maximise NPV scenario (952 in total) and the minimise GHG emissions scenario (955 in total), respectively. Hence, only the transport of white rice is needed to facilitate product distribution between zones in both scenarios. The mode of transport is primarily by barge (Figures 7c and 8c) given its lower economic and environmental impacts over transport by truck (Figures 7d and 8d) in both scenarios. Examining Figures 7c and 8c, both show several lines converging to zone 23 (Metro Manila), which is the capital of the country with the highest white rice demand (1.26 M odt/yr or 11.93% of the total). Metro Manila is highly urbanised and densely populated, with most lands being dedicated to housing and

Location and area of allocated farm lands (kha)

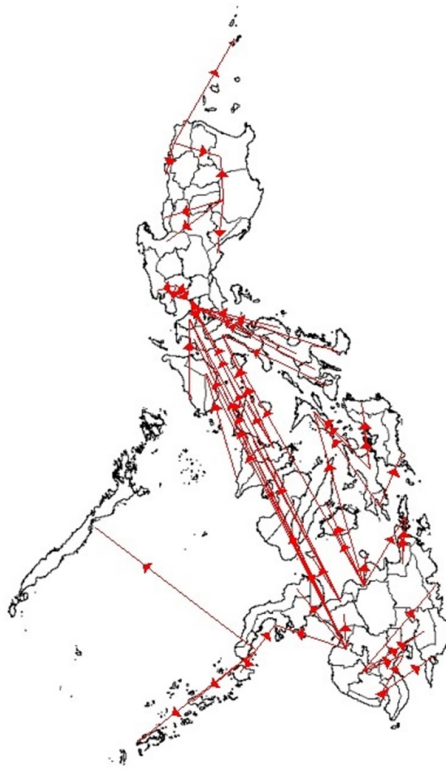


(a)

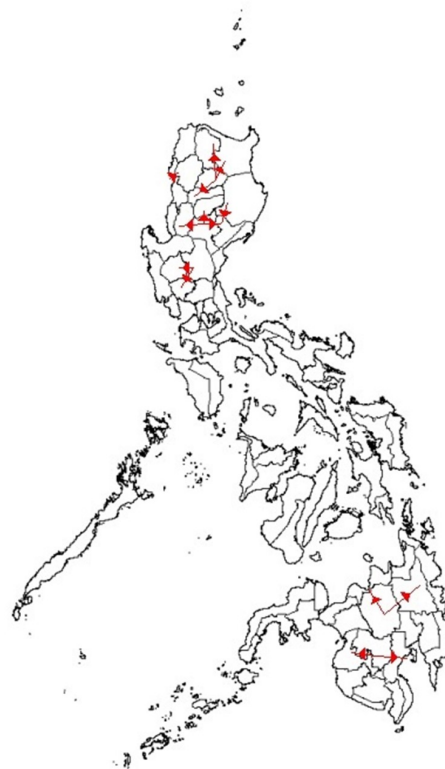
Location and number of rice mill facilities - 1.30 odt/h



(b)



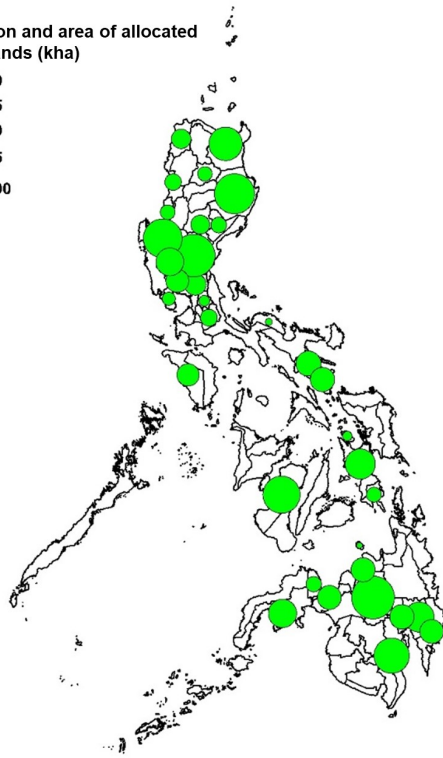
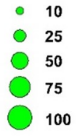
(c)



(d)

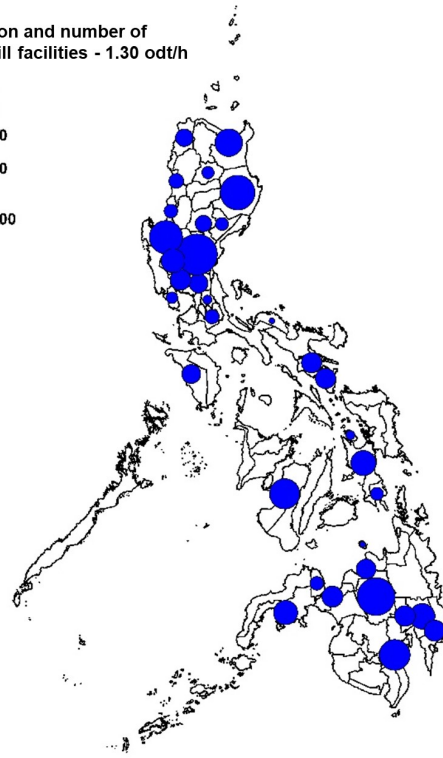
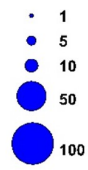
Figure 7: Optimal results for food production only in the maximise NPV scenario: (a) Allocated farmlands; (b) Rice mill facilities built; (c) Operation of transport by barge for white rice; and (d) Operation of transport by truck. (See Figure 3 for zone numbers.)

Location and area of allocated farm lands (kha)

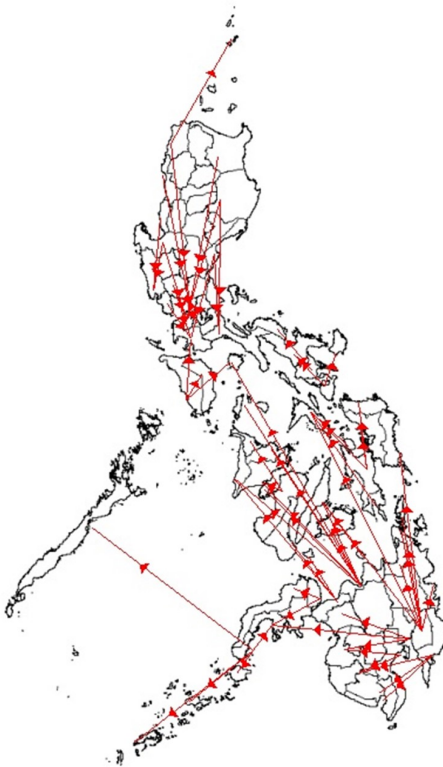


(a)

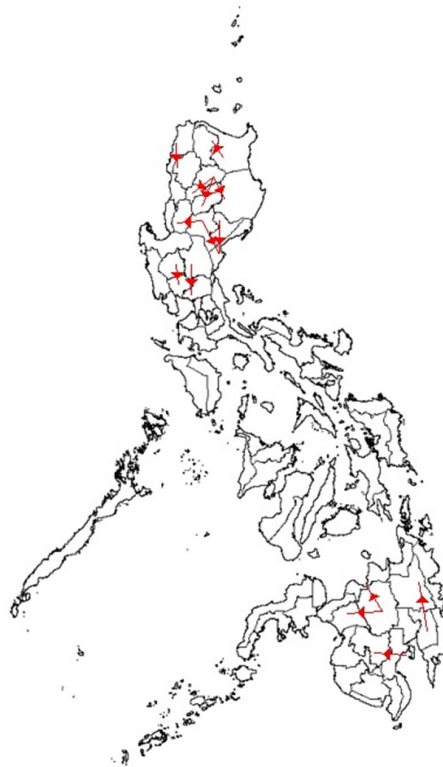
Location and number of rice mill facilities - 1.30 odt/h



(b)



(c)



(d)

Figure 8: Optimal results for food production only in the minimise GHG emissions scenario: (a) Allocated farmlands; (b) Rice mill facilities built; (c) Operation of transport by barge; and (d) Operation of transport by truck. (See Figure 3 for zone numbers.)

commercial developments (OECD, 2017). In order to satisfy Metro Manila’s food demand: zones 19, 29, 30, 31, 33, 41, 45, and 72 in the maximise NPV scenario and zones 02, 03, 12, 13 and 22 in the minimise GHG emissions scenario, are recommended to supply white rice by barge transport. Their relatively close proximity to zone 23 along with the high yield of paddy rice and/or the low associated impacts can be attributed to these results. Considering the total number of rice mill facilities to be built in both scenarios is similar, the difference in total GHG emissions for optimal RVCs is attributed to the transport of white rice. Since GHG emissions associated with transport is a function of distance; so transport distances in the minimise GHG emissions scenario (Figure 8c) are shorter than in the maximise NPV scenario (Figure 7c). In the minimise GHG emissions scenario, rice farming is to be located in provinces with high yield potential but low in GHG emissions, which are relatively close to zones with high white rice demand.

Since grains are the only source of income in Case 1; so integrated multi-product RVCs could potentially improve farm productivity by revenues from the sale of non-food products. Their feasibility was explored in Cases 2 and 3, wherein their planning includes the available farmlands of Metro Manila and losses of transporting resources. Allocation of all available farmlands in this zone could efficiently supply the zone’s high food demand with little to no impact in the costs and GHG emissions. Current inefficiencies of transporting technologies and infrastructures of the Philippines must be represented as the total area of farmlands allocated for rice farming increases with losses in transporting grains. (See Supplementary Material for further details of this discussion.)

6.2. Optimal scenarios for integrated food-energy production

Table S3 presents the compiled optimisation results of Case 2. In the maximise NPV scenario, NPV was PhP 2.84 tn (USD 53.88 bn) with GHG emissions of 373 MtCO₂e and total area of allocated farmlands at 4.59 Mha; while in the minimise GHG emissions scenario, NPV was PhP 2.31 tn (USD 43.86 bn) with GHG emissions of 340 MtCO₂e and total area of allocated farmlands at 4.31 Mha. In spite of transport losses, the positive value of the NPVs in both scenarios indicate the economic feasibility of integrating energy production with food production. In contrast to the NPV of Case 1 with transport losses of 20% (Figures S4b and S5b), integrating energy production resulted in increased NPVs by 25% and 8% in the maximise NPV scenario and the minimise GHG emissions scenario, respectively. Total farm productivity also improved by PhP 0.62 M/ha (USD 11.75 k/ha) and PhP 0.54 M/ha (USD 10.18 k/ha). Enhanced total farm productivity can potentially offset the high cost of rice farming in the country (PhP 18.75/ha) (Ponce and Inocencio, 2017). Furthermore, the environmental performance of the RVCs improved with GHG emissions reductions of 21% and 24% in the maximise NPV scenario and the minimise GHG emissions scenario, respectively, relative to the results of Case 1.

Transporting resources and installation of processing technologies contributed for higher GHG emissions of the RVCs relative to Case 1. Installation and subsequent operation of processing technologies had the largest increase in GHG emissions by a factor of 15 and 16 in the maximise NPV scenario and the minimise GHG emissions scenario, respectively. In the maximise NPV scenario, 993 rice mill facilities and 152 boiler-steam turbine facilities (Figure 9b) were built to meet both the food and energy demands, respectively; while 993 rice mill facilities, 124 boiler-steam turbine facilities, 9 gasification facilities, 6 FT jet synthesis facilities and 3 CCGT facilities (Figure 10b) in the minimise GHG emissions scenario. In the maximise NPV scenario, zone 23 (Metro Manila) have the highest number of facilities built with 82 units of rice mill and 14 units of

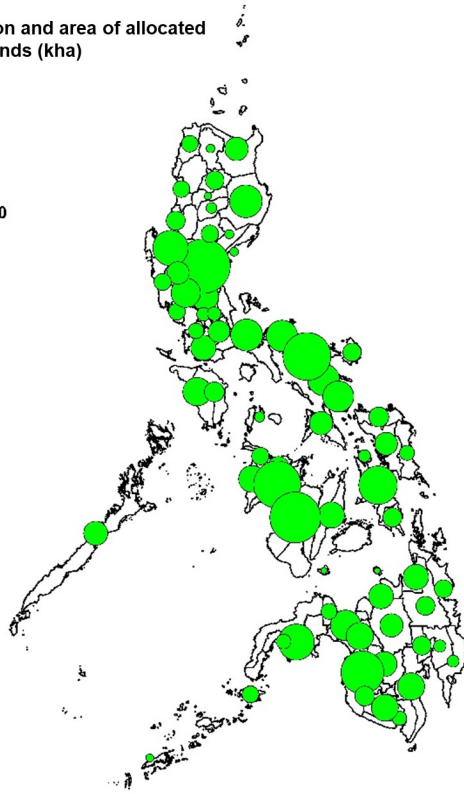
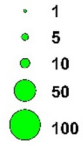
boiler-steam turbine. However, the number of rice mill facilities and all boiler-steam facilities are reduced to 5 units and replaced with a single unit combination of gasification-CCGT facility, respectively, in the minimise GHG emissions scenario. Overall, a decentralised system in both scenarios is recommended given the spatial distribution of crop residues. The decision between centralized vs. decentralised system has to take into account not only the available resources and processing technologies specifications but also impacts and losses of transporting resources (Samsatli and Samsatli, 2018a).

In general, the difference in the number and/or type of processing technologies built in a particular zone between the two scenarios is also seen in the operation of the transport networks, which had an 64% and 53% increase in GHG emissions relative to the results of Case 1. Barge is also the recommended primary transport mode in both scenarios for which paddy rice (Figures S6a and S7a), white rice (Figures S6b and S7b), rice straw (Figures 9c and 10c) and rice husk (Figures 9d and 10d) are distributed between zones. In contrast to Case 1, transporting paddy rice becomes crucial in compensating for food losses incurred during distribution. Transporting rice straw and rice husk becomes relevant in facilitating energy production in zones with high electricity demand and/or relatively insufficient amount of crop residues.

Operation of the transport networks corroborated with the location and area of allocated farmlands for rice farming. Several large areas are located in the central and southern) portions of the Philippines (Figure 9a) in the maximise NPV scenario; while these large areas are shifted mostly to northern Philippines with remaining large areas still located in southern Philippines in the minimise GHG emissions scenario (Figure 10a). In both scenarios, Central Luzon Region, led by zone 17 (Nueva Ecija), has the largest area given its proximity to zones with high demands. Allocated farmlands are located in 71 provinces with a total of 4.59 Mha in the maximise NPV scenario (only a 0.09% increase relative to Case 1). In the minimise GHG emissions, allocated farmlands are located in 55 provinces with a total of 4.31 Mha (only a 0.05% rise relative to Case 1). Finally, increase in GHG emissions associated with rice farming for Case 2 were only 0.17% and 0.10%, in the maximise NPV scenario and the minimise GHG emissions scenario, respectively.

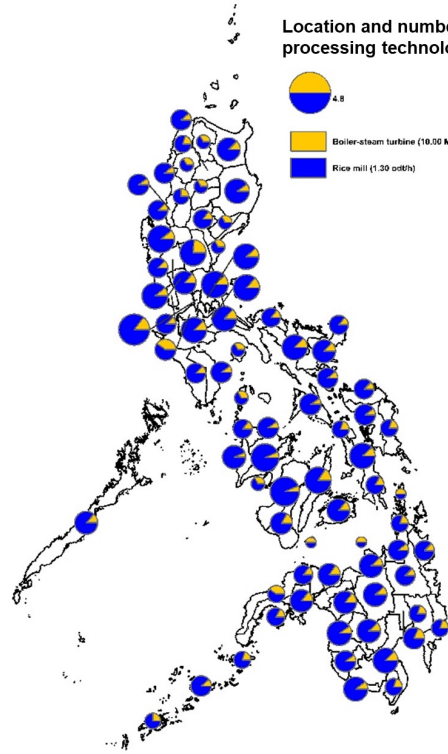
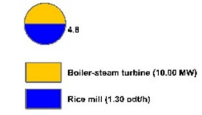
When consumers utilise bio-electricity over grid electricity, the GHG emissions associated is displaced. Overall GHG emissions displaced in the maximise NPV scenario and the minimise GHG emissions scenarios are 209 and 220 MtCO_{2e}, respectively. While 10% was set compulsory of the national electricity demand, 12% and 13% of the demand in the maximise NPV scenario and the minimise GHG emissions scenario, respectively, can be more than satisfied by bio-electricity from RVCs with integrated food-energy production.

Location and area of allocated farm lands (kha)

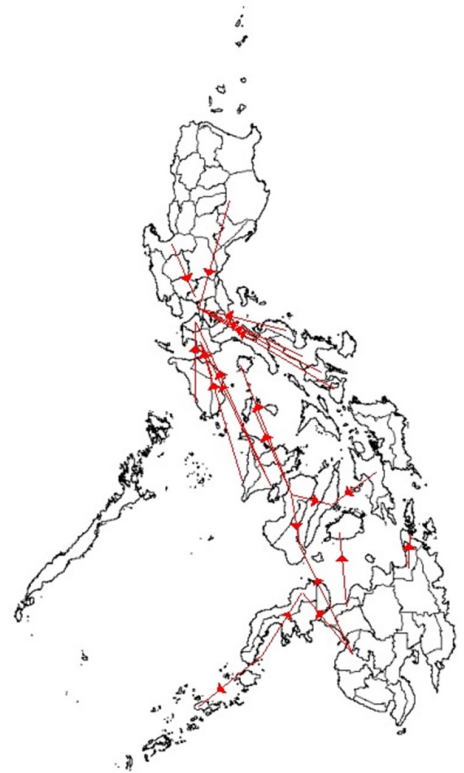


(a)

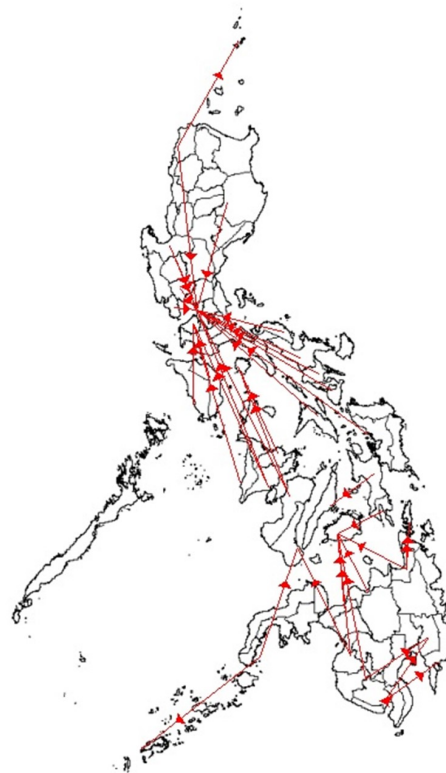
Location and number of processing technologies



(b)



(c)



(d)

Figure 9: Optimal results for integrated food-energy production in the maximise NPV scenario: (a) Allocated farmlands; (b) Processing technologies built; (c) Operation of transport by barge for rice straw; and (d) Operation of transport by barge for rice husk. (See Figure 3 for zone numbers.)

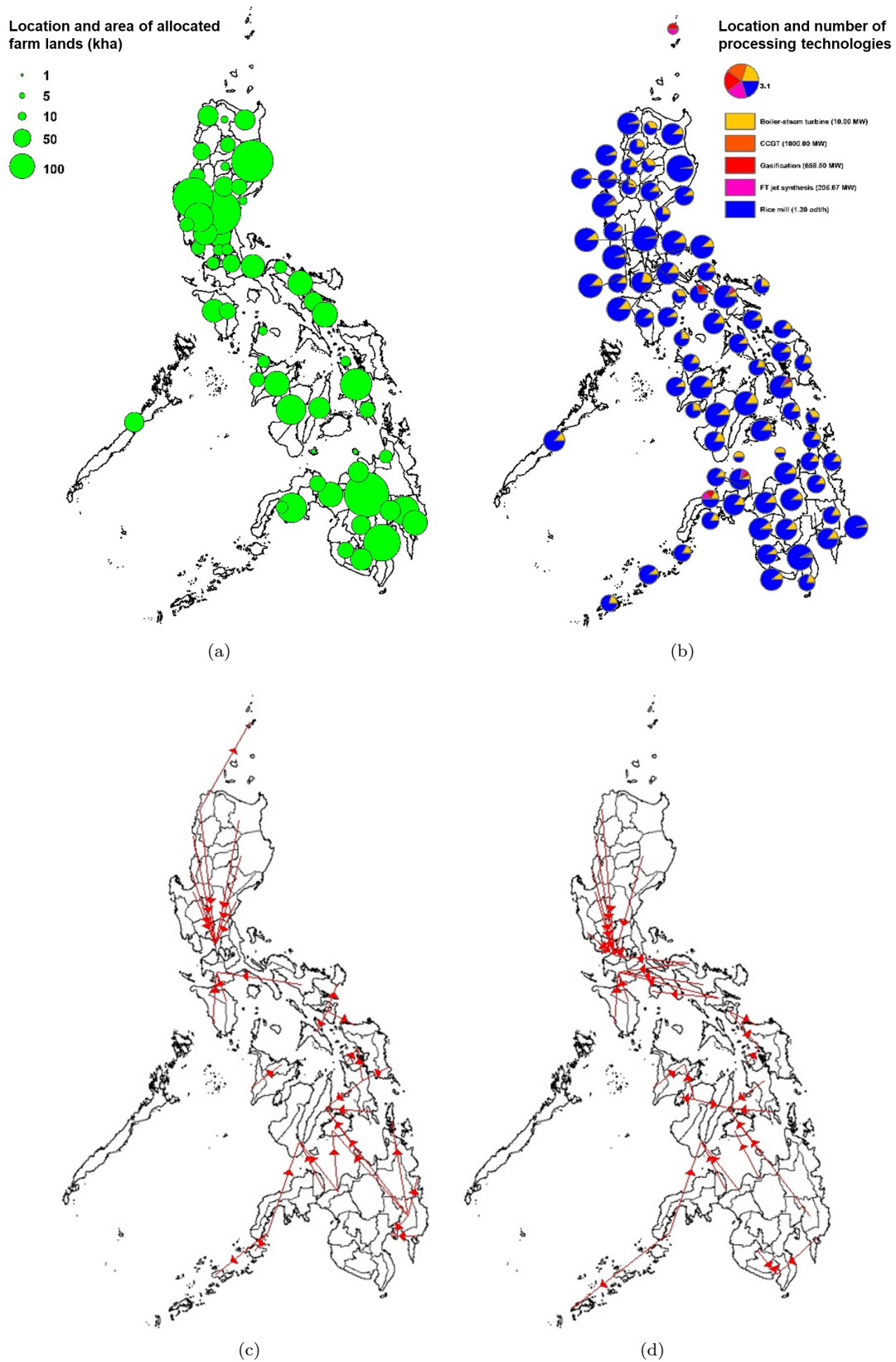


Figure 10: Optimal results for integrated food-energy production in the minimise GHG emissions scenario: (a) Allocated farmlands; (b) Processing technologies built; (c) Operation of transport by barge for rice straw; and (d) Operation of transport by barge for rice husk. (See Figure 3 for zone numbers.)

6.3. Optimal scenarios for integrated food-energy-fuels-chemicals production

Table S4 summarises the optimisation results of Case 3. The NPV are -PhP 4.62 tn (-USD 53.88 bn) and -PhP 4.51 tn (-USD 43.86 bn) in the maximise NPV scenario and the minimise GHG emissions scenario, respectively, which reveal that RVCs with integrated production of food, energy, fuels and chemicals are economically infeasible. Despite increase in revenue by 31% and 32% relative to Case 1 in the maximise NPV scenario and the minimise GHG emissions scenario, respectively, this was outweighed by the overall economic impact. The economic impacts of building, operating, and maintenance of processing technologies contribute to the majority of the overall economic impact at 66% (PhP 6.89 tn or USD 130.74 bn) and 63% (PhP 6.55 tn or USD 124.33 bn), in the maximise NPV scenario and the minimise GHG emissions scenario, respectively. Figures 11b and 12b, depict the location and number of processing technologies installed in the maximise NPV scenario and the minimise GHG emissions scenario, respectively.

Rice straw is utilised at an average of 17.62 M odt/yr (92% produced); while, rice husk is utilised at an average of 5.28 M odt/yr (95% produced). The total resource production of crop residues increased in Case 3 in order to meet the demand of non-food products, which is an average increase of 53% and 32% relative to Case 1 for rice husk and rice straw, respectively. Enhanced production of rice husk corroborated with higher number of rice mill facilities installed relative to Case 1, which are 48% increase at a total of 1,509 units installed in the maximise NPV scenario and 52% increase at 1,526 units installed in the minimise GHG emissions scenario. Corresponding to increased milling capacity is increased quantity of paddy rice processed, which would mean the amount of rice straw harvested also rose. As displayed in Figures 11a and 12a, the allocated area of farmlands is greater by 69% (at 7.16 Mha and 77 provinces in total) and 73% (at 7.43 Mha and 73 provinces in total) relative to Case 1 in the maximise NPV scenario and the minimise GHG emissions scenario, respectively, which are about the same in both scenarios. The economic impact of rice farming is the second main contributor to the overall cost at an average of PhP 3.54 tn or USD 67.13 bn (34% of the overall cost).

The economic impacts of importing and transporting resources have minor contributions to the overall economic impact, which is at 1% only in both scenarios. The operation of the barge transport network for paddy rice, white rice, rice straw and rice husk is shown in Figures S8a, S8b, 11c and 11d, respectively, in the maximise NPV scenario. Figures S9a, S9b, 12c and 12d illustrate the operation of the barge transport network for paddy rice, white rice, rice straw and rice husk, respectively, in the minimise GHG emissions scenario. Rice straw and rice husk are primarily transported by barge in Case 3, in order to supply the demands for energy, fuels and chemicals. The transport networks of the crop residues show a decentralised system is recommended by the model in both scenarios. In contrast to Cases 1 and 2, transporting grains become less significant in Case 3, which is evident from fewer transport routes from high-yielding to low-yielding zones. This lessened dependence on grain transport can be attributed to over production of grains in most zones. Due to higher requirements for crop residues, which must be produced together with paddy rice, there was an excess supply of grains produced from the RVCs. Hence, the priority of rice farming in Case 3 shifted from food production to non-food production.

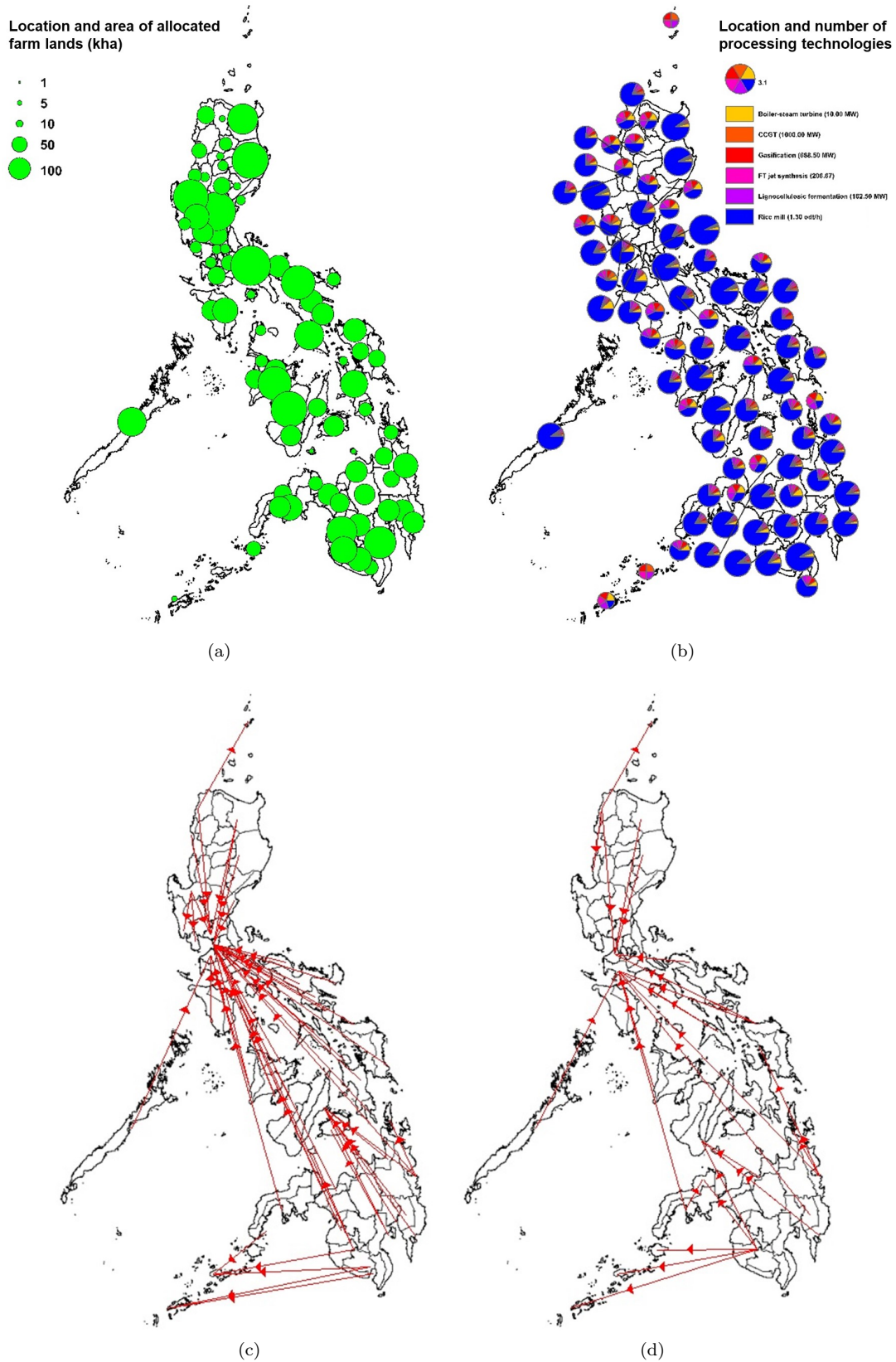


Figure 11: Optimal results for integrated food-energy-fuels-chemicals production in the maximise NPV scenario: (a) Allocated farmlands; and (b) Processing technologies built; (c) Operation of transport by barge for rice straw; and (d) Operation of transport by barge for rice husk. (See Figure 3 for zone numbers.)

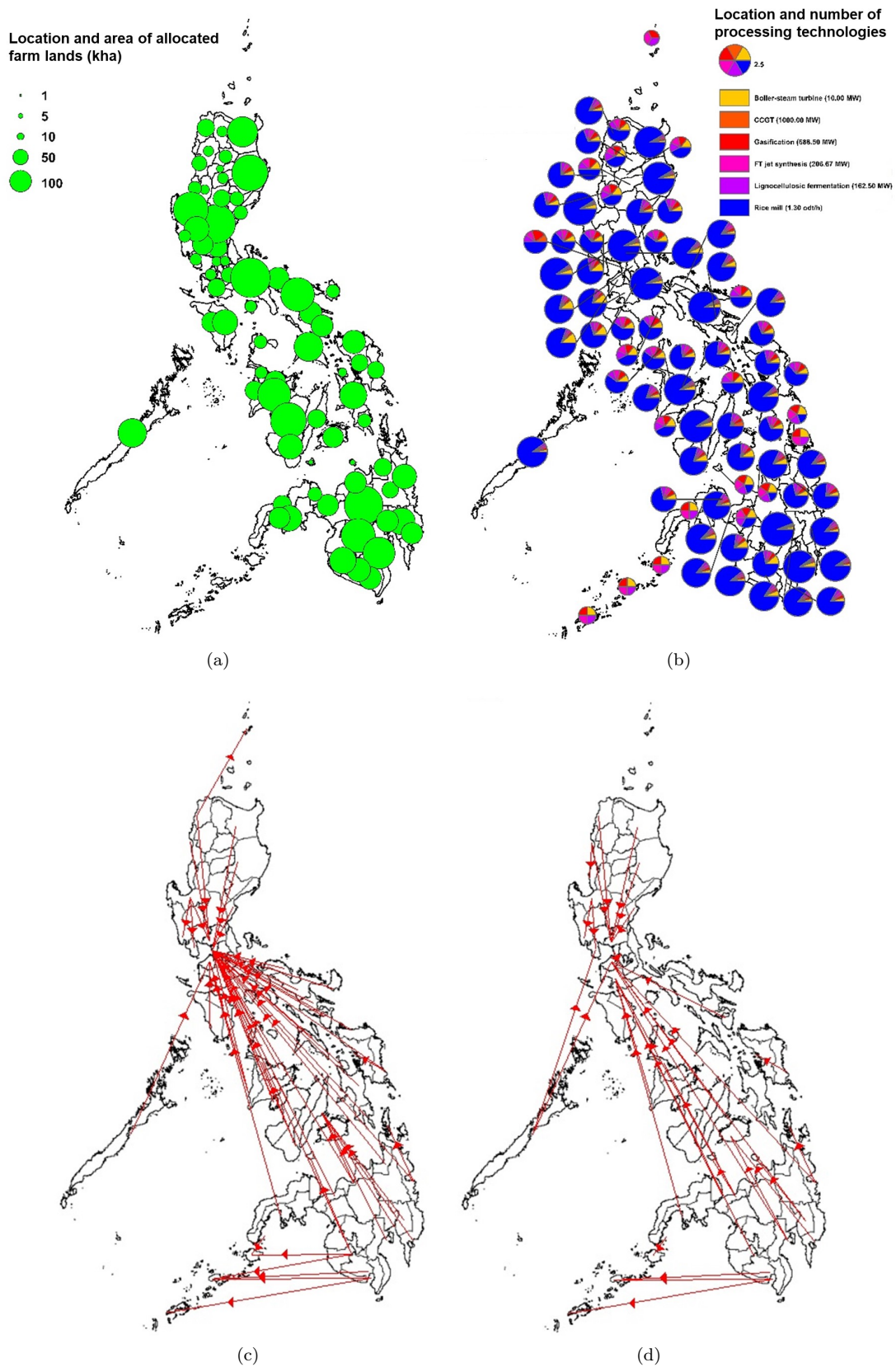


Figure 12: Optimal results for integrated food-energy-fuels-chemicals production in the minimise GHG emissions scenario: (a) Allocated farmlands; (b) Processing technologies built; (c) Operation of transport by barge for rice straw; and (d) Operation of transport by barge for rice husk. (See Figure 3 for zone numbers.)

RVCs with integrated production of food, energy, fuels and chemicals also performed environmentally unfavourably. Relative to Case 1, overall GHG emissions increased by a factor of 3 at an average total of 1,196 MtCO₂e. GHG emissions from intensive rice farming is the main contributor, which are at 712 MtCO₂e (58% of the overall environmental impact) in the maximise NPV scenario and 740 MtCO₂e (64% of the overall environmental impact) in the minimise GHG emissions scenario. GHG emissions from operating and maintenance of processing technologies is the second contributor, which are at 303 MtCO₂e (25% of the overall environmental impact) in the maximise GHG emissions and 236 MtCO₂e (20% of the overall environmental impact) in the minimise GHG emissions scenario. Building of processing technologies is the third contributor, which is at an average of 14% (169 MtCO₂e). GHG emissions from importing and transporting of resources have minor contributions to the overall environmental impact. GHG emissions from importing resources (due to grid electricity consumption) is 23 MtCO₂e (about 1.5% of the overall environmental impact) in both scenarios, while GHG emissions from resource transportation is at an average of 9 MtCO₂e (1% of the overall environmental impact). In contrast to Case 1 and 2, GHG emissions from importing and transporting resources in Case 3 significantly increased due to higher number of processing technologies and volume of resources being operated and transported, respectively.

Despite unfavourable economic and environmental performance, compulsory demands for bio-FT jet fuel and bio-naphtha were more than satisfied by 18% and 24%, respectively, in the maximise NPV scenario and 19% and 25%, respectively, in the minimise GHG emissions scenario. Compulsory demands (10%) for bio-electricity, bio-ethanol and bio-FT diesel were also completely satisfied in both scenarios. When consumers utilise these products, associated GHG emissions of their fossil-based counterparts are displaced. GHG emissions displaced are 351 MtCO₂e and 358 MtCO₂e in the maximise NPV scenario and the minimise GHG emissions scenario, respectively. However, the displaced GHG emissions are less than a third to the overall environmental impact in both scenarios.

6.4. Comparison of the optimal results of the case studies

Figure 13 compares the optimisation results of the Philippine case studies. Philippine RVCs with integrated food and non-food production are the least economically and environmentally favourable in both scenarios (Figures 13a and 13b). The net GHG emissions of integrated food-energy-fuels-chemicals production RVCs is about twice relative to food production only RVCs. The shift in priority of rice farming in Case 3 is also evident in increased allocation of farmlands (Figures 13c and 13d) and operation of processing technologies (Figures 13e and 13f). (See Supplementary Material for summary of the implications of each case study.) Philippine RVCs with integrated food-energy production are the most economically and environmentally favourable without affecting the priority on food production of rice farming. Sensitivity analysis reveal transporting resources is crucial for the smooth operation of these RVCs (see Supplementary Material). Socio-political challenges, climate change and pandemic are also expected to disrupt the smooth operation of rice value chains and many important food value chains (Garnett et al., 2020). Optimising value chains under several uncertainties would require robust and stochastic modelling (Tapia et al., 2019). Studying the resilience of rice value chains to these uncertainties is beyond the scope of this work and is recommended as future work.

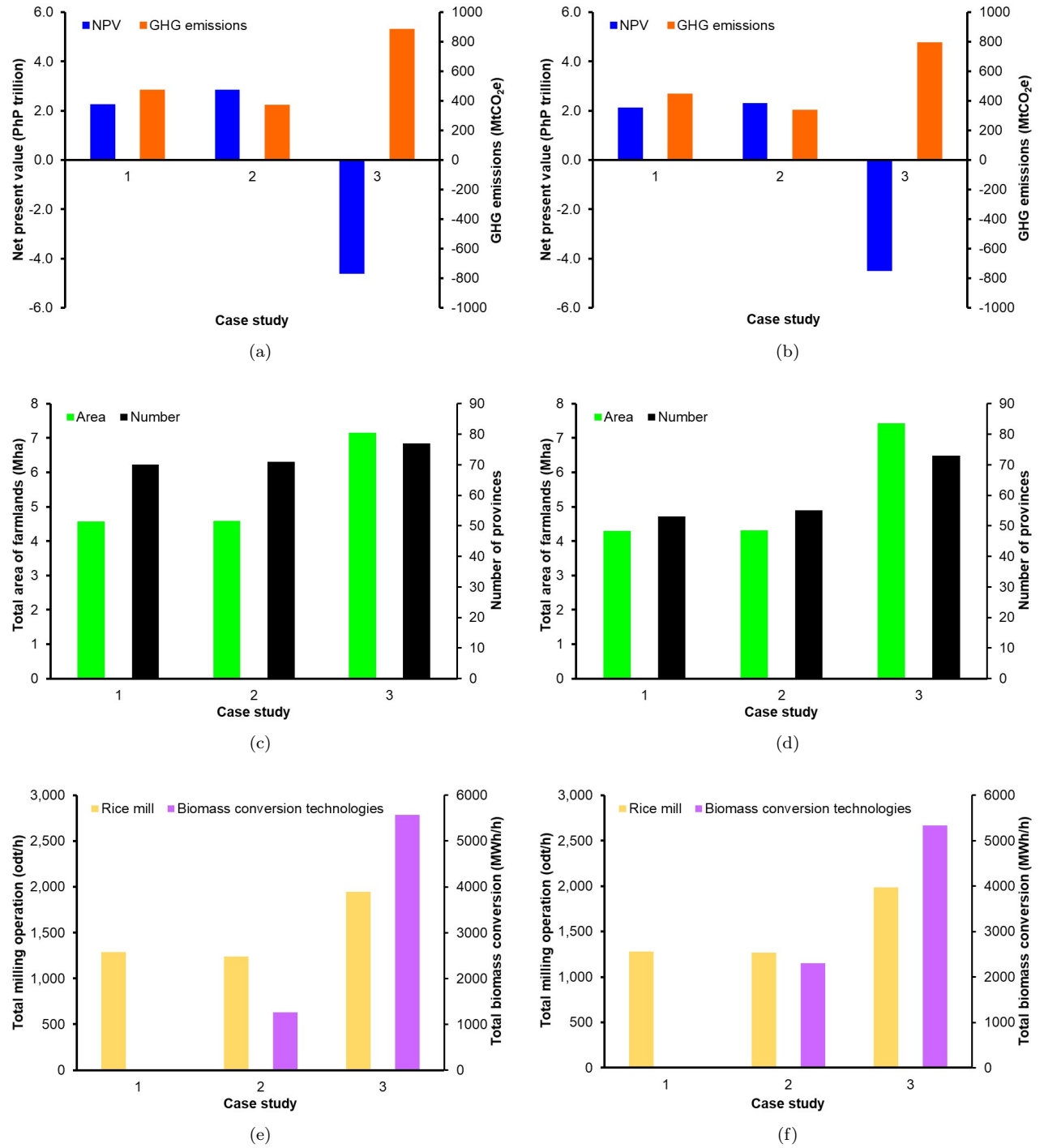


Figure 13: Comparison of optimisation results from the three case studies: Net present value and GHG emissions in the maximise NPV scenario (a) and the minimise GHG emissions scenario (b); Total area of farmlands and number of provinces in the maximise NPV scenario (c) and the minimise GHG emissions scenario (d); and Total rice milling operation and total biomass conversion in the maximise NPV scenario (e) and the minimise GHG emissions scenario (f). Note that optimisation results of Case 1 presented considered 20% losses in transporting resources.

7. Conclusions

Transforming major global food systems into more efficient and sustainable food value chains could help meet United Nations' SDG on food and agriculture from 2050 and beyond. Dramatic lengthening of RVCs, due to shifting patterns of global trade and booming economies of major rice-producing nations, hampers cost-effective efficient rice provision. Rice farming also continues being highly input-intensive in many rice sufficiency-seeking tropical countries, which is disruptive to their EFEW nexus. There is a need to plan, design and operate RVCs that can eliminate hunger with affordable food production and accommodate co-production of high-value commodities while maintaining sustainable ecosystems. In order to facilitate understanding of complex issues, formulating of effective strategies and assessing trade-offs among sustainability criteria, the first multi-objective spatio-temporal mixed integer linear programming model, based on the Value Web Model, was developed for the planning, design and operation of efficient and sustainable RVCs.

The model was applied to minimise the cost and GHG emissions of Philippine RVCs through three case studies: food production only, integrated food-energy production, and integrated food-energy-fuels-chemicals production. By rice farming in optimal locations and efficient product distribution, optimised RVCs solely for food production can make the Philippines 100% rice self-sufficient without further expanding farmlands and potentially reduce rice retail prices by 6 times. Barely little land expansion needed, optimised multi-product RVCs with integrated food-energy production can enhance total farm productivity by 25% and decrease GHG emissions by 24%. Integrated food-energy production can also satisfy the country's white rice (100%) and renewable electricity (10%) requirements with favourable economic and environmental performance. However, implementing multi-product RVCs with integrated food-energy-fuels-chemicals production will require careful and strategic planning as they may need 70% more farmlands and emit twice more GHG than RVCs with food production only.

The mathematical formulation of the model is general and applicable to any rice provision system. Using available and reliable data for a particular region, the model can be conveniently configured for the planning, design and operation of RVCs and gain key insights for their implementation. The model will be potentially useful to many rice-producing countries, particularly in Sub-Saharan Africa and Latin America, which are seeking to be 'fully' rice self-sufficient but are constrained with food insecurity, economic globalisation, biodiversity loss and climate change. Policy-makers and planning authorities of these regions can benefit from systematic and holistic analyses in transforming their current rice provision systems into more efficient and sustainable RVCs, while taking into account for synergistic and non-cooperative interactions with their regional environment, food, energy and water sectors.

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Nomenclature

Note the following: 1) resources can have units in odt for biomass feedstocks and in MWh for energy vectors and 2) impact can have units in PhP for economic performance and in kgCO₂e for environmental performance.

Definition of indices and sets

$b \in \mathbb{B}$	Transporting infrastructures
$c \in \mathbb{C} \subset \mathbb{R}$	Biomass feedstock (crop e.g. paddy rice, crop residues e.g. rice straw)
$d \in \mathbb{D}$	Types of day
$\mathbb{E} \in \mathbb{R}$	End vectors
$f \in \mathbb{F}$	Directions of flow
$i \in \mathbb{I}$	Performance metrics (e.g. unit economic impact, unit environmental impact)
$h \in \mathbb{H}$	Hourly intervals
$l \in \mathbb{L}$	Transporting technologies
$p \in \mathbb{P}$	Processing technologies
$\mathbb{P}^D \in \mathbb{P}$	Processing technologies at the domestic-scale
$\mathbb{P}^C \in \mathbb{P}$	Processing technologies at the industrial-scale
$r \in \mathbb{R}$	Resources (primary, intermediates, food products, non-food products)
$t \in \mathbb{T}$	Seasons
$y \in \mathbb{Y}$	Thirty-two-year planning period
$\tilde{y} \in \tilde{\mathbb{Y}}$	Contiguous yearly intervals for discounting of unit economic impact
$z \in \mathbb{Z}$	Zones of transmissions

Definition of parameters

$A_{zy}^{\text{Bio,max}}$	Maximum available area of farmlands in zone z in planning period y (ha)
BR_{py}	Maximum total quantity of processing technologies p that can be built in planning period y (build rate)
b_b^{max}	Maximum capacity of transporting infrastructure b (odt/h)
C_{biy}^B	Unit capital economic or environmental impact of infrastructure b in planning period y (PhP/km or kgCO ₂ e/km)
C_{piy}^P	Unit capital economic or environmental impact of processing technology p in planning period y (PhP or kgCO ₂ e)

c_{city}^{Bio}	Unit economic or environmental impact of producing (planting, cultivation and harvesting) biomass c in season t of planning period y (PhP/odt or kgCO ₂ e/odt)
c_{rihdy}^M	Unit economic or environmental impact of importing resource r during hour h , type of day d , season t and planning period y (PhP/odt, PhP/MWh, kgCO ₂ e/odt or kgCO ₂ e/MWh)
c_{rihdy}^U	Unit economic or environmental impact of producing resource r during hour h , type of day d , season t and planning period y (PhP/odt, PhP/MWh, kgCO ₂ e/odt or kgCO ₂ e/MWh)
c_{rihdy}^X	Unit economic or environmental impact of exporting resource r during hour h , type of day d , season t and planning period y (PhP/odt, PhP/MWh, kgCO ₂ e/odt or kgCO ₂ e/MWh)
$D_{\star iy}^C$	Discounting factor for the capital impact in planning period y back to 2018 ($\star \in \{b, p\}$ of transporting infrastructures and processing technologies, respectively)
D_{iy}^{OM}	Discounting factor for the O&M impact in planning period y back to 2018
D_{rzhdy}^{act}	Actual demand for resource r in zone z during hour h , type of day d , season t and planning period y (odt/h or MWh/h)
D_{rzhdy}^{com}	Compulsory demand that must be always satisfied for resource r in zone z during hour h , type of day d , season t and planning period y (odt/h or MWh/h)
D_{rzhdy}^{opt}	Optional demand that can be satisfied when economically or environmentally feasible for resource r in zone z during hour h , type of day d , season t and planning period y (odt/h or MWh/h)
$d_{zz'}$	Distance between the demand centres of zone z and z' (km)
f_{zy}^{loc}	Portion of farmland area for production of biomass in zone z that can be utilised in planning period y
f_y^{nat}	Portion of the total farmland area in the country that can be utilised in planning period y
LB_{lb}	= 1 if transporting technology l can use infrastructure b ; = 0 if otherwise
m_{rzhdy}^{max}	Maximum importing rate of resource r in zone z during hour h , type of day d , season t and planning period y (odt/h or MWh/h)
n_h^{hd}	Duration of hourly intervals h (h)
n_d^{dw}	Frequency of type of day d happens in week
n_t^{wt}	Frequency of repeated week in season t
n_y^{yy}	Frequency of repeated years in planning period y
N_{pz}^{EPC}	Quantity of processing technologies of type p at the industrial-scale that exist in zone z
NR_{pz}^{EPC}	Quantity of processing technologies of type p at the industrial-scale that retire in zone z at the start of planning period y

$N_{bzz'}^{\text{EB}}$	Quantity of transporting infrastructures with connections of type b that exist between zones z and z'
p_p^{max}	Rate of maximum capacity of processing technology p (odt/h or MWh/h)
p_p^{min}	Rate of minimum capacity of processing technology p (odt/h or MWh/h)
q_l^{max}	Maximum rate of transmission for transporting technology l (odt/h or MWh/h)
$RF_{py'y}^{\text{P}}$	Binary parameter: = 1 when the technology installed at start of planning period y' retires at the start of planning period y ; = 0 if otherwise
V_{riy}	Unit sale price of resource r in planning period y
x_z	x-coordinate (abscissa) of the demand centre of zone z
y_z	y-coordinate (ordinate) of the demand centre of zone z
Y_{czt}^{Bio}	Potential yield of biomass c in zone z in season t of planning period y (odt/ha/season)
α_{rpy}	Conversion of resource r in processing technology p in planning period y
β_b	Specifies the bidirectionality of transporting infrastructure b : = -1 when unidirectional; = 0 when independent bidirectional (separately link); = 1 when bidirectional
γ	Finance (interest) rate
ι	Discount rate
$\lambda_{\star}$	Technology economic life (y) ($\star \in \{b, p\}$ of transporting infrastructures and processing technologies, respectively)
ν	Binary parameter equivalent to 1 when zone z is next to zone z'
ζ	Scaling factor that converts unit economic impact from PhP to PhP M and unit environmental impact from kgCO ₂ e to MkgCO ₂ e
$\bar{\tau}_{lrfy}$	Distance-independent factor of conversion for transporting technology l when transmitting resource r in planning period y
$\hat{\tau}_{lrfy}$	Distance-dependent factor of conversion for transporting technology l when transmitting resource r in planning period y
ϕ_{biy}^{B}	Annual fixed O&M impact of transporting infrastructure b in planning period y (PhP/km/yr or kgCO ₂ e/km/yr)
ϕ_{piy}^{P}	Annual fixed O&M impact of processing technology p in planning period y (PhP/km/yr or kgCO ₂ e/km/yr)
φ_{piy}^{P}	Unit variable operating impact of processing technology p in planning period y (PhP/odt, PhP/MWh, kgCO ₂ e/odt or kgCO ₂ e/MWh)
$\bar{\varphi}_{liy}^{\text{Q}}$	Distance-independent unit variable operating impact of transmission process l in planning period y (PhP/km/odt, PhP/km/MWh, kgCO ₂ e/km/odt or kgCO ₂ e/km/MWh)
$\hat{\varphi}_{lrfy}^{\text{Q}}$	Distance-dependent unit variable operating impact of transmission l in planning period y

$\chi_{rzhdt}^{\max}$	Maximum exporting rate of resource r in zone z during hour h , type of day d , season t and planning period y (odt/h or MWh/h)
w_i	Weight set on performance metrics i for the objective function

Definition of positive variables

A_{czy}^{Bio}	Allocated area of farmlands for the production of biomass feedstock c in zone z during planning period y (ha)
D_{rzhdt}^{sat}	Satisfied optional demands for resource r in zone z during hour h , type of day d , season t and planning period y (odt/h or MWh/h)
$\mathcal{J}_{iy}^{\text{P}}$	Overall net present capital economic or environmental impact of installing new processing technologies in planning period y (PhP M or MkgCO ₂ e)
$\mathcal{J}_{iy}^{\text{Q}}$	Overall net present capital economic or environmental impact of installing new transporting infrastructures in planning period y (PhP M or MkgCO ₂ e)
$\mathcal{J}_{iy}^{\text{Bio}}$	Overall net present capital economic or environmental impact of biomass production in planning period y (PhP M or MkgCO ₂ e)
$\mathcal{J}_{iy}^{\text{m}}$	Overall net present economic or environmental impact of importing resource in planning period y (PhP M or MkgCO ₂ e)
$\mathcal{J}_{iy}^{\text{fp}}$	Overall net present fixed O&M economic or environmental impact of processing technologies in planning period y (PhP M or MkgCO ₂ e)
$\mathcal{J}_{iy}^{\text{fq}}$	Overall net present fixed O&M economic or environmental impact of transporting infrastructures in planning period y (PhP M or MkgCO ₂ e)
$\mathcal{J}_{iy}^{\text{Rev}}$	Overall net present revenue from the sales of products (food and non-food) for demand satisfaction in planning period y (PhP M or MkgCO ₂ e)
$\mathcal{J}_{iy}^{\text{U}}$	Overall net present economic or environmental impact of utilising resource in planning period y (PhP M or MkgCO ₂ e)
$\mathcal{J}_{iy}^{\text{vp}}$	Overall net present variable operating economic or environmental impact of processing technologies in planning period y (PhP M or MkgCO ₂ e)
$\mathcal{J}_{iy}^{\text{vq}}$	Overall net present variable operating economic or environmental impact of transporting infrastructures in planning period y (PhP M or MkgCO ₂ e)
$\mathcal{J}_{iy}^{\text{x}}$	Overall net present economic or environmental impact of resource exportation in planning period y (PhP M or MkgCO ₂ e)
M_{rzhdt}	Importing rate of resource r in zone z during hour h , type of day d , season t and planning period y (odt/h or MWh/h)
N_{pzy}^{PD}	Total quantity of processing technology at the domestic-scale $p \in \mathbb{P}^{\text{D}}$ in zone z at the start of (and throughout) planning period y
U_{rzhdt}	Utilising rate of resource r in zone z during hour h , type of day d , season t and planning period y (odt/h or MWh/h)

$u_{rzhdy}^{\max}$	Peak availability of resource r in zone z during hour h , type of day d , season t and planning period y (odt/h or MWh/h)
X_{rzhdy}	Exporting rate of resource r in zone z during hour h , type of day d , season t and planning period y (odt/h or MWh/h)
$\mathcal{P}_{pzhdy}$	Total rate of utilising processing technology p in zone z during hour h , type of day d , season t and planning period y (odt/h or MWh/h)
$\mathcal{Q}_{lzz'hdy}$	Transmission rate of transporting technology in zone z during hour h , type of day d , season t and planning period y (odt/h or MWh/h)

Definition of free variables

P_{rzhdy}	Net production rate of resource r in zone z during hour h , type of day d , season t and planning period y (odt/h or MWh/h)
Q_{rzhdy}	Net transmission rate of resource r in zone z from all other zones during hour h , type of day d , season t and planning period y (odt/h or MWh/h)
Z	Objective function

Definition of integer variables

$N_{bzz'y}^B$	Quantity of transporting infrastructure b installed between zone z and z' at the start of (and usable during) planning period y
N_{pzy}^{PC}	Total quantity of processing technology at the industrial-scale $p \in \mathbb{P}^C$ in zone z at the start of (and during) planning period y
$NI_{bzz'y}^B$	Quantity of new transporting infrastructure b installed at the start of planning period y between zones z and z'
NI_{pzy}^{PC}	Quantity of new processing technology at the industrial-scale $p \in \mathbb{P}^C$ installed at the start of planning period y
NR_{pzy}^{PC}	Quantity of retired processing technology at the industrial-scale $p \in \mathbb{P}^C$ installed at the start of planning period y

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Supplementary Material

Integrated production of food, energy, fuels and chemicals from rice crops: Multi-objective optimisation for efficient and sustainable value chains

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This Supplementary Material comprises two sections. Section [S1](#) provides further details on the mathematical formulation of the model (see Section 5 of the Manuscript). Section [S2](#) reports additional results and discussion of the optimal scenarios for the Philippine case studies (see Section 6 of the Manuscript). See co-submitted Data in Brief article ([Doliente and Samsatli, n.d.](#)) for complete details and data of the components of the rice value chain (RVC) model as discussed in Section 3 of the Manuscript.

S1 Further details of the mathematical formulation of the model

With permission from the authors, Samsatli and Samsatli ([Samsatli and Samsatli, 2018](#)), further details of the mathematical formulation of the Value Web Model are presented in this section of the Supplementary Material. Some additional variables, parameters and constraints for the case studies reported in Section 5 of the Manuscript are defined and explained below.

S1.1 Definition of the impact terms

Each of the term in the right-hand side of Eq. 1 signifies an impact in planning period y on a performance metrics i . These terms are defined as follows:

- Overall net present capital impact of installing new processing technologies:

$$\mathcal{J}_{iy}^P = \varsigma \sum_{pz} D_{piy}^C C_{piy}^P N_{pzy}^{PC} \quad \forall i \in \mathbb{I}, y \in \mathbb{Y} \quad (S1)$$

- Overall net present capital impact of installing new transporting infrastructures:

$$\mathcal{J}_{iy}^Q = \varsigma \sum_{bzz'} D_{biy}^C C_{biy}^B N_{bzz'y}^B d_{zz'} (1 - 0.5|_{\beta_b=1}) \quad \forall i \in \mathbb{I}, y \in \mathbb{Y} \quad \mathbb{Y} N_{bzz'}^{EB} \quad (S2)$$

- Overall net present fixed O&M impact of processing technologies:

$$\mathcal{J}_{iy}^{fp} = \varsigma D_{iy}^{OM} \sum_{pz} \phi_{piy}^P N_{pzy}^{PC} \quad \forall i \in \mathbb{I}, y \in \mathbb{Y} \quad (S3)$$

- Overall net present fixed O&M impact of transporting infrastructures:

$$\mathcal{J}_{iy}^{fq} = \varsigma D_{iy}^{OM} \sum_{bzz'} \phi_{biy}^B C_{biy}^B N_{bzz'y}^B d_{zz'} (1 - 0.5|_{\beta_b=1}) \quad \forall i \in \mathbb{I}, y \in \mathbb{Y} \quad (S4)$$

- Overall net present variable operating impact of processing technologies:

$$\mathcal{J}_{iy}^{vp} = \varsigma D_{iy}^{OM} \sum_{pzhdt} \varphi_{piy}^P \mathcal{P}_{pzhdt} n_h^{hd} n_d^{dw} n_t^{wt} \quad \forall i \in \mathbb{I}, y \in \mathbb{Y} \quad (S5)$$

- Overall net present variable operating impact of transporting infrastructures:

$$\mathcal{J}_{iy}^{vq} = \varsigma D_{iy}^{OM} \sum_{lzz'hdt} \left(\bar{\varphi}_{liy}^Q + \hat{\varphi}_{lrfy}^Q \right) \mathcal{Q}_{lzz'hdt} n_h^{hd} n_d^{dw} n_t^{wt} \quad \forall i \in \mathbb{I}, y \in \mathbb{Y} \quad (S6)$$

- Overall net present impact of utilising resources:

$$\mathcal{J}_{iy}^U = \varsigma D_{iy}^{OM} \left(\sum_{r \in \mathbb{R}-\mathbb{C}} \sum_{zhdt} c_{rihdt}^U U_{rzhdt} n_h^{hd} n_d^{dw} n_t^{wt} + \sum_{czt} c_{city}^{Bio} A_{czy}^{Bio} Y_{czt}^{Bio} \right) \quad \forall i \in \mathbb{I}, y \in \mathbb{Y} \quad (S7)$$

- Overall net present impact of importing resources:

$$\mathcal{J}_{iy}^m = \varsigma D_{iy}^{\text{OM}} \sum_{rzhdt} c_{rihdt}^M n_h^{\text{hd}} n_d^{\text{dw}} n_t^{\text{wt}} \quad \forall i \in \mathbb{I}, y \in \mathbb{Y} \quad (\text{S8})$$

- Overall net present impact of exporting resources:

$$\mathcal{J}_{iy}^x = \varsigma D_{iy}^{\text{OM}} \sum_{rzhdt} c_{rihdt}^X X_{rzhdt} n_h^{\text{hd}} n_d^{\text{dw}} n_t^{\text{wt}} \quad \forall i \in \mathbb{I}, y \in \mathbb{Y} \quad (\text{S9})$$

- Overall net present revenue (or displaced GHG emissions for environmental impact) from the sales of food and non-food products (bio-electricity and biofuels):

$$\mathcal{J}_{iy}^{\text{Rev}} = \varsigma D_{iy}^{\text{OM}} \sum_{rzhdt} V_{riy} (D_{rzhdt}^{\text{com}} + D_{rzhdt}^{\text{sat}}) n_h^{\text{hd}} n_d^{\text{dw}} n_t^{\text{wt}} \quad \forall i \in \mathbb{I}, y \in \mathbb{Y} \quad (\text{S10})$$

Note the following for the equations presented:

1. For Eqs. S5 and S6, the impact of operating a technology does not account for the consumption of any raw material. Instead, the resource balance (Eq. 2) warrants any resource consumed must be balanced by the available resource utilised, produced by other technologies, transported from another zone, and/or imported/exported. Such that any of these routes that provides the raw material for the operation of a technology accrues their own impact(s). Hence, impacts are accounted on system-wide basis, rather than “per technology”.
2. For Eqs. S2 and S4, the term $0.5|_{\beta_b=1}$ is only applicable for infrastructures that are bidirectional (e.g. $\beta_b = 1$). Hence, the cost of links in only one direction is accounted even by the constraint $N_{bzz'y} = N_{bz'zy}$ (Eq. 16). However, when $\beta_b \neq 1$, the term $0.5|_{\beta_b=1}$ disappears and the links in each direction incurs costs independently. (See Subsection S1.3 for setting bidirectionality of transporting infrastructures.)
3. For Eqs. S1 and S2, when $i = \text{economic}$, the capital economic impacts are calculated by assuming investments are financed over the economic life of the technology λ_* . Such that for an investment made in a technology during planning period y , the capital economic impact (at the prices of planning period y) is multiplied by a factor to provide the annual repayments of λ_* that must be made based on a finance rate of γ . The first repayment is a year after the receipts of funds every start of the year during the period. Then a second factor discounts all the annual repayment back to the start of period y with a discount rate ι . Thereafter, a third factor also discounts all the annual repayment back to the start of period y with a discount rate ι . The total product of these factors is symbolised by $D_{\star iy}^C$ and expressed as:

$$D_{\star iy}^C = \begin{cases} (1 + \iota)^{-32(y-1)} \left[\frac{\gamma(1+\gamma)^{\lambda_*}}{(1+\lambda)^{\lambda_*-1}} \right] \sum_{\tilde{y}=1}^{\lambda_*} (1 + \iota)^{-\tilde{y}} & \forall i = \text{economic}, \\ & y \in \mathbb{Y} \\ 1 & \forall i \neq \text{economic}, \\ & y \in \mathbb{Y} \end{cases} \quad (\text{S11})$$

The subscript $\star$ in Eqs. S1 and S2 is replaced by p or b to signify that $\lambda_\star$ and $D_{\star iy}^C$ is for a processing technology or an transporting infrastructure, correspondingly.

4. From Eqs. S3 to S10, the economic impact of operating and maintenance of the technologies are assumed to be paid at the start of each year in any planning period y . These are discounted back to the start of the period y and back to the first period by using the parameter D_{iy}^{OM} expressed as:

$$D_{iy}^{\text{OM}} = \begin{cases} (1 + \iota)^{-32(y-1)} \sum_{\tilde{y}=1}^{32} (1 + \iota)^{-\tilde{y}} & \forall i = \text{economic}, \\ & y \in \mathbb{Y} \\ 32 & \forall i \neq \text{economic}, \\ & y \in \mathbb{Y} \end{cases} \quad (\text{S12})$$

S1.2 Planned installments and retirements of technologies

Owing to investments and retirements, the quantity of technologies and infrastructures existing in a zone z may vary each planning period. These are given by Eqs. S13 and S14 for processing technologies and transporting infrastructures, respectively:

$$N_{pzy}^{\text{PC}} = \begin{cases} N_{pz}^{\text{EPC}} + NI_{pzy}^{\text{PC}} - NR_{pzy}^{\text{PC}} - NR_{pz}^{\text{EPC}} & \forall p \in \mathbb{P}^C, z \in \mathbb{Z}, y = 1 \\ N_{pz,y-1}^{\text{PC}} + NI_{pzy}^{\text{PC}} - NR_{pzy}^{\text{PC}} - NR_{pz}^{\text{EPC}} & \forall p \in \mathbb{P}^C, z \in \mathbb{Z}, y > 1 \end{cases} \quad (\text{S13})$$

$$N_{bzz'y}^{\text{B}} = \begin{cases} N_{bzz'}^{\text{EB}} + NI_{bzz'y}^{\text{B}} & \forall b \in \mathbb{B}, z \in \mathbb{Z}, y = 1 \\ N_{bzz'y-1}^{\text{B}} + NI_{bzz'y}^{\text{B}} & \forall b \in \mathbb{B}, z \in \mathbb{Z}, y > 1 \end{cases} \quad (\text{S14})$$

The terms N_{pzy}^{PC} and $N_{bzz'y}^{\text{B}}$ denote the total quantity of processing technologies at the industrial-scale in zone z and transporting infrastructures linking zones z and z' , respectively; terms N_{pz}^{EPC} and $N_{bzz'}^{\text{EB}}$ represent the quantity of existing processing technologies at the industrial-scale and transporting infrastructures, respectively; NI_{pzy}^{PC} and NI_{pzy}^{PC} are the quantity of additional processing technologies at the industrial-scale and transporting infrastructures installed at the start of planning period y , respectively; NR_{pz}^{EPC} corresponds to the quantity of existing processing technologies at the industrial-scale that retired during planning period y ; and NR_{pzy}^{PC} is the quantity of processing technologies at the industrial-scale that retired at the start of planning period y , which is expressed below as:

$$NR_{pzy}^{\text{PC}} = \sum_{y'} RF_{py'y}^{\text{P}} NI_{pzy}^{\text{PC}} \quad \forall p \in \mathbb{P}^C, z \in \mathbb{Z}, y \in \mathbb{Y} \quad (\text{S15})$$

S1.3 Bidirectionality of transporting infrastructures

By setting the parameter β_b , the model can be able to designate bidirectional and unidirectional links of transporting infrastructures. When $\beta_b = -1$, the link is unidirectional and can only be built in a single direction (e.g. pipelines for CO_2). When $\beta_b = 0$, the link is unidirectional, however, two separate connections can be built in opposite directions (e.g. roads, railways) – each link is independent from the other; hence, a bidirectional link of this type costs twice as much as a single link. When $\beta_b = 1$, then a single bi-directional link can be provided (e.g. electricity transmissions lines, pipelines for natural gas, hydrogen, etc.). Note that in the case studies of the model, the transporting infrastructures were assumed to have single bi-directional links. Nevertheless, the constraints for bidirectional and unidirectional infrastructures are shown by Eqs. S16 and S17, respectively:

$$N_{bzz'y}^B = N_{bz'zy}^B \quad \forall b \in \mathbb{B} | \beta_b = 1, z \neq z' \in \mathbb{Z} \quad (\text{S16})$$

$$N_{bzz'y}^B + N_{bz'zy}^B \leq 1 \quad \forall b \in \mathbb{B} | \beta_b = -1, z \neq z' \in \mathbb{Z} \quad (\text{S17})$$

S2 Further optimisation results from the case studies

The detailed description and assumptions for the three Philippine case studies developed using the RVC model are discussed in Subsection S2.1. Subsections S2.2, S2.3 and S2.4 presents further optimisation results in support to the discussion in Section 6 of the Manuscript. Each subsection also includes a summary of implications of the case study results. The results of the sensitivity analysis of the operational parameters of the RVC model are reported in Subsection S2.5.

S2.1 Case studies

The optimisation model assessed the economic and environmental feasibility of current and multi-product RVCs according to the following case studies:

Case 1: RVCs are solely for food production. (Base case, see Subsection 6.1 of the Manuscript.)

The maximum available farmlands in each province, except Metro Manila, and the whole country were considered in the planning. Both paddy rice and white are to be transported by truck and barges through available transporting infrastructures. The effects of losses in transporting resources and inclusion of available farmlands in Metro Manila (zone 23) were not yet considered.

Case 2: RVCs wherein production of energy is integrated with food production. (See Subsection 6.2 of the Manuscript.)

Food (white rice) demand is to be completely (100%) satisfied, while 10% of the grid electricity demand (10 times of the current levels satisfied by biomass-based power) set compulsory and the rest (90%) set optional are both to be satisfied by bio-electricity. Similar to transporting grains, rice husk, rice straw and their pelletised forms are to be transported. Losses in transporting resources was set to 20%.

Case 3: RVCs wherein production of energy, fuels and chemicals are integrated with food production. (See Subsection 6.3 of the Manuscript.)

Demand for white rice is to be completely satisfied, while each demand (at the current levels) for bio-electricity, bioethanol, bio-FT jet, bio-FT diesel and bio-naphtha is to be compulsory at 10% and optional at 90%. The transport (with losses of 20%) of grains (paddy rice and white rice) and crop residues (rice straw and rice husk and their pelletised forms) were considered.

In each case study, optimal results in the maximise net present value (NPV) scenario and the minimise greenhouse gas (GHG) emissions scenario were compared in terms of allocated area of farmlands for paddy rice production, location and number of processing technologies built, and operation of transport network for food and/or non-food products. The size of the optimisation model depends on the case study but typically the problems consisted of 41,000 to 63,000 variables (about 1,200 were integers) and approximately 90,000 constraints. Solutions converge quickly from 1 to 16 s also depending on the case study. The following are additional data and conditions assumed in the case studies:

1. There is a single season only because, on average, rice farming occurs all-year round based on Philippine cropping calendar ([PhilFSIS, 2018](#)).
2. The paddy rice yield and white rice consumption was assumed constant within the planning period based as shown in Figure [S1](#). While population growth could drive the increase in rice consumption, the diversification of diet, income increase and urbanisation could counterbalance this ([Dawe et al., 2014](#)).
3. Discount rate of 10% was based on the recommend value set by the National Economic Development Administration (NEDA), Republic of the Philippines ([Dominguez and Pernia, 2016](#)).
4. Finance rate of 4.5% was based on the lending rates set by the Central Bank of the Philippines ([BSP, 2018](#)).
5. Marketing gross margins and all other market intermediary costs were not taken into account in the case studies.
6. Planned installments and retirements of the technologies were not included in the scope of the case studies.
7. Electricity used in operating processing technologies was imported and sufficient in supply via the local grid in each province.
8. Impact of technologies for storage was not included. There are also only a few storage facilities available for rice farmers in the Philippines ([Mopera, 2016](#)).
9. Physical losses incurred in transporting crop residues are similar to those incurred in transporting grains.
10. Capacities of transporting technologies (truck and barges) and transporting infrastructures (road and waterways networks) were not a limiting factor in any of the optimal value chains. Hence, only sensible (sufficiently large) estimates of the maximum transport rates were required. Furthermore, no investments and retirements of the infrastructures were involved in the case studies.

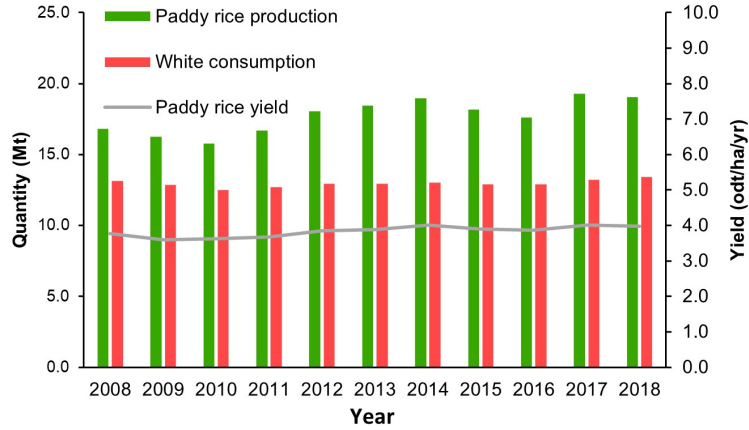


Figure S1: Production of paddy rice, yield of paddy rice and consumption of white rice in the Philippines from 2008 to 2018. (Plotted using available data on area harvested (PSA, 2019) and paddy rice production (PSA, 2020) both from the Philippine Statistics Office and on white rice consumption (IRRI, 2018) from the International Rice Research Institute.)

S2.2 Further optimisation results from the case study on food production only

S2.2.1 Full rice self-sufficiency of the Philippines

As reported in Subsection 6.1 of the Manuscript, the Philippines can be fully rice self-sufficient without needing to farm rice crops all over the country. Tables S1 and S2 show the farmland characteristics of optimal locations selected for paddy rice production determined in the maximise NPV scenario and the minimise GHG emissions scenario, respectively.

Table S1: Farmland characteristics of the optimal locations of paddy rice production in the maximise NPV scenario.

Maximise NPV scenario				
Province	Zone	Unit economic impact (PhP/odt)	Allocated area of farmlands (kha)	No. of rice mill built
Bukidnon	69	11.33	317.00	83
Nueva Ecija	17	9.97	313.45	97
Isabela	3	12.41	278.00	70
Negros Occidental	45	9.63	273.30	60
Cotabato	68	11.58	245.00	55
Camarines Sur	30	9.82	243.00	52
Iloilo	43	11.65	236.83	43
Maguindanao	78	11.57	195.00	29
Leyte	54	9.49	158.00	37
Sultan Kudarat	67	11.80	152.00	33
Zamboanga del Sur	76	11.33	139.00	34
South Cotabato	66	11.59	122.00	27
Albay	31	9.36	108.00	24
Camarines Norte	29	9.62	104.00	23
Sorsogon	32	9.14	102.00	24
Lanao del Norte	72	11.56	99.00	26
Capiz	41	12.42	92.51	16
Pampanga	19	11.66	91.82	25
Occidental Mindoro	38	11.58	86.30	21
Bulacan	22	12.00	80.73	21
Lanao del Sur	77	11.65	79.00	12
Antique	42	10.34	77.05	16
Agusan del Norte	58	11.79	69.00	14
Ilocos Norte	12	12.41	65.83	18
Nueva Vizcaya	5	12.48	62.21	16
Laguna	26	10.85	50.00	12
Misamis Occidental	73	12.15	42.00	11
Southern Leyte	55	9.09	39.00	10
Catanduanes	33	12.38	38.00	7
Kalinga	9	10.94	37.00	9
Aklan	40	11.92	32.80	6
Tarlac	18	12.68	31.75	8
Rizal	24	11.44	20.00	5
Biliran	50	8.39	16.00	5
La Union	14	12.74	10.14	3

Table S2: Farmland characteristics of the optimal locations of paddy rice production in the minimise GHG emissions scenario.

Minimise GHG emissions scenario				
Province	Zone	Unit environmental impact (tCO ₂ e/odt)	Allocated area of farmlands (kha)	No. of rice mill built
Bukidnon	69	0.6879	317.00	83
Nueva Ecija	17	0.5788	313.45	97
Isabela	3	0.7129	278.00	70
Pangasinan	15	0.7299	260.64	64
Negros Occidental	45	0.8122	238.69	53
Davao del Sur	64	0.7048	216.00	55
Cagayan	2	0.7925	194.76	44
Leyte	54	0.7650	158.00	37
Compostela Valley	61	0.7513	157.00	38
Zamboanga del Sur	76	0.7487	139.00	34
Tarlac	18	0.7364	133.78	33
Albay	31	0.8028	108.00	24
Davao del Norte	63	0.7561	104.00	25
Sorsogon	32	0.7842	102.00	24
Misamis Oriental	70	0.7880	101.00	23
Lanao del Norte	72	0.7018	99.00	26
Davao Oriental	62	0.6910	98.00	26
Pampanga	19	0.6772	91.82	25
Occidental Mindoro	38	0.7500	86.30	21
Bulacan	22	0.6969	80.73	21
Ilocos Norte	12	0.6615	65.83	18
Nueva Vizcaya	5	0.7170	62.21	16
Laguna	26	0.7432	50.00	12
Ilocos Sur	13	0.7097	47.86	13
Quirino	4	0.7936	43.00	10
Misamis Occidental	73	0.7376	42.00	11
Southern Leyte	55	0.7327	39.00	10
La Union	14	0.6793	38.30	11
Kalinga	9	0.7462	37.00	9
Bataan	21	0.7722	30.39	8
Rizal	24	0.7836	20.00	5
Biliran	50	0.6766	16.00	5
Camarines Norte	29	0.8256	8.65	2
Camiguin	71	0.7811	6.00	2

S2.2.2 Effect of including farmlands of Metro Manila in the planning

Metro Manila (zone 23) is historically reported with little to no rice farming ([Tepora, 2018](#)). However, there are about 20 kha of farmlands available ([Bersales, 2018](#)). When these available farmlands are included in the planning, the entire area is allocated to rice farming. This allocation of farmlands in Metro Manila (zone 23) resulted in a reduction of the allocated farmlands in zone 18 (Tarlac) by 60% in the maximise NPV scenario (Figure [S2a](#)); while in the minimise GHG emissions scenario, the reduction of allocated farmlands are in zones 29 (Camarines Norte) by 100% (no rice farming occurs in this zone) and 45 (Negros Occidental) by 5% (Figure [S2b](#)). The total area of farmlands allocated for rice farming are 4.11 Mha and 3.78 Mha

in the maximise NPV scenario and the minimise GHG emissions scenario, respectively, which are similar to the results in the planning without including the farmlands of Metro Manila (see Subsection 6.1 of the Manuscript).

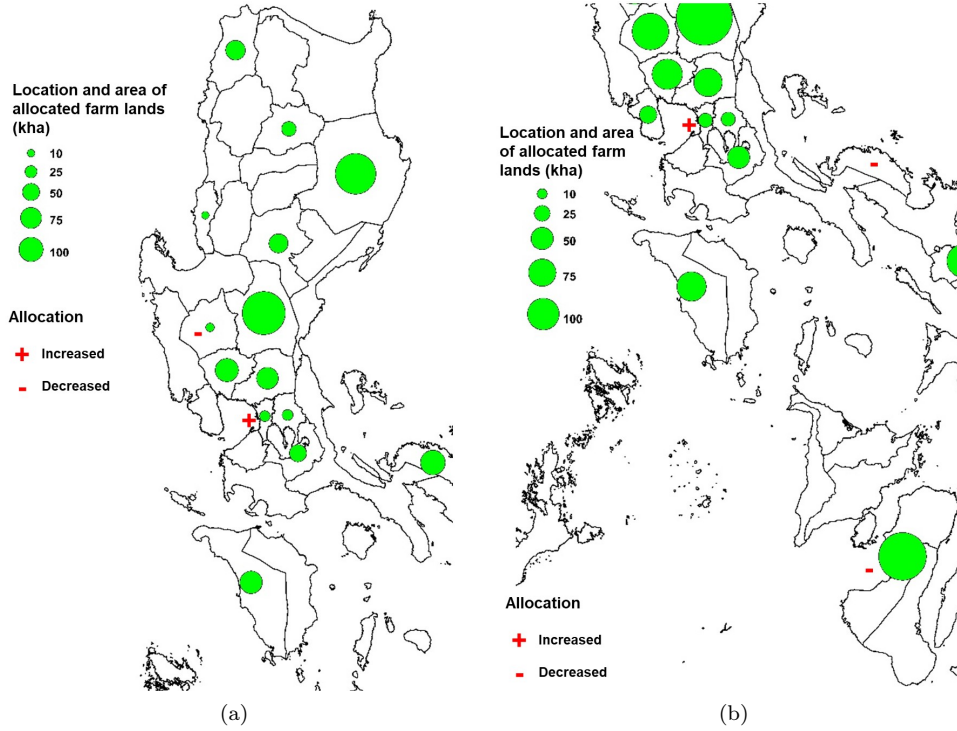


Figure S2: Effect of including farmlands of Metro Manila (zone 23) in the planning: (a) Reduction of area for allocated farmlands in zone 18 in the maximise NPV scenario; and (b) Reduction of area for allocated farmlands in zones 29 and 45 in the minimise GHG emissions scenario. There were no changes in the regions not shown. (See Figure 3 in the Manuscript for zone numbers.)

The total number of rice mill facilities built in both scenarios is the same as when Metro Manila (zone 23) is not included in the planning (Figures 7b and 8b). In the planning wherein its entire farmlands are completely allocated for rice farming, five rice mill facilities are to be built in zone 23 for both scenarios. Correspondingly, the number of rice mill facilities built in Tarlac (zone 18) was reduced by five in the maximise NPV scenario relative to the planning without the available farmlands of Metro Manila (zone 23); while the number of rice mills built was decreased by three in Negros Occidental (zone 45) and two in Camarines Norte (zone 29) in the minimise GHG emissions scenario.

Relative to the transport networks shown in Figures 7c, 7d and 8d, the operation of the transport of white rice by barge and truck in the maximise NPV scenario as well as with the transport by truck in the minimise GHG emissions scenario did not change with the allocation of the farmlands in Metro Manila for rice farming. However, the operation of transport of white rice by barge in the minimise GHG emissions scenario shown in Figure S3 had changes in the routes of transporting white rice relative to Figure 8c. A new route from zone 2 (Cagayan) to zone 29 (Camarines Norte) was established to deliver white rice as there are no farmlands allocated for rice farming in the terminal zone. Corresponding adjustments in the transport rate of white

rice resulted in longer old routes from zone 61 (Compostela Valley) to zone 34 (Masbate) and zone 70 (Misamis Oriental) to 35 (Romblon) being replaced with shorter new routes from zone 32 (Sorsogon) to zone 34 (Masbate) and from zone 38 (Occidental Mindoro) to zone 35 (Romblon).

When the farmlands of Metro Manila (zone 23) were allocated in this planning, the NPV is PhP 2.50 tn (USD 40.26 bn) and GHG emissions is 427 MtCO₂e in the maximise NPV scenario while the NPV is PhP 2.37 tn (USD 37.43 bn) and 394 MtCO₂e in the minimise GHG emissions scenario. These NPV and GHG emissions are not significantly different to the optimal results in both scenarios shown in Figure 6a. The levelised cost of white rice are PhP 5.82/kg and PhP 6.22/kg in the maximise NPV scenario and the minimise GHG emissions scenario, respectively, which are the same values presented in Figure 6b. These results imply that including Metro Manila (zone 23) in the operation of the optimal RVCs could have little to no impact in the costs and GHG emissions. The optimal RVCs could also efficiently supply white rice demand of zone 23 (Metro Manila) as it is the highest for the country. Thus, Cases 2 and 3 considered the available farmlands of Metro Manila (zone 23) in their planning.

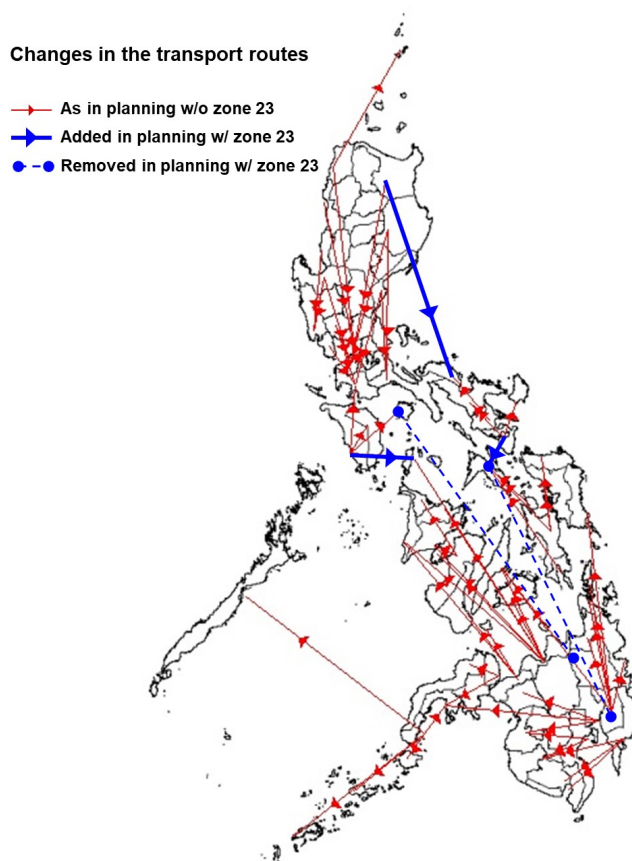


Figure S3: Effect of including the farmlands of Metro Manila (zone 23) in the planning (cont.): Operation of transport by barge for white rice in the minimise GHG emissions scenario. (See Figure 3 in the Manuscript for zone numbers.)

S2.2.3 Effect of transport losses in the planning

Losses in rice during its distribution, which range from 10% to 40%, have been attributed to underperforming transport and lack of infrastructures in the country (Mopera, 2016). The effect of losses in transporting white rice to the total area of farmlands allocated for rice farming and number of provinces with rice farming is shown in Figures S4a and S5a. In the maximise NPV scenario, the number of provinces that need to grow paddy rice increased from 35 to 79 (total area of 5.02 Mha or 61% of available) as the transport losses increased from 0% to 10%. Similarly, the number of provinces increased from 34 to 74 (total area of 4.85 Mha or 59% of available) in the minimise GHG emissions scenario. In both scenarios, increase in transport losses also corresponded to decrease in NPV and increase in GHG emissions (Figures S4b and S5b). At transport losses of 40%, NPV reduced by 18% to PhP 2.05 tn (USD 38.87 bn) and GHG emissions grew by 22% to 519 MtCO₂e in the maximise NPV scenario, and in the minimise GHG emissions scenario, NPV reduced by 19% to PhP 1.91 tn (USD 36.29 bn) and GHG emissions grew by 28% to 502 MtCO₂e. These results confirm that food losses due to lack of infrastructure and inefficient logistics translate to unnecessary economic losses and environmental costs as more farmlands are needed to compensate for the wasted grains. Therefore, the improvement of the midstream and downstream components of the conventional RVCs is essential for the efficient and sustainable provision of food for the Philippines. In order to reflect the current inefficiencies of the transport and logistics systems of the Philippines, Cases 2 and 3 included 20% transport losses in their planning

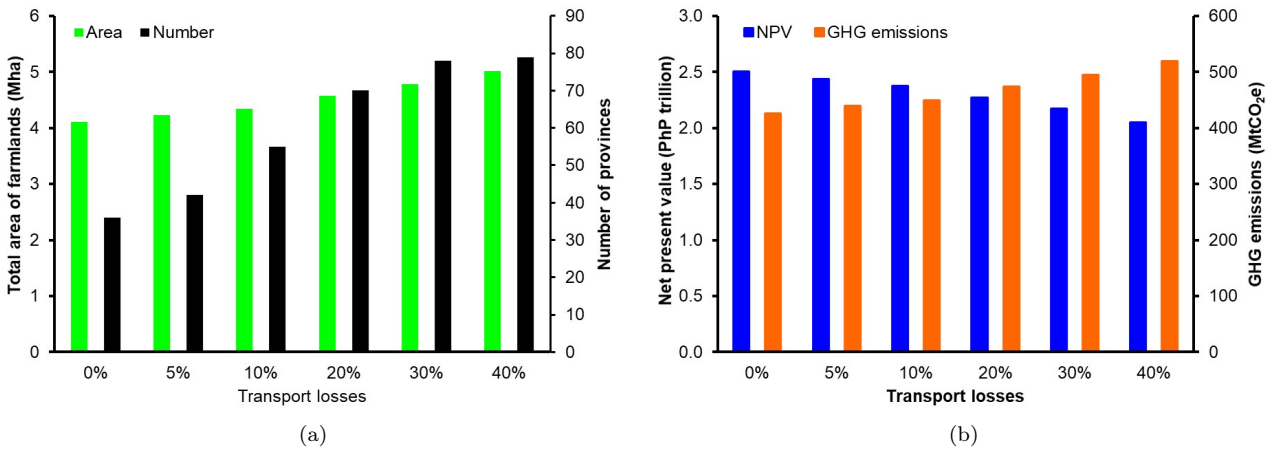


Figure S4: Effect of transport losses on the food-only rice value chains in the maximise NPV scenario: (a) Total area of farmlands and number of provinces; and (b) Net present value and GHG emissions.

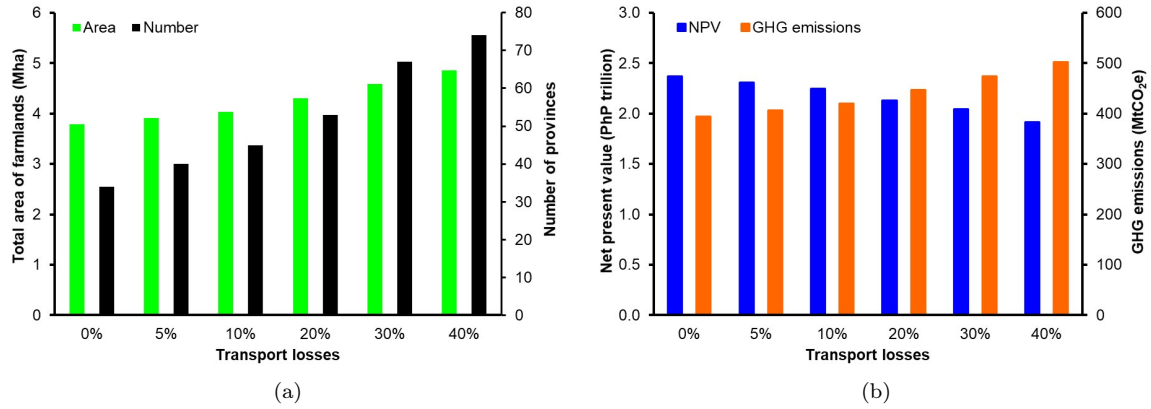


Figure S5: Effect of transport losses on the food-only rice value chains in the minimise GHG emissions scenario: (a) Total area of farmlands and number of provinces; and (b) Net present value and GHG emissions.

Based on the results presented here and discussed for Case 1, systematic and holistic planning, design and operation of conventional RVCs in the Philippines can potentially result in ‘full’ self-sufficiency even without further expansion of existing farmlands, overall cost reduction in rice provision, and environment-friendly food distribution. These would imply the following to the country’s rice industry:

1. More strategic decision-making is needed when locating and allocating productive farmlands for rice farming;
2. Investments in improving the transport and logistics system must be prioritised that would facilitate efficient and sustainable distribution of food; and
3. Shift in the policy objectives from achieving rice self-sufficiency towards increasing total farm productivity is needed through product diversification.

S2.3 Further optimisation results from the case study on integrated food-energy production

Table S3 is the summary of the optimisation results in both the maximise NPV scenario and the minimise GHG emissions scenario for Case 2. Figures S6a and S6b illustrate the operation of transport by barge for paddy rice and white rice, respectively, in the maximise NPV scenario and Figures S7a and S7b illustrate the operation of transport by barge for paddy rice and white rice, respectively, in the minimise GHG emissions scenario.

Based on the results presented here and discussed for Case 2, these are potential implications of integrated food-energy production RVCs for the Philippines:

1. Integrated food-energy RVCs would be economically and environmentally beneficial.

There has been a bioenergy resource assessment on rice crop residues in the Philippines (Elauria et al., 2005). However, the profitability and sustainability of a jointly production of food and energy has been proven for the first time using a comprehensive and data-driven model.

2. Production of bio-electricity from paddy rice would not compete with food production.

Since the availability and sufficiency of land is a major issues for bioenergy production; so a successful synergistic food and bioenergy production is highly preferred in the long-term (Souza et al., 2017). Through Case 2, energy production integrated with food production in the Philippine RVCs has been shown to be possible with little to no land expansion when designed, operated and managed efficiently.

3. Managing ash produced from combustion of rice crop residues would be crucial.

Considering the ash content of rice straw (19%) and rice husk (20%), slagging and fouling is expected that reduce heat transfer efficiency and pose maintenance issues of combustion systems (Yao et al., 2017). Rice husk ash is less corrosive due to its lower alkali and chloride content than rice straw ash (Yao and Xu, 2015), but variability of composition, operating temperature and combustion device have to be considered (Horák et al., 2019). These solid wastes when not disposed properly may also have adverse environmental effects (Moraes et al., 2014). Their pozzolanic characteristics make them as potential cement filler, which is a waste management strategy and an additional source of income (Prasara-A and Gheewala, 2017).

4. Accelerating the development and commercialisation of biomass-based electricity production is needed.

While there are rice husk-based power plants (PH DOE, 2017), there are no known rice straw-based power plants built. With vast amounts of rice straw are underutilised (Mendoza, 2015), it can become a key feedstock in meeting at least 10% of the national electricity demand as demonstrated in Case 2 (at 90% utilisation rate). Alternatively, the vast amounts of rice crop residues could be utilised for co-firing in several existing coal power plants of the country (PH DOE, 2019). The benefits of this option are reduced capital costs, less dependence on fossil fuels, decreased net GHG emissions and decreased emissions of air pollutants (Xu et al., 2020), which could be integrated and explored as future work using the model. Co-firing of crop residues with coal having high aluminium and silicon content has also been found to remedy ash-related problems of biomass fuels (Madhiyanon et al., 2020).

5. Protection and conservation of water resources and ecosystems must be considered.

Since rice farming is a known water-intensive activity (Sims et al., 2015); so the impact on water systems can be potentially exacerbated by RVCs with integrated food-energy production. Biomass power plants consume fresh water for steam generation and discharge wastewater (Chungsangunsit et al., 2005). The richly biodiverse Philippine marine ecosystems, but highly under threat, are also at risk from extensive operation of barges shown in Case 2. Shipping has comprehensively been shown to have significant cumulative impacts on global marine ecosystems (Halpern et al., 2015).

Table S3: Summary of the optimisation results for integrated food-energy production rice value chains.

Description	Maximise NPV scenario	Minimise GHG emissions scenario
Total allocated land area for paddy rice production (Mha)	4.59	4.31
Percentage of total allocated to total available farmlands	56%	52%
Satisfied bio-electricity demand (TWh)	11.01	11.60
Percentage of satisfied demand to total bio-electricity demand	12%	13%
Total rice straw produced (M odt)	11.17	11.49
Percentage of rice straw utilised to total	96%	94%
Total rice husk produced (M odt)	3.33	3.41
Percentage of rice husk utilised to total	91%	92%
Total no. of processing technologies built	1113	1135
Rice mill	961	993
Gasification	-	9
FT jet synthesis	-	6
CCGT	-	3
Boiler-steam turbine	152	124
Overall economic impact (PhP tn)	2.40	2.97
Overall utilising resource economic impact (PhP tn)	2.12	2.24
Overall importing resource economic impact (PhP tn)	0.04	0.04
Overall processing technologies capital economic impact (PhP tn)	0.13	0.41
Overall processing technologies fixed O&M economic impact (PhP tn)	0.07	0.21
Overall transporting technologies operating economic impact (PhP tn)	0.03	0.06
Overall revenue (PhP tn)	5.24	5.28
NPV (PhP tn)	2.84	2.31
Levelised cost of white rice (PhP/kg)	6.93	8.38
Overall environmental impact (MtCO ₂ e)	582	560
Overall utilising resource environmental impact (MtCO ₂ e)	456	429
Overall importing resource environmental impact (MtCO ₂ e)	7	8
Overall processing technologies capital environmental impact (MtCO ₂ e)	44	45
Overall processing technologies fixed O&M environmental impact (MtCO ₂ e)	70	72
Overall transporting technologies operating environmental impact (MtCO ₂ e)	5	6
Overall environmental impact displaced (MtCO ₂ e)	209	220
GHG emissions (MtCO ₂ e)	373	3400

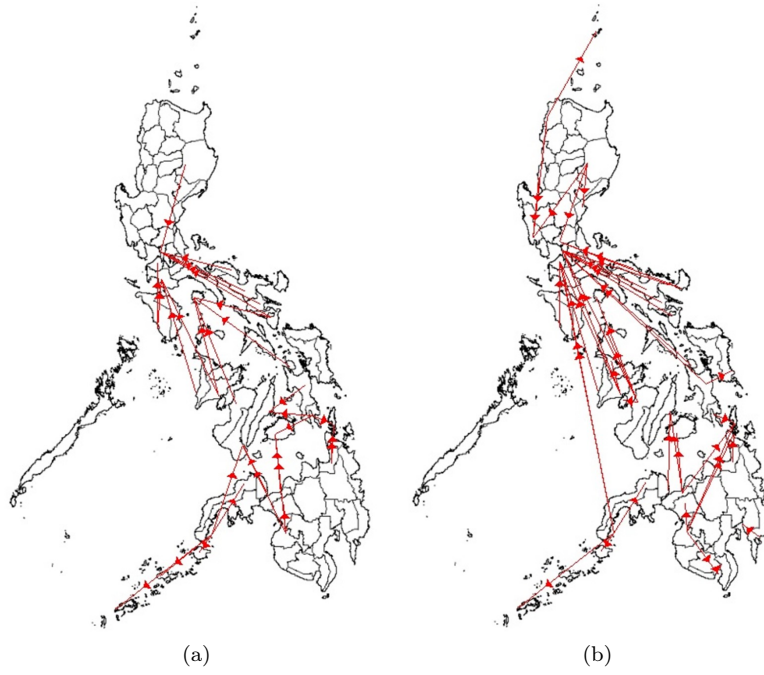


Figure S6: Optimal results for integrated food-energy production in the maximise NPV scenario (cont.): (a) Operation transport by barge for paddy rice; and (b) Operation transport by barge for white rice. (See Figure 3 in the Manuscript for zone numbers.)

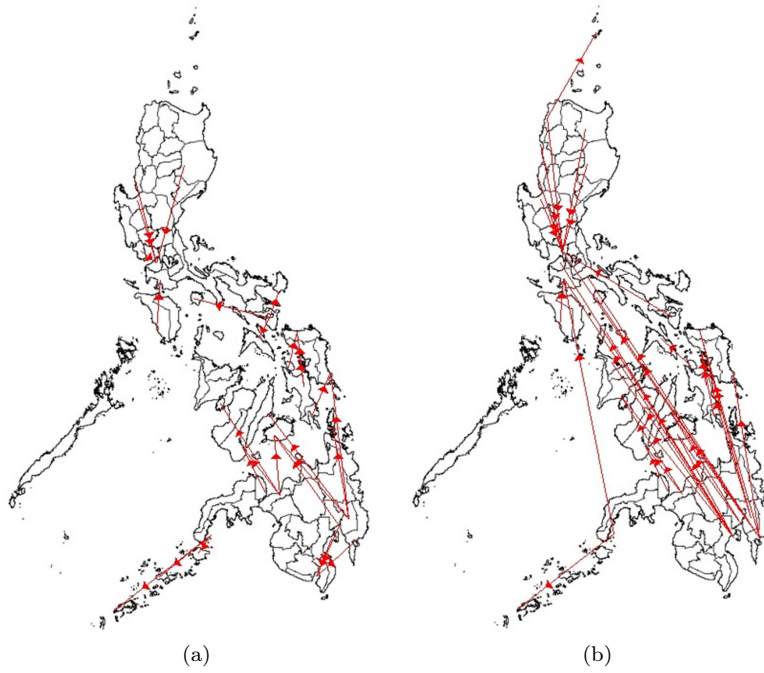


Figure S7: Optimal results for integrated food-energy production in the minimise GHG emissions scenario (cont.): (a) Operation transport by barge for paddy rice; and (b) Operation transport by barge for white rice. (See Figure 3 in the Manuscript for zone numbers.)

S2.4 Further optimisation results from the case study integrated food-energy-fuels-chemicals production

Table S4 is the summary of the optimisation results in both the maximise NPV scenario and the minimise GHG emissions scenario for Case 3. Figures S8a and S8b illustrate the operation of transport by barge for paddy rice and white rice, respectively, in the maximise NPV scenario and Figures S9a and S9b illustrate the operation of transport by barge for paddy rice and white rice, respectively, in the minimise GHG emissions scenario.

Based on the results presented here and discussed for Case 3, these are potential implications of RVCs with integrated production of food-energy-fuels-chemicals for the Philippines:

1. Integrated production of energy, fuels and chemicals is highly likely to compete with food production in the Philippines.

Since the priority of the RVCs shifted from food production to non-food production; so, more paddy rice is cultivated primarily for the crop residues instead of the grains. With about 70% of total farmlands allocated for rice farming in Case 3, competition with farmlands needed for other major staples will result.

2. Export of surplus paddy rice and/or white rice could be additional source of revenue for Philippine rice farmers.

Considering there was more grains produced than needed by the country in Case 3, exporting these can potentially improve the economic performance of the RVCs. However, the environmental and economic impacts associated have to be accounted for in the overall impact.

3. Homegrown processing technologies is needed by the country.

Capital economic impact of processing technologies had the second largest share in the overall cost. Since capital investment is a barrier to the feasibility of a renewable energy project (Brahim, 2014); so locally researched and developed biomass conversion technologies can potentially reduce costs.

4. Sequestration of GHG emissions from extensive rice farming and deployment of processing technologies is a crucial mitigation measure.

Rice cultivation must reduce water use in irrigation and post-harvest processing must increase use of renewable and/or low carbon energy sources (e.g. solar, wind, bio-electricity, biofuels) (Maraseni et al., 2018). Biomass conversion technologies with carbon capture and storage can potentially have negative GHG emissions. However, these technologies are high-cost and overly dependent on the operation and design of the value chains (Fajardy and Mac Dowell, 2017).

Table S4: Summary of the optimisation results for integrated food-energy-fuels-chemicals production rice value chains.

Description	Maximise NPV scenario	Minimise GHG emissions scenario
Total allocated land area for paddy rice production (Mha)	7.16	7.43
Percentage of total allocated to total available farmlands	87%	900%
Satisfied bio-electricity demand (TWh)	9.08	9.08
Percentage of satisfied demand to total bio-electricity demand	10%	10%
Satisfied bioethanol demand (TWh)	0.18	0.18
Percentage of satisfied demand to total bioethanol demand	10%	10%
Satisfied bio-FT jet demand (TWh)	5.23	5.44
Percentage of satisfied demand to total bio-FT jet demand	18%	19%
Satisfied bio-FT diesel demand (TWh)	11.50	11.97
Percentage of satisfied demand to total bio-FT diesel demand	10%	10%
Satisfied bio-naphtha demand (TWh)	4.18	4.35
Percentage of satisfied demand to total bio-naphtha demand	24%	25%
Total rice straw produced (M odt)	17.12	18.12
Percentage of rice straw utilised to total	92%	92%
Total rice husk produced (M odt)	5.23	5.33
Percentage of rice husk utilised to total	97%	92%
Total no. of processing technologies built	1872	1884
Rice mill	1509	1526
Lignocellulosic fermentation	81	81
Gasification	82	82
FT jet synthesis	22	2
CCGT	81	81
Boiler-steam turbine	97	112
Overall economic impact (PhP tn)	10.51	10.42
Overall utilising resource economic impact (PhP tn)	3.43	3.65
Overall importing resource economic impact (PhP tn)	0.13	0.13
Overall processing technologies capital economic impact (PhP tn)	4.52	4.30
Overall processing technologies fixed O&M economic impact (PhP tn)	2.37	2.25
Overall transporting technologies operating economic impact (PhP tn)	0.05	0.09
Overall revenue (PhP tn)	5.88	5.91
NPV (PhP tn)	-4.62	-4.51
Levelised cost of white rice (PhP/kg)	19.34	18.79
Overall environmental impact (MtCO ₂ e)	1236	1155
Overall utilising resource environmental impact (MtCO ₂ e)	712	740
Overall importing resource environmental impact (MtCO ₂ e)	23	23
Overall processing technologies capital environmental impact (MtCO ₂ e)	190	147
Overall processing technologies fixed O&M environmental impact (MtCO ₂ e)	303	236
Overall transporting technologies operating environmental impact (MtCO ₂ e)	8	90
Overall environmental impact displaced (MtCO ₂ e)	351	358
GHG emissions (MtCO ₂ e)	885	797

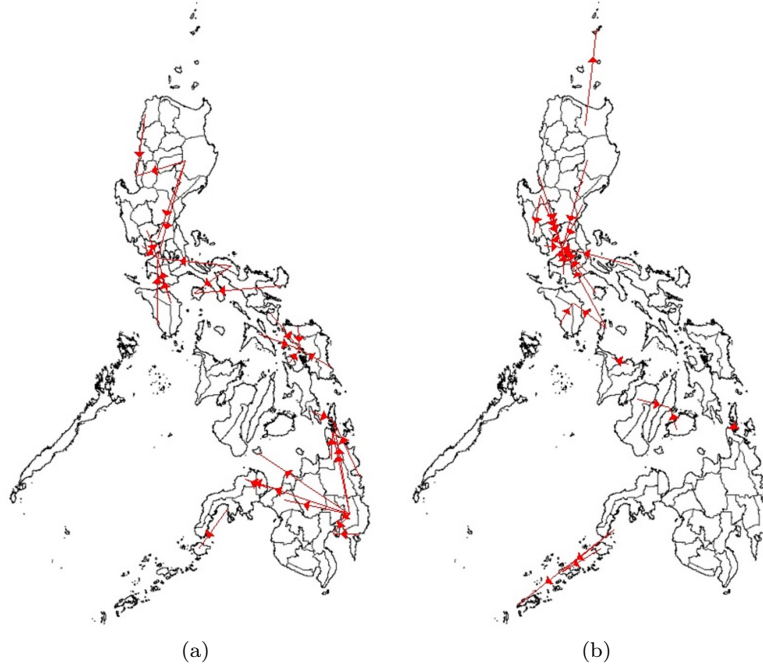


Figure S8: Optimal results for integrated food-energy-fuels-chemicals production in the maximise NPV scenario (cont.): (a) Operation transport by barge for paddy rice; and (b) Operation transport by barge for white rice. (See Figure 3 in the Manuscript for zone numbers.)

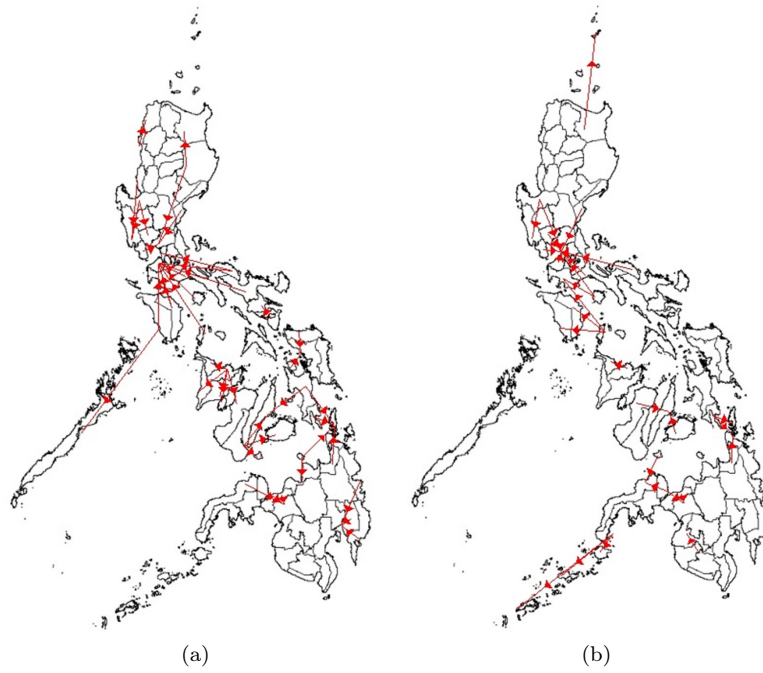


Figure S9: Optimal results for integrated food-energy-fuels-chemicals production in the minimise GHG emissions scenario (cont.): (a) Operation transport by barge for paddy rice; and (b) Operation transport by barge for white rice. (See Figure 3 in the Manuscript for zone numbers.)

S2.5 Sensitivity analysis

This section presents the sensitivity analysis to understand the influence of uncertain input parameters to the operational parameters of the RVC model. Biomass feedstock production rates for paddy rice and straw, processing rates for rice milling and biomass conversion and transporting rates for grains and crop residues were the operational parameters studied. The input parameters varied (one at a time) are paddy rice yield, paddy rice production (or rice farming) cost, processing technologies cost and transporting technologies cost. The range of variation of the input parameters was $\pm 20\%$ of collected data (see accompanying Data in Brief article). The sensitivity analysis is conducted on the maximise NPV scenario of Case 2 (RVCs with integrated food-energy production), which was modelled 40 more times in this investigation.

S2.5.1 Effect of variation in paddy rice yields

Paddy rice yield relates to the area of farmlands allocated for rice farming and to the volume of rice crop production. As depicted in Figure S10a, the variation in paddy rice yield have little to no impact on paddy rice and rice straw production rates which was compensated by the allocated area of farmlands. The results indicate that as long as there is sufficient farmlands biomass production rate will not be disrupted. The variation in paddy rice yield also have little to no impact on biomass conversion rate as shown in Figure S10b. However, there is a moderate decreasing effect on the rice milling rate as paddy rice yield increases also shown in Figure S10b, which means there is a modest decrease in the total number of rice mills built. Since there are more paddy rice as yield increases, so its transport rates by barge and truck generally increase (Figure S10c). In contrast, there is a general downward trend for transporting rates by barge and truck for white rice (Figure S10c), which could mean more zones are white rice self-sufficient at higher paddy rice yields. Variation on paddy rice yield show more influence on the transporting rate by barge for crop residues than on its transporting by truck (Figure S10d). A downward trend is shown by the transporting rate by barge for rice husk, which could suggest the more rice husk self-sufficiency of zones at increased paddy rice yields. An upward trend is shown by the transporting rate by barge for rice straw, which could suggest more rice straw must be distributed at higher paddy rice yields.

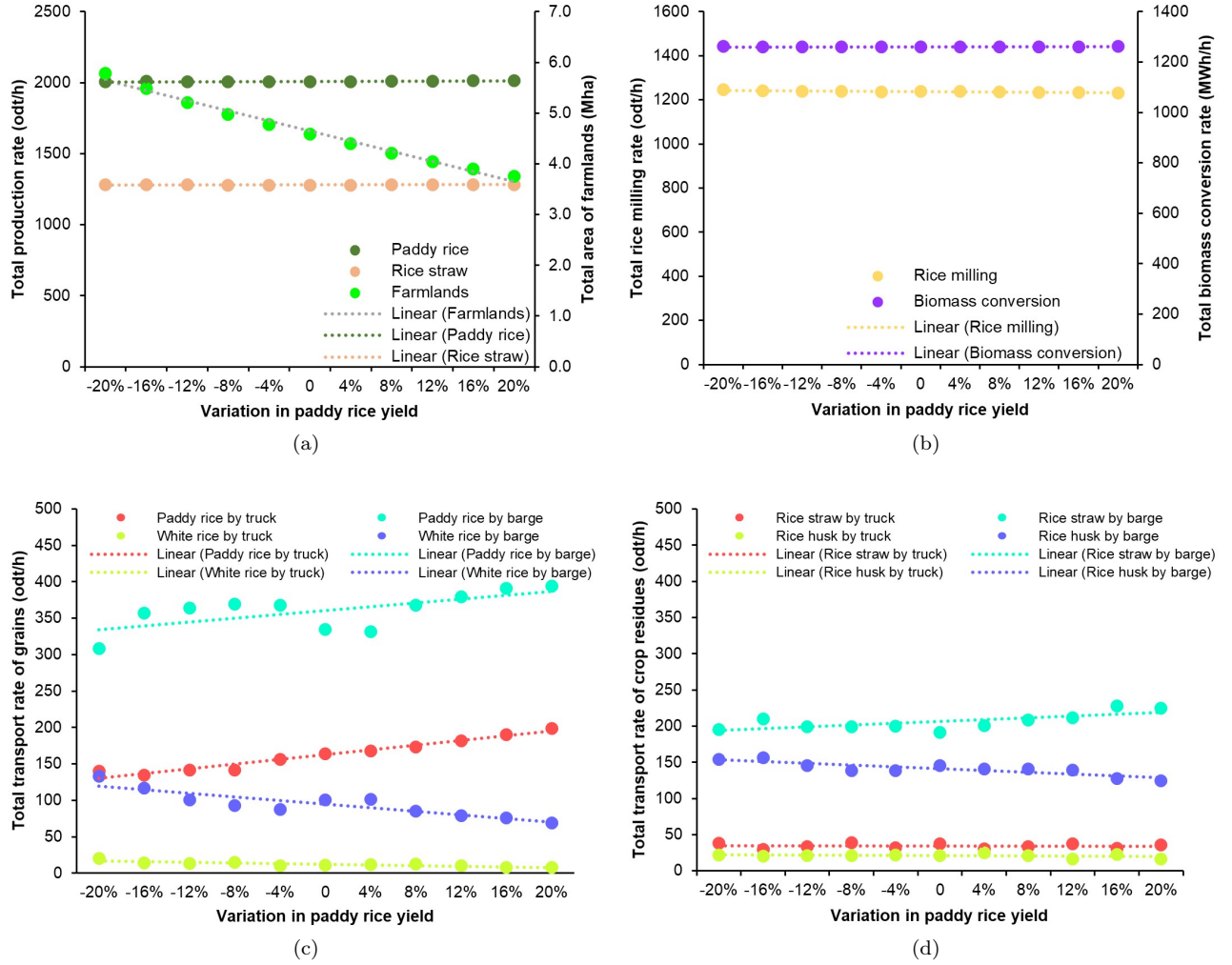


Figure S10: Sensitivity of operating parameters to variation in paddy rice yield: (a) Biomass feedstock production rates, (b) Processing rates, (c) Grains transporting rates, and (d) Crop residues transporting rates.

S2.5.2 Effect of variation in paddy rice production cost

Rice farming cost is expected to affect the volume of crop production and economic performance of the rice value chains. Results reveal production rates for paddy and rice straw and processing rates for rice milling and biomass conversion have little to no sensitivity to variation in the rice farming cost as shown in Figures S11a and S11b, respectively. Within this variation range of the rice farming cost, the rice value chains are performing economically favourable. Given that Case 2 is the integrated production of food and energy, the sale of bio-electricity balances the losses in profit from more expensive white rice whilst still meeting 100% of the demand. The transporting rates by barge for grains and crop residues are sensitive to the rice farming cost as depicted in Figures S11c and S11d, respectively. In contrast, rice farming cost has little to no impact on the transport rates by truck for grains and crop residues as depicted also in Figures S11c and S11d, respectively. The downward trend of the transport rates by barge for paddy rice and rice straw could

be attributed to decreasing amount of rice crop produced due to increasing rice farming cost. The upward trend of the transporting rates by barge for white rice and rice husk could suggest the reduced self-sufficiency of zones due to relatively lower quantity of rice crop produced.

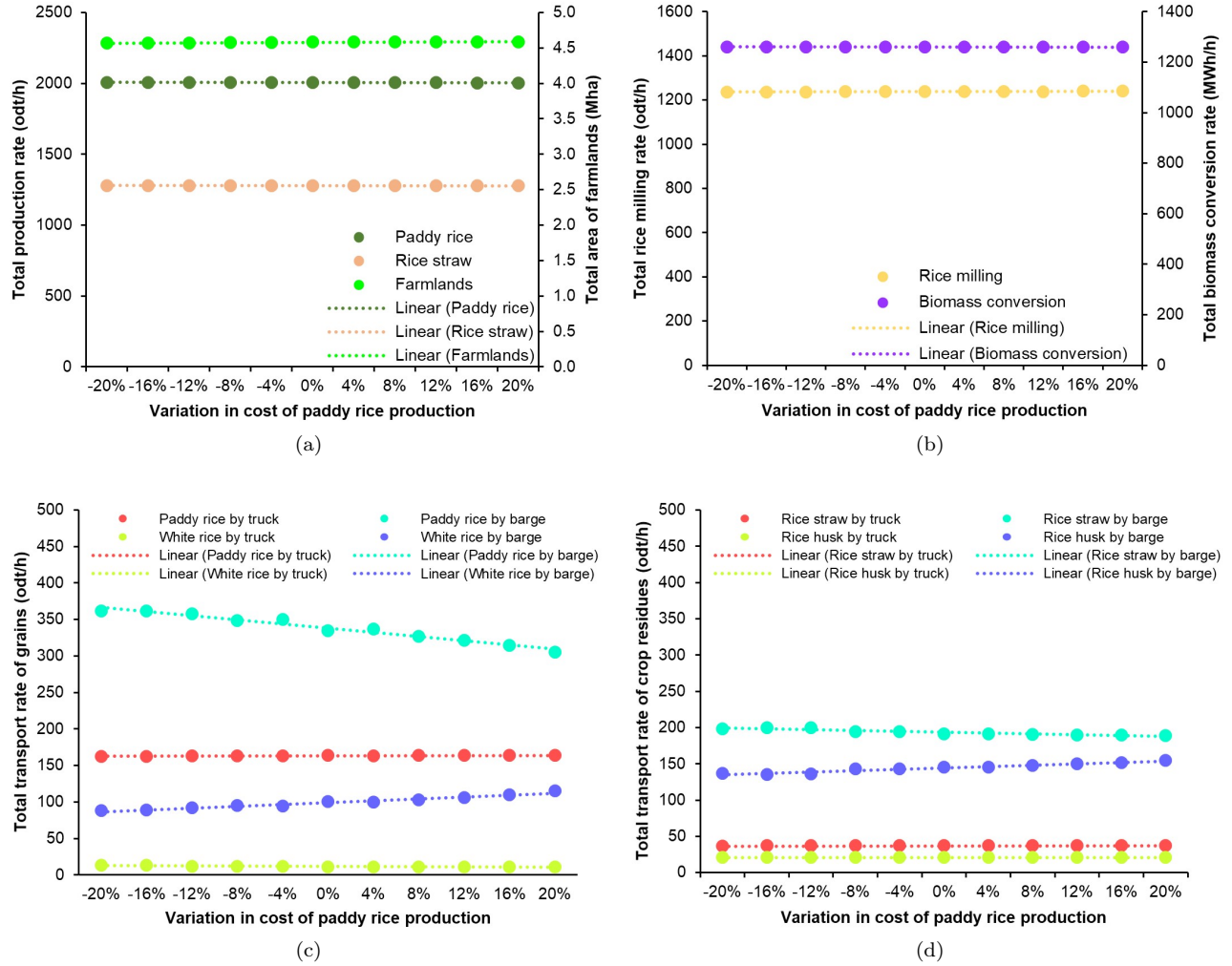


Figure S11: Sensitivity of operating parameters to variation in paddy rice production cost: (a) Biomass feedstock production rates, (b) Processing rates, (c) Grains transporting rates, and (d) Crop residues transporting rates.

S2.5.3 Effect of variation in processing technologies cost

Processing technologies cost, which is comprised of the capital and fixed operating economic impacts, is expected to affect the number of facilities invested by the rice value chains. Paddy rice and rice straw production rates are not affected by variation in processing technologies costs (Figure S12a). The processing rates of rice milling and biomass conversion are also not affected by variation in processing technologies cost (Figure S12b). Grains transporting rates by truck show little to no sensitivity to variation the cost of processing technologies, while grains transporting rates by barge show sensitivity that could be attributed

to the reduced number of rice mill built (Figure S12c). Except for transport of rice husk by truck, crop grains transporting rates show some sensitivity to variation the cost of processing technologies that could be attributed to the increased number of boiler-steam turbine built (Figure S12c).

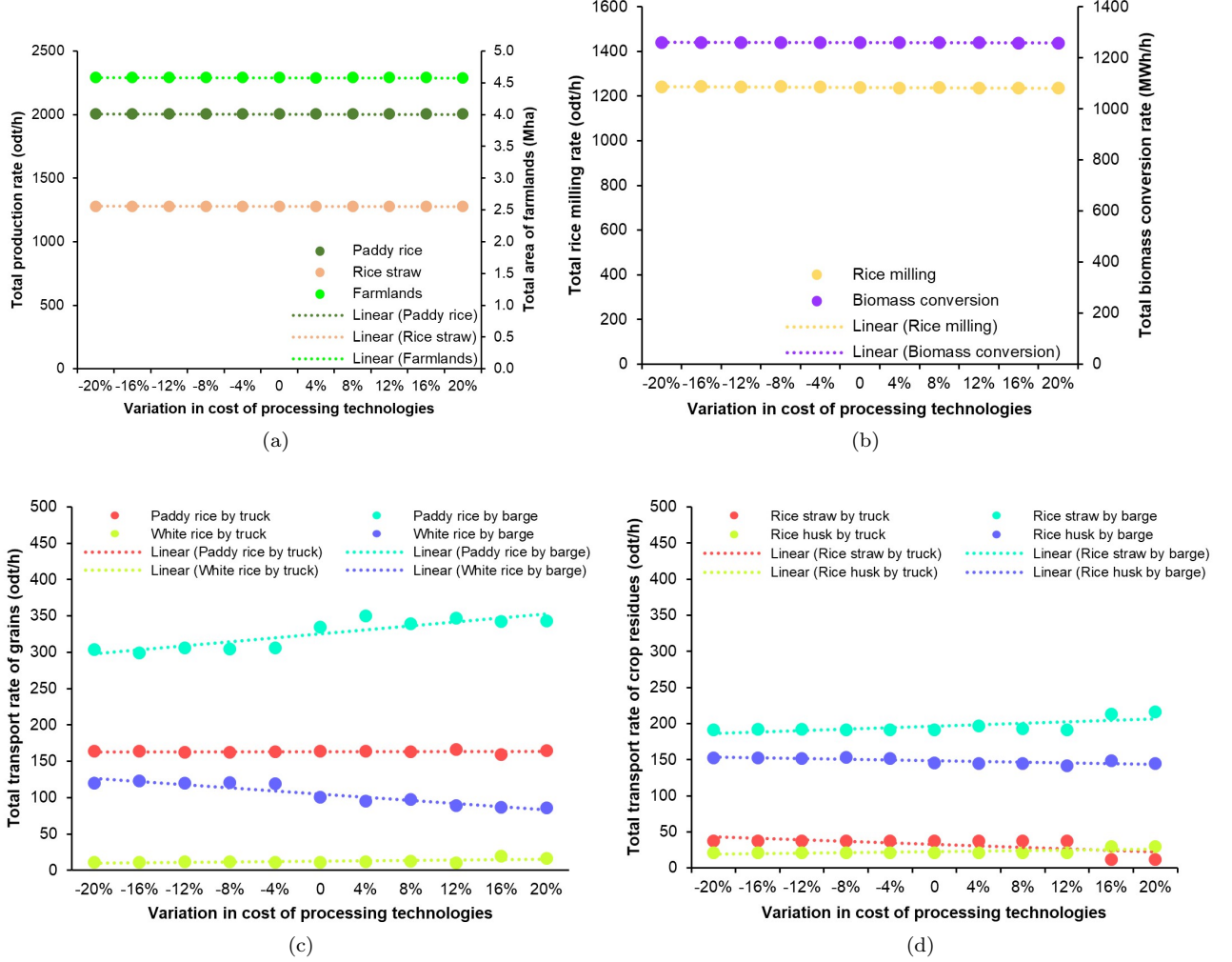


Figure S12: Sensitivity of operating parameters to variation in processing technologies cost: (a) Biomass feedstock production rates, (b) Processing rates, (c) Grains transporting rates, and (d) Crop residues transporting rates.

S2.5.4 Effect of variation in transporting technologies cost

Transporting technologies cost is expected to influence the distribution resources. Biomass feedstock production rates for paddy rice and rice straw and processing rates for rice milling and biomass conversion display no sensitivity to variation in transporting technologies cost as depicted in Figures S13a and S13b, respectively. Grains transporting rates by truck also display no sensitivity to variation in transporting technologies cost, while grains transporting rates by barge display apparent sensitivities to the variation S13c. At higher cost of transporting technologies, the model recommends more distribution of white rice than

paddy rice as displayed by their ascending and descending trend of transporting rates by barge, respectively. Crop residues transporting rates by truck show little to no sensitivity to variation in cost of transporting technologies while crop residues transporting rates by barge show moderate sensitivity to variation in cost of transporting technologies (Figure S13d). The moderately ascending trends of crop residues transporting rates by barge could be attributed to decreased distribution of paddy rice at higher cost of transporting technologies. The reduced movement across zones for paddy rice, which feeds into rice mills, means the movement across zones of rice husk, which feeds into boiler steam turbine, is also reduced.

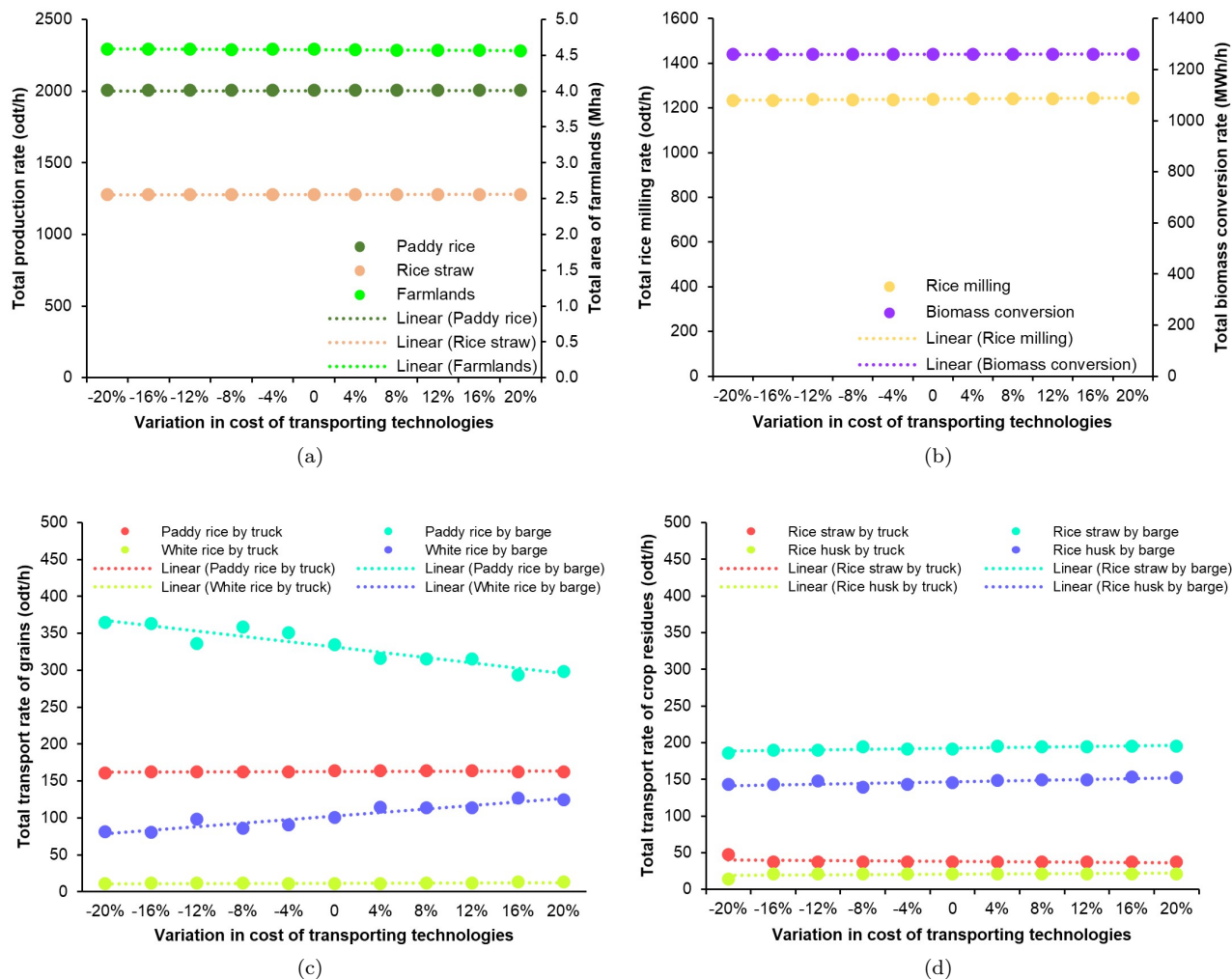


Figure S13: Sensitivity of operating parameters to variation in transporting technologies cost: (a) Biomass feedstock production rates, (b) Processing rates, (c) Grains transporting rates, and (d) Crop residues transporting rates.

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