ABSTRACT

Title of Dissertation: SOCIO-ECONOMIC IMPACTS OF POLICY INTERVENTIONS IN THE FOOD-ENERGY-WATER NEXUS

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The food-energy-water (FEW) nexus is considered essential for human survival and critical for the achievement of the Sustainable Development Goals. However, pressures on each component of the nexus are growing as a result of population and economic growth. The FEW nexus can also be affected by competition for limited land, climate change, and demand and supply changes. Although government policies targeting one of the components of the nexus will directly affect the others, they are still not accounting for the interconnectedness of all three.

The dissertation, through three essays seeks to understand how government policies would affect the FEW nexus, focusing on Thailand or Brazil. The first essay assesses challenges with crop residue burning in Thailand. Additionally, the essay highlights policies implemented that target residue burning or its use and the potential solutions through crop residue use. The second essay examines specific policies on crop residue burning and renewable energy (RE) production to understand their impacts on sustainability. An extended input-output model is

run to using policy scenarios for the future to gauge its impacts on total output, gross value added, employment, labor income, key input use, land use, water use and CO_2 emissions on Thailand and Northeast Thailand. The final essay explores food and energy security given water supply limitations as water availability greatly impacts availability of food and energy. It uses a region in São Paulo, Brazil, where RE policies and other interventions have helped make ethanol production and use cost effective. A model is developed to maximize profits while optimally allocating water to food, energy and municipal water. The study looks at a normal rainfall year, and also runs a future demand change scenario. The dissertation concludes by detailing the challenges that exist, future potential for the FEW nexus policies, limitations and uncertainties.

The dissertation establishes that given the interlinked nature of the FEW nexus, policies need to be implemented to account for all three components. The first essay shows that over time, an increasing number of policies in Thailand target crop residue burning through controlling burning or its use in RE production. Although these policies have been implemented, there are still shortcomings in the policy targets for biomass use, and in the large water use by the sector, as highlighted in essay 1 and 2. Essay 2 also demonstrates social, economic and environmental benefits of using crop residue for RE through employment generated, labor income increases, and CO_2 emission reduction in Thailand and Northeast Thailand. We also see increasing competition for land for energy, with sugarcane potentially overtaking rice in Northeast Thailand. In essay 3, we see that while Brazil has implemented sound policies on RE, there are water security challenges, and competition between food, energy and municipal water supply. We see that the current infrastructure cannot satisfy future demand, leading to competing demands and equity challenges. Finally, in the conclusion, the research highlights uncertainties about future demand, water supply, technology, price, etc. along with potential policies.

SOCIO-ECONOMIC IMPACTS OF POLICY INTERVENTIONS IN THE FOOD-ENERGY-WATER NEXUS

by

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Dedication

To my late mother, Sangeeta Prasad, and my father Manoj Kumar.

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List of Abbreviations

AEDP	Alternative Energy Development Plan
AOI	Agricultural Orientation Index
ASEAN	Agreement by the Association of Southeast Asian Nations
CILQ	Cross-Industry Location Quotient
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRR	Crop Residue Ratio
DEDE	Department of Alternative Energy Development and Efficiency
DGG	Distributed-Green-Generation
ENCON	Energy Conservation
EPPO	Energy Policy and Planning Office
FAO	Food and Agriculture Organization
FEW	Food-Energy-Water
FFV	Flex Fuel Vehicles
FLQ	Fleggs Location Quotient
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GRP	Gross Regional Product
GTAP	Global Trade Analysis Project
GVA	Gross Value Added
GWh	Gigawatt Hour
IO	Input-Output
MT	Metric Tons
MW	Megawatt
NO_x	Nitrogen Oxides
ONWR	Office of National Water Resources
OCSB	Office of the Cane and Sugar Board
PAH	Polycyclic Aromatic Hydrocarbons
PM	Particulate Mater
PROALCOOL	Brazilian Alcohol Program (Programa Nacional do Álcool)
RE	Renewable Energy
SABESP	State Water and Sanitation Autonomous Utility (Saneamento Básico Do Estado De São Paulo)

SDG	Sustainable Development Goals
SLQ	Simple Location Quotient
SMA	Sao Paulo State Secretary of Environment (Secretaria de Infraestrutura e Meio Ambiente)
SPP	Small Power Producers
SO_2	Sulfur Dioxide
TE	Total Employment

Chapter 1: Introduction

1.1 Background

In 2012, global leaders and other stakeholders met at The United Nations Conference on Sustainable Development - more commonly known as the Rio+20 - to bring forth the idea of the Sustainable Development Goals (SDGs). Following the conference, a working group of the United Nations member states was set up, with the objective of producing *a set of universal goals that meet the urgent environmental, political and economic challenges facing our world* [1]. In 2015, these SDGs, which included 17 goals, 169 targets and 232 unique indicators were adopted, to achieve by 2030. These SDGs provided *a shared blueprint for peace and prosperity for people and the planet, now and into the future* [2].

While the SDGs have various goals, targets and indicators, there are interactions and overlaps between them. It is therefore significant to incorporate nexus approaches to achieve the individual and overall goals. The food-energy-water (FEW) is one such nexus, which directly targets the SDGs of zero hunger (Goal 2), clean water and sanitation (Goal 6), affordable and clean energy (Goal 7), decent work and economic growth (Goal 8), responsible consumption and production (Goal 12), and climate action (Goal 13). The food-energy-water (FEW) interactions highlight the interdependence of resources required by society, the economy and the environment. As population and economies grow, so does the demand for food, energy and water, as does

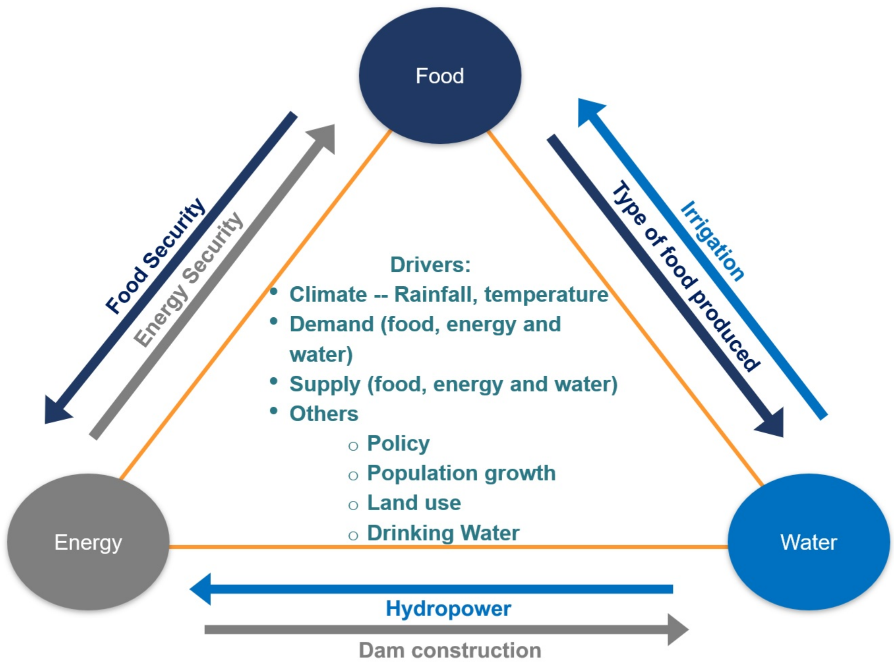


Figure 1.1: The Food-Energy-Water Nexus, interactions, competition and drivers of change

the competition for limited resources. Changing production and consumption patterns of food and energy can directly and/or indirectly affect land use, water use, greenhouse gas (GHG) emissions, employment, etc, as seen in Figure 1.1. Although agriculture is the largest consumer of freshwater in the world [3], there is increasing competition for the resource from other sectors, for example, energy generation. According to the World Water Development Report, nearly all major agricultural systems (18 of 22) globally will face medium to very high water stress by 2050 [3]. The report also states that the industry and energy sector water demand will grow 24% by 2050 (from 18% in 2010). At the same time, climate change will affect the availability, quality and quantity of water. Therefore, strategies need to be implemented to better manage and adapt to these changes, while also incorporating the FEW nexus.

As mentioned, the FEW nexus is the backbone to achieving many of the SDGs. Although currently, 800 million people face hunger, by 2050, global food production would have to increase by 50% to feed the projected 9 billion plus people [4]. This becomes a water security challenge as well, given its high reliance of water. Global water use has been increasing at the rate of 1% per year for the past 100 years, and is expected to rise significantly in the future [5]. Currently, approximately 3.6 billion people, or nearly half the worlds population live in potentially water-scarce areas at least one month per year, and this population could increase to 4.8–5.7 billion by 2050. Additionally, 90% of the global power generation is considered water intensive and by 2035, water withdrawals for energy production could increase by 20% and consumption by 85% [6]. There are also external challenges as there is limited land, leading to competition between food and energy production as countries begin to use biomass for energy generation, and climate change affecting water, food and energy production.

Given these challenges, governments are moving towards a more sustainable future, by implementing policies, which help reduce energy imports, increase renewable energy use, and develop further infrastructure to improve efficiency, etc. To achieve these goals, there needs to be a better understanding of the trade-offs that exist in the FEW nexus, socio-economic impacts of these trade-offs, and how to better manage water given competition between the many sectors, and the changing supply, demand. Policy interventions also need to align with the interests of food, energy and water security by countries.

Government policies targeting one pillar of the FEW nexus will directly affect all three. Although many countries globally face challenges with the FEW nexus, the research in this dissertation will focus on Thailand and Brazil. With regard to the current trajectories, Thailand implemented renewable energy policies at a large scale in 2015 [7], whereas Brazil began its' ethanol production in 1975 [8] and can be a learning experience for many low and middle income countries. While they are at the forefront of renewable energy production and consumption, these two countries face many challenges with renewable energy production from biofuels. These challenges are not just pertinent to the success of the SDGs, but with the COVID pandemic, supply disruptions, inflation and the war in Ukraine, they also become critical for the economic success of a country and for its' energy security.

1.2 Case Studies

1.2.1 Case for Thailand

Thailand faces challenges with the food-energy-water nexus. According to the World Resources Institute [9], 10.3% of the population in Thailand is at risk of hunger, and 69.2% (or 78 million tonnes) crops produced in Thailand experience medium to high drought risk. Additionally, to meet the growing demand for electricity, Thailand has increased its imports of electricity since 2009 [10]. In Thailand, there has been an increase in the total amount of electricity import, as well as the share of import in the electricity mix over time. This reliance on electricity imports makes Thailand vulnerable from an energy security perspective, given the challenges above. There is also an expectation that reliance on imports will continue to rise. Coal import are expected to rise from 18,287 GWh in 2015 to 54,365 GWh in 2036, or an annual average growth rate of 5.3% [11]. The same study shows that the share of hydropower import in the total power supply will rise from 7% in 2014 to 15-20% in 2036.

While import and overall demand for electricity increases, there is also a growing production of crops, in particular, rice and sugarcane. The production of rice paddy increased from 17.2 million tonnes in 1990 to 32.2 million tonnes in 2018. At the same time, sugarcane production increased from 33.6 million tonnes in 1990 to 104.4 million tonnes in 2018 [12]. Given the increase in production of crop, there is also a large production of crop residue in the country from these two crops leading to a great potential for use in electricity generation in the country. Crop residues have traditionally been burned in Thailand, with rice and sugarcane accounting for 83% of the total burning [4]. Crop residue burning does not just have severe environmental, socio-economic and health impacts, it is also an inefficient use of a resource. Reduction in crop residue burning would additionally reduce emissions into the atmosphere. Currently, in Thailand, paddy husk and sugarcane bagasse account for 71% of the country's electricity production from biomass [13], and although this number is high, it is a very small percentage of its potential. In 2017, the total paddy husk and industrial sugarcane bagasse for electricity generation as a percentage of the total energy potential from these two crops were 7.44% and 14.75% respectively [13]. However, this is significantly higher than 0.51% and 0.82% for paddy husk and sugarcane bagasse respectively in 2009 [13].

Given the increased reliance on import of electricity, the large potential for electricity from crop residue, the negative effects of crop residue burning, and the potential rise in future import of electricity, the Government of Thailand implemented two major policies. The aim is to achieve energy security, a more sustainable energy system and improves infrastructure and technology in the country. One policy targets crop residue burning, while the other targets crop residue use. The first policy, implemented by the Ministry of Industry, targets industrial sugarcane residue burning by ending burned sugarcane use in sugar production, and therefore, sugarcane burning by 2022 [14]. The second policy, implemented by the Department of Alternative Energy Development and Efficiency (DEDE), Ministry of Energy titled the Alternative Energy Development Plan (AEDP), seeks to achieve 20% electricity from renewable resources, and in particular, 5570 MW from biomass by 2036 [14]. These interventions however, do not have just effects to the economy and society directly. With increasing production in the electricity sector, other sectors who supply to them have to increase capacity throughout the supply chain. This is also reflected in employment and income from labor in particular, as purchasing power of people increases. Further, Thailand also faces water stress for these crops. An estimated 3.6 million hectares (of 11.6 million hectares) of irrigated rice, and 0.2 million hectares (of 1.05 million hectares) of irrigated sugarcane is growing under high and extremely high water stress conditions. The study also shows that by 2030, all of rice and sugarcane farming, which relies on rainfall, will have high to extremely high water stress [9].

It is also important to look at the Northeast of Thailand given the importance of agriculture and renewable energy in the region. The Northeast region of Thailand produces 37% of paddy, 44.7% of sugarcane and 47% of electricity from biomass in the country [15–17] making it an important region to study.

Within Thailand, it is important to understand what the challenges with crop residue burning are, what policies exist to curtail that burning, the potential of the crop residue use through best practices around the world. It is also important to understand the impacts of renewable energy policies and policies targeting crop burning in the future to the economy, society and the environment. This would help us understand the challenges and potential for achieving the SDGs in the future. Given the importance of the production of agriculture and renewable energy in the Northeast region of Thailand, it would be important to look into the how national level policies will impact the region as well.

1.2.2 Case for Brazil

Moving away from Thailand into Brazil, renewable energy in Brazil accounted for 45% of the total energy supply in 2019, of which, 70% came from biomass [18]. They are also a major exporter of bioethanol to Europe, United States and Japan [19] and the second largest producer and the third largest consumer of bioethanol globally [20]. The success of biomass use and production in Brazil has been achieved through government interventions, and its mechanized production process in a bid to ensure energy security. The Brazilian Alcohol Program (Programa Nacional do Álcool PROALCOOL) began in 1975 to reduce its reliance on oil imports, which was a result of the oil embargo in the Middle East. Grad [21] cited that Brazil's production is mechanized from the level of farming to energy production. Although Brazil has a long growing season, and an abundance of fertile land, it is not the sole reason for its success [8]. The Government of Brazil provided low interest loans to expand mills and distilleries along with guaranteeing prices. They also invested in research and innovation through public-private partnerships, and invested in new technologies. They also incentivized purchases of Flex Fuel Vehicles (FFVs) to increase sales of ethanol-only vehicles by reducing taxes during purchases and annual licensing fees. All this led to a reduction in the production cost of ethanol from sugarcane by 70% from 1975 to 2010. Therefore, Brazil was able to reduce costs through research and development (yield increases), economies of scale (distillation plants), and the effects of learning by doing induced by the demand [8]. Although Brazil is far ahead of other middle income countries, they face other challenges. For example, the state of São Paulo, the largest producer of ethanol in the country [22] faced a major drought from 2013-15 [23] and another in 2021 [24] which was the worst dry spell in the country as a whole in 91 years [25] leading to reduction in yield for crops [26].

The most recent drought of 2021 affected many parts of Brazil, with reports of people in the Northeast of Brazil relying on trucks for water supply for their basic needs of drinking, cooking and hygiene and farm production significantly falling or completely ruined [27]. In Rio Branco, the capital of the Amazonian state Acre, the mayor declared an emergency due to shortage of potable water. To avoid complete shortage of water, the Rio Branco municipal government sent out tanker trucks (5000 liters) of water twice a week, serving 12 rural communities on the capital's outskirts [28]. The drought also led to the country losing hydropower outputs equal to the energy consumed by the city of Rio de Janeiro in five months [29]. Hydropower is the largest source of energy in Brazil and could lead to major challenges for the future energy security in the country. Between March and May, dry weather in South-Central Brazil led to many major reservoirs reaching 20% capacity, prices of soybean increasing by 67% from June 2020 to May 2021 and electricity costs increasing by 130% [30]. During the year 2021, the Cantareira reservoir system, that provides water to 8.8 million people along with agriculture and hydropower, was at maximum capacity on a single day at 53% and a minimum of 36% [31]. This is critical as it not just provides to industry, but also drinking water to a large part of the population of the city of São Paulo.

Although Brazil can be seen as a prime example of government intervention and policies that have worked well in terms of increasing renewable energy production and consumption. It is however, critical to understand how to optimally allocate water while ensuring production, profits, and drinking water supply.

1.3 Objectives, Essay Questions and Research Design

The overall objective is to understand how policies implemented by countries affect social, economic and environmental issues within the country or a region within a nation. This is done by first understanding what challenges exist and the policies currently in place (Essay 1), and then understanding what the consequences of renewable energy policies on society, economy and the environment (Essay 2) and finally understanding how to ensure food and energy security given increasing droughts and water security challenges even if good renewable energy policies and plans exist (Essay 3). The motivation of the dissertation is to develop models which are transparent, replicable in other nations, and can be less computational demanding so as to facilitate conversations with stakeholders. The study will put forth three essays targeting one challenge within the FEW nexus. The dissertation research takes different approaches to answer missing gaps in understanding how policies can affect the FEW nexus. The challenges for Thailand and Brazil, while critical to the FEW nexus, also delves into challenges of land use, climate change and energy security. The thesis comprises of 3 essays:

Essay 1 (Chapter 2): Limiting rice and sugarcane residue burning in Thailand: Current status, challenges and strategies

Crop residue burning is a major challenges in Thailand, especially for rice and sugarcane. It has implications to the FEW nexus, as well as sustainability as a whole, which has impacts on health, environment and society. It is also a wasted resource, which has economic potential in many industries. The first essay is reviewing existing literature and assess the available data to (1) understand current status of residue burning and practices in Thailand, and their impacts on environment; (2) discuss existing government policies in Thailand and regions within Thailand

and their impact; and (3) discuss sustainable residue management practices, along with some examples from other countries, and required strategies to implement them.

Essay 2 (Chapter 3): **Adoption of biomass for electricity generation in Thailand: Implications for energy security, employment, environment, and land use change**

As we understand that crop residue burning is a challenge in Thailand, and the Government of Thailand is implementing renewable energy policies, it is important to understand the consequences of these policies. To understand the social, economic and environmental consequences of changes in crop residue use for energy generation in Thailand, this paper estimates changes to total output, gross value added, employment, key input use, and land and water use, as a result of policy changes and resulting changing demand over time using the extended input-output (IO) model. Adoption of biomass for electricity generation through the two policies implemented by the Government of Thailand, will serve as scenarios for the study. The study compares these policies for the country, and the Northeast region of Thailand. National level policies can have different impacts on a region as compared to the country as a whole, and it is important to highlight the difference in these impacts. This is particularly notable for Northeast Thailand, given its importance for agriculture and energy generation for the country and therefore, an important region to study.

Input-output models, and in particular, extended IO will help us understand the direct, indirect and induced effects of renewable energy and crop burning policies on the economy, society and the environment. The study also discusses challenges that the policies my face which may not be captured by the model.

Essay 3 (Chapter 4): **Multi-reservoir, multi-demand water optimization model through maximization of profits and social equity: A case for São Paulo, Brazil**

Although Brazil has been successful in being the prime example of how government policies can successfully increase production, consumption and export of biomass for electricity generation, droughts can greatly affect the yield, and overall production of crops. It is therefore important to optimally allocate water to ensure maximum profits but also a minimum allocation to drinking water supply. The study looks at 4 reservoirs targeting 22 municipalities in São Paulo state, including the city of São Paulo. The region is selected as the state is the largest producer of ethanol in the country. The study assesses how to optimally allocate water to the different municipalities and sectors given the inflow into reservoirs. The study also delves into the challenges between food and energy given the limited availability of water and land in the area. It also looks at social equity through minimum allocation of municipal water supply. While the study is conducted for São Paulo, the model is easily replicable for other regions in Brazil, as well as globally.

Finally, Chapter 5 of the thesis summarizes and concludes all three essays, including the key findings and the future direction of the research.

Chapter 2: Limiting rice and sugarcane residue burning in Thailand: Current status, challenges and strategies

2.1 Introduction

Increasing population and economic growth have driven up demand for food around the world. This has led to an increase in agricultural production, and therefore crop residue generation. However, proper management of crop residues is yet to be addressed in many countries. Traditionally, crop residues have been burned in many parts of the world, contributing to approximately 10% of the total annual emissions globally from the agricultural sector [32]. The major regional contributor has been Asia, which accounted for nearly 50% of the total biomass burned, of which, rice and sugarcane burning holds the largest share [4].

Crop residue burning has many negative impacts, affecting air quality, and emitting a range of pollutants (e.g. PM10, PM2.5, NO_x, SO_2) into the atmosphere [33–35]. The air pollutants released into the atmosphere has many other harmful effects, including poor visibility and/or haze [36], deterioration of human health [37], soil quality [38] and local and global climate change [35, 39]. It therefore also hinders the overall achievement of the Sustainable Development Goals. Due to its negative impacts on environment and society, crop residue burning has received large attention at the global, national and local levels, and sustainable residue management practices have been promoted. Further, some examples include phasing out of manual harvesting in Brazil [40] to control residue burning, inclusion of sustainable agricultural practices in the Sustainable Development Goals, and Transboundary Haze Pollution Agreement by the Association of Southeast Asian Nations (ASEAN). Some of the management practices alternative to residue burning include 1) recycling residue in the soil through incorporation, surface retention and mulching to improve the soil physical, chemical and biological properties [41]; 2) using for livestock feed [42]; 3) bioenergy production [43]; and 4) cooking and lighting source in rural areas [44].

Thailand faces similar problems with crop residue burning as other developing countries. It is the 6th and 4th largest producer of rice and sugarcane, respectively, in the world [45]. It ranks 14th in emissions (CO_2 equivalent) from agriculture in the world with a total of 70795.6 gigagrams of emissions in 2014 [46] and ranks 10th in the world for total biomass burned with a total of 6.8 million tonnes of biomass burned from maize, rice and sugarcane and wheat in 2016 [4]. However, majority of the residue burning comes from rice and sugarcane. A total of 5.6 million tonnes or 83% of the total residue burned comes from these two crops. Therefore, residue management in rice and sugarcane farming is a critical challenge for Thailand. In 2019, an estimated 32,000 people died prematurely attributed to to PM2.5 [47] which is largely due to crop residue burning.

Considering the impacts of residue burning and its severity in Thailand, the objectives of this paper are to review existing literature and assess the available data to 1) understand current status of residue burning and practices, and their impacts on environment; 2) discuss existing government policies and their impact; and 3) discuss sustainable residue management practices, along with some examples from other countries, and required strategies to implement them.

2.2 Current status and dynamics of rice and sugarcane residue burning in Thailand

Residue burning in rice and sugarcane contributes approximately 83% of total residue burned in Thailand. Rice tops in total residue burned with an average, 4.8 million tonnes (70% of the total) of residue burned annually followed by sugarcane with on average 1.1 million tonnes (13% of the total) [4]. Although the percentage of total harvested area subjected to burning in rice (45%) [48] is less than that of sugarcane percent residue burned harvested area (77%) [49], total harvested area and residue to product ratio are significantly higher in rice resulting higher amount of residue burned. For instance, total harvested area in rice was about 10.6 million ha in 2016 which is 7.6 times higher than that of sugarcane (1.4 million ha) [45]. Further, the residue to product ratio (RPR) for rice straws (1.2) and husk (0.3) is higher than the ratio for sugarcane tops and leaves (0.2) [50]. Recent trends suggested that although total rice biomass burned is higher, since 2012, there has been a declining trend in total rice residue burned area while biomass burned area in sugarcane is increasing. This could be primarily attributed to changes in harvesting areas of rice and sugarcane with change in market conditions and government priorities for agriculture, as seen in Figure 2.1.

Regionally, the Central and Northeastern region has the highest fraction of rice residue burned, while the North has the highest fraction of sugarcane residue burned (Table 2.1). These coincide with the production of rice but not for sugarcane. The Northeast and Central region are the largest producers of rice, and for sugarcane, the Northeast region is the largest producer of sugarcane.

Residue burning practices vary for rice and sugarcane depending on management practices. For rice, residue burning is more widespread under irrigated paddy cultivation. [52] showed that

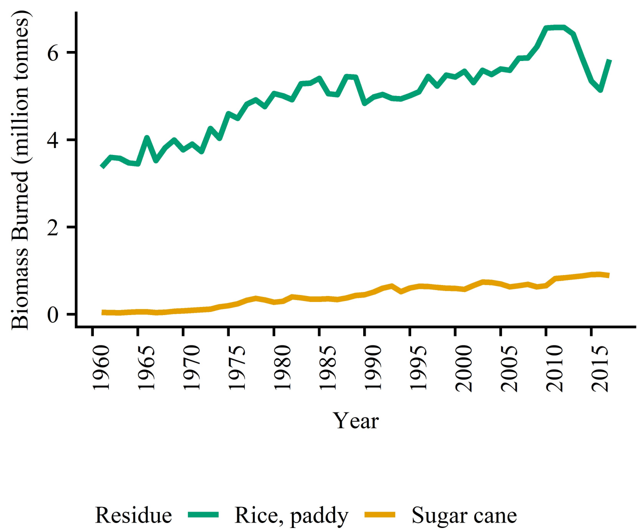


Figure 2.1: Biomass burned (million tonnes) from 1961-2017 in Thailand from rice and sugarcane.

Source: [4]

	Rice	Sugarcane
	Fraction (%)	
Central	53.99	54.07
North	17.1	81.7
Northeast	57.91	53.61
South	7.9	–

Table 2.1: Fraction of crop residue burned by region in Thailand.

Data Source: [51]

2.69 million ha of irrigated paddy fields and 1.21 million ha of rain-fed paddy fields were subject to open burning. This area accounted for 70% of irrigated rice field area and 18% of rain-fed rice field area of Thailand. Further, post-harvesting burning is typical in rice whereas pre-harvesting residue burning is common in sugarcane. A survey conducted in Pathumthani, an intensive rice burning area in the Bangkok Metropolitan Region showed that 90% of the rice paddies in the high harvesting season (November-December) were burned after crop was harvested. The study also showed the intensive burning period of rice straw in Pathumthani lasted from November to April [53]. In another study, 82% of the total burned area in sugarcane was found to be resulted from pre-harvesting burning where fire was used to burn residue before cutting sugarcane to facilitate manual cane harvesting, and remaining 18% residue burned was result of post-harvesting burning to protect ratoon crop or to prepare the soil for the next crop [49].

2.3 Impacts of crop residue burning on the environment

Various studies were conducted to understand the impacts of open field burning on air quality and visibility in Thailand [49, 54, 55]. Phairung et. al., [54] reported that rice and sugarcane account for 64% of PM10, 60% of PM2.5, 86% of NO_x and 84% of SO_2 emissions from all agricultural crops and forest fires in Thailand. The air pollutants emitted from residue burning in rice were reported by different studies while there was a single study reported for sugarcane, as seen in Table 2.2. These studies showed that the PM10 and PM2.5 emissions in rice peaked in 2008, later emissions were shown to decline slightly. While we see in Figure 2.1, since 2012, biomass burning has reduced, some of the changes over time for all emissions could be attributed to different crop residue ratio and emission factors used in the calculation of emissions by the studies. For example, the emission factor ranges from 1177 g/kg by [56] to 1460 g/kg by [57]. Similar pattern was found in the greenhouse gases showing decline after 2008.

	YEAR	PM10	PM2.5	NO_x	SO_2	CO_2	CO	Source
Rice	2002-06	30.9	108	—	—	12.21	290	1
	2008	120	350	—	—	14.87	1670	2
	2010	80	70	—	—	10.3	787	3
	2014	88.5	80.8	54.6	7.6	—	—	4
	2018	43	38	—	—	5.3	422	5
Sugarcane	2014	54.2	39.5	19.3	4.6	—	—	4

Table 2.2: Emissions of air pollutants (Kilotonne/Year) from different crops in Thailand.

Source Note: (1) [57]; (2) [48]; (3) [58]; (4) [54]; (5) [56]

A study in Lampang Province of Northern Thailand where approximately 5000 tonnes of rice is burned showed that the ultra-fine, fine and coarse particles were 12.6, 2.1 and 3.6 times higher respectively than during non-burning period [59]. These particles, known as Polycyclic Aromatic Hydrocarbons (PAHs) increases the risk of developing lung cancer, especially high molecular mass PAHs, which are observed during rice burning. A study by Kanabkaew et. al. [60] showed that rice straw burning was the largest contributor to the total emissions, with an average of 80% of emissions from crop residue burning. The primary reason for these large numbers are because rice has a higher crop production, and higher residue to crop ratio compared to other crops. According to Thongboonchoo et. al. [61], rice is the major source of CO_2 and PM2.5 emissions, accounting for 87% and 93% of the total emissions in the country. Sornpoon et. al. [49] reported detrimental effects of sugarcane burning on soil carbon stocks. This study showed that the areas which had 5 years of no burning had 15% higher soil total carbon stock at 0-30 cm depth compared with carbon stocks in areas with burning.

Although there has been extensive research conducted in understanding the amount of emissions generated by residue burning, their effects on health risks in Thailand are not well understood. The need for quantitative information on health risks with residue burning was emphasized by [62]. Similarly, Vichit-Vadakan and Vajanapoom [63] pointed out that epidemiological studies have been limited with some reports of respiratory illnesses after episodic events. Given the severity of residue burning in Thailand, it is critical that there are comprehensive studies to assess the impact of individual pollutants released from burning on human health risks.

2.4 Existing programs and policies and their implications

There are various existing programs and policies targeting regulation of rice and sugarcane production, market stabilization, and promoting renewable energy, which considerably impact crop residue management. Some of these programs and policies and their implications are described below.

2.4.1 Cane and Sugar Act of 1984

The Office of the Cane and Sugar Board (OCSB), a government body under the jurisdiction of the Ministry of Industry of Thailand initiated the Sugar Cane and Granulated Sugar Act on July 27th, 1984 [64], which regulates Thai sugar sector and rules sugar policy. Under section 56, a revenue-sharing scheme was introduced. Under this scheme, farmers earn 70 percent of the revenue from domestic and export sales of sugar and molasses, while mills receive the remaining 30 percent. This scheme did not consider any other sugarcane by-products such as bagasse and crop residue, which restricts growth of energy production market to some extent. Inclusion of crop residues in this scheme will encourage farmers to sell the residue for energy purpose and control residue burning. Considering the air pollution concerns, Thai government has been working with OCSB to make amendments to existing cane and sugar act to include a larger range of products which may foster sustainable management of sugarcane residues.

2.4.2 Renewable Energy Policies

Thai government has been promoting renewable energy since 1990's and has implemented some policies mandating renewable energy production targets. Thailand's Energy Conservation (ENCON) Fund was established by the 1992 Energy Conservation Promotion Act and was launched in 1994 [65]. The program sought to achieve a wider utilization of renewable energy in order to reduce the negative impacts on the environment. This fund led to financing of 15 biomass projects in Thailand, with a total investment of $70 million from 1995-2004 [66]. Following ENCON, the framework of national energy strategy, which included renewable energy development was approved in principle by a cabinet resolution in 2003. The Ministry of Energy set targets for share of renewable energy from 0.5% in 2002 to 8% by 2011 [66].

The Electricity Generating Authority of Thailand, through a small power solicitation plan, adopted the small power producers (SPP) program. The SPP is a multinational sector program, which accounts for about 15% of the country's total installed generating capacity. Fuel from biomass is included in these SPPs [67]. Of these SPPs (10-90 MW), 16 fully or partially use rice husk as fuel with an installed capacity of 140 MW. Another 9 are registered under the very small power plants (under 10MW), with a production capacity of 50 MW. However, rice straw hasn't been used for energy production yet due to unclear logistics, and cost of the resource for large-scale production [68].

As a continuation of the earlier initiatives, Thailand government implemented Alternative

Energy Development Plan (AEDP) in 2012. Through the AEDP, Thailand hopes to achieve 5570 MW of power from biomass by 2036 [7] which was then increased to 5790 MW by 2037 [69]. To achieve this goal, various strategies have been implemented [70] including 1) Promoting the installation of Distributed-Green-Generation (DGG); 2) Supporting financial support to increase the efficiency of biomass power plants; 3) Supporting financial incentives to expand the transmission and distribution systems; 4) Conducting knowledge campaigns to educate youth on biomass management and networking in areas where biomass production systems can be installed; and 5) Research and development on biomass pellet for production, consumption and standards. An initiative that has been critical to the success of the AEDP was a feed-in premium or "adder" policy, which was later, superseded by a Feed-in Tariff Policy, implemented by Energy Policy and Planning Office (EPPO), Ministry of Energy, Thailand. The policies have been providing subsidies to biomass energy over time for all sized power plants, and in particular, to rice husk and sugarcane bagasse [71, 72].

These policies helped in using crop residues for alternative energy instead of burning to some extent but not to the total potential. A collection of data from the Department of Alternative Energy Development and Efficiency, Ministry of Energy [13], showed that currently, a small fraction of paddy husk and sugarcane bagasse has been used for electricity generation relative to the total potential usage of husk and bagasse, as seen in Figure 2.2. Further, currently, paddy straw and sugarcane top and trasher is yet to be used for energy generation. The current usage of solid biomass for energy is at 9,283 ktoe which is only 42% of the total potential (i.e. 22,100 ktoe) [73]. Of the total bioenergy target, 5570 ktoe (i.e 64,779 GWh) amount of electricity is expected to be generated [7]. However, total generated amount as of 2017 is approximately 2495 ktoe (i.e. 29,021 GWh) [74], which is less than half of the target. A study by Heo and Choi [75]

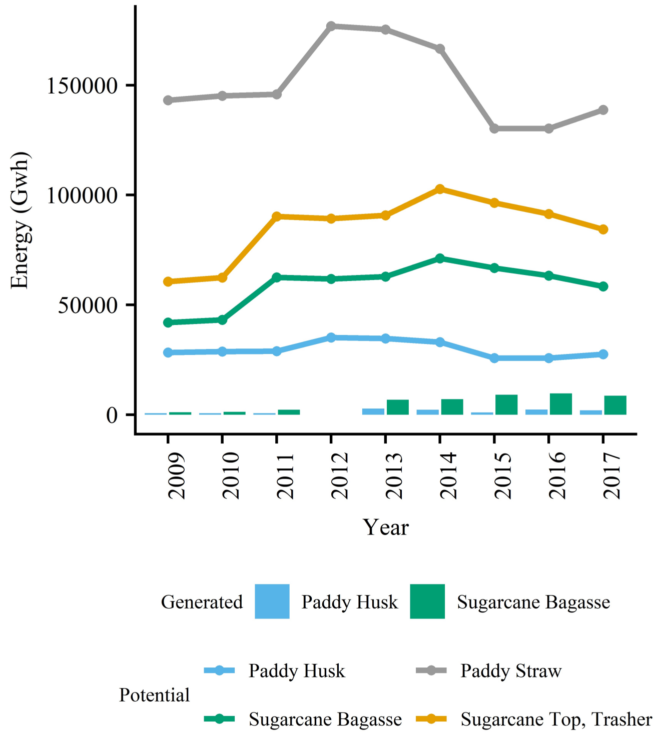


Figure 2.2: Energy Generated and Potential in GWh from 2009-2017 in Thailand. Source: [13]

used 3 scenarios to assess future potential of biofuels in Thailand. The three scenarios were based on 22%, 44% and 66% residue extraction rates respectively. The results from the study are seen in Table 3.1, which show that there is large economic and environmental benefits from all scenarios.

2.5 Direct efforts to reduce residue burning

There are various ongoing efforts at regional and national scale to control the crop residue burning in Thailand. The Thailand government-initiated Pollution Management Plan 2012-2016 in 2012. This Plan provided guidelines to control open burning of agricultural residues, and to promote alternative sustainable approaches to manage agricultural residues [56]. Further,

Table 2.3: Environmental and Economic Potential for Second Generation Biodiesel and Bioethanol in 3 Scenarios.

	National Gasoline Consumption Potentially Offset	National Diesel Consumption Potentially Offset	CO_2 Decrease in the Gasoline Sector	CO_2 Decrease in the Diesel Sector	Profit Gains for Bioethanol Sector	Profit Gains from Biodiesel Sector
	%	%	Mega Ton	Mega Ton	Million USD	Million USD
Scenario 1	7.2 - 19.6	4.1 - 10.9	1.3–3.5	1.4–3.8	27–74	30–81
Scenario 2	15.8 - 43.2	9.0 - 23.9	2.8–7.7	3.2–8.4	60–163	67–178
Scenario 3	23.7 - 64.8	13.4 - 35.8	4.2–11.6	4.7–12.6	90–244	100–267

Source: [75]

as part of this plan, the government started various subsidy programs to encourage the use of soil equipment and farming technologies to reduce the air pollution in the country [56]. The Disaster Prevention and Mitigation Act B.E. 2550 was established in 2007 to have a principal legal mechanism for disaster risk management practices in Thailand. The efforts under this act were shown to improve the air quality in the nine provinces of Northern Thailand affected severely with residue burning. For instance, the number of days with particulate matter exceeding standard value was reduced from 61 days to 38 days in the affected provinces, and also noticed a significant reduction in the number of hotspots of air pollution in Northern Thailand. Note that in this case, the cause of air pollution includes forest fires as well [76]. Provincial governments also have launched various initiatives to address the residue burning problem. For example, Chiang Rai Provincial Government imposed 60 day bans on burning from February 17 to April 16 and also have set high fines for violating this regulation [77]. The violations are reported through reporting from the village headman and members of public [78].

The most recent initiative to reduce burning came after the severe smog in 2019. The Ministry of Industry, Government of Thailand proposed a plan beginning the 2019-2020 sugarcane crop period that enforces sugar mills to limit purchase of burning sugarcane to 30% of the total cane purchased in 2019-2020 period and drop it to 20% in the 2020-21 crop year [14]. To achieve this, millers and farmers have sought support from the Government of Thailand, as the burnt cane prices will also be dropped by the disincentives provided. The government will provide low interest soft loans to farmers to buy cane harvesters, and some loans to sugar millers to purchase machinery [79]. Burning sugarcane reduces the quality of the cane, and well below the requirement of many companies [80]. This led to the Office of Cane and Sugar Board (OCSB) to work with stakeholders from the industry to implement a 3-stage strategy. The three stages include the targeting of sugarcane factories to use fresh cane (minimum of 60% fresh cane) rather than burnt cane; incentives to farmers to provide fresh cane, and demarkating burning-free zones, and a long-term plan of no burning of sugarcane by 2022 by reducing burnt cane by 10% a year [80]. During the same time, a national crisis was declared by the Government of Thailand, and led to the Pollution Control Department to come up with plans to address the problem, which included tacking the problem when pollution levels reached ”unsafe” levels, and better management and tackling the pollution at source [47]

Thailand is part of the Association of Southeast Asian Nation (ASEAN) and signed the Transboundary Haze Pollution Agreement [81] and ratified it in 2013. An alternate agreement built on Transboundary Haze Pollution Agreement was the ASEAN Zero Burning Policy [82], which provides guidelines to each nation to reduce any land and forest fires at a regional and national level.

2.6 Challenges to control residue burning in Thailand

Although there are different policies and programs to control residue burning and promote sustainable residue management practices, there are various challenges to implement policies and adopt controlling strategies developed under various programs. Some hurdles include farmer's unwillingness, cost of farm machinery, labor cost and shortage, and farmer's lack of awareness on the implications of burning. Cheewaphongphan et. al. [73] conducted a study to understand farmer's willingness to sell residue rather than burning. This study showed that 82.3% of the farmers in the country expressed willingness to bale and sell the rice residue. However, there was significant variation by region. In the Northern and Central region, 96.7% and 86.4%

farmers responded positively, respectively, while farmers in Northeast and Southern (60.2% and 60%) showed relatively less willingness, respectively. Some farmers concerned that farm machinery operated for harvesting and baling may likely damage the field and compact the soil making tillage difficult while some others are not interested due to the high cost of machinery. Another study by Kanokkanjana et. al. [83] cited that lack of enough straw balers is a problem, even though selling residue is profitable for farmers. This study reported that managing and transporting large volumes of straw (even when compressed) is highly challenging because the volume of straw is still too high without dealing with issues of illegal overloading of trucks.

In another study by Adeleke et. al., [77], farmers were interviewed in the Chiang Rai province located in northern Thailand. This study revealed that the farmers were well aware of the health effects of burning but were not very familiar with environmental consequences. As mentioned before, Chiang Rai Provincial Government imposes a 60 day bans on burning. However, some farmers still practices burning citing that it would be difficult to plant in time if residue is not burnt. [77] suggested that shortage of time and cost of harvesting were the primary reasons for large scale burning in the region. Similar findings were reported by Pasukphun et. al. [84].

With regard to sugarcane burning, labor costs and shortages were cited as the primary reason for not adopting alternative residue management practices [85].A study interviewed approximately 400 farm workers involved in The Coca-Cola Company's (TCCC) sugarcane supply chain in Thailand. These interviews suggested that there has been a considerable difference in the payments given for harvesting burned cane and fresh cane. The wages (1.2 baht/bundle) and transportation (2.2 bahts/bundle) payments for green cane harvesting are higher than that of burned cane (1.0 and 2.0 bahts/bundle wage and transportation payment, respectively). Although the wages and transportation payments are higher for green cane, workers often prefer working with burnt cane because harvesting burned cane requires less amount of time and net earnings per day is significantly higher compared to daily amount earned for fresh cane harvesting [86]. Therefore, farmers, particularly marginal farmers, often find difficulty to have labor to harvest fresh cane which lead them to practice residue burning. Another study by Silalertruksa et. al., [87] identified that to break even, the area required for mechanical use for farming would need to be above 0.8 ha to reduce any idle time for machinery, and to reduce costs. Therefore, a way to reduce cost of mechanization would require small scale growers and millers to combine their planted area and to prepare land together.

The study by Heo and Choi [75] also pointed that there is currently little being done to develop commercial second generation biofuel technology in Thailand. This is a challenge as crop and residue production is rising in Thailand.

A study by Nikam et. al., [47] that interviewed key stakeholders working towards air quality improvement, studied barriers to proper enforcement. A key barrier to change is the conflict between economy and environment. This leads to a severe lack of political will to properly tackle the issue of air pollution. For example, they cited that the the Ministry of Industry is more focused on financial returns for industrial investors and is heavily lobbied by investors who don't see a substantial return on investment on clean technologies. Some other barriers specific to agriculture and air quality the study cited was 1. Insufficient air quality monitoring (including up to date databases), 2. Lack of public awareness regarding health impacts of haze and open burning (including lack of government support, knowledge sharing, etc), 3. Slow progress to increase energy efficiency; and 4. Inadequate and inefficiently implemented policies (including lack of harmonization of laws targeting biomass burning)

2.7 Potential strategies and recommendations

There are some potential strategies which could complement existing plans and policies targeting controlling residue burning and promoting alternative residue management practices. Some of these strategies were successfully implemented in other countries.

2.7.1 Renewable energy

The Alternative Energy Development Plan (AEDP) has paved the way for use of crop residue use for energy generation. Although the AEDP has set targets, with the Cane and Sugar Act of 1984 yet to identify sugarcane by-products and the use of sugarcane for energy production in the compensation for lower prices of sugarcane. The government also directed the sugar mills to stop purchasing burnt cane, but it did not target rice production, which generates larger residue per unit of rice produced. Therefore, policies could be developed to better target residue use for renewable energy.

According to Chaiprasert et. al. [88], and as identified in the previous sections, there have been incentives put in place to support and promote biogas technology through government subsidies, soft loans, tax incentives, etc. in the Alternative Energy Development Plan. This has a potential to increase the use of residue in the country. However, an analysis of policies for ethanol by Chaya et. al., [89] showed that while the AEDP has done well in identifying a strategy for the production of feedstock and finding areas suitable for production, it has to some extent addressed the management of feedstock, including efficient use, but not looked at the promotion of technology for production and use of ethanol, and the improvement of infrastructure for production and use of ethanol. As mentioned before, and stated by the authors, there is a hindrance to ethanol production due to the Sugacane Act of 1984. Since it targets the process of sugar production, ethanol, and other residue use has been left out of the Act. For incentivization of use of crop and residue for energy production, the Act would require an addition of use for energy production.

Examples from other countries demonstrate that there are both economic and other benefits of using residue for energy production. While cost is a critical issue faced in Thailand, as mentioned above, studies in Brazil showed that the co-benefits of energy generation from sugarcane outweighed the costs associated with high pressure boilers and of connecting production facilities to the national grid [90].

In 2009, Brazil produced 18.2% energy from sugarcane, and 13.9% from biomass [91]. Renewable energy in Brazil accounted for 45% of the total energy supply in 2019, of which, 70% came from biomass [18]. They are also a major exporter of bioethanol to Europe, United States and Japan [19], and the second largest producer and the third largest consumer of bioethanol globally [20]. The success of Brazil has been both, government interventions, and its mechanized production process. The Brazilian Alcohol Program (PROALCOOL) began in 1975 to reduce its reliance on oil imports, which was a result of the oil embargo in the Middle East. Grad [21] explains that Brazil's production, which is mechanized from the farm level to the energy production level. Meyer [8] stated while Brazil has a long growing season, and an abundance of fertile land, that is not the sole reason for its success. They provided low interest loans to expand mills and distilleries along with guaranteeing prices. They also invested in research and innovation through public-private partnerships, and invested in new technologies. They also incentivized purchases of Flex Fuel Vehicles (FFVs) to increase sales of ethanol-only vehicles by reducing taxes during purchases and annual licensing fees. All this led to a reduction in the production cost of ethanol from sugarcane by 70% from 1975 to 2010. Therefore, Brazil was able to reduce costs through research and development (yield increases), economies of scale (distillation plants), and the effects of learning by doing induced by the demand [8].

While the AEDP has put forth strategies to promote the development of renewable energy, they do not include an emphasis on yield improvement or increases, or cutting costs down. The AEDP can greatly benefit from learning from Brazil in achieving their goals. Aside from the above success, to achieve its target, a clear policy and legal framework for land tenure and use, improvements in the pricing mechanism with long term purchase guarantees, a fair regulatory framework between farmers and energy producers, and an overall improvement in supply chain is recommended for the production of bioenergy [92]. Further, looking at energy from a big picture perspective, or a sectoral perspective, by including and empowering stakeholders is an important way to ensure energy security from residue [93]. This big picture takes away the burning of residue from solely the perspective of agriculture and energy to the economy, society, education, and policy. To achieve this, an organized network would need to be achieved, where Bhuvaneshwari [93] uses the case of municipal solid waste, where the municipality establishes a mechanism to manage to waste.

2.7.2 Green harvesting

A significant alternative to burning has been green harvesting, where the residues are left in the soil, which has shown benefits like balancing the nutrient flow in the soil [94], increase in organic carbon and total soil nitrogen in the top 5-15 cm of soil [95]. This has shown benefits in some other countries like Brazil, where currently both, burning of residue, and green harvesting is being practiced [96]. Sugarcane burning in Brazil led to an increase in air pollutant dispersion, posing health risks, especially among children and the elderly [97]. In the State of São Paulo, which has 4.1 of the 7.5 million hectares of land for sugarcane (Ella, 2012), shifting to green harvesting from the burning has a potential to save 310.7 kg CO_2 equivalent/ha/year in the state of Sao Paulo alone [96]. Similarly, studies in Brazil show that mulching is able to return large amounts of carbon back into the soil, which is usually lost when residues are burned [98, 99].

To achieve some of these practices, government legislation and incentives as well as private participation have played a significant role in the mechanization of harvesting. For example, in São Paulo, in 2007, the Sao Paulo State Secretary of Environment (SMA), the Sugarcane Industry Union, and the supplier associations signed the "Green Ethanol" Protocol. The idea of the protocol was to promote sustainable practices for the production of sugarcane in Sao Paulo State [100]. This protocol not just works to reduce crop burning, but efficient in the production of sugarcane by reducing water use, to recover riparian forests, reduce air pollution and to conserve the native vegetation of the state.

Thailand needs to look into similar approaches for green harvesting, through mechanization of harvesting, improvements in irrigation, etc. This could be achieved through financial and other incentives to leave some of the residue in the soil to encourage improvement in the soil nutrient.

2.7.3 Other uses

While the above use of residue for energy production and in improving soil nutrition are closely aligned with the policies and realities of Thailand, there are others ways residue could be used. A study by Bhuvaneshwari [93] looks at other uses of residue to improve soil quality, which include composting, and production of biochar. These are seen to significantly improve soil quality, by improving microbial population, native microflora and fauna, nutrient retention, etc. Biochar, according to the authors, can also be used for purposes other than improving soil quality, for example, for water treatment, in the construction industry, food industry, cosmetic industry, metallurgy, treatment of waste water along with other chemical applications.

Some other notable examples come from India, where majority of the rice and is used for cattle feed and roof thatching, and wheat straw is used for cattle feed, domestic fuel, paperboard making and oil extraction [42]. Cattle feed is an important aspect of crop residue use, as India has been the largest producer of milk in India since the mid-1990s [101]. Livestock also contributed 29.7% of the value of output from agriculture and allied sector to GDP [102]. For the production of milk, the availability of feed for livestock is critical. While Thailand is using some rice for feed, it is at less than 1% use [103], a lot more can be used for feed.

2.8 Conclusion

As crop production increases, so dos the production of residue. The traditional management of residue has been to burn it. Thailand is the 6th largest producer of rice paddy and 4th largest of sugarcane in the world. These two crops contribute to 83% of the total residue burned in the country. This burning has major impacts on the environment. Rice and sugarcane burning account for 64% of the PM10, 60% of PM2.5, 86% of NO_x and 84% of SO_2 emissions from all agricultural crops and forest fires in Thailand. While there is a lot of potential for energy production from residues, very little is being used. One reason could be a result of the Sugarcane Act of 1984, which did not target the use of sugarcane or sugarcane residue for use in anything other than for the production of sugar. This disincentivizes farmers to gather the residue. At the same time, The Government of Thailand has implemented policies for the use of residue for renewable energy production since the 1990s. The most recent policy is the Alternative Energy Development Policy of 2012, which has set targets for the use of biomass for energy production. The recent air pollution problem also led the government to implement strict guidelines for purchase of burned cane by sugar mills, with a plan to have zero burnt cane use by 2022. Although there are policies in place, there are many challenges. Small farmers are unable to afford machinery to roll and bale residue or hire labor. There is also lack of awareness of the impacts of residue burning, and farmers in general find it inconvenient to handle the residue. To reduce crop residue burning, sustainable residue management needs to be considered. These practices include using residue for renewable energy. While AEDP is being implemented, the government need to promote new technologies and improve the infrastructure. Another practise is green harvesting, where residue is left in the soil to improve the soil nutrient flow, soil nitrogen and organic carbon. In each of these cases, Thailand can also learn from policies and practices implemented in other developing countries who deal with similar challenges with the use of crop residue.

Chapter 3: Adoption of biomass for electricity generation in Thailand: Implications for energy security, employment, environment, and land use change

3.1 Introduction

As population and economies grow, the demand for limited resources increase, including food, energy and water. In particular, changing production patterns for food and energy could affect changes to land use, water consumption and greenhouse gas emissions. This transition leads to economic, social and environmental challenges through re-balancing the supply and demand in the economy. There is an additional trade-off with the production of food and energy given the limited land available, and other inputs used like water, labor, capital, etc. under environmental constraints. These trade-offs are exacerbated through policy interventions, which target production of energy. Thailand is currently facing such challenges from the perspective of the food-energy-water nexus.

To meet the growing electricity demand, Thailand has increased imports of electricity since 2009, from 2,451.4 GWh (or 1.65% of the total domestic electricity use) in 2009, to 29,550.57 GWh (14.3% of the total domestic electricity use) in 2020 (Figure B1) [10]. This increasing reliance on electricity imports makes the country vulnerable to to energy security challenges in the future. It is expected that the reliance on energy imports will continue to rise, especially coal import, which is projected to increase from 18,287 GWh in 2015, to 54,365 GWh in 2036, or an annual average growth rate of 5.3% per year [11]. This leads the country not just to be vulnerable to energy security but burning of coal would increase emissions in the country.

Looking into the food security, a report of the World Resources Institute showed that 10.3% of the population of Thailand is at risk of hunger, and 69.2% (or 78 million tonnes) of crops produced in the country experience medium to high drought risk [9] with agriculture accounting for 75% of the water demand [104]. Additionally, prevalence of severe food insecurity in the total population (as a 3-year average) has gone up from 4.2% in 2014-16 to 8.5% in 2018-2020 [105]. During the time period 2014 to 2019, cereal production also went down from 54.54 million tonnes to 47.45 million tonnes [12]. With land moving from food production to energy generation, there is a posed challenge for food security as well. From 1990 to 2019, while rice production has increase from 17.2 to 28.4 million tonnes, sugarcane production increased from 33.6 to 131 million tonnes [12]. As crop production increases, the production of residue also increases. Crop residue are traditionally burned, with rice and sugarcane accounting for 87.21% of the burning in 2019 [12]. Crop residue burning does not only have severe environmental and health impacts, but also wastes biomass resources that can lead to income and employment generation. An effective utilization of crop residues as biomass resources could reduce the impact of the competition between land for food or energy. In 2017, the total paddy husk and industrial sugarcane bagasse for electricity generation as a percentage of the total energy potential from these two crops were merely 7.44% and 14.75% respectively [74]. This shows the large untapped potential of biomass which could together address environmental concerns, energy security, and generate revenues for farmers and energy producers. Given that agriculture continues to be the basis of the livelihood of the majority of Thailand's population, the use of more crop residue for electricity generation could positively affect the economy, environment and society.

Although Thailand has been implementing many renewable energy policies since 1990, the recent increases in electricity imports and added food security problems signal the coming challenges to achieving the SDGs of zero hunger (Goal 2), clean water and sanitation (Goal 6), affordable and clean energy (Goal 7), decent work and economic growth, responsible consumption and production (Goal 12), and climate action (Goal 13). Additionally, national level policies can have differing impacts on the regional level. It is therefore important to see the impacts of some policies on the sustainability, through impacts on income, employment, emissions, etc. Most recently, the Government of Thailand has implemented two major policies. One policy targets crop residue burning, while the other targets crop residue use. The first policy, implemented by the Ministry of Industry, targets industrial sugarcane residue burning by ending burned sugarcane use in sugar production, and overall sugarcane burning by 2022 [14]. The second policy, implemented by the Department of Alternative Energy Development and Efficiency (DEDE), Ministry of Energy titled the Alternative Energy Development Plan (AEDP), seeks to achieve 20% electricity from renewable resources, in particular, 5,570 MW from biomass by 2036 [7]. The additional goal of the AEDP is to achieve energy security by reducing the country's reliance on imports, reducing costs so as to improve socio-economic conditions of its citizens, and to reduce the impacts of energy production and use on the environment and community. However, studies have not been conducted to look at the impacts of these policies on the achievement of the SDGs, and the local impacts it may cause in the different regions in the country. Input-output models, which quantifies the inflows and outflows of goods and services, help us understand social, economic and environmental impacts on the food-energy-water interactions [106, 107]. Few studies have looked at the impacts of policies in the interaction [108–110]. Some input-output models have been conducted for water use in Thailand [104, 111], and other input-output studies in Thailand [112,113] but not for the food-energy-water interactions. Extending the input-output method helps understand the direct, indirect and induced effects of a change in policy to the use of intermediate inputs, capital, employment, and water. These studies are fewer for the Extended Input-Output method [106, 114–116] and have not been conducted in Thailand.

To understand the social, economic and environmental consequences of changes in crop residue use for energy generation in Thailand, this paper estimates changes to total output, gross value added, employment, key input use, and land and water use, as a result of policy changes and resulting changing demand over time using the extended input-output model. Adoption of biomass for electricity generation through the two policies implemented by the Government of Thailand as mentioned above, will serve as scenarios for the study. The study compares these policies for the country, and the Northeast region of Thailand. National level policies can have different impacts on a region as compared to the country as a whole, and it is important to highlight the difference in these impacts. This is particularly notable for Northeast Thailand, as it produces 37% of paddy, 44.7% of sugarcane and 47% of electricity from biomass in the country [15–17] making it an important region to study.

3.2 Material and Methods

3.2.1 Extended Input Output Model

The conventional Input-Output (IO) model, developed by Leontief, looks at a country as a huge accounting system, through the inflow and outflow of goods and services across economic sectors in an economy, along with the interrelations between them [117]. The basic equation of the IO model is

$$X_i = \sum_{j=1}^{n} X_{ij} + Y_i = \sum_{j=1}^{n} a_{ij} X_j + Y_i \tag{3.1}$$

In the above equation, X_i is the total output produced in sector i, $X_i j$ is the output of sector i used in the production of sector j, Y_i is the final demand from sector i, $a_i j$ is the quantity of input from sectors i required to produce one unit of sector j's output. Equation 1 in matrix form would be the following

$$X = (I - A)^{-1} Y \tag{3.2}$$

Where X is the column vector of total output, Y is a column vector of final demand. A is a matrix of all $a_i j$ and $(I - A)^{-1}$ is referred to as the Leontief inverse matrix (L).

Equation 2 shows the direct and indirect effects of the flow of goods and services in the economy, shown through the Type 1 multiplier. Multipliers are used to estimate the effects of an exogenous changes on the total output in the economy or on income, capital employment, etc. These total effects can be seen as direct, indirect, or induced changes [118]. The induced effects show that while an increase in total output or demand can lead to an increase in demand for inputs from other sectors, an increase in labor income and employment can induce increases in demand and production in the economy. For this study, direct, indirect and induced effects are looked into. The Type 2 multipliers includes the increase of demand induced by increase in income, employment, etc., seen in a closed input-output model includes all three effects. An expanded $\bar{A}$ matrix is used to include these effects, which is a matrix that includes A, an added (bottom) row of Gross Value Added, or labor income per unit of sectoral output and an added (last) column of consumption share per sector. The expanded $\bar{A}$ matrix will then give the results, as seen in the equation below

$$\bar{L} = (I - \bar{A})^{-1}Y = \begin{bmatrix} \bar{L}_{11} & \bar{L}_{12} \\ \bar{L}_{21} & \bar{L}_{22} \end{bmatrix} \tag{3.3}$$

In this case, when calculating the direct, indirect and induced effects of the n production sectors in the study, $\bar{L}_{11}$ is used. Additionally, $\bar{L}_{22}$ is considered zero.

Once the total output is calculated using Eq. (2), the study looks at the effects on changes to energy use from different sources on Gross Value Added (GVA), labor income, and employment. The equations for direct and indirect effects for GVA, labor and employment are given below

$$GVA = GV(I - A)^{-1}Y \tag{3.4}$$

$$VA_{Lab} = V_{Lab}(I - A)^{-1}Y \tag{3.5}$$

$$EM = E(I - A)^{-1}Y \tag{3.6}$$

In the above equations GV, V_{Lab} and E are diagonal matrices which includes the share of Gross Value Added and labor income in the output of each economic sector, and total employment per unit of sectoral output, respectively. Similarly, to assess the direct, indirect and induced effects of gross value added ($G\bar{V}A$), labor income ($V\bar{A}_{Lab}$) and employment ($E\bar{M}$) using the closed model are given below

$$G\bar{V}A = GV(I - \bar{L}_{11})^{-1}Y \tag{3.7}$$

$$\bar{VA}_{Lab} = V_{Lab}(I - \bar{L}_{11})^{-1}Y \tag{3.8}$$

$$\bar{EM} = E(I - \bar{L}_{11})^{-1}Y \tag{3.9}$$

As we look at the different scenarios, changes to demand leads to direct, indirect and induced changes to total output, demand for inputs from other sectors, employment, labor income and GVA. Therefore, for the scenario analysis, a demand-based analysis is run, where a change in demand for electricity from paddy husk, sugarcane bagasse and other sources of electricity, or a ΔY leads to changes in total output (ΔX), gross value added (ΔGVA), Labor income (ΔVA_{Lab}) and total employment (ΔEMS). Equations (2), (4-9) would therefore show the changes in different scenarios to the left hand side as a result of ΔY. These results are run for both, the national level and the Northeast region of Thailand.

In order to capture both the direct and indirect environmental impacts, the matrix of environmental impact coefficient K (by environmental category, sector and by region) are muliplied with the Leonteif matrix L and changes in final demand vector ΔY, as oresented in Equation (10)

$$\Delta T = K(I - A)^{-1}\Delta Y \tag{3.10}$$

Here ΔT is a matrix representing changes in different environmental-impact indicators as driven by ΔY. In matrix K, each element k_j^{e}, represents direct impact on the environmental category e caused by per unit of economic output of sector j. The environmental coefficients are assumed to be fixed within the study period. The environmental categories included in the research are water (k^{w}), arable land (k^{l}), and CO_2 emissions (k^{e}).

To run the above equations for Northeast Thailand, the data needs to be disaggregated to the regional level. For this, the Fleggs Location Quotient (FLQ) model is used. Location quotient methods are considered the most cost-saving method to downscale the model, which used sectoral outputs at both, the national and regional level to calculate the local IO Model [119, 120]. Technical details of the FLQ method are presented in the Supplementary Materials. Following the FLQ method, to properly balance the IO model for Northeast Thailand, the study minimizes the sum of squares of the percentage difference (Euclidian distance) between the cell figure in the unknown balanced regional table and the corresponding figure in the known unbalanced regional table (subject to the sectoral balance conditions) to get the final local IO table (Equation A1 - A9) [121,122]. The above steps for the extended IO model are implemented for Northeast Thailand. Once the local IO table is created using FLQ, equations (1-9) are run for the region to understand the regional effects, and to compare it with the national level effects.

To calculate the environmental impacts, the study looks at the impacts of the policies on water use, land use, and CO_2 emissions. Impacts on water use is calculated using the changes to final demand leading to changes to the ΔX_i with i as the water use sector in million dollars. To calculate the impacts on land use, the 2014 values are taken and scenarios are built to understand the effects of shifts from rice to sugarcane as a result of the policy. We assume that no land is being shifted from other use to agriculture and we calculate the changes to land use if 30% and 50% land is shifted from rice to sugarcane production, with the rest coming from other agricultural crops. To calculate the effects of CO_2, the emissions from 2014 represent the baseline emissions, which increases with the increase in total electricity demand over time, based on the three scenarios. The reduction in emissions represent the shift from other sources of electricity to the use of rice and sugarcane for electricity consumption. The proposed model is run for the baseline year 2014 and 3 policy scenarios as presented in Section 2.2 below. The modeling analysis in these scenarios give us insight into the value of policy on labor income, employment, the supply chain, water use, land use, etc. Jointly with the three scenarios, the model is run for Thailand and the Northeast region of Thailand. One of the policy scenarios, as explained in section 2.2 will also be considered the optimal, or best-case scenario. However, with the model, the technology represented by the A Matrix in Equation (2) is assumed to be the same, and is considered a limitation to the model.

3.2.2 Scenarios

As mentioned above, the study looks into three scenarios, which address two policies implemented by the Government of Thailand, with specific targets and timelines. The three scenarios are: (i) Scenario 1: Policy for the reduction of sugarcane burning by 2022, (ii) Scenario 2: Alternative Energy Development Policy (AEDP) with a 2036 target, and (iii) Scenario 3: increasing the AEDP targets of 2036 by 50% for biomass electricity. The choice for the 2 years i.e., 2022 and 2036 are based on the target years for the policies. These policies are based on changes to crop residue burning, and use of it in energy generation as the future demand for electricity consumption increases. It is therefore important to see how the demand increases and subsequent policies on crop residue burning and use could trigger changes to total output, gross value added, employment, key input use, and land use. The demand for electricity, according to the Department of Alternative Energy Development and Efficiency, Ministry of Energy will increase from 174,467 million units in 2014 to 326,119 million units in 2036 [7] or an annual growth rate of 2.88%. This increase in demand leads to increasing targets for electricity production from paddy husk and sugarcane bagasse as a percentage of the electricity mix in the country. For the first scenario, the zero burning policy implemented by the Ministry of Industry targets the purchase of burned sugarcane by sugar mills. The policy developed seeks to force sugar mills to reduce the share of burned cane in their total sugarcane purchase and eventually reducing it to less than 5% by 2022 [14]. To achieve this, the policy also provides cheap loans for farming cooperatives and community enterprises to purchase cane cutting machinery, as the cost of such machinery is high, and without which, it is highly labor intensive [123]. In 2014, the energy potential from industrial sugarcane bagasse was 5,021.9 ktoe, of which, we assume 40% is used for electricity generation. Over time, there is also an annual projected growth rate of 1.16% for sugarcane [124]. Considering both, we expect 12.16% electricity coming from sugarcane bagasse in 2022. As this policy does not target rice paddy burning, we assume the same percentage from 2014 being used for electricity generation. We also call this the best-case scenario as we are assuming a high use of the total energy potential for industrial sugarcane bagasse. The second scenario looks into the Alternative Energy Development Plan which seeks to have 20% electricity from renewable sources, of which, 5,570 MW coming from biomass and a projection of 27,789 ktoe of electricity demand in 2036 [7]. Here we assume the electricity coming from sugarcane bagasse and paddy husk increase in accordance with the percentage from biomass, and the total projected electricity demand increase or 1.61% and 5.09% from paddy husk and sugarcane bagasse respectively [125]. In the third scenario, we assume an increase of 50% of biomass electricity targets of the AEDP, or 8,355 MW coming from biomass, which is an increase to 2.42% and 7.64% from paddy husk and sugarcane bagasse. Additionally, as the Thailand Government implemented a 20% burned cane requirement for the country as a result

Table 3.1: Scenario setting for the model for paddy and sugarcane for electricity production

	Baseline	Scenario 1	Scenario 2	Scenario 3
Policy		Zero Burning Policy for sugarcane	Alternative Energy Development Policy (AEDP)	Increasing AEDP targets by 5%
Name	2014	No Burn (Best Case)	AEDP	AEDP1.5
Target Year		2022	2036	2036
Paddy husk in electricity	1.33%	1.33%	1.62%	2.43%
Sugarcane bagasse in electricity	4.19%	12.16%	5.1%	7.65%

of the policy implementation of Scenario 1, we assume that the percentage of burned cane is below that in the production of electricity [126]. This assumption is based on the use of industrial sugarcane bagasse in the production of electricity. These scenario will help us understand the potential of biomass electricity. The summary of the three scenarios can be seen in Table 3.1 below.

3.2.3 Data

The input-output model data from 2014 is obtained from the Global Trade Analysis Project (GTAP) v10 database, which includes 65 sectors, including electricity generation [127]. The electricity sector for the study are split into three sectors, electricity from paddy husk, electricity from sugarcane bagasse, and other sources of electricity, based on the demand increases and percentage from each of the three sources, as provided in the previous sections. Through data obtained from the Department of Alternative Energy Development and Efficiency, Government of Thailand, 1.33% and 4.19% of total electricity came from paddy husk and sugarcane bagasse respectively in 2014 [125]. As a result of changing demand, we do not change a_{ij} for the different scenarios, as we have assumed technology remains the same. The empirical analysis of the economic effects used publicly available data from various sources. The national level data used employment information [128], household income per capita [129], and population data [67]. The downscaling of the model for Northeast Thailand required local Gross Regional Product (GRP) [130], paddy production and land area for paddy and cane [15], sugarcane production (OCSB, 2015), employment [128], household income per capita [131], population data [132], and biomass electricity production [17]. For the case of Northeast Thailand, the GTAP database from 65 sectors are consolidated to 10 sectors given the GRP data for Northeast Thailand. This consolidation keeps electricity from paddy husk, electricity from sugarcane bagasse, and other sources of electricity as three separate sectors. The data sources for the 2036 demand scenarios come from the AEDP policy scenarios which provides the projected demand for electricity and subsequent aims of biomass production as a percentage of the electricity demand [7]. These two data helps us provide the future demand projections of electricity from paddy husk, sugarcane bagasse and other sources of electricity.

3.3 Results

3.3.1 Social and Economic Impacts for Thailand and Northeast Thailand

The demand driven solutions run for Thailand and Northeast Thailand help us understand how changes to the final demand over the baseline and scenarios would affect the changes to the total economy, as well as for each source of electricity. Demand changes to the electricity sector would lead to changes in total output from all sectors, by driving the demand for inputs, as well as the total output of the individual electricity sectors. Figure 3.1 shows the changes to total output in the entire economy as a result of the changes in final demand under three scenarios. The images show that the induced effects in the country are 2.8, 6.42 and 6.43 times higher than in in the Northeast Thailand under scenario 1-3 respectively. As demand increase and technology remains the same for the two 2036 scenarios, the total output increase remains the same for AEDP and AEDP1.5.

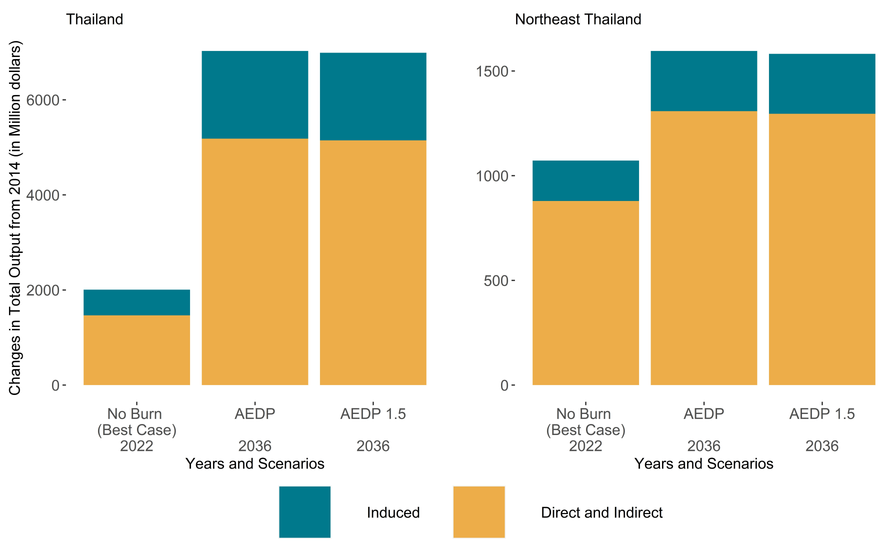


Figure 3.1: Changes in total output of the economy driven by demand changes (direct, indirect and induced) for 3 scenarios from the 2014 baseline in Thailand (left) and Northeast Thailand (right)

We also see a difference in increases to the total output in the three electricity sectors. We see in figure 3.2 that for Thailand, increase in the total output of the electricity sector triggered by the use of sugarcane bagasse for electricity generation is the highest in the best-case scenario in 2022. The best-case scenario, as mentioned above, uses 40% of the total electricity potential from industrial sugarcane bagasse, accounting for 12.16% of the total electricity. This leads to sugarcane bagasse accounting for 43% of the increased output for the electricity sector. The best-case scenario highlights the large potential of electricity from biomass, and how an increasing reliance on electricity from biomass improves its goals of energy security and the attainment of the SDGs. The AEDP and AEDP1.5 scenarios leads to an increase in electricity from paddy husk and sugarcane bagasse, but it is leaving out a large potential of crop residue to generate electricity. The production of electricity also induces approximately $35 million of electricity output value in the AEDP and AEDP1.5 scenario. For the case of Northeast Thailand, which accounts for large shares of paddy, cane and electricity from biomass, we see very different results. The Gross Regional Product of electricity in the Northeast Thailand accounts for 6.8% of the region's GDP, and while the share of rice , sugarcane and biomass electricity production (37%, 44.7% and 47% respectively) is higher percentage of the national figures. income and demand for electricity in the region are closer to the share of the regions GDP. The total output for the three electricity sectors shows that the increase in the use of sugarcane residue is highest for the AEDP1.5 scenario. At both, the national and regional level, AEDP falls short of using the high potential of biomass for electricity generation, although relative to the no burn scenario, AEDP with 50% target increase, Northeast does better. Given the goal of achieving energy security, they fall behind It is worth highlighting that the percentage of households in debt in the Northeast Thailand (56.5%) is noticeably higher than the country average (47.2%). Therefore, both AEDP and AEDP1.5 could be more incentive compatible for making additional sources of income in the Northeast region [15], where the production levels of cane and rice are significantly higher than the other regions, resulting in an additional benefit to the agricultural households in the region.

The study also addresses how changes to the final demand over the scenarios would change employment, gross value added (GVA) and labor income, as seen in table 3.2. Employment generation through the implementation of these policies shows much smaller impact in Northeast Thailand than in Thailand. For electricity from the cane sector, the best case scenario shows

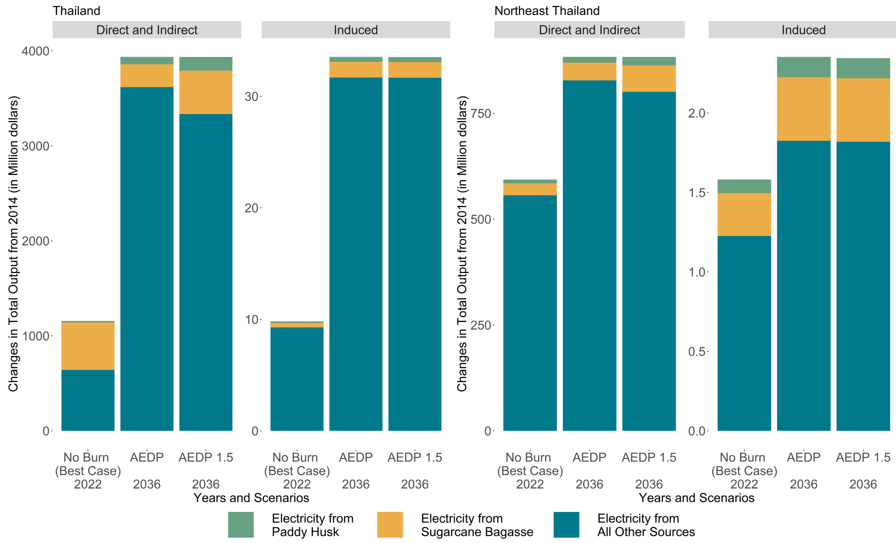


Figure 3.2: Changes in the total output of the electricity sector (direct, indirect and induced) for 3 scenarios from the 2014 baseline in Thailand (left) and Northeast Thailand (right)

that employment doubles in Thailand, and for the AEDP1.5 scenario, there is a 30% increase in employment in Northeast Thailand. Agricultural sector currently employs 30% of total labor force, but contributes to 10% of the GDP, but 40% of farming households live below the national poverty line, and 42% do not own land [133]. Given that majority of crop residue is burned, selling crop residue can be an additional revenue and employment source for the farming community. Gross value added for Thailand, which includes land income, capital, tax, and labor income, shows most significant increases for electricity from sugarcane in the case of the best-case scenario. For Northeast Thailand, the highest increases are seen in AEDP and AEDP 1.5, with a 30% increase in GVA in the AEDP1.5 scenario. The labor income increases for other electricity production for AEPD and AEDP1.5 are 857 and $791 million for Thailand, respectively looking at all direct, indirect and induced effects. Labor income increases resulting from changes to electricity production will lead to higher purchasing power, and therefore, inducing demand for other products in the economy. For Northeast Thailand, labor income from sugarcane bagasse increases by \$8, \$12, and \$18 million under the best-case, AEDP, and AEDP1.5 scenarios, respectively . Given the prevalence of poverty, an increase in employment and labor income for the region would positively impact the Northeast economy. In addition, employment increases show significant social benefits of crop residue use though most powerplants in Thailand are very small power plants with a capacity of less than 10 MW [134]. To improve energy security through crop residue use, these powerplant capacities and numbers would need to increase significantly. Through research and development, and infrastructure growth, employment would increase, along with income and output from other the electricity sector. The social, environmental and economic benefits of that growth will be significant in Thailand, and could help achieve the SDGs.

With increases in demand, there are also increases in inputs used for the production of the electricity. As the electricity sector relies on other sectors for their inputs, any changes to the demand in the electricity sector will see changes in total output and production in other sectors. The six key sectors for electricity production are seen in Figure 3.3 for Thailand and Figure 3.4 for Northeast Thailand. In the case of Thailand, gas extraction, gas manufacturing and distribution and other financial intermediaries see large increases in direct and indirect effects, but very little induced effects. Other business services, petroleum and coke manufacturing and wholesale retail and trade leads to large induced effects as well through the supply chain. Increase in gas extraction, gas manufacturing and distribution and petroleum and coke manufacturing has significant effects on the environment, land use,water use, etc. The increase in wholesale retail and trade causes large induced effects of nearly 81 million, while the direct and indirect effects are approximately \$139 million. The effects in the key sectors show that there are large direct, indirect as well as induced effects to the Thai economy as a result of increasing electricity demand and production. The direct, indirect and induced effects, especially in gas extraction, gas manufacturing and distribution and petroleum and coke manufacturing are a cause of concern in many aspects. Firstly, to achieve the SDGs, this would post an issue with many of its' goals, especially the two goals targeting affordable and clean energy, and climate action. Secondly, with a goal of reducing the impact of energy production on the environment, the AEDP would fail to meet that target. Finally, it can cause an increase in energy imports. According to the ITA [135], more than half if the country's energy sources are dependent on imports, which is also likely to increase as domestic known oil and gas reserves deplete. However, the increase in biomass production can cause enough benefits to counteract these negative impacts. Increases from 2014 in total input from the key sectors (direct, indirect and induced) for 3 scenarios in Thailand (listed from the largest increase to the smallest).

Table 3.2: Scenario setting for the model for paddy and sugarcane for electricity production

Employment (in persons)									
		Thailand				Northeast Thailand			
		Electricity from Paddy	Electricity from Cane	Other Electricity	Total	Electricity from paddy	Electricity from Cane	Other Electricity	Total
2014	D+I	2,628	8,473	177,800	22,816,345	1,359	4,356	9,376	3,113,948
(Level)	Induced	846	2,727	57,230	4,712,682	149	477	1,502	327,696
No Burn	D+I	242	8,063	9,599	27,176	187	601	8,179	22,989
(Change)	Induced	2	7	139	11,441	2	6	18	3,935
AEDP	D+I	1,206	3,889	54,208	94,427	279	894	12,171	34,211
(Change)	Induced	7	23	475	39,087	3	9	27	5,855
AEDP1.5	D+I	2,281	7,354	49,958	94,244	414	1,328	11,774	33,791
(Change)	Induced	7	23	474	39,068	3	8	27	5,836
Gross Value Added (in Million Dollars)									
		Thailand				Northeast Thailand			
		Electricity from Paddy	Electricity from Cane	Other Electricity	Total	Electricity from paddy	Electricity from Cane	Other Electricity	Total
2014	D+I	141.66	456.66	9,582.89	301,935.17	62.12	199.19	428.74	31,341.61
(Level)	Induced	45.6	146.99	3,084.53	72,793.99	6.8	21.8	68.67	3,430.78
No Burn	D+I	13.05	434.57	517.35	1,153.23	8.57	27.47	373.99	591.65
(Change)	Induced	0.11	0.36	7.49	176.72	0.08	0.26	0.82	41.19
AEDP	D+I	65.02	209.61	2,921.67	3,923.47	12.75	40.88	556.54	880.44
(Change)	Induced	0.38	1.22	25.58	603.75	0.12	0.39	1.23	61.3
AEDP1.5	D+I	122.97	396.38	2,692.60	3,923.47	18.94	60.73	538.39	880.44
(Change)	Induced	0.38	1.22	25.57	603.46	0.12	0.39	1.22	61.1
Labor income (in Million Dollars)									
		Thailand				Northeast Thailand			
		Electricity from paddy	Electricity from Cane	Other Electricity	Total	Electricity from paddy	Electricity from Cane	Other Electricity	Total
2014	D+I	41.21	132.85	2,787.86	120,470.95	18.07	57.95	124.73	12,063.57
(Level)	Induced	13.27	42.76	897.35	31,935.32	1.98	6.34	19.98	1,389.88
No Burn	D+I	3.8	126.42	150.51	373.61	2.49	7.99	108.8	212.36
(Change)	Induced	0.03	0.1	2.18	77.53	0.02	0.08	0.24	16.69
AEDP	D+I	18.92	60.98	849.98	1,310.84	3.71	11.89	161.91	316.02
(Change)	Induced	0.11	0.35	7.44	264.87	0.04	0.11	0.36	24.83
AEDP1.5	D+I	35.77	115.32	783.33	1,302.68	5.51	17.67	156.63	314.16
(Change)	Induced	0.11	0.35	7.44	264.74	0.04	0.11	0.36	24.75

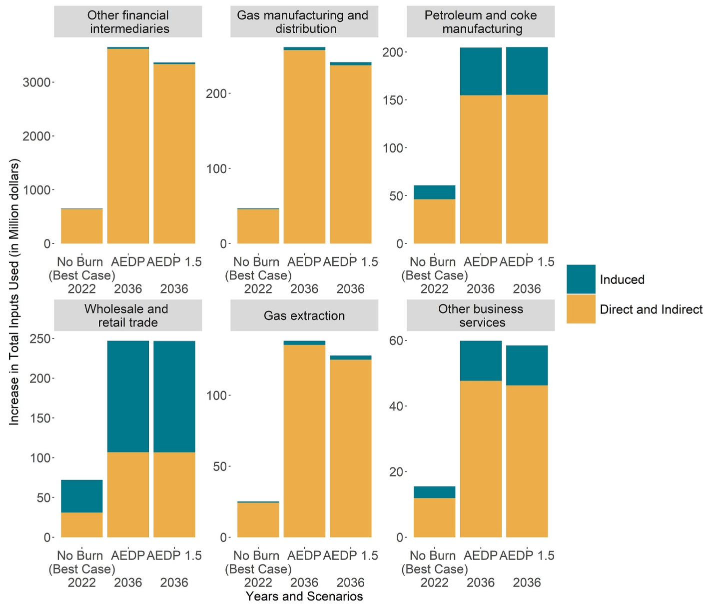


Figure 3.3: Increases from 2014 in total input from the key sectors (direct, indirect and induced) for 3 scenarios in Thailand (listed from the largest increase to the smallest).

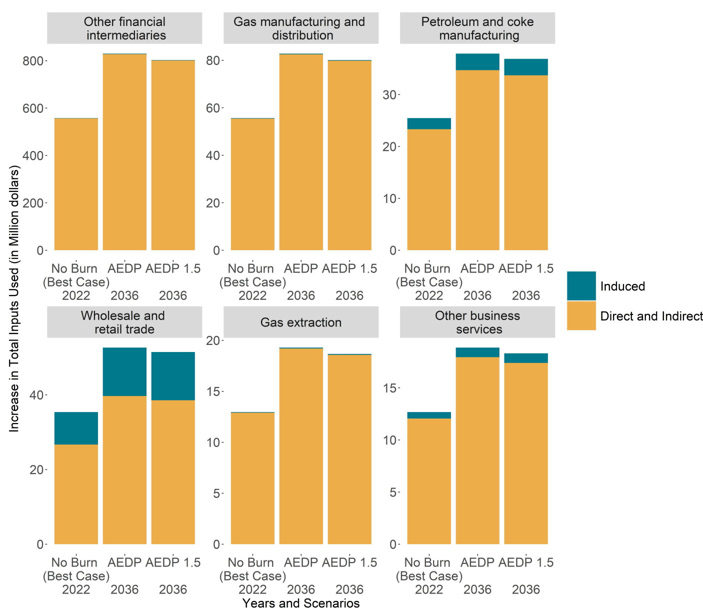
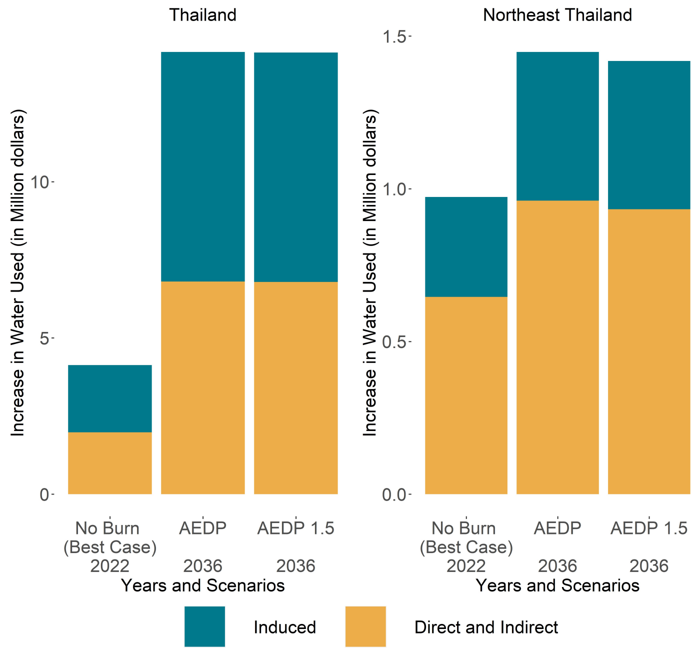


Figure 3.4: Increases from 2014 in total input from the key sectors (direct, indirect and induced) for 3 scenarios in Northeast Thailand (listed from the largest increase to the smallest)

3.3.2 Environmental Impacts for Thailand and Northeast Thailand

Figure 3.5 shows the effects on water-use caused by the increases in electricity demand and changes in the source structure of electricity generation. In Thailand, the direct and indirect, and induced effects on increase in water-use are nearly equal, with \$2.51 million being direct and indirect effect and \$2.49 million induced effect in the best case scenario, which accounts for 270 and 300 thousand m^3 of increase in water use respectively while in the AEDP and AEDP1.5, direct and indirect effects are \$8.54 million while induced effects are \$8.48 million (940 and 1,020 thousand m^3 of increase in water-use respectively). As mentioned previously, 69.2% of crops produced in Thailand experience medium to high drought risk [9]. The drought in 2020, which was worst drought in 40 years, led to sugar output reduce by about 30%, cane output fall from 130 million tonnes to 90 million tonnes from the previous year, cost the country 46 billion baht or 0.27% of the GDP (Bangkok Post, 2020). Additionally, just 26% of agricultural households have access to irrigation in Thailand [133]. Although the increase in water use in the electricity sector is not as large as the agriculture sector, it is important to ensure water security in order to achieve energy security, which is a goal of the AEDP. Additionally, droughts can impact production of crop residue inputs in the country. Northeast Thailand faces different effects than the national average. The direct and indirect effects are large for Northeast Thailand, but the induced effects are much lower than that of the country with a direct and indirect increase of 130 thousand m^3 of water, and induced increase of 70 thousand m^3. During the 2020 drought, 10 out of the 25 regions that declared a drought disaster were in Northeast Thailand [136]. With just 10% of the cultivated area irrigated in the Northeast Thailand [137], droughts will have a larger impact on the input supply in the region. In 2021, the water levels of the three main tributaries of the Mekong River in Thailand were at 10-20% of their capacities in the Northeast, leading to the Government asking farmers to rely on other sources of water supply. They also targeted groundwater distribution as the Office of National Water Resources (ONWR) given the shortage of water in some provinces in the region [138]. Additionally, as mentioned before, while 26% of agricultural land is irrigated in Thailand, it is mostly concentrated in the Central, lower North and Bangkok and its vicinities [133]. Irrigation percentage in the Northeast is much lower, at 10% of the cultivated area [137]. As mentioned before, although water use is not as high as the agricultural sector, Northeast Thailand would be impacted in terms of agricultural production, Northeast Thailand produces large quantities of crop, and therefore crop residue, and biomass production in the country, making even small increases in water use in the electricity sector more challenging. Therefore, high direct and indirect effects can greatly affect electricity supply in the region.

As a result of the Office of Cane and Sugar Board Sugarcane and Granulated Sugar Act of 1984 [64] a revenue sharing scheme where farmers earn 70% of revenue from domestic and export sales of sugar and molasses, with the mills receiving 30% revenue. Although there are no such incentives for the use of biomass to produce electricity, the production of sugar is more appealing given the observed and foreseen rising price of sugar relative to rice in the international market. We assume that there would be a growth of land-use for sugarcane at the same rate from 2000 to 2014, or a 2.16% annual increase. Assuming that there is not deforestation, the land for sugarcane is taken from other agricultural land or reclaimed land. For Thailand, we take an increase in the sugarcane land with 30% and 50% coming from rice as two land-use scenarios, with the rest coming from other crops or reclaimed land not identified in the research. Value-added from land input increase is significantly lower for sugarcane at the national level and

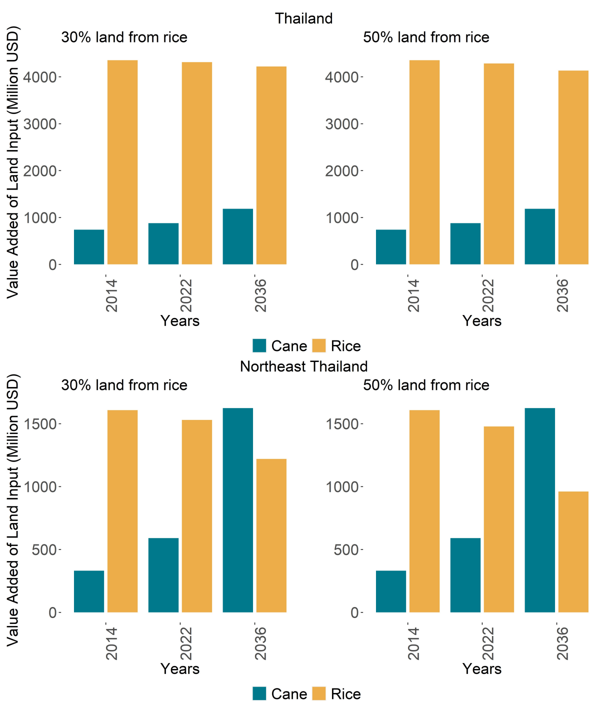


Increase in Water Used (in thousand m^3)

		Thailand	Northeast Thailand
No Burn (Best Case)	Direct and Indirect	270	90
	Induced	300	50
AEDP	Direct and Indirect	940	130
	Induced	1020	70
AEDP1.5	Direct and Indirect	940	130
	Induced	1010	70

Figure 3.5: Increase from 2014 in water use in electricity generation (direct, indirect and induced) for the 3 scenarios in Thailand and Northeast Thailand in million dollars, and in thousand m^3.

therefore sees little change in land use from rice to cane (Figure 3.6) but the value added per 1000 hectare for sugarcane is higher than that of rice. Similar to the case for Thailand, the land use changes take 30% of 50% of value added of land input from rice. However, a study of Northeast Thailand shows that there is a 7.5% increase in sugarcane area from 2006 to 2015 for the 3 largest sugarcane-producing provinces in Thailand [139]. Using this as a rate of increase of sugarcane in the region, sugarcane would significantly be higher in the region by 2036 and will overtake rice production (Figure 3.6). Additionally the larger difference in value added per hectare between rice and cane in Northeast Thailand increases the incentive to shift from rice to cane. This could also have implications to water supply, as sugarcane uses much lesser water than paddy, but with increasing reliance on energy security, and incentives to irrigate land for energy security, the tradeoff may not be as high. At the same time, this can become a major food-security challenge. As mentioned in the introduction, prevalence of severe food insecurity in the total population went up since 2014, and cereal production went down. With sugarcane production increasing for sugar and electricity production, this could exacerbate these challenges. These results are also in lines with the shifts being seen from rice to sugarcane [140]. This shift could potentially be seen as the government plans to improve rice production practices or alternately, changing from rice to other crop production to reduce stress on natural resources, etc. [141]. These practices can, however, pose food security challenges [142], but is more beneficial to farmers, as they receive better prices for sugarcane [140].



Value Added of Land per Hectare (USD/Ha)

		2014	2022 30% from rice	2022 50% from rice	2036 30% from rice	2036 50% from rice
Thailand	Rice	373.8	372.6	371.9	370	367.4
	Cane	551.3	551.3	551.3	551.3	551.3
Northeast	Rice	267.7	261.3	256.8	231.9	201.8
	Cane	520.5	520.5	520.5	520.5	520.5

Figure 3.6: Value Added of Land input scenarios for sugarcane increase in 2014, 2022 and 2036 for Thailand (upper) and Northeast Thailand (lower) and the Value added per hectare (USD/Ha) for the different crops

Finally, in terms of CO_2 reduction resulting from crop residue use rather than other sources of electricity, the data for Thailand is gathered from the GTAP database for each sector. The highest reduction in CO_2 emissions are for the AEDP1.5 scenario at 12.63 MT, followed by the best case at 11.38 MT and AEDP at 8.42 MT respectively, with the best-case scenario having lower emissions in total (Figure A2). An increased use of biomass for electricity generation can lead to another focus of the AEDP, which is to reduce impacts on the environment.

3.4 Discussion: Potential and critical future supply changes

The study above shows that the AEDP has not been able to capture a large potential of energy from paddy husk and sugarcane bagasse at the national level but does a little better for the Northeast of Thailand. According to IRENA [92], to reach the current target for electricity generation, an additional capacity of 11,721 MW would need to be generated, and in particular, there would be a doubling of installed generation capacity from biomass. Even with a lower target, the biomass generation capacity is low. Incentives would therefore need to be put in place to install and increase infrastructure and technologies. While the Northeast Thailand produces a lot of rice, sugarcane and biomass for electricity, the local consumption is low, with high levels of poverty. The study shows that increasing the AEDP targets, for the third scenario, shows significant increase in income, and employment in the country and the region.

The inability to capture the electricity potential from crop residue is not just a lost opportunity for the AEDP, employment, and income, but it also fails to achieve the threefold focus of the policy to reduce its reliance on imports, keeping costs low so as not to be an obstacle to socio-economic development, and to reduce its impact on the environment and community. Increasing the use of crop residue also could help achieve the SDGs. However, transition from rice to sugarcane in Thailand, and the Northeast in particular, can pose challenges to food security, given that the land for cane would replace a noticeable share of paddy by 2036 in both scenarios.

Technology is an important factor that should be considered for future production of crops, as well electricity production technologies. According to Heo Choi [75], commercial second generation biofuel technology in Thailand is not being developed. This not just poses a challenge to the production of biofuels, but also energy in general. A similar study on policies by Chaya et al. [89], which studied the AEDP shows that not a lot of incentives have been placed to promote technology for the production and use of ethanol, and improvement of infrastructure. These are not just challenges, but could also affect future production and supply electricity from crop residue. However, some of the AEDP goals include improvements in technologies, which could steer the development of technologies in the residue use sector. This could include expansion of power generation capacity, transmission and distribution, and other technologies to make biomass electricity generation more efficient and cost effective. As mentioned previously, many of the powerplants in Thailand are less than 10MW, and therefore, investments are necessary for infrastructure development, and scaling up the size of existing and future powerplants. In the No burn scenario, where 40% of the electricity potential from industrial sugarcane bagasse is used, the capacities would increase significantly.

Another important element is to ensure improvement in machinery's for farming. Through the policy used as a representation of the No burn scenario, the government provides low interest soft loans to farmers to buy cane harvesters, and some loans to sugar millers to purchase machinery [79]. However, these costs are still too high for farmers to pay back those loans. Increasing debt is a challenge in the country, especially for small-scale farmers and some farmers feel that mechanization for harvesting and baling could likely cause damage to the field and compact soil, making tillage difficult [48,133,140]. While farmers admit that they want cleaner air, they choose to burn as a last resort, as their profits are not enough to purchase these machines, which cost 6-7 million Baht [140]. These issues become even more challenging in the Northeast given the higher quantities of rice and cane production and the larger levels of debt. Therefore, more subsidies need to target mechanization of crop production by farmers. This could be done while managing potential trade-offs for soil health as a result from increasing mechanization and changes in residue management practices. Additionally, as mentioned previously, a higher wage is given to farmers who provide fresh cane, as opposed to burned cane, and the use of crop residue can provide an additional source of income to the farming community. As a very large percentage of households in the country are in debt, with an even higher percentage in the Northeast, therefore subsidies would be an effective solution to prevent debt trap occurrence and to ensure a potential increase in revenue sources for the households.

While we see that there are significant changes to policy affecting the output of electricity, it is also important to highlight some other changes and factors which could affect the supply side of this problem. There has been an overall reduction in the past decade for area harvested under rice paddy, with some increases since 2016 (Figure A3). Sugarcane area has increased slightly but at a much lower rate (Figure S3). There is also an expected shift from rice to sugarcane production as addressed in section 3.2., which can affect the production of electricity using paddy husk and sugarcane bagasse along with food security. We also see that there is more fluctuation in producer price of rice paddy than for sugarcane in Thailand [143] that farmers have cited as a reason to shift from rice to sugarcane [140]. The ITA [135] also shows that there are moderately high risk of raw material shortages and rising prices. Additionally, because of the

Sugar Cane and Granulated Sugar Act [64], which guarantees a price for sugarcane producers for sugar production. This could show a potential shift from rice to sugarcane. As seen before, in the Northeast, in both cases, the land for sugarcane would surpass land for rice, and this could pose a significant challenge to an already increasing food insecurity problem in Thailand. This could also impede the development and achievement of the zero-hunger goal of the SDGs.

Although the above talks about the price of the crop for use, the crop residue price has not been set or considered. The Thailand Government implemented a Feed-in Tariff scheme to incentivize investment to mitigate any investment risks. According to the Thailand Board of Investment [144], they ".. fixed [a] buying rate for electricity calculated from initial investment of power plant construction and the full lifetime used of its operation and maintenance cost. Further, price inflation for raw material used in biological energy production (for waste, biomass and biogas) is expected. As such, the scheme will also compensate for this by adding an additional rate (FiTv,2017) on top of the fixed buying rate (resulting in FiT(1))." Subsidies have also been provided to biomass energy over time for all sized power plants, including paddy husk and sugarcane bagasse [71, 72]. This could go a long way in incentivizing the sale of crop residue to support farmers, and the powerplants. Given the long period of 20 years, it is a consistent source of income, and can improve technology and mechanization in the areas.

An important resource use is water, which is not just affected by climate, but also affected by changes to irrigated and unirrigated areas. In all scenarios for Thailand, there are equal direct and indirect, and induced effected for water use as an input. For Northeast Thailand, there are large direct and indirect effects. As we move towards food and energy security, irrigation would be an important aspect to consider. According to WRI [9], just 44% of crop area in Thailand is irrigated, and of this land, 45.1% and 20.5% face high to extremely high water stress respectively.

Rainfed agriculture has additional challenges to water supply security with droughts increasing in the region. At the same time, 69.2% of total crop production has mid-high drought risk. When it comes to water stress, 27 of 68 provinces in Thailand with data show high to extremely high water stress, with the overall Thailand score for agriculture to be 3.04, which is high water stress [9]. As mentioned before, droughts have great effects on the farming and the GDP of the Thailand economy. With increases in water stresses, there could be further changes to production of crops, leading to further energy security challenges. Additionally, with a very small percentage of farmers having access to irrigation in Thailand, and an even smaller percentage in the Northeast, droughts would exacerbate the inequity. Irrigation, while can be a solution, it is still a challenge with increasing droughts, increasing agricultural production, consumption, and competition with other sectors. Here again, technological innovations to effectively and efficiently use water for both, crop and energy production would be a key solution.

3.5 Conclusion

Thailand faces current and future challenges with food and energy security, alongside socio-economic and environmental concerns. To address some of these issues, Thailand introduced two policies, one targets adoption of biomass for electricity generation, which could achieve energy security, lower costs, and reduced impacts on the environment. The second policy targets sugarcane residue burning for the production of cane, which helps reduce the impacts of crop burning in the country. While these policies are implemented, it is important to see how these policies could impact the economy, society and environment and through those, the achievement of the Sustainable Development Goals (SDGs).

The Extended Input-Output model for Thaialand and Northeast Thailand provides the direct, indirect and induced effects of Government policies as a result of changing demand on the output, labor income, employment, water, land use, and CO_2 emissions. With 2014 as a baseline, and three future scenarios represented by the two aforementioned policies (best case scenario, AEDP and AEDP1.5) we assess impacts of increasing demand on production, labor income, employment, input use, land use and other environmental impacts.

The results show that the total output increase as a result of increasing demand significantly for both, Thailand and Northeast Thailand. For the three electricity sectors, we see that the best-case scenario is most effective in capturing the potential of biomass at the national level, while in Northeast Thailand, can capture a much larger potential of biomass in the AEDP1.5 scenario. Because of demand and output increases, the input used for production also increases. The largest sectors that see increases include gas extraction; gas manufacturing and distribution; and petroleum and coke manufacturing.

When addressing the impacts on the environment, the first impact is on water use for the three electricity sectors, sees equally high direct and indirect; and induced effects at the national level. For the Northeast Thailand, while the direct and indirect effects are high, the induced effects are much lower than at the national level. Additionally, Northeast, which is more vulnerable to droughts could see worsening impacts. As land use shifts towards sugarcane, as policies incentivize its production, Northeast Thailand would see sugarcane surpassing rice production in the region, which could cause food security challenges. Finally, CO_2 emission reduction through biomass production can be seen to be significant for Thailand.

For the national level, the AEDP policy has not captured the full potential of biomass for electricity production, and this can set back achievement of the policy goals, as well as the

Sustainable Development Goals (SDGs). Although adoption of biomass can improve the impacts on the environment and improve energy security, it is also important to keep food security in the policies too, as replacement of rice to sugarcane can lead to food insecurity in a country which is seeing increasing food insecurity.

These policies overall, for Thailand and Northeast Thailand, through accelerating the use of renewable energy can lead to the achievement of SDGs. These policies are able to ensure energy security while using an untapped potential of crop residue, which leads to energy security, technological development and energy efficiency. Through these results, we see they also help in achieving decent work and economic growth, responsible consumption and production, through reduced residue burning, work towards climate action.

Chapter 4: Multi-reservoir, multi-demand water optimization model through maximization of profits and social equity: A case for Sao Paulo, Brazill

4.1 Introduction

As climate change affects rainfall and temperature, droughts are worsening in many parts of the world. Inadequate water supply threatens achievement of the sustainable development goals, given the importance of water in achieving the goals, including food security, clean water and sanitation, affordable and clean energy, sustainable consumption and production, etc. The food-energy-water nexus exacerbate this conflict through competition for an even more limited resource, and can lead to scarcity of food and energy supply. This can cause additional stress to human well-being, poverty reduction and sustainable development. According to D'Odorico et. al., [145] an overlooked aspect within the FEW nexus is the increasing competition for water resources between food and energy, which they state will dominate the water security debate within the next few decades. With growing demand for food, energy and shifts towards renewable energy, the competition for water within the sectors will become an imminent challenge. While these demands increase, the competition the same or a depleting quantity of water is a cause for major concern [6, 146, 147].

Although there are major challenges, one solution is to optimally allocate the limited water given economic, social and environmental challenges that countries might face. Water managers need to make critical decisions, when it comes to allocating drinking water supply, ensuring economic growth from different sectors, and allocating essential drinking water to municipalities. Many techniques have been developed to achieve the objective of water policy making, which include statistical [148–153], dynamical [154–156] or mixed models [157, 158]. At the same time, optimization models are being considered to deal with the challenge of water demand, given the changing supply. The models target demands through looking into single sectors like irrigation [159–161], hydropower [162, 163], single or multiple industries [164–166] or drinking water [167–169]. Some models also many objectives, for example, many sectors, multiple reservoirs, or include climate predictions [170–174].

Although there have been these various advances in the modeling of water, and for water delivery, there are challenges to application of these models in the field, especially when it *involves complex quantitative operations at different levels* [170]. The objective of this essay is therefore to present a economic model for profit maximization at the study region level, that is linear, requires lower computing power and replicable. The replicable nature of this model also allows for transparency and could facilitate conversations between different stakeholders, which could include policy makers, civil society, water managers, etc. Additionally, the replicable nature of the model also allows for climate predictions through changes to water supply, and infrastructural and policy scenarios through adding reservoirs, including new demand sources, etc. The model includes multiple demand sources, sectors, reservoirs and timeline. The objective of the essay is to run the model for a region in the state of São Paulo to show the usability of the model. São Paulo state is chosen given the challenges it faces with water supply along with the economic importance of the region to the country in the food-energy-water nexus, along with industry. The essay will go through the model, describe the case study, present the results, go through a discussion which includes limitations followed by the conclusion.

4.2 Methodology

4.2.1 Profit Maximization Model

To maximize profit, we look at the sectors of rice, sugarcane, ethanol, hydropower and municipal water supply. The optimization model maximizes profits from different reservoirs (d) and for a specific time period (t), different municipalities producing rice (r), sugarcane (c), ethanol (e), reservoirs producing hydropower (h) and the total municipalities to be supplied (p) as seen in equation 1 below

$$
\begin{aligned}
\textit{Maximize } Z = \sum_{t=1}^{T} \sum_{t=1}^{T} \Big\{ & [A_{rt} \times Y_{rt}(P_{rt} - C_{rt}) - Q_{drt} \times CW_{drt}] + \\
& [A_{ct} \times Y_{ct}(P_{ct} - C_{ct}) - Q_{drt} * CW_{dct}] + \\
& [A_{et}(P_{et} - C_{et}) - Q_{det} \times CW_{det}] + \\
& A_{dht}[P_{dht} - C_{dht} - CW_{dht}] + \\
& [Q_{dpt}(P_{pt} - CW_{dpt})] \Big\}
\end{aligned}
$$

$$\text{for all } t = 1, \ldots, T \text{ and } d = 1, \ldots, D \quad (4.1)$$

where

A_{rt} $\rightarrow$ Area under rice production at time t

P_{rt} $\rightarrow$ Per unit price of rice at time t

Y_{rt} $\rightarrow$ Rice yield at time t

C_{rt} $\rightarrow$ Cost of input per unit area of rice at time t

Q_{drt} $\rightarrow$ Water required to cultivate area of rice at time t for reservoir d

CW_{drt} $\rightarrow$ Cost of water for rice at time t for reservoir d

A_{ct} $\rightarrow$ Area under cane production at time t

P_{ct} $\rightarrow$ Per price of cane at time t

Y_{ct} $\rightarrow$ Cane yield at time t

C_{ct} $\rightarrow$ Cost of input per unit area of cane at time t

Q_{dct} $\rightarrow$ Water required to cultivate area of cane at time t for reservoir d

CW_{dct} $\rightarrow$ Cost of water for cane at time t for reservoir d

A_{et} $\rightarrow$ Amount of electricity produced from cane at time t

P_{et} $\rightarrow$ Per unit price of electricity at time t

C_{et} $\rightarrow$ Cost of producing electricity at time t

Q_{det} $\rightarrow$ Water required to producing electricity from cane at time t for reservoir d

A_{ht} $\rightarrow$ Amount of electricity produced from hydropower at time t

P_{ht} $\rightarrow$ Price of hydropower at time t

C_{ht} $\rightarrow$ Cost of hydropower at time t

CW_{dht} $\rightarrow$ Cost of water required for hydropower at time t for reservoir d

Q_{dpt} $\rightarrow$ Water required for municipalities from reservoir d at time t

P_{pt} $\rightarrow$ Price of water supply at time t

$CW_{dpt}\rightarrow$ $\rightarrow$ Cost of water supply from reservoir d at time t

The above equation has some constraints given below. The first constraints are the demand constraints, where the supply to the different sectors and municipalities should be within the minimum and maximum demands of water supply as seen in the equations below

$$\begin{aligned}
WD_{rt} &\geq \sum_{d=1}^{D} \delta_{dr} Q_{drt} \geq MinQ_{rt} \\
WD_{ct} &\geq \sum_{d=1}^{D} \delta_{dc} Q_{dct} \geq MinQ_{ct} \\
WD_{et} &\geq \sum_{d=1}^{D} \delta_{de} Q_{det} \geq MinQ_{et} \\
WD_{ht} &\geq \sum_{d=1}^{D} \delta_{dh} Q_{dht} \geq MinQ_{ht} \\
WD_{pt} &\geq \sum_{d=1}^{D} \delta_{dp} Q_{dpt} \geq MinQ_{pt}
\end{aligned} \tag{4.2}$$

In the above equations WD is the maximum amount of water for each sector and municipality, $MinQ$ is the minimum amount of water allocated to each sector and municipalities δ is a matrix which represents the reservoir providing water to each source, with 1 for if the reservoir provides water to the demand source, and 0 otherwise.

The second constraints are the yield constraints to rice and sugarcane that is dependent on water availability [175], and how sensitive the crop is to the available water as seen in the equation below

$$Y_{rt} = Ymax_{rt}\left[1 - CS_r\left(\frac{\sum_{d=1}^{D} Q_{drt}}{WD_{rt}}\right)\right]$$
$$Y_{ct} = Ymax_{ct}\left[1 - CS_c\left(\frac{\sum_{d=1}^{D} Q_{dct}}{WD_{ct}}\right)\right] \tag{4.3}$$

Where CS is the crop sensitivity of water for rice and cane and $Ymax$ is the maximum yield for rice and cane. Then there are constraints to hydropower generation [176]

$$A_{ht} = \frac{Q_{dht} \times (H - HL) \times TE \times GE \times 9.907}{1000} \tag{4.4}$$

In the above equation H is the average head available for power generation (m), HL is head loss at the rated head and flow (m), and TE and GE are turbine and generator efficiencies at rated head and flow. The numbers 1000 represents water density (1000 kg/m^3 divided by 1000,000 (for transferring final value to MW) 9.907 is multiplication of gravity (9.8 m/s^2) by efficiency factor.

The final constraints is the reservoir mass balance constraint

$$S_{dt} = \sum_{t=1}^{T}\sum_{d=1}^{D}\{S_{d(t-1)} - Inflow_{dt} - E_{dt} - \delta_{dr}Q_{drt} - \delta_{dc}Q_{dct} - \delta_{de}Q_{det} - \delta_{dh}Q_{dht} - \delta_{dp}Q_{dpt} - MinFlow_{dt}\} \tag{4.5}$$

Here $S_{d(t-1)}$ is the initial storage for reservoir d, $Inflow_{dt}$ is the inflow coming into reservoir d at time t, E_{dt} is the total evapotranspiration from the reservoir, δQ is the total supply from reservoir d to the different demand sources and $MinFlow_{dt}$ is the minimum releases from the reservoir back into the river.

The above model can be replicable by replacing the numbers of $r, c, e, h, p, d,$ and t. Policy infrastructure and climate scenarios can similarly be changed by changing $Inflow_{dt}$, d and other variables.

4.2.2 Case Study

The state of São Paulo is the largest producer of sugarcane (55.1%) [177] and ethanol in the country [22]. Ethanol plays an important part of the Brazilian economy, as renewable energy in Brazil accounted for 45% of the total energy supply in 2019, of which, 70% came from biomass [18]. This renewable energy progress has been through decades of government intervention, public private partnership, mechanization from farm to energy [8, 21], and other measures. It began in 1975 through the Brazilian Alcohol Program (Programa Nacional do Álcool PROALCOOL) to reduce its reliance on oil imports.

The state is important beyond ethanol production. It accounts for approximately 31% of the GDP of the nation [178], 41 million people or 22% of the country's population [179], and for this reason, they have been given the nickname of *locomotive of Brazil*. In particular the city of São Paulo, the largest city in the Americas, accounts for 10.3% of the Brazilian GDP and over 12 million people in 2018 [180].

Droughts at the same time are becoming increasingly common on Brazil and São Paulo. The 2014 drought, was the worst water crisis on record in the city of São Paulo [181] and nearly running out of water [182]. This led to school closures, crop failure and severe economic losses [182]. The following drought in 2021 led to similar challenges. Between March and May 2021, dry weather in South-Central Brazil led to many major reservoirs reaching 20% capacity, prices of soybean increasing by 67% from June 2020 to May 2021 and electricity costs increasing by 130% [30]. In 2021, the Cantareira reservoir system, that provides water to 8.8 million people along with agriculture and hydropower, was at maximum capacity on a single day at 53% and a minimum of 36% [31]. This is critical as it not just provides to industry, but also drinking water to a large part of the population of the city of São Paulo.

The study looks at a region in the state of São Paulo, which includes the integrated Cantareira reservoir system (including the reservoirs Jaguari/Jacareí, Cachoeira, Atibainha) and 3 other reservoirs (Guarapiranga, Taiaçupeba and Cachoeira do França). The system supplies water to 22 municipalities in total, of which some provide agricultural products, and one ethanol production system in the region. This integrated system and connections can be seen in figure 4.1. Of these 22 municipalities, 10 produce rice, and 2 produce sugarcane,that are also highlighted in the figure. Although the model allowed for hydropower, and the Jaguari reservoir provides hydropower, it was excluded from the study due to lack of available data. The study looks at a normal rainfall year, in 2017, and a scenario for water demand changes in 2040 to show the status of current infrastructure accounting for the future demand. The future predictions show that the area for rice would increase by approximately 77% by 2040, with some reduction in municipal demand, and a replacement of sugarcane in the region to rice.

The data, units and sources can be found in B.1. Studies on equity and efficiency of water allocation state that human consumption require *social efficiency*, that is defined as the achievement of highest efficiency when utilizing limited resources to produce more social wealth and to satisfy human needs, in order to achieve the SDGs [170]. To achieve social equity, domestic, or municipal water supply have a higher minimum water allocation to the sector and a study by Hu et. al. [183] have put minimum water allocation as 70-80% of the maximum use

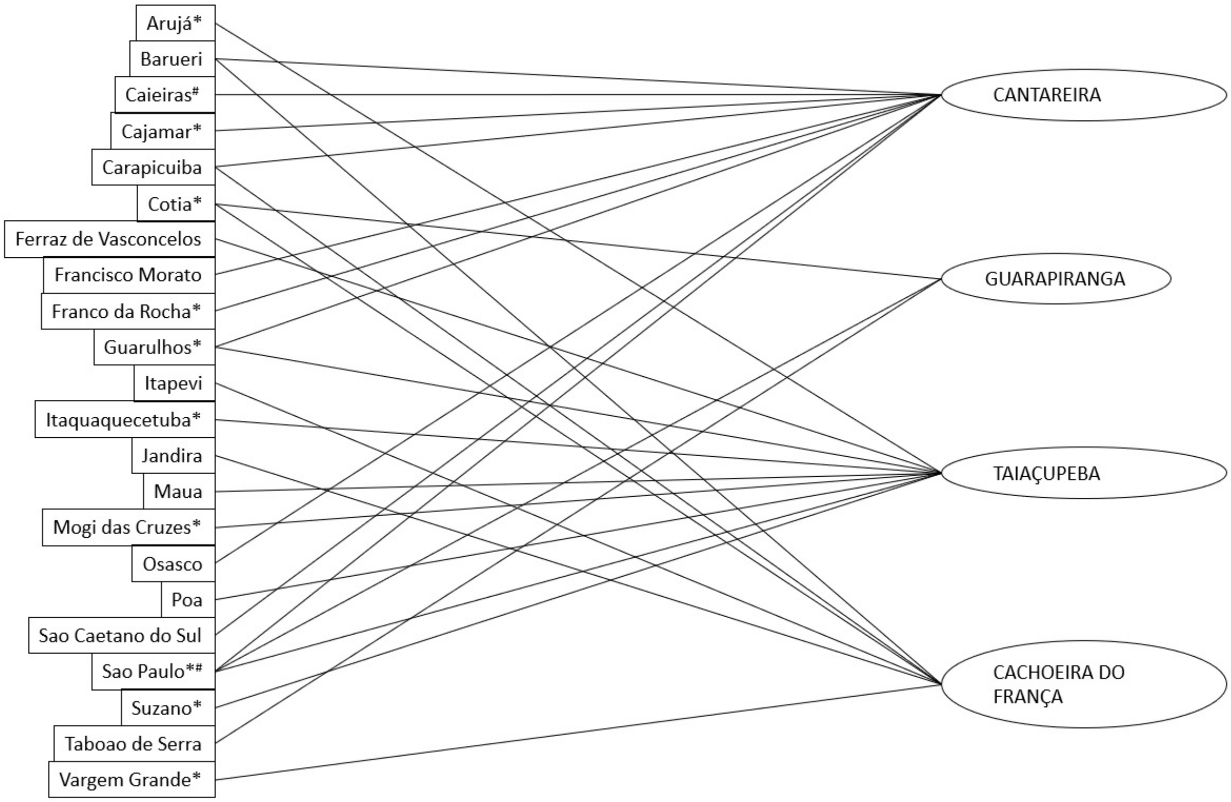


Figure 4.1: Municipal and Reservoir Connections for the study region of São Paulo State
Note: * represents municipalities that also produce rice, and # represents municipalities that also produce sugarcane

depending on the region. Additionally, as mentioned, the city of São Paulo accounts for 69.3% of the total municipal water demand, also accounts for 10.3% of the Brazilian GDP. Therefore, disruptions in the region would greatly affect the economic output of the city and the country. For the reason of equity, the minimum supply is taken as 50% for municipal water supply to ensure the minimum availability of drinking water and industrial water supply.

4.3 Results

4.3.1 Current status of water use

The case study gives us the water allocation to the different sectors, which paints a picture of the food-energy-water nexus priorities, and security challenges. Firstly, in figure 4.2 we see that water is provided 100% in six months of the year for the production of rice. This poses challenges not just for food security, but is also a challenge for economic output, as Brazil is the ninth largest exporter of rice in the world [184] and the largest consumer of rice in the Latin America and Caribbean nations. This becomes even more pertinent during drought time periods, where crop production was seen to be declining, and yield reducing [26]. This poses an added food security challenge for the nation.

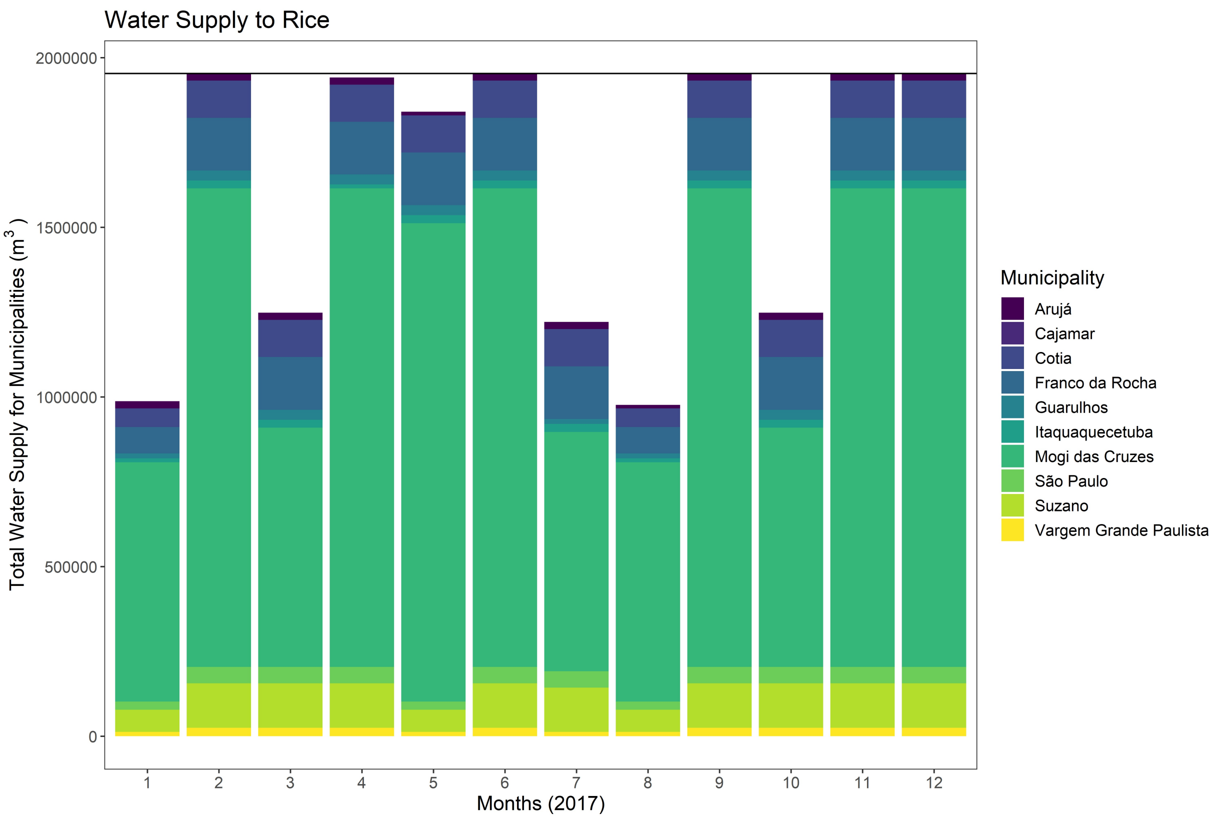


Figure 4.2: Rice water supply for 2017 demands

For sugarcane production, there are more months with 100% supply of water for their demand as seen in Figure 4.3. This shows the prioritization of energy over food security with limited water. This is also because the price of sugarcane [185] is significantly higher than the price of rice [186], and the price of rice fell through the year reaching its lowest in December (Figure B.1). The water supply to sugarcane in São Paulo poses municipal water challenges too, where the priority is given to sugarcane in the metropolitan region over municipal supply. The importance of sugarcane is not just for ethanol manufacturing, but also export, as Brazil is the largest producer and exporter of raw cane in the world and constitutes nearly half the world's sugar market [184], and has therefore been named the *exporter of the world's breakfast* (through their export of oranges, coffee, sugar and cocoa) [187]. While it exports large quantities of sugar around the world, according to the World Bank [188], in 2019 23.5% of the population faced moderate to severe food insecurity, and it rose to 28.9% in 2020. Looking into for water supply to ethanol, these discussions become even more pertinent. With the highest profit coming from ethanol production, water supply is guaranteed for ethanol production (Figure B.2). This has a positive impact on energy security, however, it is a challenge when it comes to the competition between food and energy. Ethanol production, as mentioned is a major source of renewable energy in the country, and with government incentives, there are reductions in the costs for the production of ethanol, making it a bigger incentive for farmers to produce sugarcane, and finally ethanol. Its market importance is also large. As mentioned previously, Brazil is the second largest producer of ethanol in the world, of which, most is intended for domestic consumption [189]. This becomes pertinent today, where energy price are soaring to have created the biggest surge in crude oil prices since the 1970s as with an increase of 350% from April 2020 to April 2022. Similarly, coal and gas prices have also reached historic highs. It is expected that overall energy prices will increase by 50% on average and coal, natural gas and crude oil prices are projected to increase by 81%, 74% and 42% respectively [190]. Therefore, from the energy security perspective, this is a great benefit for the Brazilian economy.

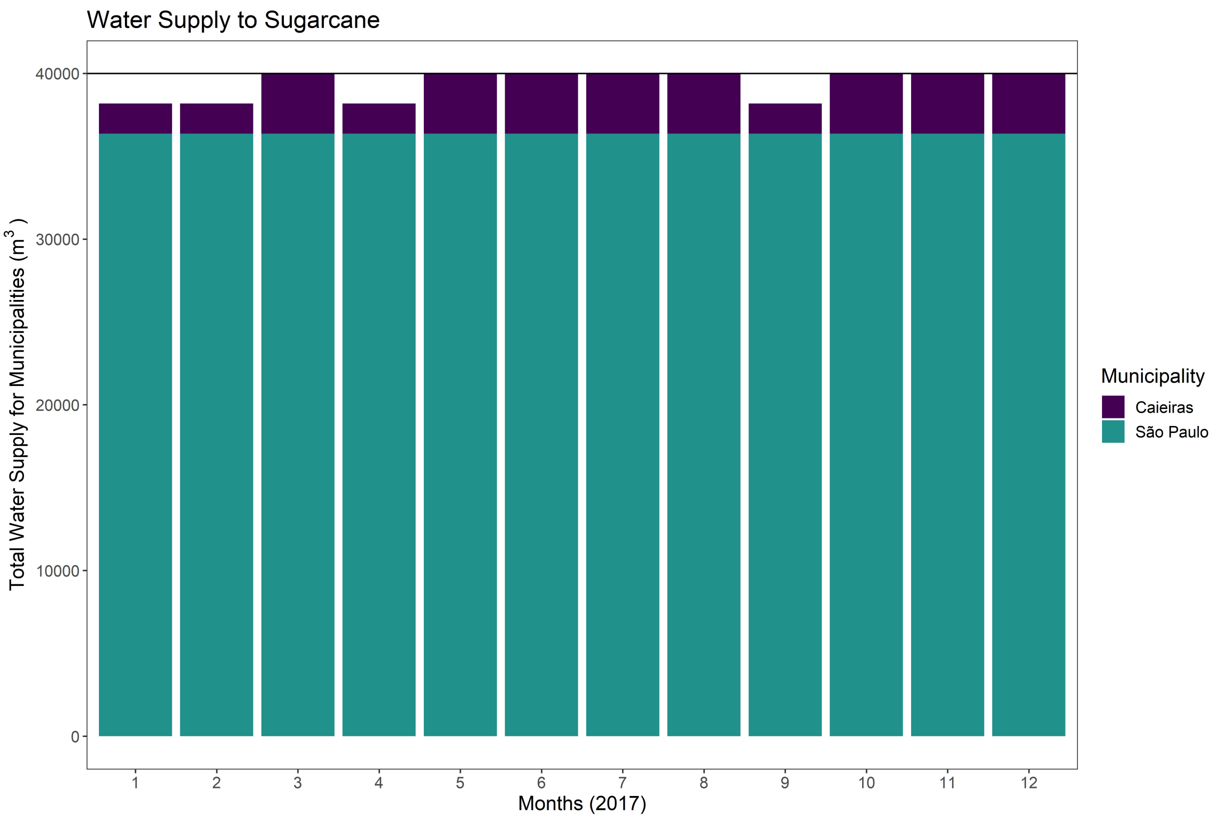


Figure 4.3: Cane water supply for 2017 demands

With the lowest amount of profit coming from municipal water supply, the municipal water supply does not reach the total water demand for any year. With São Paulo contributing to 69.3% of the total municipal water demand and accounting for a large part of the Brazilian GDP, water security critical for the region. This is a major challenge for water security from the drinking water perspective and the achievement of the Sustainable Development Goals 6 on water and sanitation. With regard to the goal, the latest data shows that 86% of the country has access to safe drinking water and 63% in terms of integrated water resource management [191]. Droughts in the region are a major challenge, and in 2014, it led to water rationing, and tanker trucks being sent around the state [192], and many relying on mineral or bottled water deliveries for cooking, showering, etc [193] and many going days without household water supply [194]. This also becomes a social and equity challenge for the country, where costs of water from bottled water is not affordable to many. During the drought, the water utility also reduced water pressures for 13 to 18 hours in a day [194, 195].

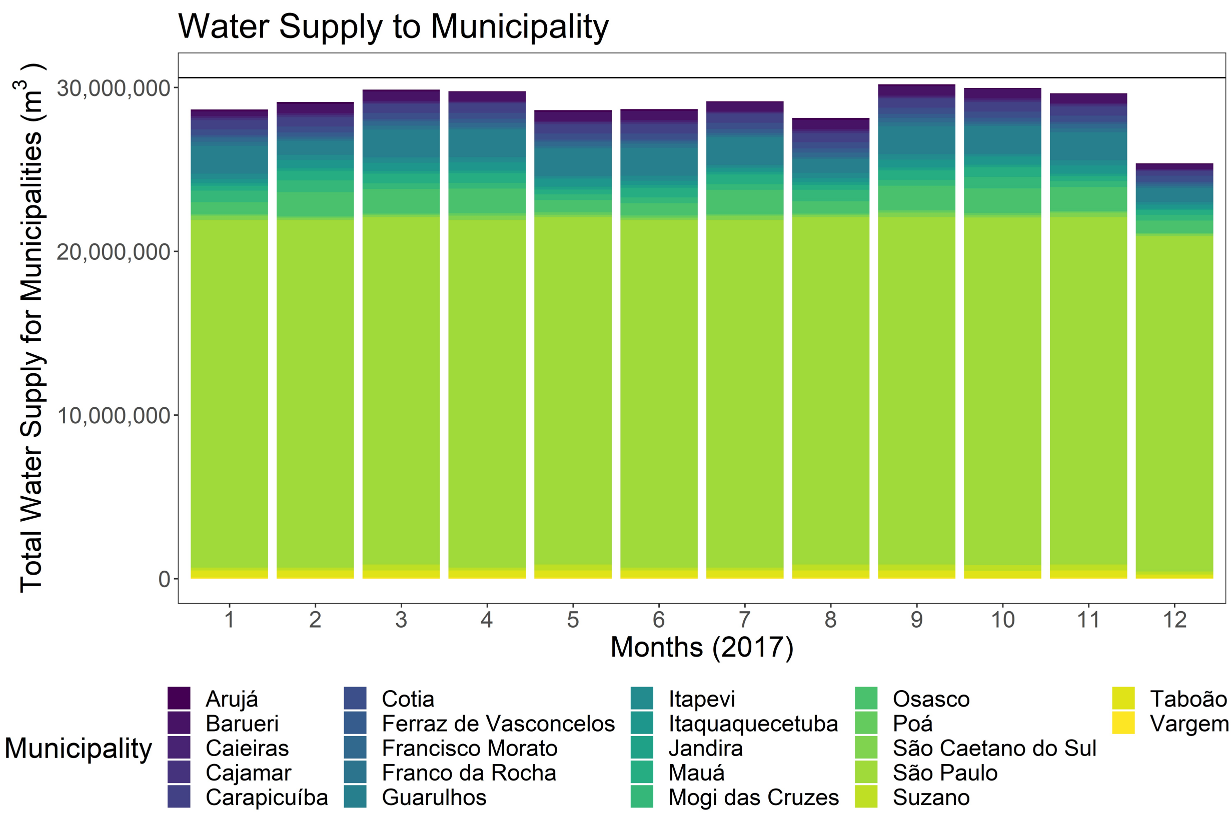


Figure 4.4: Municipal water supply for 2017 demands

Although with a profit maximization model, such results are expected, it is also important for the model to consider minimum water supply to each sector, especially during times of shortage, to ensure a balance between profit and equity. Although the water supply profits do not show the need for water, the importance of São Paulo state for the GDP of the nation, it is also critical to ensure this distribution of water to municipal water supply. Policies from governments need to be made in conjunction with climate predictions to better plan for droughts, and in ensuring water supply to each sector. Although there have been plans made to build more reservoirs [194], construction of reservoirs will take time, and increasing population, consumption, etc. is going to continue increasing the demand for limited water.

The model also highlights the competing interests of land use along with the water use from the rice and sugarcane sector. With priority given to water use, and higher profits, there are incentives to shift from food to energy production. The sugarcane crop area in São Paulo have already seen an increase from 52% in 2000 to 68% in 2020 with an overall increase in agricultural land by 71% [196]. This shows two challenges, firstly, with food security, and the second with the land cover and land use change.

4.3.2 Future status of water use and delivery

The future scenarios, which would represent changes to water demand from rice and municipal water supply in particular shows the future infrastructural challenges the region might face. In the future, the demand for water from rice would increase by approximately 77% in the region as a direct result of increase in area for rice production and overall increase in agricultural area, while the municipal water supply would reduce.

We see from figure 4.5 that the water supply to rice is significantly lower, even during a normal rainfall year. This shows the threats the region could face in terms of food insecurity in the future. As mentioned before, the population facing moderate to severe food insecurity was at 28.9% in 2020 [188] which was at 18.3% in 2015. The status of food security would also affect the global supply, as Brazil is currently among the largest exporters of rice in world. Additionally, a drought year could significantly impact the production of rice. The current status shows the infrastructural challenges and policies that would need to be implemented in the future to address this. Additionally, while the supply of water to rice is unable to meet the demand, the demand for water for ethanol production remains at 100%, which highlights the importance of energy security. One of the limitations of this projection is that the prices of ethanol and rice remain at the 2017 levels, as it is hard to predict the future prices of food and energy in the future.

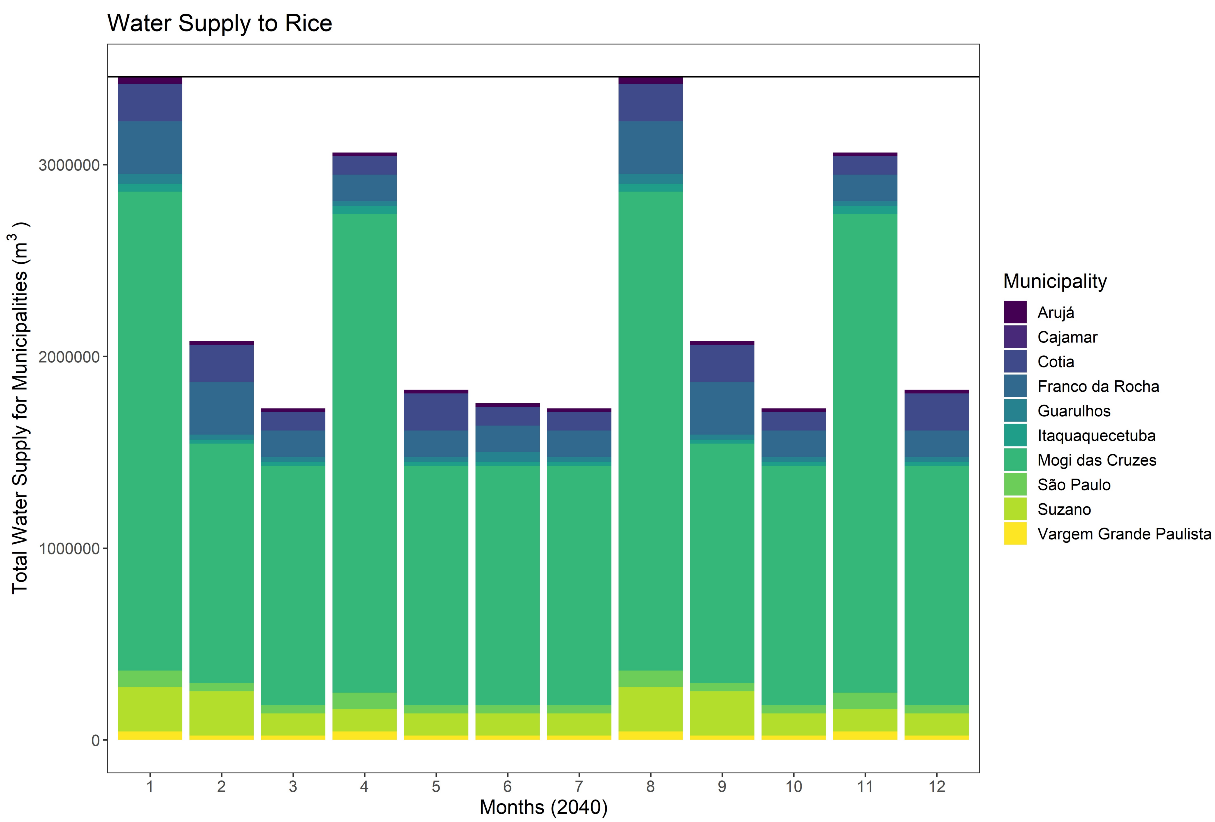


Figure 4.5: Rice water supply for 2040 demand

Although some months in the year receive full quantities of water for rice production, the supply to municipalities remains close to the minimum water supply. This becomes a bigger challenge with equity and the economic role São Paulo faces in the country's economy. The 2014 drought showed the impact on industrial output and agriculture [197], highlighting the importance of water to the municipalities in the region.

The Food and Agriculture Organization, that is tracking some progress of the SDGs by

2030 [198], shows that Brazil is *very far from the target* in achieving the reduction people living with moderate or severe food insecurity. It additionally sees a *deterioration since baseline year* for investments in the agricultural orientation index (AOI) that is measured as the ratio between the agriculture share of government expenditure and the agricultural value added as a share of GDP. It has seen *slight improvement since baseline year* for total and agricultural water use efficiency. In terms of achieving the SDGs, the country still face *significant challenges* to achieving the goal of zero hunger, and faces *major challenges* to reducing inequalities (with a decreasing trend overall), decent work and economic growth. This put forth the questions on equity and food insecurity in the country as a fundamental challenge and hampers the achievement of the SDGs.

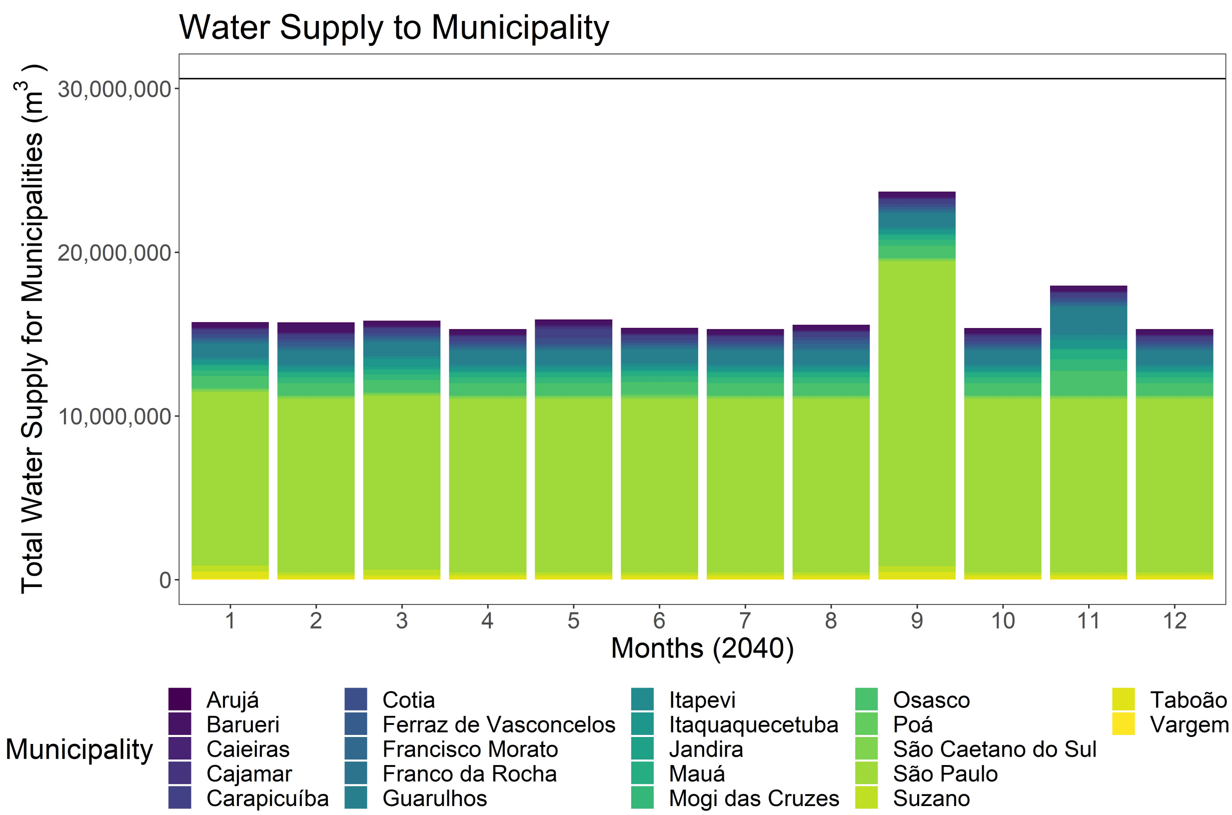


Figure 4.6: Municipal water supply for 2040 demand

Here again, we see challenges with increasing land use in agriculture, coming from increase in rice production area, which is also occurring in the state of São Paulo as a whole. Overall this is a challenge as there is also a conflict between agriculture and other land use in the state. The model results show that while in the current scenario, the future water demand with the current infrastructure shows the deficits of the water system in the region studied. There is a need for investment in the future infrastructure for both, water, food and energy systems. Policies and plans would need to include short term drought management plans, along with medium to long term plans to cope with drought stresses through building new infrastructure, technological innovations, financial mechanisms that include risk factors, including climate predictions.

4.4 Conclusion

With climate change affecting rainfall, droughts are worsening in many parts of the globe, and inadequate supply of water threatens food and energy security, and the achievement of Sustainable Development Goals. Although water security is a challenge, it is sometimes not considered as important and food and energy security, even though there is a link between all three. Although these challenges exist, one solution to this challenge is to optimally allocate the limited water given economic, social and environmental challenges. To do this, the study presents a model for profit maximization and water supply. The model is linear, requires low computing power, and is replicable. Although models exist, computing power and complicated models are less accepted in the decision and policy making space. The model maximizes profits given the water supply and demand from different sectors, reservoirs, and can adjust for climate, policy and infrastructure scenarios. The study is conducted in a region of the state of São Paulo, which includes the city of São Paulo. Brazil was selected as they are leaders in the renewable energy and biomass movement in the world, with São Paulo producing the largest amount of ethanol in the country. It is increasingly facing challenges to water supply, and has dealt with two major droughts in 2014-15 and 2021. The model includes societal equity by ensuring a minimum water supply for each sector (rice, sugarcane, ethanol and municipal water supply). The results show that the highest priority is given to water supply to ethanol, followed by food, and lastly to municipal water supply in 2017. Although in 2017 the water supply seems more reliable for nearly all sectors, the future demand for 2040 shows that the current infrastructure would be unable to cope with the increasing demands, with the highest priority being given to ethanol production. This poses many challenges to food and drinking water security. This study also highlights the increasing area being used for agricultural production over time, which can become a great challenge in the water use, but also for other land uses in the state. Given the economic and food security importance of water supply, along with equity in the aspect of municipal water supply, policies would need to be put in place to better manage water supply, while also accounting for increasing demands for water, and climate predictions. Government policies would also need to address interlinkages between food, energy and water, along with climate predictions, infrastructural challenges and technological innovations. These interlinkages are particularly important in the achievement of the Sustainable Development Goals in the country as a whole. This study shows that while Brazil has advanced greatly with regard to renewable energy, it is still vulnerable to droughts, that can disrupt the entire economy through affecting food, and energy production.

Chapter 5: Conclusion

Food, energy and water (FEW) security can no longer work in isolation if we seek to achieve their individual Sustainable Development Goals. Addressing the FEW nexus would help in highlighting the trade-offs between the three at the policy level, and to eventually identify and develop solutions that target all three. The three essays highlight this through looking at the current status, challenges, limitations and future potential of this growing field. Through each essay we investigate how policies implemented by countries affect social, economic and environmental issues within the country or a region within nation.

The first essay helps us understand what the current challenges exist with crop residue burning in Thailand. The essay concludes that crop residue burning is a potential for use in renewable energy production, with the best case example from a middle income country being Brazil. The second essay then looks at renewable energy policy and to see its' effects on society, economy and the environment. The essay uses extended input-output models to see the effects of such policies on Thailand and the Northeast region of Thailand. One result of the essay is that there is an increasing direct, indirect and induced increase in water use in the country as a result of renewable energy policies. The final essay then address that if we have well defined and implemented renewable energy policies and plans, how do we optimally allocate water. The study uses a region in the state of São Paulo to look at water allocation for food, energy and municipal consumption. The essay concludes that there is a priority given to energy supply, followed by food, and finally municipal water supply. Water security challenges get exacerbated with the current infrastructure when addressing the questions of future increases in water demand, especially for food production. These three essays highlight the key issue or addressing the inter-linkages of the FEW nexus and that policies cannot work in isolation.

5.1 Summary of Key Findings

5.1.1 Essay 1 (Chapter 2): Limiting rice and sugarcane residue burning in Thailand: Current status, challenges and strategies

The study provides an overview of the current status of crop residue burning in Thailand. We see that residue burning from rice and sugarcane account for 83% of the total crop residue burning in the country. Regionally, the Central and Northeastern region of Thailand account for most of the burning in the country. The highest burning practices are for irrigated paddy in the country. The study then addresses the impacts of crop residue burning in the country. The major impacts of the residue burning is seen for rice and cane, which account for majority of the PM10, PM2.5, NOx, and SO_2 emissions. These emissions have led to health hazards, that include increased risks of lung cancer. There is also a highlighted need to improve research on risks associated with crop residue burning.

The study then looks at the existing programs and policies targeting regulation of rice and sugarcane production, market stabilization, and promoting renewable energy, which considerably impact crop residue management. The first policy is the *Cane and Sugar Act of 1984*, which regulates the sugar industry in the nations, including setting prices for sugar for farm and industry.

While the Act targets the rice sector, the government has not yet targeting the use of burned cane in the sector. The study also looks at renewable energy policies and plans from the government, and highlighting that promotion of renewable energy began in the 1990s. The earliest plan, the Energy Conservation (ENCON) Fund, was established in 192, that aimed at funding projects, including 15 biomass projects in Thailand. Other policies developed renewable energy targets, air pollution reduction, and others. One of the most recent and major policies that have been implemented by the Government of Thailand was the Alternative Energy Development Plan (AEDP), in 2015, which seeks to achieve 20% energy from renewable sources, including 5570 MW of power from biomass by 2036 [7] which was then increased to 5790 MW by 2037 [69]. The aim of the AEDP is not just about reduction in crop residue burning, but looks at sustainability as a whole.

The essay then studies the challenges to controlling residue burning. Although many policies have been implemented to target crop residue burning or its use for energy generation, there are still some challenges with its implementation. Hurdles and challenges include farmer unwillingness, cost of mechanization, labor costs and shortages, and lack of awareness about the implications of burning on the environment. The study also highlights that the major barrier is cost of mechanization and the cost of labor. While there are some policies that have given out low interest loans, it is still very high for small and medium sized farmers. Additionally, while farmers were aware of the health effects of residue burning, fewer were aware of its' environmental impacts.

Finally, the essay presents future potential use of crop residue, that include examples from other countries. One strategy is to use the crop for production of renewable energy. Although the AEDP has paved the way for the use of biomass for energy generation, the country could learn from the success of Brazil that started its ethanol program in 1975, and has succeeded through various government interventions from farm to consumption level, and public-private partnerships. Another solution would be through using the crop residue to improve soil health through green harvesting or production of biochar. Other solutions include use of crop residue for livestock feed, paperboard making, etc.

5.1.2 Essay 2: Adoption of biomass for electricity generation in Thailand: Implications for energy security, employment, environment, and land use change

From essay 1, we saw that renewable energy production is one solution to dealing with the negative impacts of crop residue burning, and the Government of Thailand has begun implementing policies that targeting crop residue for renewable energy production and the use of burnt cane. This essay addressed the impacts of crop residue use in electricity generation on the economy, environment and society. The study in particular, looks at the AEDP, and a policy targeting burned cane use in industrial sugarcane production. It uses an Extended Input Output (IO) model to understand the effects of these policies as scenarios on total output, employment, labor income, water use, etc. The study uses crop residue use from rice and sugarcane and understands the effects of these policies on Thailand and the Northeast Thailand, which is the largest producer of rice, cane and electricity from biomass in the country. The scenarios are run for the two policies (Zero burning or best case scenario, AEDP), and a third scenario which increases the AEDP targets by 50% (AEDP1.5 scenario). The scenarios are run by increasing the demand according to the Government of Thailand in the use of electricity, and production of biomass for electricity generation. The demand driven solutions run for Thailand and Northeast Thailand help us understand how changes to the final demand over the baseline and scenarios would affect the changes to the total economy, as well as for each source of electricity.

From the study we see that these policies are not ambitious enough in using crop residue use in electricity production. For Thailand, increase in the total output of the electricity sector triggered by the use of sugarcane bagasse for electricity generation is the highest in the best-case scenario in 2022. For Northeast Thailand, the highest increase is in the AEDP1.5 scenario. Employment generation through the implementation of these policies shows much smaller impact in Northeast Thailand than in Thailand. In the best case scenario shows, we see that employment doubles in Thailand for electricity generated from sugarcane, and for the AEDP1.5 scenario, there is a 30% increase in employment in Northeast Thailand. Gross value added for Thailand, which includes land income, capital, tax, and labor income, shows most significant increases for electricity from sugarcane in the case of the best-case scenario. On the other hand, in the case for Northeast Thailand, the highest increases are seen in AEDP and AEDP 1.5, with a 30% increase in GVA in the AEDP1.5 scenario. Labor income increases are fairly high in both, Northeast Thailand and in the country. The environmental impacts for the study show a large increase in water use as a result of these policies in both Thailand and Northeast Thailand, although CO_2 emissions in the country reduce. Finally, for the purpose of land use, this study shows that while in Thailand the land use shift from rice to cane is lower in the country as a whole, it would surpass rice production in the Northeast region posing a challenge for the competition between food and energy production.

The study also addressed issues which were not included in the model. These policies need to address the competing interests in land use for food and energy production. Technological innovations also need to be considered for future demand changes. Studies have shown that the AEDP is not addressing or funding innovation and technological development. These policies would also need to address mechanization at the farm level including the cost of mechanization. Farmer profits are not enough to incentivize reduction in crop residue burning. The study showed that there is an increasing use of water with the implementation of these policies, which can be a great challenge given increasing droughts, and could lead to reduction in the production of crop, and therefore residue. Finally, the price fluctuation would also need to be considered through interventions from the Government.

5.1.3 Essay 3 (Chapter 4): Multi-reservoir, multi-demand water optimization model through maximization of profits and social equity: A case for São Paulo, Brazil

From essay 2, we see that increasing renewable energy production from biomass can lead to increasing water use, which poses a challenge to the limited resource. We also saw from essay 1 that Brazil has been a great example for the use of biomass for energy generation. The country has developed a strong system for biomass production through the entire supply chain through government interventions, and public private partnership. While they have been successful in terms of energy generation, Brazil faces severe water security challenges, that affect food and energy production and municipal water delivery in the country. The two most recent droughts in 2014 and 2021 disrupted the entire economy, including crop production, energy supply, economic growth and socioeconomic development.

To address these challenges, it is important to optimally allocate water, given the demand from different sources, and the limited resource. To address this, the study develops an economic model for water allocation. The model also accounts for minimum water allocation, especially for municipal water supply, given the need for equity, and the lower profits from municipal water supply. The model is also built in a way that it is linear, requires low computing power, and is replicable. The replicable nature of the model allows for transparency, and can be used for comparison through conducting scenarios that could include supply side changes using climate predictions or infrastructure development and demand side changes through changes to demands or using different areas. This could help facilitate conversations between the different stakeholders.

The study is conducted in a region of the state of São Paulo, as it is the largest producer of sugarcane and ethanol in the country. It also accounts for 31% of the GDP of the country and 22% of the country's' population. The region studied includes 3 reservoirs and one reservoir system, 22 municipalities, which includes municipalities that produce rice and/or sugarcane, and water for ethanol production. The study includes the city of São Paulo that accounts for 10.3% of the GDP of the country, and has a population of over 12 million people. Aside from the economic importance of the region for the country, São Paulo has been severely affected by the two droughts mentioned, that affected the economy of the state, and therefore the country. The model is run for a normal rainfall scenario, the year 2017, and a scenario run using the normal rainfall year of 2017, but changing the demand for the projection of 2040.

The model run shows that in 2017, the highest priority for water use is given to ethanol production, then to food, and finally to municipal water supply. None of the 12 months in the year provide 100% water to municipal water supply. This has implications of food versus energy, as well as profits versus equity. Although the water supply is guaranteed at a higher rate in 2017, looking at the demand changes for 2040 show that the current infrastructure is unable to provide water to most the demand sources for majority of the time periods even with the normal rainfall of 2017. In particular, municipal water supply remains around the minimum guarantee of 50% for each month causing a debate around equity. This also highlights the challenges the region would face when droughts exacerbate the competing demand for the limited resource. It also highlights the interlinkages between the FEW Nexus and the need for policies to address them.

5.2 Future Policy Development

Given the cross-sectoral, and interlinked nature of the FEW nexus, future policies would need to be implemented to highlight all three, and at all levels of development (from farm up to consumption). While Brazil has been successful in considering renewable energy development through the farm to consumption approach, it fails to address issues related to water, and food. Policies would also need to consider equity through access of water for municipalities, costs of mechanization at the farm level, etc. Governments agencies with overlapping mandates would need to ensure the need for working together to achieve the SDGs. This could also include creation or strengthening of institutions that are effective, accountable and inclusive. It is also important to have knowledge exchanges and public awareness of the issues at hand. Technological innovation, mechanization and research and development need to be prioritized through policies and funding. Strengthening public private partnerships, interactions with other stakeholders like NGOs, etc would help with larger scale implementation of policies. Policies would also need to address land cover and land use change. Investments in infrastructure, including water and energy would be critical to deal with the future demand and supply challenges. Improving the data availability of this would help with transparency and accountability of policies. Finally, it is also important to integrate different models into the policy making and implementation process. These models can then highlight any limitations that exist in the current model, to make it more comprehensive for the different questions that need to be answered.

5.3 Challenges with Uncertainty in the Future

As technologies advance, decision making for the future advances through reduction in uncertainties. However, even with the advancements, challenges still remain. These uncertainties can be internal, or external, which are seen in every chapter of this dissertation.

In essay 1 (chapter 2), the essay provides potential solutions to the current crop burning practices using other countries as examples. The example of use of residue in renewable energy assumes a constant supply, and with changing rainfall patterns, the availability of input could change. There are also uncertainties in price of rice and sugarcane, and such fluctuations in prices could lead to shifts from one crop to another. There are also uncertainties with policy changes in the future, for example the changes to the AEDP targets over time, as mentioned in the research.

In essay 2 (chapter 3), there are uncertainties in the model, in the scenarios and the results, some of which were highlighted in the discussion section. The model uses a_{ij}, which is the quantity of input from sectors i required to produce one unit of sector j's output, and it assumes that technology remains the same. However, we know that through time, technologies will evolve, however there is uncertainty about what that would look like in the future. Similar to essay 1, there can be uncertainties in the availability of inputs for the production of energy. For the scenarios, we take into account the increases in demand provided by the Government of Thailand,

and with demand, or consumption, patterns could potentially change over time. Additionally, policies could be put into place which could change the demand patterns in the country. There are also uncertainty in climate, and therefore supply of water, which could lead to reduction in input availability, and the results could change in the future. This uncertainty can be handled through incorporating water supply scenarios in the future. Finally, similar to essay 1, there is uncertainty in the price for the future.

In essay 3, similar to essay 1 and 2, there are uncertainties through the availability of water in the future, the changes in demand, technology, and changes to policy. Additionally, there are uncertainties in infrastructure development which could handle droughts, and future demand. There are also uncertainty about land use, and whether food demand would outweigh demand for sugarcane demand for ethanol production. There are also uncertainties with the prioritization of water use for municipalities, food and energy through potential policy interventions, demand and consumption changes. Finally, there are also changes to whether there could be future competition for water demand from other sectors.

5.4 Where do we go from here? Future Research

Although this study has highlights some of the influences policies may have on the food-energy-water nexus, and the challenges that the current policies face when not linking the three sectors, there is substantial work that is still required. Firstly, data quality and quantity has been limiting in the study. For example in essay 2, the limited availability of the data required the downscaling of the model using the Fleggs Location Quotient. In essay 2, hydropower water use was excluded from the study as a data limitation.

Another future study would need to include the importance of technology into the model. The studies have shown the limitations AEDP still has in terms of encouraging technological innovations, it is also a major factor in promoting the use of biomass for electricity production, and for water use in the future. Technology can play an important role in the future achievement of the SDGs as a whole, and is a tool for positive change. Incorporating this into the models would benefit decision making, and in understanding the need to incorporate technological innovations into policies.

We also see that economic models need to look at equity, through water use needs from municipalities as a priority for government policies and plans for the use of limited resources. Although essay 3 included equity by allocating a minimum amount of water for municipal water supply, it becomes a double-edged sword as economies and societies usually grow together.

Climate change scenarios also need to be incorporated, especially in essay 3. We also need to understand the status of water use during drought scenarios to help validate the model.

Finally, it is also important to look at the price of individual commodities. Although the models have incorporated them, there is a need to protect farmers from fluctuating prices. We see through the COVID pandemic starting 2020, inflation of 2022, energy price increase of 2022 and recessions and inequality that prices need to be regulated by governments to ensure the economic stability.

Appendix A: Appendix for Chapter 3

A.1 Methodology for Fleggs' Location Quotient

Based on the methodologies to downscale the model for the Northeast of Thailand, the Flegg Location Quotient (FLQ) model is used. Location quotients in the case for Northeast Thailand used the Gross Regional Product (GRP) for Northeast Thailand, and GDP for Thailand to get the Northeast Input-Output results. With the data from the Government of Thailand, the national IO model with 67 sectors was consolidated into 10 sectors, based on the GRP data availability for Northeast Thailand [130].

Step 1: We created a table for the National level by adding up different sectors to get the 10 broader sectors at the national level. We also used the GRP data from the Office of the National Economic and Social Development Council (NESDC, 2014) at the national and the Northeast level. ***Step 2:*** We create a transitional regional input-output table based on the national level and using a simple location quotient. Let X_i^{NE} and X^{NE} denote the gross output of sector i and total output respectively from Northeast Thailand. Similarly, X_i^{Th} and X^{Th} denote the gross output of sector i and total output respectively at the national level. We first get the conventional location quotients, the Simple Location Quotient (SLQ) and the cross-industry LQ (CILQ), which are defined as the following

$$SLQ_i^{NE} = \frac{X_i^{NE}/X^{NE}}{X_i^{Th}/X^{Th}} \tag{A1}$$

$$CILQ_{ij}^{NE} = \frac{SLQ_i^{NE}}{SLQ_j^{NE}} \tag{A2}$$

Using the CILQ, we then get the Fleggs Location Quotient (FLQ)

$$FLQ_{ij}^{NE} = CILQ_{ij}^{NE} \times \lambda \tag{A3}$$

Where

$$\lambda = \left[log_2(1 + TE^{NE}/TH^{Th})\right]^{\delta} \tag{A4}$$

Here TE^{NE} and TE^{Th} are the total employment in the Northeast of Thailand and the national level respectively, and $0 \leq \delta < 1$ and in the case study is set at 0.3. This helps keep a balance between regional difference in output and the sensitivity of TE^{NE}/TE^{Th} in the study [119].

$$a_{ij}^{NE} = \begin{cases} a_{ijTh} \times FLQ_{ij}^{NE}, & \text{if } FLQ_{ij}^{NE} < 1 \\ a_{ijTh}, & \text{if } FLQ_{ij}^{NE} \geq 1 \end{cases} \tag{A5}$$

$$b_{vj}^{NE} = b_{vj}^{Th} \tag{A6}$$

$$c_{iu}^{NE} = b_{iu}^{Th} \tag{A7}$$

Where

a_{ij}^{NE} is the estimated transitional direct input coefficient for Northeast Thailand

b_{vj}^{NE} is the estimated transitional value added coefficient for Northeast Thailand

c_{iu}^{NE} is the estimated transitional final demand coefficient for Northeast Thailand

$a_{ij}^{Th} = (X_{ij}^{Th})/(X_j^{Th})$ is the standard direct input coefficient at the national level

$b_{vj}^{Th} = (N_{vj}^{Th})/(X_j^{Th})$ is the share of factor input in the sectoral gross input at the national level

$c_{iu}^{Th} = (Y_{iu}^{Th})/(Y_u^{Th})$ is the standard final demand coefficient at the national level

Step 3: We then find the row and column sums of the transitional input-output tables from the results from above

$$\widetilde{X}_i^{NE} = \sum_j a_{ij}^{NE} X_j^{NE} + \sum_u c_{iu}^{NE} Y_u^{NE} \tag{A8}$$

$$\widetilde{\widetilde{X}}_j^{NE} = \Big(\sum_i a_{ij}^{NE} + \sum_v b_{vj}^{NE}\Big) X_j^{NE} \tag{A9}$$

We then calculate the row ratio of $\widetilde{X}_i^{NE}$ by X_i^{NE} and column ratio from $\widetilde{\widetilde{X}}_j^{NE}$ by X_j^{NE}. We then divide $a_{ij}^{NE} X_j^{NE}$ (intermediate use matrix) and $c_{iu}^{NE} Y_u^{NE}$ (final demand matrix) with the row ratio and $b_{vj}^{NE} X_j^{NE}$ (value added matrix) with the column ratio. This would give us the transitional unbalanced input-output table for the Northeast region, in which, the row and column sums are fairly close to the actual values obtained of the total output originally derived from the

GRP data.

Step 4: We generate the intermediate use matric, value added matrix, and the final use matrix by using RAS rebalancing.

A.2 Supplementary Images

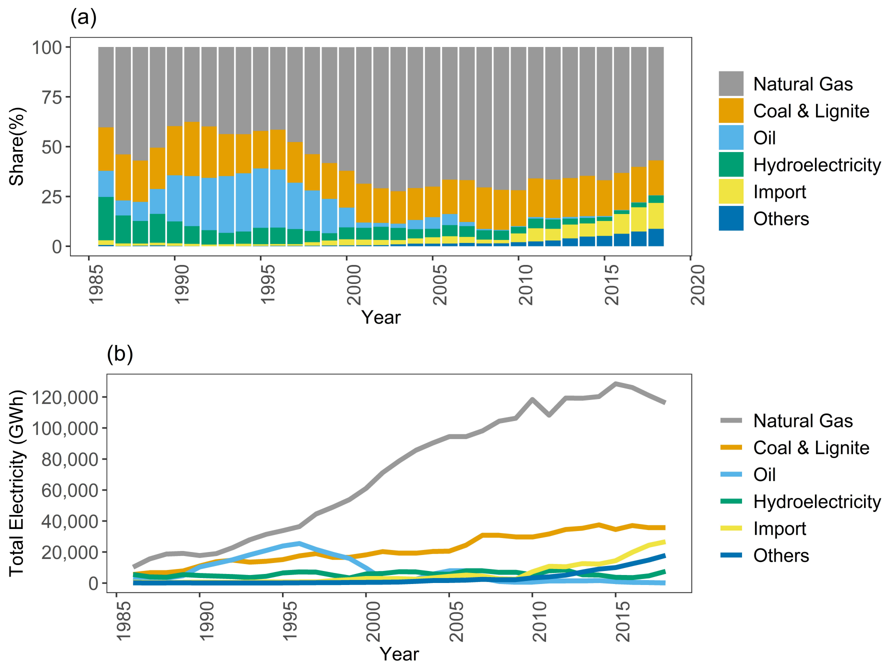


Figure A.1: (a) Share of electricity (%) by type in Thailand (1986-2020) (b) Total electricity consumed (GWh) in Thailand by type (1986-2020).

Source: [10]

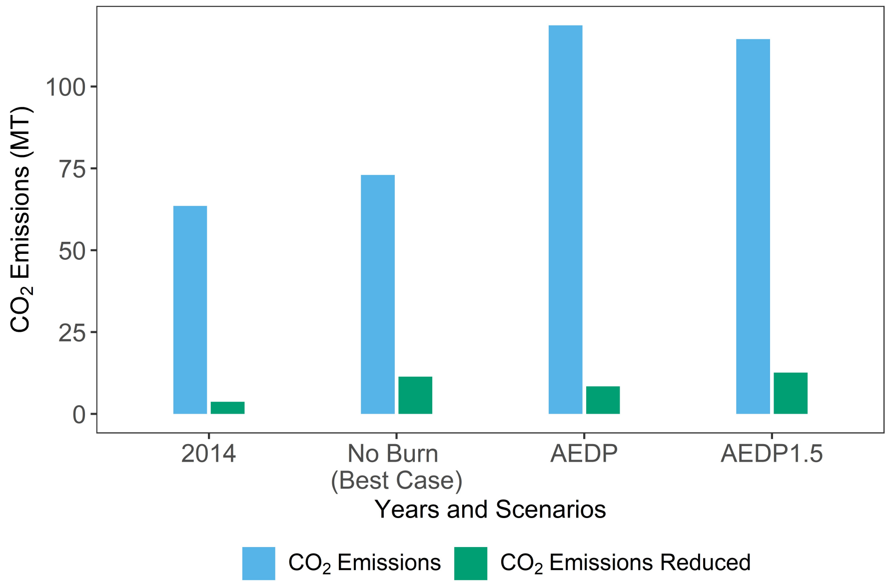


Figure A.2: Emissions reduction for 2014 and three scenarios as a result of biomass use in Thailand

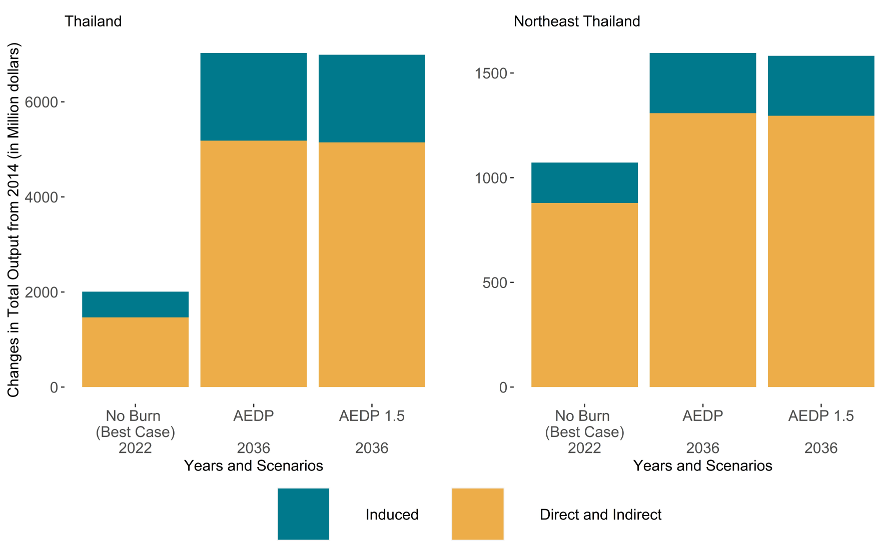


Figure A.3: Area harvested and producer price of rice and sugarcane in Thailand from 1991 to 2018

Source: [143, 199]

Appendix B: Appendix for Chapter 4

The data sources for

Category		Data	Data Description	Units	Data Source
Rice		A_{rt}	Area Under Rice	Hectares	[196]
		P_{rt}	Price of Rice	USD/Ton	[186]
		$Ymax_r$	Maximum Yield of Rice	Ton/Ha	[196]
		CS_r	Crop sensitivity of Rice	No Unit	[175]
		DW_{rt}	Max Demand for Water from Rice	m3/Month	[200]
		CW_{rt}	Cost of water from Rice	USD/m3	[31]
		C_{rt}	Cost of Rice production per ton	USD/Ton	[201]
		$MinQ_{rt}$	Min amount of water for Rice		
		δ_{dr}	Dams supplying to Rice	No Unit	[202]
Cane		A_{ct}	Area Under Cane	Hectares	[196]

		P_{ct}	Price of Cane	USD/Ton	[185]
		$Ymax_{ct}$	Maximum Yield of Cane	Ton/Ha	[196]
		CS_c	Crop sensitivity of Cane	No Unit	[175]
		DW_{ct}	Max Demand for Water from Cane	m3/mont	[200]
		CW_{ct}	Cost of water from Cane	USD/m3	[31]
		C_{ct}	Cost of Cane production per per ton	[203]	
		$MinQ_{ct}$	Min amount of water for Cane		
		δ_d	Dams supplying to Cane	No Unit	[202]
		EL_{et}	Amount of Energy Produced per unit of residue	L/Ton	
		P_{et}	Price of Energy	USD/L	[204]
		CW_{et}	Cost of Water for Energy Production	USD/m3	[31]

		C_{et}	Cost of Energy	USD	
		DW_{et}	Max Demand of water for Energy	m3	[200]
		$MinQ_{et}$	Min amount of water for Energy		
		Del_{de}	Dams Supplying to energy	No Unit	[202]
Municipality		P_{pt}	Price of municipal water		[31]
		CW_{pt}	Cost of municipal water	USD/m3	[31]
		DW_{pt}	Mx demand of water for Muncipality	m3/Month	[200]
		Del_{dp}	Dams Supplying to municipality	No Unit	[202]
Dams	Cantareira	$S_{d(t-1)}$	Intial Reservoir Storage	m3	[205]
		$Inflow_{dt}$	Inflow into Reservoirs	m3/month	[205]
		E_{dt}	Evapotranspiration		[206]
		$Minflow_{dt}$	Minimum release to river	m3	
	Cachoeira do França	$S_{d(t-1)}$	Intial Reservoir Storage	m3	[205]
		$Inflow_{dt}$	Inflow into Reservoirs	m3/month	[205]

	E_{dt}	Evapotranspiration		[206]
	$Minflow_{dt}$	Minimum release to river	m3	
Guarapiranga	$S_{d(t-1)}$	Intial Reservoir Storage	m3	[205]
	$Inflow_{dt}$	Inflow into Reservoirs	m3/month	[205]
	E_{dt}	Evapotranspiration		[206]
	$Minflow_{dt}$	Minimum release to river	m3	
Taiacupeba	$S_{d(t-1)}$	Intial Reservoir Storage	m3	[205]
	$Inflow_{dt}$	Inflow into Reservoirs	m3/month	[205]
	E_{dt}	Evapotranspiration		[206]
	$Minflow_{dt}$	Minimum release to river	m3	

Table B.1: Data name, units and Sources

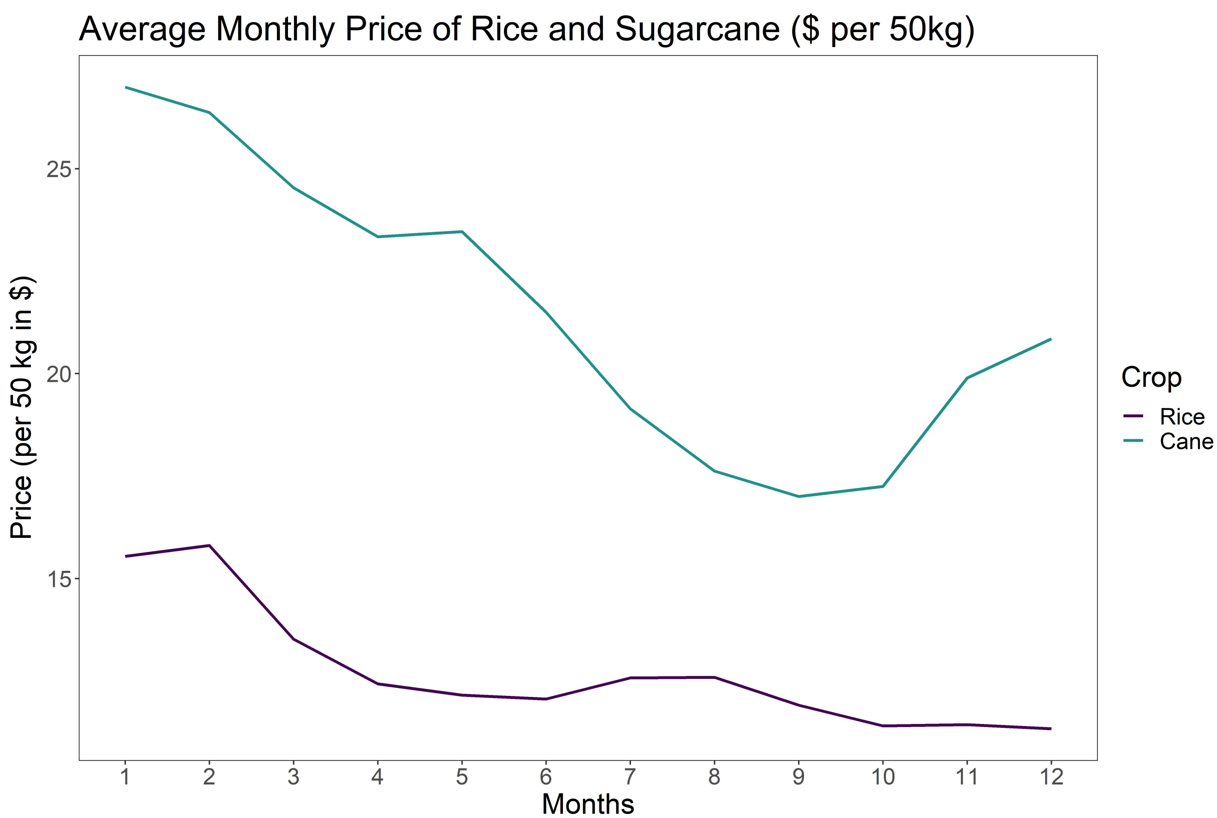


Figure B.1: Monthly Average price of rice and sugarcane (USD Per 50 kg)

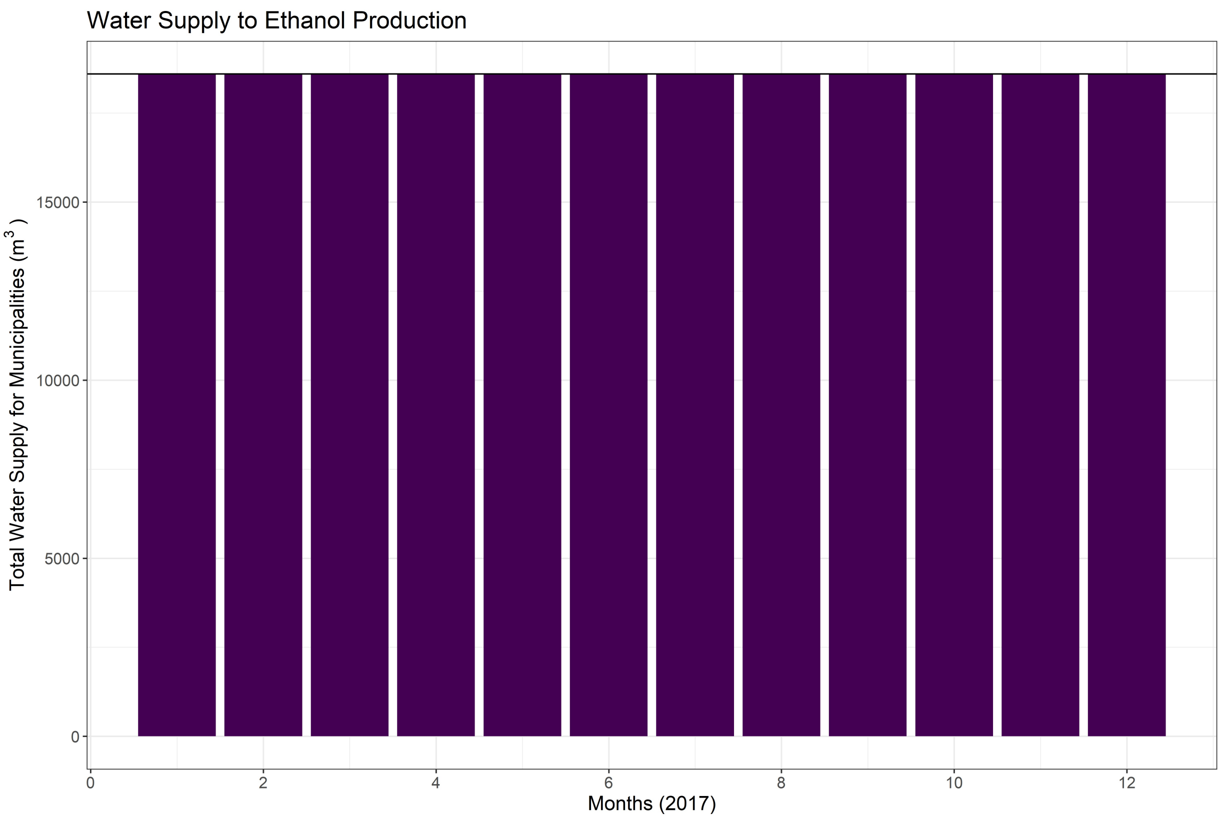


Figure B.2: Energy water supply

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