

REVIEW OF THE POTENTIAL FOR CO-FIRING OF CASSAVA RHIZOME FOR GENERATING HEAT AND POWER IN CASSAVA BASED BIO-ETHANOL PLANT IN THAILAND

Natikorn Prakobboon, Maria Vahdati

School of Construction Management and Engineering, University of Reading, Reading RG6 6UR, UK

Abstract

Biomass is an important source of energy in Thailand and is currently the main renewable energy source, accounting for 40% of the renewable energy used. The Department of Alternative Energy and Efficiency (DEDE), Ministry of Thailand, has been promoting the use of renewable energy in Thailand for the past decade. The new target for renewable energy usage in the country is set at 25% of the final energy demand in 2021. Thailand is the world's fourth largest producer of cassava and this results in the production of significant amounts of cassava rhizome which is a waste product. Cassava rhizome has the potential to be co-fired with coal for the production of heat and power. With suitable co-firing ratios, little modification will be required in the co-firing technology. This review article is concerned with an investigation of the feasibility of co-firing cassava rhizome in a combined heat and power system for a cassava based bio-ethanol plant in Thailand. Enhanced use of cassava rhizome for heat and power production could potentially contribute to a reduction of greenhouse gas emissions and costs, and would help the country to meet the 2021 renewable energy target.

Keywords: cassava rhizome; biomass co-firing; bio-ethanol; Thailand

1. Introduction

The Department of Alternative Energy Development and Efficiency (DEDE), Ministry of Energy, Thailand, has promoted renewable energy in Thailand for the past decade. In 2011, DEDE announced a new renewable energy plan, namely the Alternative Energy Development Plan (AEDP) 2012-2021, and set a target for renewable energy usage in the country of 25% of the final energy demand in 2021. Energy Policy and Planning Office (EPPO) reported in 2010 that the energy demand in Thailand is met by 12% coal, 44% natural gas, 37% petroleum and 7% other sources. Energy use in Thailand in 2008 was attributed to the industry sector (37%), followed by transportation (35%), residential & commercial (23%) and agriculture (5%) [1].

Biomass is the main renewable energy source in Thailand, and DEDE [2] reported that the installed capacity of biomass power generation was about 70.4% in 2012, followed by solar energy (13.5%) and biogas (6.9%). This is mainly due to the fact that Thailand has an abundance of different agricultural residues such as bagasse, rice husk, straw, and wood. Furthermore, combustion, gasification, pyrolysis, anaerobic digestion and co-firing technologies are well known and have been used in biomass power plant to generate electricity and heat in Thailand. As reported by Office of Agricultural Economics (OAE) 2010, approximately 4 million tonnes of cassava waste are leftover in the field every year. One of the main components of this waste is cassava rhizome,

which has the potential to be used as a fuel [17]. Cassava is one of the most important economic crops next to rice, rubber and sugarcane in Thailand [3]. Cassava rhizome's lower heating value is approximately 18 MJ·kg⁻¹ [26], which compares well to other agricultural residues but its moisture content is around 44-51% when it is fresh [5]. This cassava rhizome has the potential to be used as a fuel for cassava based bio-ethanol plant in Thailand.

Biofuels have been strongly promoted for the past ten years by the Thai government in order to decrease dependence on crude oil as well as reduce greenhouse gas (GHG) emissions. Currently, there are 48 plants legally licensed to produce bio-ethanol in Thailand with a total capacity of around 4.12 billion litres per year [2]. These bio-ethanol plants depend heavily on fossil fuels; a 150,000 litres per day cassava based bio-ethanol plant in Thailand uses about 120 tonnes of coal daily (0.8 kg of coal per litre of bio-ethanol) [2].

One of the most attractive biomass energy technologies is co-firing. Demirbas [6] and Wright et al. [7] concluded that 20% of biomass co-fired with coal in an existing coal boiler has been successful without any major problems. However, some studies [8, 9] have found that, in general, biomass co-firing in an existing coal boiler required slight modifications and additions to fuel handling, storage and feed systems to introduce and burn the supplemental fuel. Biomass co-firing technologies can provide great benefits such

*Corresponding author. Tel: +xxxxxxxxxxxxxx

E-mail address : E-mail: xxxxxxxxxxxxxxxxxxxxxx School of Construction Management and Engineering, University of Reading, Reading RG6 6UR, UK

as lower fuel costs, avoidance of landfill and reduction of NO_x, SO_x and GHG emissions [9].

This article is concerned with a review of the potential for cassava rhizome for co-firing technology in a combined heat and power (CHP) system for the provision of heat and power for a cassava based bio-ethanol plant in Thailand.

2. Bio-ethanol Plants in Thailand

For the past decade, biofuels have been promoted in Thailand in order to decrease the dependence on crude oil and reduce GHG emissions. In 2011, 85% of the crude oil used in Thailand was imported and the cost was about 327 billion baht [10]. Thai government has set a target of 9 million litres per day for the production of bio-ethanol by 2021.

In addition, DEDE reported that in 2010 there were 48 factories legally licensed to produce bio-ethanol with a total capacity of 12.5 million litres per day or 4,125 million litres per year [11].

Table 1. Number of bio-ethanol plants in Thailand [2]

Feedstock	No. of registered bio-ethanol plants		No. of existing bio-ethanol plants	
	plants	million litre/day	plants	million litre/day
Molasses	16	2.89	9	1.36
Cassava	24	8.39	5	0.83
Molasses & Cassava	8	1.22	6	1.08
Total	48	12.5	20	3.27

Table 1 shows that the two main feedstocks for the production of bio-ethanol in Thailand are molasses and cassava in [11]. Forty factories use only a single feedstock and eight factories use both feedstocks; 16 factories use molasses with a total bio-ethanol production capacity of 2.89 million litres per day, 24 factories use cassava with a total bio-ethanol production capacity of 8.39 million litres per day and 8 factories with a total bio-ethanol production capacity of 1.22 million litres per day. Currently, there are 20 bio-ethanol plants, with a total capacity of over 3 million litres per day in order to supply a variety of fuels in the country (e.g. E10, E20 and E85). According to Table 1, 28 bio-ethanol plants will be built in Thailand over the next few years. These will be located in the north eastern and central/eastern of Thailand.

Fig. 1 shows that most of the existing bio-ethanol plants are located in central and north east of Thailand where sugar cane and cassava are planted; this reduces the logistic cost for bio-ethanol production. Significant amounts of fossil fuels are used to supply the daily demand for electricity and steam for producing bio-ethanol; a 130,000 litres per day cassava based bio-ethanol

plant annually requires 0.8 kg of coal for every litre of bio-ethanol for generation of heat, and also purchases around £600,000 (30,000,000 Thai Baht) of electricity from the grid [2].



Figure 1. Bio-ethanol plants in Thailand [2]

Nguyen et al. [12] reported that biogas from the plant waste water was used with rice husk to substitute for use of coal in the bio-ethanol conversion process. This led to 83.3% GHG emissions reduction in molasses based bio-ethanol plant in Thailand. At the present, biogas is used in both molasses and cassava based bio-ethanol plants in Thailand. However, only 10-20% of steam demand in cassava based bio-ethanol plant is supplied by biogas (with 65% methane gas), which is captured from the waste water (spent wash) of the bio-ethanol production process [13]. Coal is still required for the rest of steam demand for the ethanol conversion process. In terms of molasses based bio-ethanol plants, bagasse and biogas from the plant's waste water are used in some plants in order to generate electricity and steam for the plant and any surplus electricity is sold to the grid.

Bio-ethanol plants operate 330 days per year. Sriroth et al. [11] determined that a 130,000 litres per day cassava based bio-ethanol plant requires 25,000 – 47,000 kWh per day of electricity and 300-500 tonnes of steam at a pressure of 3-10 bar, and emits around 120 tonnes per day of carbon dioxide. DEDE [2] reported that about 50 tonnes of coal, some biomass (wood chip and palm shell) and biogas are also burnt daily in order to produce the steam for bio-ethanol production process in cassava based bio-ethanol plant.

Papong [13] reported that for a 130,000 litres per day cassava based bio-ethanol plant, the major energy consumption takes place in the bio-ethanol conversion stage which accounts for about 78% of the energy usage. This is currently supplied by using coal for the production of steam used in the process and the electricity is purchased directly from the commercial grids.

3. Potential of Biomass Residues in Thailand

Biomass is an important source of energy in Thailand and is currently the second energy source in the country, especially in households and small industries in rural areas [14]. Biomass is widely used in the residential and commercial sectors as well as in industry. The demand for biomass residues has been growing recently due to its significant benefits and the growth of total energy demand in Thailand which has been around 4.5% per year [15]. The most important agricultural residues are bagasse, rice husk, straw, and wood. Biomass and agricultural residues have been used through combustion, gasification, pyrolysis and anaerobic digestion in many applications in order to generate electricity and heat in Thailand [10], [16]. However, direct combustion has been the most common process in converting biomass to other useful forms of energy in Thailand. The recent rapid growth in the use of biomass energy and the government's recent campaign encouraging the use of biomass residues have resulted in an increase in demand in the market, leading to a shortage and higher prices [17].

Biomass residues have a variety of combustion characteristics [18]. Yin [19] found that the properties of a particular biomass varied with location, climate and exact species. Not all biomass residues can be used for energy production because of their specific properties. The availability of biomass residues depends on agricultural production each year.

Tables 2 and 3 show that the four major sources of biomass in Thailand are sugar cane, rice, oil palm and wood wastes which together yield about 60 million tonnes per year. Sugar cane is the most important crop in Thailand; sugar cane production was 68 million tonnes in 2010, followed by rice (32 million tonnes) and cassava (22 million tonnes). Several biomass residues have been used to generate electricity in Thailand. Biomass residues with the most potential are sugar cane and rice residues; bagasse and leaves have been used in sugar mills in order to produce electricity and steam for sugar production, and rice husk is used for power generation in Thailand. As reported by DEDE [19] and Laohalidanond [20], cassava rhizome has been identified as one of four main agricultural products in Thailand. Cassava residues nationwide (cassava stems and cassava rhizomes) could generate approximately 78 TJ per year of energy (Table3). Cassava waste could be used in power plants or industries which are located around central and north east of Thailand. In this paper, estimate of the amount of cassava rhizome

available has been made by examining the cassava production data in Thailand. The properties of cassava rhizome have been examined by looking at previous studies and the potential usage of cassava rhizome as a fuel is assessed.

Table 2. Agricultural production in Thailand in 2008-2010 [3]

Crops	2008		2009		2010	
	Area (kilohectare)	Production (kilotonne)	Area (kilohectare)	Production (kilotonne)	Area (kilohectare)	Production (kilotonne)
Sugarcane	1,054	73,502	964	66,816	1,009	68,807
Rice	10,684	31,651	10,963	31,508	11,141	32,115
Corn	1,043	4,249	1,105	4,616	-	-
Palm	462	9,271	510	8,162	568	8,223
Cassava	1,184	25,156	1,373	30,088	1,168	22,005
Rubber	1,820	3,166	1,856	3,090	2,873	3,051

Table 3. Energy of biomass residue [19]

	Production (tonne)	Residue	Production (tonne)	Energy content (MJ·kg ⁻¹)	Energy Potential	
					(TJ)	(ktoe)
Sugar cane	66,816,446	bagasse	4,190,794.31	14.4	60,347.44	1,428.54
		leaf	13,439,727.21	17.39	233,716.86	5,532.52
Rice	31,508,364	husk	3,510,598.90	14.27	50,096.25	1,185.87
		straw	25,646,547.96	10.24	262,620.65	6,216.73
Palm oil	8,162,379	EFB	1,024,868.34	17.86	18,304.15	433.29
		fiber	162,970.06	17.62	2,871.53	67.97
		Shells	38,959.04	18.46	719.18	17.02
		fronds	2,203,740	9.83	21,824.24	516.62
Cassava	30,088,025	stem	2,439,236.19	18.42	44,930.73	1,063.60
		rhizome	1,834,466.88	18.42	33,790.88	799.89
Rubber	3,090,280	stem	312,118.28	14.98	4,675.53	110.68
Total	145,853,073		59,539,905.20		504,339.40	11,938.67

Remark: EFB = empty fruit bunches

4. Cassava and Cassava Rhizome Supply

Cassava (*Manihot esculenta*(L.) Crantz) is the third most important economical crop in Thailand (Table2) which is the world's fourth cassava producer with 22 million tonnes of cassava produced in 2010. The other main producers of cassava are Nigeria (37.5 million tonnes), Brazil (24.3 million tonnes) and Indonesia (23.9 million tonnes) [21]. Thailand is also the world's number one cassava exporter followed by Vietnam [21]. *Manihot esculenta* Crantz is known by many names, but cassava or tapioca are the most widely used in Thailand. Thailand produced over 30 million tonnes of cassava in 2009 from 1.33 million hectares of plantations [3].

Generally, the cassava plant comprises top/leaves 5%, stem 11%, rhizome 8% and root 76% (Fig. 2). About 75% of cassava roots are processed into pellets and chips and 25% are processed into starch. Cassava root and cassava starch are mainly used as a raw material for several industrial and commercial purposes such as food, beverage, sweetener, textile, paper, glue and bio-ethanol; one third of cassava production is used for bio-ethanol production in Thailand [5]. The remaining parts of cassava plant become a leftover surplus comprising of cassava rhizome and cassava stem. 25% of cassava

surplus comprising of cassava rhizome and cassava stem. 25% of cassava rhizome is ploughed in the soil in order to increase soil organic matter and nutrients, and 20% of cassava stem is used for generating a new harvest [23]. The rest of cassava waste unused and farmers will normally collect it in piles, leave it to dry out in the field or burn it away. Laohalidanond [20] reported that cassava rhizome was one of four main agricultural products based on crop year 2005-2006 in Thailand (these being rice husk, bagasse, cassava waste and oil palm). The agricultural economics office in Thailand reported that more than 4 million tonnes of cassava waste are leftover every year in the field. This causes farmers a disposal problem. FINPRO's study [5] stated that cassava rhizome is typically not used for any other purpose and does not contain any significant fertilising importance. However, Andrews [24] found that crop residue could increase the organic matter and nutrients in soil, and also help to prevent soil erosion.

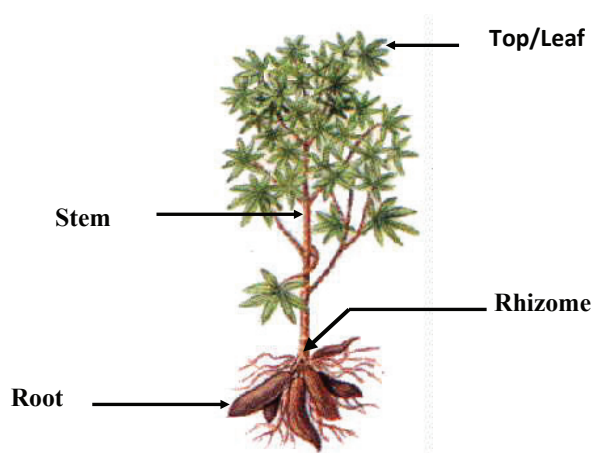


Figure 2. Cassava plant [22]

More than 85% of cassava plants are grown in Northeast and central Thailand. Nakhon Ratchasima province had a highest cassava waste available (1.2 million tonne per year) in 2010 [3].

5. Cassava Rhizome Properties

Both physical and chemical characteristic of biomass are significant issues for power generation [25]. Yin [19] found that the properties of a particular biomass varied with location, climate and exact species.

In terms of physical characteristics, the composition of cassava rhizome is similar to other biomass residues such as wood chip, oil palm shell and bagasse. Cassava rhizome contains mainly cellulose [26]. In addition, cassava waste characteristics have been investigated in many previous studies (Table 1A in appendix).

Table 4 shows the comparison of cassava rhizome characteristics with other biomass residues. The calorific value of cassava rhizome is around 17.62-18.47 MJ.kg⁻¹ (with an average moisture content of 10%). Coal (bituminous) has a heating value of about 24-35 MJ.kg⁻¹ and moisture content of not over 12% [60]. Cassava rhizome has a high moisture content (around 15-30%) compared to coal, and therefore has a significantly lower calorific value and bulk density, and high content of volatiles (77.75% on dry weight basis), it is easier to convert to gas, but has a high carbon content (about 52%) compared to other biomass residues. Cassava rhizome also has low nitrogen, carbon, sulphur and ash content which are 1.27 %, 51.59%, <0.1 % and 4.05% on dry weight basis, respectively (Table 4). These properties have a direct effect on GHG emissions, corrosion and ash deposition [18]. Jarinee and Kiatfa [27] found that shell of cassava rhizome contains a large quantity of silica networks which affect its strength and is hard to ignite.

Table 4. Characteristics of biomass residues

Fuels	Moisture	Ash	VM	FC	N	C	S	H	O	Calorific value	Reference
	(wt%)	(wt%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(MJ.kg ⁻¹)	
Rice straw	8.11	15.25	61.1	15.54	0.69	38.52	0.29	6.13	39.28	14.66	[59]
Corn cob	6.41	7.55	70.24	15.8	0.49	44.53	0.11	6.89	45.97	16.98	[59]
Rubber plant	8.88	9.9	62.92	18.3	0.97	48.69	0.11	7.29	39.03	18.14	[59]
Cassava rhizome	8.31	4.05	77.75	18.2	1.27	51.59	<0.1	6.69	40.45	18.47	[54]
Bituminous coal	2.83	20.08	28.33	49.08	1.13	63.78	0.97	3.97	10.08	34	[59]

A very important characteristic of biomass fuel with regard to power generation is moisture content. Biomass needs to be kept dry. The average moisture content of fresh cassava rhizome is around 50% and stalk 65% [5]. Cassava rhizome pre-treatment is required in order to expel the moisture and resize for effective firing in a combustor.

In addition, the particle size of cassava rhizome is also important. Its size could be slightly bigger than coal particle when cassava rhizome is fired in an existing coal boiler but should not be larger than the size requirement of boiler type. FEMP (Federal Energy Management Program) [9] stated that large fuel particles (≤ 3 inches) should be fired in a stoker (travelling or vibrating grate) and a fluidized bed boiler. Pulverized coal and cyclone boilers are suitable for only small particles ($\leq \frac{1}{4}$ inches). Inappropriate particle size of cassava rhizome can cause flow problems in the fuel handling equipment or incomplete burnout in the boiler which could lead to a low system efficiency. A study by Jaruwat et al [28] reported that burnt chopped cassava rhizome (3 – 5 mm) in a furnace gave the highest efficiency (90.62%) compared to a small logs (87.35%) and whole cassava rhizome (70.76%). Sengpetch [29] noted that cassava rhizome also could not be easily pulverised.

Chemical characteristics are important for the energy efficiency, environmental effects and ash related operating problems (slagging and fouling). Generally, most woody materials and waste papers are low in alkali and chlorine [9]. A study by Aho [30] and Doshi et al. [31] found that high alkali and chlorine content of

biomass can lead to corrosion problems and acidic emissions. Slagging and fouling problems also cause deposits in the furnace, and high operation and maintenance costs [32]. These problems can be minimized or avoided by limiting the proportion of cassava rhizome when co-firing with coal in a boiler, by using fuel additives, or by increased sootblowing in the process [33]. Cassava rhizome has low alkali and chlorine content (0.122%) [5] and also contains less sulphur and nitrogen compared to coal [34]. This could reduce SO₂ and NO_x emissions when it is mixed with coal in co-firing.

As reported by Sengpetch [29], dried cassava root chips were tested in a travelling stoker boiler for bio-ethanol production in Thailand. Six metric tonnes of dried cassava root chips were consumed to generate 2 MW of electrical power from 28 tonnes per hour of steam. The study showed the excellent burning characteristics of dried cassava root chips and the flue gas was clean due to low sulphur content (<0.1%). Sengpetch found that cassava rhizome could be used instead of dried cassava root chip due to lower price and similar calorific value.

According to its availability and characteristics, cassava rhizome has a high potential to be used as a fuel for heat and electricity generation.

6. Biomass Co-firing Technologies

Direct and indirect biomass co-firing technologies are well known and established in many parts of the world. Co-firing has been successfully demonstrated and practised in all types of coal boiler; pulverized, cyclones, stokers and fluidized beds. As reported by IEA [33], biomass co-firing with coal in power stations is common in Finland, the United States, Germany, Sweden and United Kingdom; in 2012, co-firing was 4.3% of renewable energy source in UK [61]. Biomass co-firing has significant benefits, which includes a reduction in costs and GHG emissions, an increase in the use of renewable energy and it enhances energy security in the country [9]. There are several biomass combustion (direct co-firing) and gasification (indirect co-firing) technologies for power generation at the present.

Table 5 shows the comparison of biomass combustion, gasification and pyrolysis technologies. As reported by Koukouzas et al. [35], most of biomass indirect co-firing technologies (gasification) are very attractive and efficient way of generating power. However, Puig-Amavat [36] found that gasification is suitable and profitable for generating electricity in only small scale, due to the high investment costs and complex multi stage processes compared to biomass direct co-firing (combustion).

Table5. The comparison of the different biomass technologies

Technology	Efficiency	Environmental benefit	Investment	Commercial Scale	Fuel Flexibility	Comments	References
Biomass Combustion system							[40]
Stoker	low	low	low	small	fair	simple, low efficiency, low environment	
Stationary grate fired	low	low	low	medium to large	medium	flue gas emission high, more sensitive to change fuel, difficult to control, fouling and slagging	
Traveling grate fired	low	low	low	medium to large	medium		
Vibrating grate fired	medium	fair	low	medium to large	medium		
BFB (Bubbling fluidized bed)	84%	high	medium	small to medium (5-100MW)	high particle size < 80 mm.	cannot operate with high alkali fuel	
CFB (Circulating fluidized bed)	high	high	medium	medium to large (20-500 MW)	high particle size < 40 mm.		
Pulverised	33-40%	low	medium	large	fair	ash slagging and fouling were found	
Biomass Gasification system							[58]
Updraft fixed bed gasifiers	medium	medium	medium	small (0.5 - 5MW)	specific physical characteristic of fuel	sensitive to tar and moisture content of fuel but good thermal efficiency	
Downdraft fixed bed gasifiers	medium	medium	medium			low sensitivity to charcoal dust and tar content of fuel, low tar	
Entrained flow gasifiers	high	fair	medium	large	fair	particle size <1mm, 15% moisture, low ash %	
BFB (Bubbling fluidized bed) gasifiers	high	high	high	medium (15-80 MW)	high	particle size <50-150mm, 10-55% moisture, care with ash	
CFB (Circulating fluidized bed) gasifiers	high	high	high	large (40-100 MW)	high	particle size <20mm, 5-60% moisture, care with ash	[36]
BIGCC	high	high	high	large	high	particle size <75mm, 10-50% moisture, care with ash	
Biomass Pyrolysis							[40]
Fixed bed	high	high	high	small: still under development	high	10% moisture, main product biochar	
Fluidized bed	high	high	high	medium: still under development	high	10% moisture, main product bio-oil	

Indirect co-firing is more suited to fuels containing contaminants such as municipal waste [37]. As reported by IEA [33], integrated gasification combined cycles (IGCC) were already used in some pulp and paper industries in European countries. Gasification technologies also require a gas cleaning system because of high flue gas emissions and high amounts of unburnt carbon in the fly ash. Fast pyrolysis is another technology for producing liquid fuel which could be used for energy production or chemical feedstock in the future. Liquid fuel (bio-oil) can be stored until required and easily transported. As reported by Bridgewater [38], bio-oil was successfully tested in engines, turbines and boilers. However, this technology is still in a pilot plant and laboratory scale as cost of fuel (bio-oil) is high compared to fossil fuels; it is 10 to 100% more expensive than fossil fuels [39].

Direct co-firing combustion is a widely used technology, and has been used for CHP generation as it is simple [40]. However, corrosion and fouling issues need to be carefully considered [41]. CHP systems based on biomass combustion are available in medium and large scale. The steam turbine process is economically and technically feasible primarily for large scale CHP plants. Co-firing biomass in an existing coal boiler usually requires at least slight modification or additions such as fuel handling, processing, storage, feed systems and specific requirements vary from site to site [9].

A study by Yamamoto [42] and Broek, et al. [32] found that fluidized bed (FB) combustion seems to be the most suitable technology for biomass co-firing. Foster wheeler [43] investigated co-firing biomass with coal and found that pulverized coal (PC) and circulating fluidized bed (CFB) technologies were most common for power generation in European countries. As reported by Aho [30], CFB furnace could capture SO₂ better than bubbling fluidized bed BFB due to a smaller bed area. A large number of grate fired boilers have been replaced by fluidized bed boilers due to the advantages of fluidized bed combustion, such as possibility to use a wide variation of fuels (possible to use mixture of different kinds of biomass or to co-fire them with other fuels), high efficiency, low GHG emissions and long residence time [37].

Sami, et al. [44] stated that the percentage of biomass co-fired with coal is another important parameter which could affect efficiency and cause other problems such as the temperature drop, corrosion, fouling and slagging. Tillman [45,46]; Mann [47]; Berggen [48] noted that 15% biomass (on energy basis) can be co-fired in coal plants without any major problems with corrosion, slagging, fouling in the combustion chamber, fuel handling and fuel feeding. A study by Granada [8] reported that 50% biomass co-firing with wood pellet could reduce efficiency significantly, and found that 25% biomass co-firing with wood pellet was the most suitable option. It is stated that burner redesign could allow higher percentage of biomass to be used with little loss of efficiency. Zabetta and Hotta [49] reported

that a CFB boiler, made by Västärås, is capable of co-firing mixes of biomass and coal up to 50% share. For high percentage of biomass co-firing, it is recommended to use the indirect co-firing method but its internal rate of return (IRR) is less than 2 times of direct co-firing technology [41].

The co-firing of cassava rhizome and other biomass residues with coal could produce electricity and steam in cassava-based bio-ethanol plant in Thailand. In terms of the economics, the optimum commercial scale of bubbling fluidized beds (BFB) is 5-100 MW which could be suitable for a bio-ethanol plant. Furthermore, Broek et al. [32] claimed that BFB have lower capital requirement at modest scales of up to 20 MWe than CFB.

In terms of biomass for CHP systems for bio-ethanol plant, Seabra [50] examined use of bagasse and cane trash (supplementary) in order to produce heat and power for sugarcane biorefinery and sugarcane-based bio-ethanol plant in Brazil. Electricity surplus was sold to the grid which presented an attractive business option for Brazilian sugarcane mills. Corn stover has also been used as a bioenergy source to generate electricity and heat in corn-based bio-ethanol plant [51, 52]. Economics of a corn stover fired CHP system were unattractive compared to coal fired CHP system due to higher fuel costs. However, the GHG emissions per mg of fuel for a corn stover fired CHP system were 32 times lower than coal fired CHP systems [53].

Co-firing can be economically attractive under certain circumstances. Firstly, price of coal should be high; FEMP [10] noted that co-firing can be economically attractive when biomass fuel supplies cost at least 20% less, on a thermal basis, than coal prices. Secondly, annual cost usage is significant. Thirdly, the availability of biomass is abundant avoiding the shortage and higher prices. Fourthly, the cost of biomass disposal is high.

7. Conclusions

DEDE, Ministry of Thailand, has promoted renewable energy in Thailand in order to increase the use of renewable energy and enhance energy security. Thai government intends to decrease dependence on imported crude oil and also reduce the use of fossil fuels in the country. The bio-ethanol industry in Thailand has been growing significantly during the past ten years, and significant amounts of fossil fuels are used to supply the demand for electricity and steam. At present there are 4 cassava based bio-ethanol plants in Thailand. There will be about 20 more cassava based bio-ethanol plants in the future. Cassava rhizome could be a significant biomass fuel for these plants. Co-firing cassava rhizome with coal could be a great opportunity to reduce fuel costs and minimise the waste problem in the field, as well as reduce GHG emissions for cassava based bio-ethanol plants. Biomass co-firing technology with a CHP system is a potential solution for cassava based bio-ethanol plant in

Thailand. Such co-firing would be successful depending on many factors including, fuel characteristics, fuel costs, the availability of biomass residues, the renewable energy market and government policy.

Acknowledgement

The authors are grateful to Energy Policy and Planning Office (EPPO), Ministry of Energy, Royal Thai Government for their financial support.

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Appendix

List of abbreviations

DEDE	Department of Alternative Energy Development and Efficiency
AEDP	Alternative Energy Development Plan
EPPO	Energy Policy and Planning Office
OAE	Office of Agricultural Economics
GHG	Greenhouse gas
CHP	Combined heat and power
FEMP	Federal Energy Management Program
IEA	International Energy Agency
IGCC	Integrated gasification combined cycles
PC	Pulverized coal
CFB	Circulating fluidized bed
BFB	Bubbling fluidized bed
IRR	Internal rate of return
EFB	Empty fruit bunches