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Article

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International Journal of Energy Economics and Policy

International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2022, 12(1), 62-72.

Grid-connected Electricity Generation Potential from Energy Crops: A Case Study of Marginal Land in Thailand

Thanarat Pratumwan[1], Warunee Tia[1]*, Adisak Nathakaranakule[2], Somchart Soponronnarit[2]

[1]Energy Management Technology Program, School of Energy, Environment and Materials, King Mongkut's University of Technology Thonburi, Thung Khru, Bangkok, Thailand, [2]Energy Technology Program, School of Energy, Environment and Materials, King Mongkut's University of Technology Thonburi, Thung Khru, Bangkok, Thailand. *E-mail: warunee.tia@kmutt.ac.th

Received: 09 August 2021 **Accepted:** 14 November 2021 **DOI:** https://doi.org/10.32479/ijeep.11903

ABSTRACT

This paper provides an assessment of the geographical potential of grid-connected electricity generation from the planting of energy crops using GIS while also estimating the levelized costs of electricity (LCOE) under three biomass-prices scenarios. To avoid competition for land use between food and energy crops, marginal land or unsuitable areas (low soil fertility) were used as case study sites for planting energy crops (Napier grass). The total estimated potential based on the location of energy crops and electrical substations was 11,224 MW or 66,367 GWh/y, equivalent to approximately 26.5% of Thailand's total electricity demand in 2037. The LCOEs under the three scenarios ranged from 0.103 to 0.120 USD/kWh for a 9MW capacity power plant, which were lower than the feed-in tariff rate. The results of economic assessment under three scenarios showed positive NPV values but relatively long discounted payback periods. The project and equity IRR ranged from 11.94 to 14.04% and 24.40 to 30.89%, respectively. These findings can be used for land-use planning and energy crop promotion to increase the share of grid-power generation from biomass.

Keywords: Economic Analysis, Energy Crops, Geographic Information System, Grid Connection, Marginal Land, Power Generation Potential
JEL Classifications: Q2, Q42, Q5

1. INTRODUCTION

Many countries still use fossil fuel as the main source of electricity generation, especially non-OECD members (IEA, 2019) such as Thailand, where 76% of the electricity generated in 2019 was from fossil fuels (natural gas 59.5%, coal 16.5%, oil 0.1%) (DEDE, 2019). Fossil fuel-based power generation plants contribute approximately 38% of Thailand's total CO_2 emissions from greenhouse gases (GHG) (DEDE, 2019). In addition, Thailand is a net importer of fossil fuels. Thus, both energy security and greenhouse gas emissions are significant issues for the country. To reduce GHG emissions and dependency on imported fossil fuels by the power sector, the government has developed the Alternative Energy Development Plan for Thailand 2018–2037 (AEDP 2018) to promote local renewable alternative energy. The target of the AEDP 2018 aimed to increase the capacity of accumulative renewable power to 29,411 MW by 2037, of which 10,715 MW had already been contracted by the end of 2017 (DEDE, 2020). The contract capacity consists of hydro (29%), solar (27%), biomass (21%), wind (14%), municipal and industrial waste (5%), and biogas (4%). The remaining target of 18,696 MW, potentially achievable from solar (12,015 MW), biomass (3,500 MW), wind (1,485 MW), biogas (1,183 MW), waste (444 MW), and hydro (69 MW), is expected to be reached during the period from 2018 to 2037 (DEDE, 2020).

In 2019, the total renewable electricity generated in Thailand was 38,016.3 GWh, of which 50.3% came from biomass, mainly biomass residue such as bagasse, rice husk, and agricultural waste (DEDE, 2019). Biomass residue is also commonly used as a fuel source for heating in industrial processes. Biomass has high reliability in terms of grid-connected power generation

(Dasappa, 2011). However, the availability of biomass from agricultural residue depends on the harvesting seasons of each crop (Yang et al., 2015). Energy crop plantation can provide regular biomass feedstock for power generation with an assured supply all year round over the lifetime of a power plant. In addition, the use of biomass from energy crops can increase local economic development, energy security, and reduce the greenhouse gas emissions (CIS, 2002). Therefore, increasing the electricity generation potential of energy crops is an interesting option.

Several crops demonstrate high potential for energy use. Therefore, selecting which crop to grow should be based on the general characteristic guidelines for the ideal energy crop such as high biomass productivity, low nutrient requirement, drought resistance, and low production costs (McKendry, 2002). Napier grass (*Pennisetum purpureum Schum*) is a fast-growing plant native to Africa, and has received attention for its potential cultivation as a prospective energy crop due to its high biomass productivity under low-input requirements (Manouchehrinejad et al., 2018), low nutrient requirements, ability to grow in degraded soils (Strezov et al., 2008), and drought resistance (Sawasdee and Pisutpaisal, 2014). It has high productivity and a heating value of up to 45 tDM/ha/y (Basso et al., 2014) and 18.11 MJ/kg, respectively, which is close to the values of fast-growing trees such as Eucalyptus cladocalyx (18.87 MJ/kg) (Rocha et al., 2017). Therefore, several studies have investigated the use of Napier grass as feedstock for the generation of heat and electricity (Oliveira et al., 2015), biofuel (Coffin et al., 2016), and biogas production (Suaisom et al., 2019). Moreover, according to Morais et al. (2018), Napier grass is a highly appropriate biomass feedstock for energy production by direct combustion, due to the relatively high ratio of energy obtained (calorific value) compared to the energy used in the biomass production process (approximately 15:1).

The Thai government continues to promote the use of Napier grass as feedstock for biomass power plants (Waramit et al., 2014). Thus, a number of studies have been conducted on planting Napier grass in Thailand to determine its yield under various planting conditions and harvesting methods. For instance, Waramit et al. (2016) conducted field experiments by planting nine Napier grass cultivars: Bana, Chakapadi, Common, Kasetsart, King, Mauklek, Pakchong1, Surat, and Tifton, in different types of degraded areas (subject to seasonal floods, low soil fertility, and drought). The average dry yield from areas with low soil fertility and drought was about 38.91 tDM/ha/y. Haegele and Arjharn (2017) studied the effect of planting methods and seasons on Napier grass yield, while Jeenanurukg et al. (2014) evaluated the feasibility of investing in Napier grass cultivar (Pakchong 1) for power generation. To avoid competition between food and energy production over the use of land, previous studies suggest that marginal, polluted, and degraded land unsuitable for food-based agriculture should be utilized to plant energy crops (Lovett et al., 2009; Schreurs et al., 2011; Saha et al., 2018; Uchman et al., 2017). Thailand's agricultural land has been zoned for planting the country's six main economic crops, namely cassava, maize, palm oil, rice, rubber, and sugar cane, based on land suitability and the government's annual crop yield requirement. Available agricultural land can be classified into four groups according to suitability: (i) high, (ii) moderate, (iii) low, and (iv) unsuitable. To increase biomass power generation, areas deemed unsuitable for planting the six most economic crops (USEC areas) could potentially be utilized for planting Napier grass as an energy crop. A detailed study of the potential and economic feasibility for generating electricity through this method is essential when making investment and policy decisions.

Therefore, this study aims to (i) assess the potential of biomass feedstock production from planting Napier grass in USEC areas, (ii) assess the potential of Napier grass for grid-connected power generation through direct combustion, and (iii) assess the levelized cost of electricity generation (LCOE) and economic feasibility. The location of national electric substations and transmission lines are also included in the criteria for explicit assessment of the power potential and economic feasibility of investing in grid-connected biomass power plant. Since some of the USEC areas are located within the agricultural land reform (ALR) zone, designated and managed by government offices, there is a strong possibility that they can be used for planting energy crops under the government's energy crop policy. Thus, in this study, the USEC areas located within agricultural land reform zones (USEC-ALR) are also identified and assessed for biomass power potential.

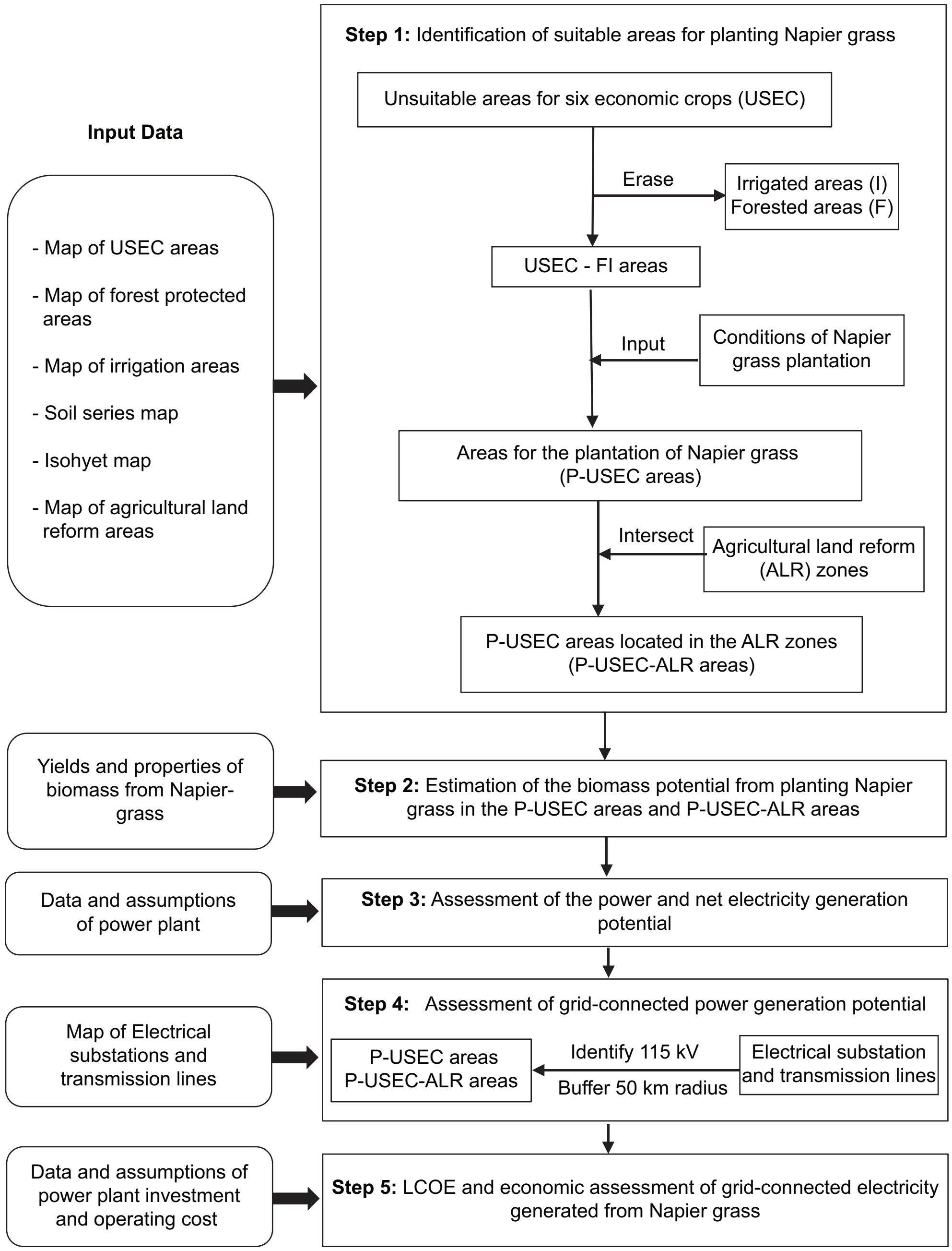
2. MATERIALS AND METHODS

According to the previous studies on geographical biomass potential, the Geographic Information System (GIS) is widely used for spatial assessment of the biomass potential for power generation (Dasappa, 2011; Sun et al., 2013; Hiloidhari and Baruah, 2014; Lourinho and Brito, 2015; Stich et al., 2017; Sun et al., 2017), biomass production (Saha et al., 2018), and biomass power sites (Davtalab and Alesheikh, 2018). Thus, ArcGIS is used in this study to identify suitable areas for planting Napier grass, assessing the potential of biomass and electricity production, and the feasibility of grid-connected power generation from Napier grass plantation. The assessment procedure for assessing power generation potential from planting Napier grass can be divided into the five steps shown in Figure 1: (1) identification of areas for planting Napier grass; (2) estimation of the biomass potential; (3) assessment of the power and net electricity generation potential; (4) potential assessment of grid-connected biomass power generation; and (5) LCOE and economic assessment.

2.1. Study Area

Located in South-East Asia between latitudes 5° 37' N and 20° 27' N and longitudes 97° 22' E and 105° 37' E, Thailand covers a total area of 51.31 million ha (or 320.69 million rai). Approximately 46.5% of Thailand's total land area or 23.87 million ha is utilized for agriculture. Thailand is divided into five geographical regions: central, eastern, northern, northeastern, and southern. In 2012, the government designated areas suitable for cultivating the country's six most economic crops, namely, cassava, maize, palm oil, rice, rubber, and sugar cane, to establish a database for effective crop planning and policy. Dispersed across the country, 3.13 million ha was deemed unsuitable for planting any of the six main crops (USEC areas) (OAE, 2012), and this study proposes the use of such land for planting energy crops.

Figure 1: Overview of the GIS-based assessment steps for grid-connected power generation from Napier grass



2.2. Identifying Suitable Areas for Planting Napier Grass

The areas available for planting Napier grass were identified in this study with the use of ArcGIS software and digital map data at a scale of 1:50,000. Table 1 shows the digital map data: USEC areas, soil series, agricultural land reform zones, irrigation areas, forest protected areas, electrical substations and transmission lines and those on the isohyet map. To mitigate the effects on forest and food sustainability, the irrigated and protected forest within the USEC areas identified from the digital map data were extracted from the land under consideration for planting Napier grass (USEC-FI areas). Since the USEC-FI areas have low soil fertility, the conditions for planting Napier grass and the biomass yield data used in this study were based on the field experiments carried out by Waramit et al. (2016). These researchers planted nine Napier grass cultivars, namely Bana, Chakapadi, Common, Kasetsart, King, Mauklek, Pakchong1, Surat, and Tifton, in

Table 1: Digital map data used for assessing the power generation potential of Napier grass

Map data	Data sources
Map of agricultural land reform areas	Agricultural Land Reform Office
Map of electrical substations and transmission line	Map and Geographic Information System Department, Survey Division, Electricity Generating Authority of Thailand (EGAT)
Map of forest protected areas	Royal Forest Department
Map of irrigation areas	Royal Irrigation Department
Isohyet map	Thai Meteorological Department
Map of USEC areas and Soil series	Land Development Department

the soil with low fertility (soil organic matter of 0.87%) and drought areas (rainfall of 83 mm). Moreover, Pongtongkam et al. (2006) observed that Napier grass could not be grown in saline soil (≥2 deciSiemens per metre: ds/m). Another important consideration was that areas with steep slopes greater than 35% were unsuitable for Napier grass due to the high planting and harvesting costs. Based on these conditions, the areas considered suitable for planting Napier grass (P-USEC areas) were identified and mapped using the maps of USEC-FI areas, soil series, and isohyet. The P-USEC areas located in the agricultural land reform zones (P-USEC-ALR) were then identified by intersecting P-USEC with ALR areas.

2.3. Estimation of the Biomass Potential from Planting Napier Grass

Napier grass yield and its potential heating value depend on the harvesting intervals. Increasing the harvesting age results in Napier grass with a higher dry yield (Waramit et al., 2016; Haegele and Arjharn, 2017) and lower moisture content. In addition, Napier grass harvested at 360 days produces the highest heating value, making it suitable for generating electricity through direct combustion technology (Waramit et al., 2016). As mentioned in Section 2.2, the biomass potential in this study was assessed based on the yield obtained from field experiments (planting in low fertile soil under drought conditions) carried out by Waramit et al. (2016). The average biomass yield of nine Napier grass cultivars (Bana, Chakapadi, Common, Kasetsart, King, Mauklek, Pakchong1, Surat, and Tifton) at a 360-day cutting interval ranged from 20.59 to 67.70 tDM/ha/y with a heating value ranging from 15.05 to 16.45 MJ/kg depending on their cultivars (Waramit et al., 2016) as presented in Table 2.

Bana produced the highest biomass yield while Chakapat exhibited the highest heating value. Since the distribution selected by the farmers for planting these nine grass cultivars in the study areas was not disclosed, the average yield at a 360-day cutting interval of 38.91 tDM/ha/y and an average lower heating value of 15.64 MJ/kg were used to assess the biomass potential of planting Napier grass in P-USEC areas. Biomass loss during the harvesting and transportation processes is assumed to be 10% (Yokoyama et al., 2000) for this study. The biomass potential from planting Napier grass in P-USEC and P-USEC-ALR areas in five regions was estimated using the following equation:

Table 2: Yield and lower heating value of the nine Napier grass cultivars at a 360-day cutting interval

Cultivar	Average biomass yield[a] (tDM/ha/y)	Lower heating value[b] (MJ/kg)
Bana	67.70	15.31
Chakapat	35.32	16.45
Common	41.56	15.40
Kasetsart	20.59	15.74
King	36.61	15.97
Muaklek	18.72	15.05
Pakchong1	24.67	15.29
Surat	51.95	16.26
Tifton	53.07	15.30
Average	38.91	15.64

[a]Source: Waramit et al. (2016). [b]Calculated from the data of higher heating value

$$BF = \sum_{r=1}^{5} Y \times A(r) \times (1 - \frac{L}{100}) \tag{1}$$

where BF is the annual biomass production (tDM/y), Y is the average Napier grass yield (tDM/ha/y), $A(r)$ is the total plantation area in the region r (ha), and L is the percentage biomass loss during the harvesting and transportation processes.

2.4. Assessment of Grid-connected Power Generation Potential

Among the various methods used for converting biomass feedstock into heat/power, direct combustion is the most common (Mehmood et al., 2017; Moon et al., 2011; Oliveira et al., 2015) and employed in rice-husk fired power plants (Ueasin et al., 2015). Napier grass is also used as fuel in the grate-fired boilers of the Rankine cycle cogeneration system in the steelmaking industry (Oliveira et al., 2015). Moreover, carbon dioxide (CO_2) released during the combustion of biomass is consumed during plant regrowth, and thus considered to be CO_2 neutral (Oliveira et al., 2015). In Thailand, approximately 70% of the active biomass power plants selling electricity to the national power grid have an installed capacity of less than 10 MW due to the lower complexity of the permission process and the lower risks involved in biomass supply. Most of the plants use direct combustion/steam turbine systems installed capacities ranging from 8 to 9.9 MW (ERC, 2020). Thus, a biomass-fired boiler/steam turbine system with an installed capacity of 9 MW is chosen for electricity generation in this study. The potential power and net electricity generation from Napier grass yield are estimated using Equations (2) and (3).

$$P = \sum_{r=1}^{5} \frac{BF(r) \times \eta \times LHV}{3.6 \times H} \tag{2}$$

$$E = \sum_{r=1}^{5} P(r) \times H \times (1 - \frac{U}{100}) \tag{3}$$

where P is power generation potential (MW), η is the overall efficiency of the power plant (decimal), LHV is the lower heating value of the Napier grass (MJ/kg), H is the yearly operating hours of the power plant (h/y), E is the amount of net electricity generated per year (MWh/y), and U is the percentage consumption rate of the power plant. According to the operational data obtained from the power plant, Napier grass at moisture content of 40% wet basis is used as fuel. Previous research reveals that the electricity consumption of the power plant and the gross efficiency exhibited by a biomass power plant with a direct-fired boiler and steam turbine are assumed to be 10% of the total electricity produced (Tangmanotienchai et al., 2014) and 23% (Delivand et al., 2011), respectively. Based on these figures, the net efficiency of the power plant equates to about 21%, which is a conservative value compared to the 20 to 40% mentioned in previous studies (Singh, 2016). The assumptions used for estimating the potential of power generation from Napier grass are summarized in Table 3.

To facilitate the sale of generated power to the national power grid while also minimizing the cost of the transmission line and biomass

Table 3: The assumptions used for calculating the power and electricity generation potential of Napier grass

Assumptions	
Annual operating hours	6570 h/y
Overall efficiency of the power plant	23%
Average lower heating value of the 9 cultivars of Napier grass	15.64 MJ/kg [a]
Average lower heating value of the 9 cultivars of Napier grass at 40% w.b.	8.984 MJ/kg [b]
Assumed biomass losses during harvesting and transportation	10%
Self-consumption of biomass power plant	10%

[a]From Table 2. [b]Calculated from the data in Table 2

transportation, the power plant should be located near an electrical substation (Guerrero et al., 2016) and plantation area. According to previous studies (Monforti et al., 2013; Masum et al., 2020), the potential of grid-connected power generation is estimated based on the areas identified as being suitable for Napier grass cultivation within a 50 km radius of electrical substations. Currently, Thailand has a total of 224 high voltage substations, of which 18, 79, and 127 are 500, 230, and 115 kV, respectively (EGAT, 2018). From the Regulations of the Power Network System Interconnection Code (PEA, 2016), very small power producers (VSPP) are defined as those with an installed capacity of less than or equal to 10 MW with power supplied to the national grid through a 115 kV transmission system. Suitable Napier grass plantation sites within a 50 km radius of electrical substations were identified using ArcGIS software, a digital map of national substations and transmission lines obtained from the Electricity Generating Authority of Thailand (EGAT), and spatial distribution maps of P-USEC and P-USEC-ALR areas. The potential electricity generated was then calculated based on the amount of Napier grass produced in the proposed areas using Equations (1) to (3).

2.5. Economic Assessment of Grid-connected Power Generation

As mentioned in Section 2.4, a biomass-fired boiler/steam turbine system with an installed capacity of 9 MW was for the economic assessment based on the life-cycle cost approach. The LCOE and economic feasibility are usually considered as the key aspects of policymaking to develop incentive measures for promoting power generation from renewable sources. The LCOE is a method for obtaining the unit cost of the electricity generated, calculated using the net present value of the total life-cycle cost divided by the present value of the total lifetime of electricity generation, as presented in Equations (4) and (5) (Tran and Smith, 2018):

$$LCOE = \frac{Total\ cost\ over\ lifetime}{Total\ electricity\ generated\ over\ lifetime} \quad (4)$$

$$LCOE = \frac{\sum_{t=1}^{n} \frac{TC_t}{(1+i)^t} + IC_0}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}} \quad (5)$$

$$TC_t = BFC_t + OM_t \quad (6)$$

where IC_0 is the initial investment cost (USD), BFC_t is the biomass fuel cost in the year t (USD), OM_t is the operations and maintenance costs in the year *t* (USD), TC_t is the total cost in the year ***t***, E_t is the net electricity generated in the year *t* (kWh), ***i*** is the percentage discount rate, and ***n*** is the useful life of the power plant (y). The total capital cost includes the power plant construction including equipment and grid-connection costs. The cost of the latter varies, depending on the transmission distance, voltage level, and technical requirements under the regulations. According to the Power Network System Interconnection Code (PEA, 2016), VSPP power plants is connected to 115 kV substations. The transmission distance from the power plant to the substation is generally 10 km. Thus, the grid-connection cost is estimated based on 115 kV transmission systems with a connection distance of 10 km. Annual biomass consumption and electricity production are estimated according to Equations (2) and (3), respectively. According to the interview data obtained from an officer at the biomass power plant, the biomass fuel cost is estimated based on the price of freshly chopped Napier grass with a moisture content of 40% wet basis, including the transportation cost within a 50 km radius of approximately 21.51 USD/ton and used as a base-case scenario of biomass price. The total annual operating and maintenance costs of the power plant and grid-connected system are comprised of both fixed and variable costs, including land rent and equipment replacement. All the costs of grid-connected power generation from Napier grass are summarized in Table 4. Since the discount rate and biomass cost are sensitive to LCOE estimation, in this study the LCOE is calculated at various discount rates (8 to 11%) for three scenarios of Napier grass price: (1) base-case Napier grass price of 21.51 USD/ton, (2) a 10% increase in the base-case price (23.66 USD/ton), and (3) a 20% increase in the base-case price (25.81 USD/ton).

The feasibility of investing in a 9MW biomass power plant with a grid-connected system using Napier grass as fuel is assessed based on the common economic indicators: the net present value (NPV), discounted payback period (DP), project internal rate of return (P-IRR), and equity internal rate of return (E-IRR). All revenue and costs over the lifetime of the power plant are considered in the NPV, while DP is the period of time (years) during which the initial investment cost is recouped. The P-IRR focuses on an assessment of the project's return, excluding the effects of debt leverage by assuming no debt (Guilhermino et al., 2018). In general, funding sources for such projects consider the proportion of debt and equity (debt-to-equity ratio), therefore, the E-IRR is used as a feasibility indicator in this case. The E-IRR is the rate of return on equity, which can be calculated by comparing cash flow with equity, including payments on the principal loan, interest, and income tax. The weight average cost of capital (WACC), often used as a discount rate for estimating the feasibility of a renewable project (Steffen, 2020) and LCOE (IRENA, 2012) are employed in this study. The following equations can be used to assess the economic feasibility of the project:

$$DP \rightarrow \sum_{t=1}^{T} \frac{(R_t - TC_t - tax_t)}{(1+i)^t} \approx IC \quad (7)$$

Table 4: Data and assumptions for calculating the levelized cost and economic feasibility of the grid-connected power generation from Napier grass

Parameters	Data	Sources
Net electricity production (kWh/y)	53,217,000	Calculated from Equation (3)
Investment costs		
9 MW Power plant (million USD/MWe)	2.026	Estimated from power plant investment data
Grid-connection system (million USD)	1.423	EGAT
Tractors (million USD)	0.0482	Assumed
Operating costs		
Napier grass consumption (t/y)	103,018	Calculated from Equation (2)
Price of chopped Napier grass (40% moisture w.b.), including transportation cost (USD/t)	21.51	Obtained from the biomass power plant
Land rent (USD/y)	32,823	Estimated from power plant investment data
Labor expenditure including welfare (USD/y)	223,410	Estimated from labor data
Fuel cost (USD/y)	25,520	Estimated from fuel consumption
Other operating costs (% of biomass cost)	1	Assumed
Maintenance and replacement costs (% of investment cost)		
Power plant	3.5	Assumed
Grid-connection system	3.5	Assumed
Tractors	8	Tangmanotienchai et al., 2014
Feed-in tariff (Fixed rate + variable rate)		
Fixed rate (USD/kWh) in 2017	0.0734	EPPO, 2017
Variable rate (USD/kWh) in 2020	0.0579	ERC, 2020
Expected return on equity (after-tax) (%)	23	Assumed
Debt to equity ratio	70:30	Assumed
Loan interest rate (% per annum)	6.0	Assumed
Loan repayment period (y)	10	Assumed
Income tax (%)	25	Tangmanotienchai et al., 2014
Escalation rate (% per annum)		
Fuel cost	1	Assumed
Land rent	2	Assumed
Operating and maintenance costs	2.5	BOT, 2020
Napier grass and variable rate of Feed-in tariff	0.5	Estimated from the data of core inflation rate during 2017-2020
Lifetime (years)		
Power plant and Grid-connection system	20	Estimated from period support of Feed-in tariff
Tractors	10	Assumed

1 USD = 32.55 THB (as of 30 April 2020)

$$NPV = \sum_{t=1}^{n} \frac{(R_t - TC_t - tax_t)}{(1+i)^t} - IC \quad (8)$$

$$P-IRR \rightarrow \sum_{t=1}^{n} \frac{(R_t - TC_t - tax_t)}{(1+i)^t} - IC \approx 0 \quad (9)$$

$$E-IRR \rightarrow \sum_{t=1}^{n} \frac{(R_t - TC_t - Tax_t - IR_t - PP_t)}{(1+i)^t} - E \approx 0 \quad (10)$$

$$WACC = e \times r_e + d \times (1 - t_r) \times r_d \quad (11)$$

where T is the discounted payback period (year), R_t is the annual revenue from the sale of electricity to the grid in the year t (USD), IR_t is interest in the year t (USD), IC is the initial investment cost (USD), PP_t is the principal payment in the year t, E is equity (USD), e is equity ratio, r_e is the expected percentage return on equity (after tax), d is the debt ratio, t_r is the percentage tax rate, and r_d is the percentage debt interest rate.

The revenue of the power plant is obtained from the sale of generated electricity to the grid. Thailand's rate of feed-in tariff (FiT) policy for VSPP biomass power plants with a capacity of more than 3 MW was 0.1313 USD/kWh in 2020, comprising two main components: (i) the fixed rate of 0.0734 USD/kWh (EPPO, 2017); and (ii) the variable rate in 2020 of 0.0579 USD/kWh (ERC, 2020). The variable rate of FiT is set to increase based on the core-inflation rate, assumed as 0.5% per annum. The debt-to-equity ratio, debt interest rate, and tax rate are assumed to be 70:30, 6% per annum and 25%, respectively. Based on the expected return on equity of 23% (after tax), WACC equates to approximately 10% and this is used as the discount rate for calculating NPV and DP. All data and assumptions for calculating the economic feasibility of the project are summarized in Table 4.

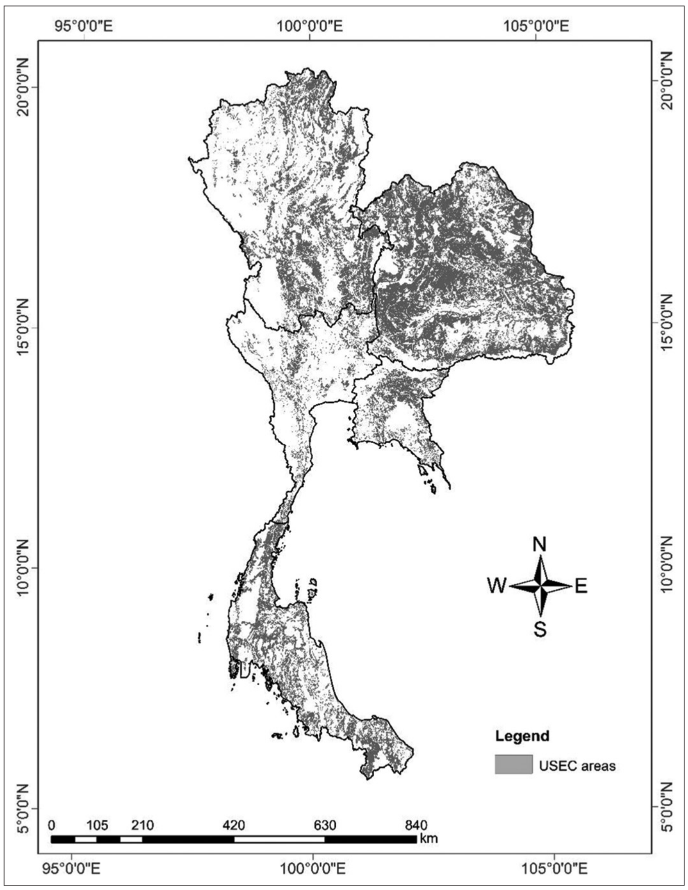
3. RESULTS AND DISCUSSION

Based on the methodology presented in the previous sections, the identification of available USEC areas in Thailand for planting Napier grass, the geospatial potential of Napier grass production and grid-connected power generation, as well as the corresponding LCOE generation and economic feasibility are presented and discussed.

3.1. Available Areas for Planting Napier Grass

The spatial distribution of the total area unsuitable for planting the six major economic crops (USEC areas) was identified as 3.133 million hectares, equating to approximately 14.3% of the agricultural zone as shown in Figure 2. However, protected forests of 0.46 million hectares and irrigation areas of 0.17 million hectares exist within the USEC areas. The forest areas should be protected while food crops can be planted in the irrigated areas. Therefore, in this study, these areas were subtracted from the USEC areas. In the remaining 2.498 million hectares, the organic matter in the soil is lower than 1% and therefore unsuitable for planting food crops but appropriate for planting Napier grass based on the criteria mentioned in Section 2.2. Approximately 2.490 million hectares (P-USEC) can be planted with Napier grass. There are 0.898 million hectares (P-USEC-ALR) within the P-USEC located in agricultural land reform zones. Figure 3 shows the spatial distribution of the available plantation area for Napier grass in both P-USEC and P-USEC-ALR. The spatial distributions of P-USEC according to geographical region are as follows: 56.4% in the northeastern, 17.8% in the northern, 17.5% in the southern, 5.0% in the eastern, and 3.3% in the central. Whereas 62.0% of the P-USEC-ALR is distributed in the northeastern, 19.5% in the northern, 10.4% in the southern, 7.9% in the eastern, and 0.2% in the central region. The results for both P-USEC and P-USEC-ALR in each region are presented in Table 5.

Figure 2: Spatial distribution of the USEC areas



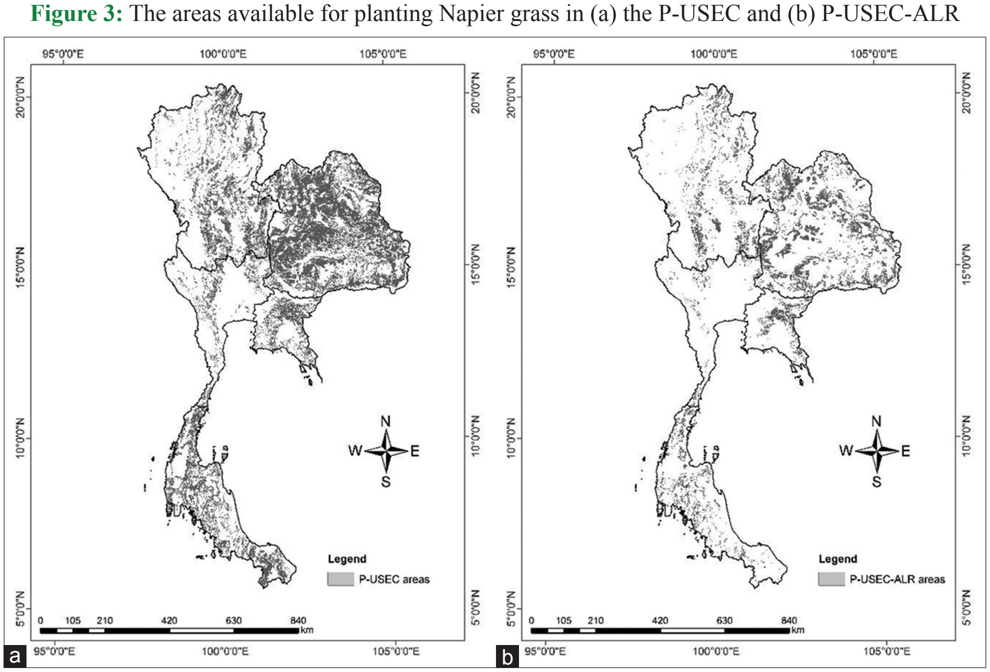
3.2. Napier Grass Production and Power Generation Potential

Based on the average Napier grass yield mentioned in Section 2.3, the assessment results of annual Napier grass production outputs in the P-USEC and P-USEC-ALR areas are presented in Table 5. The total potential of biomass production from Napier grass in the P-USEC area is 87.21 MtDM/y or equivalent to 32,286 ktoe/y, of which 36.1% (31.44 MtDM/y or 11,641 ktoe/y) is produced in P-USEC-ALR areas. According to the estimated annual biomass production (Equation (1)) from Napier grass in the P-USEC areas and Equation (2) under the assumption presented in Table 3, the power generation potential (Table 5) equates to 13,263 MW or approximately 3.8 times the biomass power generation target for 2037 in ADEP2018. The power generation potential by region is presented in Table 5. The northeastern region has the highest potential of 7,478 MW, approximately 2.14 times the ADEP2018 target (DEDE, 2020), while the northern (2,358 MW) and southern (2,322 MW) regions show almost equal potential. The eastern and central regions show a power generation potential of only 666 MW and 440 MW, respectively. For the P-USEC-ALR areas, the power generation potential is 4,782 MW, approximately 1.37 times the AEDP2018 target. The power generation and biomass energy potential at regional level are shown to be the same.

3.3. Napier Grass Potential for Grid-connected Electricity Generation

For more precise results, the potential of grid-connected electricity generation from Napier grass is estimated based on the location of electrical substations. As previously mentioned, most biomass power plants in Thailand have an installed capacity lower than 10 MW and can be connected to 115 kV transmission systems conforming to the regulations of the Power Network System Code.

Figure 3: The areas available for planting Napier grass in (a) the P-USEC and (b) P-USEC-ALR



Consequently, the power generation potential is assessed according to the available plantation area within a 50 km radius of the 127 115 kV substations, covering a total plantation area of approximately 2.1 million hectares. The resulting potential of 11,224 MW (66,367 GWh/y) as shown in Figure 4, is approximately 3.2 times higher than the biomass power target of AEDP2018 or approximately 26.5% of the total projected electrical energy demand in 2037 (DEDE, 2020). The potential grid-connected biomass power and net electricity generated from the five regions and the number of electrical substations in Thailand is summarized in Table 6. The northeastern region is shown to have the highest potential (6,530 MW); almost twice the AEDP2018 target, followed by the northern (2,015 MW), southern (1,677 MW), eastern (613 MW), and central (389 MW) regions. The 0.73 million hectares of plantation areas located in agricultural land reform zones have a power generation potential of 3,885 MW (22,971 GWh/y), approximately 62% of which can be generated in the northeastern region. While the northern, eastern, southern, and central regions have the potential to general 21, 9, 8, and 2%, respectively. The geospatial potential of grid-connected biomass power, as shown in Figure 4, can be used for land-use planning to increase the share of grid-power generation from biomass, thereby reducing Thailand's grid emissions.

3.4. Evaluating the Unit Cost of Electricity Generation

The estimated results of LCOE for a 9 MW grid-connected biomass power plant at a discount rate of between 8 and 11% based on three Napier grass price scenarios range from 0.103 to 0.120 USD/kWh (Figure 5). The blue, red, and green lines present LCOE values ranging from 0.103 to 0.111 USD/kWh at a biomass price of 21.51 USD/ton, 0.108 to 0.116 USD/kWh at a biomass price of 23.66 USD/ton, and 0.112 to 0.120 USD/kWh at a biomass price of 25.81 USD/ton, respectively. These estimated LCOE values are still lower than the current feed-in tariff for VSPP biomass power plants; thus, the electricity generated from Napier grass has the potential to be sold to the grid. As can be observed, the LCOE with a discount rate of 8% for each biomass price scenario is the lowest. As reported in previous works, the discount rate parameter impacts the LCOE value (Garcia-Gusano et al., 2016; Sung and Jung, 2019). When a higher discount rate is used, the levelized cost in the future will also be higher as well. Based on the base-case biomass price, fuel costs account for approximately 40% of the LCOE followed by capital costs of 39% and operating and maintenance costs of 21%. Hence, a rise in Napier grass price ranging from 10 to 20% of the base-case, yielded increases of 4 and 8% in the LCOEs, respectively, and are in agreement with those reported by Abdelhady et al. (2017).

Table 5: Napier grass production and power generation potential in P-USEC and P-USEC-ALR areas

Region	P-USEC areas				P-USEC-ALR areas			
	Plantation areas	Biomass production		Power potential	Plantation areas	Biomass production		Power potential
	(Mha)	MtDM/y	ktoe*/y	(MW)	(Mha)	MtDM/y	ktoe*/y	(MW)
Northern	0.443	15.50	5,739	2,358	0.175	6.12	2,267	931
Northeastern	1.404	49.17	18,204	7,478	0.557	19.49	7218	2,965
Central	0.083	2.89	1,070	440	0.002	0.068	25	10
Eastern	0.125	4.38	1,622	666	0.071	2.47	916	376
Southern	0.436	15.26	5,651	2,322	0.094	3.28	1,215	499
Total	2.490	87.21	32,286	13,263	0.898	31.44	11,641	4,782

*1 ktoe=42.244 GJ

Figure 4: Potential of grid-connected power generated from Napier grass production in (a) P-USEC and (b) P-USEC-ALR areas

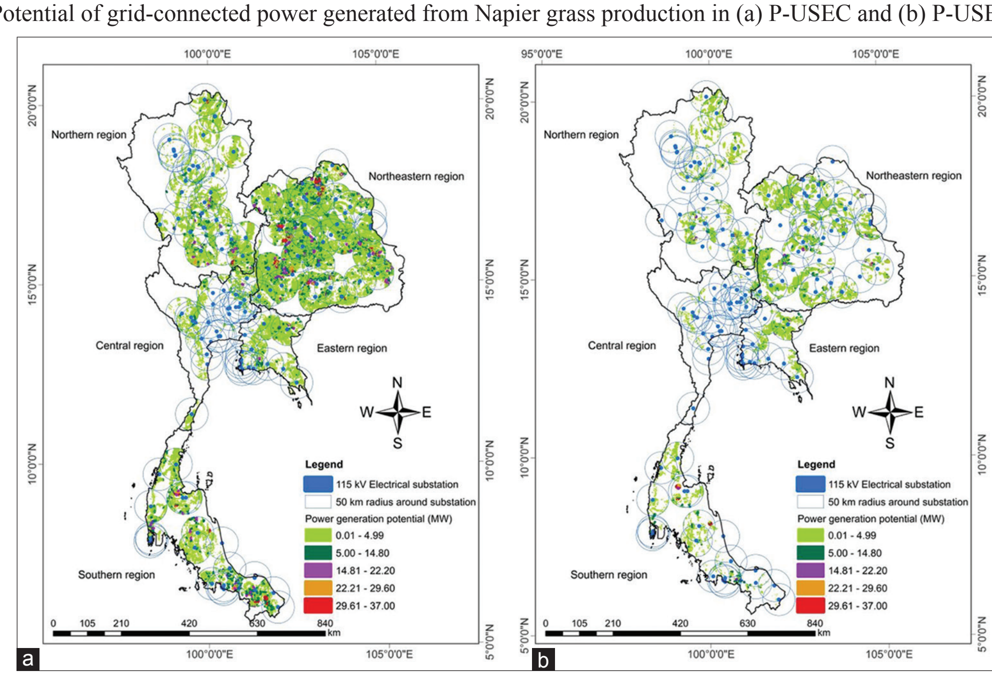


Table 6: Potential of grid-connected power and net electricity generated from Napier grass in P-USEC and P-USEC-ALR areas

Region	No. of Sub stations	P-USEC areas			P-USEC-ALR areas		
		Plantation areas (Mha)	Power* (MW)	Net electricity (GWh/y)	Plantation areas (Mha)	Power* (MW)	Net electricity (GWh/y)
Northern	30	0.378	2,015	11,914	0.157	835	4,938
Northeastern	37	1.226	6,530	38,612	0.431	2,294	13,565
Central	26	0.073	389	2,299	0.016	87	520
Eastern	15	0.115	613	3,625	0.063	336	1,991
Southern	19	0.314	1,677	9,917	0.062	330	1,957
Total	127	2.107	11,224	66,367	0.729	3,885	22,971

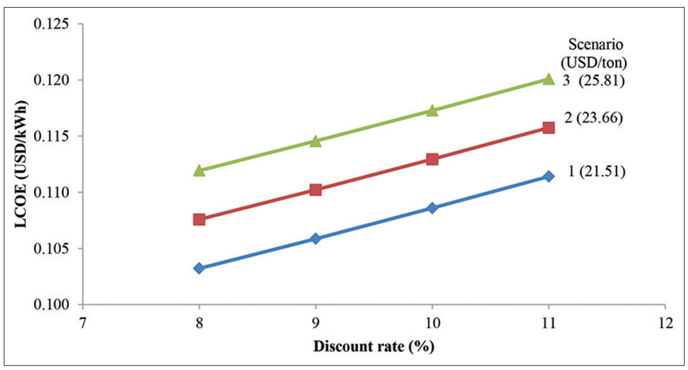
*Gross power generation (excluding self-consumption)

Table 7: Economic results for 9 MW grid-connected electricity generation from Napier grass

Scenario (Napier grass price)	NPV* (million USD)	DP* (years)	P-IRR (%)	E-IRR (%)
1 (21.51 USD/ton)	5.54	11.2	14.04	30.89
2 (23.66 USD/ton)	4.06	12.5	13.00	27.61
3 (25.81 USD/ton)	2.59	14.3	11.94	24.40

*10% discount rate

Figure 5: LCOEs under three scenarios for 9 MW grid-connected biomass power generation from Napier grass



Based on the data and assumptions presented in Table 4, the investment potential of 9 MW grid-connected electricity generation is presented in Table 7. Scenario 1 (base-case) shows the highest return on investment with NPV, DP, P-IRR, and E-IRR of 5.54 million USD, 11.2 years, 14.04%, and 30.89%, respectively, due to the low biomass price of 21.51 USD/ton. Under scenario 2, with a 10% rise in the biomass price compared to the base value, the NPV, P-IRR, and E-IRR decreased to 4.06 million USD (equivalent to 27%), 13.00%, and 27.61%, respectively, while the DP increased to 12.5 years. In scenario 3 (a 20% rise in the biomass price compared to the base price), the NPV, DP, P-IRR, and E-IRR changed to 2.59 million USD (equivalent to 53%), 14.3 years, 11.94%, and 24.40%, respectively. Based on the results, the biomass price was shown to have a significant impact on these key economic indicators. From the perspective of project returns (without debt), the NPVs in all scenarios were positive while the P-IRR exceeded the weighted average cost of capital, indicating a profitable investment. However, the DP was relatively long, especially in the case of scenario 3, thus the project is likely to be considered less attractive. From the project finance perspective, the debt-to-equity ratio is 70:30 while the E-IRRs under scenarios 1, 2, and 3 equate to 30.89, 27.61, and 24.40%, respectively. The E-IRRs were higher than the expected return on equity (23%), indicating that the project is financially viable.

4. CONCLUSION

To avoid competition over land use between food and energy crops, areas unsuitable for planting the six economic crops (USEC areas) in Thailand were used as the case study for planting Napier grass. The corresponding potential of grid-connected power generation from Napier grass, LCOE, and their economic feasibility were also assessed.

Approximately 79% of USEC areas are available for planting Napier grass (P-USEC areas), with 36% of these being located in agricultural land reform zones (P-USEC-ALR areas). Based on the average yield of nine Napier grass cultivars, the estimated power generation potential was 13,263 MW, of which 11,224 MW (66,367 GWh/y) had the potential to connect to the national grid. The P-USEC-ALR areas had a grid-connected power generation potential of 3,885 MW, which was higher than the biomass power generation target for 2037 in AEDP2018. In addition, the geospatial potential was also presented based on the location of electrical substations.

Based on a 9 MW grid-connected biomass power plant under three price scenarios for Napier grass, LCOEs with a discount rate of between 8 and 11% range from 0.103 to 0.120 USD/kWh (less than the feed-in tariff rate). The results of the economic assessment showed positive NPV values with long DP and P-IRRs higher than WACC. In the case of a project fund comprising a 70:30 debt-to-equity ratio, the E-IRRs were greater than the expected return on equity, thus the investment is financially viable.

5. ACKNOWLEDGMENTS

The authors would like to thank the Agricultural Land Reform Office, Electricity Generating Authority of Thailand, Land

Development Department, Royal Forest Department, Royal Irrigation Department and Thai Meteorological Department for providing the digital map data and the Geospatial Engineering and Innovation Center, King Mongkut's Institute of Technology Thonburi for providing the ArcGIS software (ESRI Customer Number: 515187). The financial support provided by the Thailand Research Fund (Grant No. DPG5980004) and Energy Conservation Promotion Fund (Grant No. 58202), Energy Policy and Planning Office is gratefully acknowledged.

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