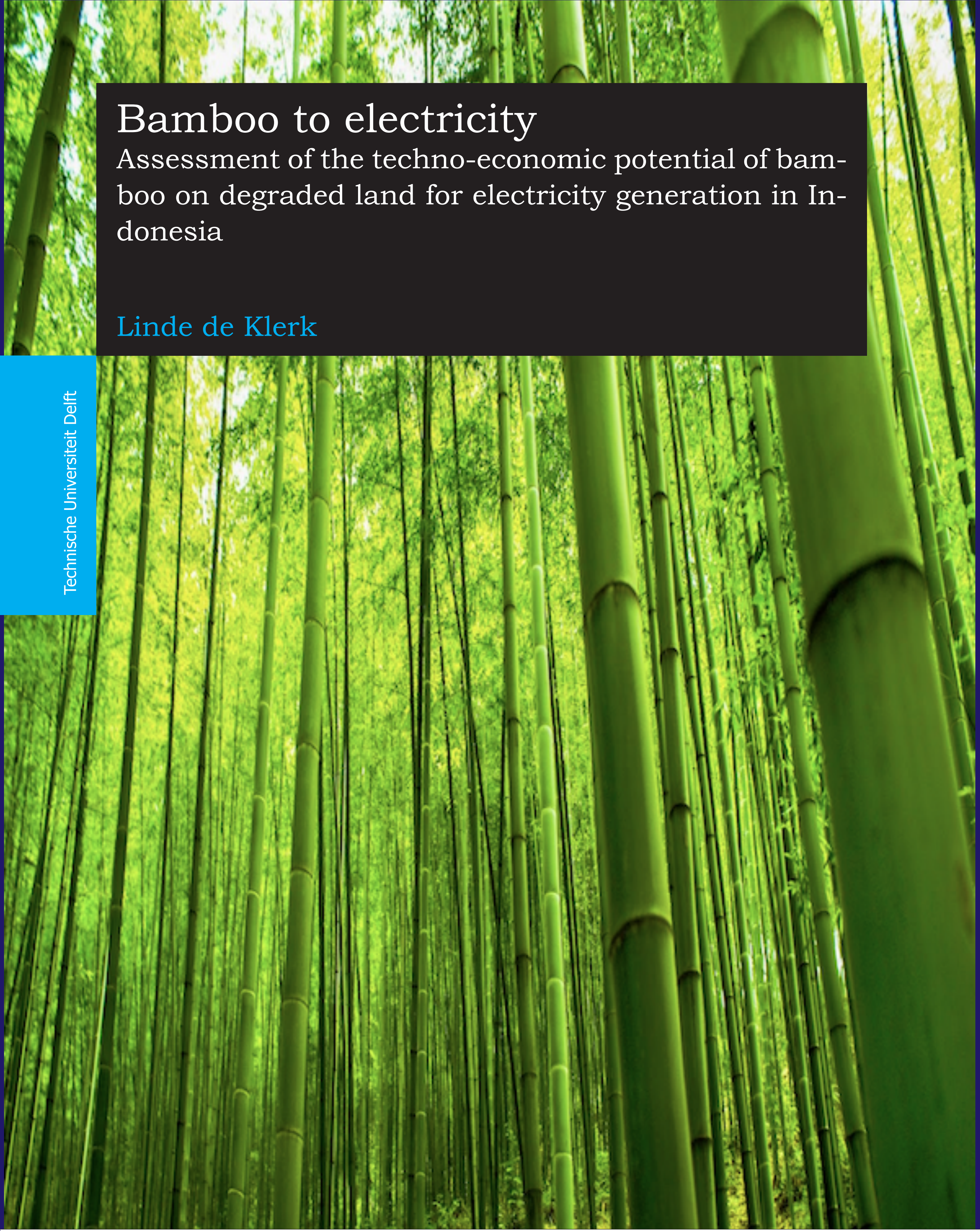

Bamboo to electricity

Assessment of the techno-economic potential of bamboo on degraded land for electricity generation in Indonesia

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Challenge the future

Bamboo to electricity

Assessment of the techno-economic potential of bamboo on degraded land for electricity generation in Indonesia

by

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Abstract

Following the Paris Agreement of 2015, Indonesia aims to reduce emissions by 29% by 2030, compared to the business as usual scenario. In Indonesia it is expected that between 2015 and 2030 the electricity demand could triple and the total energy demand could increase by 80%. Bioenergy would account for more than half of all renewable energy in 2030 in Indonesia. However, the expansion of energy crops contributes to negative effects like deforestation, loss of biodiversity, and competition with food production. An other problem Indonesia currently deals with is the large amount of degraded land. A solution to these problems would be to cultivate biomass on degraded land. Bamboo can be used as a biomass feedstock, as it meets all selection requirements to be produced on degraded land.

This thesis report quantifies the extent and finds the location of degraded land in Indonesia. Also, the technical and economic potential of bamboo cultivation on the degraded land locations is assessed. The research question that will be answered is: how much degraded land would be needed to cover Indonesia's electricity demand by 2030, when using bamboo as a biomass feedstock, and how likely is this land available?

This research question is answered by first doing a geographic information system (GIS) analysis. Through the QGIS software, the degraded land locations in Indonesia which are suitable for bamboo plantations can be found. This is done by layering multiple data-sets on top of each other in four steps. Next, the techno-economic potential analysis is done by calculating how much degraded land would be needed to cover a certain percentage of Indonesia's electricity demand by 2030, and calculating the levelized cost of electricity (LCOE) of different biomass conversion technologies.

The results show that between 0.21% and 49.9% of Indonesia's total land area can be considered degraded according to different scenarios. The suitable area for bamboo plantations lays between the 0.01% and the 13% of Indonesia's total land area. Using these areas the potential electricity that can be reached lays between the 0.4-732 TWh for gasification, 0.3-533 TWh for combustion, 0.3-506 TWh for anaerobic digestion, and 0.1-266 TWh for pyrolysis. The area needed to cover 25% of Indonesia's electricity demand by 2030 ranges from 2.0-5.6% of Indonesia's total land cover when using different conversion technologies. For 100% electricity demand this area increases to the range of 8.1-22.4% of Indonesia's total land cover. The LCOE goes from 13 US$ct./kWh for gasification, to 16 US$ct./kWh for combustion, 22 US$ct./kWh for anaerobic digestion, and finally to 45 US$ct./kWh for pyrolysis.

The result show that when using the least strict degraded land scenarios, it would be possible to cover a significant amount of Indonesia's electricity demand. However, it is not likely that these scenarios will be applied. The definition of degraded land, still is not completely clear, and extensive field research needs to be done to validate the degraded land results. This research shows that bamboo cultivation on degraded land for electricity generation in Indonesia might not be applicable to generate large amounts of electricity. Nevertheless, it can be applied on smaller scales and it is a step in the right direction of Indonesia's energy transition.

Finally, some recommendations for future research can be made. First of all, uncertainty exists about the data-sets used to assess the extent of degraded land in Indonesia. It is recommended that the data-sets are validated through field research. Furthermore, in this research an assumption for the yield of bamboo is made, which can be tested against the actual yield of a bamboo plantation on degraded land in Indonesia. Also, socio-economic and environmental effects of bamboo plantations are not considered, which provides the opportunity to address these in further research. Finally, other end uses like biofuel, other conversion technologies like co-firing, and pre-treatment technologies to enhance the conversion efficiency can be evaluated in more detail in future research.

Contents

Nomenclature

Abbreviations

FC	Fixed carbon content
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross Domestic Product
GHG	Green House Gas
GIS	Geographic Information System
HWSD	Harmonized World Soil Database
IRENA	International Renewable Energy Agency
ISSCAS	Institute of Soil Science, the Chinese Academy of Sciences
IUCN	International Union for Conservation of Nature
JRC	Joint Research Centre of the European Commission
MC	Moisture content
NDC	Nationally Determined Contribution
PLN	Perusahaan Listrik Negara (Indonesian utility company)
UNCCD	United Nations Convention to Combat Desertification
VM	Volitale matter

Symbols

$A_{plantation}$	Plantation area	km^2
C_f	Capacity factor	%
E_t	Annual electricity production	kWh
E_i	Electricity potential per conversion technology	kWh
F_t	Fuel costs	US$/kWh
HHV	Higher heating value	MJ/kg
I_t	Initial investment costs	US$/kW
LHV_{bamboo}	Bamboo lower heating value	MJ/kg
$LCOE$	Levelized cost of electricity	US$ct./kWh
$O\&M_{t_{fixed}}$	Operation & maintenance costs	US$/kW
$O\&M_{t_{variable}}$	Operation & maintenance costs	US$/kWh
P_{bamboo}	Bamboo productivity	kg/ha
r	Discount rate	%
$Y_{moisture}$	Moisture content	%
Y_H	Hydrogen content	%
η_i	Conversion efficiency	%

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Introduction

In 2015, 196 parties signed the Paris Agreement, at the COP 21 in Paris. The main goal of the agreement is to keep the global warming below 2°C, and preferably below 1.5°C (United Nations, 2015). Similarly to the other countries, Indonesia submitted their Nationally Determined Contribution (NDCs). According to Indonesia's first NDC, the aim is to reduce emissions by 29% by 2030 on its own efforts, going to 41% reduction in case of international help (Republic of Indonesia, 2016). These values are compared to a business as usual scenario. According to The World Bank both the population and the Gross Domestic Product (GDP) of Indonesia have grown immensely over the last few decades (World bank, 2020). It is expected that the energy demand increases similarly to the population and the GDP.

Between 2015 and 2030 the electricity demand could triple and the total energy demand could increase by 80% (IRENA, 2017b; Choi et al., 2020). In 2020 Indonesia's total electricity demand was 283 TWh (Lolla and Yang, 2021). As mentioned in Chapter 1, it is expected that the electricity demand could triple between 2015 and 2030. This is due to the economic growth which results in a higher electricity consumption from household appliances. Another factor that caused the electrification rate to increase is urbanisation, from 2000 to 2014 the population living in urban areas increased from 42% to 53% (IRENA, 2017c). However, a more recent report published by PLN corrected the estimations according to the changes in demand due to the COVID-19 pandemic. The new forecast is that the electricity demand will grow with 4.9% yearly. The report, the New Electrical Generation Plan for 2021-2030 (RUPTL), estimates that the electricity demand will be 445.1 TWh by 2030 (PLN, 2021).

In 2020, only 14.7% of the electricity in Indonesia was generated by renewables, the majority (49.7%) was generated by coal (Statista, 2022). Following the scenario proposed by IRENA (2017c), renewable energy should cover 38% of the electricity generation in 2030. This provides an opportunity for renewable energy sources, like biomass, to be implemented to generate electricity and reduce the greenhouse gas emissions.

However, currently there are some issues with the way that biomass is used in Indonesia. One of the issues is deforestation. Currently, the main resource for bioenergy is palm oil waste. These palm oil plantations are the cause of deforestation and peatland drainage (Sharma et al., 2018). Globally, the deforestation rate is the highest in Indonesia (Wicke et al., 2011). This results in a loss of biodiversity and Green House Gas (GHG) emissions of carbon that was stored in the natural tropical forests and peatlands (Obidzinski et al., 2012). It is estimated that between 10% and 20% of total global GHG emissions result from land-use change in the tropics (Petrenko et al., 2016).

Another issue related to biomass is competition with food production. Increasing the amount of biomass plantations can result in a lower availability of land for agricultural production (Ignaciuk et al., 2006). Not only direct land use change can be a problem, but also indirect land use change should be taken into consideration. Due to indirect land use change, land in different locations can be converted to agricultural cropland, extra to the land that is used for energy crops and biomass production (Kim and Dale, 2011). This happens because the demand for food crops does not change when biomass is produced on existing agricultural land (European Commission, 2012). This means that energy policies that work in favor of biodiesel production, do not always meet sustainability principles (Dharmawan et al., 2020).

A solution to the land-use conflicts can be found by using degraded land for the production of energy crops (Immerzeel et al., 2014; Dauber et al., 2012; van Vuuren et al., 2009; IRENA, 2017c;

NL Agency, 2012). Doing so might avoid the issues faced by the abovementioned biomass types, like competition with crop production and biodiversity loss(Immerzeel et al., 2014; van Vuuren et al., 2009; Choi et al., 2020). Furthermore, cultivation of degraded land might improve the quality of the soil (van Vuuren et al., 2009). One of the feedstocks that can be grown on degraded land in Indonesia is bamboo (Sharma et al., 2018; Mishra et al., 2014; Boissière et al., 2019). Bamboo meets all selection requirements when evaluating energy crops which are suitable to be produced on degraded land, since it is a lignocellulosic, perennial, fast growing plant.

1.1. Problem statement and research objectives

As mentioned before, problems might occur when growing biomass in Indonesia. Possibly, some of these problems can be solved by growing biomass on degraded land. However, currently the main issue with doing so is that the location and extent of degraded land in Indonesia is not fully clear. Many different degraded land definitions exists, and there is no general method on how this land is quantified. Also, knowledge gaps are brought to light when looking at the development of degraded land for biomass, and the economics and benefits of bamboo on these types of land.

The research objectives result from the previously stated problem statement. The first research objective is to find how degraded land is defined and in what way the definition influences the results of the research. Then, the second research objective is to quantify the extent and location of degraded land in Indonesia. The third research objective is to quantify the potential of bamboo plantations as a biomass feedstock on the found locations.

1.2. Research questions and approach

The main research question can be derived from the problem statement, research objective, and literature review, doing so results in the following research question:

> *How much degraded land would be needed to cover Indonesia's electricity demand by 2030, when using bamboo as a biomass feedstock, and how likely is this land available?*

To be able to form an answer to the main research question stated above, multiple sub-questions are formulated. The different sub-questions will be answered using different approaches.

1. What bamboo species native to Indonesia, is suitable to use as a feedstock for land restoration and energy generation on degraded land?
2. What is degraded land and which factors should be taken into account when evaluating degraded land using GIS?
3. What is the extent and location of degraded land in Indonesia and which degraded land areas in Indonesia are suitable for bamboo plantations?
4. Which conversion technologies are available to convert bamboo to electricity and what is their technical and economic potential?

The first two questions will consist of a literature study. Different online search libraries will be informed to obtain an answer to the sub-question. Then for the third question the GIS software will be used. In this software the different factors found in sub-question 2 will be implemented in the form of different layers, each layer contains a data-set. When adding these layers on top of each other on the map of Indonesia, the optimal locations for bamboo plantations can be found. This method will be similar to methods used in the articles described in Section 2.3. To obtain an overview, different scenarios will be considered, which each different definitions of degraded land. The severity of the degradation will differ per scenario. For the fourth sub-question the technical and economic potential of cultivating bamboo on degraded land for electricity generation is calculated. After this is done, the available degraded land area can be compared with the degraded land area that would be required to cover a certain percentage of Indonesia's electricity demand.

1.3. Thesis outline

The report is structured as follows, first a literature review is done in Chapter 2. Next, a theoretical background on bamboo as an energy crop is given in Chapter 3. In this chapter also the different conversion technologies are discussed. Then, in Chapter 4 the methods used in this research are described. The results of the first part of the method, the degraded land analysis, can be found in Chapter 5. After this the results of the second part of the method, the technical and economic potential analysis can be found in Chapter 6. Finally, the discussion, conclusion, and recommendations are given in Chapters 7, 8, 9, respectively.

2
Literature Review

In this chapter, literature found in academic digital libraries such as Google Scholar, TU Delft Library and Scopus, is reviewed which concludes in multiple knowledge gaps. First, in Section 2.1 literature about biomass in general on degraded land is evaluated. Next, in Section 2.2 literature concerning bamboo as a biomass feedstock on degraded land is evaluated. In Section 2.3 literature on how GIS is used to map and evaluate degraded land locations is reviewed. Finally, in Section 2.4 discusses different definitions, found in literature, used for degraded land.

2.1. Biomass on degraded land

Much general research on the energy transition has been done worldwide as well as specifically for Indonesia (PwC, 2018; IRENA, 2017c; International Energy Agency and The World Bank, 2015). This literature provides general information on the energy transition in Indonesia, and gives an overview of the current status of renewable energy in Indonesia.

To find specific knowledge gaps literature was evaluated using different search terms. After this articles on research that combines these terms are reviewed. The different terms are the biomass potential in general, degraded land, biomass on degraded land, and finally bamboo as a biomass feedstock. The location Indonesia is taken into account during the research, but also studies done in different locations can be helpful, and thus will be evaluated as well. During the final search only studies done on the potential of bamboo as a biomass feedstock for power production on degraded land in Indonesia will be evaluated.

When looking at example researches where biomass is used in combination with degraded land, multiple studies can be found. First, a study done by Van der Laan et al. (2017) looks at how land use change can be mitigated while producing palm oil, rice, pulpwood and rubber. Results showed that producing on underutilised/degraded land is the most important mitigation measure. The study mentions that thorough field research is needed to improve estimates of underutilised land (Van der Laan et al., 2017). Also, a study on the global potential of biomass for energy shows the potential of bioenergy production on degraded land is between the 8-110 EJ per year globally. However, it assumes a high area of degraded land and that all this land can be used for energy crops (M. Hoogwijk et al., 2003). Furthermore, a spatial assessment of degraded land for biofuel production is done by Jaung et al. (2018), this study evaluates five different biofuel species which can be grown on 3.5 Mha of degraded land. Further research is recommended to better understand the potential of degraded land for bioenergy production. Also, research was done on the suitability of four tree species, to grown on degraded land in Central Kalimantan. Results show that nyamplung is the most adaptive of the four for growth on degraded peatland. In this study it is mentioned that an improvement of the accuracy of the measurement variables is needed to get additional data (Maimunah et al., 2018). All these studies conclude that further research on degraded land is needed.

By looking at research done on the potential of biomass in Indonesia the following knowledge gaps can be found. Signh states that utilization of biomass is not done in a sustainable way, but in a traditional way (R. Singh and Setiawan, 2013). There is general consensus on the potential of biomass and land resources, but more should be done to map these resources and analyze the problem and challenge of bioenergy in Indonesia (Pirard et al., 2016; R. Singh and Setiawan, 2013).

2.2. Bamboo as a biomass feedstock on degraded land

When looking at the potential of bamboo as a biomass feedstock in Indonesia some more knowledge gaps can be found. According to Sharma et al. (2018), there is a dearth of literature on bamboo in the context of Indonesia, and Mishra et al. (2014) recommends to raise awareness on the importance of bamboo for land restoration and to include local people in restoration programs. Sharma et al. (2018) recommends further research on the production and management of bamboo for bioenergy in Indonesia, as well as further research on the economics and benefits of restoration using bamboo, since bamboo can contribute substantially to achieve renewable energy targets set by the government of Indonesia. Mishra et al. (2014) generally mentions that further extensive research on this topic is needed to be able to integrate local people in restoration programs. Research done on bamboo utilization in Indonesia showed that Betung bamboo would be suitable for bioenergy (Yusuf et al., 2018). Also, the biomass and carbon storage potential of a bamboo forest in Bali are evaluated, and this study results in the finding that forest management is an important tool to manage carbon sinks (Sujarwo, 2016). However, the last two researches do not take degraded land into consideration.

Next, research on degraded land in Indonesia is reviewed. Dauber states that further research is needed to determine the environmental and socio-economic implications of developing degraded land for bioenergy use. This is important to decrease the rate of loss of the biodiversity (Dauber et al., 2012). Wicke mentions that uncertainties exist about the actual extent and location of degraded land in Indonesia, and that this needs to be investigated further to limit land tenure conflicts which can result in ILUC (Wicke et al., 2008).

In Scopus only one article appears if the search terms related to the topics above are combined (bamboo as a biomass feedstock on degraded land in Indonesia). This is the article by Sharma et al. (2018), which is discussed above. Since only one article comes up when combining these search requirements, it becomes clear that there is a lack of research on the potential of bamboo as a biomass feedstock on degraded land in Indonesia. From the literature review multiple knowledge gaps are found. First, the challenges, potential and land resources of biomass should be further analyzed in general. Then the extent, location, potential, and environmental and socio-economic implications of degraded land that can be used for bioenergy should be evaluated. Finally, the production and management of bamboo in Indonesia and the economics and benefits of using bamboo for land restoration form a knowledge gap.

2.3. GIS

The method that will be used to assess the degraded land areas and locations in Indonesia, is the GIS software. This system provides the tools to map the important bioresources. The geographical, technical, and economic potential can be analysed using this method (M. M. Hoogwijk, 2004). As stated in (Hiloidhari et al., 2017), the GIS software has been used for many different types of research concerning biomass, like supply chain optimization, mapping of the feedstock density, and estimate the technical potential of biomass. To find out how GIS was used previously, in combination with degraded land and biomass, literature was reviewed.

GIS has been used in many different studies to evaluate the potential of biomass in general and on degraded land. For example, GIS was used to evaluate energy crops in the UK, Portugal, and Boston (Lovett et al., 2009; Abreu et al., 2020; Saha and Eckelman, 2018), oil palm development in Kalimantan (Fairhurst and McLaughlin, 2009), and land use, biomass and carbon status of dry tropical forest in India (Bijalwan et al., 2010). In all these studies it was concluded that GIS is an effective approach to identify land areas suitable for energy crops. The studies done by Fairhurst and McLaughlin (2009), Saha and Eckelman (2018), and Abreu et al. (2020) focus on degraded land. The land that could be used was found by adding multiple spatially referenced layers on top of each other, like soil quality, soil slope, land cover, water and protected areas. It will not be possible to compare the results from these studies with the results of this research, because of the different study locations and the lack of information provided by the literature.

When searching on Scopus for the combination of degraded land, GIS and Indonesia, only three articles can be found of which only two were relevant to review for this study. The first is a research on the level of degraded land in the Central Java province. Here different parameters (slope, erosivity, erodibility, slope length and steepness, cover and management, support practice, and canopy cover) are evaluated to find the best formula for the level of degraded land. It turned out that degraded land could be most accurately found using only erosion parameters (Sulistyo et al., 2017). This finding will be interesting for further research into degraded land for the whole country since this indicates which parameters can be used. The second article is a study on the rehabilitation of degraded forest land in Kalimantan. A model was built to evaluate the rehabilitation value of different forest fragments (Marjokorpi and Otsamo, 2006). By searching other online search libraries, it became clear that degraded land studies using GIS in Indonesia have only been done for specific regions (Lestariningsih et al., 2018; Narendra et al., 2019; Eddy et al., 2021). Parameters used are land use, slope, soil erosion and erodibility, land productivity and management, and rainfall erosivity (Narendra et al., 2019; Eddy et al., 2021).

From this review, it can be concluded that a degraded land study in combination with biomass cultivation for electricity, for the entire country of Indonesia has not been done before. Different parts of Indonesia have been evaluated, but the connection of these different locations is currently missing in literature, especially in combination with biomass production on these locations. Van der Laan et al. (2017) mentions that the selected areas are chosen because for the analysed provinces most data is available. The locations used by Fairhurst and McLaughlin (2009) were chosen because of their different land covers, and the fact that field research could be done.

2.4. Degraded land definitions

To determine the amount of degraded land available in Indonesia, it is important to have a clear definition of degraded land. To get a better understanding of degraded land, different definitions are compared to each other. An overview of the definitions is given in Table 2.1, here the cause, characteristics and the possible quantification of degraded land are visualized for each definition.

Table 2.1: Overview of degraded land definitions

Reference	**Cause**		**Characteristics**					**Quantification**	
	Human	*Natural*	*Productivity loss*	*Low carbon stock*	*Loss of ecological integrity*	*Loss in human value*	*Change in soil characteristics*	*<35 tonnes of C per ha*	*<40 tonnes of C per ha*
Abdel-Kader, 2019	X	X	X						
Abreu et al., 2020	X	X	X			X	X		
FAO, 2022b			X		X	X			
Gingold et al., 2012				X	X			X	
Olsson and Barbosa, 2019	X	X	X		X	X			
Prince et al., 2009							X		
Rothman et al., 2007			X		X				
Ruysschaert et al., 2011	X								X
Sharma et al., 2018			X						
UN, 2007; OECD, 2001	X	X	X						
UNCCD, 2015			X		X		X		
Wicke et al., 2008	X	X	X		X				
WRI, 2022	X		X						

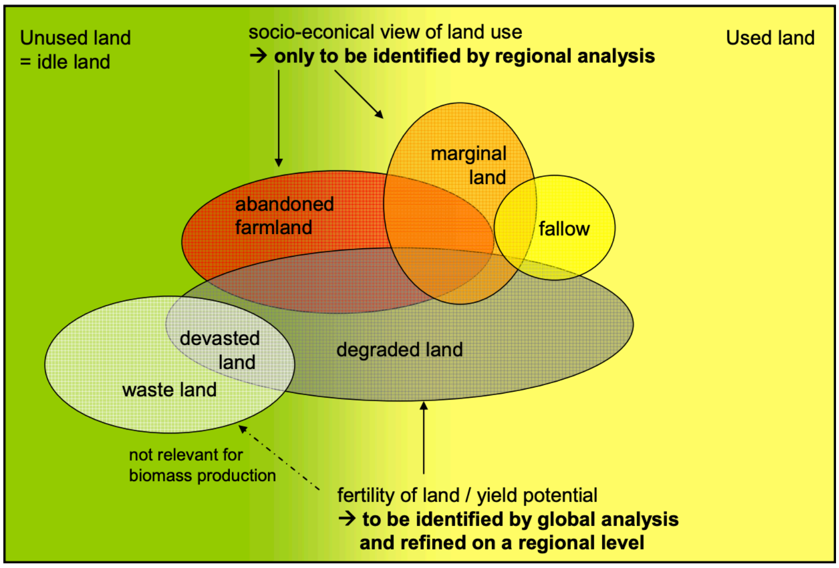
When analyzing Table 2.1 some similarities and differences can be found. First, looking at the cause of degraded land, it becomes clear that a distinction is being made between human activities and natural processes that cause the degradation to happen. Not all definitions include a cause for the degradation, however from the definitions that do, it can be concluded that most definitions state that both human activities and natural processes can result in degraded land. This is in contrast with the definitions which specifically only mention the human cause. There are no definitions that only state natural events as a cause of degraded land.

Next, the characteristics of the land degradation can be evaluated. Most definitions give a qualitative indication of what happens to the land when it becomes degraded. Concluding from the different definitions, degraded land has suffered a loss of productivity, low carbon stock, loss of ecological integrity, loss of value to humans, or a change in physical, chemical, and biological characteristics of the soil. One or multiple results are mentioned in all the definitions (UN, 2007; OECD, 2001; Rothman et al., 2007; Olsson and Barbosa, 2019; Abreu et al., 2020). Loss of natural, biological, or economic productivity and loss of ecological integrity are the most common results of degraded land. However, how this is measured is not described by the definitions.

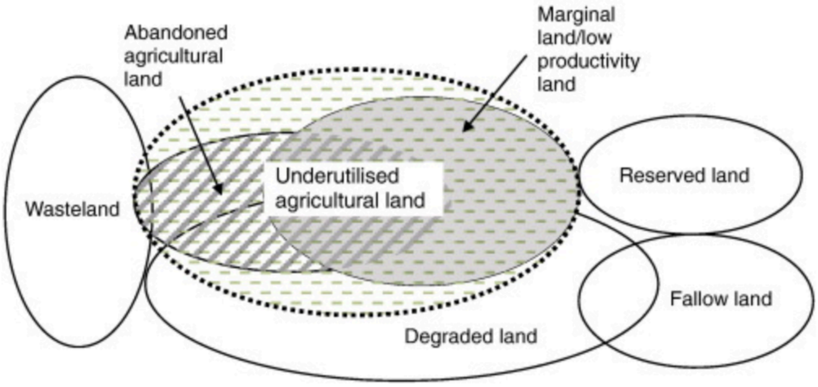
Finally, a quantitative way of indicating degraded land is only given by two definitions. The definitions by Gingold et al. (2012) and Ruysschaert et al. (2011) state that degraded land can be measured by the amount of carbon stored per hectare. If the land contains less than 35 or 40 tonnes of carbon per hectare, it will be classified as degraded according to these definitions (Gingold et al., 2012; Ruysschaert et al., 2011).

Two definitions that clearly show the difference are given here as an example. First, according to the Food and Agriculture Organisation of the UN, degraded land is " degraded land covers all negative changes in the capacity of the ecosystem to provide goods and services (including biological and water related goods and services – and in Land Degradation Assessment in Drylands (LADA) its vision - also land-related social and economic goods and services)" (FAO, 2022b, p. 1). However, the definition by Gingold et al. (2012, p. 2) only states that "land is considered degraded if it contains less than 35 tons of carbon per hectare". According to Van Rooijen (2014) the exact definition of degraded land is not clear. They do however state that biofuel which is obtained from a feedstock grown on degraded land will not compete with food production (Van Rooijen, 2014). This implies that land use/cover needs to be included in the degraded land definition as well.

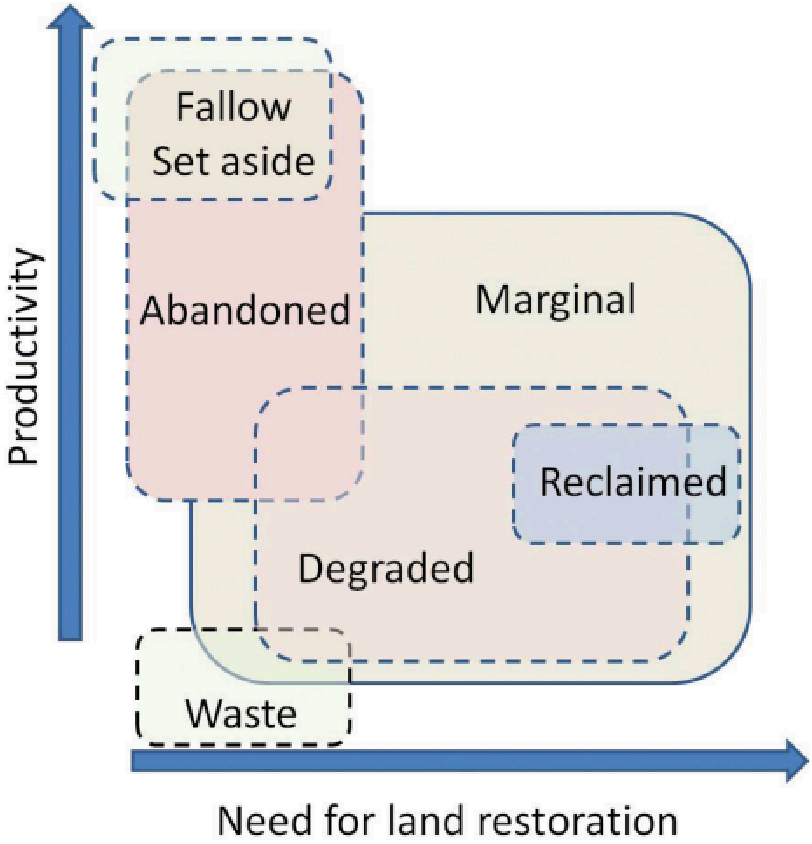
Furthermore, Figure 2.1a shows different types of surplus land in relation to each other according to different sources. Similar to the differences in the definitions, these figures indicate that there is no agreement on what degraded land is. For example, in Figure 2.1c, degraded land completely falls in the marginal land area, while in Figures 2.1a and 2.1b this is not the case. Also, fallow land is related to degraded land in a different way. Between Figure 2.1a and Figure 2.1b, the main difference is whether or not there is an overlap between waste land and degraded land.



(a) Land categories scaled from unused to used land (Rettenmaier et al., 2012)



(b) Different land categories compared to underutilised agricultural land (Miyake et al., 2015)



(c) Different classes of surplus land visualized based on productivity and need for land restoration (Dauber et al., 2012)

Figure 2.1: Three different ways of visualizing degraded land based on the use of (agricultural) land and productivity

Due to these different definitions, also different assessments of the amount of degraded land in Indonesia have been made. In 2013, 24.3 million ha of land in Indonesia was classified as degraded land according to the United Nations Convention to Combat Desertification (UNCCD). The main cause of the degradation was inappropriate land use and conversion of forests and peatlands for agriculture (Sharma et al., 2018; UNCCD, 2015). However, according to the International Renewable Energy Agency (IRENA), the amount of degraded land in Indonesia lies between the 12 and 74 million ha, depending on the definition of degraded land (IRENA, 2017c).

Besides the differences in the definitions for degraded land, there are some other problems with how degraded land is defined. Often, it is not clear whether the focus of the definition lays on the end condition of the land, the process of the degradation, or even the perceived risk of degradation (Gibbs and Salmon, 2015). Another problem is that often the focus lays on soil degradation, while the issue of land degradation can also be approached by evaluating the ecosystem, thus including both the soils and the vegetation (Gibbs and Salmon, 2015).

Furthermore, the method by which land is considered to be degraded below a certain level of carbon storage per hectare results in problems as well. Using this method, land that is currently being cultivated or land that naturally has a low carbon stock is wrongly considered to be degraded (Gingold et al., 2012; Gibbs and Salmon, 2015). This land might provide food or medicinal resources for indigenous people (Dauber et al., 2012). Another problem with this way of quantifying degraded land is that this measurement only includes above ground biomass (AGB), meaning the carbon stored in vegetation (Ruysschaert et al., 2011). Carbon stored in the soil, soil organic carbon (SOC), is neglected, while this also plays an important role in an ecosystem (Chan, 2008). A final problem arises with land that is classified as degraded according to all criteria, which is that even degraded land can harbour high levels of biodiversity, or can harbour unique components of biodiversity which are of high value to the ecosystem (Dauber et al., 2012).

For this research, degraded land is assessed in two ways, following two different definitions. These two definitions are chosen because the different characteristics used and the quantification that is given by one of the two definitions. The first definition used is by the UN (2007, p. 140): ”Land degradation means reduction or loss of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns, such as: (i) soil erosion caused by wind and/or water; (ii) deterioration of the physical, chemical and biological or economic properties of soil; and, (iii) long-term loss of natural vegetation. Land degradation, therefore, includes processes which lead to surface salt accumulation and waterlogging associated with salt-affected areas”. The second definition used is one that quantifies the degraded land by carbon stock, it is the definition by Gingold et al. (2012, p. 2): ”land is considered degraded if it contains less than 35 tons of carbon per hectare”. The use of these definitions in this research is further explained in Section 4.1.

3

Theoretical background of bamboo as an energy crop

As mentioned in Chapter 1, bamboo is a biomass feedstock that can be grown on degraded land (Sharma et al., 2018; Mishra et al., 2014; Boissière et al., 2019). In this chapter bamboo as a biomass feedstock is further researched. First, the land restoration qualities of bamboo are discussed in Section 3.1. Then, in Section 3.2, the most suitable bamboo species for the degraded land plantations in Indonesia is selected. Section 3.3, explains which bamboo yield can be obtained from a plantation. Next, options for agroforestry/intercropping with bamboo and other energy or agricultural crops are evaluated in Section 3.4. Finally, possible bamboo to electricity conversion technologies are discussed in Section 3.5.

3.1. Land restoration

The main advantage of bamboo is that it can be grown on degraded land, doing so results in a decrease of soil erosion, the loss of soil fertility becomes smaller, more water can be conserved and high amounts of carbon can be stored (Boissière et al., 2019; Aswandi and Kholibrina, 2020; Sofiah and Susim, 2020; Setiawati et al., 2017). Also, bamboo litter supplies organic matter to the soil, in case it stays there for a long period of time it protects the soil against surface erosion (Sofiah and Susim, 2020). Bamboo has a survival rate of 99% on degraded land (L. Singh et al., 2020). Furthermore, growing bamboo on this land should not cause indirect land use change elsewhere, social conflicts or human right violations (Wicke et al., 2008).

As mentioned before, bamboo has the ability to restore degraded land. Bamboo effectively 'pumps' nutrients back into the soil because the roots contain extremely high values of biomass and the litter is slowly decomposed (Christanty et al., 1996). First, when looking at the carbon storage potential of bamboo, it is found that the carbon storage lays between the 30-121 t C/ha and the carbon sequestration rate is 6-14 t C/ha per year (Nath et al., 2015). Bamboo has a below ground carbon stock in the range of 2.5-19.7 t C/ha, and a soil carbon sequestration rate ranging between 9.5-19.1 t C/ha per year (Teng et al., 2016). Furthermore, the roots and rhizomes (underground horizontal plant stems that can produce shoots and roots of a new plant) which form underground have the capacity to bind up to 6 m^3 of soil which prevents soil and water erosion (Ben-Zhi et al., 2005). For water conservation the litterfall of the bamboo plays an important role. The total above ground litter fall is estimated to lay between 4.1-7.2 t/ha per year for mature bamboo. This bamboo litter can store as much moisture as 2.75 times its own dry weight (Ben-Zhi et al., 2005).

Land is considered to be successfully restored when the ecosystem again has a fully functioning state, so the water and carbon cycles should be intact, the soil should be healthy, and the biodiversity level should be good as well (BAMBoo, 2014). Two projects operated by EcoPlanet Bamboo showed that using native bamboo species to the countries operated in, degraded land could be restored while at the same time creating jobs at the plantations (BAMBoo, 2014).

3.2. Most suitable bamboo species

When evaluating which biomass feedstocks can be grown on degraded land, multiple selection criteria should be met. The first selection criteria is the type of crop. There are different types of energy crops that can be assigned to three different categories. The first being oil-bearing crops, secondly carbohydrate-rich crops, and finally lignocellulosic crops (IRENA, 2017a). The first two types do not grow well on degraded land, and compete with food production in case they are grown on non-degraded land, also they have a limited ability to lower emissions (IRENA, 2017a). Thus, for the feedstock that can be used on degraded land, the focus should lay on lignocellulosic energy crops. Furthermore, it would be most beneficial to use perennial energy crops since these offer environmental advantages compared to annual crops, and they provide more benefits to the ecosystem (Dauber et al., 2012). Finally, it is preferred to have a biomass source from a grass or herbaceous plant, since these are fast growing and have a greater biomass production (Ling Chin et al., 2017). Bamboo meets all these selection criteria.

Bamboo is a lignocellulosic perennial crop, and is the biggest member of the grass family, which is called the Poaceae (Poppens et al., 2013; Sharma et al., 2018; Dauber et al., 2012). Worldwide, there are close to 1500 species under 87 genera of bamboos (Mishra et al., 2014). In Indonesia, between 120 and 161 species of bamboo can be found, of which 56 species are native to Indonesia (Widjaja, n.d.; Hafzari et al., 2019; Bamboo U, 2019; Sofiah and Susim, 2020; Setiawati et al., 2017; Nasendi, 1995; Park et al., 2021). The total area occupied by bamboo in Indonesia is estimated to lay between two and five million ha (Nasendi, 1995; Park et al., 2021). The traditional use of bamboo is as a source of food, firewood, and fire (Sharma et al., 2018). Recently the use expanded to durable tools, furniture, and building material. Bamboo now has more than 1500 applications. Currently bamboo is mostly used for construction and handicrafts, but because of its fuel characteristics, short rotation, and high productivity, bamboo has the potential to be used as a biomass feedstock (Sharma et al., 2018; Widjaja, n.d.; Nasendi, 1995).

Using degraded land for bamboo plantations needs consultation from the villagers to gain insight in the local know-how in addition to a scientific approach (L. Singh et al., 2020). A study done in Central Kalimantan showed that land owners prefer bioenergy species that are familiar to them for restoration of degraded land (Artati et al., 2019). Therefore, one of the most common bamboo species in Indonesia will be planted. The most common bamboo genera in Indonesia are the Bambusa, Gigantochloa, and the Dendrocalamus (Widjaja, n.d.; Abdullah et al., 2017; Auman et al., 2018; Utami et al., 2018).

The species that have been used in other studies for bioenergy generation are the D. Asper, G. pseudorundinacea, B. Vulgaris, G. Apus, and G. Atroviolacea (Widjaja, n.d.; Abdullah et al., 2017; Auman et al., 2018; Utami et al., 2018). Therefore, the fuel properties of these five species are shown in Table 3.1. The proximate analysis is used to determine the compounds in a mixture, and the ultimate analysis is used to determine the chemical elements in the compounds.

Table 3.1: Fuel properties of bamboo species according to different sources. In this table VM is volatile matter, FC is fixed carbon content, MC is moisture content, C is carbon, H is hydrogen, O is oxygen, N is nitrogen, S is sulfur, and HHV is the higher heating value.

	Proximate analysis [%]				**Ultimate analysis [%]**						
Species	*Ash*	*VM*	*FC*	*MC*	*C*	*H*	*O*	*N*	*S*	*HHV [MJ/kg]*	**Reference**
D Asper	**2.44**	**75.4**	**15.1**	**7.1**	**48.7**	**6.0**	**44.9**	**0.33**	**0.05**	**18.41**	Park et al., 2019
D Asper	15.16	62.65	5.19	17	43.06	6.57	50.19	0	0.17	17.29	Pattanayak et al., 2020
D Asper	2.7	71.7	19.8	5.8	-	-	-	-	-	17.59	Truong and Le, 2014
G Pseudorandinacae	**2.08**	**78.0**	**11.5**	**8.4**	**49.0**	**6.09**	**44.4**	**0.4**	**0.05**	**18.65**	Park et al., 2019
B Vulgaris	**1.15**	**72.0**	**16.7**	**10.2**	**49.5**	**6.3**	**43.7**	**0.43**	**0.04**	**18.27**	Park et al., 2019
B Vulgaris	8.69	74.3	9.41	7.61	39.75	5.75	-	-	-	-	Sucipta et al., 2017
B Vulgaris	2.12	80.13	17.75	20.19	46.78	6.38	46.59	0.25	-	18.21	Rousset et al., 2011
G Apus	**1.89**	**80.0**	**10.8**	**7.3**	**50.9**	**6.44**	**42.3**	**0.24**	**0.07**	**18.7**	Park et al., 2019
G Apus	2.45	74.3	18.35	8.89	44.29	6.16	46.47	0.53	0.1	17.38	Purbasari et al., 2016
G Atroviolacea	**1.36**	**72.4**	**18.4**	**7.8**	**50.3**	**6.21**	**42.9**	**0.46**	**0.05**	**18.75**	Park et al., 2019
G Atroviolacea	3.29	71.7	16.88	8.13	44.11	6.26	45.8	0.47	0.07	17.11	Purbasari et al., 2016

As can be seen in the table, the values of the proximate and ultimate analysis differ a lot from each other in the different reference studies. This difference can be explained by the different ages of the bamboo sample and whether or not the bamboo is dried before sampling. The data by Park et al. (2019), is obtained by analyzing bamboo samples which have been dried naturally for three months. The samples were obtained from harvesting the bamboo five years after it was planted. Next, the samples analysed by Purbasari et al. (2016), were sun-dried for one day. The age of the bamboo used for these samples is not known. The data by Sucipta et al. (2017) is taken from bamboo samples which have been sun dried for six days, the age of the bamboo is not known. The samples used by Pattanayak et al. (2020) were first sun-dried for seven days, and then further dried at a temperature of 80°for one hour, again the age of the bamboo used in this study is not known. No information is given about the samples used by Truong and Le (2014) and Rousset et al. (2011). Also, what is remarkable about the proximate analysis done by Rousset et al. (2011), is that the total percentage does not add up to 100%, but to 120%.

To be able to make a reliable comparison between the bamboo species, the data used should be obtained via a similar method. Data of which the drying period or age of the bamboo samples is not know is thus not useful to make a comparison. Because of this only the fuel properties of the samples by Park et al. (2019), are used to further evaluate the optimal bamboo species for electricity generation. In Park et al. (2019), samples are taken from all five species using the same method, so the data can be used to compare the different species to each other. In Table 3.1, the further evaluated values are indicated in bold.

In Table 3.1, the HHV of the bamboo species is shown. Both the water present as moisture and the water which is chemically formed from the fuel-bound hydrogen content are assumed to be in the liquid form by the HHV. The lower heating value (LHV) assumes that both types of water remain in the vapor phase. This means that the difference between the two heating values is the latent heat of the vaporization of water at room temperature (25°C) of both water types that are released in the combustion process (de Jong and van Ommen, 2015).

$$LHV^{db} = HHV - 2.4 \cdot 8.9Y_H \tag{3.1}$$

$$LHV^{wb} = LHV^{db}(1 - Y_{moisture}) - 2.4Y_{moisture} \tag{3.2}$$

Equations 3.1 and 3.2 are used to calculate the LHV from the HHV. The first is used to correct for the hydrogen content in the dry fuel, and the second corrects for the moisture content of the wet fuel. In the equations Y_H is the hydrogen content and $Y_{moisture}$ is the moisture content of the biomass. LHV^{db} and LHV^{wb} are the lower heating value on a dry basis and on a wet basis, respectively. The value 2.4 comes from the heat of the evaporation of water at 25°, which is 2.44 MJ/kg, and the 8.9 stands for the mass of water created per unit mass of hydrogen, so the unit is kg/kg (Blok and Nieuwlaar, 2021). Usually, in energy conversion processes the heat of condensation is not used, so the LHV is used in calculations (de Jong and van Ommen, 2015). The calculated LHV values for the selected bamboo species are shown in Table 3.2.

Table 3.2: Lower heating values of the selected bamboo species

Species	**LHV [MJ/kg]**
G Apus	15.88
Dendrocalamus Asper	15.74
Gigantochloa Atroviolacea	15.88
Gigantochloa Pseudorandinacae	15.69
Bambusa Vulgaris	14.95

The relatively low ash content, high volitale matter, fixed carbon, and HHV, make bamboo have desirable fuel characteristics compared to some other biomass feedstocks (Shah et al., 2021; Fialho et al., 2019). Different bamboo species might have fuel characteristics which make the species more suitable for different conversion technologies. For example, biomass species with a low moisture content are better suitable for thermochemical conversion technologies, and species with a higher moisture content are more suitable for biochemical conversion technologies (Cuiping et al., 2004). Which thermochemical conversion technology is most suitable for a certain biomass species mainly depends on the fixed carbon, volitale matter, ash content, and the oxygen, hydrogen, and carbon content (Pattanayak et al., 2020).

The FC/VM ratio gives an indication on how difficult it will be for the biomass to combust, lower values indicate easier combustion (Pattanayak et al., 2020). The ash content of biomass influences the fouling and slagging during combustion. Slagging and fouling happens when inorganic material melts and deposits in the furnace (Erickson et al., 1995). A higher ash content means that the thermal behaviour of the particles will change more, char particles in the end of the burnout will break into smaller pieces. A lower ash content provides a higher effectiveness of the oxidation process of a biomass (Pattanayak et al., 2020).

For the thermochemical processes the species are desired to have a low FC/VM ratio (preferably below 2.5) , since this makes combustion easier due to a higher VM content (Vega et al., 2019; Toptas et al., 2015; Pattanayak et al., 2020). Furthermore, species with low ash contents are more suitable for pyrolysis and gasification and species with a low oxygen plus ash content are more suitable for combustion (Cuiping et al., 2004; Pattanayak et al., 2020; McKendry, 2002). For combustion and pyrolysis, the species with a higher hydrogen and carbon content are more suitable, and for gasification a lower H + C content is desired (Pattanayak et al., 2020). An overview of these selection criteria is given in Table 3.3.

Table 3.3: Biomass selection criteria for different thermochemical conversion routes (adapted from Pattanayak et al., 2020)

Conversion Technology	**Biomass characteristic**			
	FC/VM ratio	*Ash content*	*O + Ash content*	*H + C content*
Combustion	low	-	low	high
Gasification	low	low	-	high
Pyrolysis	low	low	-	low

When evaluating the fuel properties of the five selected bamboo species using the selection criteria mentioned above, Table 3.4 can be constructed. What becomes clear is that the differences between the bamboo species is relatively small. In Pattanayak et al. (2020), the range over which the ash content and the O + ash content spread was around 15%, and the range of the H + C content also was only 3%. The conclusion that can be drawn from comparing Table 3.4 with Table 3.3, is that the species B Vulgaris and G Apus best match a specific conversion technology, compared to the other species. B Vulgaris matches best with the selection criteria for pyrolysis, and G Apus matches the criteria of gasification and combustion best. Since the species G Apus also has the highest LHV, in combination with a low moisture content, this species will be used for further calculations in this research.

Table 3.4: Selection criteria values of the five selected biomass species (calculated from Table 3.1)

Bamboo species	**Biomass characteristic**			
	FC/VM ratio [-]	*Ash content [%]*	*O + Ash content [%]*	*H + C content [%]*
D Asper	0.200	2.44	47.34	54.70
G Pseudoarundinacae	0.147	2.08	46.48	55.09
B Vulgaris	0.232	1.15	44.85	55.80
G Apus	0.135	1.89	44.19	57.34
G Atroviolacea	0.254	1.36	44.26	56.51

3.3. Bamboo plantation biomass yield

The amount of biomass that can be harvested from a bamboo plantation depends on multiple factors. Bamboo can be harvested three years after it was planted (Dwivedi et al., 2019; Liese and Köhl, 2015).

However, waiting longer before harvesting increases the biomass yield significantly (A. N. Singh and Singh, 1999; Kuehl, 2015). Besides the age of the plants, also the spacing has a big influence on the biomass yield. When the clumps are more densely spaced, the yield decreases (B. Patel et al., 2019; Behera et al., 2016). The optimal spacing depends on the size of the bamboo species used, for smaller species a smaller spacing can be applied. The optimal spacing for a medium diameter species is 5 x 5 meters (Guadua Bamboo, n.d.). When the goal is not to obtain a high biomass yield, but primarily to stabilize the soil, a smaller spacing of 3 x 3 meters can be applied (Guadua Bamboo, n.d.).

That the yield of bamboo plantations varies a lot becomes clear when evaluating different studies. According to Darabant et al. (2014) the range of biomass yield lays between the 4-50 t/ha, while (Rathour et al., 2022) mentions a biomass yield of 67 t/ha. Furthermore, the biomass yield is expected to decrease by 50% when growing bamboo on degraded land (B. Patel et al., 2019). With the most optimal spacing the yield decreases from 57.7 t/ha to 28.8 t/ha, when the plantation is located on degraded land (B. Patel et al., 2019). An other study found a biomass yield of 24.2 t/ha when growing bamboo on degraded land (B. Patel, Patel, et al., 2021). Therefore, in this research the average of these two studies, a biomass yield of 26.5 t/ha, will be applied for further calculations.

3.4. Intercropping

An advantage of bamboo is that it can also be used in intercropping agricultural systems (Mollins, 2021). Intercropping has some benefits like a higher economic return, improved biodiversity, higher soil improvements, and more acceptance by the community (Zhang et al., 2020; Andriyana et al., 2020; Hiwale, 2015; B. Patel, Patel, et al., 2021). The first three years after planting the bamboo, the plant is not fully grown and ready for harvesting yet. During this period the inter space can be used to grow other crops to get an income from the plantation (Toppo, 2022). After the three years, crops that are tolerant to shade (ginger, tumeric, large cardamom) can still be grown on the plantation (Hiwale, 2015).

Bamboo intercropping can be done with many different species like tea plants, conifer/other broadleaf trees, agricultural crops, fish ponds, edible fungi, and medicinal plants (Sastry et al., 1996). However, what is important is that the species with which the bamboo is intercropped on the plantation is also able to grow on degraded land. In India and Thailand, it proved to be feasible to plant soybean, wheat, peas, mustard, maize, and peanuts as the intercropping species on degraded land (Solomon et al., 2020; Hiwale, 2015; Nirala et al., 1996). Furthermore, there is a possibility to grow bamboo together with other tree species. In general, mixed plantations where a combination of bamboo and teak (tectona grandis) or bamboo and khair (acacia catechu) are planted are most common (L. Singh et al., 2021). Both teak and khair grow well on degraded land (Kaewkrom et al., 2005; Jha and Mandal, 2019).

Also, agroforestry systems like the talun-kabun system, used in Indonesia, can be applied. The system has a cycle length of six years, where in the first year mixed vegetable species are grown (kebun), followed by a year of growing cassava, and finally bamboo is grown for four years (talun) (Christanty et al., 1996). When looking at the nutrient accumulation in the soil during this cycle, it became clear that during the talun stage the soil humus built and in site nutrient reserves increased (Mailly et al., 1997). The bamboo is important since it restores the soil fertility on the plantations (Christanty et al., 1996).

3.5. Bamboo to electricity: conversion technologies

There are two main ways to convert bamboo into heat, electricity, or fuel, the first being thermochemical conversion and the second being biochemical conversion (Ediriweera, Palihakkara, et al., 2020). Thermochemical processes use heat to transform bio-matter in biomass into various end products, like heat, electricity, and fuel (Ediriweera, Palihakkara, et al., 2020). Processes that can be classified as thermochemical conversion are combustion, gasification and pyrolysis, the suitable conversion process depends on the type of bamboo biomass used (Pattanayak et al., 2020). In biochemical conversion, microorganisms are involved in transforming the biomass to biogas or biofuel (Ediriweera, Palihakkara, et al., 2020). Anaerobic digestion and fermentation are the two processes that classify as biochemichal conversion, and can be used for bamboo biomass to produce energy (Truong and Le, 2014). The main routes for the conversion of biomass are shown in Figure 3.1.

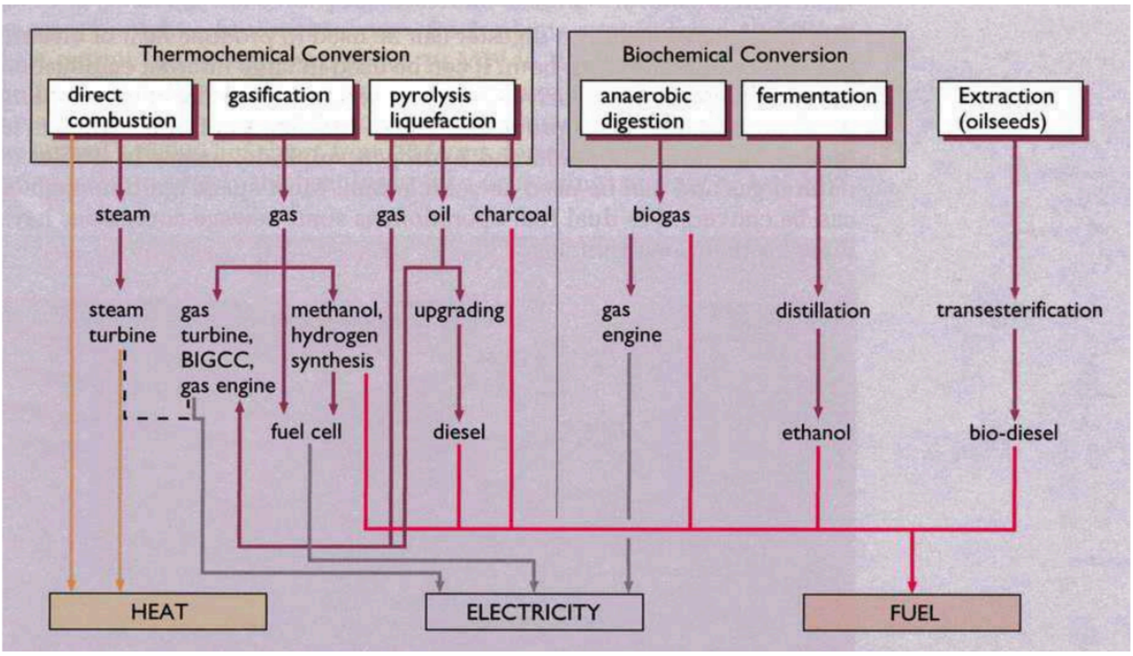


Figure 3.1: Biomass conversion routes (Truong and Le, 2014)

Currently, energy policies for biomass in Indonesia are oriented towards the transport sector and power generation (electricity) (Dani and Wibawa, 2018). Biomass can help to make electricity accessible to small communities (Dani and Wibawa, 2018). As mentioned in Chapter 1, the electricity demand is expected to increase significantly. To meet the electricity demand expected in 2030, the conversion technologies shown in Figure 3.1 can be used to turn the harvested bamboo into electricity.

From the figure, it becomes clear that the thermochemical conversion route possibilities to convert bamboo into electricity are direct combustion (or co-firing (Liu et al., 2016; Chao et al., 2008; Fryda et al., 2014)) using a steam turbine, gasification using either a fuel cell or gas turbine, and pyrolysis liquefaction which then routes back to a gas turbine as well. Also one biochemical conversion route is suitable for conversion of biomass into electricity. This is anaerobic digestion using a gas engine. To improve the fuel quality of the bamboo pretreatment like wet and dry torrefaction can be done (Fryda et al., 2014). The different conversion technologies are explained below.

First, in Subsection 3.5.1, direct combustion is explained. Subsection 3.5.2 explains how gasification of a biomass works. Then the final thermochemical conversion technology, which is pyrolysis, is explained in Subsection 3.5.3. Finally, in Subsection 3.5.4 the biochemical conversion technology, anaerobic digestion, is discussed.

3.5.1. Direct combustion

Combustion is the most common technology used to convert biomass into energy. Combustion is made up out of four processes: drying, pyrolysis, combustion of the volatile matter, and combustion of the residual char (de Jong and van Ommen, 2015; Kerlero De Rosbo and Bussy, 2012). The most used technology for electricity generation through combustion in thermal power plants is a steam turbine (de Jong and van Ommen, 2015). There are other possibilities, like the Rankine cycle, the Stirling engines, the externally fired combined cycle (de Jong and van Ommen, 2015; Makwarela et al., 2017).

Focusing on the most common technology, the steam engine, electricity is generated by first burning the biomass in a boiler which generates steam as well as hot exhaust gasses, and then the steam is led into the steam engine. Here it pushes against a piston, so mechanical power is produced. The steam expands, the pressure is lowered and the steam is cooled down. Now the steam can be condensed, reheated and pumped back into the boiler, or be released into the atmosphere (Kerlero De Rosbo and Bussy, 2012; Truong and Le, 2014). A schematic overview of this process is given in Figure 3.2. In this figure the blue blocks are inputs, and the green block is the output of electricity. The electrical efficiency of this process, based on the lower heating value, lays between the 10% and the 30% (Kerlero De Rosbo and Bussy, 2012; de Jong and van Ommen, 2015).

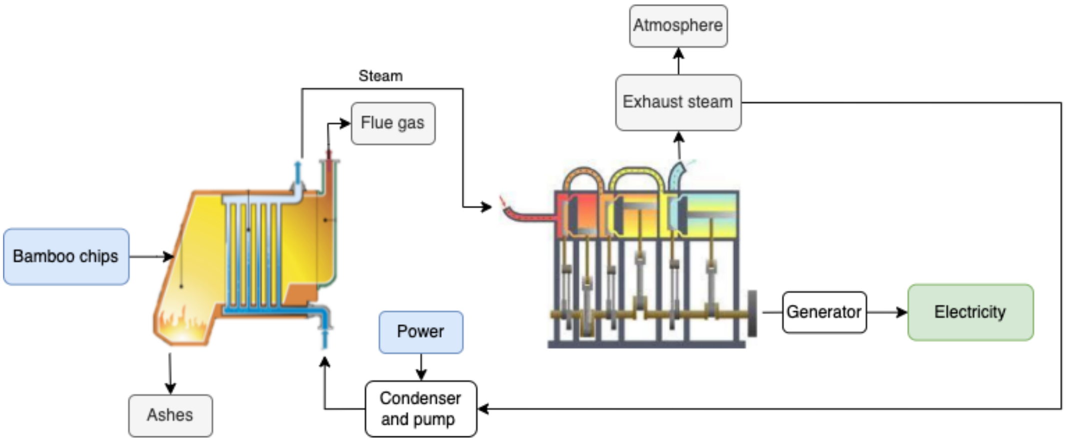


Figure 3.2: Combustion process (adapted from (Kerlero De Rosbo and Bussy, 2012; Truong and Le, 2014)

Combustion is also possible in another form, biomass can be co-fired with coal. A biomass to coal ratio of around 10-30% is optimal when looking at the amount of pollutant emissions per unit of energy output (Chao et al., 2008). Co-firing will reduce the CO_2 and NO_x emissions, as well as the amount of fossil fuel needed, in a fossil fuel power plant (Makwarela et al., 2017; Truong and Le, 2014). Currently in Indonesia, PLN (the Indonesian utility company) is co-firing biomass at 17 thermal coal power plants however the government wants to make this mandatory for all coal power plants (which currently supply more than 60% of the electricity) (Modi, 2021; Davies, 2021).

3.5.2. Gasification

From the three thermochemical conversion routes that can be taken, gasification is the best option for power production (Kerlero De Rosbo and Bussy, 2012). Both a pyrolysis and a partial combustion step are included in gasification. During gasification, a gaseous agent is used to convert a liquid/solid fuel into a combustible product gas (de Jong and van Ommen, 2015). A limited amount of oxygen is available during the gasification process, and it occurs at high temperatures, between 750-1000°Celcius (Truong and Le, 2014).

For small scale operations of a few MW, fixed and moving bed gasifiers can be used. For mid-scale operations between 10 and more than a 100 MW, fluidized bed reactors can be used, and for operations of more than 100 MW, entrained flow gasifiers are applied (de Jong and van Ommen, 2015). In Figure 3.3 an overview of the gasification process is shown, in this figure a fixed bed reactor is used. Electricity can be generated either via a gas turbine, gas engine, or fuel cell. In the figure the path of the gas turbine and fuel cell are shown. To be able to use the syngas as an input for the fuel cell it needs to be cleaned, so dust and tars are filtered out (Truong and Le, 2014). Both a molten carbonate and a solid oxide fuel cell can be used to process bio syngas, however since a solid oxide fuel cell has a higher resistance to gas contaminates this cell is shown in Figure 3.3 (de Jong and van Ommen, 2015).

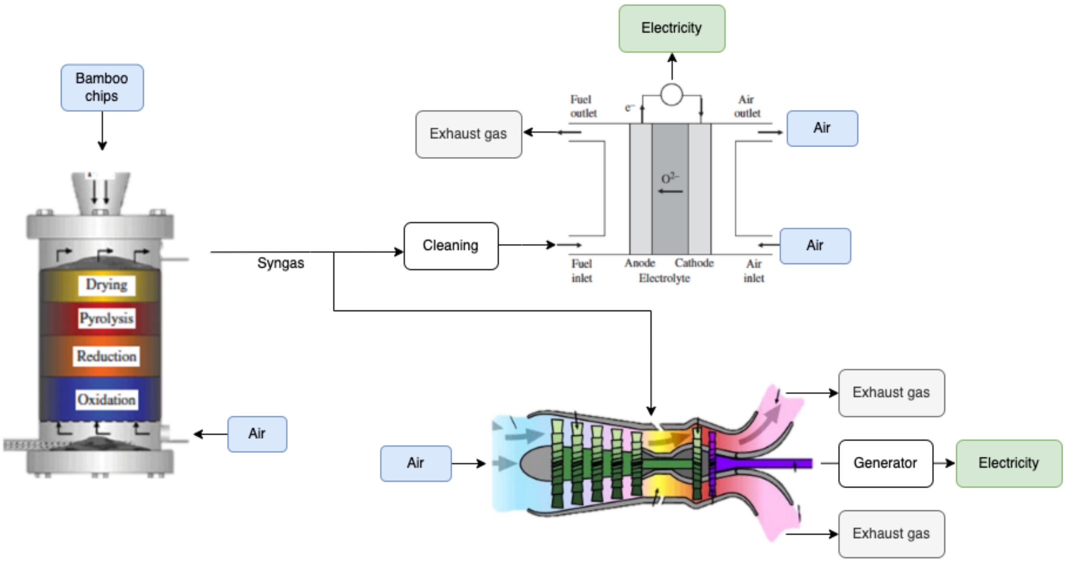


Figure 3.3: Gasification process (adapted from (de Jong and van Ommen, 2015; ipieca, 2014)

The electrical efficiency of this process, based on the lower heating value, lays between the 20% and the 35% (Kerlero De Rosbo and Bussy, 2012).

3.5.3. Pyrolysis

Pyrolysis is the first step of the combustion and gasification processes of biomass. During pyrolysis, biomass is converted into bio-oil, syngas, and charcoal in the absence of oxygen. These outputs then can be used as an input for a power production process (de Jong and van Ommen, 2015; Truong and Le, 2014). For electricity, the best product of the pyrolysis to use is the syngas, using the oil would require more steps and energy to separate the oil from the tars and purify it (Truong and Le, 2014). The syngas can be burnt in either a boiler, similar to the combustion process explained in Subsection 3.5.1, or in a gas engine (Truong and Le, 2014).

Most pyrolysis reactions are conducted in fluidized bed reactors at a temperature between 350-600°Celcius, in these reactors the produced syngas is often recycled back into the reactor to keep the reaction going and prevent the need for additional input gas once the reaction has started (de Jong and van Ommen, 2015; Kerlero De Rosbo and Bussy, 2012). However, since the syngas is needed for power generation this will not be possible in this case. This means that a constant input of additional gas is needed to keep the reaction running. The production of gases is optimized when the pyrolysis reaction is done at low temperatures of 350-400°Celcius, this process is also called carbonization (Kerlero De Rosbo and Bussy, 2012).

Figure 3.4 gives an overview of the process to convert bamboo into electricity using pyrolysis. Either the steam turbine or the gas turbine path can be followed. Again, the blue blocks are inputs, and the green blocks are outputs.

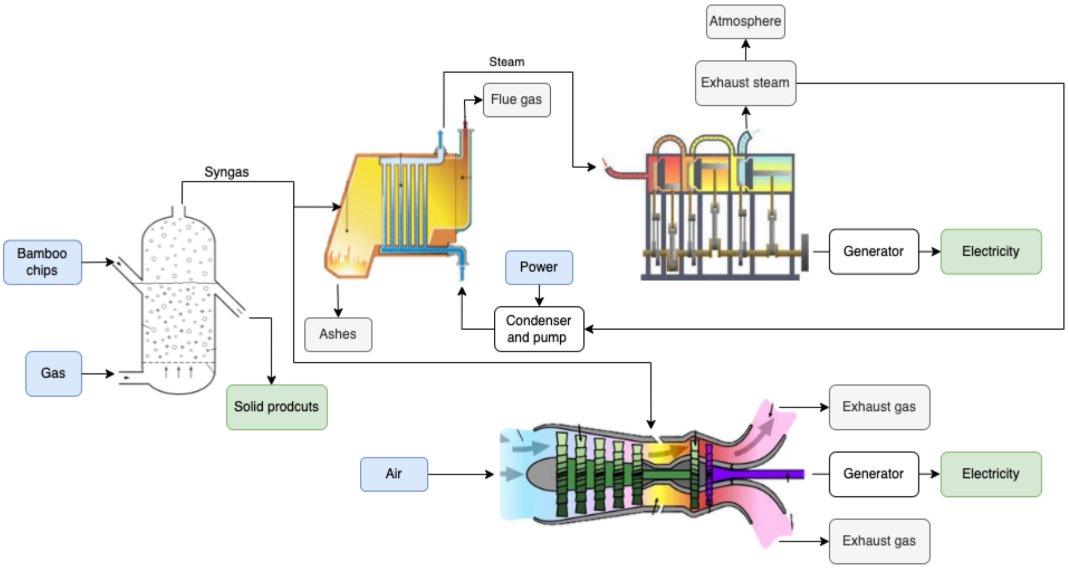


Figure 3.4: Pyrolysis process (adapted from (ipieca, 2014; Ebrary, n.d.; Truong and Le, 2014)

The electrical efficiency of this process, based on the lower heating value, is around the 10% (Kerlero De Rosbo and Bussy, 2012).

3.5.4. Anaerobic digestion

During anaerobic digestion, organic matter in biomass is biologically degraded by microorganisms without the presence of oxygen (Truong and Le, 2014). The biogas that is produced consists of approximately 60% methane and 40% CO_2 (Truong and Le, 2014; de Jong and van Ommen, 2015). Anaerobic digestion exists of four steps being: hydrolysis, acidogenesis, acetogenesis, and methanogensis (Truong and Le, 2014). Reactors used for this process are the plug flow reactor and the continuous stirred tank reactor. Theoretically, it is optimal to have a plug flow reactor in which the catalyzing microorganisms for the methanogensis step are maintained by a recirculation rate (de Jong and van Ommen, 2015).

Figure 3.5 shows a schematic overview of the anaerobic digestion process. The reactor in this figure is a plug flow reactor, and the syngas is converted to mechanical energy in a gas engine. The generator is used as a final step to convert the mechanical energy to electricity. The efficiency of anaerobic digestion varies between 20-70%, and the efficiency of a gas turbine is around 43% (Mei et al., 2016; Weiland, 2010). This gives an overall electrical efficiency of 19%.

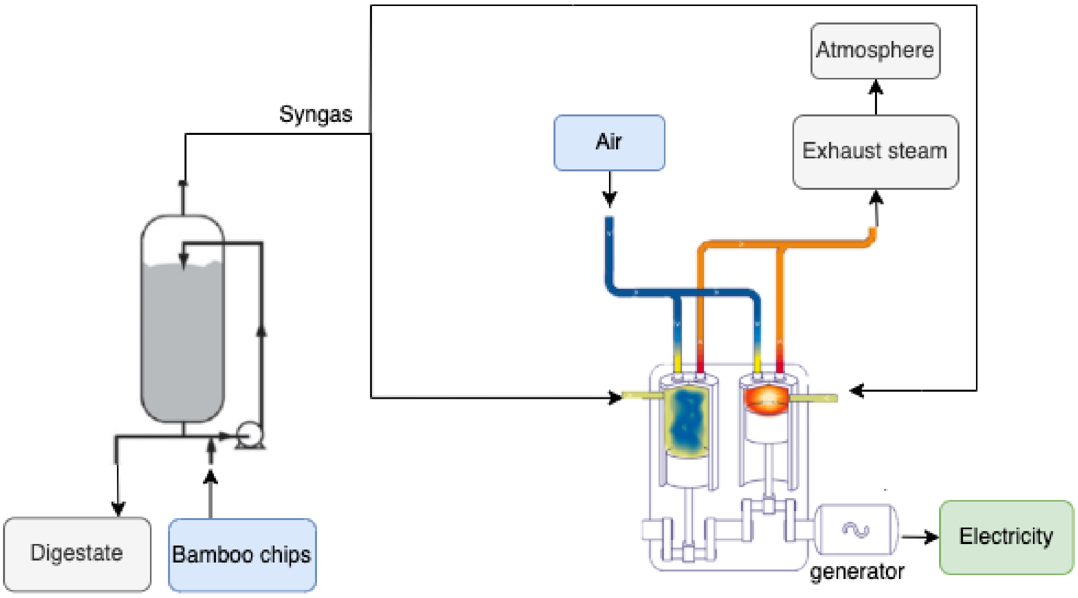


Figure 3.5: Anearobic digestion process (adapted form (Coney et al., 2004; de Jong and van Ommen, 2015)

4
Methodology

In this chapter the methods for both the potential assessment and the QGIS degraded land assessment are explained. First, to be able to select the degraded land areas which are suitable for a biomass plantation a GIS analysis is conducted. As mentioned in Chapter 2, a GIS approach has been used for similar studies. In this study the QGIS software is used, this is a free and open source geographic information system software (QGIS.org, 2022). The method used to find the suitable locations is explained in Section 4.1. After this, in Section 4.2, the method used for the potential analysis is described.

4.1. QGIS method

To determine the optimal locations for bamboo plantations in Indonesia, multiple classification criteria have been used. The QGIS analysis consists of four different steps, in each step different criteria are evaluated. Figure 4.1 gives an overview of the steps described below, and the data-sets used in each step. In this figure, the grey blocks indicate a data-set, the blue blocks represent the different steps, and the green blocks are outputs. Multiple data-sets are used for the different steps of the QGIS analysis. An overview of the data-sets used is given in Table 4.1.

Table 4.1: Data-sets used for the GIS analysis

Data	Year	Source
Soil quality (HWSD)	2008	Fischer et al., 2008
Above ground biomass (AGB)	2016	Avitabile et al., 2016
Land cover	2017	MoEF, 2017
Protected areas	2022	UNEP-WCMC and IUCN, 2022
Protected areas	2015	Global Forest Watch, 2019
Key biodiversity areas	2021	Key Biodiversity Areas, 2022
Peat lands	2016	Global Forest Watch, 2016
Elevation	2018	3 CGIAR-CSI, 2018
Roads	2022	OpenStreetMap, 2022

The first step, described in Subsection 4.1.1, is to find degraded land locations. This is done by analyzing two different data-sets, first the Harmonized World Soil Database (HWSD) is used to assess the quality of the soil and second the above ground biomass (AGB). Criteria used in literature which analysis the soil quality are for example: soil erosion, water erosion, salinization, sodification, peat, nutrient status, and physical, chemical and biological degradation (Abdel-Kader, 2019; AbdelRahman et al., 2016; Hou et al., 2016; Dauber et al., 2012; Edrisi and Abhilash, 2016). In the above ground biomass data-set, the amount of carbon per hectare is used to find degraded land areas (Ruysschaert et al., 2011; Gingold et al., 2012). The next step, described in Subsection 4.1.2, adds ecological and peat constraints to the degraded land areas found in Step 1. Key biodiversity areas, peat lands, and areas that are both legally classified as protected and found in the World Database on Protected Areas (WDPA), are excluded (Dauber et al., 2012). Then the third step, described in Subsection 4.1.3, is to take the social criteria into account, in literature the following criteria have been used: land cover, land productivity, GDP, population density (Romshoo et al., 2020; Kusratmoko et al., 2017; Hou et al., 2016; Fauzi et al., 2019). Finally, the fourth step includes the economic considerations, including the size of the plantation, the slope and elevation, and the accessibility (Dauber et al., 2012; Edrisi and Abhilash, 2016). This final step is described in Subsection 4.1.4.

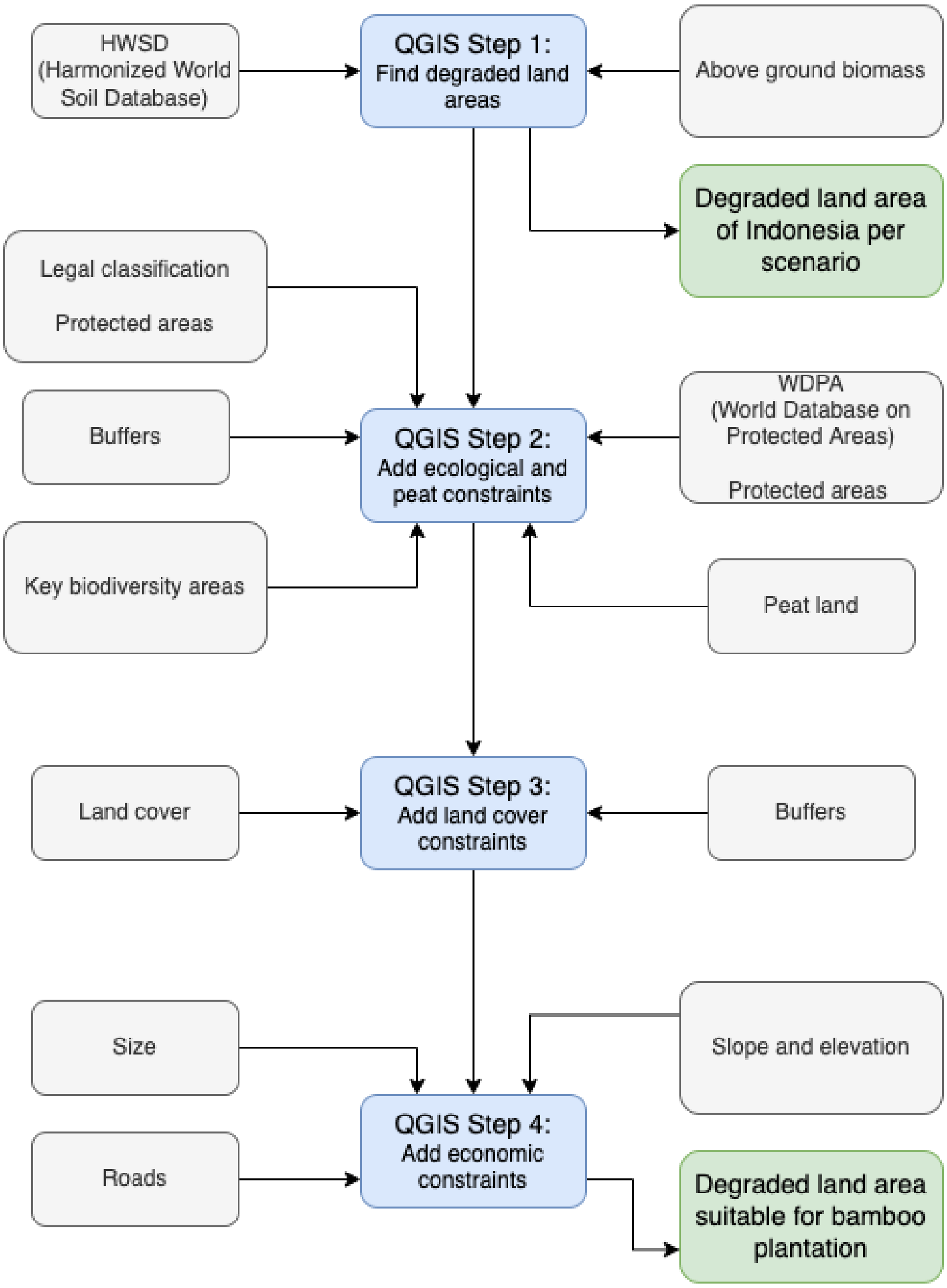


Figure 4.1: Schematic overview of the QGIS method

4.1.1. Step 1: Find degraded land areas

In the first step, two different approaches to find degraded land are used. These approaches are based on different focus points of the degraded land definitions. The first approach makes use of the HWSD data-set. The second approach uses the AGB data-set.

Soil quality constraints

In this research, the focus lays growing bamboo on degraded land, as a biomass feedstock. Therefore, in this case, the quality of the soil is the most important parameter to measure degraded land. This follows the first definition, as mentioned in Section 2.4, which indicates that the properties of the soil form a parameter by which land degradation can be assessed. A data-set from the harmonized world soil database (HWSD) is used to get an overview of the quality of the soil and the matching growth potential. From this data-set areas with a growth potential of 60% to less than 40% will be classified as degraded. This limited growth potential implies a reduction of the land's production capacity as mentioned in definitions by WRI (2022), UN (2007), OECD (2001), FAO (2022b), Olsson and Barbosa (2019), Rothman et al. (2007), and Abdel-Kader (2019).

As mentioned the HWSD data-set is used in this first step. The data-set is part of a collaboration between the FAO, the ISRIC-World Soil Information, the Institute of Soil Science, the Chinese Academy of Sciences (ISSCAS), and the Joint Research Centre of the European Commission (JRC) (FAO, 2022a). The data-set provides information on problems of land competition for food production, bio-energy demand, and threats to biodiversity (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). From this data-set, seven raster data files, with a resolution of 30 arcsec (1 km), concerning soil quality are implemented in the QGIS software for the degraded land analysis. The soil quality parameters are the nutrient availability, nutrient retention capacity, rooting conditions, oxygen availability to roots, excess salts, toxicity, and workability (constraining field management) (Fischer et al., 2008). The characteristics matching each of these seven soil qualities are shown in Table 4.2. All these characteristics are summarized in the soil quality parameters. The reference crop on which the data is based is maize (FAO, 2022a).

In this report, the data-set by the Food and Agriculture Organization of the United Nations (FAO) is used, which was generated using the methods described below. For more information, please see FAO (2022a). The FAO compiled the data-set by evaluating different soil characteristics for each of the seven soil qualities. For the different soil qualities a different estimation procedure was followed. Since the soil characteristics of the nutrient availability are slightly correlated, the soil characteristic that is most limiting was combined with the average of the remaining less limiting characteristics. The same was done for the nutrient retention capacity. Then for the rooting conditions the soil depth limitation was multiplied with the most limiting soil or soil phase property for the estimation. To estimate the excess salts the most limiting of the combined soil salinity, sodicity conditions, and occurrence of saline and sodic soil phase was selected. Again for the toxicity soil quality the most limiting of the combination of excess calcium carbonate and gypsum in the soil, and the occurrence of petrocalcic and petrogypsic soil phases was used. Finally, for the workability the same method as for the first two soil quality was followed. The most limiting soil phase attribute was combined with the average of the remaining attribute conditions (FAO, 2022a). This method was used by the FAO to assign the numbers 1 to 7, as shown in Table 4.3, to each location per soil quality.

Table 4.2: Soil qualities and characteristics (FAO, 2022a)

Soil quality	**Soil characteristics**
Nutrient availability	Soil texture Soil organic carbon Soil pH Total exchangeable bases
Nutrient retention capacity	Soil organic carbon Soil texture Base saturation Cation exchange capacity of soil and clay fraction
Rooting conditions	Soil texture Bulk density Coarse fragments Vertic soil properties Soil phases affecting root penetration Soil depth Soil volume
Oxygen availability to roots	Soil drainage Soil phases affecting soil drainage
Excess salts	Soil salinity Soil sodicity Soil phases influencing salt conditions
Toxicity	Calcium carbonate Gypsum
Workability (constrainting field management)	Soil texture Effective soil depth/volume Soil phases constrainting soil management (soil depth, rock outcrop, stoniness, gravel/concretions, hardpans)

For each soil quality parameter, there is a separate raster file in which each location is linked to a number. These numbers range from 1 to 7, then each number is matched with a different class, as shown in Table 4.3. The first four classes are matched to a growth potential range, going from 100% growth potential to less than 40% growth potential in four equal steps (Fischer et al., 2008). These classes are used to determine which pieces of land can be classified as degraded land.

Table 4.3: HWSD classifications (Fischer et al., 2008)

Number	**Class**	**Growth potential**
1	No or slight limitations	100 - 80 %
2	Moderate limitations	80 - 60 %
3	Severe limitations	60 - 40 %
4	Very severe limitations	< 40 %
5	Mainly non-soil	–
6	Permafrost area	–
7	Water bodies	–

It is assumed that (very) severe limitations, thus a growth potential below 60%, result in a loss of value and a reduced production capacity of the land, as stated by the degraded land definitions. To include different levels of loss of value or reduced production capacity, three different degraded land scenarios are constructed. Scenario HWSD_1 contains the least constraints, this scenario includes all areas that score number 3 or 4 in at least one of the seven soil quality parameters. Next, scenario HWSD_2 includes all areas that score number 4 in at least one of the seven soil quality parameters. Finally, scenario HWSD_3 only includes areas that, when taking the average of the seven parameters, have an average score which is higher than 2. Since some of the parameters data-sets have missing data points, the average is calculated by dividing the sum of the scores by the number of inputs. Going from scenario HWSD_1 to HWSD_3, the scenarios become more strict. Examples of the data for each scenario are given in Tables 4.4, 4.5, 4.6. In these tables the index column provides information on the location.

To separate the data and bundle it into the three different scenarios a Python code was written. The input for the program is an attribute table extracted from QGIS, formatted as a CSV file, which includes all information from the seven soil quality parameters. The output of the Python code gives three different CSV files with only the locations that apply to each scenario. Then these CSV files can be converted back to QGIS shape files, resulting in three different maps of Indonesia, with the degraded land location for each scenario.

Table 4.4: Examples HWSD_1 data (at least one number 3)

Index	Excess salt	Nutrient retention capacity	Nutrient availability	Oxygen available to roots	Rooting conditions	Toxicity	Workability	Average
155	1	2	**3**	1	1	1	1	1.42857
166	1	1	1	1	**4**	1	**4**	1.85714

Table 4.5: Examples HWSD_2 data (at least one number 4)

Index	Excess salt	Nutrient retention capacity	Nutrient availability	Oxygen available to roots	Rooting conditions	Toxicity	Workability	Average
842	1	1	1	1	3	1	**4**	1.71429
863	1	1	1	1	**4**	1	**3**	1.71429

Table 4.6: Examples HWSD_3 data (average of at least 2)

Index	Excess salt	Nutrient retention capacity	Nutrient availability	Oxygen available to roots	Rooting conditions	Toxicity	Workability	Average
4490	**4**	**4**	**4**	**3**	**3**	**3**	**3**	3.28571
4497	2	**3**	**4**	**3**	2	2	2	2.57143

Carbon stock constraints

As mentioned in Chapter 2, another way to estimate the degraded land area is by evaluating the carbon stock per hectare. The second definition mentioned in Section 2.4 is used for this part of the method. The definition mentions that land is degraded when it contains a carbon stock lower than 35 t C/ha. Using this adds an extra scenario to the degraded land analysis, being scenario CS_4. A threshold of 35 tonnes of carbon per ha is used by (Gingold et al., 2012). A different study uses a threshold of 40 tonnes of carbon per ha, this value is chosen by comparing the current carbon stock to that of an oil palm plantation. It is mentioned that converting land below the threshold to a plantation will lead to a carbon stock gain (Ruysschaert et al., 2011). An important note is that these analysis only take above ground biomass, which means vegetation, into consideration (Ruysschaert et al., 2011; Gingold et al., 2012). Soil organic carbon and below ground biomass are neglected.

In this research the more restricting value of 35 tonnes of C/ha is applied. The above ground carbon stock data-set was added to the QGIS analysis, and modified in such a way that only areas containing less than 35 tonnes of C/ha remained (Avitabile et al., 2016). These remaining areas are considered to be degraded in this fourth scenario. The resolution of this data-set is 1 km. For comparison, to evaluate what happens if this carbon threshold would be reduced to a lower number, also three other carbon stock limits were applied using this data-set. The values used are a carbon stock lower than 25 t C/ha, lower than 15 t C/ha, and lower than 5 t C/ha.

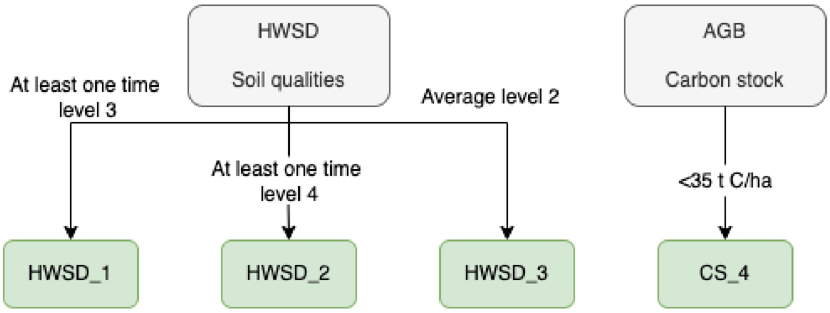


Figure 4.2: Schematic overview of the proposed degraded land scenarios

Figure 4.8 gives a schematic overview of the four scenarios that will be used to find the degraded land locations. As can be seen in the figure, the first three scenarios follow from the HWSD data-set, for each scenario this data-set is filtered using different criteria. These scenarios are based on soil quality parameters, which can also be used to assess soil erosion. This proved to be a good measurement criteria to assess degraded land, as mentioned in Section 2.3 (Sulistyo et al., 2017; Narendra et al., 2019). The fourth scenario results from the AGB data-set, in this scenario the data is filtered by the carbon stock threshold of 35 t C/ha.

4.1.2. Step 2: Ecological and peat constraints

For the second step, multiple data-sets are used. In this step legally protected areas, peat lands, and key biodiversity areas, including the added buffers, are removed from the degraded land areas. The data-sets used are explained below.

First, the legal classification layer, developed by the Indonesian Ministry of Forestry, is added to the QGIS analysis to be able to eliminate areas that are legally classified as protected areas. The layer shows the protection status of the land (Global Forest Watch, 2019). The total area of this layer is 48,878 km^2. A buffer of 1000m was added to these locations to ensure the protection of these areas (Dauber et al., 2012). Land covers that are classified as protected according to this data-set can be found in Appendix B.

The second data-set concerning protected areas is part of a collaboration between the UN Environment Programme and the International Union for Conservation of Nature (IUCN), the data-set is managed by the UN Environment Programme World Conservation Monitoring Centre (UNEP-WCMC), governments, NGOs, and international secretariats (protectedplanet.net, 2022, UNEP-WCMC and IUCN, 2020). The total area of this data-set is 30,235 km^2. Again a buffer of 1000m was added around the protected areas (Dauber et al., 2012). Land covers that are classified as protected in this data-set are also given in Appendix B. The overlapping area of the two protected area data-sets is 23,716 km^2, this shows that the legal classification layer is more elaborate in evaluating protected areas. This is due to the fact that the legal classification data also includes marine areas.

Next, the key biodiversity area layer is added to the QGIS analysis to make sure that the habitats and ecosystems of the world's threatened species are excluded from the potential plantation areas. Key biodiversity areas are globally threatened or geographically restricted ecosystems, these areas are risked to be lost because of unsustainable human activity (Key Biodiversity Areas, 2022). The total area of this layer is 33,379 km^2, again around these conservation areas a buffer of 1000m is added (Dauber et al., 2012).

Finally, the peat land data-set is added. Peat lands consists of wetlands where organic matter is accumulated faster than it is decomposed, this results in peat formation (Paavilainen and Päivänen, 1995). Similar to natural forests, peat lands contain a high level of carbon (Dauber et al., 2012; Warren et al., 2017; Petrenko et al., 2016). Since peat lands are not explicitly categorized in the land cover data-set from Section 4.1.3, this peat layer is added to the QGIS analysis to make sure peat lands are considered not suitable. From the QGIS analysis it can be concluded that the total peat land area is 149,166 km^2.

4.1.3. Step 3: Land cover constraints

In the third step the land cover data is added to the QGIS analysis. The land cover layer is separated into three different groups, based on the possibility of starting a biomass plantation in each location. The groups are ″not suitable″, ″used land″, and ″unused land″, and are connected to the degraded land layers in QGIS (Gingold et al., 2012).

The land cover data used is obtained through the Ministry of Environment and Forestry (MoEF). The MoEF published a data-set in which 22 different forms of land use are defined. Table 4.7 shows the different land covers, assigned to their suitability class. The areas of the different land cover types and the total area per suitability class are included in the table as well. For the analysis all primary and secondary dryland forest, swamp forest, and mangrove forest areas are combined in the natural forest land cover class (Boer et al., 2018). A buffer of 100m was added around water bodies since these buffers ensure the water supply (Dauber et al., 2012).

Table 4.7: Land cover (MoEF, 2017)

Suitability class	Land cover	Area [km^2]	Percentage of total land area [%]
Unused land	Shrub/bush	152,817	7
	Savannah	25,721	1
	Bare land	35,431	2
Total unused land		*213,970*	*10*
Used land	Dry agricultural	97,156	5
	Shrub mixed dry agricultural	246,099	12
	Shrub swamp	80,021	4
	Rice field	77,616	4
	Estate crop plantation	155,590	7
	Mining area	6,986	0.3
	Plantation forest	46,282	2
Total used land		*709,753*	*34*
Not suitable	Natural forest	888,866	42
	Airport/harbour	221	0.01
	Settlement area	33,166	2
	Transmigration area	2,608	0.1
	Swamp	203,491	10
	Fish pond	9,330	0.4
	Water bodies	37,697	2
Total not suitable		*1,175,382*	*56*

A separate layer was made for each possible combination of land cover and degraded land scenario, thus this step results in eight different scenarios. An overview of these scenarios can be found in Table 4.8.

Table 4.8: The eight scenarios

Scenario	Degraded land level	Land cover level
HWSD_1A	At least one level 3 or 4	Unused land
HWSD_1B	At least one level 3 or 4	Used land
HWSD_2A	At least one level 4	Unused land
HWSD_2B	At least one level 4	Used land
HWSD_3A	Average higher than 2	Unused land
HWSD_3B	Average higher than 2	Used land
CS_4A	Carbon stock lower than 35 t C/ha	Unused land
CS_4B	Carbon stock lower than 35 t C/ha	Used land

4.1.4. Step 4: Techno-economic constraints

In the final step, the economic constraints are added to all eight scenarios. First, the elevation and slope of the degraded land areas are evaluated. Slope and elevation are added to the analysis since these factors put feasibility and economic constraints on the location of the bamboo plantation (Pertiwi et al., 2021; Dauber et al., 2012). In different studies bamboo is grown on altitudes varying from 400m - 1700m, 0m - 1647m, 900m - 1200m above sea level (Nazir et al., 2019; Utami et al., 2018; Aswandi and Kholibrina, 2020). According to Kigomo (2007) most bamboo species are grown at an elevation of 1200m to 1500m above sea level. The optimal altitude to grow bamboo is between 200m and 1600m above sea level (Plantations International, 2020). Therefore, the maximum elevation taken into account in this research is 1600m above sea level. In QGIS the data-set by CGIAR-CSI (2018) was used to remove all degraded land locations above an altitude of 1600m.

Then, from the elevation data-set the slope of the land can be derived in QGIS. Steep slopes can be used to grow bamboo (van Dam et al., 2013; Madegowda et al., 2021; Devi and Singh, 2021). According to Xu et al. (2020) bamboo can grow on slopes ranging from 15°to 30°. A study done by

Pertiwi et al. (2021) indicates that it is not feasible to grow bamboo on locations that have a slope of 40°. Furthermore, Banik (2015) mentions that locations with a slope up to 30°are most optimal to grow bamboo. Therefore, in this research the slope limit is set to 30°. From the elevation data-set mentioned before, the slope can be derived in QGIS (CGIAR-CSI, 2018). All degraded land areas with a slope steeper than 30°are removed.

Next, an accessibility constraint is added to the degraded land areas suitable for bamboo production in QGIS. It is important that the harvested biomass can be transported to the nearest road. The distance from the location to the nearest road influences the (economic) feasibility of a location (Dauber et al., 2012; Zahraee et al., 2020). A minimal distance of 5 km from the plantation to the nearest road was used by Sah (2016). In two other studies a minimal distance of 2 km was applied to ensure feasible transport of the biomass to a near road (Zahraee et al., 2020; Van Holsbeeck and Srivastava, 2020). In this research a limit of 2 km is applied. The accessibility of the possible bamboo plantations is evaluated in QGIS by using a data-set containing the road network of Indonesia (OpenStreetMap, 2022). The buffer of 2 km is added to the road data-set, and all degraded land locations that do not fall within the applied road layer are removed and considered not suitable.

Finally, a size constraint is added in this step. There is a minimal area that is needed to realize a plantation. According to JiangHua and XiaoSheng (2001) medium to large scale plantations can be around 1 hectare, or expand on many square kilometers. Another study mentions that small scale plantations range from two to eight hectares, and large scale plantations are anywhere above eight hectares (NIOS, n.d.). In this research a minimal plantation size of one hectare was applied to the data. This means that all degraded land areas smaller than one hectare are removed.

4.2. Potential analysis method

The potential analysis is split up into two parts, first the technical potential of bamboo as a biomass feedstock is assessed following the method described in Section 4.2.1. Next, the economic potential is assessed following the method described in Section 4.2.2.

4.2.1. Technical potential

The method used to calculate the technical potential of bamboo for electricity generation is adapted from Kerlero De Rosbo and Bussy (2012). The equation used in this research is Equation 4.1.

$$E_i = \eta_i P_{bamboo} LHV_{bamboo} A_{plantation} (1 - Y_{moisture}) \tag{4.1}$$

In this equation E is the electricity potential for each conversion technology noted by subscript i. Then η_i is the conversion efficiency of each technology. P_{bamboo} is the productivity of the bamboo in kg/ha, and LHV_{bamboo} is the lower heating value of the bamboo in MJ/kg. Next, $A_{plantation}$ is the area of the plantation in ha. Finally, $Y_{moisture}$ is the moisture content of the bamboo.

The first step of the technical potential assessment is to calculate the available electricity potential that can be achieved by bamboo cultivation on the found degraded land areas. Then after this, the amount of land needed to supply a certain percentages of electricity demand by 2030 is calculated by turning Equation 4.1 around. When these two steps are finished, the outcomes of the two steps can be compared to each other, which shows how likely it is that a certain electricity demand percentage can be covered by bamboo conversion.

The amount of land needed to cover a certain percentage of the electricity demand can be calculated for the four different conversion technologies. The different percentages of the electricity demand cover evaluated are 25%, 50%, 75%, and 100%, this equals to 111.3 TWh, 222.6 TWh, 333.8 TWh, and 445.1 TWh, respectively.

To calculate the required area for the different demand percentages, the electricity demand is used as a first input after which the conversion efficiency, LHV, moisture content, and bamboo yield are used (Kerlero De Rosbo and Bussy, 2012). The average value of the conversion efficiencies found in

Subsections 3.5.1, 3.5.2, 3.5.3, 3.5.4 is used in this calculation for each conversion technology.

In Section 3.2, it was decided that G Apus would be the most suitable bamboo species for electricity conversion. Thus the LHV and moisture content of this species will be used in these calculations. Furthermore, a yield estimation for bamboo on degraded land was done in Section 3.3, the yield of 26,500 kg/ha is used in the potential calculation. Table 4.9 shows the assumed values used to calculate the technical potential for combustion, gasification, and pyrolysis.

Parameter	Value	Unit
$\eta_{combustion}$	20	%
$\eta_{gasification}$	27.5	%
$\eta_{pyrolysis}$	10	%
LHV_{GApus}	15.88	MJ/kg
$Y_{moisture}$	7.3	%
P_{bamboo}	26,500	kg/ha
$A_{plantation}$	128 - 245,729	km^2

Table 4.9: Technical potential assumptions

4.2.2. Economic potential

To estimate the economic potential of a renewable energy technology, the levelized cost of electricity (LCOE) can be used. The LCOE is the ratio of the total costs to the total electricity generation over the entire lifetime, corrected with the discount rate (Baruah and Baruah, 2021). Equation 4.2 shows how the LCOE is calculated.

$$LCOE = \frac{\sum_{t=0}^{n} \frac{I_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{E_t c_f}{(1+r)^t}} \tag{4.2}$$

In this equation I_t is the initial investment, $O\&M_t$ is the annual cost of operation and maintenance, F_t is the annual fuel cost, E_t is the annual electricity production, and r is the discount rate. The subscript t means that the amounts may vary over the years (Blok and Nieuwlaar, 2021).

Table 4.10: LCOE assumptions

Parameter	Value	Unit	Reference
Investment costs (I_t)			
Gasification	1500	US$/kW	You et al., 2017
Combustion	1591	US$/kW	Fan et al., 2019
Pyrolysis	10,000	US$/kW	Ahmadi et al., 2020
Anaerobic digestion	4339	US$/kW	Hadidi and Omer, 2017
Fixed O&M costs ($O\&M_{t_{fixed}}$)			
Gasification	60	US$/kW	IRENA, 2020
Combustion	50	US$/kW	IRENA, 2018
Pyrolysis	400	US$/kW	IRENA, 2020
Anaerobic digestion	115	US$/kW	IRENA, 2018
Variable O&M costs ($O\&M_{t_{variable}}$)			
Gasification	0.005	US$/kWh	IRENA, 2020
Combustion	0.0045	US$/kWh	IRENA, 2018
Pyrolysis	0.005	US$/kWh	IRENA, 2020
Anaerobic digestion	0.0044	US$/kWh	IRENA, 2018
Other costs			
(independent of conversion technology)			
Fixed transport costs	2.91	US$/tonne	Agbor et al., 2016
Variable transport costs	0.0326	US$/tonne/km	Agbor et al., 2016
Harvesting costs	9.37	US$/tonne	B. Patel et al., 2019
Cultivation costs	1293	US$/ha	B. Patel et al., 2019
Capacity factor (c_f)	90	%	IRENA, 2020
Discount rate (r)	10	%	Blok and Nieuwlaar, 2021
Lifetime (t)	25	years	Agbor et al., 2016

Table 4.10 shows the assumed values to calculate the LCOE for the different conversion technologies. When assuming the gasification process will go following the steps explained in Section 3.5.2, a fixed bed gasifier will be used. The investment costs for this electricity conversion technology are between the 2140-5700 US$/kW (IRENA, 2012). However, from experience of a biomass gasification plant in combination with a gas engine in Indonesia, it was found that the investment cost was 600 US$/kW (Sulistyo et al., 2017). A similar study done in Indonesia gives an investment cost of 1500 US$/kW, when the same technology is used (You et al., 2017). Since the difference between these reference values is significant, in this research the value of 1500 US$/kW is used. This is chosen because this value is closer to the range of estimated investment costs by IRENA.

The operation and maintenance costs is split in fixed and variable costs. The fixed O&M costs are expressed as a percentage of the investment costs. The fixed O&M cost lay between the 2-6% of the investment cost (IRENA, 2020). In this research the average of these values, 4%, is used. The variable O&M costs are 0.005 US$/kW, 0.0045 US$/kW, and 0.0044 US$/kW for gasification and pyrolysis, combustion and anaerobic digestion power plants, respectively (IRENA, 2020).

The fuel cost is built up by different variable costs depending on the amount of land used to produce the feedstock. The fuel costs are built up by the cultivation, harvesting, and transport costs of the bamboo (Abdelhady et al., 2018). The cultivation costs are based on land preparation, plant, fertilizer, pruning, rotavator, weeding labour, electricity, and organic manure costs (B. Patel et al., 2019). The transport costs are again built up by a fixed and a variable value depending on the distance from the plantation to the power plant (Agbor et al., 2016). So, the fuel cost is the sum of the fixed and variable transport costs, harvesting costs, and cultivation costs shown in Table 4.10.

The capacity factor is the ratio between the electricity that a power plant annually produces to the amount of electricity that the plant theoretically could produce in case it would be running at full capacity for the entire year (Naqvi et al., 2017). Usually the capacity factor of biomass power plants lays around the 85-95% (IRENA, 2020; Ramlan and Alif, 2021). In this research the value of 90% is used.

The discount rate used is based on a social discount rate for developing countries, it is estimated to lay between the 10-12% (Blok and Nieuwlaar, 2021). In literature the value of 10% is mostly used, therefore this value is used in this research as well (Langer et al., 2021; You et al., 2017). Finally, the lifetime of the power plant is based on similar studies using gasification power plants (Abdelhady et al., 2018; Agbor et al., 2016; You et al., 2017).

5
Results QGIS analysis

The results from the method described in Chapter 4 are given in this chapter. First, the degraded land locations as well as the total degraded land area are given in Section 5.1. The current land covers of the degraded land areas area discussed in Section 5.2. Then, the locations that are suitable for a bamboo plantation are shown in Section 5.3. For all scenarios maps, areas, and land cover percentages are included.

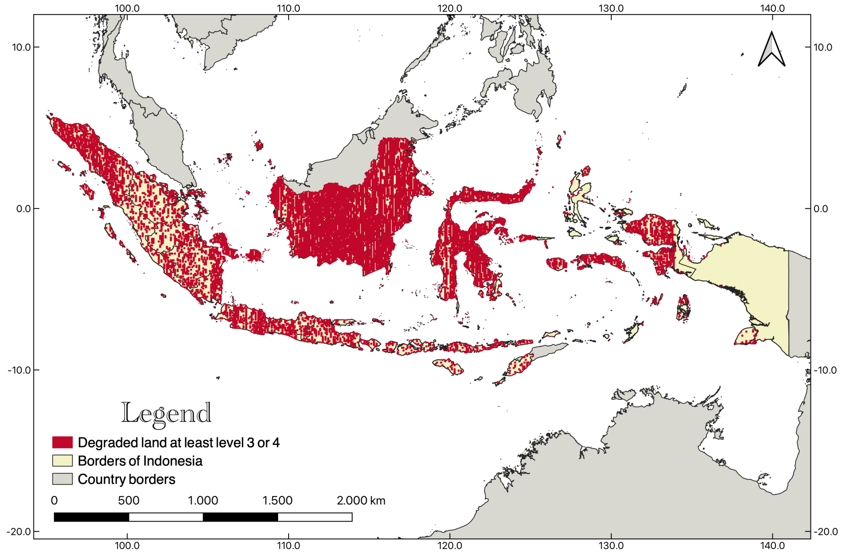
5.1. Degraded land

After the first step described in Section 4.1.1, the degraded land locations in Indonesia are found. The degraded land locations per scenario (as mentioned in Table 4.8) are shown in Figures 5.1 and 5.2, the figures are based on the HWSD data-set (HWSD_1, HWSD_2, HWSD_3) and the AGB data-set (CS_4), respectively. The areas of the degraded land for each scenario as well as the percentages of Indonesia's total land area (1,826,440 km^2) are shown in Table 5.1. In general, most degraded land is found in the east of Indonesia. Sumatra contains many degraded land locations, and only few degraded land locations are found on Papua. This might be due to the different land covers and population densities on the islands.

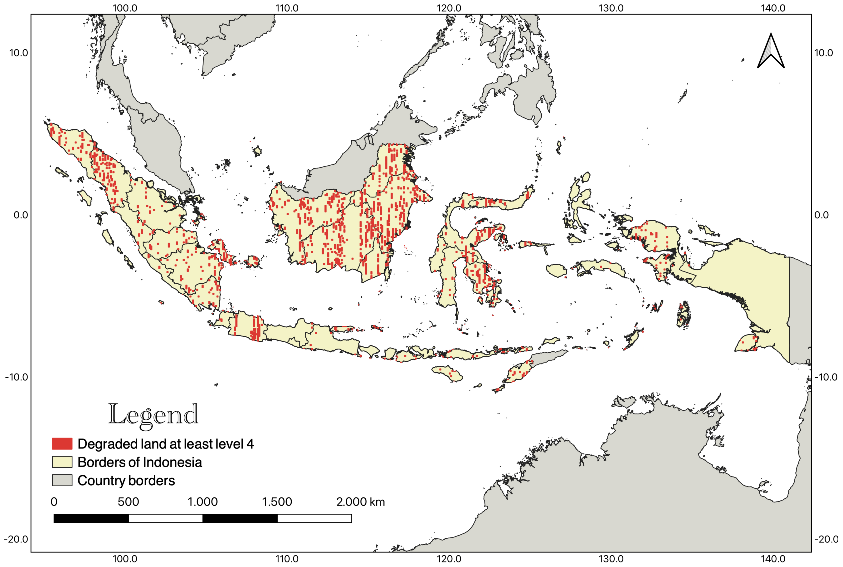
When analysing Figure 5.1, it becomes clear that the degraded land area decreases when going from scenario HWSD_1 to HWSD_3. First, looking at Figure 5.1a, it can be seen that degraded land areas are spread almost equally over the entire country, except for on the island Papua. Only the west and a small part of the south of this island are considered degraded according to this scenario. The reason for this might be the large amount of natural forest (94% in the year 2000) on the island which possibly has a lower risk of becoming degraded, however the same goes for the island Kalimantan (75% in the year 2000) (globalforestwatch.org, 2022). An other possibility for the lack of degraded land on Papua would be the low population density (10 people/km^2) (dbcity, n.d.). In case the only cause of degraded land is a human cause, this island has a lower chance of being degraded because it has one of the lowest population densities of all Indonesian islands, and thus less land is utilised by the local population. An other thing that can be seen in Figure 5.1a is that the highest density of degraded land can be found on the islands Kalimantan and Sulawesi. The islands Sumatra and Java have a large degraded land area as well, however the density of degraded land area is a little lower compared to Kalimantan and Sulawesi. This might be due to different land uses, which have a lower change of becoming degraded.

Looking at Figure 5.1b, it clearly shows that fewer locations are considered to be degraded according to this scenario (HWSD_2), compared to scenario HWSD_1. The density of the degraded land areas is almost equal on all the islands and decreases equally compared to scenario HWSD_1. The only difference in the way that the degraded areas are spread over the country is that fewer locations are found on Java, here the amount of degraded land areas decreases more than on the other islands when going from scenario HWSD_1 to HWSD_2. According to Figure 5.1b Sumatra and Kalimantan can be considered the most degraded islands.

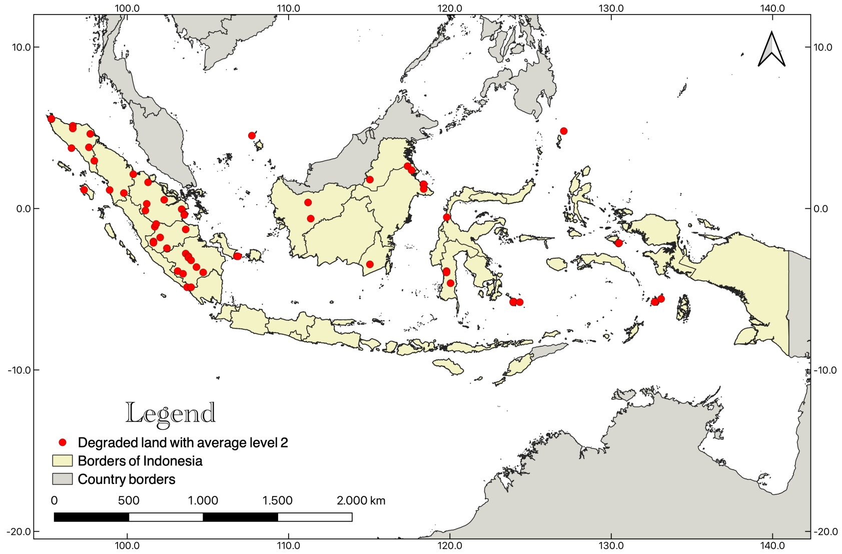
Finally, in Figure 5.1c, only a few degraded land locations remain. In this figure the areas are represented by dots to increase visibility, the dots do not represent the actual size of the degraded land areas. In this scenario, no degraded land areas on Java or Papua remain. The amount of degraded land areas on Kalimantan and Sulawesi decreases significantly, and with a higher ratio than on Sumatra compared to scenario HWSD_2. The highest density of degraded land areas can be found on Sumatra according to scenario HWSD_3.



(a) Locations which score at least one level 3 or level 4 (Scenario HWSD_1)



(b) Locations which score at least one level 4 (Scenario HWSD_2)



(c) Locations which score level 2 on average (Scenario HWSD_3) (to increase visibility points are shown on the map, these points do not represent the size of the areas)

Figure 5.1: Degraded land locations scenario HWSD_1, HWSD_2, HWSD_3

Figure 5.2 shows the results of scenario CS_4. Using the carbon stock as a threshold for the degraded land gives a total area that is close to the area found in scenario HWSD_2. However, as can be seen in Figures 5.1b and 5.2, the locations of the degraded land differ from each other. In Figure 5.1b, the locations area more evenly spread over the entire islands, especially on Sumatra and Kalimantan. Also, only a few degraded land locations are found on the island Java. This is opposite to the locations found in Figure 5.2, here many degraded land locations are found on Java. And in general, the locations are more concentrated in the coastal areas of the islands Sumatra and Kalimantan. Furthermore, there is a degraded land area in the south of Papua, which is not present in Figure 5.1b.

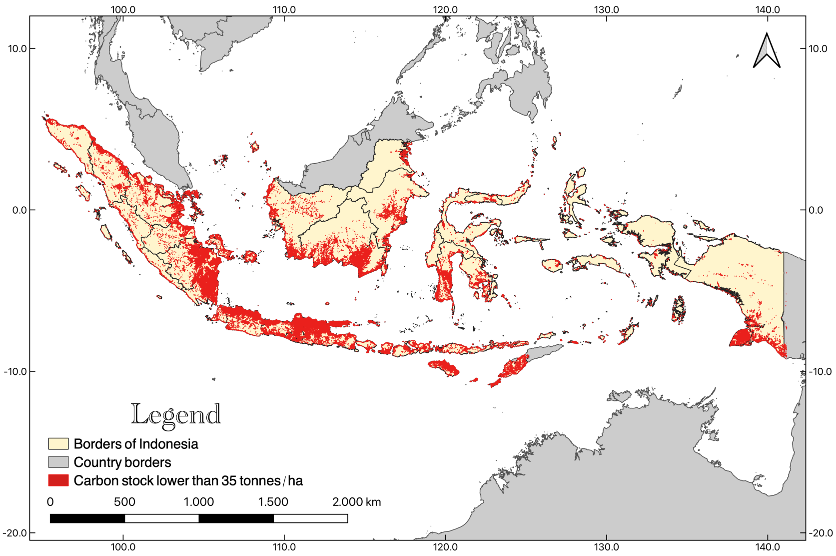


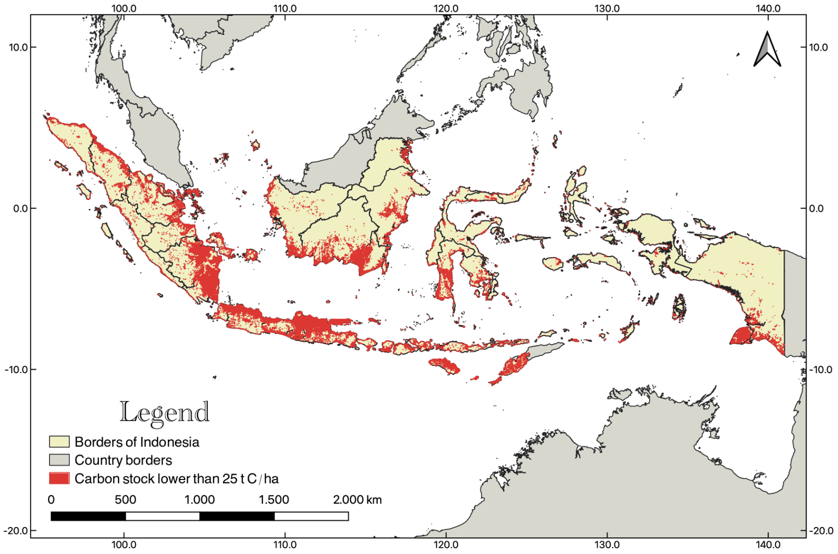
Figure 5.2: Degraded land locations scenario CS_4

As mentioned before, the degraded land areas found for the different scenarios are shown in Table 5.1. In Chapter 2 is was mentioned that the degraded land area in Indonesia ranges between 12 and 74 million ha (120,000 and 740,000 km^2) according to IRENA, and is equal to 24.5 million ha (245,000 km^2) according to the UNCCD (IRENA, 2017c; UNCCD, 2015). Comparing these values with the results from Table 5.1, only scenario HWSD_2 and CS_4 fall within the range from IRENA. Scenario HWSD_1 falls outside of the range, which means that not enough degraded land constraints are applied to this scenario. While on the other hand, the selection criteria for scenario HWSD_3 are too strict, since this scenario also falls outside of the range proposed by IRENA.

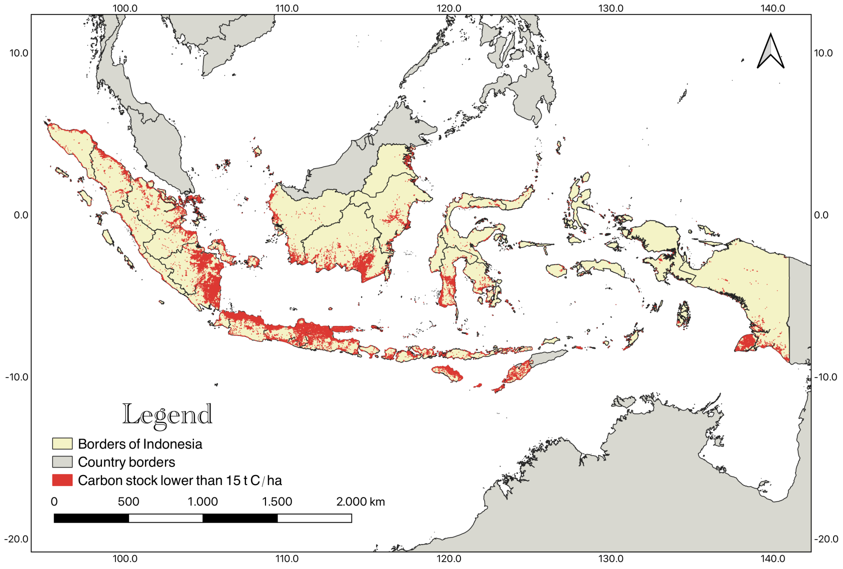
Table 5.1: Degraded land area per scenario

Scenario	**Area [km^2]**	**Percentage of Indonesia's total land area [%]**
HWSD_1	910,604	49.9
HWSD_2	138,484	7.6
HWSD_3	3,804	0.21
CS_4	143,724	7.9

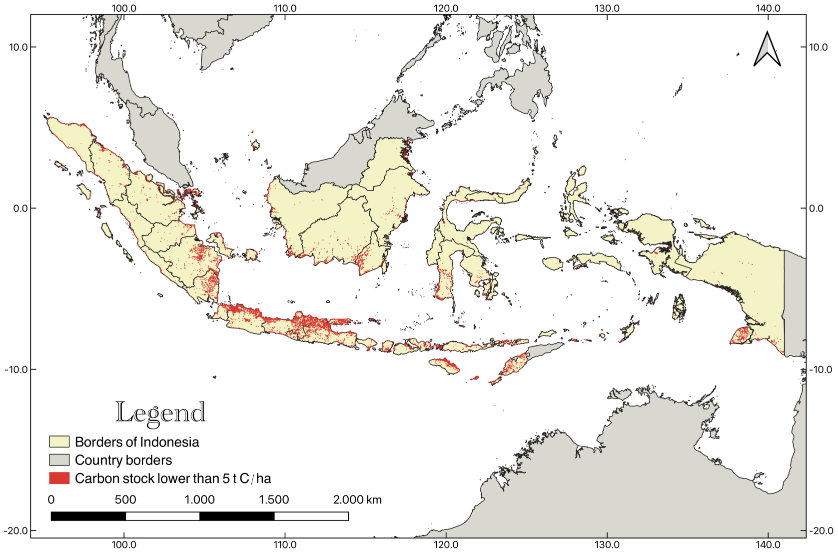
To see what would happen to the degraded land area of scenario CS_4 if the carbon threshold of 35 t C/ha would change, three different carbon stock limits were applied to the data-set. These limits are a carbon stock lower than 25 t C/ha, 15 t C/ha, and 5 t C/ha. The results of this analysis are shown in Figure 5.3. The areas that remain after changing the carbon stock limit are 104,241 km^2 (5.7% of the total land area), 52,207 km^2 (2.8% of the total land area), and 14,079 km^2 (0.77% of the total land area), when going from 25 t C/ha, to 15 t C/ha, to 5 t C/ha, respectively.



(a) Locations with a carbon stock lower than 25 t C/ha



(b) Locations with a carbon stock lower than 15 t C/ha



(c) Locations with a carbon stock lower than 5 t C/ha

Figure 5.3: Extra carbon stock thresholds (5, 15, 25 t C/ha)

Figure 5.3 shows the locations which have a carbon stock lower than 25, 15, 5 t C/ha. When looking at how the location of the areas changes when reducing the carbon stock threshold, it becomes clear that the lower the threshold the more the locations are concentrated in the coastal areas. Locations more inland of the islands disappear. This might be because of the different land covers that can be found near the coasts of the islands. For example, settlement areas, which contain lower carbon stocks, are usually located near the coast because of the better accessibility (Saito and Prasetyo, 1999). In general, cultivated areas contain lower carbon stocks than uncultivated land areas (Saito and Prasetyo, 1999), this would mean that when following the definition that land is degraded when it contains a carbon stock lower than 35 t C/ha, the main cause of land degradation would be a human cause. This would also explain why significantly more degraded land locations remain on Java, compared with the other islands. However, also the locations in the south of Papua remain, while in Figure 5.1, these were not considered degraded. This contradicts the human cause of land degradation, since Papua has a low population density. The locations remaining in Papua can be explained by land covers that naturally contain low carbon stocks, like bush and shrub (Vinanthi and Sulistioadi, 2021).

Table 5.2: Overlapping percentage between HWSD_1, HWSD_2, HWSD_3 and carbon stock (cs) lower than 35, 25, 15, 5 t C/ha

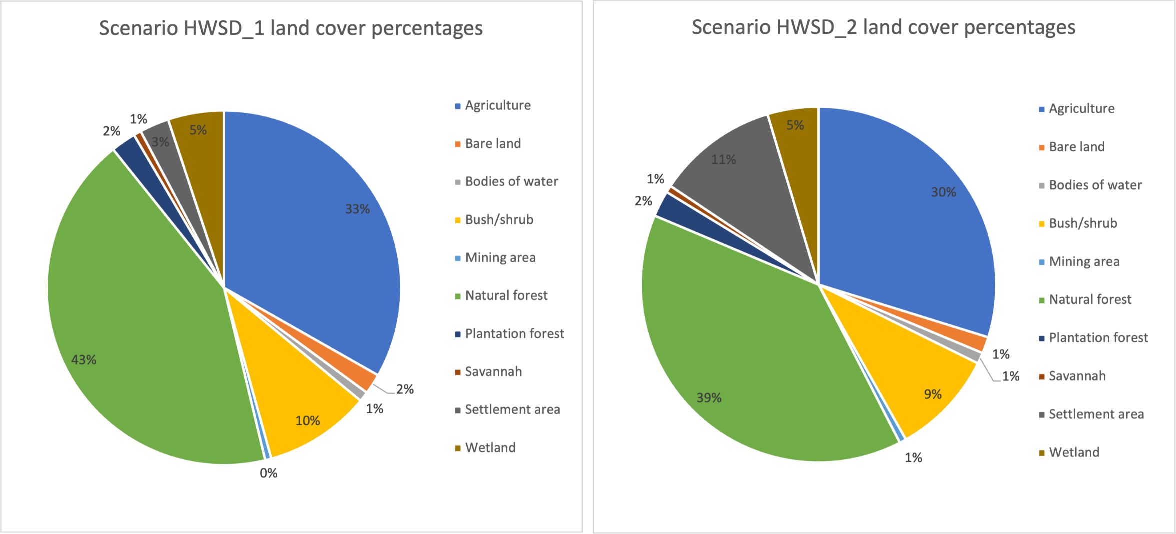
Scenarios	**CS <35 t C/ha (CS_4)**	**CS <25 t C/ha**	**CS <15 t C/ha**	**CS <5 t C/ha**
HWSD_1	7.5%	5.5%	2.7%	0.70%
HWSD_2	7.6%	5.5%	2.8%	0.75%
HWSD_3	7.3%	4.8%	2.4%	0.91%

Table 5.2 shows the percentage in which the degraded land areas from the HWSD data-set (HWSD_1, HWSD_2, HWSD_3) overlap with the degraded land area resulting from the AGB data-set (CS_4 and CS < 25, 15, 5 t C/ha). First, when looking at the overlap between CS_4 and HWSD_1, HWSD_2, and HWSD_3, it shows that the total overlapping area is decreasing (from 68,450 km^2 to 278 km^2), due to the fact that the degraded land area decreases going from scenario HWSD_1 to scenario HWSD_3 (as shown in Table 5.1). What is remarkable is that the overlapping percentage of the areas from the first three scenarios with scenario CS_4 remains almost equal. For scenario HWSD_1, HWSD_2, and HWSD_3, around 7.5% of the degraded land area contains less than 35 tonnes of C/ha.

However, since it was found that 7.9% of the total land area contains less than 35 t C/ha, it could be a coincidence that this value is almost equal to the overlapping percentages with the HWSD scenarios. It is possible that from any observed area around 7% would contain less than 35 t C/ha. The same goes for the overlap of the HWSD scenarios with the lower carbon stock thresholds. The percentage of overlapping area is similar to the percentage of Indonesia's total land area that contains a carbon stock lower than 25, 15, and 5 t C/ha. So, again it is possible that from any observed area around 5%, 3%, and 0.7% contains a carbon stock lower than 25, 15, and 5 t C/ha, respectively. This means that there might not be any correlation between the carbon stock data-set and the HWSD data-set.

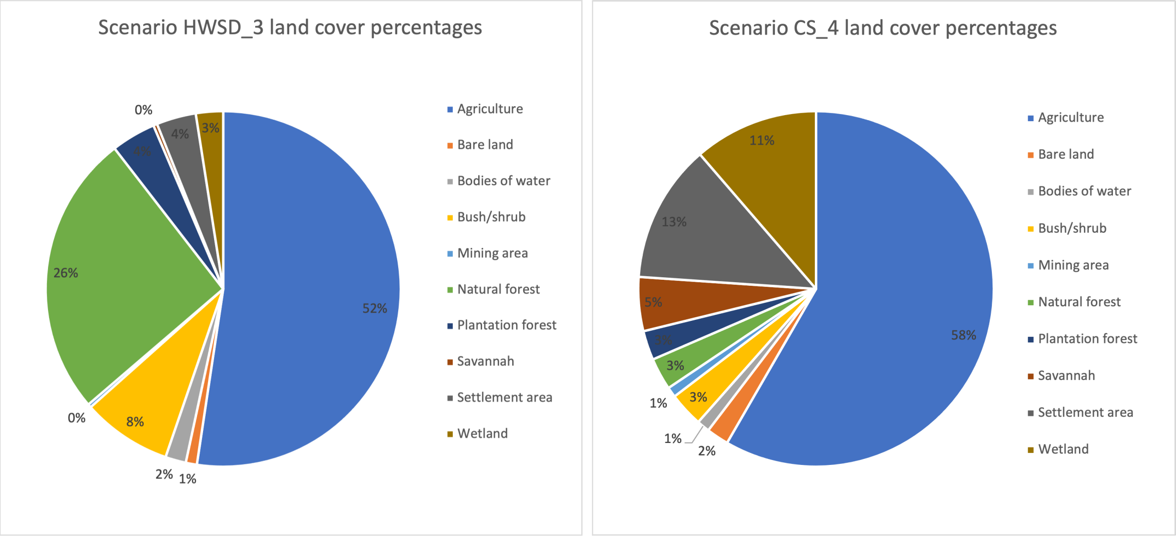
5.2. Current land cover of the degraded land areas

Now that the locations of the degraded land found through the different scenarios is known, the current land covers of these areas can be evaluated. Figure 5.4 shows the percentages of each land cover, from the data-set mentioned in Section 4.1.2, for the four scenarios. For each scenario the land covers are displayed in a pie-chart. To improve the visibility, the 22 land covers coming from the data-set have been grouped together. First, all primary and secondary dryland forest, swamp forest, and mangrove forest areas are combined in the natural forest land cover class, as was also done in Section 4.1.3. Then all agricultural land covers: dry agricultural, shrub mixed dry agricultural, rice field, estate crop plantation, and fish pond are grouped together under agriculture. Next, settlement area includes the land covers transmigration area, airport/harbour, and settlement area. Finally, swamp and swamp/shrub land covers are grouped together under the wetlands land cover in the figures.



(a) Land covers HWSD_1

(b) Land covers HWSD_2



(c) Land covers HWSD_3

(d) Land covers CS_4

Figure 5.4: Distribution of land cover types per scenario

When comparing Figures 5.4a, 5.4b, 5.4c, and 5.4d some similarities and some differences can be found. In most cases the most common degraded land land covers are natural forest and agriculture. This might be due to two possible reasons, the first being that these land covers occupy the largest area of Indonesia. Natural forest covers 42% of Indonesia, and agriculture covers 28.4% according to Table 4.7. The second possible reason is that these land covers have a higher change of becoming degraded. When looking at the definitions of degraded land, loss of biodiversity and loss of productivity are often included. So, land covers with high biodiversity and productivity levels have a higher change of losing biodiversity and productivity than land covers that do not contain high levels to begin with.

Differences are mainly found between the first three figures resulting from the HWSD scenarios (Figures 5.4a, 5.4b, 5.4c) and Figure 5.4d resulting from the CS scenario. In Figure 5.4d, natural forest covers less degraded land area, and more is covered by wetland, settlement area, savannah, and bush/shrub land covers compared to Figures 5.4a, 5.4b, 5.4c . This is due to the reason that this figure is based on the carbon stock data-set, and thus requires the degraded land areas to have a carbons stock lower than 35 t C/ha.

Similar to the large percentages of natural forest and agriculture, the small percentages of mining area and in most cases, savannah, can be explained by the percentage these areas cover of Indonesia's total land area. Mining area only covers 0.3%, and savannah covers 1 % of Indonesia's total land cover according to Table 4.7. Thus the change of the degraded land matching with these areas is smaller than for areas that cover a bigger percentages of Indonesia's total land cover. That 5% of scenario CS_4 consists of savannah according to Figure 5.4d, is because of the low carbon stock (around 11 t C/ha) (Awé et al., 2021). This is below 35 t C/ha, so savannah is considered to be degraded according to scenario CS_4.

Next to evaluating the current land cover of the degraded land areas, also the percentage per land cover of degraded land area compared to the total land area can be evaluated. This evaluation is done per scenario, and the outcomes are shown in Figure 5.5. So this figure shows what percentage of each land cover is considered to be degraded according to the four different scenarios.

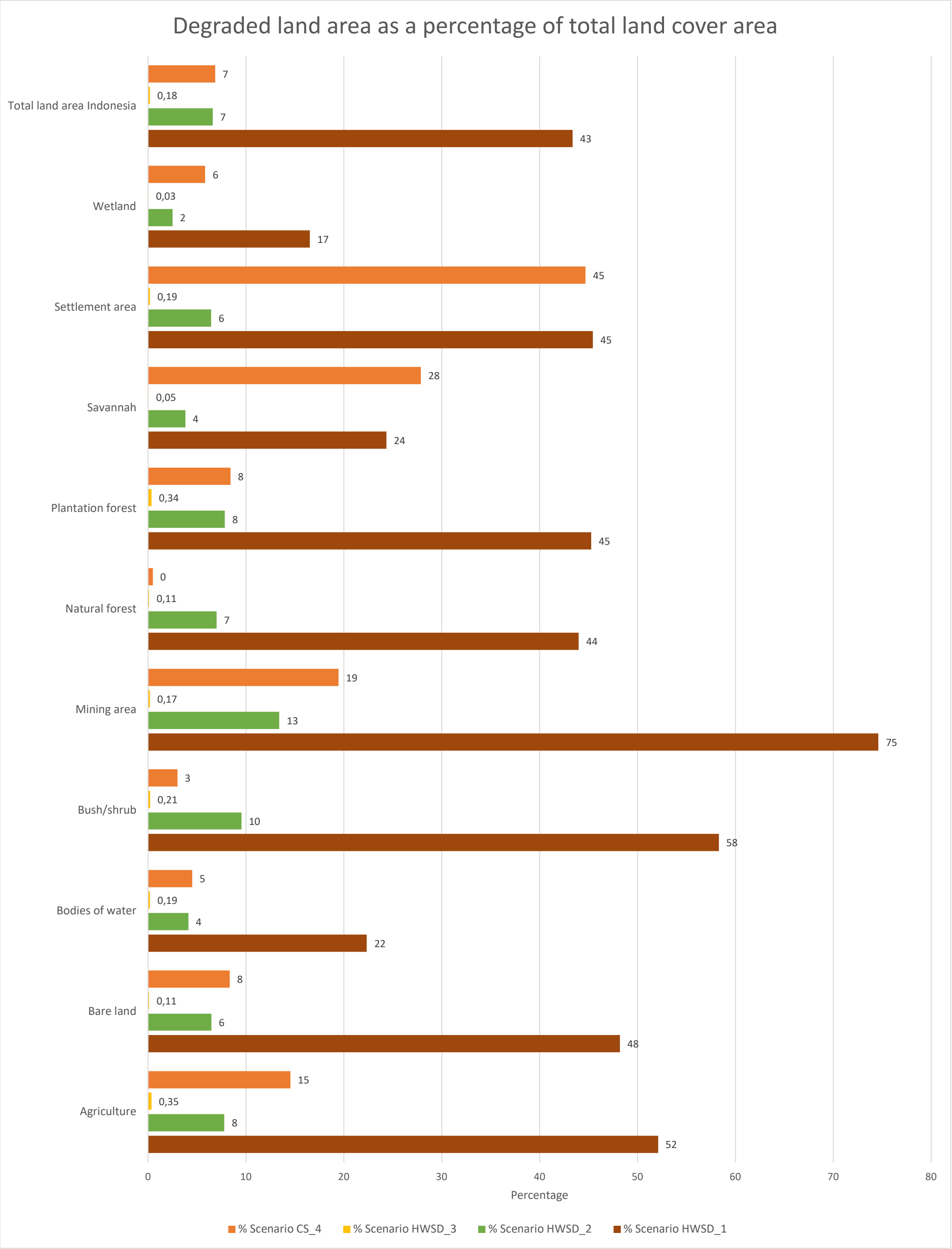


Figure 5.5: Percentage of degraded land per land cover and scenario

Again, scenario CS_4 shows some remarkable results. It would be expected that in this scenario, land covers containing less than 35 t C/ha, will be considered degraded for 100% of the land cover its total area. However, this is not the case. For example, shrub usually contains around 10 t C/ha and bare land contains around 4 t C/ha, while according to scenario 4 only 2.99% and 8.34% of the land covers are considered to contain less than 35 t C/ha, respectively (Vinanthi and Sulistioadi, 2021). And even though the degraded savannah percentages is significantly higher than the percentages for shrub and bare land, the same applies to this land cover. Savannah has a carbon stock of around 11 t C/ha, but still only 28% of this land cover is considered degraded where it would be expected that 100% of the land cover would be degraded. A possible explanation for the this might be the different years in which the data-sets were constructed. Some land cover changes might have occurred between 2016 and 2017, the years in which the AGB data-set and the land cover data-set were constructed, respectively (Avitabile et al., 2016; MoEF, 2017).

5.3. Degraded land suitable for bamboo plantations

After completing all the steps described in Sections 4.1.2, 4.1.3, and 4.1.4, the suitable locations for bamboo plantations on degraded land are found. In this section the locations for each scenario are displayed in Figures 5.6, 5.7, 5.8, and 5.9. Table 5.3 gives an overview of the total plantation area for each scenario.

Table 5.3: Degraded land area suitable for plantations per scenario (scenarios A on unused land, scenarios B on used land)

Scenario	**Area [km^2]**	**Percentage of Indonesia's total land cover [%]**
HWSD_1A	49,999	3
HWSD_2A	10,004	1
HWSD_3A	128	0.01
CS_4A	8,314	0.4
HWSD_1B	245,729	13
HWSD_2B	38,973	2
HWSD_3B	1,471	0.08
CS_4B	79,771	4

From the figures as well as the table showing the areas of the scenarios, it becomes clear that scenario HWSD_1B, HWSD_2B, HWSD_3B, and CS_4B provide a bigger opportunity for plantations than the other four scenarios. This is because these scenarios represent the used land cover, which has an area of almost three times the size of the unused land cover as can be seen in Table 4.7. However, when opting for these scenarios there will be competition with other land uses, like agriculture. This means that the actual potential resulting from these scenarios might be lower in reality. Also, changing this land to bamboo production might result in unwanted land use change elsewhere.

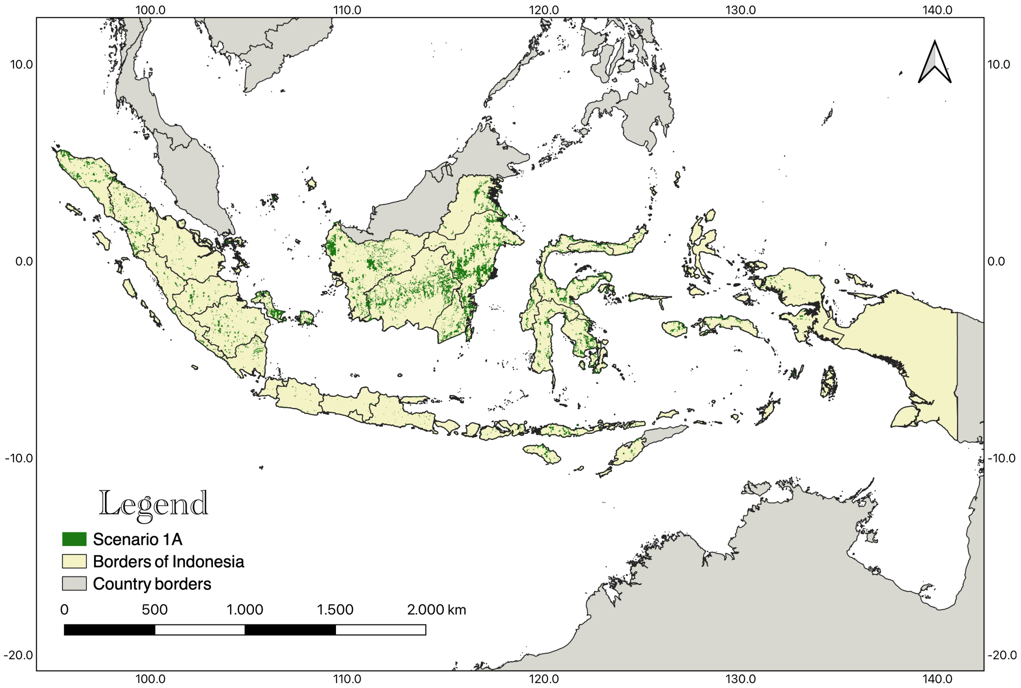
What clearly shows in all Figures 5.6 until 5.9 , on the next pages, is that going from the B scenarios to the A scenarios all locations on the island of Java disappear. This can be explained by looking at the land use on this island. Around 57% of Indonesia's total population lives on Java, so the island is very densely populated (World Population Review, 2012). There is no unused land, which might be suitable for a bamboo plantation, remaining on the island.

The main difference between Figures 5.6, 5.7, 5.8 and Figure 5.9 is the suitable locations on the most eastern island of Indonesia, Papua. This island is mostly covered by natural forest, and thus considered not suitable for bamboo plantations. However, in the south of the island there are some locations with the bush/shrub land cover, that are considered to be degraded according to scenario CS_4. According to the other scenarios these locations are not degraded.

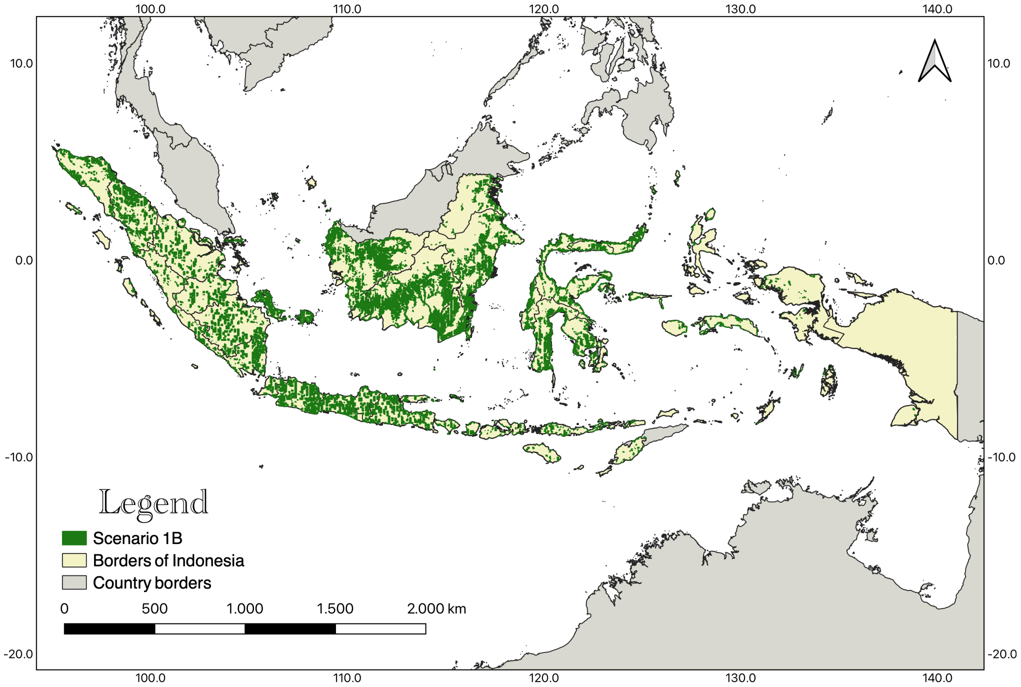
Looking at the distribution of the suitable degraded land areas over all Indonesia's islands, the figures show that the locations are quite evenly spread. However there seem to be more suitable locations in the west of Indonesia than in the east. What is remarkable, is that when looking at Figure 5.8, more locations lay on Sumatra then on Kalimantan, while in the other figures this is not the case. This implies that the degraded land on Sumatra matches with the more strict requirements of scenario HWSD_3.

The majority of the suitable degraded land locations can be found on Sumatra and Kalimantan. However, because of the high population density on Java mentioned before, the highest electricity demand comes from the Java-Bali system (Faizal et al., 2015). An option would be to transport the raw biomass from Sumatra to Java/Bali by boat, and then convert it into electricity there. However, this would increase the transportation costs and thus might not be beneficial. Another option would be to transfer the electricity through a high voltage direct current (HVDC) system connecting the two islands (Faizal et al., 2015). However, this will result in transmission losses as well as extra costs. Due to these complications, other renewable energy sources, like rooftop solar PV, or geothermal might be more applicable for renewable energy generation on Java and Bali.

The most suitable application for electricity generation using bamboo plantations on degraded land might be off-grid systems in remote areas. This would increase the electrification ratio in Indonesia since these remote areas currently are not connected to the grid. Also, the locals could work on the plantations, and in the power plant which would create jobs.

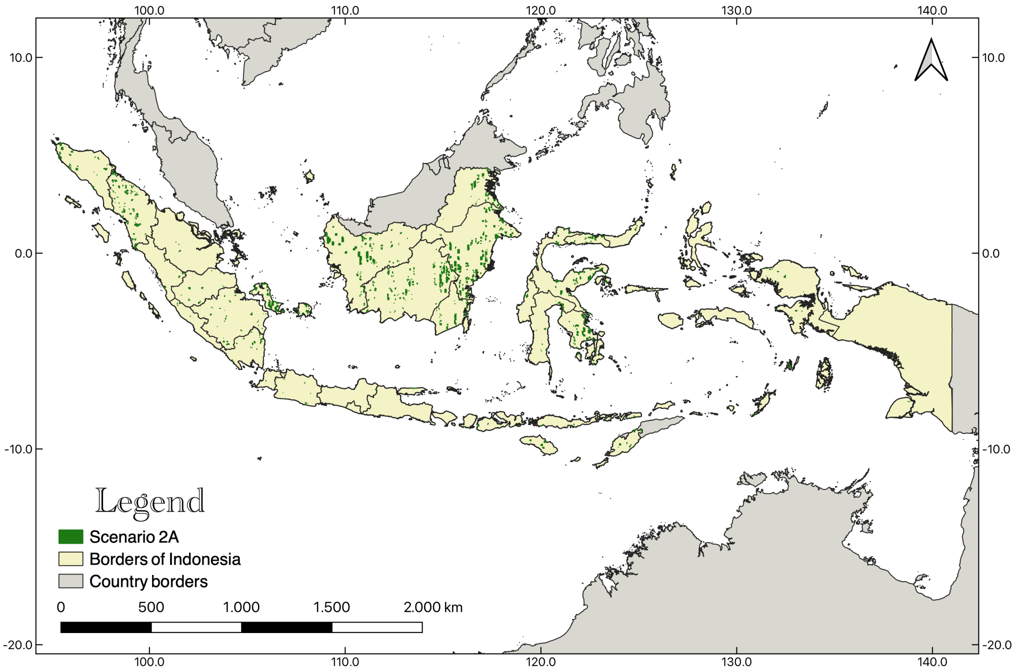


(a) Scenario HWSD_1A

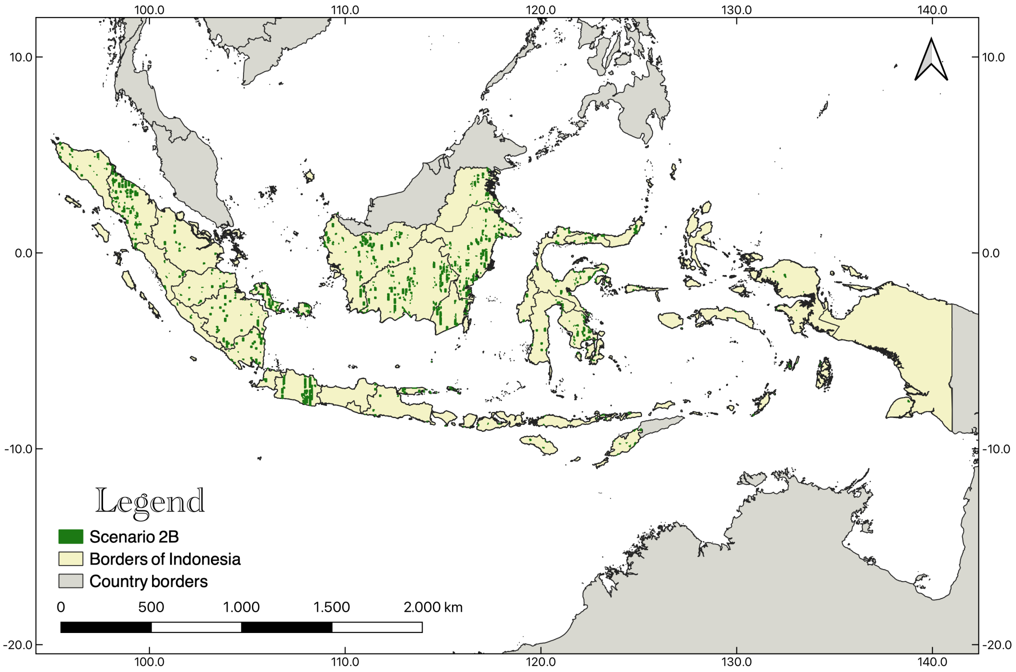


(b) Scenario HWSD_1B

Figure 5.6: Locations suitable for bamboo plantations according to scenario HWSD_1

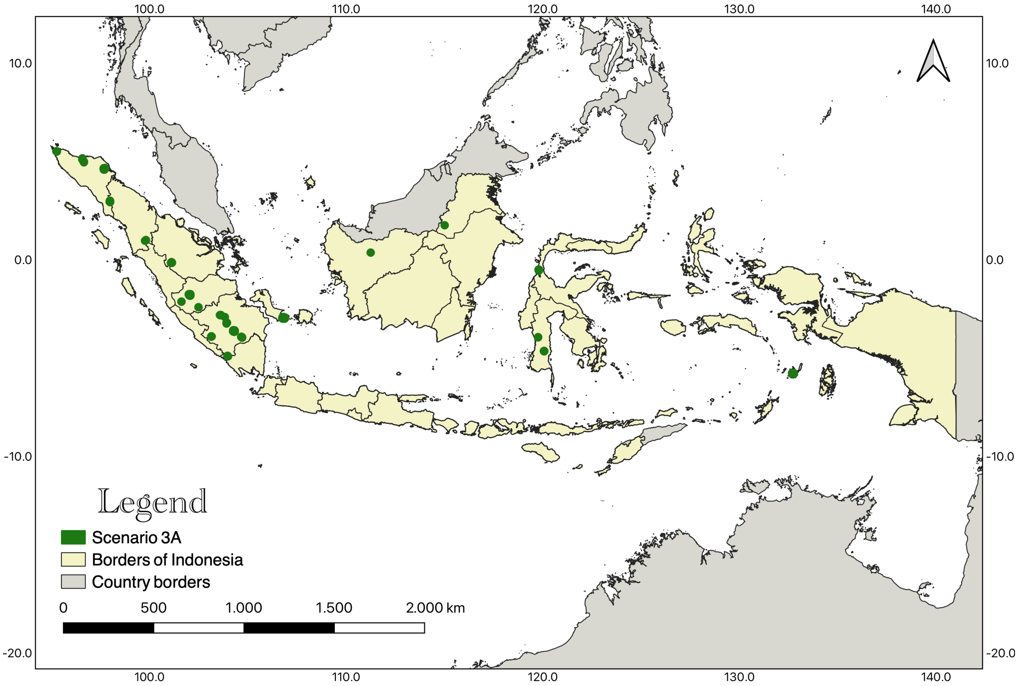


(a) Scenario HWSD_2A

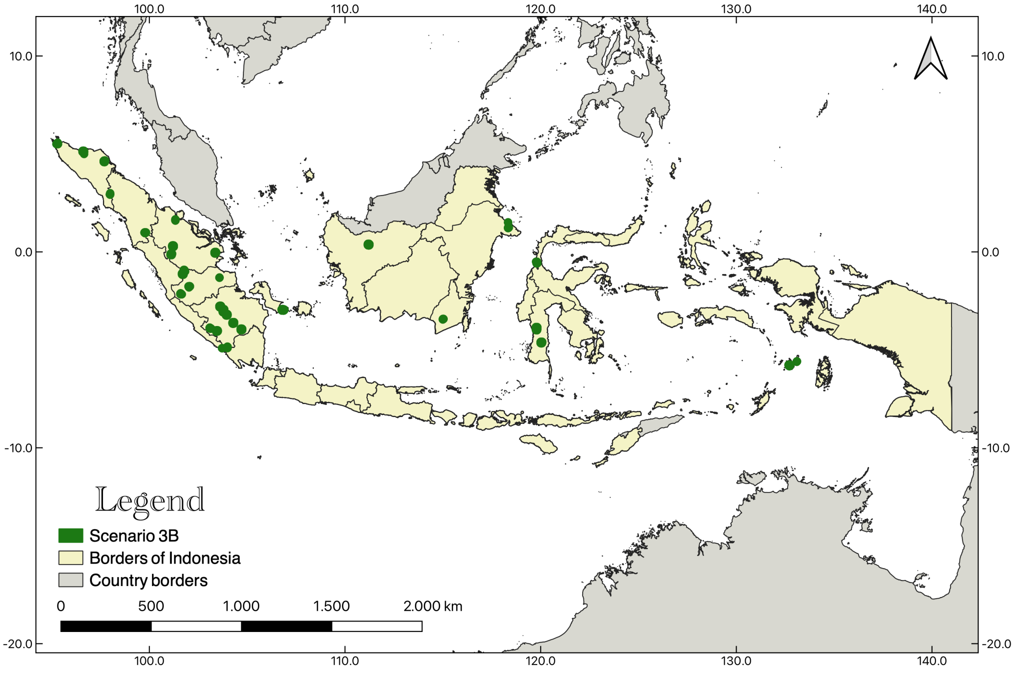


(b) Scenario HWSD_2B

Figure 5.7: Locations suitable for bamboo plantations according to scenario HWSD_2

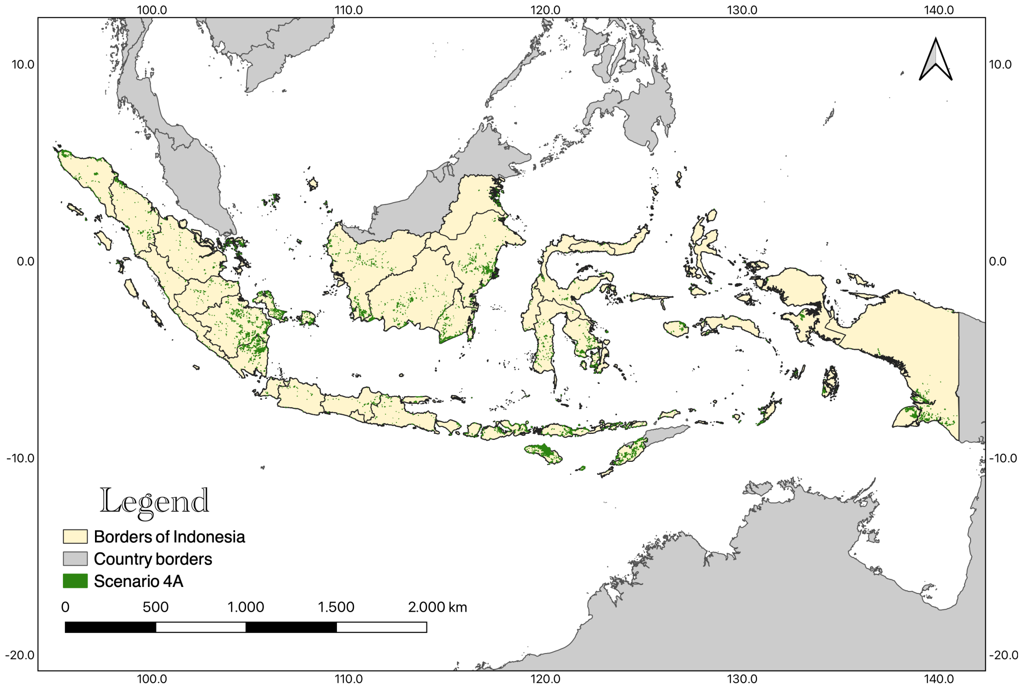


(a) Scenario HWSD_3A

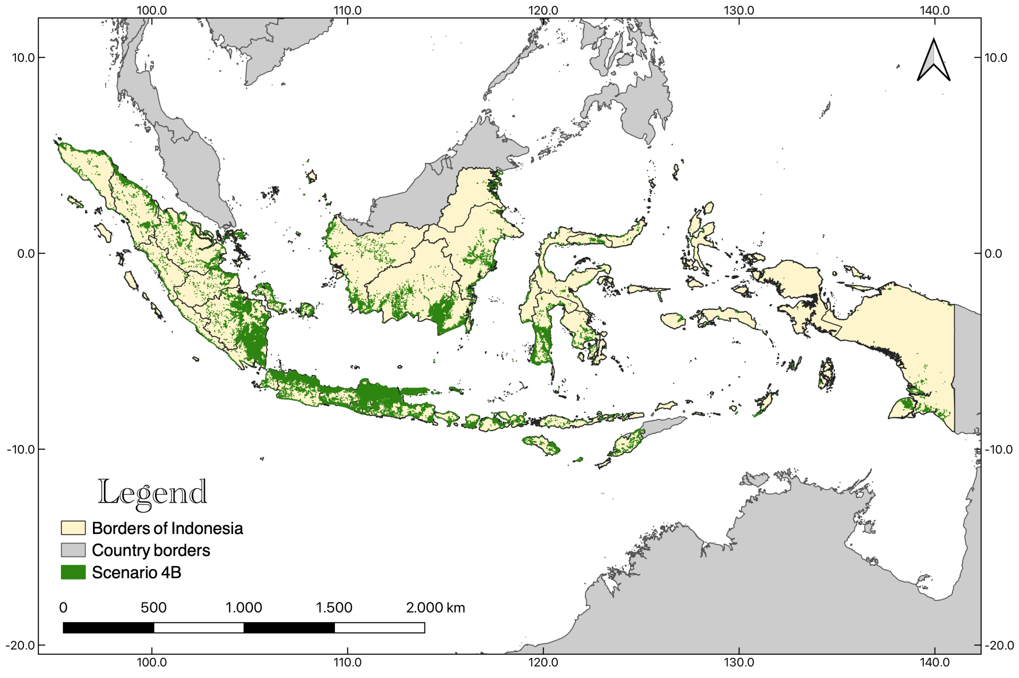


(b) Scenario HWSD_3B

Figure 5.8: Locations suitable for bamboo plantations according to scenario HWSD_3



(a) Scenario CS_4A



(b) Scenario CS_4B

Figure 5.9: Locations suitable for bamboo plantations according to scenario CS_4

To find out what would happen if the degraded land requirement would not be applied anymore, also the suitable locations when only focusing on unused land are mapped. The result of this is shown in Figure 5.10. The land covers used are savannah, bare land, or bush/shrub locations to which Steps 3 and 4, described in Subsections 4.1.3 and 4.1.4, have been applied. The suitable area for bamboo plantations found is 13,245 km^2 which is equal to 0.73 % of Indonesia's total area. This is close to the result found for scenario HWSD_2A, however comparing Figures 5.7a and 5.10 some differences in location are found. In scenario HWSD_2A, fewer suitable locations are found on Papua, and the suitable locations are mostly concentrated on Sumatra, Kalimantan and Sulawesi. While the unused land figure shows a more even distribution of the suitable locations. The possible electricity that can be converted by using only unused land locations will be approximately equal to the electricity generated when following scenario HWSD_2A.

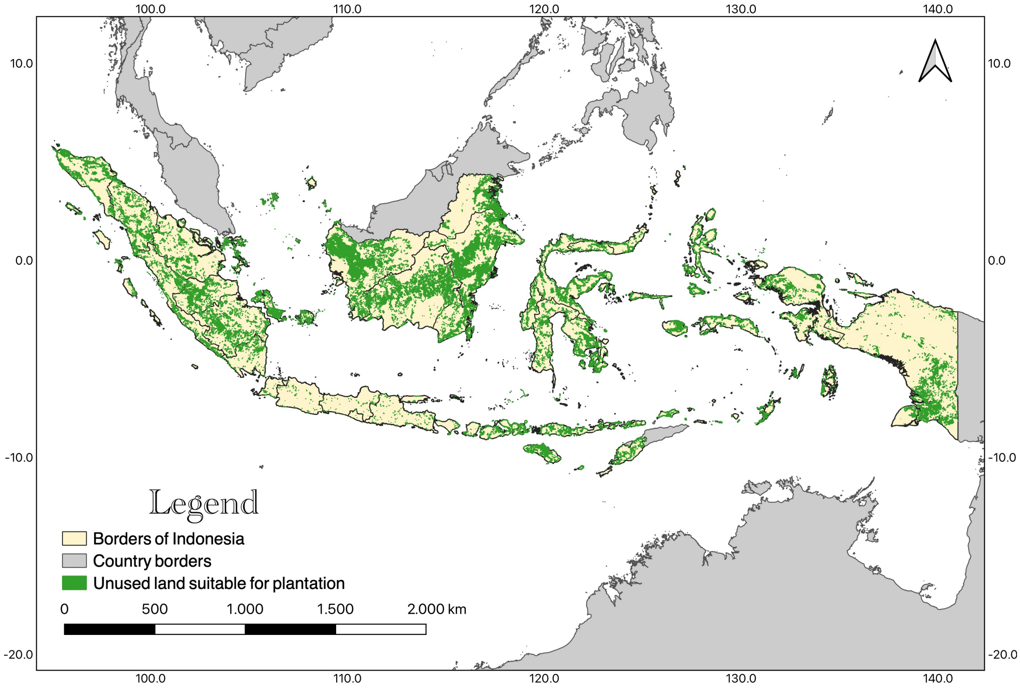


Figure 5.10: Unused land areas suitable for bamboo plantations

6

Results potential analysis

In this chapter the potential of bamboo as a biomass feedstock is evaluated. First, in Section 6.1, the technical potential of bamboo conversion is calculated for different conversion technologies. After this the area needed to cover a certain percentage of this electricity demand is evaluated in Section 6.2. The economic potential is calculated in Section 6.3 by calculating the levelized cost of electricity. Finally, a comparison between the required degraded land area and available technical potential is done is Section 6.4.

6.1. Technical potential

The results from the calculation described in Section 4.2.1, are shown below in Table 6.1.

Table 6.1: Technical potential per conversion technology and scenario

Scenario	**Potential per conversion technology [TWh]**			
	Combustion	Gasification	Pyrolysis	Anaerobic digestion
HWSD_1A	108	149	54	103
HWSD_1B	533	732	266	506
HWSD_2A	22	30	11	21
HWSD_2B	84	116	42	80
HWSD_3A	0.3	0.4	0.1	0.3
HWSD_3B	3	4	2	3
CS_4A	18	25	9	17
CS_4B	173	238	86	164

From these results, it becomes clear that the potential strongly depends on how much land degraded land is available for bamboo plantations. The range of potentials varies by a factor of a 1000. This means that it is important that there is a clear definition about what degraded land is. These results will be further evaluated and compared to the electricity demand in Section 6.4.

6.2. Plantation area required to meet Indonesia's electricity demand by 2030

To assess the plantation area that is needed to meet a certain percentage of Indonesia's electricity demand, first the electricity demand needs to be determined. As mentioned in Subsection 4.2.1, the different percentages of the electricity demand cover evaluated are 25%, 50%, 75%, and 100%, this equals to 111.3 TWh, 222.6 TWh, 333.8 TWh, and 445.1 TWh, respectively. The results show different land areas needed to cover the electricity demand, for each conversion technology. The areas with their matching percentages of Indonesia's total land cover are shown in Table 6.2. These results will be further discussed in Section 6.4.

Table 6.2: Areas required for 50%, 75%, and 100% electricity demand coverage

Percentage of electricity demand covered	**Conversion technology**				**Unit**
	Combustion	Gasification	Pyrolysis	Anaerobic digestion	
25%	51,071	37,142	102,142	53,759	km^2
	2.8	2.0	5.6	2.9	% of total land
50%	102,141	74,285	204,284	107,518	km^2
	5.6	4.1	11.2	5.9	% of total land
75%	153,213	111,427	306,425	161,277	km^2
	8.4	6.1	16.8	8.8	% of total land
100%	204,284	148,570	408,567	215,035	km^2
	11.2	8.1	22.4	11.8	% of total land

6.3. Economic potential

In this section, first the levelized cost of electricity is calculated in Subsection 6.3.1, after this a sensitivity analysis is done on the input parameters in Subsection 6.3.2.

6.3.1. LCOE

For each technology a power plant similar to an already existing bamboo power plant in Indonesia is used. The same plant capacity, of 700 kW, is used for the LCOE calculations (Yoesgiantoro et al., 2019). The results of the LCOE calculation for each conversion technology are shown in Table 6.3. These results show that gasification has the lowest LCOE, and pyrolysis gives the highest LCOE. This is due to the high investment costs of the pyrolysis power plant.

Table 6.3: LCOE per conversion technology

Conversion technology	**LCOE [US$ct./kWh]**
Gasification	13
Pyrolysis	45
Direct combustion	16
Anaerobic digestion	22

When comparing the LCOE values with LCOE values from literature it becomes clear that using bamboo as an energy crop on degraded land is not competitive with other biomass projects. The LCOE range for biomass in Indonesia lays between the 4.68 and 11.4 US$ct./kWh (IESR, 2019). This is slightly lower than the gasification LCOE calculated in this research. This might be due to the use of degraded land, this results in a (50%) lower bamboo yield than what can be obtained by growing the bamboo on healthy soils. Also, a comparison with other renewable energy technologies can be made. The LCOE's of onshore wind, utility scale solar, and geothermal energy in Indonesia lay between the 7.39-16.1 US$ct./kWh, 5.84-10.28 US$ct./kWh, and 4.56-8.7 US$ct./kWh, respectively (IESR, 2019). This shows that gasification of bamboo on degraded land can be competitive with onshore wind energy, but not yet with other renewable energy technologies. However, because of the degraded land used, land costs are not taken into account. In case used land will be used for the plantations, an extra costs of 13,315,000 Rp/m^2 (906 US$/m^2) should be added to the LCOE as this is the cost of commercial land in Indonesia (Gnagey and Tans, 2018).

Then looking at non-renewable energy technologies LCOE's ranging between 9.2-12.94 US$ct./kWh, 6.69-8.93 US$ct./kWh, and 5.01-8.41 US$ct./kWh can be found in Indonesia for OCGT plants, CCGT plants, and a range of coal power plants (IESR, 2019). The lowest value, being the upper limit of the OCGT plant, is 12.94 US$ct./kWh, this is close to the 13 US$ct./kWh, found for bamboo gasification. However, the other non-renewable technologies are all much cheaper compared to the bamboo conversion technologies.

6.3.2. Sensitivity analysis

The sensitivity of the input parameters is checked by doing a sensitivity analysis. Each parameter is decreased and increased by 20% while keeping all other parameters constant (Langer et al., 2021; You et al., 2017). The results of the sensitivity analysis of the gasification technology are shown in Figure 6.1. In this figure the percentage of change compared to the initial LCOE found in Table 6.3 is shown. The sensitivity analysis of the combustion and anaerobic digestion LCOE's are found to be similar to the sensitivity of the gasification LCOE, thus the figures resulting form the other analysis can be found in Appendix A, and are not discussed separately. The sensitivity of pyrolysis was very different from the other technologies, and is shown in Figure 6.2.

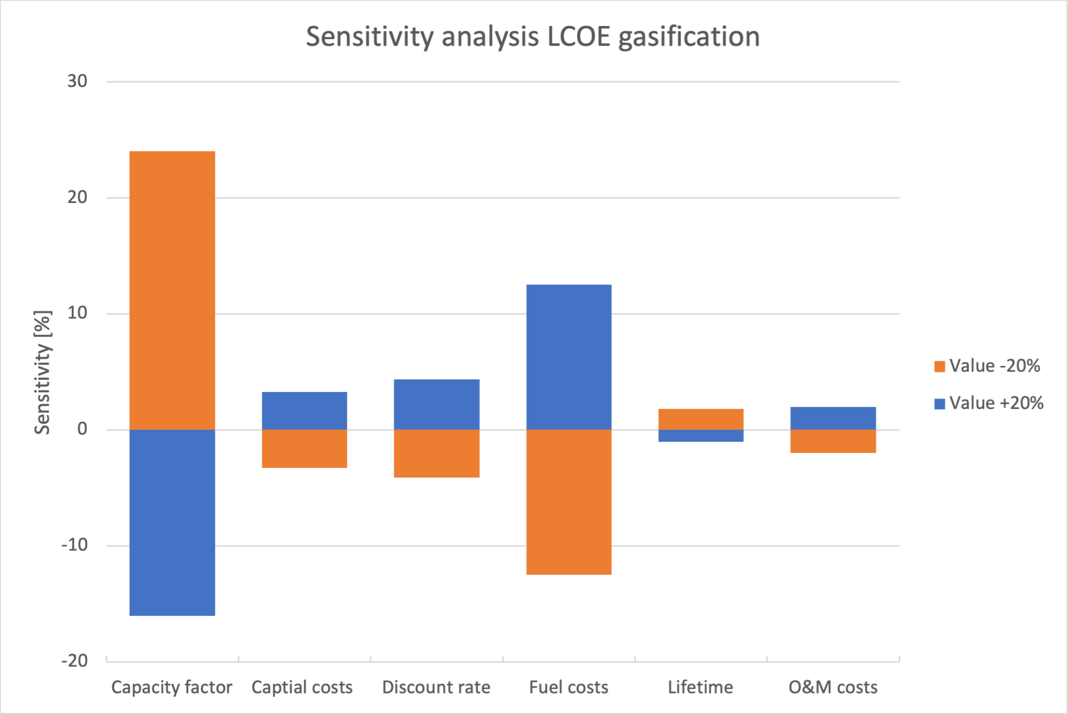


Figure 6.1: Sensitivity analysis of the gasification LCOE per input parameter

The three most sensitive parameters are the capacity factor, the fuel costs, and the discount rate. The capacity factor indicates the amount of time the plant is running, so it influences the electricity output of the power plant. When the capacity factor is increased by 20%, it increases to 1,08, which would indicate that the plant is operating for more than it actually can. The upper limit of the capacity factor is 100%, which would indicate a non-stop running power plant without any downtime during the entire year. Since the LCOE is very sensitive to the capacity factor it is important that power plant runs with the minimal required downtime.

The second most sensitive LCOE parameter is the fuel costs. The biggest part of the fuel cost exist of the cultivation cost of the feedstock. In case the yield would increase, these costs will be reduced. What is also included in these costs is the transport distance to the power plant. Reducing this distance will also reduce the fuel costs. The high sensitivity indicates that it is important that the yield is maximized and the transport distance is minimized. Thus, it is important that the (yield) data that is being used for the analysis is accurate and preferably tested in practise. The same goes for the harvesting, cultivation, and transport costs, these costs should be validated by comparing them to the actual costs experienced by bamboo plantations in Indonesia.

The discount rate is the third most sensitive parameter, however the LCOE is significantly less sensitive to this parameter than to the capacity factor and the fuel costs. The discount rate used is from a government perspective. Adding 20% to the discount rate, would increase it to 12%, which is equal to the discount rate from a business perspective in Indonesia (IRENA, 2017c). This business discount rate considers national prices in which energy taxes and subsidies are included (IRENA, 2017c). This increase in discount rate only changes the LCOE from 12.7 US$ct./kWh to 13.3 US$ct./kWh.

As mentioned in Section 4.2.2, the gasification capital costs used in this research are based on a rough estimate of multiple sources. Because of the insecurity of these costs an extra sensitivity analysis was done for the capital costs. When changing the value from 1500 US$/kW to 600 US$/kW, which is the lowest value found for a gasification project in Indonesia, the LCOE decreases to 0.12 US$/kWh. This is equal to a sensitivity of -9.8%. As already shown in Figure 6.1, the LCOE is not sensitive to the capital costs, compared to the other input parameters. So a significant change in capital costs will not result in a significant change in LCOE.

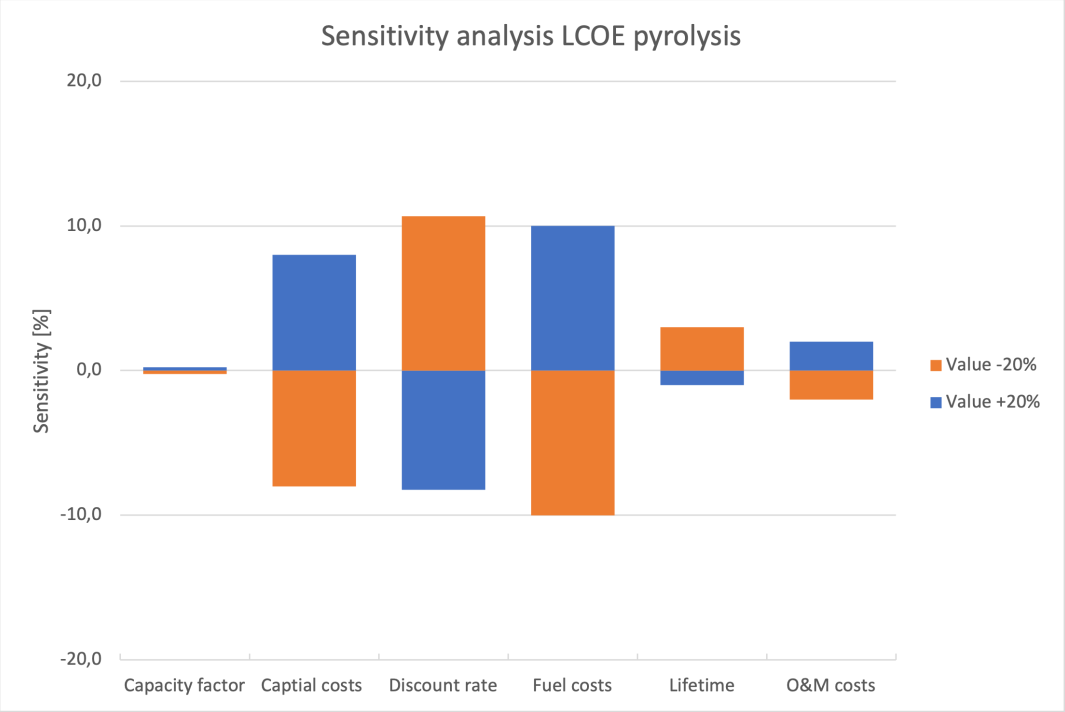


Figure 6.2: Sensitivity analysis of the pyrolysis LCOE per input parameter

Since the sensitivity of the LCOE calculated for pyrolysis differences significantly from the sensitivities of the other technologies, the pyrolysis LCOE sensitivity is discussed here. Figure 6.2, shows the results of the sensitivity analysis of the LCOE calculated for pyrolysis. Comparing the three most sensitive parameters from Figures 6.1 and 6.2 it first of all becomes clear that the percentages of the former lay further apart. The first three parameters of the pyrolysis sensitivity analysis are almost equally sensitive, while for gasification the sensitivity of each parameter decreases significantly. Furthermore, for pyrolysis the capacity factor does not rank in the top three most sensitive parameters, but instead the capital costs do.

The pyrolysis capital costs are approximately 10 times higher than the capital costs of the three other conversion technologies. This means that the capital cost have a bigger influence on the LCOE, and therefore also the sensitivity to the capital costs is higher. Reducing the capital costs for pyrolysis by 20% would reduce the LCOE from 45.4 US$ct./kWh to 41.6 US$ct./kWh. Because of this high sensitivity it is important to use up-to-date cost data and compare the costs to other projects in which pyrolysis conversion is used to be able to validate the results.

6.4. Comparison of the required and available degraded land for bamboo plantations

Now the degraded land areas that are available for bamboo plantations according to the eight different scenarios can be compared to the required bamboo plantation area per conversion technology and demand cover percentage. All the areas are combined in one figure, also the unused land area suitable for bamboo plantations is added in this figure for comparison. Figure 6.3 contains the areas needed to cover a certain demand percentages in the vertical bars, and the areas that were found to be available according to the different scenarios in the background in the horizontal bars. In this figure the left hand vertical axis shows the area in km^2, and the right hand vertical axis shows the matching percentage of the total land area of Indonesia. On the horizontal axis the different demand cover percentages are displayed.

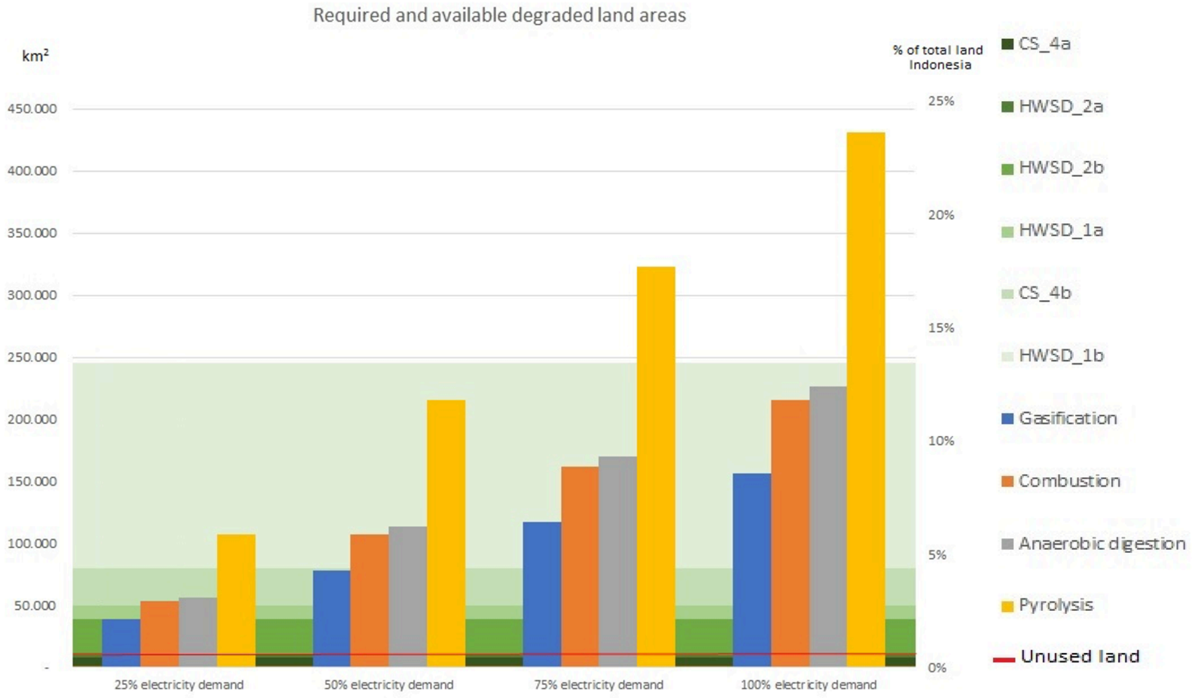


Figure 6.3: Available and required degraded land areas

From this figure it becomes clear that covering 75% or 100% of Indonesia's electricity demand by 2030 is unlikely. Even with the technologies which still fall within the green area, the demand can only be reached by one of the scenarios. This is scenario HWSD_1B, which is the least strict scenario. Then looking at 50% electricity demand coverage, this demand can be met by the combination of using gasification (78,336 km^2 required) and applying scenario CS_4B (79,771 km^2 available). The other technologies will only be possible when scenario HWSD_1B is applied, similarly to the situation for 75% and 100% electricity demand coverage. For the 25% demand coverage option more possibilities exist. Gasification becomes possible when applying scenario HWSD_1A, and both combustion and anaerobic digestion become possible when applying scenario CS_4B.

The electricity that can be generated when applying the other scenarios (HWSD_2B, HWSD_2A, HWSD_3B, HWSD_3A, CS_4A) does not come close to the 25% electricity demand of 111 TWh in 2030. The areas that are available according to these scenarios range from 128 km^2 to 38,973 km^2, while the area needed to cover 25% of the electricity demand using gasification is 39,168 km^2. When not looking at degraded land, but only looking at land use, and taking into account areas suitable for plantations on usused land the area indicated by the red line in the figure becomes available (13,245 km^2). Also, this area does not come close to the areas required to cover 25% of the electricity demand by 2030.

For Indonesia's energy transition, cultivating bamboo on degraded land would be applicable for local electricity generation, which will cover a significantly smaller percentage of the total electricity demand. Also, it is a good option for land restoration. Cultivating bamboo on degraded land areas would not be the best option when large electricity demand percentages need to be covered. This is due to the many ecological and techno-economic constraints and the efficiencies of the conversion technologies.

7
Discussion

In this discussion first, in Section 7.1, the limitations of the method used for this research are explained. After this, the implications of these limitations are discussed in Section 7.2.

7.1. Limitations

To be able to calculate the technical and economic potential of the bamboo plantations some assumptions were made. The limitations following from the assumptions are discussed below.

Pyrolysis and anearobic digestion are evaluated in the same way as gasification and direct combustion.
The end products of pyrolysis are bio-oil, biochar, and syngas. In this research only the syngas is used to produce electricity, however, the main product of pyrolysis is bio-oil and not syngas (Jahirul et al., 2012). Thus, using pyrolysis might not be the best option when electricity is the desired end use, it might be more applicable to produce biofuel. Similarly, for anaerobic digestion of lignocellulosic biomass pre-treatment is necessary. Steam explosion (or other pre-treatments) should be done to enhance the methane production of the raw bamboo (Chin et al., 2017). Like other pre-treatment technologies, this is not taken into account in this research, while it is an important first step in the anaerobic digestion technology. Without doing this methane can not be produced. The efficiency of the anearobic digestion including the pre-treatment will be lower than the value used in this report, depending on the pre-treatment technology used. This will influence the plantation area needed for the biomass conversion to electricity, as well as the LCOE of this conversion technology.

Bamboo yield is assumed to be 26.5 t/ha.
The bamboo yield is based on two bamboo plantations where bamboo is grown on degraded land which increases the reliability of the assumption. However, the yield of the bamboo plantation strongly depends on multiple factors like the precipitation, climate, and altitude, but also on the species of bamboo grown, the amount of nutrients in the soil, and the maintenance of the plantation. This means that the actual yield of a bamboo plantation on one of the found degraded land locations in Indonesia might differ from this value. This directly influences the amount of land needed to cover a certain percentage of the electricity demand as well as the LCOE. The sensitivity of the yield on the LCOE can be assessed by increasing and decreasing the yield by 20%. Doing this shows a sensitivity of 8.5%, 6.9%, 9.7% and 7.7% for gasification, pyrolysis, combustion, and anaerobic digestion, respectively. Compared to the sensitivity of the LCOE to other parameters, as shown in Subsection 6.3.2, the bamboo yield would rank as the third or fourth most sensitive parameter (depending on the conversion technology).

The fuel properties of the different bamboo species do not differ much from each other.
In Section 3.2, the fuel properties of some of the bamboo species native are evaluated to find the most suitable species for biomass conversion. However, all the LHVs and fuel properties lay very close to each other. Since also the yield is an important parameter for a biomass feedstock, it might be more beneficial to take this parameter into consideration when choosing the species instead of looking at the fuel properties.

Multiple cost assumptions for the LCOE calculation were done.
For the LCOE calculation, all parameters are based on calculations in other studies. The exact costs of developing the power plants in Indonesia should be further studied. What also plays a role in the results of the LCOE calculations is the maturity of the conversion technologies. Some technologies, like pyrolyis, are not in a far developed and commercial stage, which makes them more expensive

(Shahbaz et al., 2021). However, this might change over the coming years because of further research developments. Thus, there is a possibility that when one of the technologies matures, the costs will become lower and the efficiency of the technology will become higher which will make a technology more suitable for the conversion of bamboo into electricity.

The LCOE does not take (non-monetary) benefits into account.

As explained in Section 3.4, it is possible to grow other crops on the bamboo plantations during the first three years, when the bamboo is not ready for harvesting yet. Doing so can result in a revenue during three years, which can account for (part of) the costs of the bamboo plantations. Also, other (non-monetary) benefits like land restoration and job creation are not taken into account.

Next, to find the degraded land area and locations, also assumptions and simplifications were made for the QGIS analysis and the used data-sets. The limitations of these assumptions are discussed below.

Limitations of the HWSD data-set.

Multiple discussion points are found when looking critically at the use of the HWSD data-set. The first is that this data-set is qualitative and it is not completely clear how this data-set is constructed. As mentioned in Subsection 4.1.1 multiple soil characteristics are combined in seven soil qualities. It is mentioned that in most cases the most limiting characteristic is combined with the average of the remaining characteristics and then a growth potential limitation is given to each soil quality and location. However, there is no quantitative substantiation of this method.

Furthermore, the data-set is based on maize since this species grows on many continents. However, bamboo does not grow in the same way as maize, for example the roots of bamboo grow between 2-3 feet in the soil where maize roots can grow to 5 feet deep (Feldman, 1994; Bamboo Garden, 2022). In general, it does not mean that if there is a limiting growth potential for maize in a certain locations, the soil quality is limiting for all species. So when saying that degraded land is assessed by a 'loss of value', it might be the case that this is only true for a certain species. The land still might be valuable to grow species that can better withstand limiting soil qualities.

Another question that can be raised concerning the HWSD data-set is how the scenarios were constructed. Two of the scenarios follow the 'one out all out' principle. If one number three or one number four is assigned to one of the seven soil qualities, the location is considered to be degraded according to the constructed scenarios. However, maybe this is too strict, and a crop is still able to grow without limitations if only one of the seven soil qualities is unfavourable. Or what also might be possible is that how limited the growth potential is depends on which soil quality has the most limited characteristics. The qualities might not weigh the same in assessing the growth potential of a biomass species.

Limitations of the AGB data-set.

Similarly to the limitations of the HWSD data-set, also the AGB data-set used to evaluate degraded land according to a carbon stock limit of 35 t C/ha has some limitations. As was already quickly discussed in Section 5.2, the land cover data-set does not match perfectly with the carbon stock data. It would be expected that land covers which have a carbon stock lower than the threshold, according to definition, would be considered to be degraded for 100% of the land cover its area. It would be expected that the area for each land cover is either 0% or 100% degraded. However, this is not the case. This might be due to a mismatch in data because of the different years in which the data-sets were constructed (AGB-2016, HWSD-2017), or due to a different resolution of the data-sets. The land cover data-set is a polygon data-set, whereas the AGB data-set is a raster data-set with a resolution of 1 km. The possibility exists that multiple land covers can be found within the 1 km resolution of the AGB data-set. However, it is up for debate how strong these land cover changes can be within 1 km.

Another discussion point concerning this data-set is the threshold of 35 t C/ha, which comes from a degraded land definition according to the Reduced Emissions from Deforestation and forest Degradation (REDD) policy (Gingold et al., 2012). As mentioned in Section 4.1.1, sometimes also a value of 40 t C/ha is used, since this indicates a lower carbon stock than a palm oil plantation (Ruysschaert et al., 2011). Using these values only indicates the above ground carbon stock, and thus selects areas which usually do not contain high levels of vegetation or peat. However, it would be wrong to directly assume that these areas are degraded [J. Gebert, personal communication, March 10, 2022]. Also, when following other definitions with other degraded land parameters a carbon stock threshold is not mentioned. Land which contains low carbon stock can still be productive, have ecological integrity, have human value, and have stable and healthy soil characteristics. In case these parameters will be considered, the land will not be degraded according to the definitions evaluated in Table 2.1. This means that the carbon stock threshold can be used to find areas which most likely do not contain or sequester large amounts of carbon, but this does not necessarily mean that these areas are degraded as well.

Combinations of scenarios are not taken into account.

When adding a size constraint in step 4 of the method to find degraded land areas, all areas smaller than one hectare are removed from the possible locations. However, when combining scenarios it might be possible that less of these small areas exist. Degraded land areas from different scenarios might be connected to each other and form a suitable location with an area bigger than one hectare (with multiple levels of degradation).

To prevent land use change, used land should be considered not suitable.

Currently, scenarios with used land are considered possible when evaluating degraded land areas that can be used for bamboo plantations. This includes areas which serve agricultural purposes like rice fields, dry agriculture, and crop plantations. However, as was mentioned in Chapter 1, one of the current problems with biomass is that it takes up land that would otherwise be used for food production. This is undesired, and using degraded land for energy crop plantations would avoid having this problem. But when the degraded land is currently used for agriculture, there would again be competition with food production when transforming this land into a bamboo plantation. This would mean that agricultural land should not be used for energy crops, even if it is considered to be degraded.

Size constraint of minimal 1 ha plantation area.

In Step 4 of the methodology for the QGIS analysis, described in Section 4.1.4, a size constraint of minimally 1 ha was added, thus all available areas smaller than 1 ha were discarded. However, when opting for the application of electricity generation in decentralised systems, small-scale plantations would be feasible. As mentioned before villagers have expertise in growing bamboo and have a higher acceptance to biomass species that they are familiar with. Thus this size constraint might not be necessary.

7.2. Implications of the limitations

As mentioned before, IRENA estimates the degraded land area in Indonesia to lay between 12 and 74 million ha (IRENA, 2017c). In this research, a degraded land area between 91 and 0.38 million ha was found. This indicates that some scenarios used in this research might be constructed using too limiting restrictions for degraded land, and other scenarios might not be limiting enough. Two of the four scenarios (HWSD_2 and CS_4) do fall within the proposed range by IRENA, with degraded land areas of 13 and 14 million ha.

Because of the limitations of the data-sets used in this research, as well as the land use categories considered to be suitable and not suitable, the degraded land that can be used for plantations might differ from the results. For example, if combinations of scenarios will be taken into account and the size constraint will be smaller, possibly more land can be used for bamboo plantations, and thus more electricity can be generated. On the other hand, when agricultural land uses are considered not suitable, the possible plantation area will decrease. This might shift the position of the found areas in the range of degraded land estimated by IRENA.

Furthermore, the LCOE found in this research ranges from 13 to 45 US$ct./kWh, which as mentioned before is slightly higher than the LCOE range of biomass in Indonesia (4-11 US$ct./kWh) (IESR, 2019). Gasification and combustion of bamboo result in the lowest LCOE's, of 13 and 16 US$ct./kWh, and since these technologies are the most promising, these values are the most important. These also are the values closest to the range found in literature.

Because of the limitations of the economic analysis the actual LCOE values might differ from the values found in this research. Due to the pre-treatment which is always necessary for anaerobic digestion, the LCOE for this technology will most likely increase. Pre-treatment of the bamboo for other conversion technologies might result in a higher LCOE, since the costs will increase. However, the pre-treatment will also increase the efficiency, so more electricity can be obtained from the bamboo which will reduce the LCOE. The bamboo yield limitation can influence the LCOE since the plantation area needed can change when the yield is different. This influences the cultivation costs of the LCOE, which is part of the fuel costs. Since the fuel cost of most conversion technologies is the second most sensitive parameter of the LCOE, this might have a relative big influence, and bamboo conversion to electricity might become more competitive compared to other biomass feedstocks (in terms of LCOE).

8
Conclusion

In this study the technical and economic potential of bamboo cultivation on degraded land for electricity generation in Indonesia was assessed. Using this is a step in the right direction of Indonesia's energy transition. Especially, since the degraded lands are restored when bamboo is grown on them, and at the same time they help to generate electricity. This study shows that still, clarity on the degraded land definition is needed to assess the exact potential of biomass cultivation of these lands. It would be possible to apply the method, when validated, to other countries which suffer from a significant amount of degraded land like Indonesia. This will support the energy transition in other parts of the world. In this final chapter the research questions proposed in Chapter 1 are answered. First, the main research question is answered in Section 8.1. After this the sub-questions are answered in Section 8.2.

8.1. Answer to the main research question

How much degraded land would be needed to cover Indonesia's electricity demand by 2030, when using bamboo as a biomass feedstock, and how likely is this land available?

The first part of this main research question can be answered by using information obtained to answer sub-question 1 and 2. By combining the results found for these two questions the amount of land needed to cover the electricity demand was calculated. The amount of land needed to cover Indonesia's electricity demand varies for each conversion technology used to convert the bamboo into electricity. Also, different amounts of electricity demand coverage are considered, namely 25%, 50%, 75%, and 100%. The needed area ranges between 2.3% and 6.4% of Indonesia's total land cover for 25% electricity demand coverage, 4.7% and 12.8% for 50% electricity demand coverage, 7.0% and 19.3% for 75% electricity demand coverage, and finally 9.3% and 25.7% of Indonesia's total land cover for 100% electricity demand coverage. The lowest percentages needed are found for gasification of bamboo, and the highest percentages are found for pyrolysis of bamboo. This means that gasification currently is the most suitable technology for bamboo conversion into electricity since it requires the least amount of plantation area.

The second part of the main research question is answered by combining findings from sub-questions 3 and 4. The QGIS analysis made it possible to find the extent and location of degraded land areas in Indonesia, according to different scenarios. How likely these areas are available for bamboo plantations strongly depends on the way degraded land is assessed. The most limiting scenario provides the possibility to convert an area in the range of 128 - 1,471 km^2 (between 0.01% and 0.08% of Indonesia's total land cover) into bamboo plantations. However, this scenario might be too strict. The least limiting degraded land scenario gives an area in the range of 49,999 - 245,729 km^2 (between 3% and 12% of Indonesia's total land cover). This scenario on the other hand might not be strict enough. This means that most likely it would be possible to cover 25% of Indonesia's electricity demand when using gasification to convert bamboo into electricity. When less strict degraded land scenarios are used it would be possible to cover 100% of the electricity demand when using multiple conversion technologies, however this is not likely to happen due to the high percentages of Indonesia's total land area needed.

8.2. Answers to the sub-questions

1. *What bamboo species native to Indonesia, is suitable to use as a feedstock for land restoration and electricity generation on degraded land?*

There are 56 bamboo species that are native to Indonesia, and even more species currently grow in Indonesia (between the 120-161). In general it is mentioned that bamboo can grow on degraded land, no differentiation between the species is made in these statements. From the species growing in Indonesia, the five most common ones have been evaluated to be used as a biomass feedstock. By looking at the fuel properties, it became clear that B Vulgaris matches best with the selection criteria for pyrolysis, and G Apus matches the criteria of gasification and combustion best. Since the species G Apus also has the highest LHV, in combination with a low moisture content, this species was chosen to be used for further calculations. However, the differences in fuel properties between the species was small, so probably multiple species will be suitable for land restoration and electricity generation on degraded land.

2. *What is degraded land and which factors should be taken into account when evaluating degraded land using GIS?*
Degraded land has many different definitions, and it became clear that there is no consensus about what degraded land is and how it should be evaluated. Some definitions focus on the end condition of the land, while other focus on the process of land degradation or the risk of land becoming degraded. Furthermore, the focus of the definitions differences from each other, some focus on soil degradation, while others focus on vegetation or a combination of the two. Most definitions indicate that the cause of degraded land is due to both human and natural activities/processes, and characteristics include loss of productivity and loss of ecological integrity. Quantification has been done by looking at the carbon stock of the above ground biomass which is grown on a piece of land. Only two of the 13 definitions evaluated contain a quantification. Because of these differences in definitions, and the lack of a quantification in many definitions a wide range of degraded land is estimated in Indonesia. It is estimated by IRENA that between 12 and 74 million ha of land is degraded in Indonesia. In this research, two different methods were implemented in QGIS to find degraded land were implemented, one focusing on the soil quality and the other one on the carbon stock of the above ground biomass to include characteristics of multiple definitions.

3. *What is the extent and location of degraded land in Indonesia and which degraded land areas in Indonesia are suitable for bamboo plantations?*
According to the HWSD scenarios most degraded land areas can be found on Sumatra and Kalimantan. Locations found for the first three scenarios are evenly distributed over the islands. Going from scenario HWSD_1 to HWSD_3, locations remain on Sumatra and Kalimantan, and disappear from the other islands. This might be due to the land use, and population density on the islands. According to the carbon stock scenario most degraded land locations can be found on Java and Sumatra. In this scenario more degraded land is located in the coastal areas of the islands compared to the first three scenarios. The areas of the degraded land locations are between 3,804 and 910,604 km^2, with a median of 141,104 km^2 of the four scenarios. Then looking at the areas that are suitable for bamboo plantations, it becomes clear that the areas are significantly reduced due to the elimination of protected areas, not suitable land covers, and economic constraints. The total potential area for the used land scenarios ranges from 1,471 and 245,729 km^2, with a median of 59,372 km^2 of the four scenarios. The total potential area for the unused land scenarios ranges from 128 to 49,999 km^2, with a median of 9,159 km^2 of the four scenarios. Due to this wide range of areas, there remains uncertainty about the actual extent of degraded land in Indonesia. An extra evaluation is made by discarding the degraded land requirement but only looking at unused land which would be suitable for plantations, this results in a suitable area of 13,244 km^2.

4. *Which conversion technologies are available to convert bamboo to electricity and what is their technical and economic potential?*
To turn biomass into electricity both thermochemical as biochemical processes can be used. Possibilities include direct combustion, gasification, pyrolysis, and anaerobic digestion all in addition with boilers, steam engines, and gas engines or turbines. One of the factors influencing the technical and economic potential is the efficiency of the conversion technologies. By looking at the overall efficiencies of all these processes it was found that gasification has the highest efficiency, gasification also has the highest technical potential. Other parameters influencing the technical

potential are the plantation area, bamboo yield, lower heating value, and moisture content of the bamboo. The economic potential was assessed by calculating the LCOE of each technology. Again the results showed that gasification had the lowest LCOE, of 13 US$ct/kWh, and thus has the highest economic potential. The LCOE turned out to be most sensitive to the capacity factor and the fuel costs, these parameters showed a sensitivity of 24% and 13% for gasification when varying the input by 20%, respectively.

9

Recommendations

First, some recommendations follow from the discussion points described above. These recommendations mainly concern doing field research on degraded land and the used data-sets.

- *Test the used bamboo yield value against the actual yield of a possible bamboo plantation on the degraded land areas found in Indonesia to update the calculations.*
  The bamboo yield used in this report results from an average of two bamboo yields found on plantations on degraded land in India. However, dus to the many factors influencing the yield of a plantation (like climate, altitude, soil type, bamboo species etc.) the bamboo yield of a plantation on degraded land in Indonesia can be different from this value. To make the calculations more accurate and reliable, the bamboo yield of a degraded land plantation in Indonesia should be tested.

- *Validate carbon stock data-set.*
  Field research can be done to assess the accuracy of the carbon stock data. The data-set gives a value for the above ground carbon stock in tonnes of carbon per hectare. This value can be checked by taking samples of different vegetation types, and then the vegetation per hectare can be assessed using satellite images and checking these results with field research in different locations. Especially locations where the data from the land cover data-set does not match with the carbon stock data-set should be checked through field research. When this data-set is validated, it can be used with more certainty to evaluate the carbon stock of Indonesia, and using satellite images it can be expanded to other countries as well. What remains a challenge is the change in vegetation through the years, as well as through the different seasons. The data-set will need to be updated frequently to stay accurate.

- *Improve the research into degraded land.*
  Firstly, the assumptions made for the HWSD data-set can be tested through field research. Field research can be done to assess the accuracy of the soil quality data. Each location has a growth potential number matched to it, the actual growth potential of the locations can be tested by planting maize (the data-set's reference crop) on each location. Then also different combinations of growth potentials for different soil quality parameters can be tested by planting maize on the locations. Preferably each combination of growth potential and soil quality should be validated to get the best overview, and to see how critical each soil quality is for the growth potential.

  If the validation tests are conducted on locations found for the three scenarios, it can be determined if these locations can be classified as degraded. Furthermore, after maize has been tested, it would be possible to also test bamboo (and maybe other biomass feedstocks). This can be done to assess how the soil quality limitations influence the growth of other feedstocks and thus assess how land degradation might play a role in the growth potential of different biomass feedstocks.

  Furthermore, the degraded land definitions can critically be evaluated to see if degraded land really is found using them. When this is done, a clear and concise definition that can be uniformly used to find degraded land locations can be determined. This definition should include a statement about the water and carbon cycles in this definition, as well as information about the level of biodiversity and the vegetation. Also, to be able to find degraded land in different locations, a quantification of degraded land can be added to the definition.

Next, also some general recommendations for further research can be made. These are given and explained below.

- *Critically evaluate the socio-economic and environmental effects of a possible bamboo plantation.*
  For locals living around the degraded land areas, the consequences of transforming land to a plantation can be significant since they still might be using the land for cattle or other purposes. The same goes for the biodiversity, this might change when changing the land use. The consequences of this land use change can be further researched. Additionally, who owns the degraded land and how transforming the land to a plantation influences the land owners can be further researched as well.

- *Further research the possibilities intercropping.*
  As mentioned before, bamboo can be intercropped with other plants during the first three years of the plantation. To find out which plants would be most beneficial to plant between the rows of bamboo, field research can be done. Furthermore, the possibility of using land that is restored by the bamboo litter for other purposes like food production can be further researched, as well as the possibility to continue switching between bamboo and agricultural purposes like in the talun-kabun system, as described in Section 3.4.

- *Other conversion possibilities (like co-firing and CHP plants) and pre-treatment technologies (like torrefaction) can be evaluated.*
  In this study only gasification, pyrolysis, direct combustion, and anaerobic digestion without any pre-treatment steps are taken into account. Co-firing is quickly addressed in Section 3.5.1, however no further calculations are done for this technology. Co-firing the biomass with coal, or using the biomass in a CHP plant might result in a higher efficiency than the efficiency that can be reached with the evaluated technologies. Also, pre-treatment technologies might have the ability to improve the fuel characteristic of the bamboo, which also will result in higher efficiencies and thus lower areas of needed land to cover the same amount of the electricity demand. Therefore, these technologies can be further explored in future research.

- *The end product is decided to be electricity, while also biofuel for the transport sector might be a suitable end use of the bamboo.*
  The focus of this study lays on the power sector, however there are also possibilities for biomass in the industry sector where biofuels can be used. IRENA estimates that the biofuel consumption in Indonesia will increase to 25 billion litres per year by 2030, due to mandated biodiesel and ethanol blending starting in 2025 (IRENA, 2017c). This gives an opportunity for bamboo conversion to biofuel instead of electricity. Looking into these possibilities can be done in future research.

Bibliography

Abdelhady, S., Borello, D., & Shaban, A. (2018). Techno-economic assessment of biomass power plant fed with rice straw: Sensitivity and parametric analysis of the performance and the lcoe. *Renewable Energy*, *115*, 1026–1034.

Abdel-Kader, F. H. (2019). Assessment and monitoring of land degradation in the northwest coast region, egypt using earth observations data. *The Egyptian Journal of Remote Sensing and Space Science*, *22*(2), 165–173.

AbdelRahman, M. A., Natarajan, A., Srinivasamurthy, C., & Hegde, R. (2016). Estimating soil fertility status in physically degraded land using gis and remote sensing techniques in chamarajanagar district, karnataka, india. *The Egyptian Journal of Remote Sensing and Space Science*, *19*(1), 95–108.

Abdullah, A., Karlina, N., Rahmatiya, W., Mudaim, S., Fajrin, A., et al. (2017). Physical and mechanical properties of five indonesian bamboos. *IOP Conference Series: Earth and Environmental Science*, *60*(1), 012014.

Abreu, M., Reis, A., Moura, P., Fernando, A. L., Luís, A., Quental, L., Patinha, P., & Gírio, F. (2020). Evaluation of the potential of biomass to energy in portugal—conclusions from the converte project. *Energies*, *13*(4), 937.

Agbor, E., Oyedun, A. O., Zhang, X., & Kumar, A. (2016). Integrated techno-economic and environmental assessments of sixty scenarios for co-firing biomass with coal and natural gas. *Applied Energy*, *169*, 433–449.

Ahmadi, L., Kannangara, M., & Bensebaa, F. (2020). Cost-effectiveness of small scale biomass supply chain and bioenergy production systems in carbon credit markets: A life cycle perspective. *Sustainable Energy Technologies and Assessments*, *37*, 100627.

Andriyana, Y., Thaler, P., Chiarawipa, R., & Sopharat, J. (2020). On-farm effect of bamboo intercropping on soil water content and root distribution in rubber tree plantation. *Forests, Trees and Livelihoods*, *29*(4), 205–221.

Artati, Y., Jaung, W., Juniwaty, K. S., Andini, S., Lee, S. M., Segah, H., & Baral, H. (2019). Bioenergy production on degraded land: Landowner perceptions in central kalimantan, indonesia. *Forests*, *10*(2), 99.

Aswandi, A., & Kholibrina, C. R. (2020). Empowering women on bamboo utilization and conservation in the lake toba catchment area of the north sumatra province of indonesia. *Environmental Sciences Proceedings*, *3*(1), 47.

Auman, N., Widyowijatnoko, A., & Wonorahardjo, S. (2018). Technological contexts in developing bamboo wall system for housing in indonesia and philippines. *IOP Conference Series: Earth and Environmental Science*, *152*(1), 012005.

Avitabile, V., Herold, M., Heuvelink, G. B., Lewis, S. L., Phillips, O. L., Asner, G. P., Armston, J., Ashton, P. S., Banin, L., Bayol, N., et al. (2016). An integrated pan-tropical biomass map using multiple reference datasets. *Global change biology*, *22*(4), 1406–1420.

Awé, D. V., Noiha, N. V., & Zapfack, L. (2021). Carbon management for savannah ecosystems in central africa: A case study from cameroon. *International Journal of Low-Carbon Technologies*, *16*(4), 1290–1298.

BAMBoo, E. (2014). 4.6 commercial bamboo plantations as a tool for restoring landscapes. *Towards productive landscapes*, 139.

Bamboo Garden. (2022). Frequently asked questions. https://www.bamboogarden.com/faq

Bamboo U. (2019). The 7 bamboo species we use the most. Retrieved February 18, 2021, from https://bamboou.com/projects/the-7-bamboo-species-we-use-the-most/

Banik, R. L. (2015). Bamboo silviculture. *Bamboo* (pp. 113–174). Springer.

Baruah, D., & Baruah, D. (2021). Decision support system based planning of biomass gasification system for decentralised energy generation. *Renewable Energy Focus*, *38*, 22–35.

Behera, S., Mahapatra, A., Mishra, P., Pattanayak, S., & Panda, D. (2016). Performance of bamboo based agri-silvicultural systems in north odisha, india. *International Journal of Bio-Resource and Stress Management*, *7*(2), 218–221.

Ben-Zhi, Z., Mao-Yi, F., Jin-Zhong, X., Xiao-Sheng, Y., & Zheng-Cai, L. (2005). Ecological functions of bamboo forest: Research and application. *Journal of Forestry Research*, *16*(2), 143–147.

Bijalwan, A., Swamy, S., Sharma, C. M., Sharma, N. K., & Tiwari, A. (2010). Land-use, biomass and carbon estimation in dry tropical forest of chhattisgarh region in india using satellite remote sensing and gis. *Journal of Forestry Research*, *21*(2), 161–170.

Blok, K., & Nieuwlaar, E. (2021). Introduction to energy analysis.

Boer, R., Dewi, R., Ardiansyah, M., & Siagian, U. (2018). *Indonesia - second biennial update report, under the united nations framework convention on climate change* (tech. rep.). Ministry of Environment and Forestry. Republic of Indonesia.

Boissière, M., Beyessa, M., & Atmadja, S. (2019). Guiding principles for sustainable bamboo forest management planning benishangul-gumuz regional state (bgrs).

CGIAR-CSI. (2018). Srtm 90m dem digital elevation database. Retrieved February 9, 2021, from https://www.diva-gis.org/gdata

Chan, Y. (2008). Increasing soil organic carbon of agricultural land. *Primefact*, *735*, 1–5.

Chao, C. Y., Kwong, P. C., Wang, J., Cheung, C., & Kendall, G. (2008). Co-firing coal with rice husk and bamboo and the impact on particulate matters and associated polycyclic aromatic hydrocarbon emissions. *Bioresource technology*, *99*(1), 83–93.

Chin, K. L., Ibrahim, S., Hakeem, K. R., San H'ng, P., Lee, S. H., & Lila, M. A. M. (2017). Bioenergy production from bamboo: Potential source from malaysia's perspective. *BioResources*, *12*(3), 6844–6867.

Choi, C. S., Siregar, I. Z., & Ravi, S. (2020). Reframing the competition for land between food and energy production in indonesia. In S. J. Walsh, D. Riveros-Iregui, J. Arce-Nazario, & P. H. Page (Eds.), *Land cover and land use change on islands: Social & ecological threats to sustainability* (pp. 241–260). Springer International Publishing. https://doi.org/10.1007/978-3-030-43973-6_11

Christanty, L., Mailly, D., & Kimmins, J. (1996). "without bamboo, the land dies": Biomass, litterfall, and soil organic matter dynamics of a javanese bamboo talun-kebun system. *Forest Ecology and Management*, *87*(1-3), 75–88.

Coney, M., Linnemann, C., Sugiura, K., & Goto, T. (2004). First prototype of the high-efficiency isoengine, 5–19.

Cuiping, L., Chuangzhi, W., Haitao, H., et al. (2004). Chemical elemental characteristics of biomass fuels in china. *Biomass and bioenergy*, *27*(2), 119–130.

Dani, S., & Wibawa, A. (2018). Challenges and policy for biomass energy in indonesia. *International Journal of Business, Economics, and Law*, *15*(5), 41–47.

Darabant, A., Haruthaithanasan, M., Atkla, W., Phudphong, T., Thanavat, E., & Haruthaithanasan, K. (2014). Bamboo biomass yield and feedstock characteristics of energy plantations in thailand. *Energy Procedia*, *59*, 134–141.

Dauber, J., Brown, C., Fernando, A. L., Finnan, J., Krasuska, E., Ponitka, J., Styles, D., Thrän, D., Van Groenigen, K. J., Weih, M., et al. (2012). Bioenergy from "surplus" land: Environmental and socio-economic implications. *BioRisk*, *7*, 5.

Davies, E. (2021). Indonesia to make biomass co-firing mandatory in power plants. https://www.reuters.com/business/sustainable-business/indonesia-make-biomass-co-firing-mandatory-power-plants-2021-07-23/

dbcity. (n.d.). Papua information. https://en.db-city.com/Indonesia--Papua

de Jong, W., & van Ommen, R. (2015). *Biomass as a sustainable energy source for the future*. John Wiley & Sons.

Devi, A. S., & Singh, K. S. (2021). Carbon storage and sequestration potential in aboveground biomass of bamboos in north east india. *Scientific Reports*, *11*(1), 1–8.

Dharmawan, A. H., Fauzi, A., Putri, E. I., Pacheco, P., Dermawan, A., Nuva, N., Amalia, R., & Sudaryanti, D. A. (2020). Bioenergy policy: The biodiesel sustainability dilemma in indonesia. *International Journal of Sustainable Development and Planning*, *15*(4), 537–546.

Dwivedi, A. K., Kumar, A., Baredar, P., & Prakash, O. (2019). Bamboo as a complementary crop to address climate change and livelihoods–insights from india. *Forest Policy and Economics*, *102*, 66–74.

Ebrary. (n.d.). Fluidized bed reactor. Retrieved January 4, 2022, from https://ebrary.net/131855/engineering/fluidized_reactor

Eddy, S., Milantara, N., & Basyuni, M. (2021). Carbon emissions as impact of mangrove degradation: A case study on the air telang protected forest, south sumatra, indonesia (2000-2020). *Biodiversitas Journal of Biological Diversity*, *22*(4).

Ediriweera, A., Palihakkara, I. et al. (2020). Possibility to introduce bamboo as an energy crop. *International Journal for Research in Applied Sciences and Biotechnology*, *7*(5), 113–118.

Edrisi, S. A., & Abhilash, P. (2016). Exploring marginal and degraded lands for biomass and bioenergy production: An indian scenario. *Renewable and Sustainable Energy Reviews*, *54*, 1537–1551.

Erickson, T., Allan, S., McCollor, D., Hurley, J., Srinivasachar, S., Kang, S., Baker, J., Morgan, M., Johnson, S., & Borio, R. (1995). Modelling of fouling and slagging in coal-fired utility boilers. *Fuel Processing Technology*, *44*(1-3), 155–171.

European Commission. (2012). *Indirect land use change (iluc)*. https://ec.europa.eu/commission/presscorner/detail/en/MEMO_12_787 (accessed: 02.09.2021)

Fairhurst, T., & McLaughlin, D. (2009). Sustainable oil palm development on degraded land in kalimantan. *World Wildlife Fund, Washington, DC*.

Faizal, R., Nurdin, M., Hariyanto, N., Pack, S., & Plesch, J. (2015). Sumatra-java hvdc transmission system modelling and system impact analysis. *2015 IEEE Eindhoven PowerTech*, 1–6.

Fan, J.-L., Wei, S., Yang, L., Wang, H., Zhong, P., & Zhang, X. (2019). Comparison of the lcoe between coal-fired power plants with ccs and main low-carbon generation technologies: Evidence from china. *Energy*, *176*, 143–155.

FAO. (2022a). Fao soils portal. Retrieved January 11, 2021, from https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/

FAO. (2022b). Soil degradation. Retrieved January 20, 2021, from https://www.fao.org/soils-portal/soil-degradation-restoration/en/

FAO/IIASA/ISRIC/ISSCAS/JRC. (2012). Harmonized world soil database (version 1.2). Retrieved January 11, 2021, from http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/

Fauzi, A., Sakti, A., Yayusman, L., Harto, A., Prasetyo, L., Irawan, B., Kamal, M., & Wikantika, K. (2019). Contextualizing mangrove forest deforestation in southeast asia using environmental and socio-economic data products. *Forests*, *10*(11), 952.

Feldman, L. (1994). The maize root. In M. Freeling & V. Walbot (Eds.), *The maize handbook* (pp. 29–37). Springer New York. https://doi.org/10.1007/978-1-4612-2694-9_4

Fialho, L. d. F., Carneiro, A. d. C. O., Carvalho, A. M. M. L., Figueiró, C. G., Silva, C. M. S. d., Magalhães, M. A., & Peres, L. C. (2019). Bio-coal production with agroforestry biomasses in brazil. *Maderas. Ciencia y tecnología*, *21*(3), 357–366.

Fischer, G., Nachtergaele, F., Prieler, S., van Velthuizen, H., Verelst, L., & Wiberg, D. (2008). Global agro-ecological zones assessment for agriculture. Retrieved January 10, 2021, from https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/

Fryda, L., Daza, C., Pels, J., Janssen, A., & Zwart, R. (2014). Lab-scale co-firing of virgin and torrefied bamboo species guadua angustifolia kunth as a fuel substitute in coal fired power plants. *Biomass and Bioenergy*, *65*, 28–41.

Gibbs, H., & Salmon, J. M. (2015). Mapping the world's degraded lands. *Applied geography*, *57*, 12–21.

Gingold, B., Stolle, F., Douard, P., Rosenbarger, A., Muliastra, Y. I. K. D., Sudana, I. M., Manessa, M. D. M., Murdimanto, A., Tiangga, S. B., & Madusari, C. C. (2012). How to identify degraded land for sustainable palm oil in indonesia.

Global Forest Watch. (2016). Indonesia peat lands. Retrieved January 10, 2021, from https://data.globalforestwatch.org/datasets/gfw::indonesia-peat-lands/about

Global Forest Watch. (2019). Mgmt$_{k}awasanhutan_{2}010_{s}s$. Retrieved January 10, 2021, from https://data.globalforestwatch.org/datasets/gfw::indonesia-legal-classification/about

globalforestwatch.org. (2022). Indonesia. https://www.globalforestwatch.org/dashboards/country/IDN/?category=summary

Gnagey, M., & Tans, R. (2018). Property-price determinants in indonesia. *Bulletin of Indonesian Economic Studies*, *54*(1), 61–84.

Guadua Bamboo. (n.d.). Spacing between bamboo plants. Retrieved July 4, 2022, from https://www.guaduabamboo.com/blog/how-to-plant-bamboo

Hadidi, L. A., & Omer, M. M. (2017). A financial feasibility model of gasification and anaerobic digestion waste-to-energy (wte) plants in saudi arabia. *Waste management*, *59*, 90–101.

Hafzari, R., Setiawati, T., Irawan, B., Kusmoro, J., et al. (2019). Evaluation of rapd markers for molecular identification of five bamboo genera from indonesia. *Folia Forestalia Polonica*, *61*(4), 255–266.

Hiloidhari, M., Baruah, D., Singh, A., Kataki, S., Medhi, K., Kumari, S., Ramachandra, T., Jenkins, B., & Thakur, I. S. (2017). Emerging role of geographical information system (gis), life cycle assessment (lca) and spatial lca (gis-lca) in sustainable bioenergy planning [Special Issue on International Conference on Current Trends in Biotechnology post ICCB-2016 conference on Strategies for Environmental Protection and Management (ICSEPM-2016)]. *Bioresource Technology*, *242*, 218–226. https://doi.org/https://doi.org/10.1016/j.biortech.2017.03.079

Hiwale, S. (2015). *Sustainable horticulture in semiarid dry lands*. Springer.

Hoogwijk, M., Faaij, A., van den Broek, R., Berndes, G., Gielen, D., & Turkenburg, W. (2003). Exploration of the ranges of the global potential of biomass for energy. *Biomass and Bioenergy*, *25*(2), 119–133. https://doi.org/https://doi.org/10.1016/S0961-9534(02)00191-5

Hoogwijk, M. M. (2004). *On the global and regional potential of renewable energy sources* (Doctoral dissertation).

Hou, K., Li, X., Wang, J., & Zhang, J. (2016). Evaluating ecological vulnerability using the gis and analytic hierarchy process (ahp) method in yan'an, china. *Polish Journal of Environmental Studies*, *25*(2).

IESR. (2019). *Levelized cost of electricity in inodnesia* (tech. rep.). Institute for Essential Services Reform(IESR). Jakarta.

Ignaciuk, A., Vöhringer, F., Ruijs, A., & van Ierland, E. C. (2006). Competition between biomass and food production in the presence of energy policies: A partial equilibrium analysis. *Energy policy*, *34*(10), 1127–1138.

Immerzeel, D. J., Verweij, P. A., van der Hilst, F., & Faaij, A. P. C. (2014). Biodiversity impacts of bioenergy crop production: A state-of-the-art review. *GCB Bioenergy*, *6*(3), 183–209. https://doi.org/https://doi.org/10.1111/gcbb.12067

International Energy Agency and The World Bank. (2015). *Sustainable energy for all 2015: Progress toward sustainable energy* (tech. rep.). World Bank. Washington DC. https://doi.org/0.1596/978-1-4648-0690-2

ipieca. (2014). Open cycle gas turbines. Retrieved January 4, 2022, from https://www.ipieca.org/resources/energy-efficiency-solutions/power-and-heat-generation/open-cycle-gas-turbines/

IRENA. (2012). *Renewable energy technologies: Cost analysis series* (tech. rep.). International Renewable Energy Agency. Abu Dhabi.

IRENA. (2017a). *Bioenergy from degraded land in africa, sustainable and technical potential under bonn challenge pledges* (tech. rep.). International Renewable Energy Agency. Abu Dhabi.

IRENA. (2017b). Renewable energy prospects: Indonesia. Retrieved March 23, 2021, from https://www.irena.org/publications/2017/Mar/Renewable-Energy-Prospects-Indonesia

IRENA. (2017c). *Renewable energy prospects: Indonesia, a remap analysis* (tech. rep.). International Renewable Energy Agency. Abu Dhabi.

IRENA. (2018). *Renewable power generation costs 2017* (tech. rep.). International Renewable Energy Agency. Abu Dhabi.

IRENA. (2020). *Renewable power generation costs 2020* (tech. rep.). International Renewable Energy Agency. Abu Dhabi.

Jahirul, M., Rasul, M., Chowdhury, A., & Ashwath, N. (2012). Biofuels production through biomass pyrolysis —a technological review. *Energies*, *5*, 4952–5001. https://doi.org/10.3390/en5124952

Jaung, W., Wiraguna, E., Okarda, B., Artati, Y., Goh, C. S., Syahru, R., Leksono, B., Prasetyo, L. B., Lee, S. M., & Baral, H. (2018). Spatial assessment of degraded lands for biofuel production in indonesia. *Sustainability*, *10*(12). https://doi.org/10.3390/su10124595

Jha, P., & Mandal, R. A. (2019). Assessment of growth performance of acacia catechu. *IJARB*, *5*(1), 34–8.

JiangHua, X., & XiaoSheng, Y. (2001). *Medium and large scale bamboo plantations* (tech. rep.). Bamboo Research Division Research Institute of Subtropical Forestry Chinese Academy of Forestry.

Kaewkrom, P., Gajaseni, J., Jordan, C. F., & Gajaseni, N. (2005). Floristic regeneration in five types of teak plantations in thailand. *Forest Ecology and Management*, *210*(1-3), 351–361.

Kerlero De Rosbo, G., & Bussy, J. d. (2012). Electrical valorization of bamboo in africa. technical benchmark of small-scale woody biomass-to-electricity technologies application to inbar's project to valorize bamboo in rwanda.

Key Biodiversity Areas. (2022). Saving nature. Retrieved January 11, 2021, from https://www.keybiodiversityareas.org/about-kbas/saving-nature

Kigomo, B. (2007). Guidelines for growing bamboo.

Kim, S., & Dale, B. E. (2011). Indirect land use change for biofuels: Testing predictions and improving analytical methodologies. *biomass and bioenergy*, *35*(7), 3235–3240.

Kuehl, Y. (2015). Resources, yield, and volume of bamboos. *Bamboo*, 91–111.

Kusratmoko, E. et al. (2017). The critical land in komering watershed as a result of land use changes from 2000-2016 period. *IOP Conference Series: Earth and Environmental Science*, *54*(1), 012020.

Langer, J., Cahyaningwidi, A. A., Chalkiadakis, C., Quist, J., Hoes, O., & Blok, K. (2021). Plant siting and economic potential of ocean thermal energy conversion in indonesia a novel gis-based methodology. *Energy*, *224*, 120121.

Lestariningsih, I. D., Widianto, W., Agustina, C., Sudarto, S., & Kurniawan, S. (2018). Relationship between land degradation, biophysical and social factors in lekso watershed, east java, indonesia. *Journal of Degraded and Mining Lands Management*, *5*(3), 1283.

Liese, W., & Köhl, M. (2015). *Bamboo: The plant and its uses*. Springer.

Ling Chin, K., Ibrahim, S., Hakeem, K., Hng, P., Lee, S., & Lila, M. (2017). Bioenergy production from bamboo: Potential source from malaysia's perspective. *Bamboo for bioenergy*, *12*(3), 6844–6867.

Liu, Z., Hu, W., Jiang, Z., Mi, B., & Fei, B. (2016). Investigating combustion behaviors of bamboo, torrefied bamboo, coal and their respective blends by thermogravimetric analysis. *Renewable Energy*, *87*, 346–352. https://doi.org/https://doi.org/10.1016/j.renene.2015.10.039

Lolla, A., & Yang, M. (2021). *Indonesia - indonesia defies global trend with more coal in the generation-mix* (tech. rep.). Ember.

Lovett, A., Sunnenberg, G., Richter, G., Dailey, A., Riche, A., & Karp, A. (2009). Land use implications of increased biomass production identified by gis-based suitability and yield mapping for miscanthus in england. *BioEnergy Research*, *2*, 17–28.

Madegowda, M., Paudyal, K., & Shiping, H. (2021). Integration of bamboo in landscape restoration. Retrieved February 9, 2021, from https://bambooindonesia.net/integration-of-bamboo-in-landscape-restoration/

Mailly, D., Christanty, L., & Kimmins, J. (1997). 'without bamboo, the land dies': Nutrient cycling and biogeochemistry of a javanese bamboo talun-kebun system. *Forest Ecology and Management*, *91*(2-3), 155–173.

Maimunah, S., Rahman, S. A., Samsudin, Y. B., Artati, Y., Simamora, T. I., Andini, S., Lee, S. M., & Baral, H. (2018). Assessment of suitability of tree species for bioenergy production on burned and degraded peatlands in central kalimantan, indonesia. *Land*, *7*(4). https://doi.org/10.3390/land7040115

Makwarela, M., Bada, S., & Falcon, R. (2017). Co-firing combustion characteristics of different ages of bambusa balcooa relative to a high ash coal. *Renewable Energy*, *105*, 656–664.

Marjokorpi, A., & Otsamo, R. (2006). Prioritization of target areas for rehabilitation: A case study from west kalimantan, indonesia. *Restoration Ecology*, *14*(4), 662–673.

McKendry, P. (2002). Energy production from biomass (part 1): Overview of biomass. *Bioresource technology*, *83*(1), 37–46.

Mei, R., Narihiro, T., Nobu, M. K., Kuroda, K., & Liu, W.-T. (2016). Evaluating digestion efficiency in full-scale anaerobic digesters by identifying active microbial populations through the lens of microbial activity. *Scientific reports*, *6*(1), 1–10.

Mishra, G., Giri, K., Panday, S., Kumar, R., & Bisht, N. (2014). Bamboo: Potential resource for eco-restoration of degraded lands. *Journal of Biology and Earth Sciences*, *4*.

Miyake, S., Smith, C., Peterson, A., McAlpine, C., Renouf, M., & Waters, D. (2015). Environmental implications of using 'underutilised agricultural land'for future bioenergy crop production. *Agricultural Systems*, *139*, 180–195.

Modi, A. (2021). Indonesia co-fires biomass at 17 coal-fired plants. https://www.argusmedia.com/en/news/2227825-indonesia-cofires-biomass-at-17-coalfired-plants

MoEF. (2017). Land cover indonesia. Retrieved January 10, 2021, from https://www.arcgis.com/sharing/rest/content/items/b1126d52d6c5416496339aeb250d9b39/info/metadata/metadata.xml?format=default&output=html

Mollins, J. (2021). Biomass energy brings clean electricity to remote indonesian islands. Retrieved February 15, 2021, from https://forestsnews.cifor.org/75178/biomass-energy-brings-clean-electricity-to-remote-indonesian-islands?fnl=en

Naqvi, M., Yan, J., Dahlquist, E., & Naqvi, S. R. (2017). Off-grid electricity generation using mixed biomass compost: A scenario-based study with sensitivity analysis. *Applied Energy*, *201*, 363–370.

Narendra, B., Kusmana, C., Karlinasari, L., et al. (2019). Critical land mapping for the development of biomass-based energy in east lombok regency, indonesia. *IOP Conference Series: Earth and Environmental Science*, *314*(1), 012072.

Nasendi, B. (1995). Bamboo for socio-economic development and sustainable resource management: The case of indonesia. *ENV" ONMENT*, 56.

Nath, A. J., Lal, R., & Das, A. K. (2015). Managing woody bamboos for carbon farming and carbon trading. *Global Ecology and Conservation*, *3*, 654–663.

Nazir, N. et al. (2019). Physicochemical characteristics analysis of biomass and calorie values of several types of bamboo in typologies of altitude in different growing sites. *IOP Conference Series: Earth and Environmental Science*, *347*(1), 012127.

NIOS. (n.d.). Bamboo plantation.

Nirala, D., Kumar, J., Ahmad, M., & Kumari, P. (1996). Bamboo based agroforestry system for livelihood and ecological security in north chhotanagpur division of jharkhand. *Journal of Pharmacognosy and Phytochemistry, SP1*, *1999*.

NL Agency. (2012). *Indonesia - market opportunities for bioenergy*. Netherlands Programmes for Sustainable Biomass, Ministry of Foreign Affairs.

Obidzinski, K., Andriani, R., Komarudin, H., & Andrianto, A. (2012). Environmental and social impacts of oil palm plantations and their implications for biofuel production in indonesia. *Ecology and Society*, *17*. https://doi.org/http://dx.doi.org/10.5751/ES-04775-170125

OECD. (2001). Land degradation. Retrieved January 20, 2021, from https://stats.oecd.org/glossary/detail.asp?ID=1494

Olsson, L., & Barbosa, H. (2019). *Land degradation - climate change and land: An ipcc special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* (tech. rep.). Intergovernmental Panel on Climate Change.

OpenStreetMap. (2022). Indonesia (with east timor). Retrieved February 7, 2021, from http://download.geofabrik.de/asia/indonesia.html

Paavilainen, E., & Päivänen, J. (1995). *Peatland forestry: Ecology and principles* (Vol. 111). Springer Science & Business Media.

Park, S., Lee, M., Febrianto, F., & Wistara, N. J. (2021). Effects on morphology and chemical properties of indonesian bamboos by carbonization. *Jurnal Sylva Lestari*, *9*(2), 190–201.

Park, S., Jang, J. H., Wistara, N. J., Ferianto, F., & Lee, M. (2019). Fuel properties of indonesian bamboo carbonized at different temperatures. *Bioresources*, *14*(2), 4224–4235.

Patel, B., Gami, B., Patel, A., & Patel, P. (2019). Wasteland utilization for b. balcooa cultivation: Socio-economic and environmental impacts through bamboo-based product development. *Eur J Sustain Dev Res*, *3*, 1–11.

Patel, B., Patel, A., Syed, B. A., Gami, B., & Patel, P. (2021). Assessing economic feasibility of bio-energy feedstock cultivation on marginal lands. *Biomass and Bioenergy*, *154*, 106273.

Patel, B., Patel, M., Gami, B., & Patel, A. (2021). Cultivation of bioenergy crops in gujarat state: A consultative survey process to understand the current practices of landowners. *Environment, Development and Sustainability*, *23*(6), 8991–9013.

Pattanayak, S., Hauchhum, L., Loha, C., & Sailo, L. (2020). Selection criteria of appropriate bamboo based biomass for thermochemical conversion process. *Biomass Conversion and Biorefinery*, *10*(2), 401–407.

Pertiwi, N., Rauf, B. A., & Lullulangi, M. (2021). Analysis of riverbank stability due to bamboo vegetation in walanae river, south sulawesi, indonesia. *Journal of Ecological Engineering*, *22*(9).

Petrenko, C., Paltseva, J., & Searle, S. (2016). *Ecological impacts of palm oil expansion in indonesia*. The international council on clean transportation (ICCT).

Pirard, R., Bar, S., & Dermawan, A. (2016). Challenges and opportunities of bioenergy development in indonesia. *CGIAR*.

Plantations International. (2020). Bamboo investment profile. Retrieved February 9, 2021, from https://www.plantationsinternational.com/bamboo/

PLN. (2021). *Diseminasi rencana usaha penyediaan tenaga listrik (ruptl) 2021-2030* (tech. rep.). Menteri Energi Dan Sumber Daya Mineral Republik Indonesia. Jakarta.

Poppens, R., van Dam, J., & Elbersen, H. (2013). *Bamboo : Analyzing the potential of bamboo feedstock for the biobased economy*. NL Agency, Ministry of Economic Affairs.

Prince, S., Becker-Reshef, I., & Rishmawi, K. (2009). Detection and mapping of long-term land degradation using local net production scaling: Application to zimbabwe. *Remote Sensing of Environment*, *113*(5), 1046–1057.

protectedplanet.net. (2022). Protected areas (wdpa). Retrieved January 11, 2021, from https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA

Purbasari, A., Samadhi, T. W., & Bindar, Y. (2016). Thermal and ash characterization of indonesian bamboo and its potential for solid fuel and waste valorization. *International Journal of Renewable Energy Development*, *5*(2), 95.

PwC. (2018). *Power in indonesia, investment and taxation guide*. PwC Indonesia.

QGIS.org. (2022). Qgis. Retrieved January 7, 2021, from https://www.qgis.org/nl/site/

Ramlan, Y. P., & Alif, H. H. (2021). In searching of biomass resource for gasification in indonesia. *Energy, COVID, and Climate Change, 1st IAEE Online Conference, June 7-9, 2021*.

Rathour, R., Kumar, H., Prasad, K., Anerao, P., Kumar, M., Kapley, A., Pandey, A., Kumar Awasthi, M., & Singh, L. (2022). Multifunctional applications of bamboo crop beyond environmental management: An indian prospective. *Bioengineered*, *13*(4), 8893–8914.

Republic of Indonesia. (2016). First nationally determined contribution republic of indonesia.

Rettenmaier, N., Schorb, A., Hienz, G., & Diaz, R. (2012). *Report on sustainability impacts of the use of marginal areas and grassy biomass* (tech. rep.). Institut für Energie- und Umweltforschung and Imperial College London.

Romshoo, S. A., Amin, M., Sastry, K., & Parmar, M. (2020). Integration of social, economic and environmental factors in gis for land degradation vulnerability assessment in the pir panjal himalaya, kashmir, india. *Applied Geography*, *125*, 102307.

Rothman, D. S., Agard, J., Alcamo, J., Alder, J., Al-Zubari, W., aus der Beek, T., Chenje, M., Eickhout, B., Flörke, M., Galt, M., et al. (2007). The future today. *United nations environment programme, global environment outlook geo 4 environment for development (section e-the outlook-towards 2015 and beyond, chapter 9)* (pp. 397–454). UNEP.

Rousset, P., Aguiar, C., Labbé, N., & Commandré, J.-M. (2011). Enhancing the combustible properties of bamboo by torrefaction. *Bioresource Technology*, *102*(17), 8225–8231.

Ruysschaert, D., Darsoyo, A., Zen, R., Gea, G., & Singleton, I. (2011). Developing palm-oil production on degraded land. *Medan: PanEco, YEL and World Agroforestry Centre*.

Sah, B. P. (2016). Geo-enabled decision support system for potential clean energy mix for bali, indonesia. *Energy Procedia*, *103*, 333–338.

Saha, M., & Eckelman, M. J. (2018). Geospatial assessment of regional scale bioenergy production potential on marginal and degraded land. *Resources, Conservation and Recycling*, *128*, 90–97.

Saito, G., & Prasetyo, L. B. (1999). Spatial database development for estimation of emission of greenhouse gases using remote sensing and gis in sumatra island, indonesia. *JIRCAS International Symposium Series (Japan)*.

Sastry, C. B., Ramanuja Rao, I., Ganapathy, P., Janssen, J. A., et al. (1996). Bamboo, people and the environment: Proceedings of the vth international bamboo workshop and the iv international bamboo congress, ubud, bali, indonesia, 19-22 june 1995; volume 1, propagation and management. *INBAR technical report; no. 8*.

Setiawati, T., MUTAQIN, A. Z., IRAWAN, B., ANâ, A., ISKANDAR, J., et al. (2017). Species diversity and utilization of bamboo to support lifeâ€™ s the community of karangwangi village, cidaun sub-district of cianjur, indonesia. *Biodiversitas Journal of Biological Diversity*, *18*(1).

Shah, K. N. A. K. A., Yusop, M. Z. M., Rohani, J. M., Fadil, N. A., Manaf, N. A., Hartono, B., Tuyen, N. D., Masaki, T., Ahmad, A. S., & Ramli, A. (2021). Feasibility study on biomass bamboo renewable energy in malaysia, indonesia, vietnam and japan. *Chemical Engineering Transactions*, *89*, 127–132.

Shahbaz, M., AlNouss, A., Ghiat, I., Mckay, G., Mackey, H., Elkhalifa, S., & Al-Ansari, T. (2021). A comprehensive review of biomass based thermochemical conversion technologies integrated with co2 capture and utilisation within beccs networks. *Resources, Conservation and Recycling*, *173*, 105734.

Sharma, R., Wahono, J., & Baral, H. (2018). Bamboo as an alternative bioenergy crop and powerful ally for land restoration in indonesia. *Sustainability*.

Singh, A. N., & Singh, J. (1999). Biomass, net primary production and impact of bamboo plantation on soil redevelopment in a dry tropical region. *Forest ecology and management*, *119*(1-3), 195–207.

Singh, L., Sridharan, S., Thul, S. T., Kokate, P., Kumar, P., Kumar, S., & Kumar, R. (2020). Eco-rejuvenation of degraded land by microbe assisted bamboo plantation. *Industrial Crops and Products*, *155*, 112795.

Singh, L., Thul, S. T., & Manu, T. M. (2021). Development of bamboo biodiversity on mining degraded lands: A sustainable solution for climate change mitigation. *Phytorestoration of abandoned mining and oil drilling sites* (pp. 439–451). Elsevier.

Singh, R., & Setiawan, A. D. (2013). Biomass energy policies and strategies: Harvesting potential in india and indonesia. *Renewable and Sustainable Energy Reviews*, *22*, 332–345. https://doi.org/https://doi.org/10.1016/j.rser.2013.01.043

Sofiah, S., & Susim, H. (2020). Bio-prospecting bamboo collection in purwodadi botanic gardens. *IOP Conference Series: Earth and Environmental Science*, *456*(1), 012079.

Solomon, T., Moon, H., Abebe, S., Minale, A., & Teketay, D. (2020). Promoting bamboo-based agroforestry for enhancing ecosystem services from degraded lands. *Agroforestry for degraded landscapes* (pp. 423–444). Springer.

Statista. (2022). Energy mix for power generation in indonesia as of may 2020, by source. https://www.statista.com/statistics/993362/indonesia-energy-mix-for-power-generation-by-source/

Sucipta, M., Negara, D. P., Nindhia, T. T., & Surata, I. W. (2017). Characteristics of ampel bamboo as a biomass energy source potential in bali. *IOP Conference Series: Materials Science and Engineering*, *201*(1), 012032.

Sujarwo, W. (2016). Stand biomass and carbon storage of bamboo forest in penglipuran traditional village, bali (indonesia). *Journal of forestry research*, *27*(4), 913–917.

Sulistyo, B., Gunawan, T., Hartono, H., Danoedoro, P., & Martanto, R. (2017). Proposed model on levels of degraded land at merawu watershed, banjarnegara regency, central java province, indonesia. *Biotropia*, *24*(3), 220–229.

Teng, J., Xiang, T., Huang, Z., Wu, J., Jiang, P., Meng, C., Li, Y., & Fuhrmann, J. J. (2016). Spatial distribution and variability of carbon storage in different sympodial bamboo species in china. *Journal of environmental management*, *168*, 46–52.

Toppo, A. (2022). A complete guide to bamboo cultivation. https://krishijagran.com/agripedia/a-complete-guide-to-bamboo-cultivation/

Toptas, A., Yildirim, Y., Duman, G., & Yanik, J. (2015). Combustion behavior of different kinds of torrefied biomass and their blends with lignite. *Bioresource technology*, *177*, 328–336.

Truong, A. H., & Le, T. M. A. (2014). *Overview of bamboo biomass for energy production* (tech. rep.). Hal.

UN. (2007). *Indicators of sustainable development: Guidelines and methodologies - third edition - methodology sheets* (tech. rep.). United Nations.

UNCCD. (2015). *Indonesia - land degradation neutrality national report*. Republic of Indonesia).

UNEP-WCMC, & IUCN. (2020). The world databas on protected areas (wdpa) [Accessed through Global Forest Watch]. Retrieved January 11, 2021, from https://globalforestwatch.org/map/

?mapMenu=eyJtZW51U2VjdGlvbiI6ImRhdGFzZXRzIiwiZGF0YXNldENhdGVnb3J5IjoibGFuZFVzZSJ9%5C&modalMeta=wdpa_protected_areas

UNEP-WCMC, & IUCN. (2022). The world database on protected areas (wdpa). Retrieved January 10, 2021, from https://www.protectedplanet.net/en

United Nations. (2015). Paris agreement.

Utami, N. W. F., Arifin, H. S., & HAS N, W. S. (2018). Community-based bamboo stands management in the kali bekasi watershed, indonesia. *Canadian Centre of Science and Education. Environ Nat Res Res*, *8*(1), 61–69.

Van der Laan, C., Wicke, B., Verweij, P. A., & Faaij, A. P. (2017). Mitigation of unwanted direct and indirect land-use change–an integrated approach illustrated for palm oil, pulpwood, rubber and rice production in north and east kalimantan, indonesia. *Gcb Bioenergy*, *9*(2), 429–444.

Van Holsbeeck, S., & Srivastava, S. K. (2020). Feasibility of locating biomass-to-bioenergy conversion facilities using spatial information technologies: A case study on forest biomass in queensland, australia. *Biomass and Bioenergy*, *139*, 105620.

Van Rooijen, L. W. (2014). Pioneering in marginal fields: Jatropha for carbon credits and restoring degraded land in eastern indonesia. *Sustainability*, *6*(4), 2223–2247. https://doi.org/10.3390/su6042223

van Dam, J., Poppens, R., & Elbersen, H. (2013). Analyzing the potential of bamboo feedstock for the biobased economy.

van Vuuren, D., van Vliet, J., & Stehfest, E. (2009). Future bio-energy potential under various natural constraints. *Energy Policy*, *37*, 4220–4230.

Vega, L., López, L., Valdés, C. F., & Chejne, F. (2019). Assessment of energy potential of wood industry wastes through thermochemical conversions. *Waste Management*, *87*, 108–118.

Vinanthi, F. R., & Sulistioadi, A. S. Y. B. (2021). Estimating above-ground carbon stock of loa haur conservation forest in east kalimantan, indonesia. *Joint Symposium on Tropical Studies (JSTS-19)*, 151–156.

Warren, M., Hergoualc'h, K., Kauffman, J. B., Murdiyarso, D., & Kolka, R. (2017). An appraisal of indonesia's immense peat carbon stock using national peatland maps: Uncertainties and potential losses from conversion. *Carbon balance and management*, *12*(1), 1–12.

Weiland, P. (2010). Biogas production: Current state and perspectives. *Applied microbiology and biotechnology*, *85*(4), 849–860.

Wicke, B., Sikkema, R., Dornburg, V., Junginger, M., & Faaij, A. (2008). *Drivers of land use change and the role of palm oil production in indonesia and malaysia* (tech. rep.). Universiteit Utrecht, Copernicus Institute. Utrecht, Netherlands.

Wicke, B., Sikkema, R., Dornburg, V., & Faaij, A. (2011). Exploring land use changes and the role of palm oil production in indonesia and malaysia. *Land use policy*, *28*(1), 193–206.

Widjaja, E. (n.d.). State of the art of indonesian bamboo. Retrieved February 18, 2021, from https://www.bioversityinternational.org/fileadmin/bioversity/publications/Web_version/572/ch26.htm

World bank. (2020). Overview. Retrieved March 23, 2021, from https://data.worldbank.org/country/indonesia

World Population Review. (2012). Indonesia population 2022 (live). https://worldpopulationreview.com/countries/indonesia-population

WRI. (2022). What is degraded land? Retrieved January 20, 2021, from https://www.wri.org/forests/what-is-degraded-land

Xu, Q.-F., Liang, C.-F., Chen, J.-H., Li, Y.-C., Qin, H., & Fuhrmann, J. J. (2020). Rapid bamboo invasion (expansion) and its effects on biodiversity and soil processes+. *Global Ecology and Conservation*, *21*, e00787.

Yoesgiantoro, D., Panunggul, D. A., Corneles, D. E., & Yudha, N. F. (2019). The effectiveness of development bamboo biomass power plant (case study: Siberut island, the district of mentawai islands). *IOP Conference Series: Earth and Environmental Science*, *265*(1), 012001.

You, S., Tong, H., Armin-Hoiland, J., Tong, Y. W., & Wang, C.-H. (2017). Techno-economic and greenhouse gas savings assessment of decentralized biomass gasification for electrifying the rural areas of indonesia. *Applied Energy*, *208*, 495–510.

Yusuf, S., Syamani, F., Fatriasari, W., et al. (2018). Review on bamboo utilization as biocomposites, pulp and bioenergy. *IOP Conference Series: Earth and Environmental Science*, *141*(1), 012039.

Zahraee, S. M., Mokhtar, A. A., Tolooie, A., & Mohd Asri, N. A. (2020). Performance evaluation of efb biomass supply chain for electricity power generation based on computer simulation: Malaysia case study. *Advances in material sciences and engineering* (pp. 363–375). Springer.

Zhang, X., Gao, G., Wu, Z., Wen, X., Zhong, H., Zhong, Z., Yang, C., Bian, F., & Gai, X. (2020). Responses of soil nutrients and microbial communities to intercropping medicinal plants in moso bamboo plantations in subtropical china. *Environmental Science and Pollution Research*, *27*(2), 2301–2310.

Appendices

A

LCOE assumptions and sensitivity analysis for pyrolysis, direct combustion, and anaerobic digestion

Figures A.1 and A.2 show the sensitivity analysis of the combustion and the anaerobic digestion LCOE, respectively.

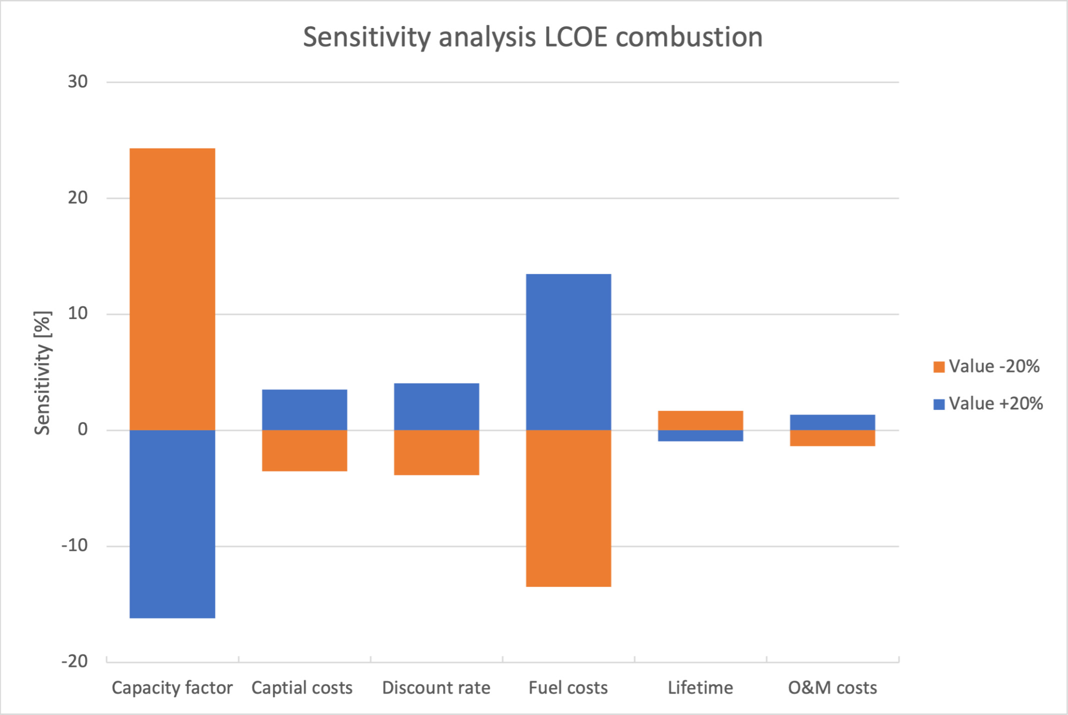


Figure A.1: Sensitivity analysis of the combustion LCOE per input parameter

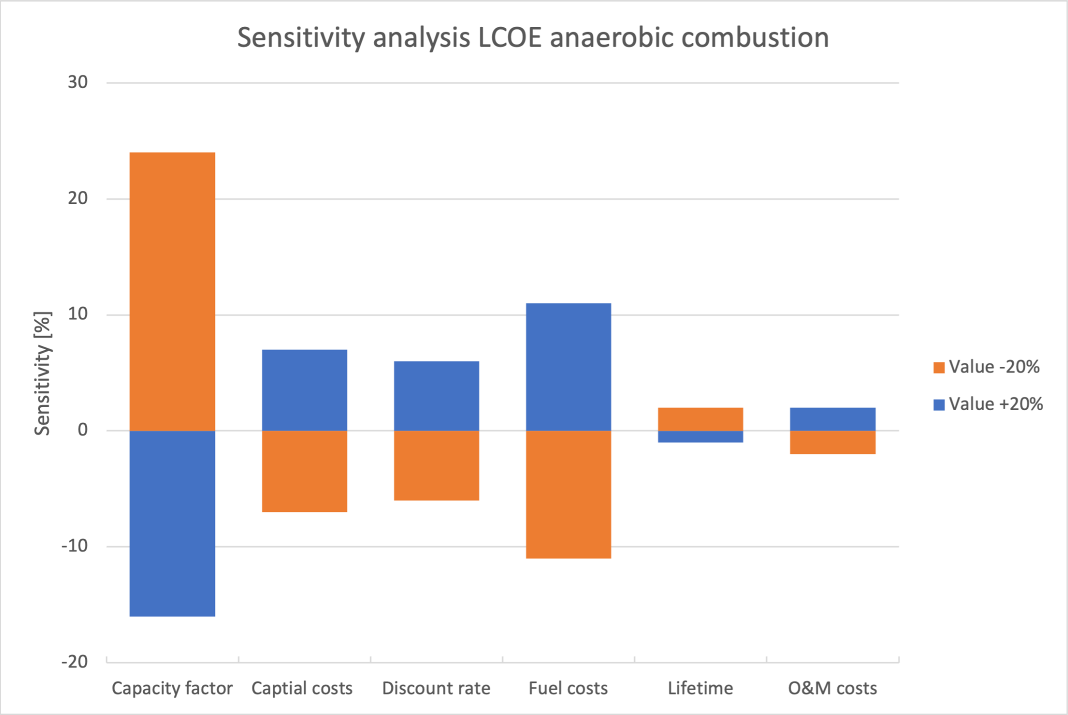


Figure A.2: Sensitivity analysis of the anaerobic digestion LCOE per input parameter

B

Locations included in protected areas data-set

According to Global Forest Watch (2019) locations that are included in the protected areas data-set area:

- Convertible production forest
- Game reserves
- Limited production forest
- Marine national park
- Marine nature recreations park
- National park
- National protected area
- Nature recreation park
- Nature reserves
- Non forestland
- Production forest
- Protected (from patch)
- Protection forest
- Wildlife reserves

According to UNEP-WCMC and IUCN (2020) the following areas are included in the protected areas data-set:

- Strict nature reserves
- Wilderness areas
- National parks
- National monuments or features
- Habitat and species management areas
- Protected landscapes and seascapes
- Protected areas with sustainable use of natural resources
- UNESCO-MAP Biosphere reserves
- World heritage sites
- Ramsar sites - wetlands of international importance