A Review on the Potential of Forest Biomass for Bioenergy in Australia

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Abstract: The use of forest biomass for bioenergy in Australia represents only 1% of total energy production but is being recognized for having the potential to deliver low-cost and low-emission, renewable energy solutions. This review addresses the potential of forest biomass for bioenergy production in Australia relative to the amount of biomass energy measures available for production, harvest and transport, conversion, distribution and emission. Thirty-Five Australian studies on forest biomass for bioenergy are reviewed and categorized under five hierarchical terms delimiting the level of assessment on the biomass potential. Most of these studies assess the amount of biomass at a production level using measures such as the allometric volume equation and form factor assumptions linked to forest inventory data or applied in-field weighing of samples to predict the theoretical potential of forest biomass across an area or region. However, when estimating the potential of forest biomass for bioenergy production, it is essential to consider the entire supply chain that includes many limitations and reductions on the recovery of the forest biomass from production in the field to distribution to the network. This review reiterated definitions for theoretical, available, technological, economic and environmental biomass potential and identified missing links between them in the Australian literature. There is a need for further research on the forest biomass potential to explore lower cost and lowest net emission solutions as a replacement to fossil resources for energy production in Australia but methods the could provide promising solutions are available and can be applied to address this gap.

Keywords: forest biomass; Australia; biomass energy potential; emission; bioenergy

1. Introduction

Forest biomass can provide additional revenue for forest managers and supply a bioenergy market to reach renewable energy targets. Using forest biomass for bioenergy has become an integrated part of forestry and a priority for all biomass utilization projects [1]. Large quantities of forest biomass are sustainably used around the world to generate heat, steam, and electricity through gasification and combustion processes [2,3]. Opposed to global bioenergy trends [4], there is little public or political support for the use of forest biomass in Australia [5]. With the lack of economic incentives, most of the non-merchantable forest harvest residues are burned in the forest or left to decompose on site. The bioenergy market represents only 4% of total energy production in Australia [6] and, of this, forest biomass is 25%, and bagasse is 29% [6,7]. Other renewables, including hydro (16%) and wind (12%) energy, have increased in the last decade [7]. Establishing a sustainable bioenergy market from

biomass in Australia requires consideration of the availability of forest biomass, sustainable harvesting, the cost of the biomass supply chain (BSC) and the greenhouse gas (GHG) emissions related to bioenergy production. The BSC encompasses many technical, economic and environmental constraints associated with harvesting, handling, storage, transport and conversion facilities [2,8–10]. Satisfying both environmental and economic objectives is a significant consideration for establishing the bioenergy industry [11].

The potential of forest biomass is categorized in the literature [12] into four sequential terms according to calculations needed in the assessment of biomass for biomass energy potential. The theoretical biomass potential relates to the annual yield of forest biomass per unit of area and can be considered the upper-bound of the potential [12]. Restrictions introduced by alternative biomass uses and efficiency at a biomass collection level are included. The term is also modified in the literature [13] as biologically available biomass and includes a range of ecological and economical reductions of the initial biomass to determine what is usable. Alternatively, a New Zealand literature example [14] refers to a similar term as total recoverable residue volume. Generally, the theoretical biomass potential captures all restrictions at a stand or production level. Secondly, the available biomass potential describes the energy that technically and economically can be harvested and transported for energy purposes before conversion [12]. This includes some limitations related to harvest machinery, truck size and transport distance. The term captures measures and restrictions of biomass energy at a harvest and transport level. Next, the technological biomass potential is defined by the energy that can be produced bound to conversion technology, the capacity of the conversion facility and the efficiency [12]. The term applies to research focused on-site identification for potential power facilities when inputs around available biomass, facility capacity and technology, and maximum allowable transport distance are known. The technological biomass potential accounts for technical restrictions on the available biomass and efficiency of the technology at an energy conversion level. At last, the economical biomass potential is the part of the energy that is distributed with respect to competing energy sources [12]. The term includes the energy production cost and the capacity of the facility, or rather the profitability of the proposed investment. A whole range of cost estimates of the entire supply chain can be included to determine if the economical biomass potential is feasible at a distribution level. The term environmental biomass potential is added to the four sequential terms described in the literature [12]. The environmental biomass potential sits at the same level of analysis as the economical biomass potential but opens perspective in emissions and other environmental measures related to bioenergy production. The term includes emissions that occur during energy production and non-biogenic emissions due to the use of machinery that affects the carbon-neutrality of the bioenergy system. In similarity to its economic counterpart, it pays respect to competing for energy sources and evaluates bioenergy in comparison with a reference or fossil energy system.

Forest biomass is considered a sustainable source of energy; however, only when grown and harvested in a sustainable manner [15]. The sustainability of forest biomass production systems must consider that forest harvest residues help sustain the fertility of the site, regulate water flow and maintain plant, microbial and animal biodiversity [1,16,17]. These considerations are classified under the constraints of the theoretical biomass potential. Additionally, economic sustainability constraints such as fuel versus food, efficient energy balance, and social constraints determine what is or is not a sustainable resource. International forestry guidelines and forest certification ensure sustainable forest management but need to address the specific impact of the additional harvest of forest biomass [18]. In Australia, guidelines such as the Forest Stewardship Council (FSC) and Responsible Wood, are inclusive of forest biomass harvesting to the extent of encouraging the harvest and respecting environmental values [19,20]. However, none of these guidelines provide directions on environmental, economic and social concepts of the theoretical biomass potential in Australian forests.

The overall cost of the BSC includes the economics related to harvest, collecting, transport and conversion of forest biomass. The cost of an economically sustainable BSC is heavily influenced by operating costs and the need to maintain a supply of forest biomass [21,22]. The economics related to

harvesting technology and collection methods [23] as well as biomass handling and storage are critical to ensure the reliability of supply [8,23]. The biggest cost contribution comes from transport which is determined by the quality and moisture content of the biomass and the mode of transport [24]. Forest biomass densities are generally low (400–900 kg/m^3) and moisture contents high (>50%), which results in transportation contributing 20–40% of the BSC cost [8,22,24–26]. Many of these cost measures determine the available biomass potential. Processing costs for converting forest biomass to bioenergy are determined by the technology used, the capacity of the plant, and the consistency/quality of supply [22]. In general, biochemical and thermochemical techniques are the most suitable for the conversion of forest biomass [27,28]. Processing into liquid or gaseous fuels can be done by biochemical conversion while combustion, gasification, and pyrolysis can be used to produce fuels, heat and electricity [11,27–30]. However possible, the forest biomass to the biofuel supply chain is still at a pre-commercial level in terms of technology [8]. These characteristics, together with the large, complex equipment required, and often the need for different transportation modes, create complex economic and logistic issues and result in losses of the technological biomass potential [8,22,31,32]. Several measures are in place to define the technological biomass potential. The input of energy, or primary energy that is already delimited by theoretical and available biomass potential constraints throughout the supply chain, and the type of technology and conversion efficiency, define how much useful energy we can get from the primary energy source. Different types of energy products are then sent to customers through the grid, networks or channels of distributors, wholesalers and retailers as net energy. In order to substitute for fossil fuel, it is important to check the energy balance of the proposed bioenergy system [33,34]. The net energy ratio, for example, is an indicative measure to ensure the system does not use more energy than it creates [33,35]. The ratio is defined by the produced energy/consumed energy ratio that equals the primary energy at the gate. The ratio is a supportive measure of the technological biomass potential and provides additional insight into the profitability of the system and thus the economical biomass potential.

The economic potential of the forest biomass supply is a function of the biomass availability and the profit during sequential steps of the value chain [8]. These measures aim to determine if the electricity production cost of a bioenergy facility is lower than the conventional power facility. Factors like internal return rate and net present value define profitability measures of the economical biomass potential and are indicators that allow us to accept or reject a proposed investment [12]. Several cost parameters should be considered to compare bioenergy and fossil energy systems. These include equipment and capital cost, the construction cost of power line and grid connection cost, stumpage cost for forest biomass, supply chain cost and additional maintenance and administrative cost [8]. Each of these costs contributes to the energy production cost or cash outflow in the net present value of the investment. The impact of the value chain can be extensive, and there is an unavoidable degree of uncertainty in the supply of forest biomass that makes the estimation of cost and profit hard to predict. Optimization and simulation models are tools that can provide further insight into the economical biomass potential, where the inclusion of a reference fossil fuel scenario should be considered [8].

Using forest biomass for bioenergy reduces GHG emissions compared to the use of fossil fuels and thus mitigates climate change. Biomass from a sustainably managed forest can be considered as a carbon-neutral energy source [36–38] since the carbon emitted during the energy conversion process is fixed relatively quickly during subsequent photosynthesis and tree-growth [37,39]. Life cycle assessment (LCA) of sustainably-sourced forest biomass for energy shows a period of climate warming impacts as a result of the delay for the CO_2 to be captured by new tree growth [36,40–42]. Evaluating environmental impact in an LCA must be comprehensive [22] and include all non-biogenic carbon emissions from the consumption of fossil fuels for production, transport, harvesting, collection, and pre-processing [43]. Other factors such as other atmospheric pollutants (e.g., methane) and the effects of direct and indirect land-use change affect the value chain and are important to the result of the LCA [11,43]. Land-use changes, due to replacing crops with intensive forest plantations, can increase GHG emission [11,44] but a change from crops that demand high fertilizer and pesticide inputs to a

forest that produces biomass for bioenergy can reduce GHG emissions [45–47]. Including emissions as a measure of the environmental biomass potential in balance with energy cost as a measure of the economic biomass potential in value chain optimization is becoming increasingly important for the sustainable utilization of forest biomass [22].

This case study review aims to identify gaps and approaches used to assess the potential of forest biomass for bioenergy generation in Australia and is structured around the hierarchical nature of biomass potential as defined in [12]. Evaluating Australian studies on forest biomass for bioenergy in Australia in their methods used to determine the theoretical, available, technological, economical and environmental biomass potential. In the next section, we explain the scope and methods that define the extent of the literature review. The following five sections review how research achieved the respective levels of detail in forest biomass potential. We discuss distinctive features and limitations in such a way as to make recommendations with regard to measures of forest biomass potential.

2. Scope and Methods

This study reviews forest biomass that includes pulpwood, forest harvest residues (FHR), and sawmill residues. Terms like remaining slash or logging residues are considered FHR and are plant materials that remain on-site after conventional logging. Pulpwood is logs harvested for pulp and paper but is also suitable for bioenergy production, usually obtained through thinning practices. Sawmill residues for this study include offcuts, dust, and shavings. Other forms of forest biomass are small hardwood logs [48]; coarse woody debris (CWD) [49] and wood from mechanical fuel load reduction [50], which resemble either FHR or pulpwood. Studies on firewood for domestic use are not included in this study unless it is part of their recourse in combination with one of the previously described forest biomass types. Regrowth and short rotation trees have potential as biomass for energy generation, but there are many uncertainties with regard to their distribution and climatic tolerance [51–53] and are not discussed in this review.

Assessing the theoretical biomass potential for bioenergy generation requires measurement of above-ground biomass. Logs used for timber and paper industries are not included in this assessment. Attributes of the supply chain using forest biomass must be present to categorize studies at a harvesting, collection and transport (available biomass potential) and conversion (technological biomass potential) level. The economical biomass potential concerns cost related to the production and distribution of biomass energy with respect to alternative energy uses and the environmental biomass potential includes GHG emissions related to the conversion of forest biomass to bioenergy along the value chain.

Online research papers published in English language academic journals were obtained by searching electronic databases including Google Scholar, Scopus, and Web of Science. The keywords used in searches were: 'Australia' and 'forest' and a combination of 'energy', 'biomass', 'bioenergy', 'waste', 'residue', 'supply + chain', 'emission' and 'sustainable'. Review papers were included, but book chapters and reports were excluded. The literature search covered the period 2000 to 2020. For each paper, the following information was collected and analyzed:

1) Primary publication data: year of publication, author(s), affiliations and journal titles;
2) Abstract and keywords;
3) Presence of the five biomass potentials;
4) Measures and attributes included in the calculation of the theoretical, available, technological, economical or environmental biomass potential.

Thirty-five original research journal articles were identified that assessed the use of forest biomass in Australia for bioenergy. The majority of these were published in the journals Biomass and Bioenergy (9), Forest Ecology and Management (6), and Australian Forestry (5). Most research (31 out of 35) considered the theoretical biomass potential and sixteen studies considered the available biomass potential. In ten research studies, the theoretical biomass potential was combined with the available biomass potential. Technological, economical and environmental biomass potential studies are far less

frequent with studies including a technological or environmental biomass potential being the lowest in frequency (6 out of 35). Figure 1 depicts the classification of the studies on forest biomass potential based on occurring measures in the research to provide an overview.
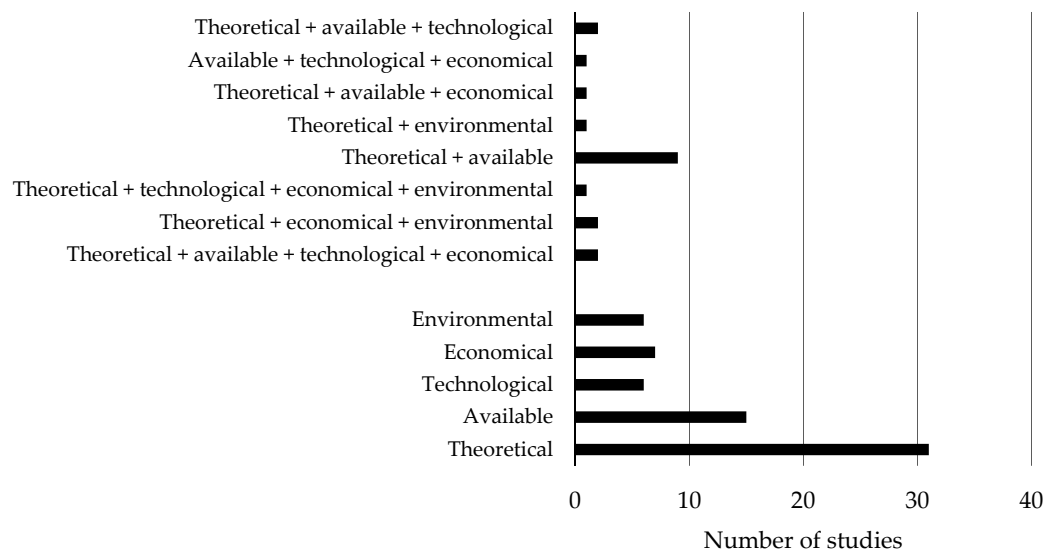

Figure 1. Classification of the reviewed studies on forest biomass for bioenergy in Australia according to the included measures of forest biomass potential.

3. Theoretical Biomass Potential

Thirty-one research studies include an assessment of the theoretical biomass potential (Table 1). In eighteen of these studies, the theoretical biomass potential is combined with the assessment of either available, technological, economical or environmental biomass potentials. Various studies have used allometric equations to predict the theoretical biomass potential based on in-field measures of height and diameter allowing them to estimate the overall above-ground biomass ratios [54–60]. For the purpose of bioenergy, these studies are rather informative literature on the ratio of above-ground biomass in order to assess the theoretical biomass potential without including any losses or alternative uses of the biomass. One can consider them indications of the upper-bound of biomass in the respective location and forest type. Similarly, an allometric equation is used to determine CWD removal benchmarks in the native forest of eastern Australia with the results being very specific for dead material only [49]. The study delivers good insight into the methods used to estimate the upper-bound of CWD but has no indication of further losses or potential of this biomass when extracted. Ximenes et al. (2006 and 2008) assessed the green weight of biomass using purpose-built trailers with built-in measuring devices [61,62]. The method provides an indication of the ratio of biomass in different forest types including some of the key tree species. The assessment of the theoretical biomass potential is once again restricted to a maximum allocation of the biomass without any indication of losses or harvestable volumes. Several papers calculated biomass quantity using the Cooperative Research Centre (CRC) for Forestry standard methodology [63] for sampling remaining slash [23,64–70]. In each of the papers, the CRC methods give a good indication of the number of residues that are left on-site before and after the removal of forest biomass. The methods have been tested in several case studies across Australia and have been applied in different harvesting systems like whole-tree, cut-to-length and integrated harvesting.

Table 1. Summary of forest biomass for bioenergy studies in Australia and indication on their inclusion of measures to assess the theoretical, available, technological, economic and environmental biomass potential.

Reference	Case	Theoretical	Available	Technological	Economical	Environmental
Fung et al. 2002	Outlining technologies for the conversion of woody biomass for heat and power generation.	×	×	×	×	
Specht and West 2003	Predicting biomass availability and carbon stock on farm forest plantations in northern New South Wales.	×				
Ritson and Sochacki 2003	Predicting biomass and carbon stock of *Pinus pinaster* trees in farm forestry plantations, southwest Australia	×				
Ximenes et al. 2006	Predicting the proportion of above-ground biomass in commercial logs and residues of spotted gum forest in southeast NSW.	×				
Raison 2006	Reviewing biomass supply technology, policy, availability and other impediments to expand forest bioenergy.	×			×	×
Cowie and Gardner 2007	Assessing GHG mitigation impacts of sawmill residues used either for the generation of electricity or the manufacture of particleboard.	×		×	×	×
Ximenes et al. 2008	Predicting the proportion of above-ground biomass in commercial logs and residues of five commercial forest species.	×				
Bi et al. 2010	Predicting above-ground biomass of *Pinus radiata* plantations from stand variables, geographical growth and yield models.	×				
Ghaffariyan et al. 2011	Evaluating biomass harvest in a poor-quality eucalypt plantation on yield and the productivity rates of equipment for harvesting.	×	×			
Rodriguez et al. 2011	Predicting the potential biomass availability for energy generation from forestry and agriculture in the Green Triangle.	×	×	×	×	
Farine et al. 2012	Predicting current and future biomass feedstocks for bioenergy, and associated estimates of the GHG mitigation.	×			×	×
Ximenes et al. 2012	Estimating GHG balance and emissions of two critical native forest areas managed for production in New South Wales in comparison with a conservation only scenario.	×				×
Ghaffariyan et al. 2012	Assessing biomass harvest using the Bruks mobile chipper for non-merchantable stem wood at the roadside in a pine plantation in Victoria.	×	×			
May et al. 2012	Assessing the energy balance of wood from softwood plantations and native hardwood forests, using a cradle-to-gate inventory.	×	×			
Moroni 2013	Reviewing GHG mitigation trade-off between storing carbon in forests and providing society with wood products.					×
England et al. 2013	Estimating GHG emissions associated with wood from softwood plantations and regrowth hardwood native forests.					×
Ghaffariyan 2013	Predicting remaining slash in different sites of plantations harvested by cut-to-length and whole tree method.	×				

Table 1. *Cont.*

Reference	Case	Theoretical	Available	Technological	Economical	Environmental
Ghaffariyan et al. 2013	Estimating BSC cost influenced by five operational factors: energy demand, moisture mass fraction, interest rate, transport distance, and truck payload.	×	×		×	
Walsh and Strandgard 2014	Predicting remaining slash after harvest stem wood biomass product from integrated cut-to-length harvest operations in *Pinus radiata* plantations.	×	×			
Mendham et al. 2014	Predicting the impact of repeated residue removal, retention, or retention of double the quantity of residues over two rotations of *Eucalyptus globulus* in southwest Australia.	×				
Ghaffariyan et al. 2014	Evaluating biomass harvest using a mobile chipper in a clear-felled area of pine plantations in Victoria.	×	×			
Meadows et al. 2014	Predicting the potential biomass for energy supply from hardwood plantations within the Sunshine Coast Council region of southeast Queensland.	×				
Ghaffariyan and Apolit 2015	Predicting remaining slash in Queensland pine plantations harvested by cut-to-length and whole tree method.	×				
Ghaffariyan et al. 2015	Evaluating biomass harvest of an integrated energy wood harvesting system compared to conventional log harvesting in a 32-year-old *Pinus radiata* plantation located in southwest Western Australia.	×	×			
Rothe et al. 2015	Predicting the current use and the potential sustainable supply of forest biomass in Tasmania.	×	×			
Cummins et al. 2016	Reviewing the biomass supply to produce liquid fuels and electricity using small hardwood logs.		×	×	×	
Crawford et al. 2016	Predicting spatial availability of biomass for bioenergy in Australia in 2010, 2030 and 2050.	×				
Wang et al. 2017	Predicting residue weight of individual trees in rotation age (28 to 42 years) *Pinus radiata* stands under three thinning regimes.	×				
Ximenes et al. 2017	Reviewing biomass harvest from mechanical fuel load reduction.	×	×	×		
Ghaffariyan et al. 2017	Reviewing biomass supply and recovery technologies from forests to gate.		×			
Ngugi et al. 2018	Predicting potential harvestable biomass for bioenergy from sustainably managed private native forests in southeast Queensland.	×				
Woo et al. 2018	Optimizing biomass energy facility locations, and allocation for supply.	×	×	×		
Garcia_Florez et al. 2019	Developing species-specific biomass estimation models (BEMs) for stem, bark, branch and crown compartments in 16-year old plantations of *Eucalyptus dunnii* and *Corymbia citriodora*.	×				
Threlfall et al. 2019	Predicting the amount of CWD in the harvested and unharvested native forest of eastern Australia.	×				
Strandgard et al. 2019	Reviewing BSC experience applied to reduce costs in emerging Australian forest BSC.	×	×			

Three studies assessed the theoretical potential of forest biomass across the nation using a range of literature assumptions applied on statistical data of the forest industry reported by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARE) [53,71,72]. Their research combines geographical distribution of the forest with annual forest production data and sawmill survey results. To estimate the quantity of biomass the research includes losses through a range of diversion and conversion parameters retrieved from the literature. The combination of statistical inventory data and literature is also applied in a method to estimate the theoretical forest biomass potential on the Sunshine Coast Council in a 20-year prediction [73]. Similarly, a current and potential forest biomass scenario was established for Tasmania [74]. The studies by Farine et al. (2012) and Crawford et al. (2016) also rely on the use of the 3-PG model [75], which is a process-based forest growth model, to estimate the theoretical biomass potential of forest biomass in the future. A similar method was applied in the Green Triangle in South Australia to assess the year-by-year biomass availability [76]. Because of the smaller scale and unified nature of the forest in the Tasmanian research paper [76], researchers were able to include more detail on forest biomass availability by including thinning practices and moisture content. Ximenes et al. (2012) used the Forest Resource and Management Evaluation System (FRAMES) model to predict the wood supply and converted yield to theoretical biomass potential of two case study areas [77]. The model includes three modules on inventory, growth and mortality models, and yield simulation including a future prediction for the next 200 years. Another case study in Tasmania [78] used a non-industrial private native forest (NIPNF) modelling approach to assess theoretical biomass potential in Tasmania. Their research includes a range of limitations on the land availability of harvest of forest biomass, year-to-year variation, moisture content and rotation of forest harvest. The importance of moisture content was also highlighted in a New South Wales case study [79] where three different scenarios of forest biomass are compared in their total emission and energy. Other than having the direct impact of moisture content on energy production, there were no other indications as to how respective biomass quantities were measured in the three cases [79].

The remaining studies review the theoretical potential of forest biomass but do this as part of a literature review of the potential of forest biomass for bioenergy in Australia or the application of biomass supply chain on a national scale [5,80,81]. Lastly, Ximenes et al. (2017) discuss some of the measures to assess the potential of CWD and standing forest biomass for mechanical fuel load reduction.

4. Available Biomass Potential

In fifteen of the reviewed studies, the available biomass potential is measured or discussed (Table 1). An international study [25] reviews some previous research in Australia on the cost related to harvesting and forwarding of biomass from forest to roadside, primarily using time-motion-studies, and reference some of the following work in different harvesting systems. Cost (USD/t), fuel consumption (L/t), and energy content (MJ/t) of slash bundling operations and total operational cost (USC/kWh) of a slash-bundler application to collect harvest residues in Eucalyptus plantation are measured using time-motion-studies [65]. The chipping cost (USD/t) and forwarding cost (USD/t) are analyzed using time-motion-studies on Bruks Chipper operations in Pine plantations [23,67]. Similarly, time-motion-studies in integrated harvest sites in Pine plantation were carried out to measure productivity and unit cost (AUD/m^3) of harvesting and forwarding operations [69]. Walsh and Strandgard (2014) also used time-motion-studies to assess the productivity of harvest and extraction in a Fibreplus operation in Pine plantations. None of these studies assess the available biomass potential after potential losses that occur during transport.

Rodriguez et al. (2011) used a transportation model to calculate the costs of transporting logs and chips. Literature values were used for the costs of collection and processing of biomass in the field. This model incorporated fixed and variable (costs to estimate the average costs per tonne-km^{-1} transport based on the one-way distance to destination and load mass. Fixed costs included capital depreciation, interest charges, labour, registration, insurance, repairs, maintenance, and salaries. Variable costs covered fuel, oil, and tyres. Using a 16–18 MJ/kg conversion, they estimated how much biomass energy

(MJ) was available before conversion. May et al. (2012) used the SimaPro model to estimate the energy use in forestry operations and included the establishment, management, harvesting and transport of logs. The analysis included calculations for transport, mean travel distance, load weight and fuel consumption and other materials. They presented an intermediate energy (MJ) value and used a 19.6 MJ/kg conversion rate for biomass chips. The BIOPLAN model [70] calculates the cost of the BSC and is based on the following factors: tonnes biomass, solid and lose volumes of biomass, truckloads, energy contents (17.38 MJ/kg), and costs of harvesting, extraction, chipping, storage and transportation. Woo et al. (2018) included the cost of transport and moisture content in a linear programming model to identify locations for new bioenergy facilities based on the available biomass potential. All of these modelling approaches include measures of the available biomass potential to the extent of what is technologically and economically harvestable.

Strandgard et al. (2019) reviewed the potential relevance to Australia of overseas supply chain models such as MCPLAN [24] and other measures of the available biomass potential (transport distance, load size, harvest rates and machine types). Ximenes et al. (2017) reviewed some considerations and conditions around different harvesting systems of CWD which result in the material either retained or captured for use. The remaining studies in Table 1 do not include any measures directly related to the available biomass potential other than the energy content of their respective resource and case study [48,74,77,79,81].

5. Technological Biomass Potential

The efficiency of conversion technology is determined as one of the most impacting factors of the technological biomass potential. The primary energy (often mentioned in MJ) going into conversion gets reduced according to the type of technology used, the output energy type (unit of Watt) and the efficiency of the process [81]. Efficiency indicates how much useful energy we can get from an energy source according to the conversion technology. Some of the Australian forest biomass research studies have included a sensitivity analysis to determine the efficiency of the conversion [48,79]. Variations in the efficiency of 10% in a combusting co-firing plant are tested with results reflecting on emission resulting from burning the biomass [79]. Variation (15–20%) in the efficiency of a Fisher–Tropsch synthesis is tested together with transportation distance to confirm if the supply of biomass supports the demand [48]. A conversion efficiency of 30% was used for a combined heat and power plant in the literature [77] and 25% for direct combustion by a Tasmanian research study [76] stating this lower-cost solution with smaller plant sizes (5 MW) tend to be more profitable in comparison with different biomass-based technologies for electricity generation. As expected, efficiency is the most common technological criteria to evaluate the bioenergy system. No further measures of energy ratio or energy balance were included.

Woo et al. (2018) determined the potential capacity of power facilities based on transport distance and moisture content by performing location-allocation network analysis. By supplying the required demand, they identify the most optimal locations to put power facilities with the least cost contribution from transport. The resulting capacity of the facility then relies on the amount of biomass that lies within the distance threshold and is economically transportable (available biomass potential). No conversion technology or efficiency was selected and no sensitivity analysis was performed. The methods can be used, however, for the design and planning of future facility locations and allocation of resources, providing that different capacities and technologies (including conversion efficiency) be tested to determine the lowest cost and emission solution.

6. Economical Biomass Potential

Several studies identify the economical biomass potential as an indicative value based on literature but do not include any measures of electricity production cost or return rates or the production of electricity of other energy types. Fung et al. (2002) mention a 3.4 TWh per year electricity potential from wood processing residues in Australia. According to Raison (2006), this potential lies 2.8 TWh

per year based on dry forest biomass. Farine et al. (2012) estimate a 13 TWh energy potential and is the most recent published value based on forest biomass.

The only study in Australia effectively measuring the economical biomass potential compared to the electricity generation cost of biomass powered system with a coal-fired generation in a case study [76]. The research estimated the Levelized Electricity Cost (LEC) using a 30-year facility life and an annual interest rate r of 7.5%. The following formula was established:

$$\text{LEC} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}, \tag{1}$$

where I_t represents the initial investment for a direct combustion biomass electricity facility and M_t represents the maintenance and operating costs (excluding biomass purchase). The feedstock expenditure F_t is estimated based on the plant gate price of the feedstock multiplied by the amount of biomass required to run the plant, and finally, E_t is the amount of electricity generated every year.

There are no literature examples on optimization or simulations of the forest biomass supply or value chain that indicate electricity production cost for a bioenergy system in Australia. In the future, there could be the potential to establish costs associated with reductions of GHG emissions and costs associated with social benefits. Thus far, no studies in Australia were able to capture these costs in their methods.

7. Environmental Biomass Potential

The environmental biomass potential, more particularly the displaced GHG, and net GHG mitigation were assessed by Farine et al. (2012) who used forest inventory reports and literature conversion factors. This study calculated the emission (the equivalent of CO_2) associated with the various pathways from feedstock to bioenergy by summing the emissions related to production, transport, conversion, and combustion in Australia. Several scenarios of using forest biomass and the role of forest in GHG mitigation in Australia are reviewed [82] and implemented in a New South Wales case study [77]. The New South Wales case study used a carbon accounting model to estimate the greenhouse gas balance in a comparison between a timber-production and a conservation scenario. Modelling considered emissions resulting from the establishment and management of forests, harvesting, transport to the mill, manufacturing, transport to consumer and disposal. The research also compared results with emissions from the manufacture of non-wood products and the use of fossil energy. No specifics of the models' calculation are provided, and most of the emission factors are retrieved from a life cycle inventory report from Australia [83].

The SimaPro LCA model used by England et al. (2013) was combined with survey data on emissions and the Australasia Ecoinvent database and incorporated emissions from burning fossil fuel, non-CO_2, fire, establishment, management, harvest, haulage, transport, and fertiliser. A sensitivity analysis was used to assess the influence of varying parameters and assumptions on carbon emission and tested in a ±20% range. No details on the LCA model and calculations are provided.

Cowie and Gardner (2007) performed a comparative study on the use of sawmill residues for the generation of electricity and the manufacture of particleboard using emission equations. Calculations of GHG emissions included those associated with harvesting, collecting, chipping transport, processing at the mill, evaporation of moisture, and re-establishment of the plantation [79]. The study uses a reference fossil fuel scenario to calculate the net emission reductions from the two alternative bioenergy scenarios. In comparison, they excluded al common factors between the reference and case scenarios. For the bioenergy cases, the avoided emission is calculated considering the variation in carbon emission per unit primary energy and the variation in the efficiency of combustion. Emission of CO_2 that are avoided are calculated as the mathematical product of CO_2 equivalent in the biomass utilized and a "displacement factor" (DF), where:

$$DF = \frac{\text{efficiency of bioenergy system}}{\text{efficiency of fossil system}} \times \frac{CO_2 \text{ emission per J fossil fuel}}{CO_2 \text{ emission per J biomass}}. \qquad (2)$$

Emissions of CO_2 as a result of biomass combustion are excluded based on biomass production from a sustainably harvested plantation.

8. Discussion

The review above demonstrates a number of methodological approaches as well as variations in data, data models, scale on which the methods are applied and the detail of calculations that are included. The purpose of this discussion is to elaborate on some of the main results and challenges that need to be addressed in future research.

Almost every study presents measures of the theoretical biomass potential to a certain degree. There is however a clear distinction between studies that do an initial measurement of forest biomass which could be referred to as the maximum or upper-bound biomass potential and studies that included a measure that reduces that potential to what will be considered usable as defined by Shi et al. (2008). Field measurements involving weighing biomass or using allometric equations based on tree height and diameter are complex and time-consuming but provide reliable estimates of that upper-bound biomass potential and provide forest or species-specific estimates. These case-specific values can then be used for large-scale or nationwide estimates of the forest biomass potential [53,71,72,84] that use these literature values with the modelled prediction on losses of the theoretical biomass potential. Inevitably, the accuracy of this combination decreases as research becomes more generalized. Using case-specific inventory data on the upper-bound biomass and generalizing this over larger, sometimes nationwide, areas give a doubtful indication of the theoretical biomass potential. It is, however, hard to say what is good or bad and often the level of accuracy is sufficient on a larger scale. This coarser resolution and large-scale are still relevant from a policy and planning point of view where it provides sufficient indication of biomass location and the possible potential. Alternatively, there are in-field measures of the usable biomass available like those referred to as the CRC for Forestry method described in the literature [63]. Methods like CRC for forestry, are applied after a timber harvest and give a better indication of the parts of the leftover biomass that could be collected for energy purposes, and reduce the level of assumption for the theoretical biomass potential. Sequentially, combining it with high accuracy growth models can predict future levels of biomass on a local scale, which then can be used as indicative measures of future potential, which will be used to establish renewable energy targets. Based on the available research around the theoretical biomass potential, there is no clear gap to identify. Future research should thus consider the level of accuracy that is required and the data that is available to guide the methodology. It is, however, worth noting that no method exists that measures only the amount of biomass that will be used for bioenergy and will be collected and transported. Even the CRC for Forestry method has an emphasis on "collectable" biomass; the results also indicate a lot of work goes into measuring biomass like cones, needles, leaves and twigs that are not feasible for collection. We suggest that this might require an approach working top-down by determining the biomass that is suitable for conversion in the facility, will have higher gate price, can be transported and harvested with high efficiency, to then determine what percentage of the total above-ground or post-timber harvest biomass this represents. To do this, the link between the theoretical biomass potential and the available, technological, economic and environmental biomass potential needs to be established in the Australian supply chain context. Another recommendation concerning the theoretical biomass potential is to use it as an instrument to inform policy in Australia and to adjust biomass-harvesting guidelines. Currently, none of the forestry guidelines including FSC and Responsible Wood is descriptive on the retention of forest biomass with respect to environmental, economic and social benefits.

Having been critical in some of the models used in the previous studies, it is worth recognizing that they provide direct insight into some of the planning issues regarding harvest and transport and thus the available biomass potential in relation to the theoretical biomass potential. More specifically,

there is a particular emphasis being placed on the use of geographical data in combination with the literature or inventory data on the forest biomass. Some of the models that were used in the reviewed studies [70,71,76,78] make this exact connection as to how the cost of harvesting and transport affect the retention of biomass in the forest. Rather than looking at a steady-state situation of the forest, a method to assess the available biomass potential should look into changes in the biomass quantity over time as well as changes in the geographical location of biomass. Several studies can be found in the international literature, simulating changes in the supply of biomass-based on stand age, fire salvage or terrain [85–88]. If research wants to inform investors and if the location is pre-defined, high resolution of the geographical area and theoretical biomass potential should be combined to assess what is the available biomass potential. In addition to that, there is a need for performance values of the equipment, used along the supply chain. Although performed in just a handful of case studies in Australia, Ghaffariyan et al. (2017) summarize some of the operational costs of harvesting forest biomass equipment. For reference to transportation costs, some international models can be used as described by Strandgard et al. (2019). The assessment of the available biomass potential opens a whole new level of detail again, from different harvesting technologies for the timber as well as the forest biomass, different sizes and loads of trucks for transport, potential pre-treatment and storage to reduce cost and emission during the supply chain. Extensive modelling can be performed and numerous constraints can be added to the research model [2,9,22]. Although not as extensively researched as some studies in other countries or geographic areas, the biomass supply chain modelling research [70,71,76,78] that has been performed in cases in Australia is adequate to give an indication of the available biomass potential and to develop strategies in the commercial harvest of biomass for bioenergy production. Given the lack of commercial cases in Australia that effectively use forest biomass for bioenergy production, there is no established supply chain as a reference. Therefore, the word "optimisation" in research should be used carefully, as Australia aims to find a range of solutions rather than one lowest-cost or lowest emission solution. The type of optimization that can be performed is illustrated by Woo et al. (2018) where a plant location-optimization is performed based on the available resource and cost estimates of the supply chain. This type of research does address the biggest cost element of the supply chain which is transport [24] but is not affected by other elements, like harvesting or storage of the resource. Instead, the optimization is used as a planning and development tool to identify locations that are suitable for biomass conversion based on the availability of the resource, and thus paying respect to the theoretical and available biomass potential. Additionally, the network analysis of this study [78] delivers insight into the demand for energy which then leads into the technological and economical biomass potential. Similar approaches can be found in the international literature combining measures of the theoretical and available biomass potential [13,89,90]

In regards to the technological biomass potential the study by Woo et al. (2018), is perhaps the most comprehensive to find in Australia, even though no selection of conversion technology or sensitivity was applied. The method they use allows for additional measures of the technological biomass potential and has been used widely in the industry [13,90–92]. Network analysis based on spatial information can be used to identify the location for bioenergy conversion based on biomass availability and cost attributes of the supply chain. The assessment of the biomass potential of a regional network should be considered carefully when expanded to larger scales. Additionally, network analysis can be used to identify the size of the processing plant based on demand, technology and supply as well which is demonstrated in several case examples in New Zealand [14], Finland [93], Mozambique [94] and the USA [95,96]. The method is a streamlined combination of geographic information systems, mathematical modelling and network analysis that aligns in a decision support system. This is where some of the gaps in research become very apparent for Australia. The number of studies that assess the technological, economic and environmental biomass potential is significantly lower than the studies identifying the theoretical and available biomass potential discussed earlier (Figure 1). A couple of studies tested the sensitivity of an established biomass conversion technology [48,79], and do well in

comparing the technology with a reference fossil conversion system which indicated gains of carbon emission and economic return over time. However, it is hard to draw conclusions from these two cases. It is imperative to have cases looking at specific conversion technology and efficiency to use in combination with planning and decision support systems to assess the large-scale technological potential of forest biomass. An example case study from the international literature [97], looks at the sensitivity of minimum energy recovery and thermal energy production constraints to impose that the amount of renewable energy produced meets the demand of the catchment area.

In addition to what Voivontas et al. (2001) introduced as the theoretical, available, technological and economical biomass potential, this review introduces the environmental biomass potential. One can assume the environmental biomass potential flows from the technological biomass potential in similarity with the economical biomass potential. Rather than having an economic output, the environmental biomass potential pays respect to carbon emissions resulting from the use of forest biomass for bioenergy. As argued in the literature [17,22], the use of forest biomass for bioenergy should consider economic and environmental constraints in order to assess its feasibility. Out of the three studies that had an economical and environmental element in their research [5,53,79], two studies were able to provide simultaneous measures of the displaced emissions and the provided energy [53,79]. Other than a potential energy production for distribution, there was no information on the cost of energy production, or cost-savings compared to a reference scenario as performed by Rodriguez et al. (2011). Whether performed separately or combined, one could argue that the use of LCA and value chain optimization provides a solution to address the potential of forest biomass from an economical and environmental point of view [8,98]. Australian studies by May et al. (2012) and England et al. (2013) estimated the embodied energy used and emissions from cradle to gate in the Australian forestry context. Their research emphasizes the difference between LCA as a means of assessing emission and energy associated with wood products including alternative uses, compared to life cycle inventory and cradle-to-gate inventory providing emissions associated with forest supply chain [84]. Thus, there is a need for a clear definition of the forest biomass for bioenergy system when it comes to assessing the economic and environmental value. Good research examples in Australia are available however not on the use of forest biomass for bioenergy. Several international studies can be found capturing constraints for the theoretical, available, technological, economic and environmental biomass potential [10,99,100]. A reference case study in Australia is research by Murphy et al. (2015) and Hayward et al. (2015) on the economics and sustainability of producing aviation fuels from energy crops in Queensland Australia. Their research indicates some of the future challenges of the industry, which include the expansion of case studies on a larger scale to make it reliable and sustainable. This challenge confirms findings in this review where we identify a need to use some of the case-specific data in combination with modelling to provide estimates on a larger or nationwide scale. A second challenge is to demonstrate that the industry can satisfy community demand and compels with sustainability expectations. Indeed, one of the findings of this review is to come up with a more comprehensive design and planning solutions for the forest biomass supply chain and the establishment of new conversion facilities. This is where the use of geospatial data and modelling comes in place to develop a decision support system that not only satisfies the supply but also lives-up to demand sustained energy production. Another recommendation is the need for full LCA to determine the total carbon footprint. However, defining the limit of LCA is important and can be challenging. Bioenergy projects in Australia are fairly new and thus the total effect on the energy market is yet to be discovered, especially in the long term. In addition, the adverse effect on the timber industry and other industries that deliver biomass feedstock needs to be considered. The last challenge that has relevance to the use of forest biomass for bioenergy is the risk of uncertainty of the supply chain and its elements. Future research has to bridge this gap mainly through securing the supply chain and finding a long-term supply of biomass for energy production. This finding enforces the need to make connections between the theoretical, available, technological, economic and environmental biomass potential once again.

9. Conclusions

In order to exploit biomass for bioenergy in Australia, the potential of forest biomass needs to be assessed, and methods need to be established to determine and evaluate the potential. This review applied four definitions of biomass potential as defined by Voivontas et al. (2001) and added a fifth definition for the environmental biomass potential. Although giving general definitions, this review evaluated some of the measures of biomass potential found in Australian forest biomass for bioenergy studies.

Almost every study includes measures to assess the theoretical forest biomass potential. The link with the available or technological, economical and environmental biomass potential is rare, however. Promising methods using decision support systems based on geographical data and modelling can be developed to make this connection and methods like LCA and value chain optimization might provide insight into the extensive possibilities around the economical and environmental biomass potential.

These methods have been used in other parts of the world and, with appropriate and accurate data, could be used in Australia to estimate costs-savings and emissions as an end-result. This information can then be used to initiate investment, simulate what can be achieved, and optimize business solutions to grow, harvest, transport and convert forest biomass for bioenergy.

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