Bioenergy options for New Zealand: key findings from five studies

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Studies on bioenergy opportunities available to New Zealand found wood from plantation forests is the largest biomass resource and the one with most potential to expand. The use of municipal solid wastes and industrial effluents for energy gave significant environmental benefits, but makes a small contribution to total energy demand. The potential of plantation forests to create a carbon store, garner environmental benefits, and create lumber and energy supplies are substantial. After considering several aspects, including domestic energy supply and demand, key to maximizing these benefits for New Zealand is the development of biomass to liquid fuels conversion technologies, focused on wood to drop-in liquid fuels. Establishment of large-scale woody biomass resources producing multiple products including energy could mitigate risks associated with other bioenergy options by

- Being based on an existing industry;
- Not impacting exports from arable and high-value pastoral land;
- Acting as significant long-term energy store;
- Providing carbon sequestration during establishment and growing phases and additional carbon stocks from new forest area;
- Providing environmental services, stabilizing erosion prone land, providing low-input (fertilizer, pesticides) land use, and improving water quality;
- Producing sustainable coproducts, traditional timber products, and high-value biomaterials and chemicals;
- Providing the forest industry with a significant alternative market for low-value log products;
- Stimulating regional development;
- Providing year round biomass supply.

The opportunity to substitute fossil fuels with domestically produced biofuels could bring long-term economic and environmental benefits to the country through better utilizing New Zealand's natural capital.

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BACKGROUND

The project, Bioenergy Options for New Zealand, was initiated to consider the potential contribution of bioenergy to New Zealand's energy future. The project began in March 2007 and ended in December 2009.

The projet began by exploring the bioenergy potential of existing biomass resources, being the residues or wastes from a range of agricultural, forestry, industrial, and municipal sources.[1] The life cycles and economics of some biomass to energy routes were assessed.[2] A research and development strategy was developed that aimed at identifying priority research areas to fill gaps specific to

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New Zealand's position.[3] Having identified that a key biomass resource was wood, and that New Zealand's climate and land resources lent themselves toward medium-to-long (20–30 years) rotation forests some large-scale afforestation scenarios were developed and their wood, energy, environmental, and economic impact assessed.[4] The project concluded with a report that outlines how New Zealand might move toward become self-sufficient in transport fuels produced from biomass grown in sustainably managed forests.[5]

This summary presents the key findings from each of the five reports in the Bioenergy Options study.

NEW ZEALAND AND ITS ENERGY DEMAND AND SUPPLY

New Zealand is a small (268,680 km^2, comparable in size to the United Kingdom) island nation in the South West Pacific. It comprises two main Islands (North and South, Figure 3) and a host of smaller mostly uninhabited islands. It has a temperate subtropical climate with a small population (4.4 million) and low average population density (6.5 ha per person). However, around 1.6 million live in the Auckland/Waikato/Hamilton area. New Zealand is a parliamentary democracy and has a developed market economy, based largely on export of primary produce (farming, forestry, horticulture, and fishing) and tourism. Key trading partners are Australia, China, the United States, Japan, and Western Europe.[6,7]

In 2010, New Zealand had a primary energy demand of ~781 pJ.[8] This demand was made up of 58 pJ of coal, 273 pJ of oil, 140 pJ of gas, and 310 pJ of various renewables (hydro, geothermal, wind, biogas, wood, etc.).

Consumer demand for electricity was 143 pJ, with ~76% from renewables made up of 89.0 pJ from hydro (62.2%), 9.5 pJ from geothermal (6.6%), 5.9 pJ from wind (4.1%), and 5.1 pJ from wood via combined heat and power (CHP) (3.6%).

Primary energy demand for electricity was ~223 pJ. In addition, some gas and coal is used for electricity generation. Electricity generation from renewables is expanding, with substantial new geothermal and wind generation both planned and being constructed.

Liquid fuels demand (domestic) was 6.836 billion liters (232 pJ) made up of a mix of petrol, diesel, jet fuel, and fuel oil. If international use (ships and planes from and returning to overseas ports refueling in New Zealand) is included the total rises to around 8.1 billion liters or 280 pJ. Oil imports cost NZ$ ~9.0 billion in 2009.

TABLE 1 | New Zealand's Plantation Forest Resource (as at April 2011) (Created Using Data from the Ministry of Primary Industries—A National Exotic Forest Description as at April 1, 2011.)

Net Stocked Forest Area (ha)[1]	1,719,400
Area by species (ha)	
Radiata pine	1,545,000
Douglas-fir	107,000
Cypress species	10,000
Other exotic softwoods	24,000
Eucalyptus species	22,000
Other exotic hardwoods	13,000
New planting (ha)	
Total estimated new planting (ha per annum)	6,000
Harvesting (ha)	
Area clear felled (ha)	43,300
Average clear fell yield (m^3/ha)	505
Area-weighted average clear fell age for radiata pine (years)	28.6
Estimated planted forest round wood removal (m^3), year ended March 31, 2011	21,926,000

[1] Excludes area awaiting replanting ~54,300 ha.

New Zealand uses 36.2 pJ of coal and 58 pJ of gas for heat. There are no gas fields in, or gas pipelines to, the South Island, so industrial use of gas in the South Island is limited. However, the South Island has abundant coal and lignite reserves. New Zealand has large coal resources; and at current consumption rates, these reserves could last several hundred years. New Zealand's largest consumer energy demand is for liquid transport fuels, and this demand is growing at around 1% per annum.

The government via the state-owned coal company Solid Energy has considered the use of the lignite resource in Otago and Southland for producing either or both liquid fuels or nitrogen-based fertilizers.

New Zealand's Forest Resource

New Zealand's exotic plantation forest resource is described in Table1. Wood production is 99.8% from plantation forests of exotic tree species, 89% of this is *Pinus radiata*, which is grown on a ~28-year rotation.

New Zealand had a forest-planting boom between 1993 and 1997, when large amounts of afforestation occurred (between 62,000 and 98,000 ha per annum). These plantings are now aged 15–20 years (Figure 1) and will be due for harvest around 2020 to 2025 (Figure 2) when they reach ~28 years of age. Current (to year ended 31 March 2012) forest harvest is expected to be ~26 million m^3.

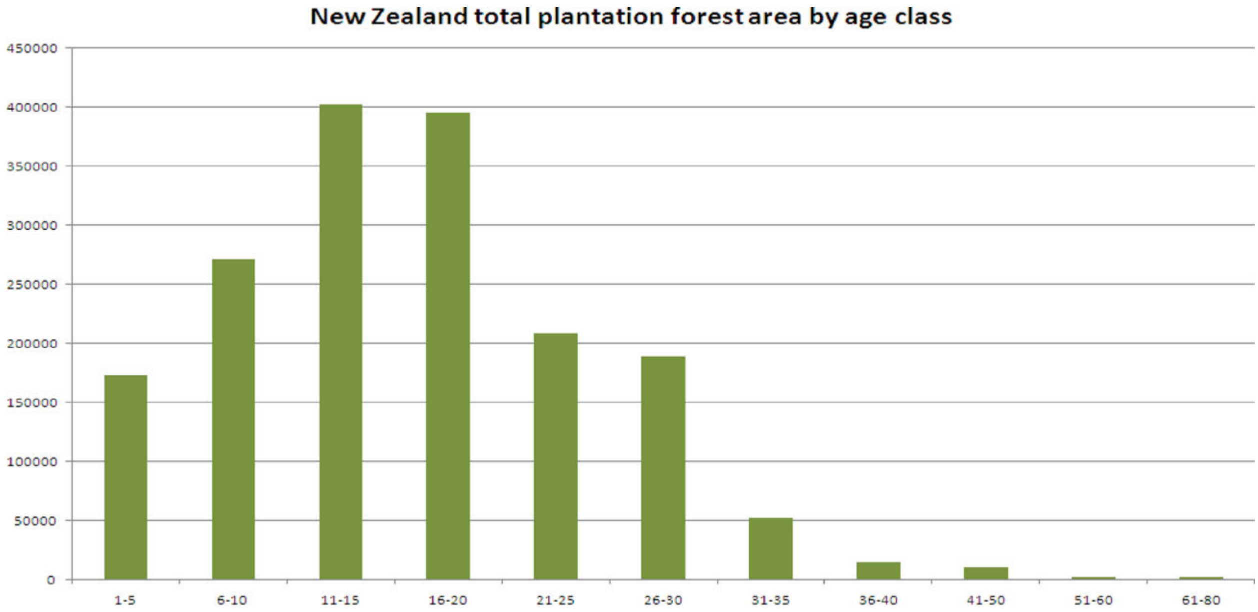

FIGURE 1 | Age class distribution of New Zealand's plantation forests.

Harvests of 30–35 million m^3 per annum will be possible for a period of around 15 years. This volume of harvest is significantly higher than current levels (25 million m^3 per annum). This increased harvest will create increased volumes of in-forest residues (Table 2).

Plantation forests in (green areas in Figure 3) New Zealand are spread over all regions, but there is a major concentration in the Central North Island.

There is also a significant area (11.7 million ha or 43.7% of land area) under indigenous vegetation cover in New Zealand.[9] Most of this area is protected

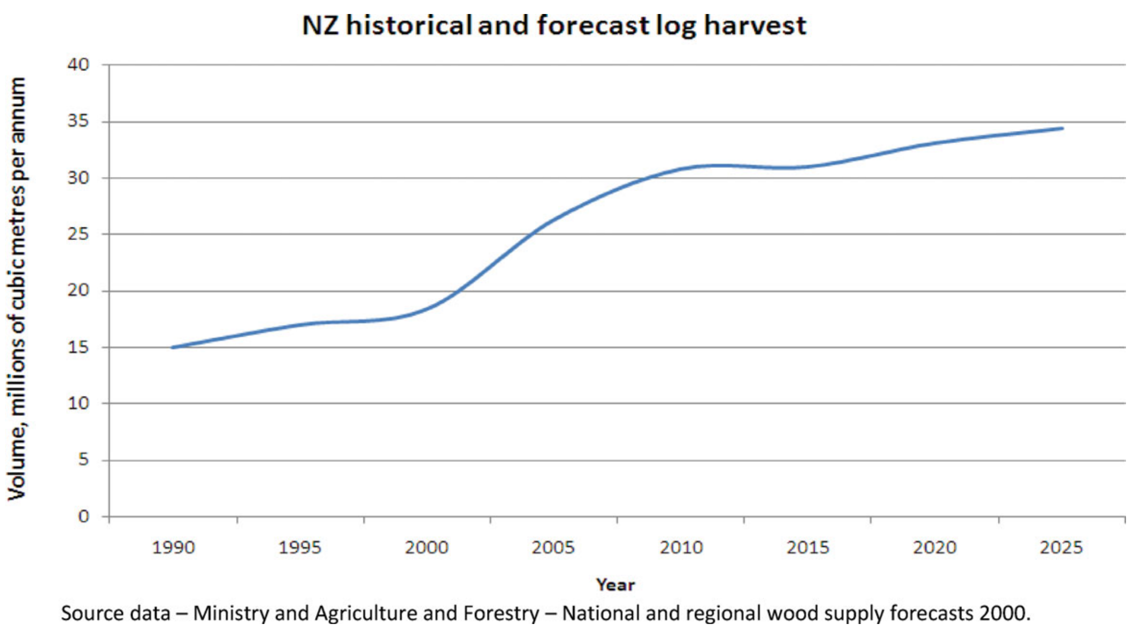

FIGURE 2 | New Zealand's potential future forest harvest volume. (Created using data from the Ministry of Primary Industries – National and regional wood supply forecasts.)

TABLE 2 | Current Residual and Waste Biomass Resources

Residuals and Wastes Type/Source	2005 (pJ per annum)	2030 (pJ per annum)
Forest harvest residues	14.6	34.4
Wood process residues	7.0	9.1
Municipal wood waste	3.5	2.2
Horticultural wood residues	0.3	0.3
Straw	7.3	7.3
Stover	3.0	3.0
Fruit and vegetable culls	1.2	1.2
Municipal biosolids	0.6	0.7
Municipal solid waste as landfill gas	1.9	2.3
Farm dairy	1.2	1.2
Farm piggery	0.1	0.1
Farm poultry	0.0	0.0
Dairy processing industry	0.4	0.4
Meat processing industry (effluent only)	0.5	0.5
Waste vegetable oil	0.2	0.2
Tallow	3.6	3.6
Total	45.9	66.5
Total as% of consumer energy	8.5	9.2
Total as% of primary energy	6.6	7.3

as National Parks and reserves and there is very little logging of indigenous forests.

REPORT SUMMARIES

Situation Analysis

This study looked at New Zealand's residual and waste biomass resources and their energy potential.

Table 2 shows the energy content of the major residual and waste streams for 2005 and projected to 2030. Projections took into account population growth and known drivers for a range of residues (plantation forest age class distribution, crop land area and limits, population growth).

Given current energy demand (especially for oil and gas) and predicted rises in the future, biomass residuals are insufficient to meet more than a small amount of the national energy demand.

Woody biomass is the largest biomass resource, and forest harvest and wood processing residues are the largest contributors to the total woody biomass resource. Forest residues have significant potential increases due to the age class distribution of the 1.75 million ha plantation forest resource (Figures 1 and 2).[10,11]

New Zealand has 9.6 million ha of land that is steep hill country, currently used for low productivity grazing (sheep and beef). Some of this land, at least 0.8 'million ha and as much as 3.0 million ha depending on the assessment criteria used, is erodible and would be more stable under plantation forest. How much of the grazing can be moved from its current use to forest is debatable, but estimates have varied from 0.7 to 5.1 million ha. The criteria used to estimate the amount of land that can be moved from grazing to forests are sometimes based on erodibility and some times earnings and profitability, hence the discrepancy between the ranges. The economics of grazing versus forestry are debatable on these sites, and often depend on the prevailing markets at the time of the analysis for the various primary products (wool, lamb, beef, logs, and lumber).

In summary, New Zealand has a large and uncommitted woody biomass resource available to utilize. The potential to expand the supply of woody biomass over the longer term is also likely to be larger than the alternative of crops (maize, etc.) from arable land due to the ability to grow forests on marginal lands at reasonable levels of productivity and produce a stem piece size that is economic to recover. Further, there is a much smaller area of land that is suitable for arable and horticultural use (2.6 million ha).

These insights, when combined, led to a concept being developed that outlined the potential of wood from new purpose-grown energy forests. It became apparent that energy forests could be a huge contributor to low-carbon energy in a New Zealand context. This initial concept envisioned 3.2 million ha of plantation forests, providing 100% of New Zealand's liquid fuels and some heat fuel.

Pathways Analysis

The *Pathways Analysis* looked at energy demand by region versus the available residual resources, but the major focus was on the potential of a variety of biomass to user energy pathways and the greenhouse gas (GHG) footprint [via life cycle assessment (LCA)] of a range of options with relevance to New Zealand's resources. LCA is a systematic methodology for assessing the environmental impacts associated with a product, such as energy. The focus of this study was on GHG emissions (measured as CO_2 equivalents) and energy return on energy invested (EROEI).

Energy Demand and Biomass Supply

There is more than sufficient fossil energy demand (504 pJ, from 58 pJ of coal, 273 pJ of oil, and

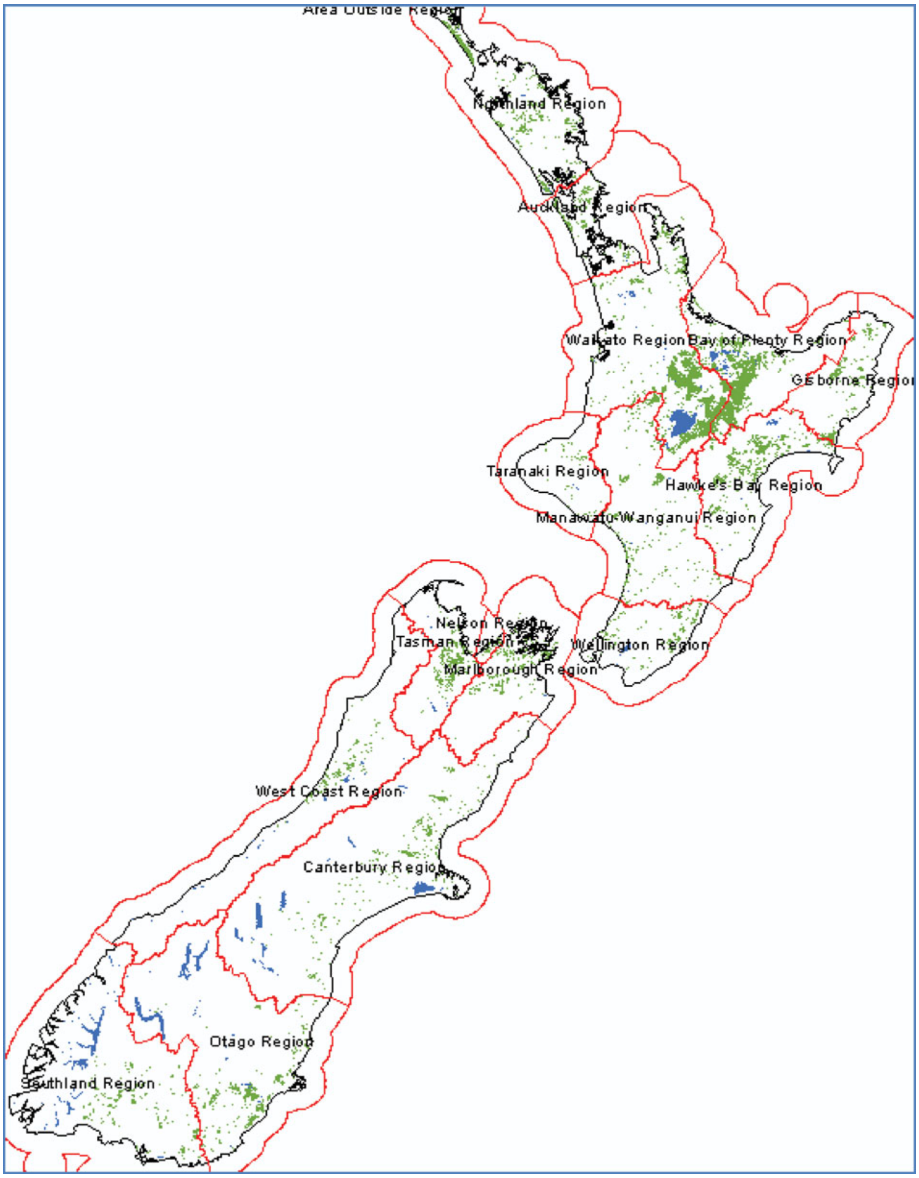

FIGURE 3 | New Zealand's plantation forest by region.

173 pJ of gas)[8] to consume all the biomass wastes and residues (46 pJ).

Life Cycle Analysis: Woody Residues to Consumer Energy

The potential scale for woody residues is currently 26 pJ per annum of primary energy, rising to a possible 46 pJ per annum by 2030.

A comparison of possible conversion routes for wood residues to energy is shown in Table 3. Combustion for heat has the highest efficiency, best EROEI, and lowest global warming potential (GWP).

The focus of the life cycle assessments done here has been material and energy flows relating to GHG production, fossil fuel use, and economic costs. The assessment approach calculated only the primary environmental impacts of the process chain (e.g., energy consumption and pollutant emission during the cultivation of energy canola; secondary effects were not covered). For instance, if the demand for canola results in the conversion of forestland or wetlands, the environmental impact of this has not been included. Economic allocation is based on 2008 prices. The price of goods depends on market dynamics and will change over time. The process chains investigated

TABLE 3 | Results Summary for Life Cycle Analysis of Woody residues to Consumer Energy

	Combustion Heat	Combustion Electricity	Ethanol	Gasification Heat	Gasification Electricity	Gasification Syn-Diesel
% Efficiency	60	42	42	51	36	35
EROEI[1]	7.5	4.9	3.5	5.6	4.0	3.9
GWP[2] (kg CO_2 equiv/GJ)	7.9	11.9	21.4	9.9	14.0	14.3
Cost/GJ[3]	$15.6	$27.6	$59.4	$31.2	$42.0	$34.5
Technology status	Mature	Mature	Developing	Developing	Developing	Developing

[1] Energy return on energy invested.
[2] Global warming potential.
[3] Combined heat and power.

TABLE 4 | Results Summary for Life Cycle Analysis of Wood from Purpose-Grown Forest to Consumer Energy

	Combustion Heat	Combustion CHP	Ethanol	Gasification Heat	CHP	Gasification Syn-Diesel
Efficiency	60	42	42	51	36	35
EROEI	10.9	6.9	4.5	7.7	5.5	5.4
GWP (kg CO_2 equiv/GJ)	4.9	7.5	17.1	6.5	9.1	9.3
Cost/GJ	$34.5	$54.8	$86.6	$53.2	$72.6	$65.4
Technology status	Mature	Mature	Developing	Developing	Developing	Developing

CHP, combined heat and power.

TABLE 5 | Results Summary for Other Life Cycle Analyses

	Straw CHP	Canola Biodiesel	Kiwifruit AD + CHP	Effluents AD + CHP
Efficiency	90%	44.9%	90%	90%
EROEI	17.6 : 1	2.2 : 1	11.3 :1	7.2 :1
GHG reduction	90%	62%	90%	120%
Scale	0.6 pJ per annum electricity 1.8 pJ per annum heat	39 pJ per annum off 1.0 million ha	0.06 pJ pa	5–6 pJ per annum
Cost/GJ	$13.94	$39.00	$38.57	$41.67
Technology status	Mature	Mature	Mature	Mature

AD = anaerobic digestion; CHP, combined heat and power.

represent only a subset of all production processes; many more production paths are conceivable. The paths chosen are considered especially relevant for the current situation in New Zealand. The most recently available existing New Zealand data have been used where possible. Where these data are not available, overseas data have been used. Note that Tables 4 and 5 assume wood to ethanol via enzymatic hydrolysis or to syn-diesel by gasification and Fischer–Tropsch catalysis.

In line with the findings in Table 3, most of the current use of woody biomass for energy is by the wood processing industry where the biomass is burned to create process and drying heat. A technology is considered to be mature if it can be bought off the shelf from a range of suppliers, is well established in the market, and widely used. A developing technology is one that is not widely used and there are few suppliers and the technology is still be widely researched.

Life Cycle Analysis: Purpose-Grown Forest to Consumer Energy

The potential scale of the new forest resource was up to 3.372 million ha of forest producing up to 600 pJ p.a. of primary energy. This is the approximate area of forest it would require to produce all of New Zealand's liquid fuels, assuming a sustained yield management of the resource, a 25 year rotation, a per hectare volume at clearfell of 650 m^3 and 95 liters of fuel produced per cubic meter (0.42 odt per cubic meter).

Table 4 shows the same conversion technologies and parameters as Table 3, but with the resource material being derived from a forest purpose grown for biomass/bioenergy production. The cost per GJ

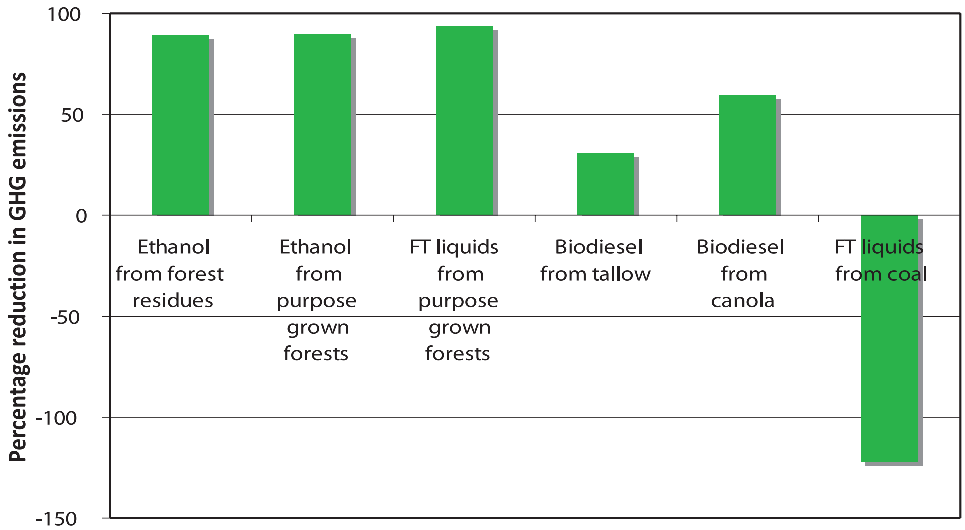

FIGURE 4 | Liquid fuel options—percentage reduction in greenhouse gas emissions when used to replace petrol or diesel.

is the estimated cost of producing the energy product (heat, electricity, etc.) by a particular route. Costs are in New Zealand dollars (Note the NZ dollar has a floating exchange rate and trades at NZ$1.00 = USD$0.70–0.80).

Table 5 shows some results for other significant biomass resources. Use of industrial and farm effluents with biological content and municipal biosolids can give significant higher GHG reductions than other biomass resources.

The use of residuals often gives an excellent energy return on energy invested.

For the effluents, there is a substantial environmental driver for their use. The GHG reductions from fossil fuel displacement are very substantial, not the least because the CH_4 emissions from the biodegradation of the material are captured and used for energy. The solid waste volume can be reduced by 80%, with major impacts on waste disposal.

Utilization of municipal waste, industrial effluent, and agricultural waste for energy has the potential benefits of

- Reducing GHGs by displacing fossil fuels;
- Reducing GHGs released during decomposition;
- Reducing effluent and landfill waste disposal volumes and toxicity;
- Reducing nutrient loading of waterways;
- Off-setting waste management costs.

The use of wood residues and purpose grown forest derived wood gives greater reductions in GHG emissions than biofuels from tallow and oil seed crops. It is vastly superior to liquid fuels derived from coal (Figure 4), an option being considered for use of the lignite resource in the South Island.

The use of biomass from forests is more efficient in its land use than seed or nut crops as the entire biomass volume can be used, as opposed to just a specific part of the plant. Land use efficiency will be critical in future development of biofuels, due to food and feed driven competition for land.

A scenario was developed that started with a look to the future: What would New Zealand's liquid fuel demand be in 25 to 30 years time? Then—what would it take in terms of afforestation to meet this demand from biomass to liquids developments? Liquid fuel demand was projected to be ~8.75 billion liters by 2030; this figure includes fuel provided to ships and planes traveling out of New Zealand and assumes a demand growth rate of 0.4% per annum. To grow enough woody biomass to meet this demand (assuming either wood to ethanol via enzymatic hydrolysis or to diesel by gasification and Fischer–Tropsch synthesis) New Zealand would need 3.3–3.4 million hectares of forest, assuming forest productivity similar to that currently achieved over a 25-year rotation.

Bioenergy Research and Development Strategy

On the basis of the findings from the first two studies (situation analysis and pathways analysis), the research and development priorities that would enable development of bioenergy in New Zealand were identified:

1. Bioenergy from plantation forestry
   (a) Develop new high-yield, low-input tree species and forest management systems

for multiple forest and wood products including energy;
   (b) Develop more efficient harvesting and logistics systems;
   (c) Adapt biomass to liquid transport fuel conversion processes for New Zealand feedstocks;
   (d) Develop an implementation plan for New Zealand.
2. Biomass waste utilization
   (a) Demonstrate technologies on site (e.g., anaerobic digestion of effluents for combined heat and power).
3. Biomass residuals for distributed generation
   (a) Develop integrated industrial solutions;
   (b) Demonstrate technologies at different scales.
4. Next-generation feedstocks and conversion technologies (e.g., ligno-cellulosic material to liquid biofuels)
   (a) Review and assess technologies and feedstocks;
   (b) Develop new feedstocks and conversion technologies.
5. First-generation biofuels
   (a) Science-based assessment of environmental impacts.

The energy challenges facing New Zealand fall into three themes: increasing energy security, improving affordability, and reducing GHG emissions. The research priorities above address these issues.

From scale of supply, GHG mitigation, energy balance and technological maturity perspectives, the bioenergy from plantation forestry theme was identified as the most promising approach for bioenergy to make a significant contribution to New Zealand.

Realizing this strategy for New Zealand will require multidisciplinary research, strong industry and pan-government involvement. It will also require close collaboration with international researchers and industries.

Large-Scale Bioenergy from Forestry

This study considered the potential nation-wide impacts of growing forests for energy through a preliminary assessment of the environmental, economic, and land-use implications. Woody biomass offers a variety of energy end use options:

- Solid fuel for heat and/or cogeneration of heat and power;
- Liquid fuel production;
- Feedstock for syn-gas production.

TABLE 6 | New Afforestation/Land Use Change Scenarios

	Descriptive Area (million ha)	Actual area (ha)
Scenario 1	0.8	765,181
Scenario 2	1.8	1,855,669
Scenario 3	3.3	3,386,648
Scenario 4	4.9	4,927,040

This information can assist in determining whether large-scale forests for bioenergy is a strategic direction worth pursuing, and what particular scenarios maximize the long-term benefits. The principal focus of this study is on the production of liquid fuels, as finding renewable options for transportation is recognized as one of the greatest challenges facing New Zealand.

Four large-scale afforestation scenarios were developed and analyzed. The land area selected for these scenarios specifically targeted low productivity grazing land on rolling to steep terrain. The current plantation forest estate is ~1.7–1.8 million ha and there is 9.2 million ha of hill country that is either marginal land or low to moderate productivity hill country grazing. The benefits of using this marginal hill country for afforestation are that competition with food production is minimized and environmental benefits are maximized.

Forest (radiata pine) biomass productivity and costs were estimated for these land area scenarios and this data was used as the basis for assessing the environmental, land use competition, and economic impacts of each of the scenarios.

The regime that was used assumed was a 25-year rotation, with an initial stocking of 833 stems per ha. The trees received initial weed control but no thinning or pruning. The yield from this was modeled at 940 m^3 per ha, with 517 m^3 (55%) being sawlog, and 423 m^3 (45%) being pulp (277) or biomass (137) grade.

The afforestation and land-use scenarios developed for the study are outlined in Table 6. Biomass and energy potentials from sustained yield harvesting for these scenarios are presented in Table 7.

During the process of this study (Scenario 2 in Table 6), 1.8 million ha was identified as the one that was most likely to be achievable whilst also giving sufficient scale (nationally and regionally) of supply to enable liquid fuel production. The larger afforestation scenarios were considered to be very challenging

TABLE 7 | Summary of Potential Biomass and Liquid Fuel Production (Assumes Sustained Yield Harvest on 25–Year Rotation)

	Scenario 1/0.8		Scenario 2/1.8		Scenario 3/3.3		Scenario 4/4.9	
	TEB	Lpe	TEB	LPe,	TEB	LPe,	TEB	LPe
	Per annum m^3 Millions	Per annum Millions	Per annum m^3 Millions	Per annum Millions	Per annum m^3 Millions	Per annum Millions	Per annum m^3 Millions	Per annum Millions
NZ total	22.59	1964.2	73.55	7,039.1	126.63	11,011.2	168.67	14,666.1

TEB, total extractable biomass = total recoverable stem volume + bark + branches × 0.8 + upper stem × 0.8 of the estimated 15% of the above ground biomass in unmerchantable stem breakage; LPe, liters of petrol equivalent.

TABLE 8 | Environmental Impacts of Four Afforestation Scenarios (at Forest Age 25 Years or ~2035*)

Scenario (Millions of ha new forest)	GHG Impacts, Reduced Emissions (Millions of Tonnes CO_2 equiv)	Stored Carbon (Millions of Tonnes CO_2 equiv)	Reduction in Erosion (%)	Reduction in N Leaching (%)	Reduction in Water Yield (%)
0.8	5.02	207.8	1.1	0.3	0.9
1.8	15.49	651.1	8.0	3.4	2.6
3.2	29.21	1188.5	16.6	8.4	5.1
4.9	37.29	2039.7	20.2	12	7.2

in terms of the competition for land with traditional grazing use. This scenario could potentially produce around 7.0 billion liters of petrol equivalent (Table 7). This production would not begin until around 2035, by which date the annual fuel demand could be as high as 8.9 billion liters assuming current demand growth continues. There are no assumptions made about what fuel type is made (ethanol, diesel, etc.) but it is assumed that a mix of fuels could and would be made, to meet the mixed demand.

The biomass production from large-scale afforestation scenarios was based on the assumption that the crop would be radiata pine. This does not mean that all the afforestation would or should be this species. It is, however, the species on which we have the most information available on its productivity at a national, regional, and site-specific level, thus allowing more detailed and accurate predictions than is possible for other species.

The forest management regime assumed in the scenarios [high stocking (plant 833 stems per ha) with low silvicultural inputs (no pruning or thinning)] gives market options for the logs produced other than 100% to energy, for example, 56% sawlog and 44% chip. It also gives high volumes of carbon sequestered or stored in the live standing volume. The regime modeled for biomass supply from new forests gives a higher volume per hectare than the current commonly used regimes, which focus on maximizing sawlog production

Table 8 summarizes the environmental impacts of the afforestation scenarios on some key variables—erosion, water yield, N leaching, and carbon storage.

The new forest area was assumed to be established at a rate of 1/25th of the total area, that is, for the 1.8 million hectare scenario annual new planting would be 72,000 ha. This is realistically achievable: New Zealand had peak afforestation rates of ~90,000 ha per annum in the 1990s.

Economic Welfare

One of the most important questions is what are the macro economic effects of large-scale forestry for energy on economic welfare measures, such as standard of living?

In most of the scenarios considered, biofuels lead to a decrease in productive efficiency; this implies a reduction in economic welfare. However, the production and use of biofuels reduces CO_2 emissions, so if there is a price on carbon, New Zealand's liability to purchase offshore emission units is reduced. This generates a gain in economic welfare reflected in increased real gross national disposable income.

Economically, it is better to use only lower value (chip grade) logs for energy and saw logs for sawn lumber as opposed to all of them for energy. Forests should be regarded as having multiple values and many potential end uses for the wood, including carbon storage.

Transition Analysis

The transition analysis focused on the potential of the existing forest estate to enable a transition from residues for energy to a large-scale bioenergy supply from new forests; that is, what volume of wood and

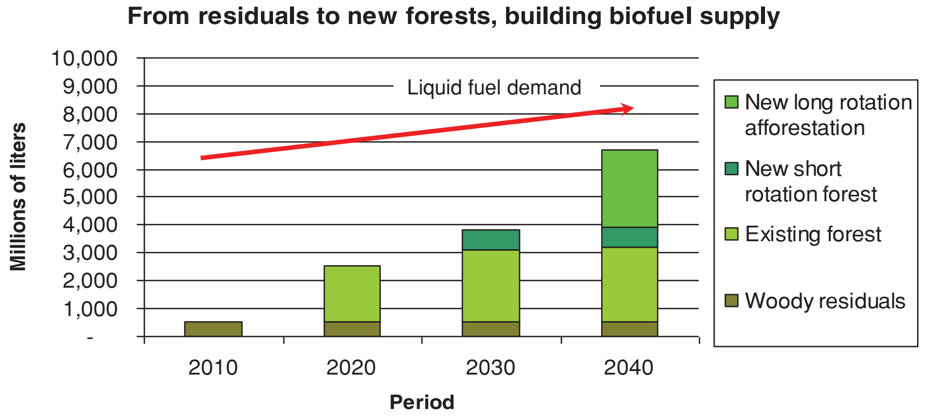

FIGURE 5 | Potential supply from existing resources.

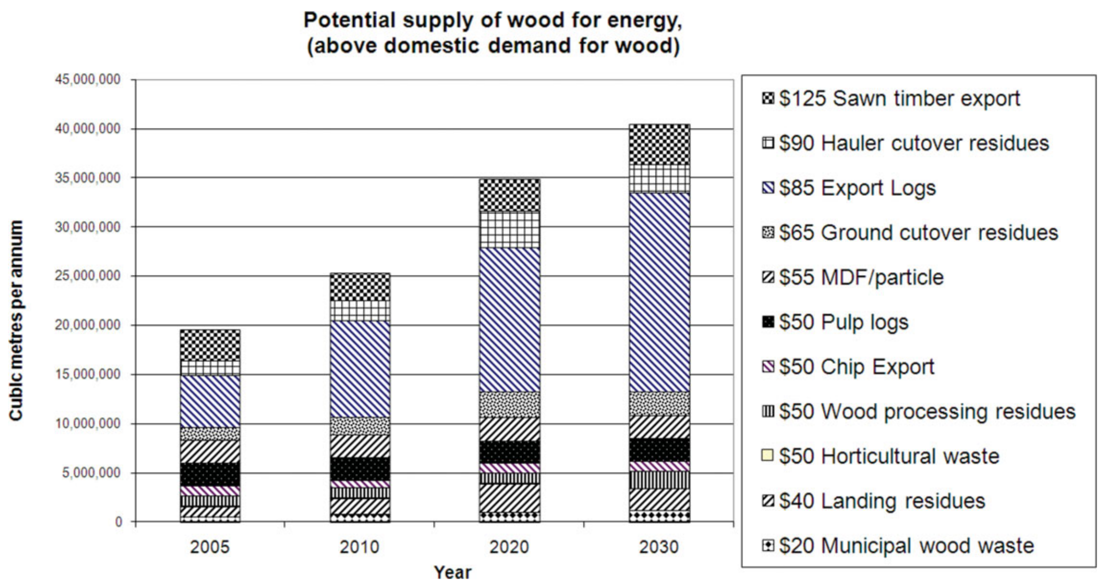

FIGURE 6 | Potential supply of wood for energy, volume by cost.

energy could be derived from the existing forest estate and what are the drivers in terms of energy supply? It also addresses potential new forest species options and economic impacts of oil price shocks.

Using some of the existing and upcoming forest harvest (chip logs) for energy production provides a stepping stone in supply to build from the small contribution from residuals to the potentially nationally significant supply from a large new forest estate (Figure 5).

Different sources of supply have different costs; the graphs shown in Figures 6 and 7 outline supply volume by cost from the existing wood residuals and forest harvest over time.

Comparatively, small volumes of wood (2 to 3 million cubic meters per annum) are available at less than \$50 per m^3. If the market price of pulp logs (\$50–55 per m^3) are assumed the volume of wood potentially available increases to around 10 million cubic meters by 2030 (Figure 6). As the demand for wood rises, the weighted average costs rises (Figure 7).

As the potential for forest harvest rises (Figure 2), the amount of chip logs produced also increases. Current market conditions do not support the development of new pulp or panel capacity. The additional chip log material is, therefore, potentially available for nontraditional uses.

Apart from the cost of feedstock the two key drivers of whether domestically produced liquid biofuels can compete with largely imported fossil fuels are the price of oil (in US dollars) and the New Zealand/US dollar exchange rate. Table 9 shows the price that oil needs to be for biofuels to be competitive by exchange rate, feedstock cost, and fuel tax

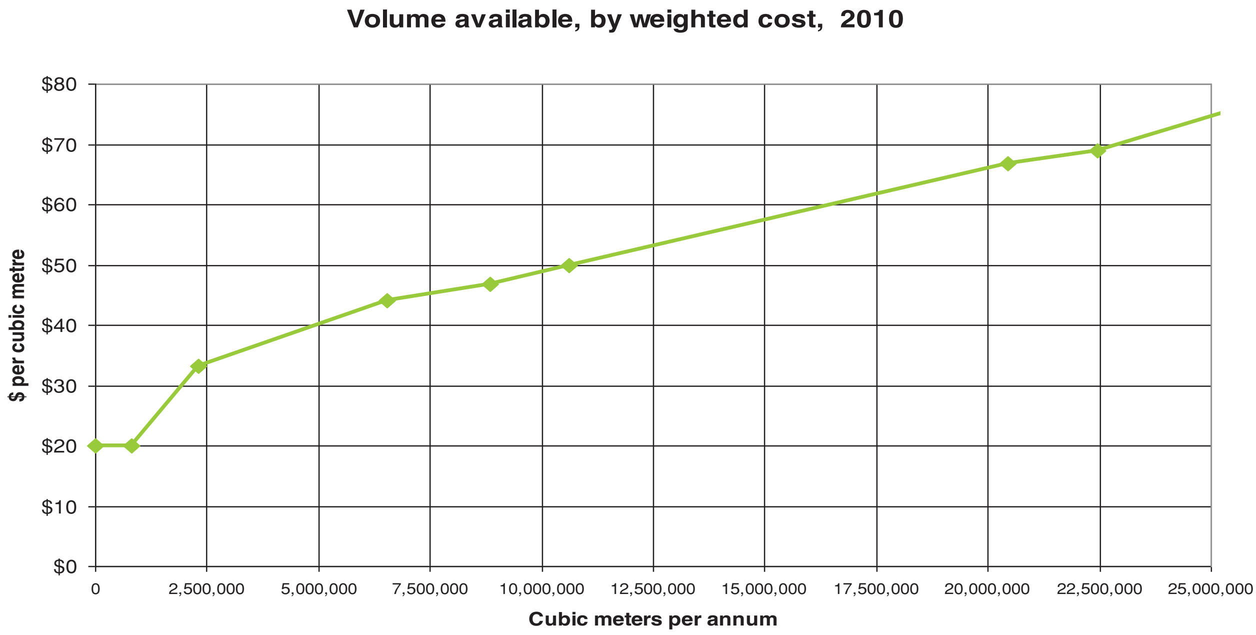

FIGURE 7 | Volume of biomass available by weighted average cost, 2010.

TABLE 9 | Price of Oil (US$ Per Barrel) Required to Make Biofuels from Purpose Grown Wood Competitive by Feedstock Price, Tax Regime, and Exchange Rate

		Foreign Exchange Rate; NZ$1 Buys US$		
Feedstock Price	Tax Applied to Fuel	0.55	0.65	0.75
$50 per m^3	GST	US$117	US$138	US$159
$50 per m^3	Excise + GST	US$156	US$185	US$212
$85 per m^3	GST only	US$144	US$171	US$196
$85 per m^3	Excise + GST	US$185	US$216	US$249

GST, goods and services tax (15%); excise tax and levies = $0.59129 per liter.

regime. Two feedstock costs were used: $50 per m^3, which represents the cost of low grade pulp logs, and $85 per m^3 which represents a cost for all the logs from a harvest. These costs are for material delivered to a processing plant, assuming an average transport distance of 75 km from forest to mill.

New Zealand's long-run historical average exchange rate versus the US dollar since the dollar was floated in March 1984 is in the range 0.6–0.62, but has been above 0.7 since 2009 (~0.800 as at August 2012). This is a critical factor in the cost of fuel in New Zealand as almost all of oil is imported and as it is priced in US dollars, if our dollar is worth less against the US dollar, the cost of fuel rises.

To alleviate some environmental issues identified with larger afforestation scenarios in the previous study (water yield in drought prone regions and biodiversity impacts in native grasslands inland Otago), a revised afforestation scenario (1.4 million ha) was developed

TABLE 10 | Potential Tree Species for Bioenergy Production

	Species	Basic Wood Density (kg/m^3)
1	*Pinus radiata*	420
2	*Eucalyptus fastigata*	500
3	*E. nitens*	520
4	*E. regnans*	460
5	*E. saligna*	610
6	*Sequoia sempervirens*	340
7	*E. maidenii*	561
8	*Acacia dealbata*	510
9	*E. botryoides*	620
10	*A. melanoxylon*	590

Tree Species Options for Future Forests

Potential species for afforestation were identified by determining maximum biomass productivity from best sites (using a national sample plot data set) and ranking them (Table 10). Some species, although highly productive on specific sites, are only suitable to a limited range of sites. This list is limited to species that have already been introduced to New Zealand and trialled in a forestry context. Introduction of new species was not considered.

The hardwoods (Eucalypts and to a lesser extent Acacias) with their higher wood density and reasonable growth offer greater productivity than many softwoods.

Other species identified as worthy of further investigation:

- *Abies grandis*: Grand fir (cool, high-altitude sites),
- *Picea sitchensis*: Sitka spruce (wet cool sites),
- *Tsuga heterophylla*: Western hemlock (shady sites),
- *Sequoiadendron giganteum*: Giant sequoia (high-altitude sites),
- *Taxodium distichum*: Swamp cypress (wet sites),
- *P. attenuata* X *radiata*: hybrid (snow-prone sites),
- *P. ponderosa* (cool, higher-altitude sites),
- *P. nigra* (cool, higher-altitude sites).

Finding species suitable for cooler, high-altitude sites would extend the land base potentially available, as would the ability to grow forest on wetter sites. *P. radiata* performs poorly on wet/poorly drained sites and is susceptible to snow damage if planted at higher altitudes.

Broadening New Zealand's plantation forests species base would potentially reduce the risk to the forests industry from pest and pathogen incursions that would affect *P. radiata* (pine pitch canker).

Economic Impacts

The earlier study[4] showed that it is cheaper to use existing forest resources (residues and pulp logs) for bioenergy than to establish a new dedicated 100% energy forest for this purpose. Even if carbon was set at \$100/tonne of CO_2, and oil was priced at US\$105/bbl, there would be no net economic benefit. This is due to the high value of the wood product exports that would be displaced in this case.

It would be simplistic to disparage biofuels in view of these high hurdle prices, because delaying action until biofuels were justified could be a very expensive strategy in the long term. Although choice of biofuels in times of low oil prices would be a suboptimal decision, and may be very unprofitable during the

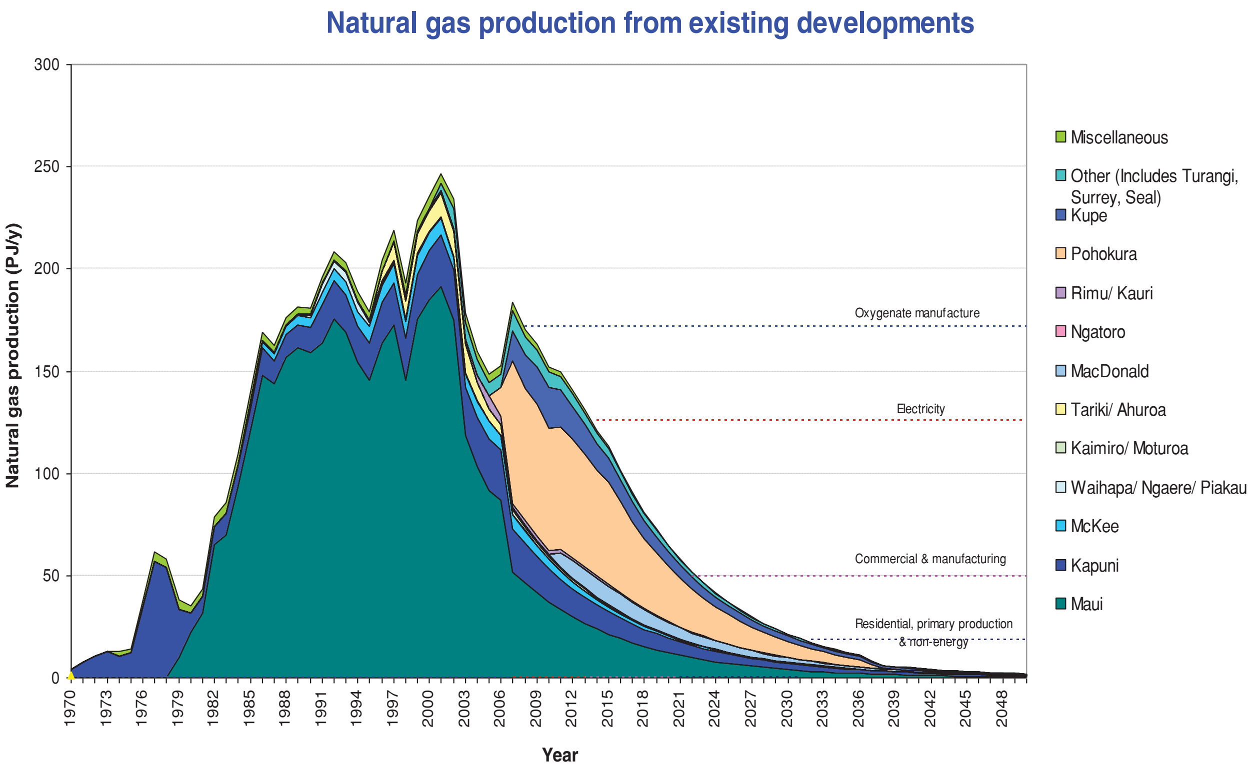

FIGURE 8 | Domestic natural gas supply.

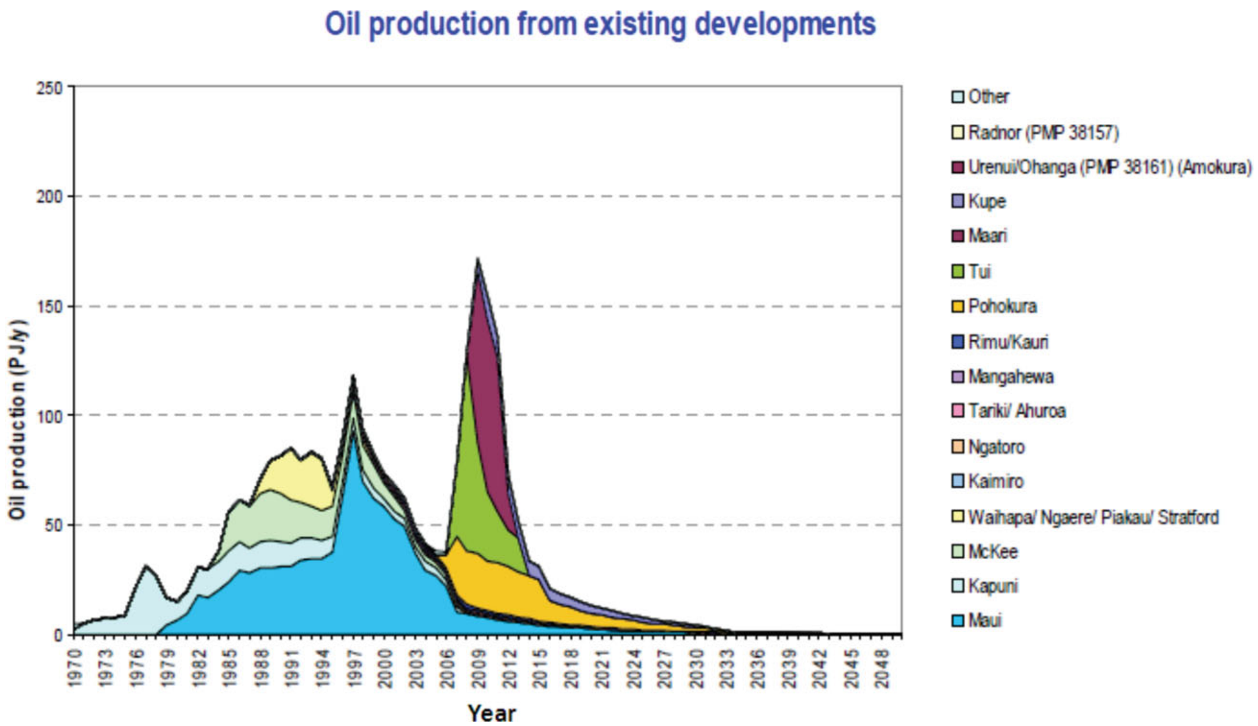

FIGURE 9 | Domestic oil production.

establishment phase, this could soon overwhelmed by the advantages gained during high oil prices.

In addition, as the New Zealand forest industry is currently facing both increasing harvest volumes without the necessary domestic processing facilities and the threat of pulp mill closures, having other options for the harvest may mitigate some of the risks. If either of these situations eventuates then biofuel production from the harvest does provide a net benefit to the economy under the above assumptions for CO_2 and oil price.

Using existing forest rather than new forest means that there is no loss of agricultural land to forest planting. But a new forest would enable a range of valuable products (timber, wood panels, paper) in addition to biofuels and this could easily outweigh the loss in agricultural production.

Drivers in Energy Supply

New Zealand faces declining gas supply in the medium term, unless new discoveries are made in the near future (Figure 8).

New Zealand's currently producing oil fields are small and being depleted at a rapid rate. Currently domestic oil production is at a historic high, but the producing fields will be heavily depleted by 2015 (Figure 9).

Although there is currently no great concern about coal supply at a national level, clearly gas and oil from domestic supply are in decline and oil has been on an upward price trend (Figure 10). Predictions of future oil price are fraught with difficulty, but a national oil company expects the floor price to be US$90 per barrel and for prices to fluctuate around US$120 a barrel for the next five years.

DISCUSSION

In summary, New Zealand's energy situation is such that New Zealand has the resources to meet electricity and heat demands, the problem is liquid fuels.

Having decided this and determined that the major biomass resource in New Zealand is, and will be, wood, the challenge is narrowed somewhat to two key areas:

1. How to make liquid fuels (preferably drop-ins) from wood;
2. How to expand the forest and wood resource quickly enough for the wood to liquid biofuels route to meet its full potential.

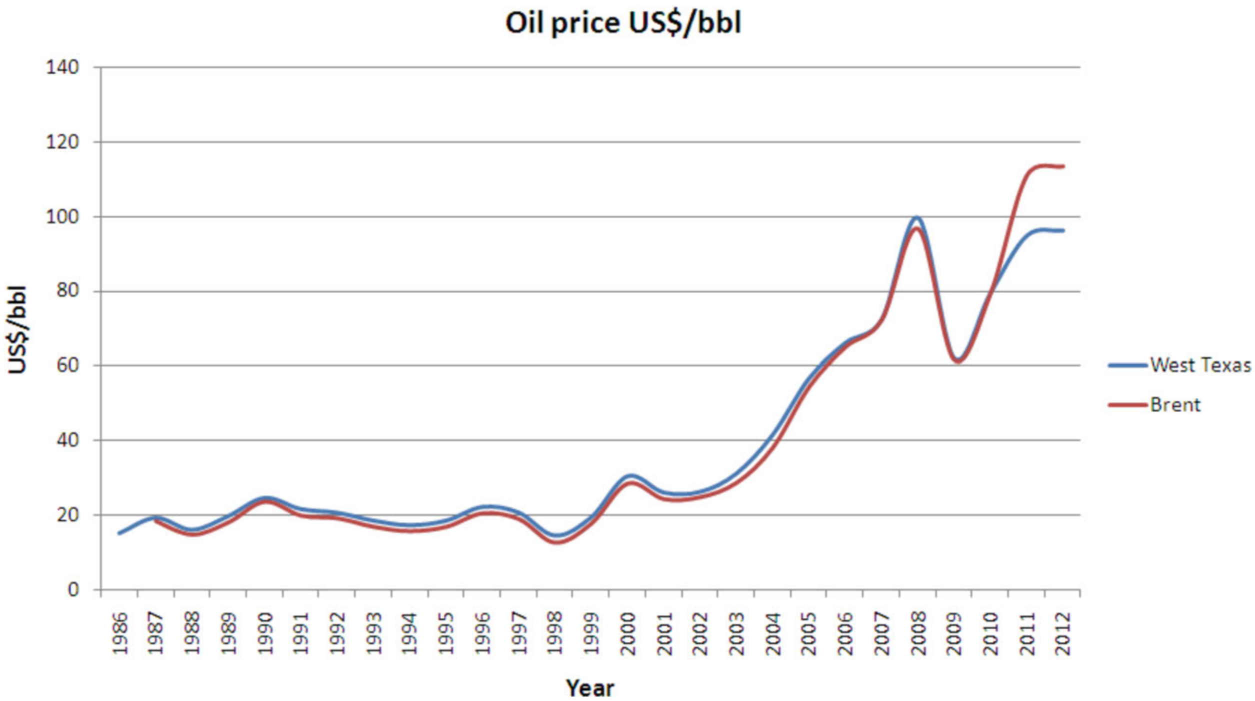

FIGURE 10 | Oil price, US$/bbl (West Texas and Brent), 1986 to 2012. (Created using date from the United States Energy Infomation Authority; http://www.eia.gov/dnav/pet/pet_pri_spt_s1_a.htm.)

Over the next 25 years, New Zealand may face substantial increases in gas and oil prices, which would negatively impact New Zealand's terms of trade.

One energy supply option is to develop domestic fossil fuel resources, requiring greater oil and gas exploration and possibly the pursuit of coal to liquids to meet growing energy demands. This is a valid short-term solution but in the longer term it may give us more of the same: high GHG emissions and volatile prices.

The alternative long-term option is the biomass scenario that, in the transition period while a large-scale forestry resource is established, utilizes the existing forestry resource with the aim of producing low-carbon liquid biofuels and synthetic natural gas.

Significant risks are associated with each pathway. The biomass scenario is dominated by techno-economic risks, due to high costs associated with immaturity of technology, but it does not have the long-term environmental and economic (oil price) risks associated with the fossil fuel development option.

Unfortunately, the key drivers of the cost of oil-based energy in New Zealand (oil price and the New Zealand dollar exchange rate) are difficult to predict in the long term. This makes a decision to pursue biofuels at a national scale a difficult one to take.

CONCLUSIONS

The Bioenergy Option outlined here puts New Zealand on a path that could meet its energy supply needs while providing other significant benefits at the same time. These benefits include reducing GHG emissions, mitigating risks in the forest industry (which is key to offsetting carbon emissions from other industries), using land more sustainably (and efficiently in some cases), and promoting regional development.

A challenge in any transition from oil is to deploy environmentally acceptable energy technologies rapidly enough to replace current options. This study shows that in New Zealand sufficient biomass resources exist from the current forest harvest for bioenergy to play a key role in this transition.

Biomass supply from existing and new plantation forests can provide a continuum of increasing biomass supply that builds over time, 2010 to 2050. This is a technically feasible means of transitioning from a fossil-based energy supply to a renewable and domestically sourced energy supply.

If fossil energy supply has declined and become substantially more expensive, it becomes even harder to build the next generation of energy infrastructure. This implies a need to consider alternative strategies.

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