Research Report

To: Marlborough District Council

From: Massey University

Repurposing Grape Marc

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1. Introduction

The wine industry continues to expand in Marlborough with estimates indicating a further 30% in land conversion to vineyard over the next five year period. The New Zealand Winegrowers 2019 Annual Report estimates vineyard area in Marlborough at 26,850 hectares, producing 305,467 tonnes. An integral part of this production is the estimated 46,000 tonnes of grape marc, the residue after the juice has been pressed from the grapes which, similarly, will also continue to increase as the industry grows. Disposal, or repurposing, of this grape marc has become problematic for Marlborough. In the absence of an informed, sustainable solution for the grape marc, this regional growth could be adversely impacted through reputational damage due to poor environmental outcomes. To address the repurposing problem, some large composting operations have been established over the years, but these have encountered compliance challenges, predominantly in relation to the control of leachate, run off and odours. Effectively, much of this composted material became stranded as stockpiles and has not been repurposed for use in vineyards or elsewhere. Without repurposing, stockpiles will accumulate *ad infinitum*, and so landfilling becomes the only societal backstop as a complete end-of-life solution, which is a cost to both the industry and the region, particularly as landfills reach capacity. Recently, other activities have begun in Marlborough. Significant quantities of raw grape marc are now directly land-spread. Some marc is also supplied as a rudimentary stock feed. Other business ventures include drying grape marc and exploring methane capture from anaerobic fermentation.

Massey University became involved in the project to investigate complete removal of the grape marc on an annual basis. To do this, three thermal processes have been investigated. Best-practice composting is used as the comparison rather than the new current practise of direct land-spreading, although some calculations are included on the economics of this activity. Best-practice composting is well understood, although does require significantly greater infrastructure than stockpiling. The three thermal processes are: combustion to make power, gasification to make heat and power, and pyrolysis to produce heat and biochar. All thermal processes start with a drying plant, as it is essential to create a dry product that can be stored indefinitely. Therefore, the economics of drying as a stand-alone process are also investigated.

The output of the study is a techno-enviro-economic analysis. The techno- (technology) analysis establishes the process complexity and the mass and heat balances and plant sizing, important for the next two stages of the study. The enviro- (environmental) analysis is focussed on carbon footprinting, which includes all activities that generate global warming emissions, including transport of the grape marc to a centralised facility. The third part is a process economic analysis. It allows the capital and operating costs to be estimated, and offers the opportunity to examine revenue and profitability. The comparison between options then allows risk and liability to be included to determine the net cost to the Marlborough region.

It needs to be made clear, this study does not present any business cases. Rather, it is a techno-enviro-economic comparison of scenarios for repurposing grape marc. It treats the entire annual yield of grape marc as a single quantity of 70,000 tonnes, which is above the current estimate of 46,000 tonnes but growing at *ca.* 6% per annum. Samples were collected from one pressing facility and measured moisture content at 67%, which we have used for the calculations. We conducted studies on mechanical dewatering, drying, proximate and ultimate analyses, X-ray fluorescence and thermogravimetric analysis. The carbon footprinting uses a life cycle approach where greenhouse gas (GHG) emissions are calculated for all the activities associated with transportation and processing of the grape marc, and accounting for different outputs from these processes. Process engineering design techniques were used to size the plants and model operating scenarios. The capital cost estimation considers only new plant, not second-hand. Operating costs are established from standard indices. Figure 1.1 illustrates the scope of the study.

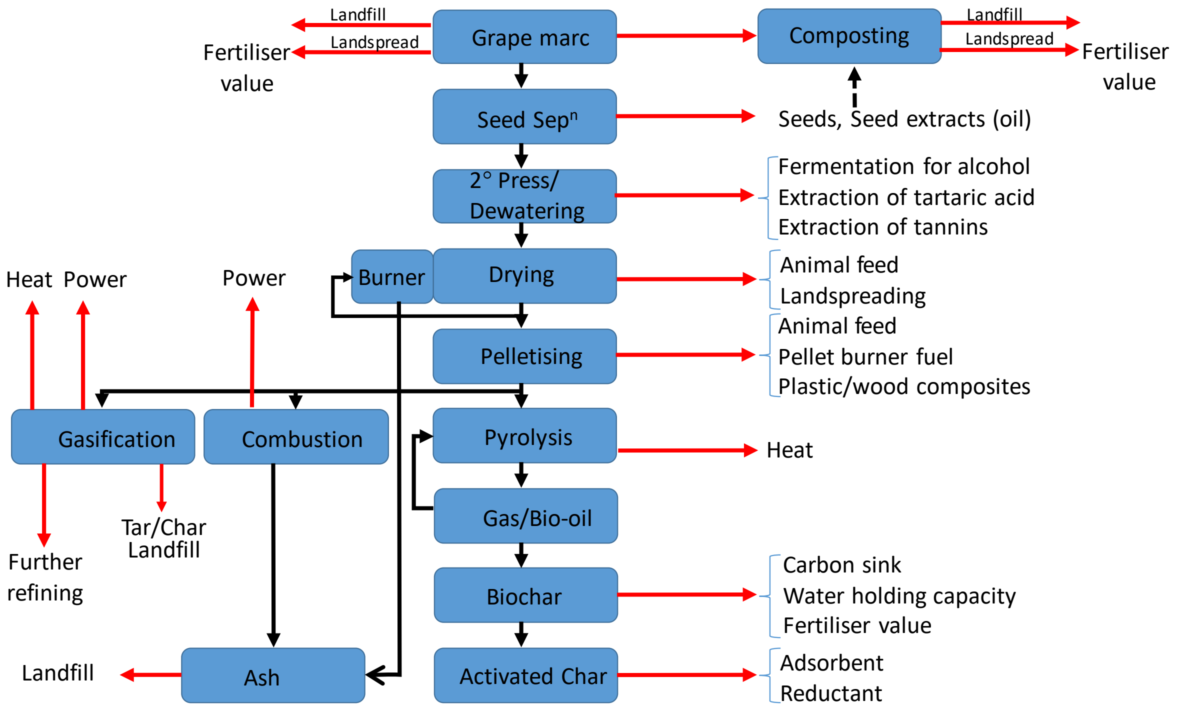

Figure 1.1. Block diagram showing the steps involved in thermal processing. The thermal processes will be compared to best-practice composting. The red streams indicate outputs and value-add products.

2. Technology Analysis

Before launching into the study of thermal options for grape marc repurposing and their comparison to best-practice composting, it is necessary to examine the principal activities that occur now in Marlborough. These are direct land-spreading of raw grape marc and the legacy of stockpiles of grape marc.

2.1 Direct Land-spreading, and Stockpiling and Composting

In the past, the Marlborough District Council has laid charges against a number of operators who have stockpiled grape marc with the intention to make compost, only to have leachate pollute waterways or groundwater. These stockpiles are not a solution to repurposing, nor are they composting. Rather, they accumulate grape marc and tie up land that could be used for other purposes. They also emit a lot more greenhouse gases than best-practise composting operations. They need to be well-sited on leachate barriers, and must capture and treat any leachate.

To reduce the disposal problem, direct land-spreading of raw grape marc has emerged as a significant activity. It is cheapest to spread to non-vineyard land, then plough it in and cultivate crops to utilise the nitrogen. Unless individual resource consents allow differently, this practice is limited by the Marlborough Environmental Plan which allows an application of up to 200 kg nitrogen per hectare per year (200 kg N/ha/yr). For raw grape marc, this is equivalent to 42.6 t/ha/yr. However, the practice exceeds the recommendation from AgResearch, determined in a 2012 report commissioned by Marlborough District Council (MDC), that raw grape marc should be applied at no more than 3 tonnes of dry matter per hectare per year (3 t DM/ha/yr is equivalent to 9 t raw grape marc/ha/yr) in order to avoid overloading the soil with biological oxygen demand (BOD), which turns the soil anoxic (i.e., removes the oxygen) where anaerobic degradation dominates. Thick layering of grape marc on the soil and heavy rain events will promote this. It is not known whether the same land can be used for spreading annually, or whether a number of years is required between applications. The study of the interactions between grape marc and soil are outside the scope of this work.

In contrast, compost is stable and so does not cause a BOD overload response when incorporated into soil; therefore, it can be applied at the nitrogen loading limit. Interestingly AgResearch recommended a spreading limit of 150 kg N/ha/yr, which is lower than the MEP limit of 200 kg N/ha/yr. The actual amount that the soil can tolerate will depend on the incorporation method and the soil type. However, because the MEP uses a standardised limit of 200 kg N/ha/yr, this affects the incentive to compost the grape marc, because composting has an added activity cost. The MEP nitrogen limits determines the land area required for spreading. Raw grape marc requires 1,643 hectares and compost 1,603 hectares, which is only slightly less despite the significant mass reduction achieved in composting. This is because *ca.* 98% of the nitrogen content is preserved within the compost and means that it can only be spread at 14.3 t/ha/yr compared to the 42.6 t/ha/yr for raw grape marc. In contrast, if the raw grape marc were spread at the loading recommended by AgResearch at 3 t DM/ha/yr (which equates to 60 kg N/ha/yr), it would require 5,470 hectares, and if compost were spread at 150 kg N/ha/yr it would require less land, at 2,140 hectares. Thus, for any of these options, the availability of land is not a limiting factor given there is approximately 26,850 ha of vineyards in Marlborough; however, the different DM and N limits have implications for the relative financial costs of spreading raw grape marc and compost.

Stockpiling and best-practice composting are not the same activity. The media reports and photographs at the time of the prosecutions in Marlborough do not indicate much about the composting activity. It is likely that the grape marc was not arranged in windrows, neither were they turned every two days (to begin with, decreasing over time), neither were they covered to prevent rain events causing excessive moisture and leaching, and neither (at that time) were they placed on barrier surfaces with leachate collection. Best-practice composting requires this level of infrastructure and operating investment.

The argument in favour of composting is that it both reduces the mass of the residue and avoids environmental liabilities. Best-practise composting will reduce 70,000 tonnes of raw grape marc at 67%

moisture content to *ca.* 23,000 tonnes at 40% moisture content. The mass loss is due to aerobic respiration of mostly water vapour and carbon dioxide, CO_2, but there is a background low-level of methane (CH_4) which is mostly metabolised within the windrows before release, and a small amount of nitrous oxide (N_2O). Nevertheless, some average release liability is expected, across a wide margin depending on compost operation, according to the IPCC from 0.04-4 kg CH_4 and 0.06-6 kg N_2O per tonne across a range of biomass feedstocks. These then equate to net global warming potential impacts calculated over 100 years (GWP_{100})[1] of 0.84-122 and 16-59 kg CO_2e per tonne of feedstock, respectively. Well-managed compost operations trend to the low end of this range, with as much as 98% of the methane metabolised within the windrows and only 2% of the nitrogen within the grape marc released as nitrous oxide as part of the denitrification cycle during the curing phase. Prolonged anaerobic stockpiling is expected to perform at the poor end of the range, which has not been established for grape marc. Lastly, best-practice composting will not generate leachate that needs further treatment; rather, any collected leachate is recycled to the windrows and is consumed during further degradation. In contrast, as experienced in Marlborough, stockpiling will generate leachate, especially if the raw grape marc is excessively wet or if heavy rain events occur on uncovered piles. This study does not include anaerobic digestion for biogas and methane, where the grape marc is in a water medium and enclosed tanks. While digestion removes some mass, it then leaves a residue that is more difficult to dewater and which still needs repurposing. The focus here is on thermal processes but benchmarked to best-practice composting.

Effective measurement and monitoring of emissions is required in order to monetise them and therefore incentivise their reduction. There is currently no method for monitoring methane emissions at scale, although this will be possible once the New Zealand satellite is launched in 2022. This satellite has the specific purpose to measure methane emissions at source. Presumably, measurement of methane emissions will affect the national emission inventory, and international commitments, e.g., the Paris Agreement. If so, generators of emissions are likely to be required to purchase New Zealand Units (1 NZU = 1 tonne of emitted CO_2e) on the NZ Emission Trading Scheme (NZETS); currently, these are priced at \$26.50/t CO_2e. This figure can be multiplied by the tonnages above to obtain the emissions liabilities, which are small for well-managed composting at \$37,000/yr rising to \$93,000/yr for poorly-managed composting, which is probably significantly less than unattended stockpiles. Financial liability for leachate has not been quantified for poor-practice composting as it was outside the focus of this work. Nevertheless, an example of the scale of the liability can be determined from another part of this study. Dewatering grape marc by further mechanical pressing yields a BOD of the exudate of 85 g/L. For dewatering 70,000 tonnes of raw grape marc from 67% (as it comes off the juice presses) to 50% moisture produces 24,566 m^3 of liquid, with a total biological oxygen demand of 2,088 tonnes. As leachate must be treated, processing costs are reflected by the trade waste charges at \$0.81/m^3 plus \$0.57/kg BOD inclusive of GST (CCC). If so, the trade waste charges amount to \$1.21M/yr.

A third liability is that stockpiles represent pseudo landfills, but are permissible because the MEP does not contain any limits on the period agricultural residues are allowed to be stockpiled without utilisation. Nevertheless, this represents a liability because, as pseudo landfills, they must be managed. The only known costs for proper storage of a material that causes slumping, leaching, creates odours, and produces excessive methane emissions, are those of a landfill. If so, the gate fee is \$135/t, which presumably reflects the true cost of land preparation, other infrastructure, operation, depreciation and GST. In this way, stockpiles of unprocessed raw grape marc have the management liability of \$9.45 M/yr of gate fees. In comparison, compost, which has been processed but becomes stranded, attracts the liability of \$3.10 M/yr.

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[1] The global warming potential of a gas is the amount emitted multiplied by a factor that relates its effect on global warming compared to carbon dioxide. The IPCC factors for biological methane is 28 and for nitrous oxide it is 265. These are determined for a 100 year timeframe. For biogenic methane emissions, the net global warming potential is multiplied by the factor minus one. The minus one accounts for the best case where only carbon dioxide is formed. Biogenic carbon dioxide does not have an additional global warming effect to itself, so is omitted.

2.2 Best practice composting technology

Best-practice composting is the baseline scenario against which the thermal processes are compared. Composting is a well-understood process which provides the most suitable comparison to the thermal technology solutions, although it is not operating at scale in Marlborough. The composting calculations here are a desk study for the purposes of comparison of the carbon footprint impact and economics.

The annual production of 70,000 tonnes of grape marc requires 12.6 hectares of land, assumed to be at a single central location within the region. (As noted before, this is a techno-enviro-economic analysis, not a business case.) At this site, the raw grape is arranged into windrows on a prepared impermeable base, which contains a leachate collection system. All windrows are under cover to avoid rain events shocking the composting process. Turning of the compost is achieved using dedicated turning machines. Turning frequency is aligned to time-temperature histories of the windrow and so will occur approximately every two days in the early stages of composting reducing over time, but averaged here at twice per week. The purpose of turning is to ensure air replacement so that aerobic degradation occurs. This work does not consider bulking agents to provide greater entrapped air volume. Otherwise, grape marc is considered to have suitable properties for composting (C:N 33, moisture 67%). Such investigations are recommended before large scale operations are undertaken, especially as it will affect the economics of turning frequency. Here, the period of turning is assumed to be 6 weeks, as expected in a well-managed facility, followed by one month minimum for the curing phase before compost can be land-spread.

The composting facility is expected to have a lifetime of 50 years, with replacement of motive machinery every 10 years. Carbon footprint impacts are determined from the construction, then annual transport of raw grape marc to the composting facility and back out for land-spreading, for the operation of the facility, and the excess emissions of methane and nitrous oxide that contribute to global warming. The overall global warming potential impact (GWP_{100}) for compost is of 20 kg CO_2e/t raw GM, and is dominated by the gaseous emissions, although these are actually quite variable depending on the management of the composting process, as discussed above.

2.3 Drying grape marc

All thermal processes need a drying plant. The advantage of drying is that it converts the easily degraded grape marc into a product that can be stored indefinitely in a low humidity environment. It can then be sold for a range of uses such as animal feed (e.g., cattle, goats, chickens), or heating fuel (e.g., pellet burners), or for delayed land-spreading. Here, in this study, drying is a precursor to thermal processing.

The drying facility consists of a delivery area for raw grape marc arrival, a combustor, an array of dryers and silos for storage of the dried grape marc. The number of dryers in the array is twelve if grape marc is processed immediately over the six week vintage season, or three if grape marc is treated with growth inhibitor and processed over five months, further reducing to one if mechanical dewatering from 67% moisture to 50% moisture precedes drying, which also produces the dewatered pressate needing biological treatment, as previously noted on page 5. The area required for the larger drying plant is 0.32 ha and silos is 0.8 ha. Plant life is assumed to be 25 years.

To avoid unnecessary fossil fuel consumption, after start up, 45.7% of the dried grape marc is recycled as fuel to a combustor to produce the heat needed to dry the remaining grape marc. This provides a significant reduction in the mass of grape marc needing disposal. In this way, the original 70,000 tonnes of raw grape marc at 67% moisture reduces to 12,695 tonnes of dried grape marc at 20% moisture. It does not need to be dried further, because at this moisture content the water activity is below 0.4 which is sufficient to avoid fungal growth (e.g., white rot) over the storage required for thermal plant operation. Each dryer is indirect, that is, the hot flue gas from combustion does not directly contact the grape marc, but is passed through a tube bundle that rotates through a bed of the material. This enables safe operation where the steam evolving from the grape marc evacuates the chamber of air, preventing the possibility of combustion. It allows higher internal temperatures and therefore driving gradient for drying. Emissions of NO_x are mitigated by controlled temperature combustion and particulate matter is removed in flue gas clean-up, both to

European standards with NO_x below 145 mg/m^3 and PM below 5 mg/m^3. To align with best international practice, flue stack emissions monitoring is expected to be continuous. The residue is 409 tonnes of ash, which needs to be landfilled.

As the drying unit is integral to each thermal processing option, the carbon footprint and process economic analyses are included within each of these. Scenarios of operation are examined in table 1.2, where the above description of the technology is for the Drying 1 scenario. Principal costs are given in table 1.3 and revenues table 1.6.

2.4 Combustion for Power

Combustion is a well-developed technology for repurposing biomass to produce steam which is then used in steam turbines to generate electricity. Combustion occurs when an excess of oxygen (in air) is supplied. The combined combustion plant requires 1.0 hectare of land (in addition to the drying plant and silos) and plant life is assumed to be 25 years. Combustion creates an additional 320 tonnes of ash, the total now being 728 tonnes, which is sent to landfill. Similarly, emissions of NO_x are mitigated by controlled temperature and staged combustion and particulate matter (PM) is removed in flue gas clean-up. Issues common with coal, such as SO_x and heavy metals, are minimal because neither sulphur nor heavy metals are significantly present in grape marc. The process produces electricity, but does not produce useful heat. Scenarios of operation are examined in table 1.2, where the above description of the technology is for the Combustion 1 scenario. Principal costs are given in table 1.3 and revenues table 1.7.

2.5 Gasification for Heat and Power

Gasification is different to combustion as the grape marc is heated in a constrained oxygen atmosphere at elevated temperatures between 800-900°C to produce the flammable gases of carbon monoxide (CO), hydrogen gas (H_2) and some methane (CH_4). These gases must be cleaned up, requiring scrubbing to remove particulate, tar and other pollutants to European emission standards. The residue is a gasification char of 1,337 tonnes, which needs to be landfilled, because at these temperatures undesirable polycyclic aromatic hydrocarbons (PAHs) will be present. The combined drying and gasification plants requires 0.7 hectares of land and plant life is assumed to be 25 years.

Six scenarios of operation are listed in table 1.2. The cleaned gas is then combusted in a gas engine (for the Gasification 1 & 2 scenarios) to produce 6,941 MWh/yr of electricity (or 1.446 MW continuously over 200 days of operation) alongside 47,865 GJ/yr of saleable heat. These figures correspond to 0.36 GJ/(t raw GM) of electricity and 0.68 GJ/(t raw GM) of heat. More heat and electricity are produced if the grape marc is mechanically dewatered prior to drying (Gasification 3). Further synergies are possible with the excess heat from gasification being able to be recycled to the drying plant, if the drying plant were extended to the same operational period as the gasification plant (Gasification 5 & 6). When this analysis is carried out, the recycle of heat means less grape marc needs to be combusted to supply the heat for drying, resulting in more grape marc entering the gasification plant. Principal costs are in table 1.3 and revenues in table 1.8.

2.6 Pyrolysis for Biochar

Pyrolysis is the thermal destruction at relatively low temperatures of carbonaceous material in the absence or highly constrained supply of oxygen. Here, we operate at 500°C to produce biochar, which is defined as charcoal produced from sustainable resources (e.g., agricultural residues) and amended to soils after manufacture. For all other uses, e.g., heating fuel, it is defined as charcoal. The yield of biochar from the dried grape marc (dry basis) is 34.5%. In addition, pyrolysis produces a condensable tarry liquid phase, which includes water, and a non-condensable syngas. While the heating value is relatively low, both are able to be combusted to provide heat for the process with an excess of saleable heat. Standard flue gas clean-up is required to remove particulate matter (PM). Catalytic conversion and low temperatures staged combustion are expected to mitigate NO_x to below European standards.

Six scenarios of operation are listed in table 1.2. The baseline process Pyrolysis 1 produces 3,500 tonnes of biochar and 14,688 GJ/yr of low grade heat. These are equivalent to 50 (kg biochar)/(t raw GM) and 0.21 GJ heat/(t raw GM). More biochar is produced when grape marc is mechanically dewatered from 67% to 50% moisture content prior to drying (Pyrolysis 3). Further synergies are possible with the excess heat from pyrolysis being able to be recycled to the drying plant, if the drying plant were extended to the same operational period as the pyrolysis plant (Pyrolysis 5 & 6). When this analysis is carried out, the recycle of heat allows more biochar production because less grape marc needs to be combusted to supply the heat for drying. Doing this is initially counter-intuitive, because the purpose of repurposing is to reduce the mass of residue. However, if biochar can demand a sufficient sale price, then greater production of biochar is desirable. Principal costs and revenues are in tables 1.3 and 1.9.

3. Environmental Analysis

All activities involve emissions. The raw grape marc must be transported from the pressing facility to the centralised composting or thermal processing facility. This requires diesel trucks that produce fossil fuel derived emissions. If compost or biochar is made, these also need transporting back to be land-spread. Each facility has embodied emissions associated with its construction, and emissions for operation and maintenance, including the use of auxiliary fossil fuels for start-up of the plant, and electricity calculated at the national mix of renewable and fossil fuel generation. Because grape marc contains carbon, its release as carbon dioxide (CO_2) is not included in the emissions accounting, because it is part of the sustainable carbon cycle. However emissions of other greenhouse gases carry a global warming potential which must be included. For these, composting has inherent emissions associated with biodegradation relating to the small quantities of greenhouse gases other than CO_2 that are released, and the thermal processes have small emissions of greenhouse gases in the flue gas, where their levels are dictated by the emissions standards under which these processes operate.

When comparing processes, it is important to do this on the same basis. Because the destination of compost is to the soil, the soil receives the nutrient benefit of the compost, wherever that may be within the Marlborough region. Neither combustion nor gasification return any fertiliser value, and so in order to deliver the same outcome, an additional process is required to add the same nutrients to the soil (i.e., manufacture, transport and application of industrial fertilisers which have their own greenhouse gas emissions). Similarly, biochar returns some but not all the nutrient value, and so the difference also needs to be made up with industrial fertilisers.

Within this study, the environmental analysis is comparative, using carbon footprint. How does each of the thermal processes compare to best-practice composting for the treatment of 70,000 of raw grape marc at 67% moisture and when each process delivers the same soil nutrient benefit? Table 1.1 shows the results. Composting has emissions of 20 kg CO_2e/tonne of raw grape marc, which means that the activity of composting generates more emissions than simple biogenic conversion of all carbon in the grape marc to CO_2.

Thermal processes are then listed for two scenarios, the second of which allows for offsetting coal emissions. Offsetting is only possible if an existing user of coal were to purchase the heat or power produced in the thermal processes in order to reduce their coal use. An example might be a large dairy plant who use coal to heat their spray dryers. Offsetting is a first mover advantage, because once all the industries able to do so have converted from coal to grape marc, offsetting is no longer possible. The scenario is included here to demonstrate the change in environmental outcome it produces, and the potential significance of displacing coal-fired heat and power generation in the short term.

Table 1.1 shows that, without coal offsetting, **combustion** has more emissions than composting and that **gasification** has less. In fact, gasification emissions are virtually neutral compared to simple biogenic conversion of all carbon in the grape marc to CO_2 (which is **0** kg CO_2e/t raw GM). This is because a certain amount of carbon is contained in the gasification char. While it is sent to landfill because it is not regarded as suitable for soil amendment, it nevertheless contains carbon, which is stable and so represents a drawdown of carbon from the atmospheric cycle. This sequestered carbon is sufficient to balance the effect of the process emissions and the fertiliser replacement. **Pyrolysis** sequesters a lot more carbon in the biochar, to the extent that is has a significantly better carbon footprint than simple biogenic conversion of all carbon in the grape marc to CO_2. In conclusion, the carbon footprint outcome is best by a considerable margin for pyrolysis to make biochar.

It must be pointed out that biochar confers benefits other than its fertiliser value to the soil, which are not captured in a carbon footprint analysis. The most notable is the water holding capacity due to its porosity, and the relatively large pore size which means the moisture is available to plants, thus providing a measure of drought resistance. Other effects such as adsorbency depend on its surface area and soil interactions. Surface area is determined by the conditions of pyrolysis, increasing with temperature. While it has not been determined here, for a 500°C operating temperature, it is expected to be *ca.* 200 m^2/g BC, which is then expected to be a reasonably effective adsorbent in soil or for bioremediation, e.g., for improved retention of nutrients as they move through the soil profile. However, further soil studies are required in order to draw firm conclusions. Activated carbons can also be made from biochar and are useful for specific pollutants removal. They typically have higher surface areas at *ca.* 1000 m^2/g carbon, which can be achieved by a secondary activation step during processing.

A sensitivity analysis explored variations in moisture content of the raw grape marc, which was determined at 67%. Wetter grape marc takes more energy to process. It was found that above 75% moisture, the carbon footprints of the thermal processes become poorer than composting. Decreasing moisture by secondary mechanical dewatering has a dramatic effect on the thermal processes, for example, if dewatered to 50% moisture, the Pyrolysis 1 & 2 carbon footprints are predicted to improve from -49 to -240 kg CO_2e/tonne raw GM, while Gasification 1 improves from 17 to -87 kg CO_2e/tonne raw GM, with combustion relatively unchanged. However, mechanical dewatering also produces a discharge rich in BOD which needs treatment. It is included in the mass balances and is accounted for by the Drying 3, Combustion 3, Gasification 3 & 6 and Pyrolysis 3 & 6 scenarios.

A second sensitivity analysis was carried out exploring the effect of poor management of the composting process, characterised here by methane not being metabolised within the windrows. Best-practice composting assumes that 98% of all methane generated is metabolised within the windrow. However, if the lesser fraction of 50% is metabolised, then the composting carbon footprint grows from +20 to +50 kg CO_2e/tonne raw GM. If none is metabolised, the footprint grows to +76 kg CO_2e/tonne raw GM. Poor management means that, in the comparison of alternatives, the thermal processes have increasingly better carbon footprints compared to composting when they displace composting. For example, reducing CH_4 removal from 98% to 50% to 0%, improves Pyrolysis 1 relative to composting from -69 to -99 to -125 kg CO_2e/tonne raw GM, respectively.

Here, the modelling of the fertilizer requirements assumes that all nutrients applied in the compost (in the baseline scenario) are used in the system, whether in vineyards or in the Marlborough region. In the absence of compost application soil, we assume that vineyard managers are actively monitoring the nutrient content of their soils and applying additional fertilisers as required at levels equivalent to that supplied by the compost.

Table 1.1. Comparison of overall carbon footprint. The numbers 1, 3 and 6 refer to the scenario presented in Table 1.2.

Process	Carbon footprint	Difference	Carbon footprint with offsetting of coal	Difference
	kg CO_2e/(tonne raw GM)		kg CO_2e/(tonne raw GM)	
Composting[a]	20		20	
Combustion 1[b]	63	+43	-64	-84
Combustion 3[b]	62	+42	-161	-181

Gasification 1[c]	17	-3	-132	-152
Gasification 3[c]	-12	-32	-253	-273
Gasification 6[c]	-38	-58	-243	-263
Pyrolysis 1[d]	-49	-69	-68	-88
Pyrolysis 3[d]	-155	-175	-181	-201
Pyrolysis 6[d]	-225	-245	-256	-276

[a] Grape marc is composted then land-spread.

[b] Grape marc is dried then combusted to produce steam for use in steam turbines to make electricity. This is the Combustion 1 scenario later used in economic analysis.

[c] Grape marc is dried then gasified to make a syngas for use in a gas engine to make electricity with excess saleable heat. This is the Gasification 1 scenario later used in economic analysis.

[d] Grape marc is dried then pyrolysed to make biochar for soil amendment and excess saleable heat. This is the Pyrolysis 1 scenario later used in economic analysis.

4. Economic Analysis

Process economic analysis has been considered for a number of configurations of the thermal processing options. The accuracy of these predictions, defined here at preliminary stage design, is expected to be ±35%. Process economic analysis establishes the total capital (CAP) cost to build the plant based on the capital cost of the equipment items with ancillary costs determined using typical Lang factors (e.g., for site preparation, piping, instrumentation and control, buildings and access roading). The composting facility has the land preparation and building costs determined separately because this is not a standard chemical engineering processing plant. Second, the operating and maintenance (O&M) costs are estimated using standard methods (e.g., to include energy and utility requirements, estimated labour, vehicle usage and annualised costs such depreciation). Table 1.2 lists the scenarios that are compared. Stockpiling of grape marc is a non-tenable activity so is not included. Rather, it is a form of landfilling and so carries the costs associated with land preparation, leachate collection and proper management, the true long-term cost of which is reflected in the gate fee of the Marlborough landfill, at $135/t minus GST.

Table 1.2. Scenarios of process configurations for economic comparison.

Scenarios	Explanation
Direct Land-spreading	Direct land-spreading repurposes the raw grape marc. It has no plant and therefore no capital costs but incurs an operating cost. Given that the activity is occurring in Marlborough, it is assumed that revenue covers costs. At a regional level, it returns its fertiliser nutrient value to land in the same way as compost. The liability is BOD overload of soil forming methane, nitrous oxide and leaching to waterways, the cost of which is not able to be estimated.
Composting (baseline scenario)	Best-practice incurs capital costs, e.g., prepared land, leachate collection, cover to avoid rain events, and O&M costs for windrow turning. Compost is then land-spread to return its fertiliser nutrient value. Liabilities result from poor management of the composting operation, resulting in a rise in methane emissions.
Drying 1	Drying is separated because dried grape marc is a saleable product. Here, drying is conducted immediately, over the 42 days vintage season, to avoid stockpiling the grape marc, and the possible deleterious environmental effects of stockpiles becoming anaerobic. At a regional level, dried marc sold for purposes other than land-spreading does not return fertiliser nutrient value, which must then be accounted for by addition of industrial fertiliser in the comparison.
Drying 2	Drying, as for D1, but a microbial growth inhibitor is used so that grape marc can be stockpiled. Drying then extends over 160 days. The result is a smaller drying plant, requiring less capital.
Drying 3	Drying, as for D2, but with mechanical dewatering prior to drying, from 67% moisture to 50% moisture. Some solids are lost in the pressate, but more particularly, it carries a high BOD which is incurs a treatment cost. The result is that drying requires less energy, and so more dried grape marc is produced. Drying extends over 337 days.
Combustion 1	Combustion of dried grape marc from D1 is used to produce electricity over 200 days. No useful heat is produced. The residue ash is landfilled. At a regional level, the industrial fertiliser are required to replace the nutrients to the soil.
Combustion 2	Combustion of dried grape marc from D2 is used to produce electricity over 200 days. No useful heat is produced. The residue ash is landfilled. At a regional level, the industrial fertiliser are required to replace the nutrients to the soil.
Combustion 3	Combustion of dried grape marc from D3 is used to produce electricity over 337 days. No useful heat is produced. The residue ash is landfilled. At a regional level, the industrial fertiliser are required to replace the nutrients to the soil.
Gasification 1	Gasification of the dried grape marc from D1 is used to produce electricity and heat over 200 days operation. The residue tar, char and captured particular matter is landfilled. The landfilled char

	contains sequestered carbon. At a regional level, no nutrients are returned to productive land and so industrial fertilisers are required.
Gasification 2	Gasification of the dried grape marc from D2 is used to produce electricity and heat over 200 days operation. The residue tar, char and captured particular matter is landfilled. The landfilled char contains sequestered carbon. At a regional level, no nutrients are returned to productive land and so industrial fertilisers are required.
Gasification 3	Gasification of the dried grape marc from D3 is used to produce electricity and heat over 337 days operation. The residue tar, char and captured particular matter is landfilled. The landfilled char contains sequestered carbon. At a regional level, no nutrients are returned to productive land and so industrial fertilisers are required.
Gasification 4[a]	Gasification of the dried grape marc from D1 is used to produce electricity and heat, but where the excess heat from gasification is recycled to the drying plant (i.e., this becomes a more integrated process) to reduce the fraction of dried grape marc that needs to be combusted in order to supply the heat for drying. The result is more dried grape marc entering the gasification plant, which produces more electricity.
Gasification 5	Gasification of the dried grape marc from D2 is used to produce electricity and heat over 200 days, but where the excess heat from gasification is recycled to the drying plant (i.e., this becomes a more integrated process) to reduce the fraction of dried grape marc that needs to be combusted in order to supply the heat for drying. The result is more dried grape marc entering the gasification plant, which produces more electricity.
Gasification 6	Gasification of the dried grape marc from D3 is used to produce electricity and heat over 337 days, but where the excess heat from gasification is recycled to the drying plant (i.e., this becomes a more integrated process) to reduce the fraction of dried grape marc that needs to be combusted in order to supply the heat for drying. The result is more dried grape marc entering the gasification plant, which produces more electricity.
Pyrolysis 1	Pyrolysis of the dried grape marc from D1 is used to produce biochar and heat over 200 days. The biochar contains sequestered carbon and retains some fertiliser nutrient value. Biochar can be sold for a range of uses. At a regional level, the missing fertiliser nutrient value not returned to soil must be replaced by industrial fertilisers.
Pyrolysis 2	Pyrolysis of the dried grape marc from D2 is used to produce biochar and heat over 200 days. The biochar contains sequestered carbon and retains some fertiliser nutrient value. Biochar can be sold for a range of uses. At a regional level, the missing fertiliser nutrient value not returned to soil must be replaced by industrial fertilisers.
Pyrolysis 3	Pyrolysis of the dried grape marc from D3 is used to produce biochar and heat over 337 days. The biochar contains sequestered carbon and retains some fertiliser nutrient value. Biochar can be sold for a range of uses. At a regional level, the missing fertiliser nutrient value not returned to soil must be replaced by industrial fertilisers.
Pyrolysis 4[a]	Pyrolysis of the dried grape marc from D1 is used to produce biochar and heat, but where the excess heat from pyrolysis is recycled to the drying plant (i.e., this becomes a more integrated process) to reduce the fraction of dried grape marc that needs to be combusted in order to supply the heat for drying. The result is more dried grape marc entering the pyrolysis process, to produce more biochar.
Pyrolysis 5	Pyrolysis of the dried grape marc from D2 is used to produce biochar and heat over 200 days, but where the excess heat from pyrolysis is recycled to the drying plant (i.e., this becomes a more integrated process) to reduce the fraction of dried grape marc that needs to be combusted in order to supply the heat for drying. The result is that drying requires less energy, and so more dried grape marc is produced, and consequently more biochar is produced.
Pyrolysis 6	Pyrolysis of the dried grape marc from D3 is used to produce biochar and heat over 337 days, but where the excess heat from pyrolysis is recycled to the drying plant (i.e., this becomes a more integrated process) to reduce the fraction of dried grape marc that needs to be combusted in order to supply the heat for drying. The result is that drying requires less energy, and so more dried grape marc is produced, and consequently more biochar is produced.

[a]These cases are omitted because recycling excess heat requires the drying plant to operate over an extended period, not commensurate to the embedded Drying 1 scenario.

For comparison direct land-spreading of raw grape marc is included in table 1.2. It does not have infrastructure so attracts no capital cost, but has an O&M cost. Its cost reflects the cost of spreading. Standard truck spreading of fertiliser, which is granular and distributes easily across a wide swathe, is estimated by MPI at $6/tonne, but here grape marc is wet and spreading costs also include ploughing into the soil. For this reason, cost estimates of $10, $20 and $30/tonne are used. These same spreading costs are used for biochar. Stockpiling of grape marc is an untenable activity, for which the liability cost of proper management is reflected by those for landfilling. In Marlborough, at $135/t gate fee, this amounts to $9.4M/yr.

Table 1.3 contains the summary of the CAP and O&M costs. This determines the required revenue to reduce the Net Present Value (NPV) to zero over a 25 years period when the cost of capital is 5%. Five percent provides a conservative margin for calculations as it is higher than industry practice for large plants, determined as the London Interbank Offered Rate (LIBOR, currently 1.8%) plus 2%. The fourth column represents the liabilities or deferred cost. The most likely deferred cost is not returning grape marc to soil which requires additional industrial fertiliser application.

As can be seen the capital cost of all facilities is significant, reflecting the infrastructure and technology needed to ensure best-practice, process performance and emission controls, as detailed in the above process descriptions. The total CAP and O&M costs for the thermal plants are the sum of the figures given for the drying plant and each thermal process. However, the required revenue in table 1.3 for the thermal processes embodies the drying plant. Gasification is the most expensive because it is the most complex plant. Drying is critical to the thermal processing overall CAP and O&M. Its CAP and O&M costs are lower when the grape marc is treated with a growth inhibitor so that drying can occur over an extended period (Drying 2 affects Combustion 2, Gasification 2 & Pyrolysis 2), further lowered if mechanical dewatering can reduce the moisture content from 67% to 50% (Drying 3 affects Combustion 3, Gasification 3 & Pyrolysis 3), and less again when, in addition, excess heat from gasification or pyrolysis are recycled to the drying plant (affecting Gasification 5 & 6, Pyrolysis 5 & 6). The consequence of these thermal efficiencies is that the drying plant size becomes smaller and less costly. While laboratory work shows dewatering is feasible, its application at industrial-scale needs to be proven. The consequence of the improved thermal efficiency in Gasification 5 & 6, Pyrolysis 5 & 6 is that more saleable electricity and heat is produced from gasification and more biochar and heat is produced from pyrolysis. The following section examines how the required revenues in table 1.3 may be achieved.

Table 1.3. Process economic analysis and comparison of scenarios. Capital cost and operating and maintenance (O&M) costs are listed for each plant. The revenue ($/yr) is the annual net revenue required to reduce the net present value (NPV) to zero over 25 years. For the thermal plant scenarios, this figure is inclusive of the drying plant, e.g., the revenue required from Combustion 1 is the $9.04M which is the sum of the $6.65M from drying and an additional $2.39 from the combustion plant. Each scenario is for 70,000 tonnes of raw grape marc at 67% moisture.

Process	Capital Cost	Operating & Maintenance Cost	Revenue[a] required to reduce NPV to zero over 25 years, $/yr	Liabilities and deferred costs
Direct Landspreading	-	@$10/t, $0.7M @$20/t, $1.4M @$30/t, $2.1M	$0.7M $1.4M $2.1M	• Carbon footprint of normal land-spreading activity including GHG emissions from soil • Carbon footprint of land-spreading activity after BOD overload of soil • Leaching impacts after BOD overload of soil • Stranded stockpiles of non-spread raw GM incurring landfill-equivalent management costs, if no take-back agreements are in place • Environmental impacts of stockpiling
Composting	$14.22M	$1.51M	$2.08M	• Carbon footprint of composting, well-managed • Carbon footprint of composting, poorly-managed • Stranded stockpiles of non-spread compost incurring landfill-equivalent management costs, if no take-back agreements are in place • Environmental impacts of stockpiling
Drying 1	$42.41M	$5.02M	$6.65M	• Mechanical dewatering produces 24,556 tonnes of pressate with 85 g/L BOD • Disposal of 181 tonnes of ash from drying plant • Air emissions of PICs and PM from drying plant • Disposal of unsold dried GM to land-spreading, if take-back agreements exist
Drying 2	$11.89M	$2.29M	$2.76M	
Drying 3	$5.10M	$2.56M	$2.76M	

				• Disposal of unsold dried GM to landfill, or to stockpiling and incurring landfill-equivalent management costs, if no take-back agreements are in place
Combustion 1 (incl. D1)	$68.58M	$6.36M	$9.04M[a]	• Carbon footprint of activity • Disposal of 704 tonnes of ash (523 t additional to drying) to landfill • Air emissions of PICs and PM Exceeding air emissions limits (particulate matter and products of incomplete combustion). Costed into design. • Deferred cost of fertiliser replacement
Combustion 2 (incl. D2)	$38.06M	$3.63M	$5.15M[a]	
Combustion 3 (incl. D3)	$31.27M	$3.90M	$5.15M[a]	
Gasification 1 (incl. D1)	$114.04M	$6.24M	$11.27M[a]	• Carbon footprint of activity • Disposal of 2,882 tonnes of gasification char to landfill • Air emissions of PICs and PM from gasification plant • Deferred cost of fertiliser replacement
Gasification 2 (incl. D2)	$83.51M	$3.51M	$6.85M[a]	
Gasification 3 (incl. D3)	$76.73M	$3.78M	$6.85M[a]	
Gasification 4 (eliminated)	-	-	-	
Gasification 5 (incl. D2)	$115.45M	$4.18M	$8.80M[a]	
Gasification 6 (incl. D3)	$90.72M	$4.24M	$7.87M[a]	
Pyrolysis 1 (incl. D1)	$55.26M	$5.62M	$8.29M[a]	• Carbon footprint of activity • Disposal of 181 tonnes of drying ash to landfill • Air emissions of PICs and PM from pyrolysis plant • Disposal of unsold biochar or charcoal to landfill, if no take-back agreements are in place • Partial deferred cost of fertiliser replacement.
Pyrolysis 2 (incl. D2)	$24.73M	$2.89M	$3.88M[a]	
Pyrolysis 3 (incl. D3)	$23.44M	$3.57M	$4.51M[a]	
Pyrolysis 4 (eliminated)	-	-	-	
Pyrolysis 5 (incl. D2)	$30.33M	$3.29M	$4.51M[a]	
Pyrolysis 6 (incl. D3)	$27.93M	$3.93M	$5.05M[a]	

[a] Required revenue of the combustion, gasification and pyrolysis scenarios includes the embodied costs of the drying plant.

4.1 Examination of revenue

Repurposing grape marc presents revenue opportunities. Not doing so carries liabilities. These are the significant costs of managing stockpiles of grape marc. Stockpiles that accumulate over time are pseudo landfills that have many of the problems that landfill have been designed to mitigate: slumping prevention, leachate collection, covering to avoid odour, and partial collection and flaring of methane emissions. They are therefore assumed to incur the same long-term management costs reflected by the gate fee of $135/tonne incl. GST. For 70,000t/yr raw GM, the management liability is $9.45M/yr, which does not include the environmental liability (a future financial liability) of excessive methane emissions during anaerobic decay of stranded stockpiles. Each of the repurposing options is discussed below.

Land-spreading raw grape marc. Direct land-spreading of raw grape marc is a current activity in Marlborough and, therefore, it is expected that contractors operate profitably. While unknown to us, the charge for transport, spreading and ploughing into the soil is expected to be in the range of $10-$30/tonne raw GM. This charge is offset by the intrinsic fertiliser value (for the nutrients) of the raw grape marc, estimated to be $16.76/tonne raw GM, which indicates that the costs of land-spreading and the fertiliser value approximately balance. For example, if the cost of spreading is $10/t, then there is a net benefit to the region of $473,000 from the fertiliser value minus the cost of spreading, but if the cost of the spreading is $20/t, then there is a net cost to the region of $227,000. The intrinsic value of raw grape marc to the region is $1.17M/yr.

Table 1.4. Scenarios for revenue from direct land-spreading of 70,000 tonnes of raw grape marc at 67% moisture content.

Cost of transport, spreading (& ploughing), $/t raw GM	$0.00	$10.00	$20.00	$30.00
Fertiliser value, $/t raw GM	$16.76	$16.76	$16.76	$16.76
Net revenue, $/t raw GM	$16.76	$6.76	-$3.24	-$13.24
Net revenue, $/yr	$1,173,000	$473,000	-$227,000	-$927,000

Manufacture and land-spreading of compost. Best-practice composting needs an annual revenue of at least $2.08M/yr to break even over 25 years. It is also land-spread and the cost of doing so is expected to be similar to that of raw grape marc, $10-$30/tonne compost. However, the net cost of transport, spreading and ploughing is less because it has reduced mass, from 70,000 tonnes of raw GM at 67% moisture to 22,960 tonnes of compost at 40% moisture. For this reason, its fertiliser value is $51.10/tonne of compost. Interestingly, this fertiliser value is about twice what, we understand, industry is willing to pay per tonne for compost in Marlborough. This reflects a market imbalance. To avoid this, we use the embodied fertiliser value to calculate the net revenue for the three land-spreading costs in table 1.5.

For the business venture of building a best-practice composting facility, in order to reduce the NPV to zero over 25 years, the breakeven compost sale price would need to be $91/tonne compost (with the incurred cost rising as the incremental spreading cost is applied, e.g., rising to $101/t when the spreading cost is $10/t). This is above the intrinsic nutrient fertiliser value of $51.10/t compost. Compost does offer other benefits than just its nutrient content, but this is not easy to determine and so is not included in the present analysis.

However, the economics are more favourable when the cost of the current activity is included. Revenue of $2.08M/yr is achievable if winegrowers were levied at $29.72/t raw GM. This would pay for the composting operation. Then, because compost has a reduced mass, the overall spreading costs are less. At $10, $20 and $30/t spreading cost, the net savings between spreading 70,000 tonnes of raw grape marc and 22,960 tonnes of compost work out to be $6.71, $13.43 and $16.29/t raw GM produced. The net cost of the levy is then*:

- at $10/t spreading fee: $29.72 – $6.71 = +$23.01/t raw GM
- at $20/t spreading fee: $29.72 – $13.43 = +$16.29/t raw GM
- at $30/t spreading fee: $29.72 – $20.15 = +$9.57/t raw GM

*The fertiliser value of compost is only 2% less than raw GM, on a per tonne of raw GM basis, so is omitted here.

So while investing in a best-practice composting operation is marginally more expensive than direct land-spreading of raw grape marc, its advantage is that it avoids the liability of BOD overload in soils. Composting also reduces the liability of stranded resource from 70,000 tonnes of raw GM to 22,960 tonnes of compost, reducing the landfill-equivalent management liability cost from $9.45 M to $3.1 M/yr. The inclusion of liabilities in the accounting is discussed later.

Table 1.5. Scenarios for revenue from compost.

Cost of transport, spreading (& ploughing), $/t compost	$0.00	$10.00	$20.00	$30.00
Fertiliser value, $/t compost	$51.10	$51.10	$51.10	$51.10
Net revenue, $/t compost	$51.10	$41.10	$31.10	$21.10
Net revenue if spread, $/yr	$1,173,000	$944,000	$714,000	$484,000

Drying to produce dried grape marc. Drying can be a standalone activity or combined with the thermal plants. If standalone, dried grape marc is the saleable product. It needs to attract revenues from sale as animal feed or bedding material, or as burner fuel (as pellets or hog fuel), or from land-spreading. It has excellent shelf life and so can be sold throughout the following year. For each of the drying options investigated, the required sale price is given in table 1.6. (The cost of ash disposal and trade waste treatment of the pressate from mechanical dewatering in D3 are included within the O&M costs, and so removing them from affecting the required revenue calculations presented here.)

Clearly, mechanical dewatering (in Drying 3) has the lowest costs although, as stated earlier, the dewatering is based on laboratory results and needs proving at scale. Notably, the required revenue for the best drying case is higher than for compost ($2.76M *cf* $2.08M, respectively) which translates to a higher sale price ($133/(t dried GM at 20% moisture) *cf* $91/(t compost)). Both are also substantially more than the intrinsic fertiliser values for compost and dried grape marc ($51.10/(t compost) and $40.63/(t dried GM at 20% moisture)). However, dried grape marc has the advantage that markets other than land-spreading are possible.

Dried grape marc can be used as burner fuel. With a lower heating value (LHV) of 12.7 GJ/t for dried grape marc at 20% moisture where industrial heat has a value of *ca.* $10/GJ, the heating value of dried grape marc is $127/t. However, pine pellets retail at $450/t (Consumer) and so the wholesale value of grape marc pellets is expected to be over $225/t. This demonstrates that with mechanical dewatering, and sale as heating fuel, drying grape marc is likely to be profitable as a business venture. The value of grape marc as animal feed is unknown. As a benchmark, palm kernel expeller is valued between $220-$300/t and so, at half this value, dried grape marc is a viable proposition.

Deferred costs are the need, at a regional level, to replace the fertiliser nutrients removed from the region when dried grape marc is used for purposes other than soil amendment. However, the destination mix of dried grape marc is highly uncertain, and so feedbacks will exist if, for example, dried grape marc is used in animal feed and later the animal manure is collected and land-spread.

Table 1.6. Scenarios for revenue from the drying of grape marc.

Option	Drying 1	Drying 2	Drying 3[b]
Required revenue, $/yr	$6.65M	$2.76M	$2.76M
Tonnage of dried grape marc[a], t/yr	12,696	12,695	20,717
Required sale price, $/t dried grape marc	$524	$217	$133

[a]At 20% moisture content. [b]Also produces 24,566 m^3 of pressate with 85 g/L BOD. Treatment costs are included.

Drying followed by combustion to generate electricity. Combustion for electricity generation is relatively straightforward to analyse because electricity is the only saleable product where ash disposal to landfill is a cost. (The cost of ash disposal is included within the O&M costs, so that it is removed from affecting the required revenue calculations presented here.) Excepting the ash, combustion removes the liability with large tonnages of stranded products, i.e., raw grape marc, compost, or biochar. Electricity value varies. MBIE state that in Blenheim retailers charge an average of 35.5 ¢/kWh and lines companies 14.8 ¢/kWh. A conservative figure of 12 ¢/kWh earned for generation is used here. Table 1.7 shows that it is not profitable to make electricity by combustion. However, the shortfall to profitability of $5.15-$2.18 = $2.97 M/yr, is bridged if winegrowers were to pay a levy of $42.43/t raw GM. The advantage is that it avoids the liabilities of both stranded grape marc and poor environmental outcomes, e.g., of BOD soil overload. Inclusion of liabilities in the accounting is discussed later.

Deferred costs to the region are the replacement of the intrinsic nutrient value with industrial fertiliser.

Table 1.7. Scenarios for revenue from drying followed by combustion to make steam for electricity generation.

Option	Combustion 1	Combustion 2	Combustion 3
Required revenue, $/yr	$9.04M	$5.15M	$5.15M
Electricity generated, kWh	11.14M kWh	11.14M kWh	18.14M kWh

Revenue at 12 ¢/kWh, $/yr	$1.33M	$1.33M	$2.18M

Drying followed by gasification to generate electricity and heat. Gasification for electricity and heat generation is also relatively straightforward to analyse because electricity and heat are the only saleable products. (The cost of gasification-char disposal is included within the O&M costs, so that it is removed from affecting the required revenue calculations presented here.) Like combustion, gasification mitigates liability associated with stranded products such as raw grape marc, compost, or biochar. However, table 1.8 shows that the revenues do not sum to anywhere near that required to break even over 25 years. To make up the shortfall, the winegrowers would need to be levied $84.86/t raw GM (in the Gasification 6 scenario). Gasification, like combustion removes all physical and environmental liabilities associated with stranded stockpiles and those of emissions and leaching that occur if raw grape marc or compost is amended to soil. Inclusion of liabilities in the accounting are discussed later. Gasification is also amenable to more complex downstream conversions of syngas to biofuel through Fisher-Tropsch processing, but this is out-of-scope for this study.

Deferred costs to the region are the replacement of the intrinsic nutrient value with industrial fertiliser.

Table 1.8. Scenarios for revenue from drying followed by gasification to make electricity in a gas engine with excess heat.

Option	Gasification 1	Gasification 2	Gasification 3	Gasification 5	Gasification 6
Required revenue, $/yr	$11.27M	$6.85M	$6.85M	$8.80M	$7.87M
Electricity generated, kWh	6.94M kWh	6.94M kWh	11.30M kWh	12.74M kWh	14.66M kWh
Revenue at 12 ¢/kWh, $/yr	$0.83M	$0.83M	$1.36M	$1.53M	$1.76M
Excess heat, GJ/yr	47,865	47,865	69,111	0[a]	16,770
Revenue at $10/GJ, $/yr	$0.48M	$0.48M	$0.69M	$0.0M	$0.17M

[a] All excess heat is recycled to the drying plant.

Drying followed by pyrolysis to produce biochar and heat. Biochar is the principal product from the pyrolysis process, with little excess heat revenue as shown in table 1.9. The final row gives the required sale price of biochar in order to break even over 25 years. Scenarios 3 and 6 give similar required revenues of $670 and $657 per tonne of biochar, with Scenario 6 yielding far more biochar. Revenue can be earned a number of ways for biochar: as a soil amendment, as an environmental adsorbent or as heating fuel. It can also be upgraded relatively simply to be sold as activated carbon. As a soil amendment, it carries fertiliser value, estimated at $87/t BC. Other values as a soil amendment include water holding capacity, adsorbency, cation exchange capacity, long-term increases in soil carbon and effect of soil biota, but none of these are able to be monetised. As a fuel, biochar has similar lower heating value (LHV) to coal at 30 GJ/t, translating to an industrial heating value of $300/t BC (at $10/GJ). However, comparing against pine wood pellets, which retail at $450/t (Consumer) but have a lower heating value of *ca.* 20 GJ/t, the higher LHV of biochar suggests it could command a price of $675/t BC. The barbecue charcoal market is even more lucrative. Activated carbons achieve higher prices again, ranging from $1,500/t to several thousand dollars depending on the grade and market. Therefore, biochar should be pitched at the activated carbon market, with fall back for lower grade product to burner fuel. If so, it has promise of profitability without needing a levy. Further investigation is needed as part of any business case.

However, sale as charcoal means biochar will not be used as a soil amendment, and so no carbon becomes sequestered. At present, sequestration of carbon in biochar is not tradeable in the NZETS, and so does not affect the economics, but does profoundly affect the carbon footprint. In this event, the carbon footprints for Pyrolysis 1, 3 & 6 in table 1.1 all change from net drawdowns of -69, -176 and -245 kg CO_2e/FU to a net emission of +24 kg CO_2e/FU which is comparable that of best-practise composting at +20 kg CO_2e/FU (recalling that 1 FU is 1 tonne of raw GM at 67% moisture). The opportunity for future NZETS earnings is discussed in the next section.

The above highlights that biochar has the best carbon footprint outcome for the Marlborough wine industry of all the options studied in this report. If this were the objective, and assuming in future the NZETS permits sequestration of carbon into biochar and soil, then the fertiliser plus the sequestration value of biochar rises to $163.66 per tonne assuming 80% of the embodied carbon is recalcitrant. So that the pyrolysis process is profitable, winegrowers would need to pay a net levy of $41.36 per tonne of raw grape marc (Pyro 3) or $54.17/t raw GM (Pyro 6). However, pyrolysis offers several products for commercialisation. Three scenarios are listed in more detail in Table 1.10 at the end the executive report, including pyrolysis to produce activated carbon, pyrolysis for heating pellets and pyrolysis for biochar for addition to soil.

Deferred costs to the region are the replacement of nutrient value either made unavailable in pyrolysis (nitrogen), or removed during processing, or if biochar is sold as charcoal pellets for burners.

Table 1.9. Scenarios for revenue from drying followed by pyrolysis to make biochar with excess heat.

Option	Pyrolysis 1	Pyrolysis 2	Pyrolysis 3	Pyrolysis 5	Pyrolysis 6
Required revenue, $/yr	$8.29M	$3.88M	$4.51M	$4.51M	$5.05M
Excess heat, GJ/yr	14,688	14,688	68,331	0[a]	0[a]
Revenue at $10/GJ, $/yr	$0.15M	$0.15M	$0.68M	$0.0M	$0.0M
Biochar produced, t/yr	3,500	3,500	5,713	5,833	7,689
Revenue required, $/t biochar	$2,330	$1,070	$459	$773	$499

[a]All excess heat is recycled to the drying plant.

4.2 Effect of monetising liabilities and sequestration of carbon

Liabilities have several facets. Stranded material in stockpiles (raw grape marc, compost or biochar) are a liability where management of these is best reflect by the costs of operating a landfill, which is designed and operated to avoid slumping, includes leachate collection, coverings to prevent odour and partial collection of methane emissions. The Marlborough landfill gate fee of $135/t is used here as a reflection of the true cost of developing, operating and depreciating a landfill over its working life minus GST. While the full liability is listed above for landfilling the entire tonnage of each product ($9.4M/yr for raw grape marc, $3.1M for compost or $0.5M-$1.1M for biochar), this is moderated by risk (probability) of not being able to repurpose them. These risks are unknown, but clearly exists as grape marc stockpiles have been noted in media reports in Marlborough in recent years.

Environmental emissions are another liability. Waterway and ground water discharges are localised issues and so liabilities are fines imposed by territorial authority, the loss of license to operate and court action, which is costly to both parties. This has played out in Marlborough, as the MDC have, in the past, moved legally against wine industry actors who have polluted the water commons. In similar action in Spain, fines for environmental transgressions rose risen ten-fold between 2000 and 2010. In this study, we assume that any liquid streams generated, e.g., when mechanically dewatering in the Drying 3 scenario, are collected and treated as trade waste and accounted for in the annual operating and maintenance costs. We have not considered the implications this may have on the regional capacity to treat this trade waste.

Atmospheric emissions are harder to see, especially when they are not particulate matter. Methane and nitrous oxide are significant global warming gases, but yet are hard to detect at scale. As noted above, this is expected to change in future with satellite monitoring of their sources and the advent of hyperspectral sensing technology already on the market. If detectable at scale, these emissions will be added to the New Zealand national inventory and the generators of these emissions will become accountable within the New Zealand Emission Trading Scheme. A New Zealand Unit (NZU) is one tonne of CO_2e and currently costs $26.50 to purchase. Because methane and nitrous oxide are global warming gases, 1 tonne of methane is equivalent to 28 tonnes of CO_2 and nitrous oxide is equivalent to 265 tonnes of CO_2. Also, because the source of these gases is the biogenic decay of grape marc which, if purely aerobic would produce only CO_2, the net global warming effect of each tonne of these gases is equivalent to an extra 27 or 264 tonnes of

CO_2 pumped into the atmosphere. With accurate monitoring, the future liabilities are able to be monetised and so are estimated here at the current value of a NZU. As noted earlier, composting liabilities vary from $29,000-$154,000 from best-practise to poor management. Stockpiled grape marc is expected to have far more severe emissions, but these have not been investigated here. The thermal processes are expected to operate within their stack emission limits (for carbon monoxide, particulate matter and other products of incomplete combustion) and so the liabilities are minimal, and indeed are more than offset by the carbon sequestration into gasification-char and biochar if these are permitted as repositories in future manifestations of the NZETS. It must be noted that these liabilities are minimal because combustion of sustainably produced renewable biomass (to CO_2 and water vapour) is not regarded as additional to the natural carbon cycle.

Sequestration of carbon into biochar or gasification-char is an opportunity if these are amended to soil or to the landfill. If sequestration were to become a tradeable activity in the NZETS, this will change the economics. Biochar has an intrinsic carbon sequestration value of $76.32/t BC in addition to its fertiliser value of $87.34/t BC. Thus, for Pyrolysis 6, which produces 7,689 tonnes of biochar per annum, assuming a conservative recalcitrant fraction, the sequestration value is estimated to be $587,000/yr.

5. Thermal Processing as a Bio-refinery Enabler

Mature industries evolve to extract value in multiple ways from a resource. Oil and gas, minerals processing, dairy and pulp and paper are good examples when a multiplicity of products are produced, usually led by a high volume commodity, then including smaller quantities of higher value products. Plastics, rare earths, fractionated proteins and cartons are examples of higher value products in the above industries. The present study on grape marc is focussed on repurposing; that is, processing to reduce volume and so avoid stranded stockpiles and the costs associated with their management and environmental damage.

However, establishing a processing facility creates an opportunity for other spinoff activities. The technology involved in the production chain is critical, involving processes such as sorting, cleaning, washing, separation, drying, forming (e.g., into pellets), thermal degradation and separation of phases. These are precursors to other processes and provides the impetus to introduce other extraction and refining technologies such as solvent or supercritical extraction, fractionation, distillation and other reaction engineering processes. Thus, a plant such as those presented in this study, will enable high-value exploitation of grape marc, where side streams can be sold and upgraded. Examples, additional to those mentioned above, as discussed in more detail in Section 2, include:

- After collection: seed or skin separation for phenolic, pigment and antioxidants extraction.
- After collection: seed separation for grape seed oil extraction and refining.
- After mechanical pressing: pressate for further processing into tartaric acid, tannins and industrial alcohol.
- Fermentation: anaerobic fermentation of grape marc or vinasse (from industrial alcohol production) to produce biogas.
- Fermentation: lignocellulosic conversion to biofuels and green plastic precursors.
- After drying: lignin extraction for a wide range of uses, e.g., in bioplastics, adhesive binders, and as a non-digestible bulking agent as a food additive.
- Gasification: upgrading through Fischer-Tropsch to biodiesels and chemical precursors.
- After slow pyrolysis: Upgrading of char to activated carbon, or leaching of mineral content to make reductant grade carbon.

6. Conclusions

The major conclusions are drawn for the most efficient thermal processes. However, in order to enable comparison with current practice, direct land-spreading of raw grape marc and composting followed by land-spreading, are discussed first.

Land-spreading raw grape marc. The costs of land-spreading raw grape marc are likely to vary from $10-$30/t raw GM given that the activity includes transport, spreading and ploughing. Therefore, the activity cost ranges between $0.7 to $2.1M/yr. Liabilities are BOD overload of soils and consequent environmental leaching and emissions, and stranded stockpiles of grape marc that have not been land-spread. Estimating the environmental impact of these was out-of-scope of the present study. The management liability for 70,000/yr tonnes of stockpiled residue is $9.45M/yr.

Composting followed by land-spreading. Composting is not profitable as a standalone business, with an activity cost of $2.38-$2.77 M/yr including landspreading. However, if winegrowers paid a levy of $29.72/t raw GM which covers the cost of the composting operation ($2.08 M), the marginal cost of compost compared to direct land-spreading then depends on cost of land-spreading. When spreading is $20/t, this means (including the levy) composting is $16.29/t GM more expensive than direct land-spreading raw GM, but this falls to $9.57/t GM when land-spreading costs $30/t GM. This is because compost, at 22,960 tonnes, requires a lot less spreading effort than the 70,000 tonnes of raw grape marc. While composting has an added cost, it avoids the liability of BOD overload in soils, but incurs the liability of poor management of composting which could raise the carbon footprint from +20 to +50 kg CO_2e/t raw GM. If emissions were included in the NZETS, the penalty value of poor compost management would be $57,000/yr.

Drying. Drying is a profitable standalone business. The activity cost is $2.76 M/yr. To be profitable the revenue needs to be $133/t of dried grape marc at 20% moisture. The fertiliser value of dried grape marc is $40.64/t dried GM, which is insufficient on its own. The industrial heating value is $125/t dried GM (at $10/GJ); however, as pine pellets retail at $450/t, this indicates that wholesale value of GM pellets will be well over $200/t for GM pellets. Possible uses of dried grape marc also include animal feed, but the value of this is unknown. Unsold dried grape marc does not represent a liability because it can be stored for long periods. The best configuration for drying involves mechanical dewatering, where the pressate treatment costs are assumed to be those for standard trade waste ($1.21M/yr). No assumptions are made about the ability of Marlborough to process the trade waste. Also, sale as heating pellets means there is a deferred the cost to the region for fertiliser replacement ($1.17 M/yr).

Drying followed by combustion. Drying followed by combustion is not profitable as a standalone business. The activity cost is $5.15 M/yr, but after sale of electricity at 12¢/kWh reduces to $2.97 M/yr. However, if winegrowers paid a levy of $42.43/t raw GM, the process would break even. This thermal processing option repurposes all grape marc and therefore removes all physical or environmental liabilities associated with stranded stockpiles and those of emissions and leaching liabilities that may occur if raw grape marc or compost is amended to soil. The remaining liabilities are the discharge of ash to the landfill, and that associated with the carbon footprint of the process, at 62 kg CO_2e/t raw GM, which is three times higher than a well-managed composting facility. However, if the combustion power plant were to replace a coal fired facility for a large industrial plant, this would offset the fossil fuel emissions of that plant. Including these offsets, the overall carbon footprint improves to − 161 kg CO_2e/t raw GM, representing a net drawdown of carbon from the atmospheric cycle. However, this is regarded as a first mover advantage. Combustion also means there is a deferred fertiliser cost to landowners ($1.17 M/yr).

Drying followed by gasification. Drying followed by gasification is not profitable as a standalone business. It is a more complex process than combustion and so the activity cost is $7.87 M/yr, which reduces to $5.94 M/yr after sale of electricity at 12¢/kWh and heat at $10/GJ. In order for the process to break even, the winegrower levy would need to be $84.86/t raw GM. Similarly to combustion, gasification removes most physical and environmental liabilities. There are 2,882 tonnes of gasification char that need to go to landfill. The process carbon footprint is −38 kg CO_2e/kg raw GM, but improves to − 243 kg CO_2e/kg raw GM, if replacing an existing coal fired plant, where the offsets for the fossil fuel emissions can be included. The base case is negative because some carbon is sequestered in the gasification char. Gasification also means there is a deferred the cost to landowners of replacing fertiliser value ($1.17 M/yr).

Drying followed by pyrolysis. Drying followed by pyrolysis has promise as a standalone enterprise. The activity cost is $5.05 M/yr (Pyro 6) or $4.51 M/yr (Pyro 3). A range of products are possible. If pyrolysis produces biochar for addition to soil, the environmental outcome of -225 kg CO2e/t raw GM is far superior to any other option investigated in this study. To achieve this, and including the land-spreading of the biochar, the activity cost (Pyro 3) becomes $4.57-$4.68 M/yr which reduces to $3.39-$3.46 M/yr when including the carryover fertiliser value, or to $3.08-$3.19 M/yr if (in future) the carbon sequestration value is included at the current NZU value ($26.50/t CO2e). The embodied value of the biochar becomes $163.66/t BC. These costs are covered if winegrowers are levied $48.42-$50.00/t raw GM, with including the sequestration value.

However, the biochar is useful as other products. Without a levy biochar (BC) must sell for $657/t BC. The intrinsic fertiliser value of biochar is $87/t BC, which falls far short. As heating pellets, they have an industrial heating value of $300/t BC (at $10/GJ), although they are worth $675/t when compared to pine pellet prices, because of charcoal has coal-equivalent heat content. Additionally, if replacing coal in an industrial burner, the charcoal has embodied value of $76/t BC in avoided NZUs. Further, because the biochar is likely to have good adsorbent properties it can be expected to attract $500/t BC as an environmental and bioremediation adsorbent. These product values show that pyrolysis for biochar is marginally profitable. However, if upgraded to activated carbon, it can attract $1500/t BC. Therefore, pyrolysis presents a significant opportunity, where more research is required in this area, specifically on grape marc biochars and their adsorbent properties.

Unsold biochar is not a liability because it can be stored for long periods. Manufacturing emissions are a liability if biochar is sold as charcoal (for burning) and not returned to land, in which case the process emissions are +24 kg CO_2e/kg raw GM, i.e. very similar to composting. As noted, when biochar is returned to the soil, the carbon footprint is -225 kg CO_2e/kg raw GM, but this improves to -256 kg CO_2e/kg raw GM if the energy generated during the process is used to replace an existing fossil fuel facility. If biochar is not returned to soil, the deferred cost to the region is the fertiliser replacement at $1.17 M/yr. If biochar is returned to soil, there is still a deferred fertiliser cost of $0.69 M/yr because not all nutrients are returned or available.

Table 1.10. Summary of options, costs, environmental outcomes and liabilities. For the thermal processes, the figures given are for the most thermally efficient process scenario (numbers given in parentheses).

Activity	Tonnage, t/yr	Activity cost, $/yr	Product Value, $/yr	Net activity cost[1], $/yr	Deferred cost[2], $/yr	Net Marlborough regional cost[3], $/yr	Liabilities	Max cost of liability $/yr	Notes
Direct land-spreading of raw grape marc	70,000 t raw GM[4]	$0.7 to $2.1M[5] Cost of land-spreading $10-$30/t	Fertiliser value[6] $1.17M Fertiliser value $16.76/t compost	–$0.47M to $0.93M	none	–$0.47M to $0.93M	1. Carbon footprint of normal land-spreading activity including GHG emissions from soil 2. Carbon footprint of land-spreading activity after BOD overload of soil 3. Leaching impacts after BOD overload of soil 4. Management of stranded stockpiles of non-spread raw GM 5. Carbon footprint of stranded stockpile over time	- Unknown[7] - Unknown - Unknown - $9.45M[8] - Unknown	No levy. Exposed to liabilities 1-5. Including the return of fertiliser value, the net cost of spreading becomes -$6.76 to $13.24/t raw GM for the range of spreading costs
Best-practice composting followed by land-spreading	22,960 t compost	$2.38M to $2.77M Annualised cost of plant, $2.08M, plus cost of spreading, $10-$30/t	Fertiliser value $1.17M Fertiliser value $51.10/t compost	$1.21M to $1.39M	none	$1.21M to $1.39M	6. Management of stranded stockpiles of stranded non-spread compost 7. Carbon footprint of composting, well-managed 8. Carbon footprint of composting, poorly-managed	- $3.04M - 20 kg CO_2e/kg raw GM ($37,000)[9] - 50 kg CO_2e/kg raw GM ($93,000)	Composting removes liabilities 1-5. A levy of $29.72/t raw GM to producers will cover the cost of operating the composting facility. After return of fertiliser value, the net cost of the levy reduces to $16.24 to $22.80/t raw GM for the range of spreading costs. Composting is exposed to liabilities 6-8.

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[1] The net activity cost is the activity cost minus the product value.

[2] A deferred cost is a cost that removal of grape marc from the land-to-land cycle incurs, e.g., if combusted, its fertiliser value becomes a deferred cost.

[3] The net Marlborough regional cost is the net activity cost plus the deferred cost.

[4] Raw grape marc (GM) has 67% moisture content ex-press.

[5] Cost of spreading is an estimate that includes transport from the pressing facility to the land, vehicle transfer, spreading and ploughing.

[6] Fertiliser value is an estimate based on elemental analysis.

[7] Unknown because research on grape marc-compost-soil interactions was out-of-scope for this study.

[8] The only feasible destination for stranded stockpiles is landfill, costed at the gate fee of $135/t inclusive of GST.

[9] These figures in parentheses assume agriculture enters the NZETS and NZUs are priced at $26.50/t CO_2e (February, 2020).

Activity	Tonnage, t/yr	Activity cost, $/yr	Value, $/yr	Net activity cost, $/yr	Deferred cost, $/yr	Net Marlborough regional cost, $/yr	Liabilities	Max cost of liability $/yr	Notes
Drying[10] (Drying 3)	20,717 t dried GM	$2.76M Annualised cost of plant	$2.59M to $4.66M For GM heating pellets, range $125/t to $225/t[11]	–$1.9M to $0.17M	$1.17M Fertiliser replacement	–$0.73M to $1.34M	9. Carbon footprint of activity 10. Mechanical dewatering produces 24,556 tonnes of pressate with 85 g/L BOD 11. Disposal of 181 tonnes of ash from drying plant 12. Air emissions of PICs and PM from drying plant[12] 13. Disposal of unsold dried GM to land-spreading, if take-back agreements exist 14. Management of unsold dried GM in stockpile	• 61 kg CO2e/t raw GM ($113,000) • Treatment of pressate as trade waste is costed into O&M[13] at $1.21M and so is not a liability • Ash disposal to landfill is costed into O&M at $0.02M and so is not a liability • Mitigated by to European limits by including emissions reduction technology in the design • $0.21-$0.62M • $2.80M	Drying removes liabilities 1-8. Liabilities 10-12 are costed within the O&M. No levy required. Drying is a viable commercial activity. Drying is exposed to liabilities 9, 13 & 14. At a regional level, the deferred cost of fertiliser replacement is $1.17M.
Drying followed by **combustion** to produce electricity (Combustion 3)	- All GM is consumed	$5.15M Annualised cost of plant	$2.18M Electricity at 12¢/kWh	$2.97M	$1.17M Fertiliser replacement	$4.14M	15. Carbon footprint of activity 16. Disposal of 704 tonnes of ash (523 t additional to drying) 17. Air emissions of PICs and PM	• 62 kg CO_2e/t raw GM ($115,000) • Ash disposal to landfill is costed into O&M at $0.10M and so is not a liability • Mitigated by to European limits by including emissions reduction technology in the design.	Combustion removes liabilities 1-9, 13 & 14. Liabilities 10-12 & 16-17 are costed within the O&M. A levy of $42.43/ t raw GM to producers will cover the cost of operation after sale of the electricity. Combustion is exposed to liability 15. At a regional level, the deferred cost of fertiliser replacement is $1.17M.

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[10] Dried to 20% moisture content.

[11] The breakeven sale price is $133/t dried grape marc. Other revenue is possible as animal feed, value unknown. The intrinsic fertiliser value dried grape marc is $40.63/t.

[12] PIC (products of incomplete combustion) and PM (particulate matter) have global warming potentials.

[13] O&M means the operating and maintenance costs. Trade waste charged at $0.81/m³ plus $0.57/kg BOD inclusive of GST. Landfill is costed at the gate fee of $135/t inclusive of GST.

Activity	Tonnage, t/yr	Activity cost, $/yr	Value, $/yr	Net activity cost, $/yr	Deferred cost, $/yr	Net Marlborough regional cost, $/yr	Liabilities	Max cost of liability $/yr	Levy to avoid liabilities
Drying followed by **gasification** to produce electricity and industrial heat (Gasification 6)	- All GM is consumed	$7.87M Annualised cost of plant	$1.93M Electricity at 12¢/kWh and industrial heat at $10/GJ	$5.94M	$1.17M Fertiliser replacement	$7.11M	18. Carbon footprint of activity 19. Disposal of 2,882 tonnes of gasification char to landfill 20. Air emissions of PICs and PM from gasification plant[14]	- –38 kg CO_2e/t raw GM (–$70,000) - Gasification char disposal to landfill is costed into O&M at $0.39M and so is not a liability - Mitigated by to European limits by including emissions reduction technology in the design.	Gasification removes liabilities 1-9, 13 & 14, and 15-17. Liabilities 10-12 and 19-20 are costed into the O&M. A levy of $84.86/t raw GM to producers will cover the cost of operation after sale of electricity and industrial heat. Gasification does not have any liabilities, as 18 is a net removal of carbon from the atmospheric cycle. At a regional level, the deferred cost of fertiliser replacement is $1.17M.
Drying followed by **pyrolysis** to produce biochar with upgrade to activated carbon (Pyrolysis 6)	7,689 t biochar	$5.05M Annualised cost of plant	$11.53M For activated carbon, $1,500/t[15]	–$6.48M	$1.17M Fertiliser replacement	–$5.31M	21. Carbon footprint of activity 22. Disposal of 181 tonnes of drying ash 23. Air emissions of PICs and PM from pyrolysis plant 24. Disposal of unsold biochar to land-spreading if take-back agreements exist 25. Disposal of unsold biochar to landfilled when no take-back agreements exist	- 24 kg CO_2e/t raw GM ($45,000) - Ash disposal to landfill is costed at $0.02M into O&M and so is not a liability - Mitigated by to European limits by including emissions reduction technology in the design. - $0.08 to $0.23M - $1.04M	Pyrolysis with upgrade to activated charcoal avoids liabilities 1-9 and 13-20. Liabilities 10-12 and 22-23 are costed within the O&M. No levy required. This is potentially a viable commercial activity. However, more research is recommended. Upgrading and activated charcoal studies were out-of-scope in this project. The activity is exposed to liabilities 21, 24 & 25. At a regional level, the deferred cost of fertiliser replacement is $1.17M.

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[14] PIC (products of incomplete combustion) and PM (particulate matter) have global warming potentials.

[15] The cost of plant to upgrade biochar to activated carbon is not included. Prices range from $1,500/t to several thousand depending on grade and market.

Activity	Tonnage, t/yr	Activity cost, $/yr	Value, $/yr	Net activity cost, $/yr	Deferred cost, $/yr	Net Marlborough regional cost, $/yr	Liabilities	Max cost of liability $/yr	Levy to avoid liabilities
Drying followed by **pyrolysis** to produce biochar for sale as charcoal heating pellets with coal-equivalent heating value. (Pyrolysis 6)	7,689 t biochar	$5.05M Annualised cost of plant	$2.31M to $5.19M For heating pellets, $300/t to $675/t[16]	–$0.14M to $2.74M	$1.17M Fertiliser replacement	$1.03M to $3.91M	21. Carbon footprint of activity 22. Disposal of 181 tonnes of drying ash 23. Air emissions of PICs and PM from pyrolysis plant 24. Disposal of unsold biochar if take-back agreements exist 25. Disposal of unsold biochar if landfilled when no take-back agreements exist	- 24 kg CO_2e/kg raw GM ($45,000) - - Gasification char disposal to landfill is costed into O&M and so is not a liability - Mitigated by to European limits by including emissions reduction technology in the design. - $0.08 to $0.23M - $1.04M	Pyrolysis to produce charcoal for sale as heating pellets avoids liabilities 1-9 and 13-20. Liabilities 10-12 and 22-23 are costed within the O&M. No levy required. This is a marginal commercial activity. The activity is exposed to liabilities 21, 24 & 25. At a regional level, the deferred cost of fertiliser replacement remains, $1.17M.
Drying followed by **pyrolysis** to produce biochar for incorporation into soil and excess heat (Pyrolysis 3)	5,713 t biochar	$4.57M to $4.68M Annualised cost of plant, plus cost of spreading at $10-$30/t	$0.71M $0.21M Industrial heat and $0.50M fertiliser value[17] ($1.04M) (If adding $0.33M carbon seq. value)	$3.86M to $3.97M ($3.53M to $3.66M)	$0.67M Fertiliser replacement[18]	$4.53M to $4.64M ($4.20M to $4.33M)	21. Carbon footprint of activity 22. Disposal of 181 tonnes of drying ash 23. Air emissions of PICs and PM from pyrolysis plant 24. Disposal of unsold biochar if take-back agreements exist 25. Disposal of unsold biochar if landfilled when no take-back agreements exist	- –225 kg CO_2e/kg raw GM (–$417,000) - Ash disposal to landfill is costed into O&M and so is not a liability - Mitigated by to European limits by including emissions reduction technology in the design - $0.08-$0.23M - $1.04M	Pyrolysis to produce biochar for incorporation into soil avoids liabilities 1-9, 13-20. Liabilities 22-23 are costed within the O&M. A net levy of $55.14 to $56.71/t raw GM to winegrowers covers the operational cost of the plant plus land-spreading the biochar minus the fertiliser value returned to soil. This decreases to $50.43 to $52.29/t raw GM when the sequestration value of the carbon into the biochar is included (at the current NZU value of $26.50/t CO2e) However, the activity is still exposed to liabilities 6, 24 & 25 and, at a regional level, the deferred cost of fertiliser replacement is $0.67M.

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[16] The industrial heat value is $300/t at $10/GJ. As pellets burner fuel with coal-equivalent LHV (30 GJ/t), the value of $675 translates from wood pellets. Other uses within this range include environmental adsorbent.
[17] Fertiliser value of biochar, $87.34/t.
[18] Biochar does not retain the nitrogen fertiliser value.

Section 2

Background to the Project

Contents

2.1 Definitions

Grape marc is the skins, pulp, seeds and stalks after pressing of the grapes, generally regarded as having two fractions, the seeds and pulp. Mechanical harvesting removes the stalks in the vineyard, which is typical in Marlborough. For white wines the pressing occurs before fermentation, but for red wines, pressing occurs after fermentation. Thus the marc will have more sugar and alcohol respectively. Currently, about 80% of Marlborough production is Sauvignon Blanc, a white wine. This project is therefore focussed on marc from this grape variety.

'Repurposing grape marc' is defined here to mean the complete utilisation of solid residue arising from the stalks, skins, seeds and pulp of the grapes after pressing has removed the grape juice. Complete utilisation means that all grape marc is processed into a product, or a range of products, that have resale value. Complete utilisation means that no grape marc becomes a stranded resource, such as marc sent to landfill, otherwise dumped or stockpiled, including poor performing compost heaps, or compost that has not been land-spread. The project applies to all grape marc produced in the Marlborough region. Therefore, any solutions must account for all of the grape marc. While 2018 estimates place this at 46,000 tonnes, the scenarios investigated here use a larger tonnage, envisaging a future production, of 70,000 tonnes.

Concomitant to repurposing the grape marc is achieving a positive environmental outcome. This section contextualises the problem in Marlborough, the project boundaries, and provides a review of the valorisation processes for grape marc.

2.2 Grape marc utilisation in Marlborough

Current practice with Marlborough includes mainly directly spread on vineyards or other land, or composting and then spreading onto land. If direct land-spreading is the aim, it needs to done immediately because, if stockpiled, it is at risk of becoming anoxic. Anaerobic processes then dominate, causing leachate and odour, which is exacerbated if excessively wet grape marc is layered thickly on the soil. Heavy rain events do not help. Composting, on the other hand, is controlled aerobic degradation, achieved by frequent turning of the grape marc arranged into windrows, which after an active and curing stage can be stored as a stable product awaiting land-spreading. Therefore composting before spreading also avoids overloading the soil with biological oxygen demand (BOD). BOD overload that can make the soils anoxic, resulting in anaerobic degradation dominating, leading to leachate and greenhouse gas emissions.

In Marlborough, some large composting operations have been established over the years but these have encountered compliance challenges, predominantly in relation to the control of leachate, run-off and odours, resulting in legal action (Eder, 2017 and 2018). The uptake of composting has been made more difficult due to the announcement in Nov 2018 of GrowCo, who had a consent to process 40,000 tonnes of grape marc into compost, to stop operations (Preece(a), 2018). While improvements have been occurring steadily, the Rural Winery Wastewater and Grape Marc Monitoring Compliance Snapshot (latest available is February, 2019) stated that only 40% of wineries were compliant with all conditions or rules. This highlights that the region is still struggling to deal with grape marc effectively.

Spreading raw grape marc directly onto land incurs no other costs than transport, the spreading itself and ploughing, depending on the application rate. Destinations can include vineyards, forests or bare land. In all cases, the activity must be compliant with its discharge consents to water and air, or to the Marlborough Environmental Plan (MEP). This requires nitrogen loading of less than 200 kg/ha and that application must not occur if the soil is water-saturated. In contrast, the assessment conducted by AgResearch (Laurenson and Houlbrooke, 2012) recommended that the maximum nitrogen loading be 150 kg/ha to account for soil variation within the region. However, they also warned of the risk of prolonged anaerobic soil conditions due to BOD overload. Such soils produce excessive amounts of methane and leachate. To mitigate this risk, their final recommendation was that grape marc application to land is always less than 3 tonnes DM/ha/yr (where DM is dry matter), which translates to a maximum practical nitrogen loading of 60 kgN/ha/yr. With a moisture content of approximately 2.0 kg/kg dry basis (~67%), this means that annually each hectare can receive 3 tonnes (on a dry matter basis) or 9 tonnes of raw grape marc.

Spreading grape marc between rows of vines necessitates small machines with multiple trips. It is cheaper to spread onto bare land where large machines with payloads of up to 30 tonnes of raw grape marc can spread, followed then by ploughing into the soil. Angeloni (2019) reports that up to 40 tonnes per hectare have been applied. While this is approximately within the MEP nitrogen loading guideline, it is several times higher than the AgResearch recommendation.

In contrast to direct landspreading of raw grape marc, composted grape marc does not carry the same BOD risk of turning the soil anaerobic. Therefore, when compost is applied incrementally over the year, the maximum nitrogen application recommended by AgResearch of 150 kg N/ha/yr can be attained. In the context of their recommendations, composting carries the advantage that higher land application rates are possible, rising from 60 kg/ha/yr for raw grape marc to 150 kg/ha/yr for composted grape marc. However, this distinction is not captured within the MEP, which treats both activities the same. As composting only loses about 2% of the nitrogen, the total land area required for both raw grape marc and compost is only slightly less. At an application of 200 kg N/ha/yr, 70,000 tonnes of raw grape marc requires 1,643 hectares, whereas compost, which has the reduced mass of 22,960 tonnes, requires 1,603 hectares. The incentive to compost is therefore only in the reduced mass that must be land-spread, not in the kilometres driven per truckload.

Composting operations involve a series of costs. Composting requires land, and many wineries do not have onsite storage. Furthermore, composting must not cause non-compliant discharges, which means any leachate must be prevented from entering groundwater or streams. Emissions to air are limited to offensive odours but not other GHGs such as methane because, until recently with the advent of hyperspectral sensing, these have been hard to monitor. Compost operations within New Zealand are difficult to assess, because Resource Consents to operate are focussed on minimising discharges (WMINZ, 2009). In Marlborough, publically available photos show heaps rather than windrows (Bell, Stuff 17 Sep, 2014; McPhee, Stuff 14 Sep 2016; Lewis, Stuff 6 Sep 2016; Lewis, Stuff 7 Nov 2016). All windrows and heaps need to be on concrete pads with leachate collection, as example of which is shown in the 2018 Compliance Snapshot (Compliance Snapshot, Feb 2019). While there is a New Zealand Standard, NZS4454, this is essential a voluntary code without any formal accreditation. As a result, there are no formal obligations for temperature-time monitoring or turning frequencies of windrows, nor that windrows be covered from rain. Once composted, further cost is incurred to spread the compost back to vineyards or fields, as noted above.

Best-practise composting, as investigated within this study, requires the grape marc to be placed in windrows and turned regularly. The windrows are placed on site-prepared land with leachate collection and recycling, and windrows are covered from rain. Even so, composting times are long to achieve a suitable and stable composted material, varying from *ca.* 8-12 weeks, when operating well, to *ca.* 52 weeks, when turning is not regular. Improper aeration can result in the windrows becoming anaerobic resulting in more leachate and methane emissions than would occur if it were operating well. Composting operations carry risk, especially in the event of heavy rainfall, if uncovered. An example is the failure of the winery Babich composting operation due to high levels of leachate having biological oxygen demand between 20,000-70,000 g O_2/m^3, which is high compared to raw sewerage at 150-400 g $O_2/$ m^3 [Preece, 2018b]. Therefore, it is important that any open air composting operation ensure containment of all leachate in the event that windrows are rained upon. In best practise, leachate can be recycled to the windrows, but the volume may be too high in open air systems. The operation of the best-practice composting is discussed and presented in Section 4, alongside the emissions that are generated in well-managed and poorly managed composting operations.

A more recent activity in Marlborough is an anaerobic digestion facility, which is under development by Remarc, a joint venture between a renewal energy company Energy3 and wine company, Indevin [Preece(a), 2018]. Anaerobic digestion produces methane which, when combusted, has energy value. The digestate is then intended to be composted and spread to land. The operation is still under development and, according to Preece, it will not be ready for the 2019 vintage.

The difficulty with both composting and anaerobic digestion is that they are intermediate processing steps that do not, on their own, significantly reduce the tonnage of grape marc needing repurposing. This introduces risk for independent processors, who may end up with a stranded compost or digestate unless they have take-back agreements with vinters. In the event of stranding, landfill is the only long-term alternative destination.

Another processing route current being scaled-up in Marlborough is the drying and pelletising of grape marc by Pacific Rim Environmental Services (Preece(c), 2018). The advantage is that dried marc can be stored almost indefinitely. During processing, some of the dried product (or other dry biomass) can be combusted to provide the heat for drying, thus avoiding the use of fossil fuels (and thereby avoiding needing to buy NZUs in the NZETS), while at the same time reducing the dry matter tonnage needing to be repurposed. Dried grape marc can be spread to land, or sold as animal feed or bedding material, or sold as pellet burner fuel.

Other agricultural uses for grape marc are limited. Some is supplied directly as a rudimentary stock feed, e.g., some went to Nelson after the 2019 summer drought and fire (pers. comm.). The difficulty with stock feed is that Marlborough does not have many high stocking density farms that may need supplementary feed. Some dairy farms are in the Rai Valley, but mostly sheep and beef graze the hilly country at low stocking densities. Other feed opportunities are several hours drive away.

Small quantities of grape marc find other uses. Seeds can be easily separated from the skins and stalks, from which polyphenols and bioactive compounds are extracted (NZ Extracts). The residue seeds are then composted and sold. The tonnage of seeds involved is *ca.* 1% of the regional grape marc.

Other forms of utilisation have been considered. The Australian company Tarac investigated secondary processing of grape marc in Marlborough in 2014 (Bell, 24 July, 2014). They held discussions with a consortium of eight wineries (Pernod Richard, Cloudy Bay, Constellation Brands, Delegat's, Giesen, Indevin, Matua, Mount Riley, NZ Wineries, Saint Clair and Villa Maria) who collectively generate about 80% of Marlborough's wine production. Tarac conducted a due diligence exercise on setting up a plant to use grape marc and other winemaking residue to extract alcohol and other products (tannins and tartaric acid) and convert the spent marc or steam distilled grape marc into compost and stock feed. Tarac did not proceed.

Water is an associated but integral issue. At juice extraction, the moisture content is dictated by the pressing equipment and so, on ejection from the press, the marc does not contain free liquid. The grape marc collected from presses for this study had a moisture content of 2.0 kg water/kg of dry matter (67% moisture content). Processors also use water for process washing and site cleaning. If the two streams are not kept apart, a significant amount of process water will become incorporated into the grape marc which, when landspread or composted, may exacerbate later leaching, causing problems for the landowner or composter.

2.3 Project boundary

The above discussion highlights that grape marc is a resource opportunity, but the options for repurposing large tonnages in Marlborough are currently limited to direct land-spreading of raw grape marc, or composting followed by land-spreading. For this reason, this study has been commissioned to investigate thermal alternatives to reduce the grape marc footprint to zero, that is, complete removal of the grape marc produced each season. Thermal processing contrasts to biological processing in that it directly addresses the tonnage of solids contained in the biomass, and does not need to involve land-spreading to facilitate repurposing. However, the thermal repurposing solutions need to be compared to an alternative. For this reason composting has been selected. Composting is well-understood by the industry and the Marlborough District Council. While it has experienced difficulties gaining traction, it is a product that becomes stable and can be stored, which ameliorates the urgency required for land-spreading of raw grape marc.

This study conducts a techno-enviro-economic analysis. The technological analysis details the processes required and determines the mass and energy flows, the equipment sizing, the utility requirements, and the discharges to the environment and the product flows. The calculated data is then used to establish the environmental analysis for the embodied carbon footprint in construction, the transport of the grape to the plant and product streams away from the plant. This is used to compare each thermal process to best-practice composting. The process economics then determines the capital and operating costs of the activities, and the required revenue from the product stream to break even over 25 years. The technology and economic analyses are presented in Section 3. The environmental analysis is presented in Section 4.

The project also recognises that within Marlborough, the current practise of repurposing grape marc fits within the context of the history, and the infrastructure, consents and expectations between council, growers and processors. This study is focussed on quantifying the opportunity for repurposing, so in no way attempts to unravel the dynamics of these relationships, or to develop a strategic plan for a way forward.

Figure 1.1 (in the Executive Report) demonstrates the thermal processing options considered: combustion for power, gasification for heat and power, and pyrolysis for biochar and heat. These are those we regard as realistic engineering solutions without high technical or scientific risk. The study also notes possible valorisation opportunities, but does not investigate full biorefinery integration of small-volume but high-value products with the high-volume, low-value necessary for the repurposing of the large tonnage of grape marc residue generated from wine-making.

2.4 Valorisation of grape marc

Repurposing of grape marc represents an opportunity for economic gain, improved soil health and positive environmental outcomes, if appropriately processed. However, all processing incurs cost that needs to be absorbed by the operators including temporary storage or disposal to landfill. Ideally, these costs are balanced by producing a saleable product that offsets the cost of processing and ideally yields a profit. The following sections summarise a number of processes that can both reduce the tonnage of residual grape marc and produce products of value. The summary is not exhaustive: a more extensive study was conducted by the Australian Wine Research Institute (AWRI, 2017).

2.4.1 Landspread grape marc as a product

The simplest activity for raw grape marc is direct land-spreading, which needs to be done immediately after pressing. The activity is limited by two effects, nitrogen loading and prolonged anaerobic soil conditions due to BOD overload, as discussed in Section 2.2 above. Costs of spreading will vary depending on the destination, whether to bare land, forests, or between vine rows. Bare land is the lowest cost destination because larger payloads can be delivered, as noted above. Spreading costs are analysed in this work between $0-$30/t in, inclusive for transport, spreading and ploughing, in order to compare the economics of direct land-spreading of raw grape marc and compost. In practice, it will be dependent on driving distance, application rate, the ease of spreading and the amount of secondary work required to plough the grape marc into the soil.

Costs of spreading are mitigated by fertiliser value. In New Zealand these are estimable at $2.56/kg P, $1.44/kg K, $0.68/kg S, $1.32/kg Mg, $0.03/kg lime (Camps Arbestain, 2019) and $1.37/kg N (Fertsmart, 2020), and so depend on the composition of the grape marc. The ash contents are relatively low (Section 3.1), and so the fertiliser benefit is here calculated at $16.76/tonne raw grape marc (where 'raw' is defined as 67% moisture content). Once incorporated into the soil, the land can be cropped to utilise the fertiliser value. Other benefits of incorporating grape marc within the soil may accrue with time, with respect to raising mean soil organic matter, including soil function which may translate to yield or extra soil water retention, or improved soil biota resilience. These benefits may not be recoverable in the short term of annual financial statements.

The need to immediately land-spread raw grape marc to avoid anaerobic degradation can be offset by composting or drying.

2.4.2 Compost as a product

Composting is a well understood process where it is expected that operators follow the New Zealand Standard for Composts, Soil Conditioners and Mulches, NZS 4454:2005. However, as noted above, this is a voluntary code. Instead, composting practice is more dictated by resource consents, which facilities require in order to operate. While these are focussed on avoiding emissions from the activity, procedures of operation are also part of the documentation.

Two factors are principally important: effective aeration and internal heating during the thermophilic phase. Aeration can be facilitated by frequent turning and the inclusion of bulking agents to help maintain the bed porosity. Reaching temperatures as high as 70°C between turning events means weed seeds (which are not likely in grape marc) become inactivated and temperatures have become hot enough to inactivate most spores. After the active period, compost is left to cure, after which it becomes stable and can be stored. The composting process used in this study and the amenability of grape marc for composting is discussed in Section 4. Composting is therefore the baseline against which the thermal processing technologies are benchmarked.

The value of compost lies in its fertiliser nutrient value and other benefits it imparts to soil. In this work, an assumed amount of 70,000 tonnes of raw grape marc at 67% moisture, once composted, reduces to 22,960 tonnes of compost at 40% moisture. It loses *ca.* 2% of its nitrogen and so its fertiliser value is calculated to be $51.10/t compost.

2.4.3 Animal feed as a product

Animal feed from grape marc comes from a variety of residues, e.g., directly dried grape marc, ensiled marc, ensiled and dried, or dried from distillery residue (e.g., in Europe). Ensiling is used as a precursor for animal feed. Ensiling is anaerobic fermentation with the temperature constrained to ca. 30°C. This assists with breakdown to reduce the phenolic content, tannin levels, and improve organic matter digestibility by releasing sugars and other nutrients from within the plant cells (Alipour and Rouzdehan, 2007). Ensiling offers a storage advantage, in that feeding out can occur over a prolonged period. Alternatively, animal feed may be simply dried without further processing, or may be dried and pelletised.

As animal feed, grape marc is of limited use as it is not regarded as nutritious enough with the low nitrogen content of 1-2% and seems to need ethylene glycol addition to recover the nitrogen digestability when used in feed mixes (Greenwood *et al.*, 2012). Seeds and pulp also have different digestibility in sheep (Guerra-Rivas *et al.*, 2017). Feeding grape marc to dairy cows has been shown to reduce methane emissions (burping), but does diminish milk yields and increase fatty acid concentrations (Moate *et al.*, 2014). The value of grape marc as animal feed is unknown. As a comparison, palm kernel expeller (PKE) varies between $220-300/t.

2.4.4 Grapeseed oil as a product

Grape seeds contains 8-15% oil which is recovered by solvent extraction and is high in linoleic (65-70%) and oleic (12-15%) fatty acids (Choi et al., 2010). It is odourless and so is a suitable carrier oil in cosmetics. Its high smoke point also makes it useful in frying. It is not extracted in New Zealand.

2.4.5 Distilled alcohol, tartaric acid and tannins as products

Alcoholic fermentation of white grape marc for secondary spirit alcohol necessitates storage in small bins for ensiling, that both prevent air ingress and the internal temperature rising above 30°C. Natural microflora conduct the fermentation and 4-10% ethanol can be obtained. Extraction is then typically by steam distillation. Tartaric acid involves washing with dilute hydrochloric acid or water. Addition of calcium salts is used to precipitate calcium tartrate which is converted back to tartaric acid with the addition of sulphuric acid. Lignocelluloses can be extracted using an organosolv method, which are useful as dietary fibre additives in food processing. Vinasse, a molasses like substance, is a by-product of secondary alcohol processing (Devesa-Rey *et al.*, 2011), which has use as a partial fertiliser replacement or for biogas gas generation (Bergman, *et al.* 2018).

2.4.6 Bioactives as products

Grape marc residues are rich in bioactive and antioxidant compounds, particularly polyphenolics, tannins and anthocyanins. Their extraction has been well studied, as summarised well by Beres *et al.* (2017). As noted above, one Marlborough company extracts polyphenols. Traditional methods are still the most used for the extractions of compounds of interest, often using washing with water, or water-alcohol or water-acetone mixtures, although many new methods such as supercritical fluid extraction (SFE) and enhancement with pulsed electric fields (PEF) are also being applied. However, while the recovery of bioactive compounds, dietary fibre and oil from grape pomace all add value, they struggle to reduce the volume residue they leave behind. Nevertheless, extracting compounds of value is very much part of the "biorefinery" approach where high-value, small-volume compound extraction can be used to offset the cost of the repurposing of the bulk of the grape marc.

The phenolics content is highest in seeds, from 5 to 8%, of which 60–70% is extractable (Shi *et al.*, 2003). Grape skin contains large amounts of hemicellulosic sugars that, after hydrolysis, produce solutions containing a wide variety of xylose and glucose monomers (Deng *et al.*, 2011). Grape skins, like many other fruits, are a higher source of soluble fibre with better insoluble/soluble fibre ratios than from cereals (González-Centeno *et al.*, 2010).

2.4.7 Biofuels as products

Grape marc is a renewable biomass that may be processed on a CO_2 neutral basis. It classified as a second generation biofuel, because it is a residue of the grape industry where the primary product is wine, rather than a first generation energy crop, such as miscanthus, that requires dedicated land. Grape marc, or its residue after secondary processing, is amenable to thermal biomass waste-to-energy conversion. This provides the wine sector the opportunity to enhance environmental sustainability while decreasing the reliance on conventional fossil forms of energy (van Eyk *et al.*, 2009).

Biomass waste-to-energy options are surveyed by Muhlack *et al.*, (2018). They report that methane production by anaerobic digestion can yield over 70 L CH_4/kg grape marc to produce *ca.* 700 kWh/t GM heat energy (Fabbri *et al.*, 2015). Higher values are obtained with specific pre-treatments (Caramiello *et al.*, 2013). In another study by Eleutheria *et al.* (2016), the payback period was calculated to be 6-7 years for a small winery producing 1000 t grapes per year with a small anaerobic digester integrated with a power plant to produce 10 kWe (electricity) over 4.5 months. This indicates the economic viability of such an investment.

Ethanol as a biofuel can be produced at 270L/t grape marc (dry basis) or up to 400 L/t if pretreatment by acid hydrolysis of the lignocellulose followed by enzymatic saccharification and fermentation (Corbin et al., 2015).

2.4.8 Thermal waste-to-energy

Thermal methods are those investigated in this study: combustion, gasification and pyrolysis. Simulation by Fiori and Florio (2010) considered combustion and gasification and obtained very similar electrical and heat energy conversion efficiencies of 21-23% and 64-69% respectively. They concluded that combustion was preferred because it is a simpler process. However, high temperatures must be avoided in combustion as the high potassium and calcium contents of grape marc ash can causing slag formation (Fernandez et al., 2012). Indeed, Eyk *et al.* (2009) and other researchers have also reported slagging problems in gasification, and so Muhlack *et al.*, (2018) suggest that pre-treatments like hydrothermal carbonisation (HTC) may be needed. HTC uses sub- and super-critical water pressures and heat to produce a hydrochar, which is then removed from the liquid phase after cooling. At these conditions, the alkali metals are soluble and so are extracted. HTC has not been explored in this study. Rather, we have assumed that low temperature controlled combustion, which is well established in advanced systems, is sufficient to avoid slagging, but this would need investigation.

Gasification is also a process route used to develop Fischer-Tropsch biodiesels (Pang, 2019) and other chemical pre-cursors. However, these more technologically advanced solutions are not explored in this study.

Pyrolysis produces solid char, condensable liquid and non-condensable gas. The proportions depend on the rate of heating and the residence time of the vapours in the reactor. Slow pyrolysis maximises the solid char production, whereas fast pyrolysis favours the formation of the condensable phase. This condensable phase contains many aromatic hydrocarbons, alkanes, phenols, ethers and alcohols (Demiral and Ayan, 2011) which may be used for chemical feedstocks or fuel for stationary heat engines. However, they are not regarded as competitive to low-value fossil fuels combined with the current low cost of emissions offsetting. Slow pyrolysis to optimise char from biomass is more promising, have a range of applications due to its coal equivalent heating value, *ca.* 30 MJ/kg, good adsorbent properties (Zhang et al., 2010; Demiral and Ayan, 2011) and use as a soil amendment, which has been extensive studied (Guo et al., 2016). In a recent study of a biorefining process to completely repurpose grape marc by producing hydrocolloids and grape seed oil, then pyrolysis to biochar, bio-oil and syngas, where the bio-oil and syngas were combusted to produce heat and power, and biochar was amended back to the vineyard soil, the added value was estimated as 4470 Euros/ha which also avoids 355 kg CO_2/t on dry pomace basis (Zabaniotou et al., 2018). This shows the promise of pyrolysis as part of a wider utilisation of grape marc. The slagging issues that are problematic in combustion at high temperatures are avoided with pyrolysis, because the mineral content remains in the biochar. However, if the biochar is used as charcoal in pellets burner rather than amended to soil, then the slagging issue again arises. Most pellet burner operate at lower temperatures than used in high-specification combustion system so, while slagging is most likely to be avoided, it needs investigation.

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Section 3

Detail Report

Thermal Processes: Technical and Economic Analysis

Contents

3.0 Introduction

In this report, we present the properties of grape marc, the dewatering and drying behaviour, and the investigation of four possible thermal processing configurations that convert wet grape marc into dried product, biochar, electricity and/or heat. These configurations are:

i) direct or indirect drying,
ii) drying and combustion for power generation,
iii) drying and gasification with a gas engine for combined heat and power generation,
iv) drying and thermal valorisation for biochar production.

The output (dried grape marc, biochar, heat and power) from these four configurations was calculated based on the total wet grape marc of 70 tonnes annually from the mass and energy balance calculations and considering the drying kinetics we measured.

3.1 Grape marc properties

Wet grape marc was sampled from two winepresses from New Zealand Winegrowers in Blenheim on 29 March 2019. The sample was shipped to Massey University in Palmerston North on the same day and immediately placed in a freezer at -28°C. In the following two weeks, various analytical work was carried out to obtain the properties of the sampled grape marc, including proximate and ultimate analysis, second pressing tests, desorption isotherm tests and drying tests.

Figure 3.1 shows the content of skin, stalk and seeds in two 20 L buckets of grape marc after drying. Table 3.1 lists the results of proximate and ultimate analysis.

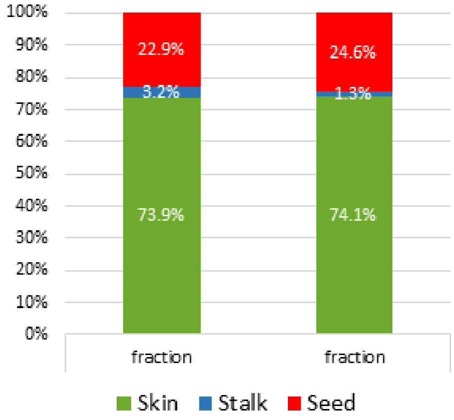


Figure 3.1 Dried grape marc composition

Table 3.1 Proximate and ultimate analysis of grape marc

Proximate analysis	
Moisture content, % as received	67.0±1.2
Volatile, % dry basis	68.4±0.7
Ash, % dry basis	3.16±0.23
Fixed carbon, % dry basis	28.4±0.4

Ultimate analysis	
Nitrogen, % dry basis	1.42±0.02
Carbon, % dry basis	47.5±0.1
Hydrogen, % dry basis	4.73±0.36
Oxygen, % dry basis	43.2±0.42
LHV*, MJ/kg, dry basis	16.47

*Lower heating value

As shown in Figure 3.2, when the moisture content in the dried grape marc is below 20%, the water activity is lower than 0.6, which is low enough to prevent microbial activity in storage.

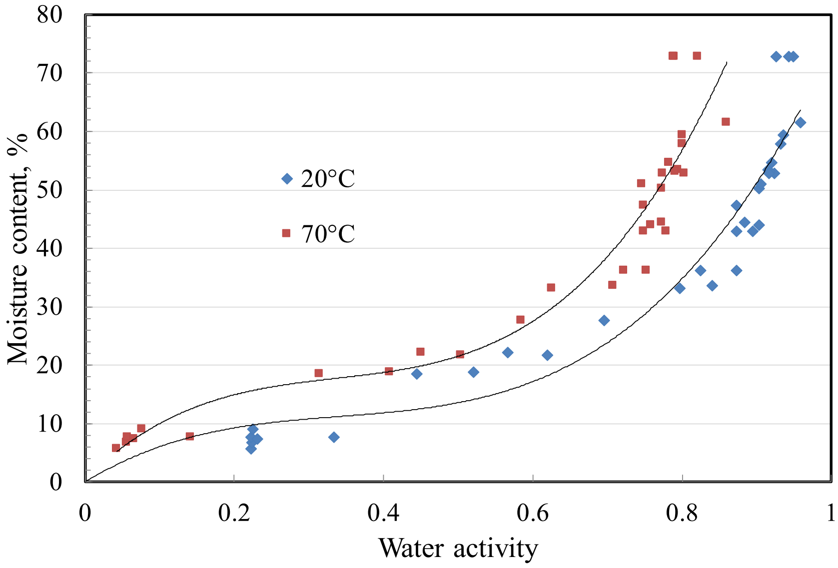


Figure 3.2 Isotherm curves of grape marc

3.2 Grape marc dewatering

Wine industry pressing of sauvignon blanc grape marc is done at 2 bar (F. Benkwitz, personal communication, March 29, 2019). Grape marc is not pressed harder to avoid bitter flavours being expressed. Here, further pressing was investigated as a method of dewatering, to more economically remove moisture than by drying. A Texture Analyser with a cuboid press was used with a bottom grate to allow the pressate to pass through. The variables were bed height, pressure, and number of pressings. Investigation was conducted in the pressure range of 2-8 bar with 8 bars being the upper limit of force that could be applied in the apparatus. Pressing was conducted for 60 seconds at a bed height of 10 mm and 20 mm respectably. Each pressing was done in triplicate. The work was carried out by Harry Anyon in an Honours Food Engineering project (Anyon, 2019).

Here, because the grape marc had been stored for some time before mechanical pressing, the initial moisture content had dropped from 0.67 to 0.62. The effect of mechanical dewatering is significant. Figure 3.3 shows that at 8 bar of applied pressure the moisture content is reduced to 50%. Figure 3.4 then investigates the effect of multiple presses where, where moisture contents of 40% are achievable.

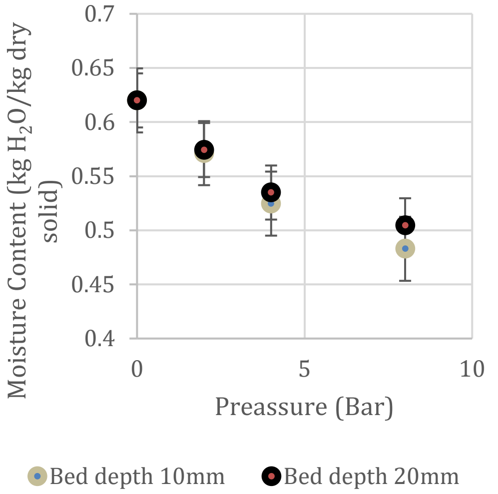


Figure 3.3. Effect of pressure on the dewatered moisture content of grape marc.

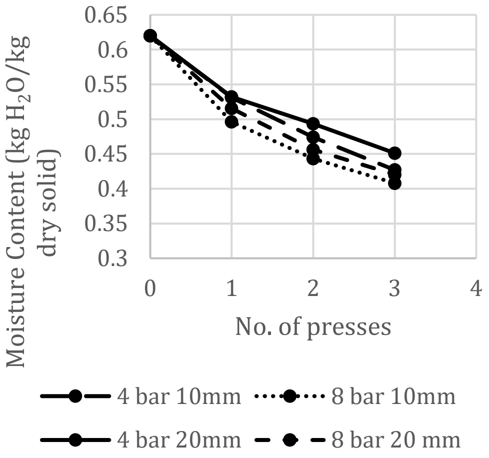


Figure 3.4. Effect of multiple applications of pressure on the dewatered moisture content of grape marc.

3.3 Grape marc drying

The initial moisture content of grape marc varies depending on the pressing process. The moisture content of our sampled grape marc is 67%. The calculation of all the drying processes was based on this initial moisture content. Industrial drying processes considered in this study include direct hot air drying, heat pump assisted hot air drying, and indirect drying.

3.3.1 Direct drying

3.3.1.1 Process descriptions

3.3.1.1.1 Hot air drying

Figure 3.5 shows the process diagram of the hot air direct drying used in this study. Wet grape marc (1) is continuously fed into an industrial dryer (e.g., a tunnel dryer, fluidized bed dryer etc) and dried in a flow of hot air (5). A portion of hot air (4) is exhausted from the drier to the ambient while the rest (3) is mixed with fresh air (2), heated to a certain temperature (5) and recirculated back to the dryer. A portion of dried grape marc

(7) is used as a fuel for heating the drying air via the furnace while the rest (8) is cooled and stored in silos for further use. Table presents the typical process parameters of the direct hot air drying for the grape marc.

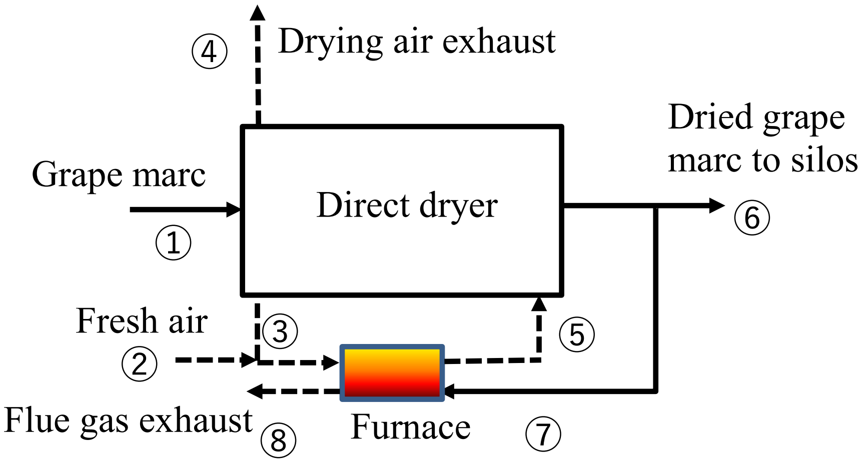


Figure 3.5 Process diagram of direct hot air drying

Table 3.2 Process parameters for the direct hot air drying of grape marc

Stream	Temperature	CV or enthalpy	Mass flow	
	°C	MJ/kg	kg/s (t/hr)	
1	15	0.06 (Sensible) 3.80 (LHV)	19.3 (69.4)	Wet grape marc (67% MC)
2	15 (RH60%)	0.031	98.7	Fresh air (mass flow in dry basis)
3	59.6 (RH85%)	0.376	888.4	Recycled hot drying air (mass flow in dry basis)
4	59.6 (RH85%)	0.376	98.7	Drying air exhaust (mass flow in dry basis)
5	110 (11%)	0.406	987.1	Hot air for drying (mass flow in dry basis)
6	59.6	0.177	1.94	Dried grape marc (Moisture content 20%, to silos after cooling)
7	59.6	0.177	6.02	Dried grape marc as fuel
8	130	11.36	81.5	Flue gas exhaust

3.3.1.1.2 Heat-pump-assisted drying

Figure 3.6 shows the diagram of the heat pump assisted direct drying of grape marc. Different from the direct hot air drying process described above, in this process, a portion of hot air (3) is extracted from the drier and passes through the evaporator of a heat pump where it is cooled and dehumidified (4). The remaining drying air (2) is then mixed with this dehumidified air (4) and preheated by the condenser of the heat pump. The mixed drying air (5) is further heated to a certain temperature (6) and recirculated back to the dryer. Again, a portion of dried grape marc (8) is used as a fuel for heating the drying air (5) while the rest (7) is cooled and stored in silos for further use. Table 3.3 presents the typical process parameters of the heat pump assisted hot air drying for the grape marc.

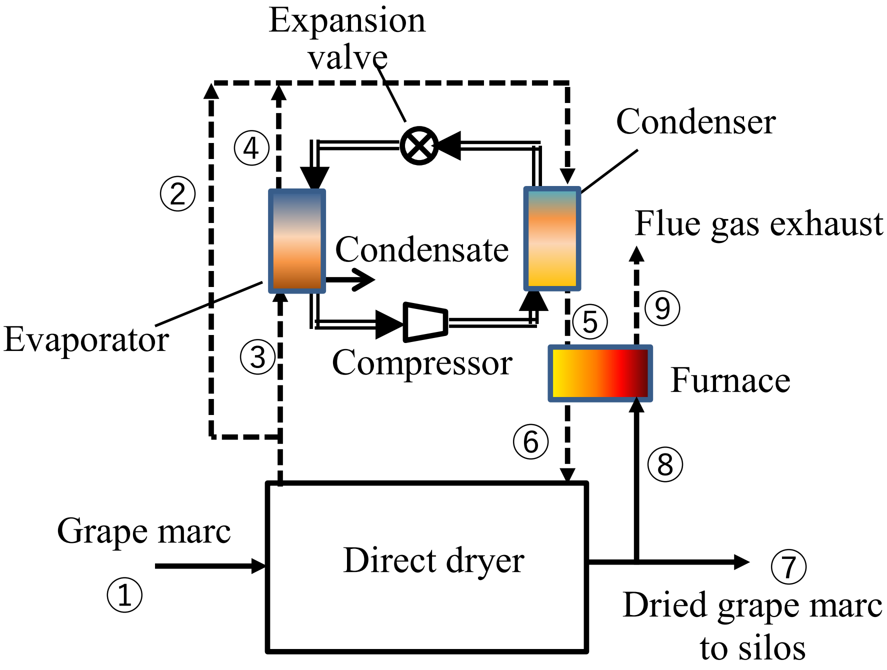


Figure 3.6 Process diagram of heat-pump-assisted direct drying

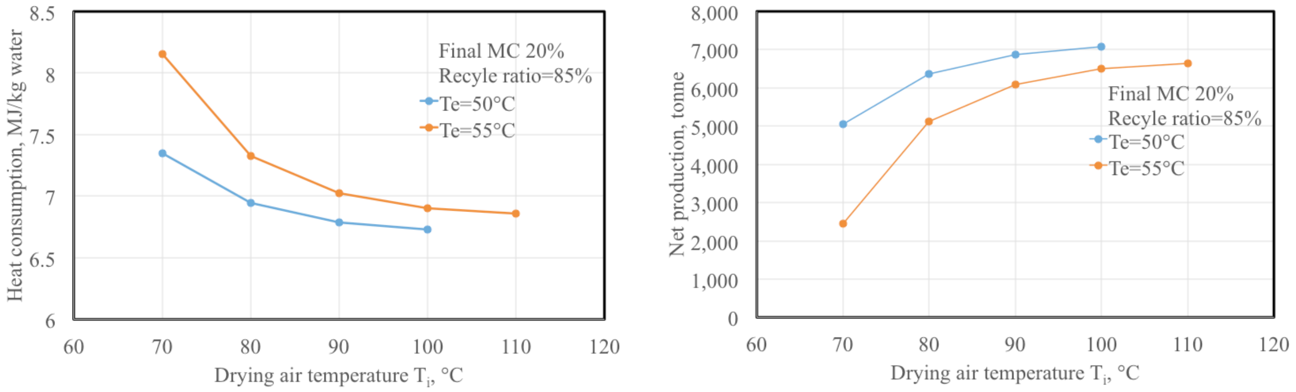
Table 3.3 Process parameters for the heat pump assisted drying of grape marc

Stream	Temperature	CV or enthalpy	Mass flow	
	°C	MJ/kg	kg/s (t/hr)	
1	15	0.06 (Sensible) 3.80 (LHV)	19.3 (69.4)	Wet grape marc (67% MC)
2	48.5 (RH85%)	0.211	2211	Recycled wet drying air (mass flow in dry basis)
3	48.5 (RH85%)	0.211	245.7	Recycled wet drying air to be dehumidified (mass flow in dry basis)
4	25 (RH100%)	0.077	245.7	Dehumidified recycled drying air (mass flow in dry basis)
5	64.5 (37%)	0.227	2457	Recycled drying air preheated by condenser (mass flow in dry basis)
6	70 (30%)	0.233	2457	Hot drying air
7	48.3	0.144	6.61	Dried grape marc (Moisture content 20%, to silos after cooling)
8	48.3	0.144	1.34	Dried grape marc as fuel
9	90	0.096	18.2	Flue gas

3.3.1.2 Effects of process conditions

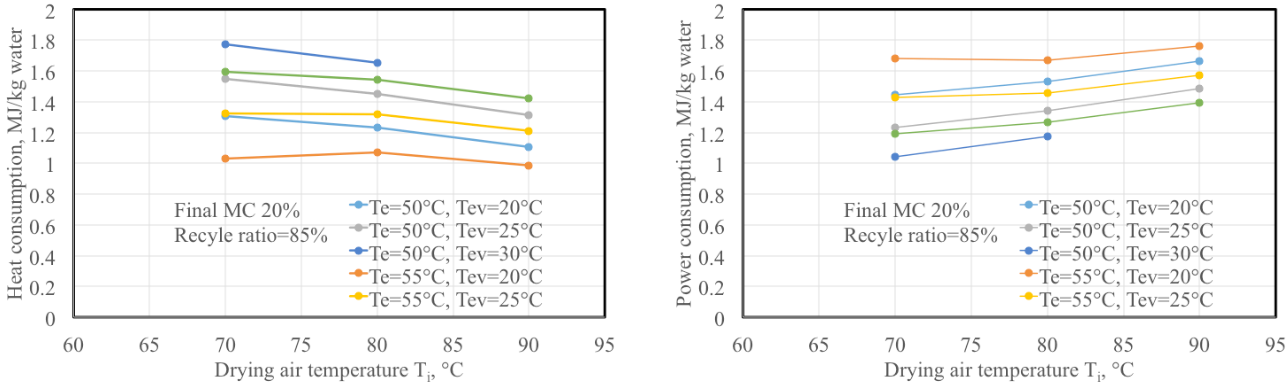
3.3.1.2.1 Drying air temperatures

Hot drying air temperatures at the inlet and outlet of the dryer influence the drying rate and energy efficiency. As shown in Figure 3.7 and Figure 3.8, higher drying air temperature at the inlet increases the energy efficiency (i.e., heat consumption decreased), thus the net production of dried grape marc increases. However, in the heat pump assisted drying, higher inlet temperature leads to higher electricity consumption. The lower temperature of drying air the outlet means higher energy efficiency.

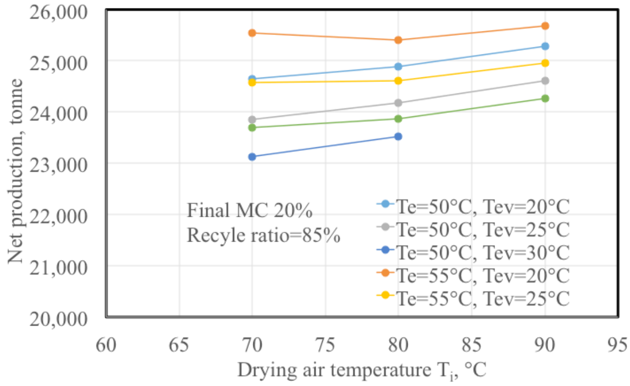


(a) Heat consumption of drying (b) Net production

Figure 3.7 Influence of drying air temperatures on the heat consumption of drying (a) and net production of dried grape marc (b) from hot air drying. Other conditions: initial moisture content 67%, final dried product moisture content 20%, drying air recycle ratio 85%, ambient temperature 15 °C, relative humidity 60%.



(a) Heat consumption (b) Electricity consumption

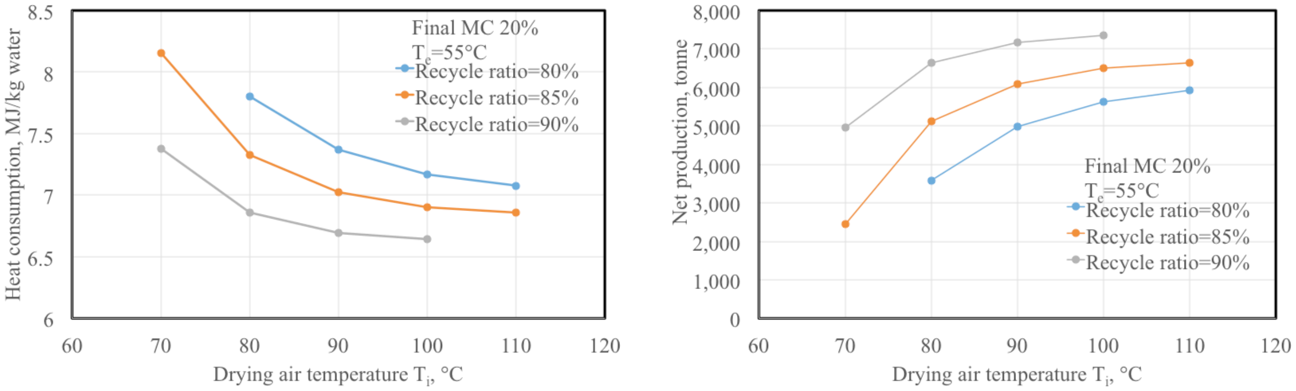


(c) Net production of dried grape marc

Figure 3.8 Influence of drying air temperatures on the heat (a) and power (b) consumptions of drying and net production of dried grape marc (c) from heat-pump-assisted drying. Other conditions: initial moisture content 67%, final dried product moisture content 20%, drying air recycle ratio 85%, ambient temperature 15 °C, relative humidity 60%.

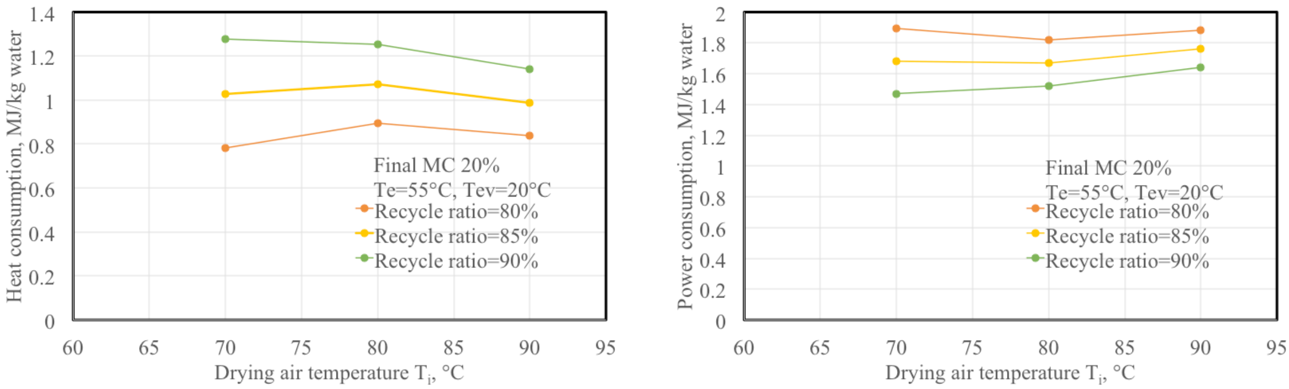
3.3.1.2.2 Recycle ratio of the drying air

In the direct hot air drying process, higher drying air recycle ratio implies less energy loss through drying air exhaust and thus higher energy efficiency, as shown in Figure . In the heat pump assisted drying, shown in Figure 3.10, the heat (sensible and latent heat) in the portion of drying air that passes through the evaporator of the heat pump is recovered with power input. A lower recycle ratio means more drying air passes through the evaporator, thus lower heat consumption but higher electricity consumption.

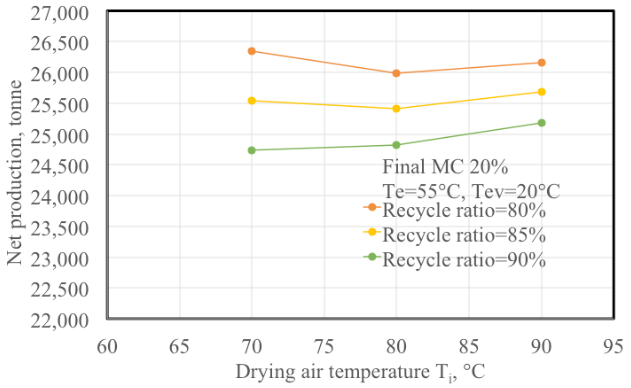


(a) Heat consumption of drying (b) Net production

Figure 3.9 Influence of drying air recycle ratios on the heat consumption of drying (a) and net production of dried grape marc (b) from hot air drying. Other conditions: initial moisture content 67%, final dried product moisture content 20%, drying air temperature at the exit 55°C, ambient temperature 15 °C, relative humidity 60%.



(a) Heat consumption (b) Electricity consumption

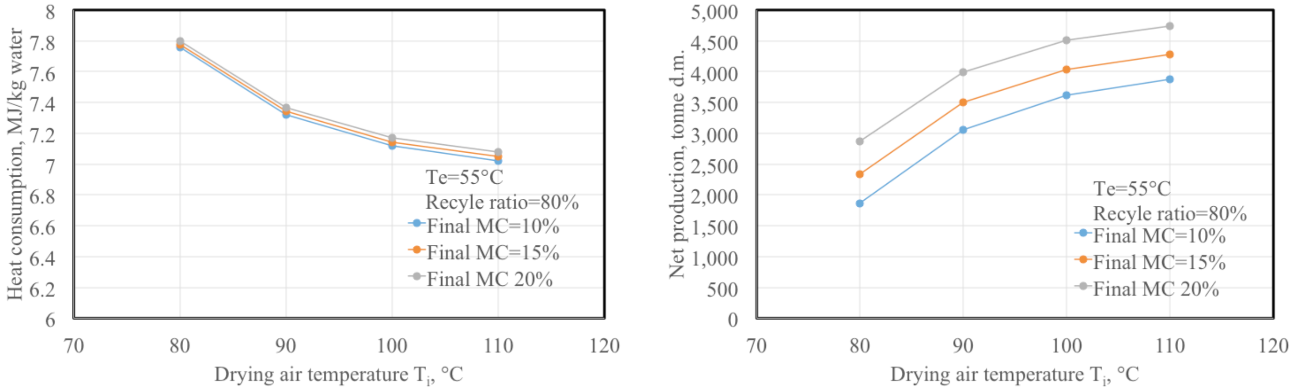


(c) Net production of dried grape marc

Figure 3.10 Influence of drying air recycle ratios on the heat (a) and power (b) consumptions of drying and net production of dried grape marc (c) from heat-pump-assisted drying. Other conditions: initial moisture content 67%, final dried product moisture content 20%, drying air temperature at the exit 55°C, refrigerant evaporating temperature in the heat pump 20°C, ambient temperature 15 °C, relative humidity 60%.

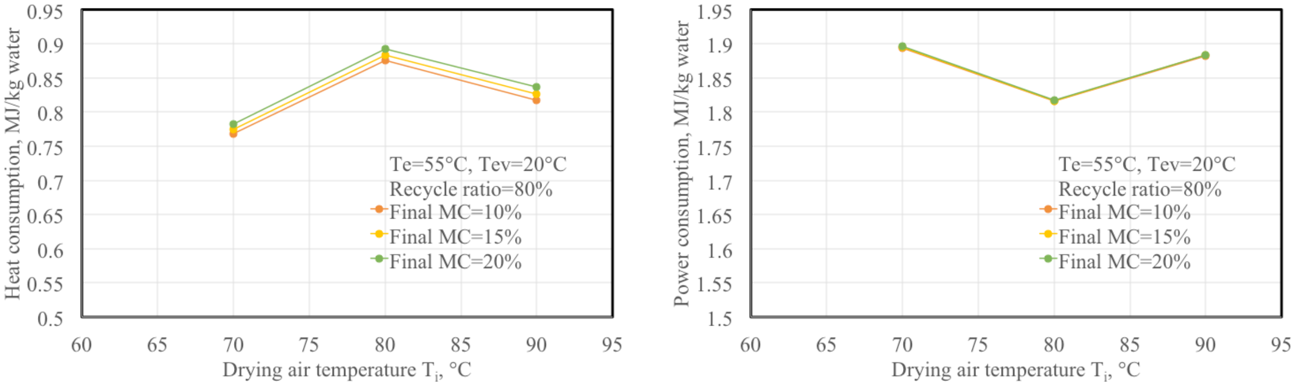
3.3.1.2.3 Final moisture content

As shown in Figure 3.11 and Figure , the final moisture content of the dried grape marc has an insignificant influence on the energy consumption. With lower moisture content in the dried grape marc, the energy loss from the furnace burning the grape marc is reduced. Therefore, the change in the overall energy efficiency of the drying process is negligible although lower final moisture content means higher drying load.

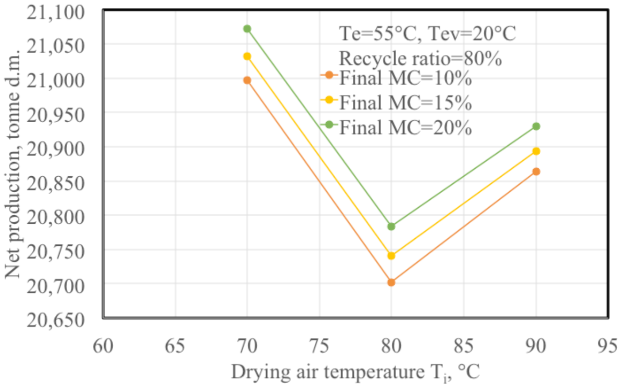


(a) Heat consumption of drying (b) Net production

Figure 3.11 Influence of the final moisture content on the heat consumption of drying (a) and net production of dried grape marc (b) from hot air drying. Other conditions: initial moisture content 67%, drying air temperature at the exit 55°C, drying air recycle ratio 80%, ambient temperature 15 °C, relative humidity 60%.



(a) Heat consumption (b) Electricity consumption

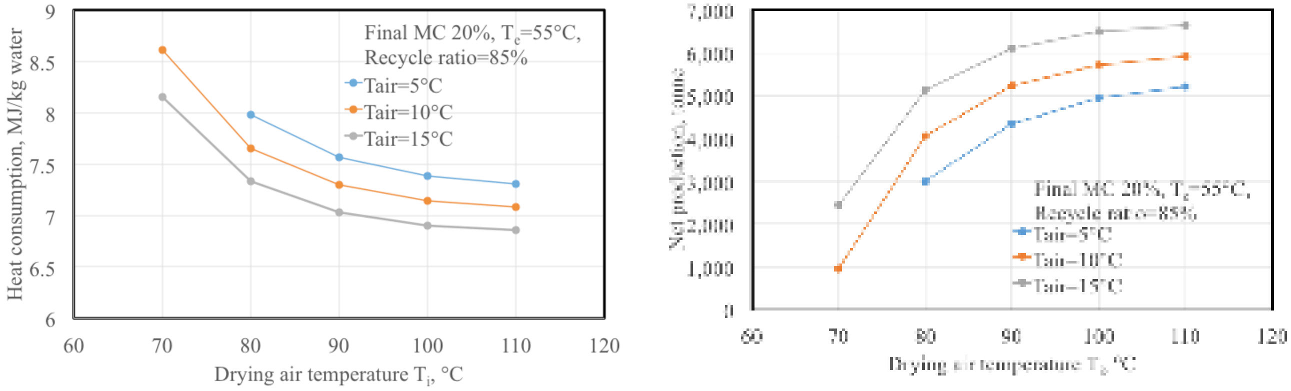


(c) Net production of dried grape marc

Figure 3.12 Influence of the final moisture content on the heat (a) and power (b) consumptions of drying and net production of dried grape marc (c) from heat-pump-assisted drying. Other conditions: initial moisture content 67%, drying air temperature at the exit 55°C, drying air recycle ratio 80%, refrigerant evaporating temperature in the heat pump 20°C, ambient temperature 15 °C, relative humidity 60%.

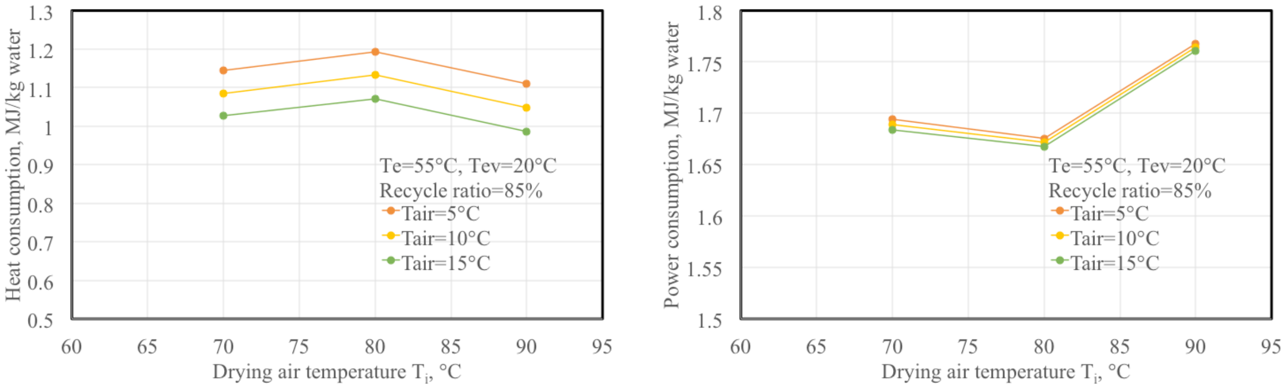
3.3.1.2.4 Ambient air temperature

More heat is needed to heat the drying air if the ambient air temperature is lower. This means more heat consumption, as shown in Figure and Figure .



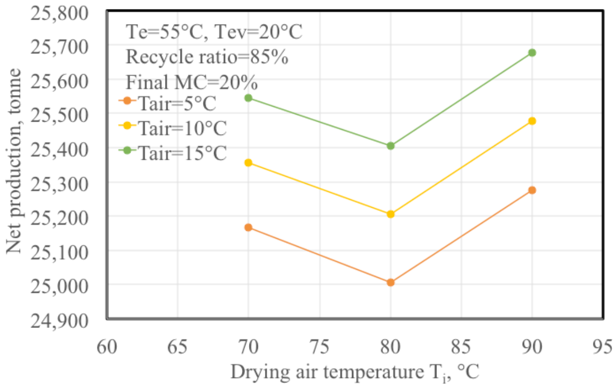
(a) Heat consumption of drying (b) Net production

Figure 3.13 Influence of the ambient air temperature on the heat consumption of drying (a) and net production of dried grape marc (b) from hot air drying. Other conditions: initial moisture content 67%, final dried product moisture content 20%, drying air temperature at the exit 55°C, drying air recycle ratio 85%.



(a) Heat consumption

(b) Electricity consumption



(c) Net production of dried grape marc

Figure 3.14 Influence of the ambient air temperature on the heat (a) and power (b) consumptions of drying and net production of dried grape marc (c) from heat-pump-assisted drying. Other conditions: initial moisture content 67%, final dried product moisture content 20%, drying air temperature at the exit 55°C, drying air recycle ratio 85%, refrigerant evaporating temperature in the heat pump 20°C.

3.3.2 Indirect drying

3.3.2.1 Process descriptions

In the indirect drying process, the dryer is a contact dryer consisting of a rotary drum with internal lifting shovels and a heating surface of tube bundles heated by hot flue gas inside the tubes. As shown in Figure 3.15 and Table 3.4, the wet grape marc (1) is continuously fed into the dryer and move through the space between the shell and the bundle of tubes with a stream of entrained air (2). Inside the dryer, wet grape marc is lifted by the internal shovels and distributed outside the flue gas heated tubes. The product is conveyed by gravity and slid towards the outlet by the rotary movement of the dryer. The energy supplier for the drying process, the flue gas (6) from dried product (10) combustion, passes through the tube side of the dryer.

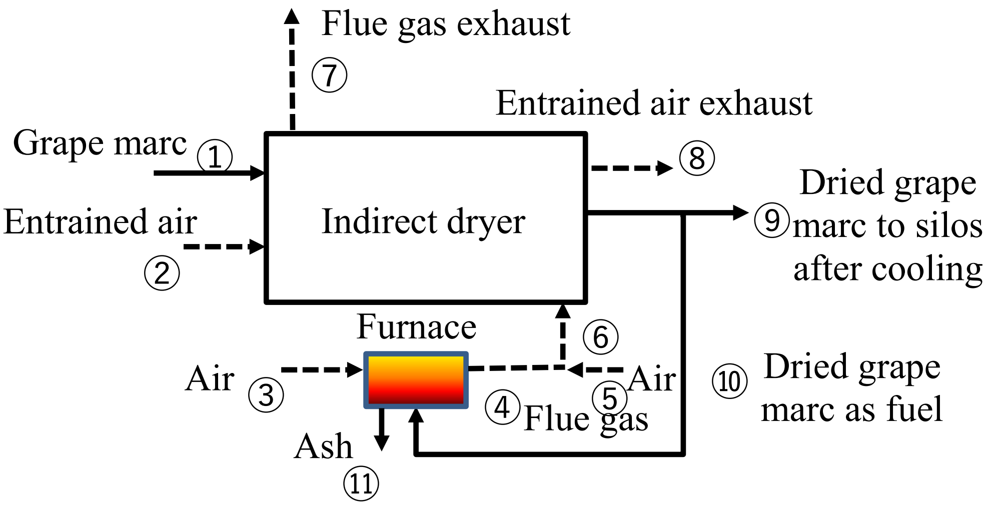


Figure 3.15 Process diagram of the indirect drying

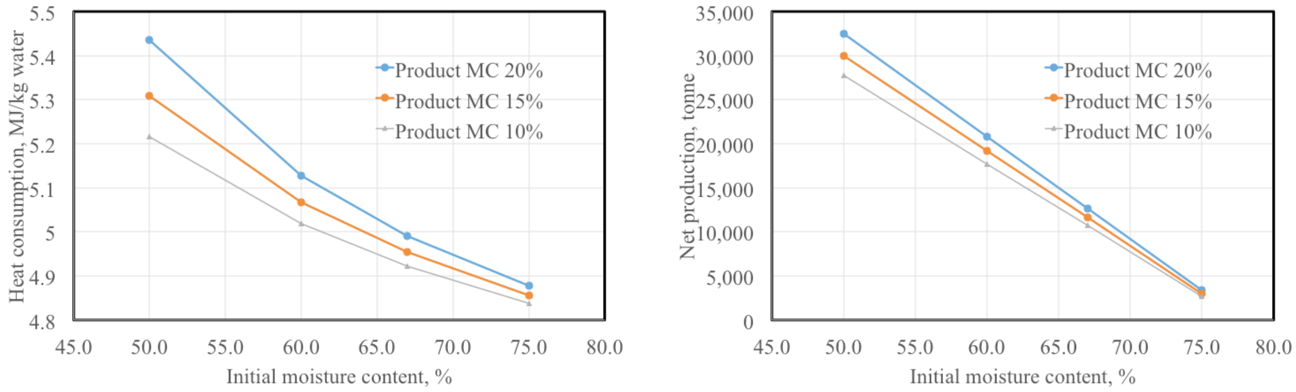
Table 3.4 Process parameters for the indirect drying of grape marc

Stream	Temperature	CV or enthalpy	Mass flow	
	°C	MJ/kg	kg/s (t/hr)	
1	15	0.06 (Sensible) 3.80 (LHV)	19.3 (69.4)	Wet grape marc (67% MC)
2	15(RH60%)	0.031	12.2	Entrained air
3	15	0.031	55.7	Combustion air
4	844	0.967	60.4	Flue gas
5	15	0.031	81.6	Air to dilute flue gas
6	180	0.438	138.9	Hot flue gas for drying (heat source)
7	60	0.145	138.9	Flue gas exhaust
8	105 (RH50%)	2.61	12.2	Air exhaust
9	105	0.31 (Sensible) 12.7 (LHV)	3.50	Dried grape marc to silos after cooling
10	15	0.04(Sensible) 12.7 (LHV)	4.46	Dried grape marc as fuel
11	844	1.55	0.11	Ash

3.3.2.2 *Effects of process conditions*

3.3.2.2.1 Initial and final moisture contents

As shown in Figure 3.16, higher initial moisture content in the wet grape marc have lower heat consumption and, as expected, less net production.

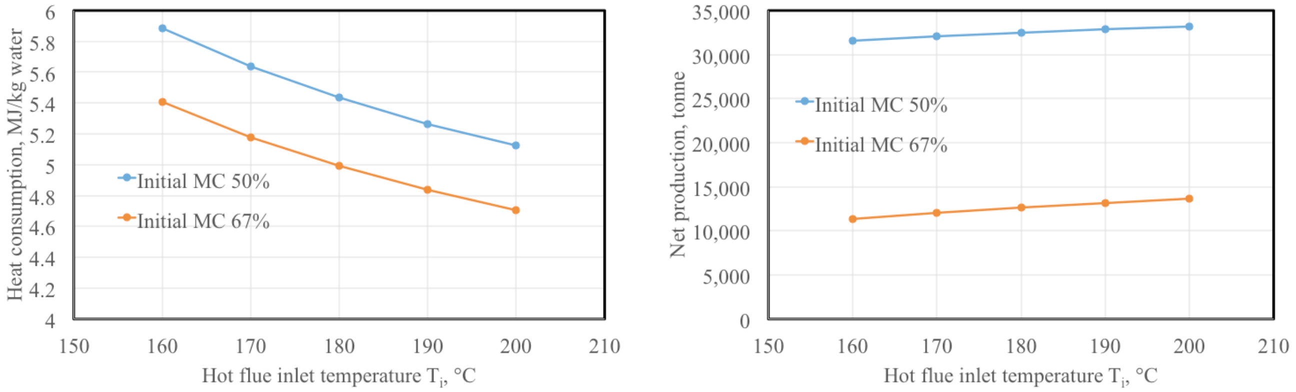


(a) Heat consumption of drying (b) Net production

Figure 3.16 Influence of the initial and final moisture contents on the heat consumption of drying (a) and net production of dried grape marc (b) from indirect drying. Other conditions: heating flue gas inlet temperature 180°C, heating flue gas outlet temperature 60°C, entrained air temperature at the outlet 105 °C, entrained air relative humidity at the outlet 50%, ambient temperature 15°C, ambient relative humidity 60%.

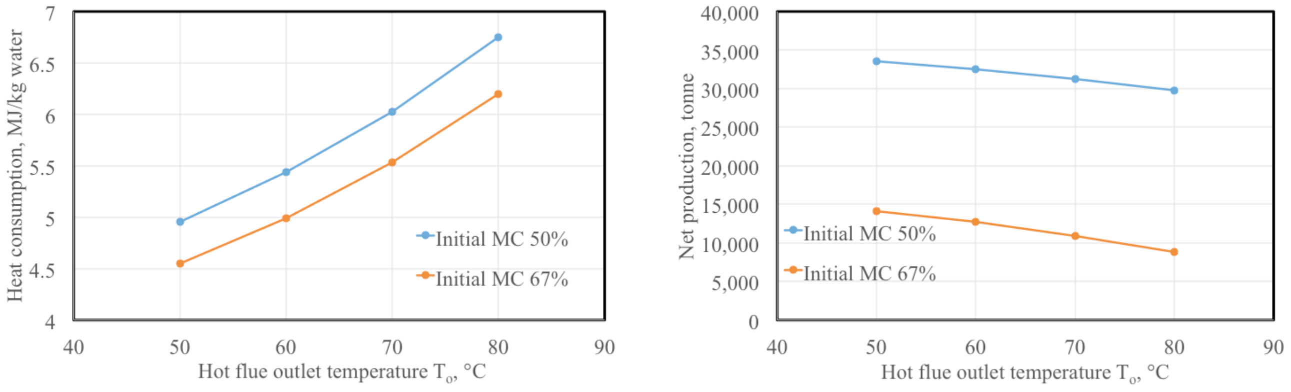
3.3.2.2.2 Flue gas (heat source) temperatures at the inlet and outlet

Similar as those for the direct hot air drying, higher flue gas temperature at the inlet and lower exit temperature result in higher energy efficiency and thus less heat consumption, as shown in Figure 3.17 and Figure 3.18.



(a) Heat consumption of drying (b) Net production

Figure 3.17 Influence of the heat source supply temperature on the heat consumption of drying (a) and net production of dried grape marc (b) from indirect drying. Other conditions: final dried product moisture content 20%, heating flue gas outlet temperature 60°C, entrained air temperature at the outlet 105 °C, entrained air relative humidity at the outlet 50%, ambient temperature 15°C, ambient relative humidity 60%.

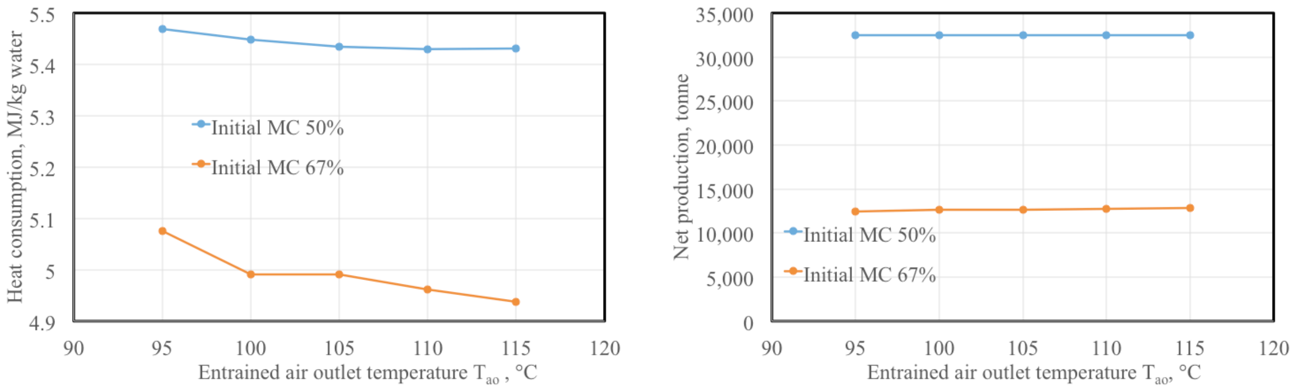


(a) Heat consumption of drying (b) Net production

Figure 3.18 Influence of the heat supply exit temperature on the heat consumption of drying (a) and net production of dried grape marc (b) from indirect drying. Other conditions: final dried product moisture content 20%, heating flue gas inlet temperature 180°C, entrained air temperature at the outlet 105 °C, entrained air relative humidity at the outlet 50%, ambient temperature 15°C, ambient relative humidity 60%.

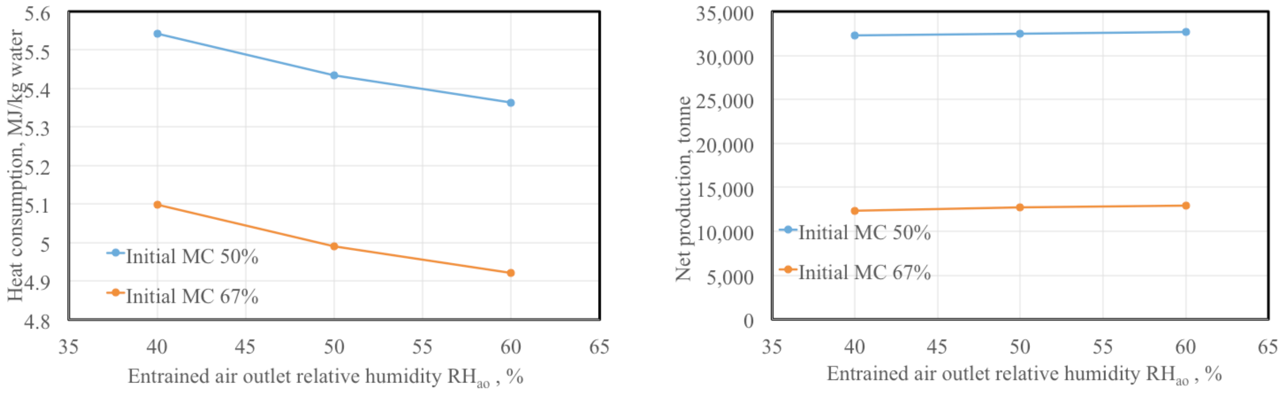
3.3.2.2.3 Entrained air temperature and relative humidity at the outlet

As shown in Figure 3.19 and Figure 3.20, increase in the entrained air temperature and relative humidity means less entrained air to be used and thus slightly decreases the heat consumption. Their effects on the net production of dried grape marc are negligible (<5%).



(a) Heat consumption of drying (b) Net production

Figure 3.19 Influence of the entrained air temperature at the outlet on the heat consumption of drying (a) and net production of dried grape marc (b) from indirect drying. Other conditions: final dried product moisture content 20%, heating flue gas inlet temperature 180°C, heating flue gas outlet temperature 60°C, entrained air relative humidity at the outlet 50%, ambient temperature 15°C, ambient relative humidity 60%.

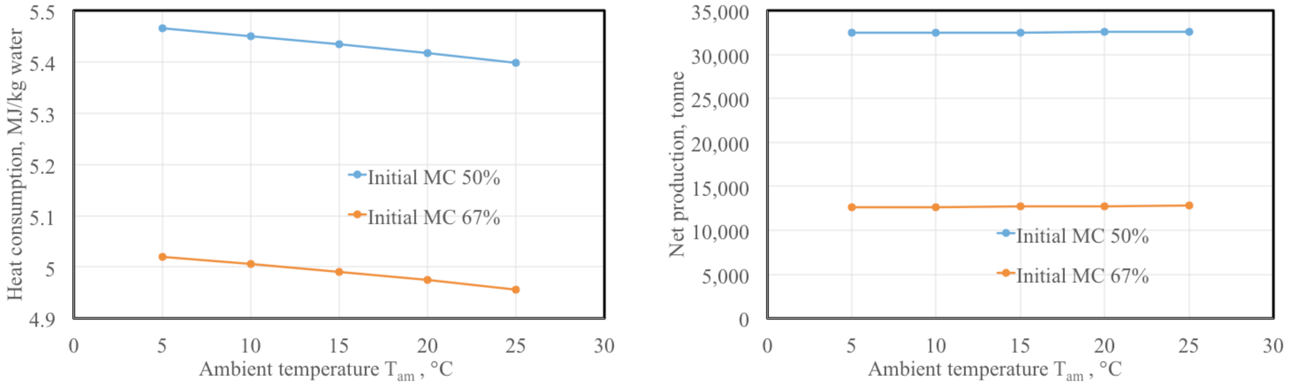


(a) Heat consumption of drying (b) Net production

Figure 3.20 Influence of the entrained air relative humidity at the outlet on the heat consumption of drying (a) and net production of dried grape marc (b) from indirect drying. Other conditions: final dried product moisture content 20%, heating flue gas inlet temperature 180°C, heating flue gas outlet temperature 60°C, entrained air temperature at the outlet 105 °C, ambient temperature 15°C, ambient relative humidity 60%.

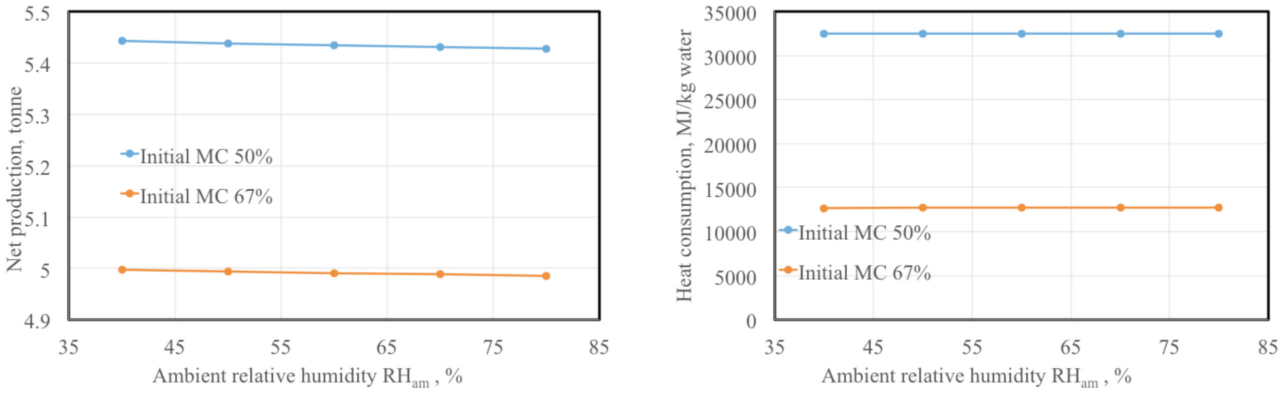
3.3.2.2.4 Ambient temperature and relative humidity

As shown in Figure 3.21 and Figure 3.22, increases in the ambient air temperature and relative humidity have insignificant effects on the heat consumption and net production of dried grape marc.



(a) Heat consumption of drying (b) Net production

Figure 3.21 Influence of the ambient temperature on the heat consumption of drying (a) and net production of dried grape marc (b) from indirect drying. Other conditions: final dried product moisture content 20%, heating flue gas inlet temperature 180°C, heating flue gas outlet temperature 60°C, entrained air temperature at the outlet 105 °C, entrained air relative humidity at the outlet 50%, ambient relative humidity 60%.



(a) Heat consumption of drying (b) Net production

Figure 3.22 Influence of the ambient relative humidity on the heat consumption of drying (a) and net production of dried grape marc (b) from indirect drying. Other conditions: final dried product moisture content 20%, heating flue gas inlet temperature 180°C, heating flue gas outlet temperature 60°C, entrained air temperature at the outlet 105 °C, entrained air relative humidity at the outlet 50%, ambient temperature 15°C.

3.3.3 Grape marc drying plant

3.3.3.1 Plant configuration and output

As can be seen from above, the heat pump assisted drying process has highest energy efficiency but the system is very complex. Direct hot air drying process is simple but with low energy efficiency. In this report, we propose to adopt the indirect drying process for grape marc treatment, with process parameters shown in Table 3.4.

According to Table 3.4, the total drying load for the grape marc drying plant is 41,125 tonne each year within the grape marc harvest period of 42 days. After an extensive search for suitable industrial scale dryers, 12 dryers in total with following performance parameters (Table 3.5) need be installed in the drying plant to fulfill the drying load. The total land area for these dryers is about 0.32 ha, or 0.05m^2/tonne wet grape marc (Figure 3.23).

Table 3.5 Performance parameters of an industrial-scale indirect dryer

Evaporation capacity, kgH$_2$O·m^{-2}·hr^{-1}	Heat exchanger area, m^2	Diameter of roller, mm	Rotating speed, r·min^{-1}	Main power, kW	Dimensions*, m
4.5	800	2800	1~5	55	16.6×3.2×4.5

*http://www.zzwgjx.cn/products/dryer/tube-bundle-dryer.html

After drying, the total amount of dried grape marc is 12,695 tonne, with 20% moisture content (see Figure 3.2). This is equivalent to 0.18 tonne product per one tonne of wet grape marc. The dried grape marc is stored in silos and then consumed in 200 days. Considering the bulk density of the dried grape marc to be 400 kg·m^{-3}, a total of 79 silos will be needed if the dimensions of each silo are 8 m in diameter and 8 m in height. The total land area for these silos is about 0.83 ha, or 0.12m^2/tonne wet grape marc.

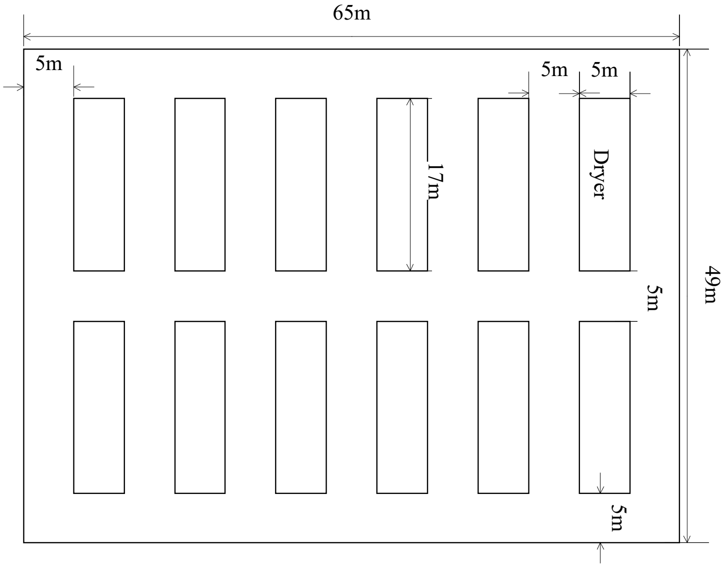


Figure 3.23 Floor plan of 12 dyers

3.3.3.2 Environmental impacts

For the dryers to be operating, the electricity consumption could be up to 665,280 kWh per year, or 9.5 kWh/tonne wet grape marc. The dried grape marc (with 20% moisture content) to be burned as fuel for heating the dryers is 16,180 tonne each year, or 0.23 tonne/tonne wet grape marc. This produces about 409 tonne ash annually, or 5.8 kg/tonne of wet grape marc. The ash contains certain level of potassium and negligible carbon content. It could be potentially either used for making fertilizer or cement, or dumped in the landfill.

The burning of dried grape marc product for heating the dryers could also produce flue gas emissions of NOx and particulate matter (PM). It is estimated that the NOx formation from combustion before flue gas treatment could be 336 ppm/Nm^3 dry flue gas (13.6% of O_2) (Houshfar, et al. 2012; Salzmann and Nussbaumer, 2001). Flue gas treatment, such as selective non-catalytic reduction and baghouse filter, may be needed to cope with the existing environmental regulations. For example, the Netherlands Ministry for Infrastructure and the Environment has set emission limit values (know as BEMS) for biomass combustor < 5 MWth: NOx 200 mg/m^3, PM_{10} 20 mg/m^3.(Environmental Protection UK, 2012)

3.3.3.3 Drying plant economic assessment

The installed cost of the drying plant includes the cost of the purchased equipment, costs of equipment installation, piping, wiring, and instrumentation (Mujumdar, 2014). The equipment cost can be directly obtained from vendor data or estimation based on known costs for similar equipment or plant built previously, or literature. Table lists the estimated equipment costs of the dryers and silos, together with the installed cost of the dryers on the basis of a Chinese vendor's data (Zhengzhou Wangu Machinery Co., Ltd).

The total capital cost of the entire plant is not only directly related to the dryer capacity but also depends greatly on the cost of the ancillary equipment, including building, utility-supply facilities, site development, etc (Mujumdar, 2014). The estimated total capital costs for the drying plant are based on two sources of equipment cost, as listed in Table 3.7 and Table .

Table 3.9 compares the operation and maintenance costs of the drying plant for the two sources of equipment costs.

Table 3.6 Equipment cost of the dryers and silos

Equipment	Base cost	Base scale	Scale units	Scale factor	Scale in this study	Cost in this study, NZ$	Reference
Dryers	US$852,200	1400	ft^2	0.65	9600m^2	21,917	Matches 2014
	US$900	800	m^2	1	9600 m^2	16,200	Installed cost (Wu, 2020)
Silos	US$32	500	m^3	1	160m^3 ×79	1,715	International Silo Assoc., 2012

Table 3.7 Capital cost of the drying plant (based on Matches 2014)

	Factor*	Costs, k$
Dryer assembly	0.45	9,863
Freight	0.07	1,534
Installed cost of dryers		33,315
Building	0.3	9,994
Utility-supply facility, site development	0.3	9,994
Total direct cost of dryers		53,304
Contractor's fee	0.2	10,660
Insurance, taxes, customs, land	0.07	3,731
Contingencies	0.2	10,660
Procurement, supervisory, admin, etc	0.1	5,330
Fixed capital investment, including silos		85,399

* Mujumdar, 2014

Table 3.8 Capital cost of the drying plant (based on vendor's cost)

	Factor*	Costs, k$
Installed cost of dryers		16,200
Building	0.3	4,860
Utility-supply facility, site development	0.3	4,860
Total direct cost of dryers		25,920
Contractor's fee	0.2	5,184
Insurance, taxes, customs, land	0.07	1,814
Contingencies	0.2	5,184
Procurement, supervisory, admin, etc	0.1	2,592
Fixed capital investment		42,406

* Mujumdar, 2014

Table 3.9 Operation and maintenance (O&M) costs for the drying plant (Annual, k$)

	Cost basis	Based on Table	Based on Table
Drying plant			
Maintenance cost	5% of the fixed capital investment (Mujumda, 2014)	4,184	2,035
Fixed operation cost	6% of the fixed capital investiment (Mujumda, 2014)	5,021	2,442
Electricity	665280 kWh×$0.15 /kWh	100	100
Labour	12096 man hours × $35 /man hour	423	423
Working capital servicing	4% of variable costs	21	21
Total O&M		9,750	5,020

If the drying system is a standalone thermal processing plant for the grape marc, then the dried grape marc product can be sold as a fertiliser for spreading, animal feed, or feedstock for other chemical processes, e.g., extraction, which are the basis of the plant revenue. The break-even revenue in 25 years is $6,649k per year (based on Table).

3.4 Dried grape marc as a fuel for power generation through combustion

3.4.1 Process descriptions

The steam turbine cycle is a common technology used in power generation. In this configuration, dried grape marc (1) is first fed into a combustor or furnace where it is burned with excess air to heat water in a boiler to create superheated steam (5) of appropriate properties. A moving grate combustion boiler is the most suitable system for this process. The steam (5) will drive a steam turbine and hence the generator to produce electricity (7). In addition, the system should also include a chemical treatment system for the feed water. The flow diagram and the parameters are schematically shown in Figure and Table . The calculation was based on the assumption that the power plant operates for 200 days each year with dried grape marc as a fuel.

Table 3.10 Process parameters of grape marc combustion for power generation

Stream	Temperature	CV or enthalpy	Mass flow	
	°C	MJ/kg	kg/s (t/hr)	
1	15	0.04(Sensible) 12.7 (LHV)	0.73 (2.64)	Dried grape marc (20% MC)
2	15 (RH60%)	0.031	8.56 (dry air)	Combustion air
3	105	0.113	9.32	Flue gas exhaust
4	891	0.967	0.02	Ash
5	356 (3.1 MPa)	3.13	2.72	Superheated steam
6	38.1	2.088	2.72	Exhaust steam
7	Electricity			2.32 MWe

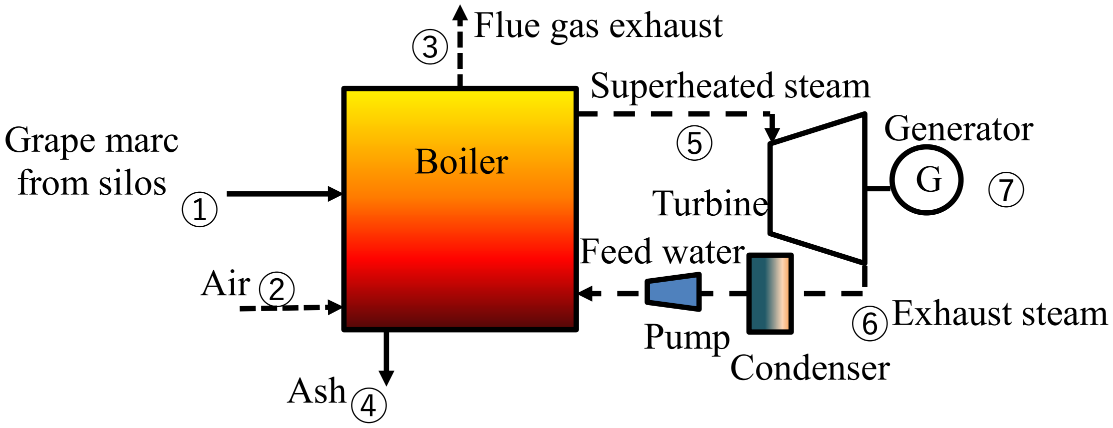


Figure 3.24 Process diagram of dried grape marc combustion for power generation

3.4.2 Outputs and environmental impacts

The output from this case is the electricity of 2.3MWe, or 11,136 MWh each year. This is equivalent to 159 kWh/tonne of wet grape marc.

The combustion of dried grape marc leaves 320 tonne of ash 4.6kg/tonne of wet grape marc each year. So combined with the drying plant, the total ash is 729 tonne annually, or 10.4 kg/tonne of wet grape marc.

As with the drying plant, dried grape marc combustion in the power plant could produce NOx and particulate matter in the flue gas. NOx formation from combustion before flue gas treatment could be 336 ppm/Nm^3 dry flue gas (13.6% of O2). To cope with environmental regulations, staged combustion, or selective non-catalytic reduction technique needs to be used to mitigate NOx formation. Fabric filters (baghouse) needs to be installed to collect particulate matter. Netherlands BEMS emission limit value for biomass boilers > 5 MWth: NOx 200 mg/m^3, PM_{10} 20 mg/m^3.(Environmental Protection UK, 2012)

3.4.3 Economic assessment for combustion for power generation

The costs of all the major equipment for the grape marc fired power generation plant were estimated according to the study of biomass-fired power plant of similar size in South California, US (TSS, 2009). In order to account for price changes due to inflation and economic fluctuations, the method of the Chemical Engineering Plant Cost Index (Table 3.11) was used to calculate the equipment costs, as listed in Table 3.12.

The estimated capital costs of the power plant are listed in Table 3.13. When combined with the drying plant, the capital cost for this thermal processing plant is totaled at $111,570k (based on the estimated cost from Matches 2014) or $68,577k (based on the dryer vendor's cost). The operation and maintenance (O&M) costs for the power generation system was estimated roughly on the basis of the plant capacity, as listed in Table 3.13. Integrated with the drying system, the O&M cost for the whole plant is $11,093k (based on the estimated cost from Matches 2014) or $6,363k (based on the dryer vendor's cost).

Table 3.11 Chemical engineering plant cost index

Year	M&S index	Year	M&S index	Year	M&S index
1995	381.1	2003	402	2011	585.7
1996	381.7	2004	444.2	2012	584.6
1997	386.5	2005	468.2	2013	567.3
1998	389.5	2006	499.6	2014	576.1
1999	390.6	2007	525.4	2015	556.8
2000	394.1	2008	575.4	2016	541.7
2001	394.3	2009	521.9	2017	567.5
2002	395.6	2010	550.8	2018	603.1

Table 3.12 Equipment costs of combustion plant

Equipment	Base cost	Base scale	Scale units	Scale factor	Scale in this study	Cost in this study, NZ$	Reference
Boiler	US$6,790	10	MWe	0.65	2.32MWe	4,553	TSS, 2009
Turbine & Gen	US$4,4470	10	MWe	0.65	2.32MWe	2,998	As above
Dedust	US$952,500	10	MWe	0.65	2.32MWe	639	As above
Cooling tower	US$421	10	MWe	0.65	2.32MWe	282	As above
Fuel handling equipment	US$1,500	10	MWe	0.65	2.32MWe	1,006	As above
SNCR, CEMS	US$3,030	10	MWe	0.65	2.32MWe	2,032	As above
In total						11,510	

Table 3.13 Capital costs of the power generation plant (k$)

	Factor	Combustion for power generation
Subtotal of equipment costs		11,510
Construction cost	0.75	8,632
Engineering	0.065	1,309
Insurance & project management	0.07	1,502
Contingency	0.15	3,218
Capital cost		26, 171

Table 3.14 Operation and maintenance (O&M) costs for the power generation plant (k$ annually)

	Cost basis	O&M costs
Fixed O&M cost	98 US$/kW × 2320 kW × 1.5 (NREL, 2016)	341
Variable O&M cost	0.06 US$/kWh × 2320 kW × 200 days × 24 hrs × 1.5 (NREL, 2016)	1,002
Total O&M		1,343

Combined with the drying system, the revenue of the grape marc fired power plant comes from the selling of electricity (11,136 MWh) each year. The break-even revenue in 25 years is $ 9,039k per year (based on the dryer vendor's cost).

3.5 Dried grape marc for heat and power generation through gasification

3.5.1 Process descriptions

Biomass gasification with gas engine is a common approach for combined heat and power generation. Gasification is a thermochemical conversion of solid fuels (such as coal, biomass or other waste) into syngas as a major product at temperatures from 700 °C to 1200 °C. The syngas is composed of carbon monoxide, carbon dioxide, methane, hydrogen, traces of higher hydrocarbons, water, and nitrogen if air is used as gasifying agent. Gasification also produces small amount of tar and ash-contained char particles. Gasification with air as agent is simple but yields low quality syngas (HHV< 7 MJ/m^3), which can be easily used for combined heat and power generation through steam cycle or IC engines (Jankes, et al., 2012).

As shown in Figure 3.25, dried grape marc (1) is fed into an atmospheric fluidised bed gasifier. With preheated sub-stoichiometric air (3), the grape marc is converted into a combustible producer gas (4). The hot producer gas (4) is used to preheat the air (2) for gasification. It is then cooled down (5) and cleaned successively by a wet scrubber (6) to removal particles, tars, and other contaminants (8). Following these suitable clean up and cooling procedures, the producer gas (6) is used to run a gas engine and thus produce electricity (9). The temperature of the exhaust gas from the gas engine is still above 300°C. The sensible heat is used to produce hot water.

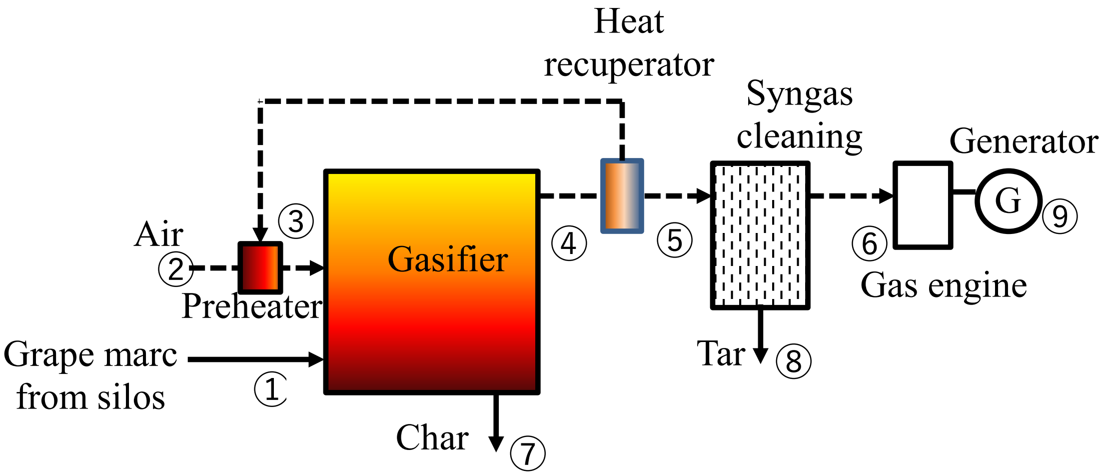


Figure 3.25 Process diagram of dried grape marc gasification for combined heat and power generation

Table 3.15 Process parameters of grape marc gasification for combined heat and power generation

Stream	Temperature	CV or enthalpy	Mass flow	
	°C	MJ/kg	kg/s (t/hr)	
1	15	0.04(Sensible) 12.7 (LHV)	0.73 (2.64)	Dried grape marc (20% MC)

2	15 (RH60%)	0.031	1.22 (dry)	Air for gasification
3	400	0.425	1.22 (dry)	Preheated air for gasification
4	850	1.138 (Sensible) 3.307 (LHV, wet)	1.882	Syngas (1.6% H_2, 12.8% CO, 4.2% CH_4, 11.5% CO_2, 48% N_2, 21.9% H_2O)
5	654	0.854 (Sensible) 2.77 (LHV, wet)	1.882	As above
6	15	0.018(Sensible)	1.882	As above
7	850	1.564	0.076	Char
8	15		0.001	Tar
9	Output			Heat: 8.81 kg/s hot water (90°C) Power: 1.446 MWe

3.5.2 Outputs and environmental impacts

The main output from this process is the electricity of 1.45MWe, or 6,941 MWh each year. This is equivalent to 99 kWh/tonne of wet grape marc. This process also produces low grade heat of 47,865 GJ each year, or 0.68 GJ/tonne of wet grape marc. The heat could be used to produce hot water of 90 °C totaled at 152 tonne per year, or 2.17 tonne hot water per one tonne of wet grape marc.

The waste from grape marc gasification include tar (about 1 g/m^3 dry syngas) of 21 tonne and char particles of 1,337 tonne annually. The char particles are collected from hot syngas through a cyclone before tar is condensed. The char residue has been found to be high in porosity and carbon content, which is similar to activated carbon (AC) (Benedetti, et al., 2018). This implies the char could be used as sorbent and catalyst support instead of as a waste to be disposed. Tar from gasification is usually undesirable. As it is captured from water scrubber, the effluent needs to be treated in a sewage system.

In this system, the syngas is burned in the gas engine after removal of particles through cleaning. The combustion in the gas engine could generate NOx and other products of incomplete combustion, e.g., CO. These pollutants could be mitigated by a complex catalytic converter system (Folkson, 2014). For environmental regulations, Netherlands BEMS emission limit value of NOx for internal combustion engine > 2.5 MWth is 100 mg/m^3 while German TA-LUFT NOx emission limits for gas engine is 500 mg/m^3 (Environmental Protection UK, 2012).

3.5.3 Economic assessment for grape marc gasification for CHP

The costs of major equipment of the gasification for CHP system was estimated based on the data in the literature with similar scale, as listed in Table 3.16. Table 3.17 is the estimated capital costs for the gasification system. When combined with the drying system, the capital cost for the whole thermal processing plant is totaled at $157,022k (based on the estimated cost from Matches 2014) or $114,029k (based on the dryer vendor's cost).

The operation and maintenance (O&M) costs for the gasification for CHP system was estimated roughly on the basis of the plant capacity, as listed in Table 3.18. When integrated with the drying system, the O&M cost for the whole plant is $11,504k (based on the estimated cost from Matches 2014) or $6,775k (based on the dryer vendor's cost).

Table 3.16 Equipment costs of the gasification plant

Equipment	Base cost	Base scale	Scale units	Scale factor	Scale in this study	Cost in this study, k$	Reference
Gasifier	€8	8.0	MWth	0.72	9.32MWth	22,775	Holmgren, 2015
Water scrubber	US$3,00	12.1	m^3/s	0.7	$5m^3/s$	3,696	Holmgren, 2015
Gas engine	€2,732,700	2.0	MWe	0.65	1.446MWe	3,763	Porcu et al, 2019
Fuel handling equipment	€617,700	2.0	MWe	0.65	1.446MWe	850	Porcu et al, 2019
Hot water boiler	65	£/kW	MWth		2.77MWth	416	NERA & AEA, 2009
In total						31,500	

Table 3.17 Capital costs of the gasification for CHP plants (k$)

	Factor	Gasification and gas engine for CHP
Subtotal of equipment costs		31,500
Construction cost	0.75	23,625
Engineering	0.065	3,583
Insurance & project management	0.07	4,110
Contingency	0.15	8,806
Capital cost		71,623

Table 3.18 Operation and maintenance (O&M) costs for all the cases(k$ annually)

	Cost basis	Estimate costs
Fixed O&M cost	3% of the installed cost (IRENA, 2012)	945
Variable O&M cost	0.04 US$/kWh × 1446 kW × 200 days × 24 hrs × 1.5	278
Total O&M		1,223

Combined with the drying system, the revenue of the grape marc based gasification for CHP plant comes from the selling of electricity (6,941 kWh) and 47,865 GJ of low grade heat each year. The break-even revenue in 25 years is $ 11,268 per year (based on the dryer vendor's cost).

3.6 Thermal valorisation of dried grape marc for biochar

3.6.1 Process descriptions

Only a few attempts have been made to exploit grape marc resources by thermal valorization. Khiari and Jeguirim (2018) studied the pyrolysis characteristics of grape marc from Tunisian wine industry and found the biochar yield close to 40% due to the high lignin and ash contents. This confirmed that grape marc could be a promising feedstock for biochar production. Later, Ferjani et al (2019) investigated the effect of pyrolysis temperature on biochar production from exhausted grape marc from the Alsace Region in France. They reported that biochar obtained at 500°C has 33% yield with high nutrient contents and porosity, thus very attractive for agricultural or environmental applications.

In this section, the thermal varolisation of dried grape marc for biochar production is introduced. In this thermal process, the dried grape marc (1) is fed into the top of a reactor moving downward by gravity. The reactor is heated from outer rim by flue gas (3) formed by burning the pyrolysis gas and volatiles from the reactor (2). The waste heat from the flue gas leaving the reactor is used to produce hot water (6). The flow diagram and the parameters are schematically shown in Figure 3.26 and Table 3.19.

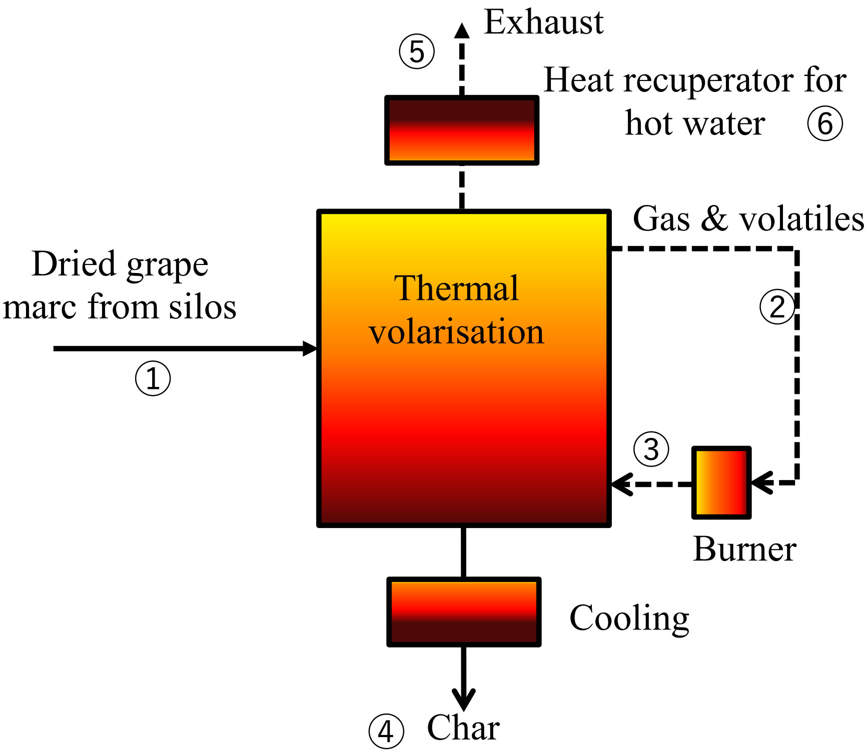


Figure 3.26 Process diagram of dried grape marc thermal volarisation for biochar production

Table 3.19 Process parameters of grape marc thermal valorization for biochar

Stream	Temperature	CV or enthalpy	Mass flow	
	°C	MJ/kg	kg/s (t/hr)	
1	15	0.04(Sensible) 12.7 (LHV)	0.73 (2.64)	Dried grape marc (20% MC)
2	500	6.57 (LHV)	0.532	Gas and volatile products from pyrolysis
3	869	1.07	3.03	Flue gas
4	30	27.83 (LHV)	0.203	Biochar
5	105	0.112	3.03	Flue gas exhaust
6	Output		2.422	Hot water (90°C)

3.6.2 Outputs and environmental impacts

The main output from this process is 3,500 tonne biochar each year. This is equivalent to 50 kg/tonne of wet grape marc. This process also produces low grade heat of 14,688 GJ each year, or 0.21 GJ/tonne of wet grape marc. The heat could be used to produce hot water of 90 °C totaled at 41,820 tonne per year, or 0.6 tonne hot water per one tonne of wet grape marc.

In this process, the heat required for grape marc decomposition is provided by burning volatiles and gases from the process itself. The major pollutant formed during the combustion could be NOx and products of incomplete combustion. The maximum NOx formation from volatile combustion is estimated to be 680 mg/Nm^3 dry flue gas (8% O_2). But the actually emissions could be much less than that when considering staged combustion technology to mitigate its formation. In addition, a catalytic oxidation converter could be installed to control the products of incomplete combustion. As the heat load for the decomposition process is low, the emission limit values could be compared with those of Netherlands BEMS for biomass combustor < 5 MWth: NOx 200 mg/m^3, PM_{10} 20 mg/m^3.(Environmental Protection UK, 2012) :

3.6.3 Economic assessment for grape marc for biochar production

The costs of the major equipment for the grape marc biochar plant were estimated according to very few data reported in the literature, as listed Table 3.20. Table 3.21 lists the estimated capital costs for the biochar production system. When combined with the drying system, the capital cost for the whole thermal processing plant is totaled at $98,248k (based on the estimated cost from Matches 2014) or $55,255k (based on the dryer vendor’s cost).

The operation and maintenance (O&M) costs for the biochar production system was estimated roughly on the basis of the plant capacity, as listed in Table 3.22. When integrated with the drying system, the O&M cost for the whole plant is $10,353k (based on the estimated cost from Matches 2014) or $5,623k (based on the dryer vendor’s cost).

Table 3.20 Equipment costs of the thermal valorization plant

Equipment	Base cost	Base scale	Scale units	Scale factor	Scale in this study	Cost in this study, k$	Reference
Pyrolyser(with combustor)	US$4,500	262	Tonne/year	0.65	3500 tonne/year	4,471	Brown et al. 2010
Biochar storage	US$6,00	262	Tonne/year	0.65	3500 tonne/year	596	Brown et al. 2010
SNCR, CEMS	US$3,030	10	MWe	0.65	0.28 MWe-equivalent	462	TSS, 2009
Boiler	65	£/kW	MWth		0.85MWth	121	NERA & AEA, 2009
In total						5,651	

Table 3.21 Capital costs of three thermal processing plants (k$)

	Factor	Biochar proudction
Subtotal of equipment costs		5,651
Construction cost	0.75	4,238
Engineering	0.065	643
Insurance & project management	0.07	737
Contingency	0.15	1580
Capital cost		12,849

Table 3.22 Operation and maintenance (O&M) costs for all the cases (k$ annually)

	Cost basis	Estimate costs
Fixed O&M cost	47 US$/tonne biochar ×3500 tonne × 1.5 (Brown, et al., 2010)	247
Solid handling	32 US$/tonne biochar ×3500 tonne × 1.5 (Brown, et al., 2010)	167
Electricity	36 US$/tonne biochar ×3500 tonne × 1.5 (Brown, et al., 2010)	189
Total O&M		603

Combined with the drying system, the revenue of the grape marc biochar production plant comes from the selling of biochar (3,500 tonne) and 14,688 GJ of low grade heat each year. The break-even revenue in 25 years is $ 8,288k per year (based on the dryer vendor's cost).

3.7 Discussion

3.7.1 Effect of further dewatering before drying

As shown previously, the capital and operation costs for grape marc drying are very extremely high. Dewatering before drying can not only reduce the size of the drying plant but also the output of the dried grape marc product and thus, the outputs of the following thermal processing plants. Table 3.23 summarises the outputs from all the thermal processing plants (42 days of drying and 200 days for other thermal processes) after different levels of dewatering treatment. When the wet grape marc is dewatered from 67% of moisture content to 50%, 20,717 tonne of water is removed. As the drying load for the drying plant is decreased, less dried grape marc is used as a fuel for drying. The number of dryers needed in the drying plant decreases from 12 dryers down to 5 while the net grape marc production increased by 70%. As a result, the outputs from other thermal processing plants increase accordingly. Of course, the effluent from wet grape marc needs to be further treated.

Table 3.23 Outputs from the thermal processes for different dewatering levels

Moisture content	67%	60%	50%
Wet grape marc, tonne	70	56,714	44,616
Effluent	0	13,286	25,384
Grape marc product after drying, tonne with 20% MC	12,695	16,894	20,717

Dryers	12 × 800m^2	8 × 800m^2	5 × 800m^2
Electricity output from power plant, kWh	11,136	14,794	18,142
Electricity output from gasification, kWh	6,941	9,220	11,296
Heat from gasification, GJ / tonne hot water	47,865 / 152	58,465 / 186,179	69,111 / 220082
Biochar from pyrolysis	3,500	4,659	5,713
Heat from pyrolysis, GJ / tonne hot water	14,688 / 41,820	17,498 / 55,720	21,458 / 68,331

3.7.2 Integrated thermal process scenarios

As both the grape marc gasification and thermal valorization processes produce heat in addition to electricity or biochar, it is nature to consider to use the heat for grape marc drying so that the overall output and energy efficiency could be improved, as shown in Figure 3.27 and Figure 3.28.

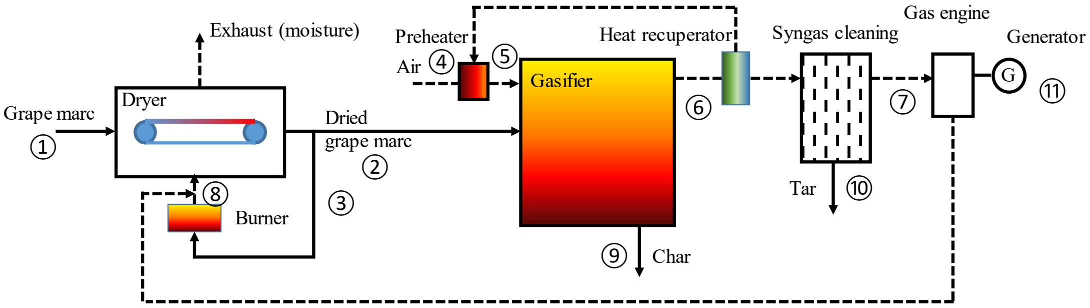


Figure 3.27 Process diagram of integrated drying and gasification for combined heat and power generation

Figure 3.27 shows the integrated drying and gasification process. In this process, the gas engine exhaust is diluted to 180°C and introduced to the indirect dryer so the amount of dried grape marc for heating the dryer could be reduced. A typical set of parameters for this process is listed in Table 3.24.

Table 3.24 Process parameters of combined grape marc drying and gasification

Stream	Temperature	CV or enthalpy	Mass flow	
	°C	MJ/kg	kg/s	
1	15	0.06 (Sensible) 3.80 (LHV)	4.05	Wet grape marc (67% MC)
2	15	0.04(Sensible) 12.7 (LHV)	1.38	Dried grape marc (20% MC)
3	15	0.04(Sensible) 12.7 (LHV)	0.29	Dried grape marc (20% MC)
4	15 (RH60%)	0.031	2.30 (d.b.)	Air for gasification
5	400	0.425	2.30 (d.b.)	Preheated air for gasification
6	850	1.14 (Sensible) 2.71 (LHV, wet)	3.54	Syngas (15% CO, 3.7% CH$_4$, 9.2% CO$_2$, 47.8% N$_2$, 24.4% H$_2$O)

7	15	0.02	2.96	Syngas (19.8% CO, 4.9% CH_4, 12.2% CO_2, 63.2% N_2)
8	180	0.25	39.3	Hot flue gas
9	850	1.56	0.14	Char
10	15		0.002	Tar
11	Output			Power: 1.446 MWe

Figure 3.28 shows the integrated drying and thermal valorisation process. In this process, the heat from the flue gas exhausted from the pyrolyser is recovered and introduced to the indirect dryer. A typical set of parameters for this process is listed in Table 3.25.

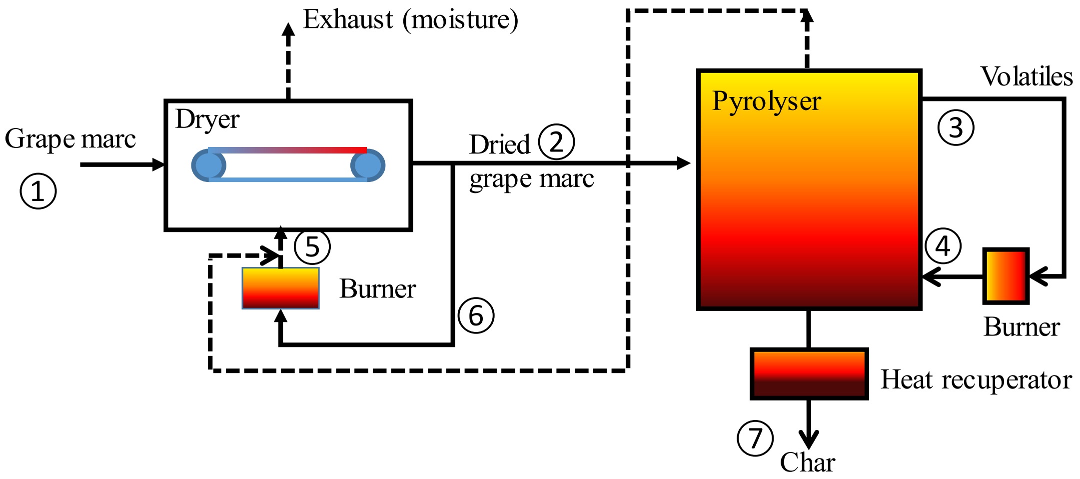


Figure 3.28 Process diagram of integrated drying and thermal volarisation for biochar production

Table 3.25 Process parameters of combined grape marc drying and thermal valorisation

Stream	Temperature	CV or enthalpy	Mass flow	
	°C	MJ/kg	kg/s	
1	15	0.06 (Sensible) 3.80 (LHV)	4.05	Wet grape marc (67% MC)
2	15	0.04(Sensible) 12.7 (LHV)	1.22	Dried grape marc (20% MC)
3	500	6.25 (LHV)	0.88	Gas and volatile products from pyrolysis
4	881	1.09	5.08	Flue gas for pyrolysis
5	180	0.19	57.2	Flue gas for drying
6	15	0.04(Sensible) 12.7 (LHV)	0.45	Dried grape marc (20% MC)
7	30	27.83 (LHV)	0.203	Biochar

3.7.3 Summary of economic scenario analysis

Different scenarios (Table 3.26) of grape marc thermal processing have been considered in order to demonstrate the effects of various conditions on the outputs and economic performance, as summarised in Table 3.27 to Table 3.30. As can be seen, with dewatering, the outputs of thermal processes increase and the size of the drying plant can be greatly reduced. As a result, the capital costs and O&M costs also decrease.

Table 3.26 Thermal processing scenarios for comparison

Scenarios	Explanation
Drying 1	Drying is separated because dried grape marc is a saleable product. Here, drying is conducted immediately, over the 42 days vintage season, to avoid stockpiling the grape marc, and the possible deleterious environmental effects of stockpiles becoming anaerobic. At a regional level, dried marc sold for purposes other than land-spreading does not return fertiliser nutrient value, which must then be accounted for by addition of industrial fertiliser in the comparison.
Drying 2	Drying, as for D1, but a microbial growth inhibitor is used so that grape marc can be stockpiled. Drying then extends over 160 days. The result is a smaller drying plant, requiring less capital.
Drying 3	Drying, as for D2, but with mechanically dewatering prior to drying, from 67% moisture to 50% moisture. The pressate from this dewatering step carries a high BOD which is incurs a treatment cost. The result is that drying requires less energy, and so more dried grape marc is produced.
Combustion 1	Combustion of dried grape marc from D1 is used to produce electricity. No useful heat is produced. The residue ash is landfilled. At a regional level, the industrial fertiliser are required to replace the nutrients to the soil.
Combustion 2	Combustion of dried grape marc from D2 is used to produce electricity. No useful heat is produced. The residue ash is landfilled. At a regional level, the industrial fertiliser are required to replace the nutrients to the soil.
Combustion 3	Combustion of dried grape marc from D3 is used to produce electricity. No useful heat is produced. The residue ash is landfilled. At a regional level, the industrial fertiliser are required to replace the nutrients to the soil. Operation extends over 337 days.
Gasification 1	Gasification of the dried grape marc from D1 is used to produce electricity and heat. The residue tar, char and captured particular matter is landfilled. The landfilled char contains sequestered carbon. At a regional level, no nutrients are returned to productive land and so industrial fertilisers are required.
Gasification 2	Gasification of the dried grape marc from D2 is used to produce electricity and heat. The residue tar, char and captured particular matter is landfilled. The landfilled char contains sequestered carbon. At a regional level, no nutrients are returned to productive land and so industrial fertilisers are required.
Gasification 3	Gasification of the dried grape marc from D3 is used to produce electricity and heat. The residue tar, char and captured particular matter is landfilled. The landfilled char contains sequestered carbon. At a regional level, no nutrients are returned to productive land and so industrial fertilisers are required. Operation extends over 337 days.
Gasification 5	Gasification of the dried grape marc from D2 is used to produce electricity and heat, but where the excess heat from gasification is recycled to the drying plant (i.e., this becomes a more integrated process) to reduce the fraction of dried grape marc that needs to be combusted in order to supply the heat for drying. The result is more dried grape marc entering the gasification plant, which produces more electricity.
Gasification 6	Gasification of the dried grape marc from D3 is used to produce electricity and heat, but where the excess heat from gasification is recycled to the drying plant (i.e., this becomes a more integrated process) to reduce the fraction of dried grape marc that needs to be combusted in order to supply the heat for drying. The result is more dried grape marc entering the gasification plant, which produces more electricity.
Pyrolysis 1	Pyrolysis of the dried grape marc from D1 is used to produce biochar and heat. The biochar contains sequestered carbon and retains some fertiliser nutrient value. Biochar can be sold for a range of uses. At a regional level, the missing fertiliser nutrient value not returned to soil must be replaced by industrial fertilisers.
Pyrolysis 2	Pyrolysis of the dried grape marc from D2 is used to produce biochar and heat. The biochar contains sequestered carbon and retains some fertiliser nutrient value. Biochar can be sold for a range of uses. At a regional level, the missing fertiliser nutrient value not returned to soil must be replaced by industrial fertilisers.
Pyrolysis 3	Pyrolysis of the dried grape marc from D3 is used to produce biochar and heat. The biochar contains sequestered carbon and retains some fertiliser nutrient value. Biochar can be sold for a range of uses. At a regional level, the missing fertiliser nutrient value not returned to soil must be replaced by industrial fertilisers.
Pyrolysis 5	Pyrolysis of the dried grape marc from D2 is used to produce biochar and heat, but where the excess heat from pyrolysis is recycled to the drying plant (i.e., this becomes a more integrated process) to reduce the fraction of dried grape marc that needs to be combusted in order to supply the heat for drying. The result is that drying requires less energy, and so more dried grape marc is produced, and consequently more biochar is produced.
Pyrolysis 6	Pyrolysis of the dried grape marc from D3 is used to produce biochar and heat, but where the excess

	heat from pyrolysis is recycled to the drying plant (i.e., this becomes a more integrated process) to reduce the fraction of dried grape marc that needs to be combusted in order to supply the heat for drying. The result is that drying requires less energy, and so more dried grape marc is produced, and consequently more biochar is produced.

Table 3.27 Comparison among three drying cases

			Drying 1	Drying 2	Drying 3
Outputs	Grape marc product	tonne, 20%MC	12,695	12,695	20717
	Ash	tonne	409	409	181
	Effluent	m^3			24,566
Dryers		Unit size	12×800m²	3×800m²	1×800m²
Costs					
	Capital costs*	k$	85,399	35,699	18,353
	or**	k$	42,406	11,885	5,103
	O&M costs	k$	9,750	4,909	2,802
	or	k$	5,020	2,289	1,345
Revenue	Break-even revenue	k$	13,308	6,337	3,537
	or	k$	6,649	2,764	1,550

* based on the estimated cost from Matches 2014

** based on the dryer vendor’s cost

Table 3.28 Comparison among three combustion for power generation cases

			Combustion 1	Combustion 2	Combustion 3
Outputs	Electricity	MWh	11,136	11,136	18,142
	Ash	tonne	729	729	704
Costs	Capital costs*	k$	111,570	61,870	44,524
	or**	k$	68,577	38,056	31,274
	O&M costs*	k$	11,093	6,252	4,145
	or**	k$	6,363	3,632	2,688
Revenue	Break-even revenue	k$	15,556	8,727	5,926
	or	k$	9,039	5,155	3,939

* based on the estimated cost from Matches 2014

** based on the dryer vendor’s cost

Table 3.29 Comparison among various gasification cases

			Gasification 1	Gasification 2	Gasification 3	Gasification 5	Gasification 6
Outputs	Electricity	MWh	6,941	6,941	11,296	12,742	14,658
	Heat	GJ	47,865	47,865	69,111		16,770
	or	tonne water	152	152	220,082		53,400
	Char	tonne	1,337	1,337	2,141	2,467	2,882
	Tar	tonne	21	21	35	40	47
Costs	Capital costs*	k$	157,022	107,322	89,976	139,259	103,965
	or**	k$	114,029	83,508	76,726	115,445	90,715

	O&M costs*	k$	10,973	6,132	4,025	6,797	4,488
	or**	k$	6,243	3,512	2,568	4,177	3,031
Revenue	Break-even revenue	k$	17,254	10,425	7,625	12,367	8,647
	or	k$	11,268	6,852	5,638	8,795	6,660

* based on the estimated cost from Matches 2014

** based on the dryer vendor's cost

Table 3.30 Comparison among various thermal valorization cases

			Pyrolysis 1	Pyrolysis 2	Pyrolysis 3	Pyrolysis 5	Pyrolysis 6
Outputs	Biochar	tonne	3500	3500	5,713	5,833	7,689
	Heat	GJ	14,688	14,688	21,458		
	or	tonne water	41,820	41,820	68,331		
Costs	Capital costs*	k$	98,248	48,548	36,692	54,146	41,180
	Or**	k$	55,255	24,734	23,442	30,332	27,930
	O&M costs*	k$	10,353	5,512	3,821	5,914	4,180
	Or**	k$	5,623	2,892	2,364	3,294	2,723
Revenue	Break-even revenue	k$	14,283	7,454	5,289	8,080	5,828
	or	k$	8,288	3,881	3,302	4,507	3,841

* based on the estimated cost from Matches 2014

** based on the dryer vendor's cost

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Section 4

Detail Report

Environmental Analysis by Carbon Footprint

Contents

Abstract

About 80% of New Zealand's wine is made in Marlborough and ~ 70,000 tonnes of grape marc (GM) is generated annually as a waste stream from winemaking in this region. However, there is no standardised post-treatment practice and mismanagement has potential to cause environmental damage and threaten the sustainability reputation of winemaking in the region. This study investigated the potential of repurposing GM in order to mitigate environmental damage with a particular focus on climate change. The global warming potential (GWP_{100}) of three different thermal treatments (combustion, gasification and pyrolysis) for grape marc waste was estimated and compared with the of windrow composting in the Marlborough region of New Zealand. The functional unit (FU) was defined as "the management of 1 tonne of fresh grape marc". The study boundaries included the transportation of the fresh grape marc to a centralised location for processing, the greenhouse gas emissions associated with each system, and the transportation of the treated grape marc back to its original location.

The results show that the gasification option yields the highest net carbon offset at −152 kg CO_2 eq./FU (the negative sign indicates carbon credits). This is largely due to displaced use of coal for heat and power generation but does require actual displacement of coal by a "first mover". If coal displacement is not an option, then pyrolysis treatment offers the highest carbon offset due to the high yield of biochar which provides long term carbon storage (leading to a net carbon offset of −69 kg CO_2 eq./FU); the biochar also contributes to improvement of the soil.

The combustion option results in a net carbon offset of −89 kg CO_2 eq./FU provided that use of coal for heat is displaced. However, when coal displacement is not applicable, this system becomes a net carbon emitter (43 kg CO_2 eq./FU) and no longer a sustainable solution.

A sensitivity analysis was undertaken to assess the influence of a change in moisture content (MC) of the fresh grape marc on the final carbon footprint for the three thermal treatments. This mainly affects the energy consumption needed for drying. All the thermal treatments will be net carbon emitters when the moisture content of the raw grape marc is at 75% or above (assuming the generated heat and power displace coal-fired heat and power); when displacement of coal does not take place, the gasification treatment option becomes a net carbon emitter at 68% MC, the pyrolysis treatment option becomes a net carbon emitter at 75% MC and the combustion treatment continues to be a carbon emitting process regardless of its moisture content. Another sensitivity analysis showed the effect of the amount of methane released based on changes in composting practice (well-managed versus mismanaged). For the mismanagement modelling, it was assumed that no methane oxidation occurs during the active period of composting, and that the net carbon footprint increased to 83 instead of 20 kg CO_2 eq./FU. It was found that the net carbon footprint of the thermal treatment options is significantly sensitive to this parameter, albeit that it is a property of the displaced composting process rather than the thermal treatment processes themselves.

4.1 Introduction

Marlborough is the largest wine producing region in New Zealand with around 26,000 ha of wine vineyards, accounting for 68% of New Zealand's total area in vineyards [1]. A significant amount of grape marc (GM) is generated as a by-product with an average between 65,000 − 73,000 tonne annually [2]. Mismanagement of this GM has potential to negatively impact on the regional environment and this poses a threat to the perceived sustainability of New Zealand's wine makers. In this research, therefore we investigated three different thermal treatment solutions (combustion, gasification and pyrolysis) that offered complete elimination of the generated GM plus added value by-products. The study assessed the carbon footprint (measured as GWP_{100}) and compared them with the carbon footprint of well-managed windrow composting of the GM. The study included transportation of the fresh GM to a centralised location for processing, the emission associated with each system and the transportation of the treated grape marc back to the original location.

4.2 Brief on composting

Composting is a biological degradation of organic matter under aerobic conditions. Bacteria, fungi and other microorganisms break down organic materials while consuming oxygen (O_2) and releasing carbon dioxide (CO_2), heat and water, a generalised equation is shown in Eq.(4.1); [3]. The final product is a disinfected, nutrient-rich and stable product know as compost [4].

$$\text{Fresh organic matter} + O_2 \longrightarrow \text{Humus-like-substances} + CO_2 + H_2O + \text{heat} + \text{mineral product} \qquad (4.1)$$

The four stages (initial stage, mesophilic stage, thermophilic stage and curing stage) of the composting process are shown in Figure 4.1. The initial stage is where mesophilic microorganisms break down starch, sugar and proteins resulting in temperature increase due to pathogen destruction. During the thermophilic stage, most of the organic matters (i.e. fats and lignin) are consumed; thus, most of the carbon-containing compounds are being degraded. When the temperature drops to ~ 50 ˚C the mesophilic stage starts with more lignin and protein degradation to generate the precursors of humic substances. During this stage the degradation activities decline which is indicated by the decrease in temperature and in the carbon degradation rate. The curing stage is where the final conditioning of the occur, this step is aimed to improve the product quality and deactivate the microbial activities by lowering oxygen supply [3-5].

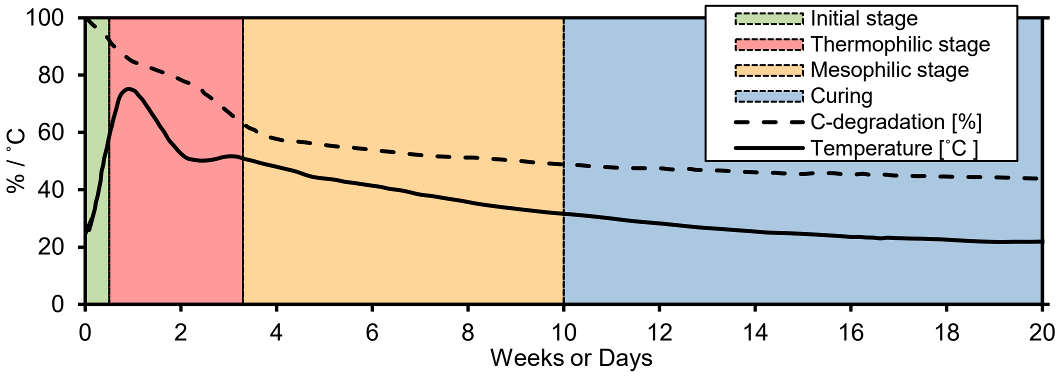

Figure 4.1: **The four stages of composting process, the composting duration depends on the composting conditions; small particle size, frequent aeration (every 1 – 2 days), higher core temperature and right level of moisture content all will help to rapidly compost the material in the shortest time, modified from [5].**

Composting is a sensitive process which is affected by the pile temperature, oxygen level in a pile, pH level, carbon to nitrogen ratio (C/N) and moisture content of the composted feedstock. These key factors must be managed in order to achieve the highest degradation rate; Table 4.1 shows the key parameters and their optimum ranges for an effective composting process.

Table 4.1: Literature overview of optimal composting parameters.

Parameter	Optimum range	Source
Temperature	43 – 66 °C	[6-8]
C/N ratio	20 – 50:1	[9, 10]
pH	5.5 – 9.0	[11, 12]
Moisture content (MC)	40 – 75%	[13, 14]
Oxygen level*	> 5%	[4, 15]

*The oxygen level is represented by free air space (FAS).

4.2.1 Composting technologies

Composting technologies are classified into nonreactor and reactor processes. A brief summary of the most common technologies that is currently in use are shown in Table 4.2.

Table 4.2: **Summary of the common composting technologies in use, adopted from [16]**

	System	Technology	Description	Advantages	Disadvantages
Non-reactor processes	Open piles (heap)		Unmanaged heap of various materials left to compost naturally	Simple and cheap; good for relatively stable waste with few odours	Poor moisture control; limited to small size; not suitable for commercial applications; poor ventilation.
	Windrows (turned)	Straddle turners	Turning blades moves along the windrow for mixing and turning the compost; where the window stays in place.	Relatively cheap; no complexity involves; good control of moisture and temperature.	Fuel intensive, the windrow size is limited by the turner dimensions; heat and moisture loss if not monitored.
	Windrow (forced aeration)	Static piles (open air)	For open or enclosed piles, the windrow is placed on a perforated base where air is drawn through the piles by mean of suction.	Very good control over the composting conditions; odour is relatively contained.	high operating cost for large facility; drainage may case issues to the pumps; regular maintenance; risk of developing pathogenic zones in the centre when temperature is not high enough due to the lack of turning.
		Contained	Generally, material piled between walls in a contained environment.	Suitable for protein rich materials; very good odour control.	Expensive capital cost; evaporative loss; development of anaerobic zones; difficulty of loading/ unloading
Reactor processes		Tunnels	Long fabricated tunnels usually 6 m wide and 2 m high; materials move along a moving floor and agitated.	Compact system; well controlled composting conditions; Continuous process	Complex system; expensive
		Rotating drum	Long drums up to 50 m long and 3 – 4 m in diameter.	Compact system; well controlled composting conditions; Continuous process	Complex system; expensive
		Cells	Sealed container (~1000 m^3) with no movable parts, air and watering are carefully controlled.	Compact system; batch process; rapid digestion rate within 14 days.	Internal compaction must be avoided; relatively expensive.

4.2.2 *Windrow composting*

Windrow composting was selected as the baseline process for the carbon footprint study due to its popularity, simplicity and low capital expenses. In windrow composting organic waste is placed in windrows and mixed with a bulking agent[1] (i.e. wood chips, biochar or shredded tires). However, based on particle analysis on the tested grape marc with 67% moisture content, 75% of the GM has a mean particle diameter of 6.3 mm and above thus, it was assumed to be suitable for composting without the need to add a bulking agent [17]. The free air space is highly dependent on the moisture content of the raw grape marc, for GM with 67% MC the void space is 27% based on difference between the bulk density from loosely packed and pressed packed samples (appendix 4.6.2, Table 4.14). The windrow pile is typically 1 – 2 m high and 2 – 5 m wide at the base. The windrow is aerated using mechanical turning by a special turners or front-end loader [4, 11].

Depending on the quality of the composting practice, emissions during composting fall into two categories: air emissions and water emissions. For the purpose of this study, water emissions were excluded due to the following assumptions: standard and well maintained composting practises are followed, there is frequent turning of the windrows twice per week which is sufficient to maintain balance between moisture level for microbial performance and ambient evaporation [18], leachate during composting is collected using a special draining system and used to maintain the windrows moisture level (this will avoid additional cost of water use for moisture emendation), and the composting facility is covered to avoid runoff and wetting of the windrows caused by rainfall.

4.2.3 *Degradation rate*

The degradation rate during composting is an important aspect because it determines the amount of time that land is occupied for the composting process. For example, static pile, where there is no mechanical turning, can take up to a year for the compost to stabilise. For windrow composting, the composting time depends upon the conditions listed in Table 4.1. Oxygen or air supply has a significant influence on the composting time, which can take between 12 – 32 weeks with infrequent turning and is reduced to 4 – 16 weeks with frequent turning [19].

For efficient composting it has been assumed that the active composting phase will take ~ 6 weeks with turning frequency of 2 turns per week using a specialized windrow turner. The curing phase is assumed to take a one minimum of one month as recommended by NZS4454 [19]

4.2.4 *Air emissions*

A limited number of studies has investigated the use of GM as an additive to composting of other organic wastes (i.e. manure or municipal organic waste) and none were found investigating the potential emissions from composting GM alone. Therefore, for this study, it was assumed that GM has similar emissions to composting of green waste; literature values for emissions of the major gases during composting of green waste are shown in Table 4.3. In this study, only CO_2, CH_4 and N_2O emissions were calculated from GM composting; the total carbon fraction emitted was modelled as 48% of the biodegradable volatiles solids (BVS). As CH_4 emission values in the literature ranged between 2.1% to 3.3% of the carbon fraction in well managed composting, an average of 2.7% was used; the rest of the carbon was released as CO_2 (97.3%). The nitrogen emitted as N_2O was calculated as 1.8% of the total nitrogen in the BVS, this

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[1] Bulking agent: is an organic or inorganic material with sufficient size used to provide structural support and maintain FAS within the composting matrix.

is based on an average ranging from 0.5% – 3.1% in the literature [20]. The N_2O was estimated based on the atomic ratio of N_2O to N from the nitrogen lost by nitrification and denitrification pathways [21, 22].

Table 4.3: The major gases evolved during aerobic biodegradation.

Feedstock	Technology	Emissions [kg/Mg Fresh waste (FW)]					References
		$^{bio}CO_2 - C$	$^{bio}CO - C$	$^{bio}CH_4 - C$	$N_2O - N$	$NH_3 - N$	
Green waste	Aerated windrow	194	–	0.604	0.178	0.354	[23]
		86 ± 10	0.12 ± 0.06	1.9 ± 0.4	0.05 ± 0.01	–	[24]
		113 ± 14	0.15 ± 0.07	2.4 ± 0.5	0.06 ± 0.03	–	[25]
		235	0.12	4.94	0.05	0.13	[26]
		301 ± 17	–	7.6 ± 0.4	0.18 ± 0.7	2.02 ± 9.4	[27]
Average		**185.8 ± 109**	**0.13 ± 0.04**	**3.5 ± 3.46**	**0.1 ± 0.09**	**0.83 ± 2.57**	
IPCC (2006) Composting		–	–	4 (0.03 – 8)	0.24 (0.06 – 0.6)	–	[28]
This study		225.5 ± 2.1	0.15 ± 0.04	2.28 ± 0.71	0.05 ± 0.06	0.27 ± 0.28	

(bio: biogenic), [23] Composted for 21 weeks at a commercial facility, [24] Ctot: 26.8% db, N_{tot}: 0.56% db, [25] From treating 15,540 Mg/yr Commercial facility, [26] Feed: 14.8 Mg, C_{tot}: 29.05% db, Ntot: 1.07% db, [27] C_{tot}: 54% db, Ntot: 1.8% db

Note: according to the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories report in volume 5, the major greenhouse gases that has been reported from different composting processes are CH_4 *and* N_2O*; the values for CO and* NH_3 *were included in Table 1.3 only for reference, and were excluded from the mass balance of composting in appendix (4.6.5, Table 4.16). The production of CO during aerobic composting declines when composting happens with sufficient oxygen level (Table 4.1), with the assumed turning frequency of the windrows the production of CO assumed to be avoided [29]. The release of* NH_3 *does not contributes to the global warming potential therefore, it was excluded from this study.*

Biogenic emissions are produced from a biological origin (plant and animals). Release of biogenic CO_2 is assumed to make no contribution to global warming because its release does not increase atmospheric concentration of CO_2; in effect this is CO_2 that was in the air relatively recently and whose carbon was fixed into plant material during photosynthesis, and then released again over a short timeframe due to plant decay or respiration (or digestion) by animals after ingesting this plant material. However, the emission of biogenic CH_4 does cause additional warming because CH_4 is a much stronger GHG than CO_2 [30, 31].

Oxidation of the CH_4 produced within the composting pile can occur, reducing the amount of methane emitted to the atmosphere. The oxidation is induced by methanotrophic bacteria during the thermophilic phase of the compost where, according to Jäckel *et.al.*, 46 – 98% of the methane produced was oxidised before it leaves the pile [32]. The oxidation rate of CH_4 is also affected by several factors such as material density, pile dimensions, feedstock type and air pockets. Here, it was assumed that the oxidation activities will reduce with the release of methane to the atmosphere by 98% (i.e. the final release from the compost windrow is 2.28 kg CH_4 × 0.02 = 0.0456 kg CH_4/t raw GM); this is according to the 2006 IPCC guidelines [28] composting guidelines which state that a well-managed composting process should prevent the release of methane. The influence of this assumption was examined in the Sensitivity analysis section.

Note: If the turning frequency is not sufficient, anaerobic pockets will develop within the windrow, which will promote volatile organic carbons (VOCs), a commercial biofilter covers or media can be used to breakdown those VOCs. A biofilter is consists of a microbial biomass layer which is in direct contact with the composted pile, allow them to consume the VOCs; the removal efficiency depending on several parameters can be up to 95% [4]

4.3 Carbon Footprint for Management of Grape Marc

4.3.1 *Goal and scope definition*

The goal of this study was to compare the carbon footprints of repurposing grape marc waste by means of four different treatment options. The baseline scenario is windrow composting of the fresh GM which produces a stable/sanitised fertiliser. The other scenarios are thermal treatment by combustion, gasification and pyrolysis; these options offer a complete elimination of the GM in addition to useful output products such as heat, power and biochar (although there is no biochar from combustion).

4.3.2 *Functional unit (FU)*

The functional unit according to [33], describes the function or service delivered by a system. For this study, the FU was defined as the management of 1 tonne of fresh grape marc.

The moisture content of the fresh GM can vary depending on the pressing efficiency during winemaking (residual juice) and addition/depletion of moisture due weather conditions after pressing (i.e. rainy or dry conditions). For the scenarios, a 67% moisture content (wet basis) was assumed but the influence of this assumption on the results was examined at sensitivity analysis (Section 4.4.5).

Note: The primary characterisation data for grape marc is shown in Table 4.14 in appendix 4.6.2

4.3.3 *System boundaries*

The study started at the point of production of the grape marc. The grape marc was assumed to be transported to one of three collection sites in the Marlborough area as shown in Figure 4.2, and then on to a central processing site (shown with a red outline on Figure 4.2). The average distance travelled by the grape marc was calculated assuming the GM from each region will have one localised point for departure. The marc will travel 6.6 km from Blenheim, 17.4 km from Seddon and 44.7 km from Wairau Valley. The central processing site highlighted in red has a land area of ~4.8 ha (according to Google Maps measuring tool).

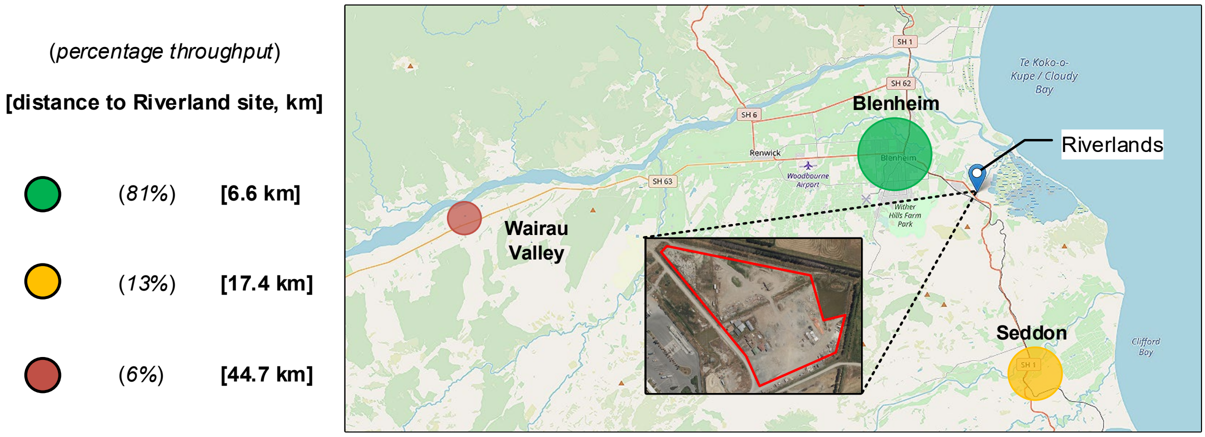

Figure 4.2: Estimation of the GM quantity and travel distances from the wine pressers going to the Riverlands site.

At the central processing area, the GM was either composted or entered one of the three alternative treatment options. These four scenarios each provide different functions and are thus incomparable. In order to make comparisons between the different pathways, system substitution was used to account for these different functions as described below;

Windrow Composting (WC) (**baseline**): fresh GM is formed into windrows and regularly turned so that it decomposes to produce a stable compost which is then applied to the vineyard's soil (Figure 4.3). The additional function of this system is the NPK content of the compost given that this compost contains nutrients that could be taken up by the vines.

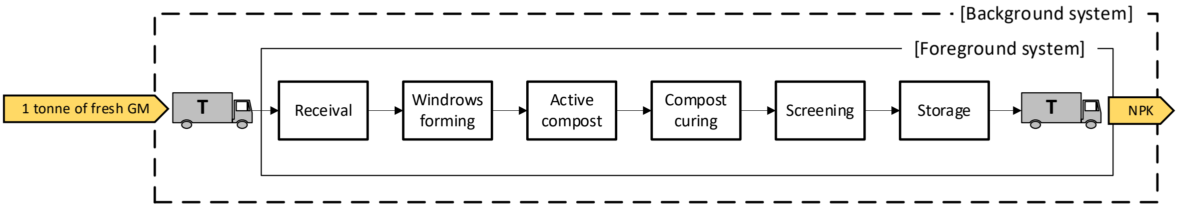

Figure 4.3: Baseline scenario (windrows composting). (T= transport)

Combustion (CB): The received GM is dried from 67% down to 20% MC using indirect dryers. From then, the dried GM is stored in silos and then consumed over 200 days. About 23% of the dried marc is recycled back and used as a burning fuel for a self-sustained drying system. The rest of the GM is fed and combusted in a boiler to produce steam which is fed into turbines for power generation as shown in Figure 4.4a. The combustion treatment produces only 1% (10 kg per tonne of fresh GM) ash residue which is assumed to be sent to landfill; these transportation emissions were found to be insignificant and were excluded from the analysis. The additional function of this system is electricity which can partly be used to run both the drying and combusting plants. However, to provide equivalent functions to the baseline scenario, it is assumed that the electricity substitutes for conventional electricity generation as opposed to coal-fired generators, and that operation of this plant means there is no need for the composting facility ("baseline scenario" in Figure 1.4b). However, this system will require the addition of commercial NPK equivalent to the baseline scenario and this is added to the system under analysis ("NPK fertiliser production" in Figure 1.4b).

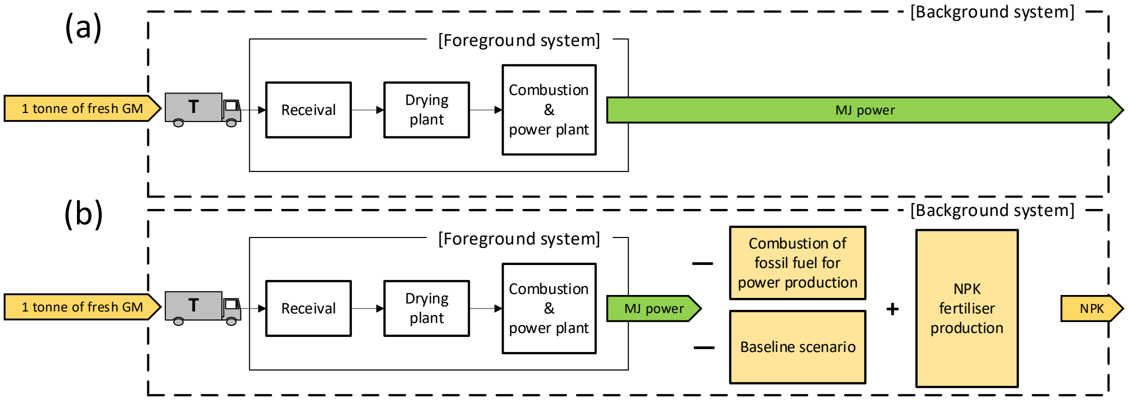

Figure 4.4: **Combustion scenario (T= transport) – (a) Attributional, (b) Consequential**

<u>Gasification (GS)</u>: Storage and drying is the same as the previous scenario. The dried GM is fed into a gasification unit with gas engine to produce heat and power, this type of system is commonly known as combined heat and power plant (CHP). The generation of power is done by passing the produced syngas (~850 °C) through a wet scrubber of contaminants removal and cooling where then the cleaned gas used to run a gas engine. The exhaust gas from the gas engine will be roughly at 300 °C, hence, the sensible heat will be used to produce hot water at 90 °C. The process also produces about 2% biochar and 0.1% tar per tonne of GM. The tar is assumed to be recycled and burned in the gasifier while the char is preserved for landfilling. The additional functions in this system (heat, power and carbon storage value in char) as shown in Figure 4.5a can be used to substitute for combustion of fossil fuel for heat and power production, the baseline case and avoid some addition of nitrogen production as a fertiliser (Figure 4.5b). The net output then will be comparable NPK value with the baseline scenario.

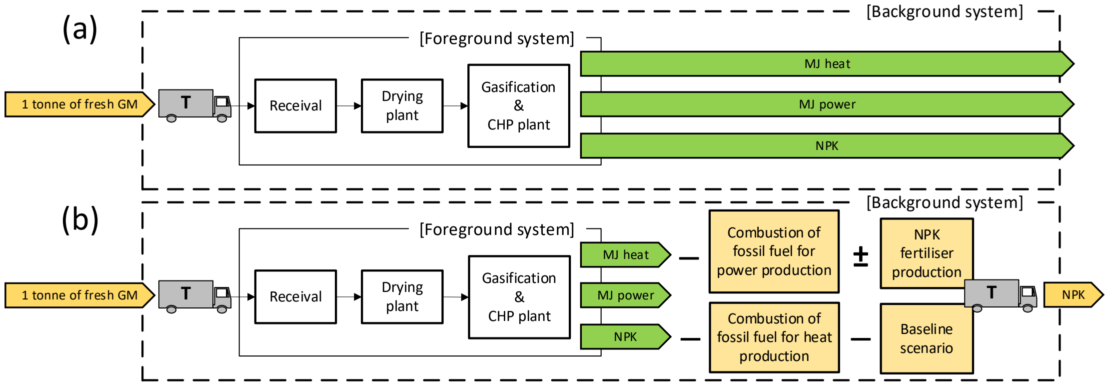

Figure 4.5: **Gasification scenario (T= transport) – (a) Attributional, (b) Consequential.**

Pyrolysis (PY): The dried grape marc is fed into a passive downward feed pot reactor on the outer rim by flue gas that is produced from burning the pyrolysis volatiles generated with the reactor. The main output will be biochar formed at 500 °C and heat as shown in Figure 4.6a. The additional functions of the system will be in form of NPK value from the biochar and hot water at 90 °C produced by the wasted heat from the flow gas leaving the reactor. The emissions from the baseline scenario are avoided, the produced heat will avoid the burn of fossil fuel for heat delivery and the biochar avoid some emission associated with the production of NPK fertiliser (Figure 4.6b). The addition of NPK is the added N-CAN fertiliser. This because the availability of nitrogen in biochar becomes less (in these cases ~10 % is available) as the temperature increase for biochar formation while the rest of nitrogen is locked within the biochar structure [34]

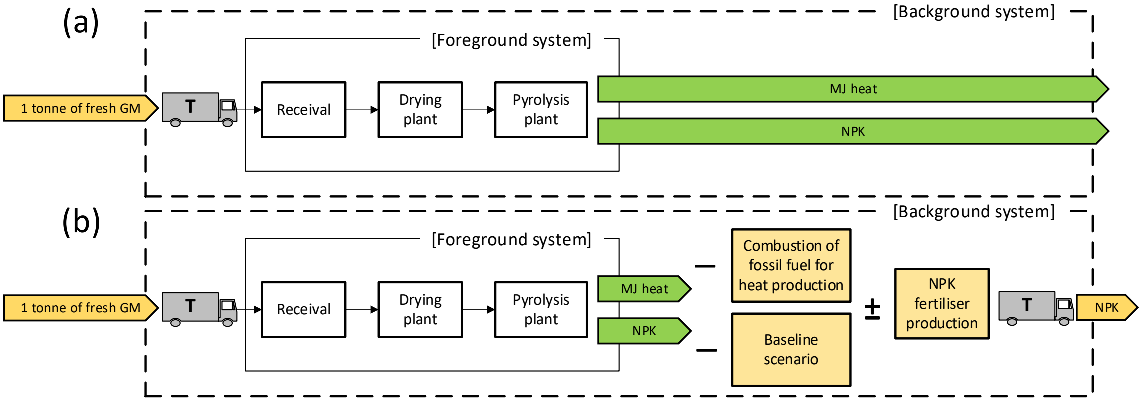

Figure 4.6: Pyrolysis scenario (T= transport) – (a) Attributional, (b) Consequential

Note: *the modelling approach for NPK substitution is done be accounting for the NPK content in the produced biochar based on the bone dried grape marc (i.e. 2.2% N, 0.29% P and 1.9% K). The P and K assumed will remain completely available while only nitrogen content will vary depending quantity of the produced biochar from each treatment scenario.*

Note: all the scenarios were assessed over 50 years' time horizon

4.3.4 *Carbon footprint inventory*

The key data used in the analysis are shown in Tables 1.4 to 1.8.

Table 4.4: Inventory results for all scenarios (per FU unit)

Parameter	Units	WC	CB	GS	PY
Land use	m^2	1.807	0.306	0.269	0.279
Energy consumption					
Fossil fuel (operation) [c]	MJ	33.75	2.71 [d]	2.71 [d]	2.71 [d]
Fossil fuel (transport) [b, c]	MJ	8.2 (×2)	8.2 (×1)	8.2 (×2)	8.2 (×2)
Electricity	MJ	3.35	34.21	34.21	34.21
Air emissions					
CO_2 (biogenic)	kg	226	575	486	224
CO_2 (fossil)	kg	(2.63) *	2.87 [d]	2.87 [d]	2.87 [d]
CO	kg	0.211	-	-	-
CH_4	kg	0.0456	-	-	-
N_2O	kg	0.0341	-	-	-
NH_3	kg	0.268	-	-	-
NOx	kg	(0.127) *	0.001 [a]	-	0.000525 [a]
HC	kg	(0.020) *	-	-	-
SOx	kg	(0.0045) *	-	-	-
$PM_{10-2.5}$	g	(3.6) *	36.3	-	-
Deliverables					
Product	kg	328 $^{\text{compost}}$	-	19 $^{\text{char}}$	50 $^{\text{biochar}}$
NPK (fertiliser)	kg	14.4 $^{\text{NPK}}$	-	-	7.29 $^{\text{NPK}}$
Ash	kg	-	5.8 $^{\text{Dryer}}$ 10.4 $^{\text{CB}}$	5.8 $^{\text{Dryer}}$	5.8 $^{\text{Dryer}}$
Heat recovery	MJ	-	-	683	188
Power recovery	MJ	-	527	328	-

a: Before NO*x* removal
b: Truck type (GLO: Truck, Euro 4, more than 32t gross weight/24.7t payload capacity) (Source: GaBi [35])
(×2) = truck travel in/out of the treatment facility, (×1) = only into the treatment facility.
c: Diesel (42.5 MJ/kg) (AU: Diesel mix at refinery) (Source: GaBi [35])
d: Start up only.
* (Equipment usage)

Table 4.5: Forms of transportation used in the LCA. (GaBi [35])

Transportation form	GaBi model	GWP_{100} excluding biogenic
Truck	GLO: Truck, Euro 4 /24.7t payload capacity	5.68×10^{-3} kg CO_2 eq./kg.km
Rail	GLO: Rail transport cargo - Diesel	2.21×10^{-3} kg CO_2 eq./kg.km
Ship	GLO: Container ship 5,000 to 200,000	7.72×10^{-4} kg CO_2 eq./kg.km

Table 4.6: GWP_{100} due to the production and transportation of commercial NPK – fertiliser to NZ

Fertiliser	GWP_{100} excluding biogenic	Note	Source
N – (CAN 27% N)	7.09 kg CO_2 eq./kg N	--	[36]
P – (RPR 33% P_2O_5)	1.86 kg CO_2 eq./kg P	With 15% active P	[36]
K – (KCl 60% K_2O)	1.12 kg CO_2 eq./kg K	With 50% active K	[36]

Shipping distance was estimated using https://www.searates.com/ from Nebel-DE to Nelson-NZ
Calcium ammonium nitrate (CAN) Reactive phosphate rock (RPR) Muriate of potash (KCl)

Table 4.7: **Forms of fossil fuel used in the LCA. [35]**

Source type	GaBi model	GWP₁₀₀ excluding biogenic
Diesel	AU: Diesel mix at refinery EU-28: Diesel mix at refinery	0.362 kg CO_2 eq./kg diesel 0.495 kg CO_2 eq./kg diesel
Heavy oil	EU-28: Heavy fuel oil at refinery (1.0wt. %S)	0.451 kg CO_2 eq./kg oil
Coal	NZ: Electricity from coal (E3) <LC> NZ: Thermal energy from coal	0.240 kg CO_2 eq./MJ 0.103 kg CO_2 eq./MJ
Grid mix (MBIE)	NZ: Electricity grid mix (MBIE)*	0.038 kg CO_2 eq./MJ

* based on BRANZ study

Table 4.8: **WC construction inventory for the whole facility to process 70,000 tonnes of GM.**

Material	Quantity	GWP_{100} excluding biogenic	Source
Concrete mix (C20/25) [a]	18.41 m^3	303 kg CO_2 eq./m^3	Allied concrete [37]
Reinforcement steel [b]	2.891 t	3.78 kg CO_2 eq./kg steel	BRANZ [38]
Structural steel [b]	544.79 t	2.85 kg CO_2 eq./kg steel	BRANZ [38]
Roofing sheet steel [b]	225.99 t	4.04 kg CO_2 eq./kg steel	BRANZ [38]
HDPE pipes [c]	2.4 t	2.54 kg CO_2 eq./kg HDPE	GaBi [35]
Soil Excavation [d]	89270 m^3	1.14 kg CO_2 eq./m^3	GaBi [35]

a: transport 44.4 t, 18 km (×5) = 76.35 kg CO_2 eq.
b: transport 773.67 t, 203 km (×31) = 2.93×10^5 kg CO_2 eq.
c: transport 2.4 t, 6.3 km = 47 kg CO_2 eq.
d: EU-28: Excavated soil with digger (EN15804 A5)

Table 4.9: **Equipment fuel consumption per 1 tonne of fresh GM**

Equipment	Consumption	Source
Windrow turner	0.54 L diesel/Mg	[39]
Front-end-loader	0.4 L diesel/Mg	[39]
Compost Screener	0.8 kWh/Mg	[39]
Composting facility	0.13 kWh/Mg	[39]
Indirect dryer	0.075 L diesel/Mg 9.5 kWh/Mg	calculated

Diesel density = 0.845 kg/L

4.4 Results of the impact assessment (GWP_{100})

The GWP values used for each of the main contributing GHGs are shown in Table 4.10.

Table 4.10: GHGs and Global warming potential for time horizon of 100 years (IPCC AR5 [40])

Traced gas	GWP$_{100}$ factor [kg CO_2 eq.]	
	Biogenic	**Fossil**
CO_2	0	1
CH_4	28	30
N_2O	265	265

4.4.1 *Carbon footprint results prior to system substitution*

The CF results prior to accounting for additional functions associated with each treatment option are shown in Figure 4.7. The WC scenario generates 20.1 kg CO_2 eq./FU in total; most of the emissions (78.4%) come from the decomposition process which accounts for 15.4 kg CO_2 eq./FU. This is mainly due to the release of N_2O (which represents 83% of the impact from biological degradation); this is assuming the optimistic case for a well-managed composting process (i.e. 98% of methane is oxidation). The use of equipment (i.e. font-end-loader and windrow turner) emit 2.91 kg CO_2 eq./FU due to diesel[2] consumption. The transportation of GM and construction of the WC facility (further analysis in following sections) are 0.87 and 0.84 kg CO_2 eq./FU respectively and only 0.6% of the total emissions are from the use of electricity in the WC.

The GS scenario results in a net carbon credit of − 43 kg CO_2 eq./FU in total, mainly due to carbon sequestrated as biochar Eq.(4.2) [41] with − 47 kg CO_2 eq./FU. The rest of the impacts are related to construction of the plant as the highest with 1.92 kg CO_2 eq./FU and 0.67 kg CO_2 eq./FU as the lowest contributed by transportation (the start-up impact is negligible over the 50 years lifetime as its only occurs once).

$$C_{SEQ} = \left(\frac{1}{\alpha}\right) \times (1 - B_{loss}) \times B_C \times \gamma_B \times CO_2{:}C \qquad (4.2)$$

Where:
C_{SEQ} = CO_2 sequestered in soil for ⩾ 100 years per FU
α = GM to biochar ratio: (GS = 23.5, PY = 8.9)
B_{loss} = biochar loss during transportation = 5%
B_C = carbon content in biochar: (GS = 82.5%, PY = 72%) [42]
γ_B = biochar stability factor: (GS = 75%, PY = 85%) [43]
$CO_2{:}C$ = carbon to CO_2 conversion factor = 44/12

The CB scenario has a total impact of 3 kg CO_2 eq./FU with about 46% of the total impact accounted by the operation of the front-end-loader (1.28 kg CO_2 eq./FU). Construction and transportation emissions account for 1.1 kg CO_2 eq./FU and 0.66 kg CO_2 eq./FU respectively.

Finally, the PY scenario has a total impact of − 100 kg CO_2 eq./FU, where − 94 kg CO_2 eq./FU is carbon stored in biochar and − 10 kg CO_2 eq./FU by NPK substitution. The plant construction adds about 1.4 kg CO_2 eq./FU to the atmosphere followed by 1.28 kg CO_2 eq./FU and 0.69 kg CO_2 eq./FU from the operation of the loader and transportation respectively.

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[2] The diesel emission data were according to (AU: Diesel mix at refinery ts)

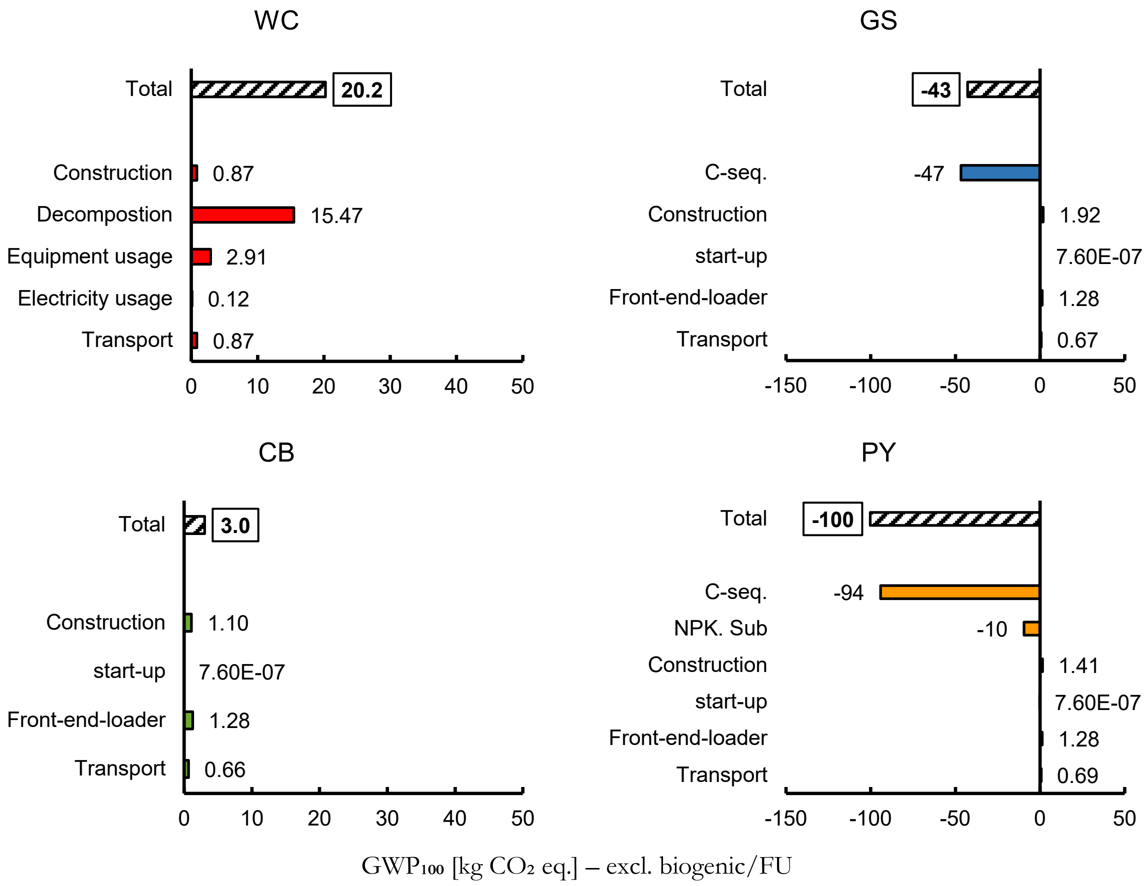

Figure 4.7: Attributional GWP_{100} impact for the studied scenarios; (-ve) impact represents carbon credit.

4.4.2 Transportation impacts

The contribution of GM transportation to the GWP_{100} was modelled based on 'GLO: truck, Euro 4, 24.7t payload capacity' for each scenario. The carbon footprint results for the GM to be delivered to the allocated treatment plant and the output product dispatch are presented in Figure 4.8. The highest impact with 0.66 kg CO_2 eq./FU is associated with transporting the fresh GM from all the localised location to Riverlands site; Blenheim has the largest share (52%) of the GM transported followed by Wairau Valley and Seddon with 26% and 22% respectively.

Dispatching the treated products back the vineyards (i.e. compost or biochar) has a smaller impact on the result. The WC case produces 328 kg of compost per tonne of fresh GM, this resulted in about 0.22 kg CO_2 eq./FU in total after weighting the result for the different destinations (see Figure 4.2). The PY scenario generates about 50 kg of biochar per tonne of GM, which translates to 0.033 kg CO_2 eq./FU in total with the same weighted distribution to the different destinations. Lastly, the GS treatment yields about 19 kg of char, with total GWP_{100} of 0.013 kg CO_2 eq./FU (that is, 61% less than the PY case due to smaller transported weight). The CB plant produces only 10.4 kg per tonne of raw GM, this correlates to 0.004 kg CO_2 eq./FU. This char from GS along with the ash from CB are assumed to return back to where the raw grape marc came from, but their end-life will be in a landfill.

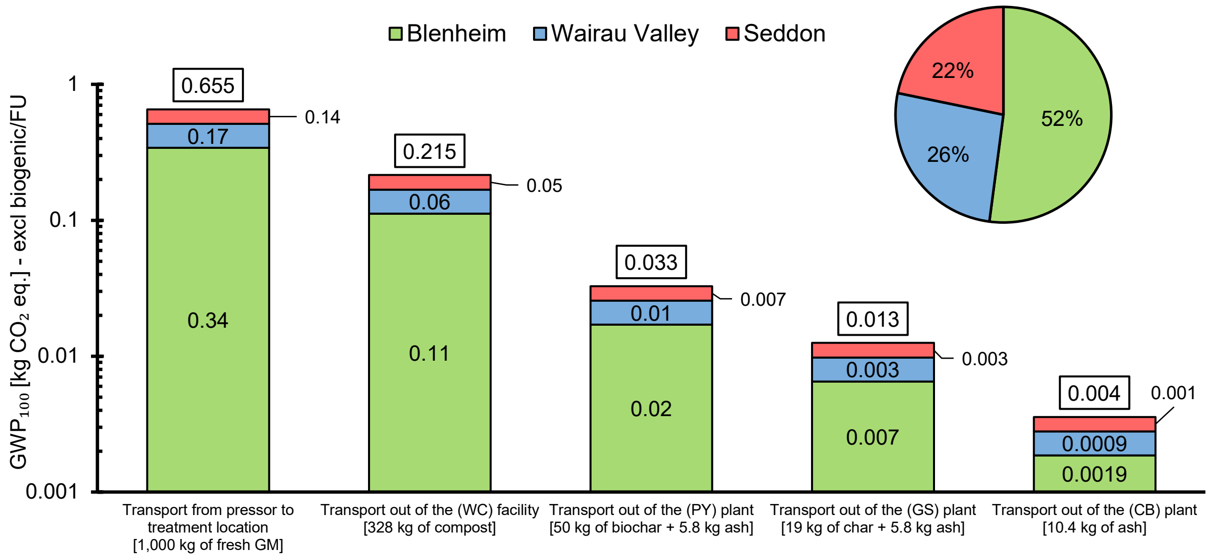

Figure 4.8: Breakdown of the GWP_{100} impact due to transportation in and out of the treatment facilities for each region (Blenheim 2×6.6km, Seddon 2×17.4km and Wairau Valley 2×44.7km); the pie chart represents the total emissions share by location. All the thermal treatment systems embedded the ash produced from the dryer burner included (5.8 kg/tonne of raw GM)

4.4.3 Construction and maintenance impacts

Plant construction and maintenance of the four studied case were modelled with an assumption of a 50 years lifetime for a WC plant and 25 years for a chemical plant (rule of thumb common lifespan for chemical plants). The climate impact arises from construction and maintenance of the plants are expressed per FU and shown in Figure 4.9.

Modelling the impacts for the WC plant was challenging due to the lack of information in the literature around the GWP_{100} of construction of a composting facility. Therefore, a CAD design (Appendix 4.6.4) was developed to roughly estimate the carbon footprint associated with construction material as shown in Table 4.8. The total impact due to WC plant construction and maintenance is 0.865 kg CO_2 eq./FU. The highest impacts are contributed by structural steel with around 54% of the total and 32% from the roofing sheets. Material transportation accounted for 0.084 kg CO_2 eq./FU (~ 10%) and the rest of the of the material collectively accounts for 4 % of the total impact. The construction work and maintenance (excluding excavation work) assumed to allocate 2.5% of the total impacts. The excavation work accounts for about 4% of the total impact, which was calculated based on the total dirt removed and reapplied on the land as a hardfill.

The thermal treatment plants were estimated based on Elsayed and Mortimer [44, 45] and plant scaling Eq. (4.3) [46]:

$$E_2 = E_1 \times \left(\frac{R_2}{R_1}\right)^{0.6} \tag{4.3}$$

Where:
E_2 = Environmental emissions of the larger plant
E_1 = Environmental emissions of the smaller plant
R_2 = MW rating of the larger plant
R_1 = MW rating of the smaller plant

Of all the three thermal treatment plant, the GS plant impact is the highest with a total impact of 1.92 kg CO_2 eq./FU with a significant contribution from boiler and drying plants (0.54 and 0.49 kg CO_2 eq./FU respectively). The structure contributes about 18% of the total impact followed by the gasification plant with 0.31 kg CO_2 eq./FU. The rest of the components account for 13% of the total emissions.

Second after is the PY plant, with GWP_{100} of 1.41 kg CO_2 eq./FU, this is mainly due to the construction of the drying and pyrolysis plants with 0.49 and 0.48 kg CO_2 eq./FU respectively, those combined represent roughly 69% of the total impact. Following that is the boiler and drying plants plant with 0.25 kg CO_2 eq./FU (25%) and 0.12 kg CO_2 eq./FU (~11%) respectively. The rest of the plant inputs accounts for 0.16 kg CO_2 eq./FU (16.4%) of the total impact.

The lowest constructional impact is from the CB plant with 1.1 kg CO_2 eq./FU in total. About 44% of this result is associated with the drying plant and ~27% from power generation plant. The structure accounts for 17% and the rest of the plant shares around 12% of the total GWP_{100}. Overall, the significant impacts from building the drying plant is due to the large number of dryers installed (12 units) in all the thermal plants.

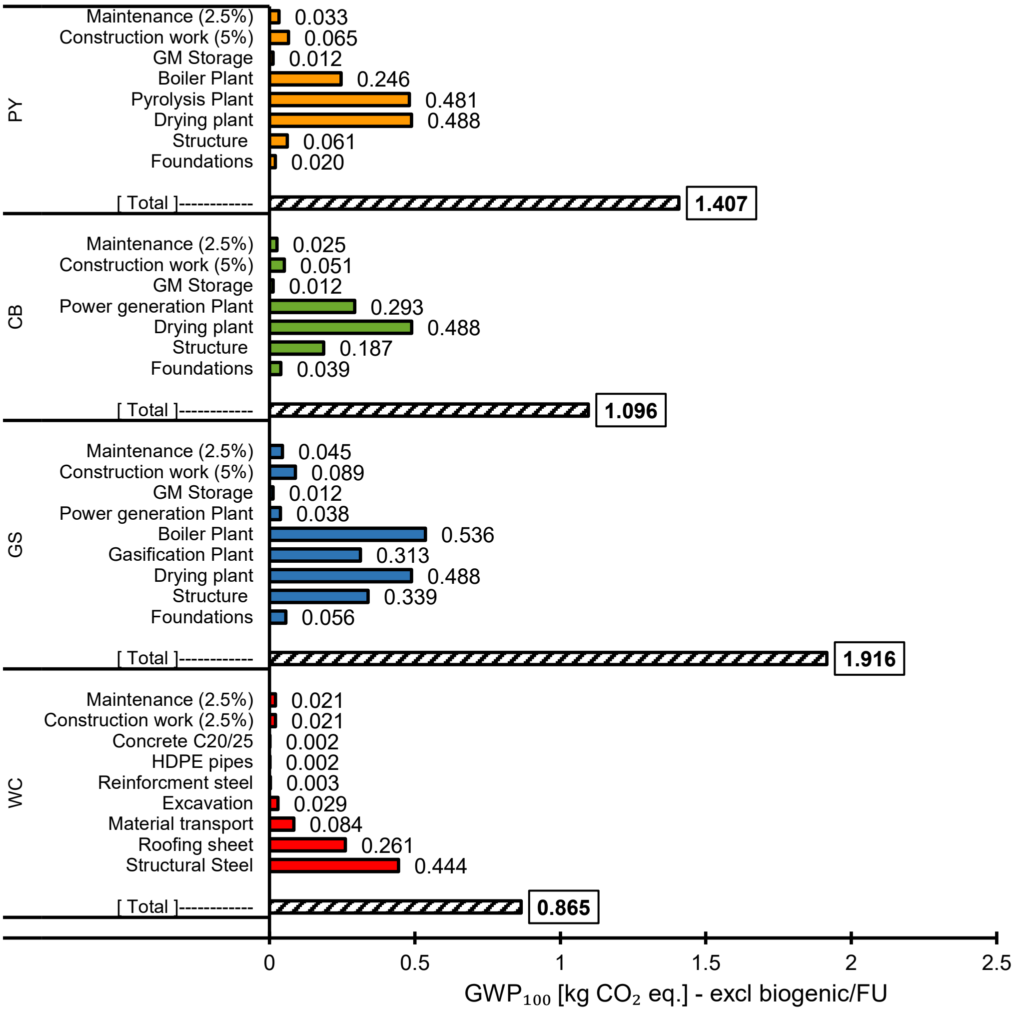

Figure 4.9: **Breakdown of the GWP_{100} impact due to facilities construction over 50 years of the life time of the plants.**

4.4.4 System substitution results

Figure 4.10 shows the GWP_{100} results after accounting for additional functions of the three thermal treatment scenarios by system substitution. The carbon balance of the GS scenario is – 152 kg CO_2 eq./FU in total. This is mainly due to the substitution of coal for energy generation which accounts for ~98% of the total carbon credit. Carbon sequestration results in – 47 kg CO_2 eq./FU. The displacement of the composting activity accounts for – 20 kg CO_2 eq./FU. The need to add additional nitrogen adds 59.9 kg CO_2 eq./FU to achieve an equal nutritional value to the one produced by the WC scenario.

The CB scenario has a net carbon balance of – 84 kg CO_2 eq./FU which is mainly due to coal replacement (– 126 kg CO_2 eq./FU). The addition of nitrogen makes the highest contribution (~ 60 kg CO_2 eq./FU).

The PY case yields – 88 kg CO_2 eq./FU where – 94 kg CO_2 eq./FU is due to carbon sequestration and – 19 kg CO_2 eq./FU for coal replacement; and the NPK offset is –10 kg CO_2 eq./FU. Unlike GS and CB, the process will still need external electricity to run the equipment (i.e. 9.5 kWh for drying and additional 5% assumed for the rest of the plant).

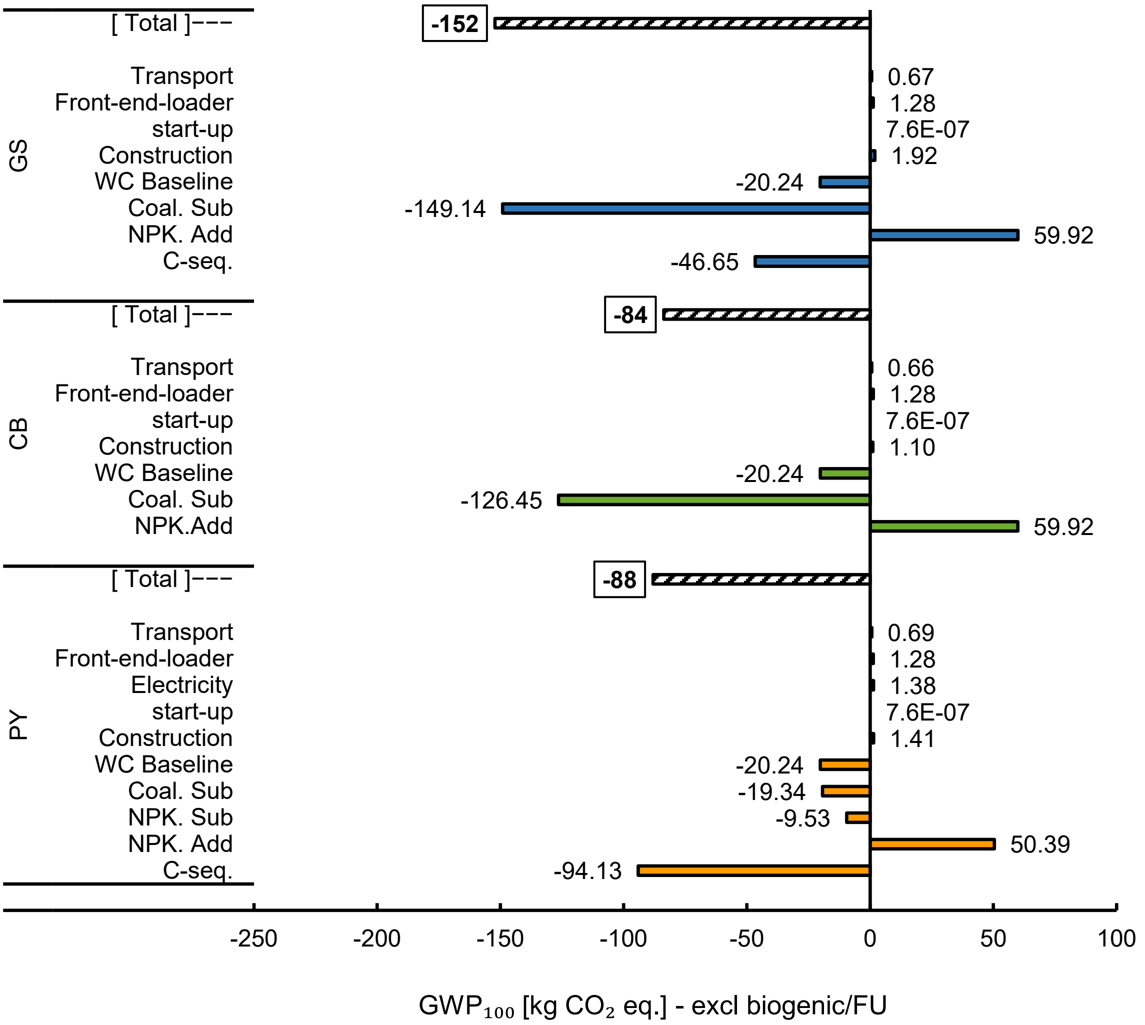

Figure 4.10: Consequential GWP_{100} impact for the studied scenarios; (-ve) impact represents carbon credit

A summary of the results for the system substitution scenarios is presented in Figure 4.11 a and b. It can be seen that the gasification treatment has the best outcome for mitigating climate change when system substitution involves substituting for coal-fired power and heat (Figure 4.11 a); the net carbon benefits for the pyrolysis and combustion treatments are approximately half those of gasification. In Figure 4.11 b, shows the net carbon balance when coal replacement is not an option, and clearly the PY treatment becomes the best option due to the amount of carbon saving.

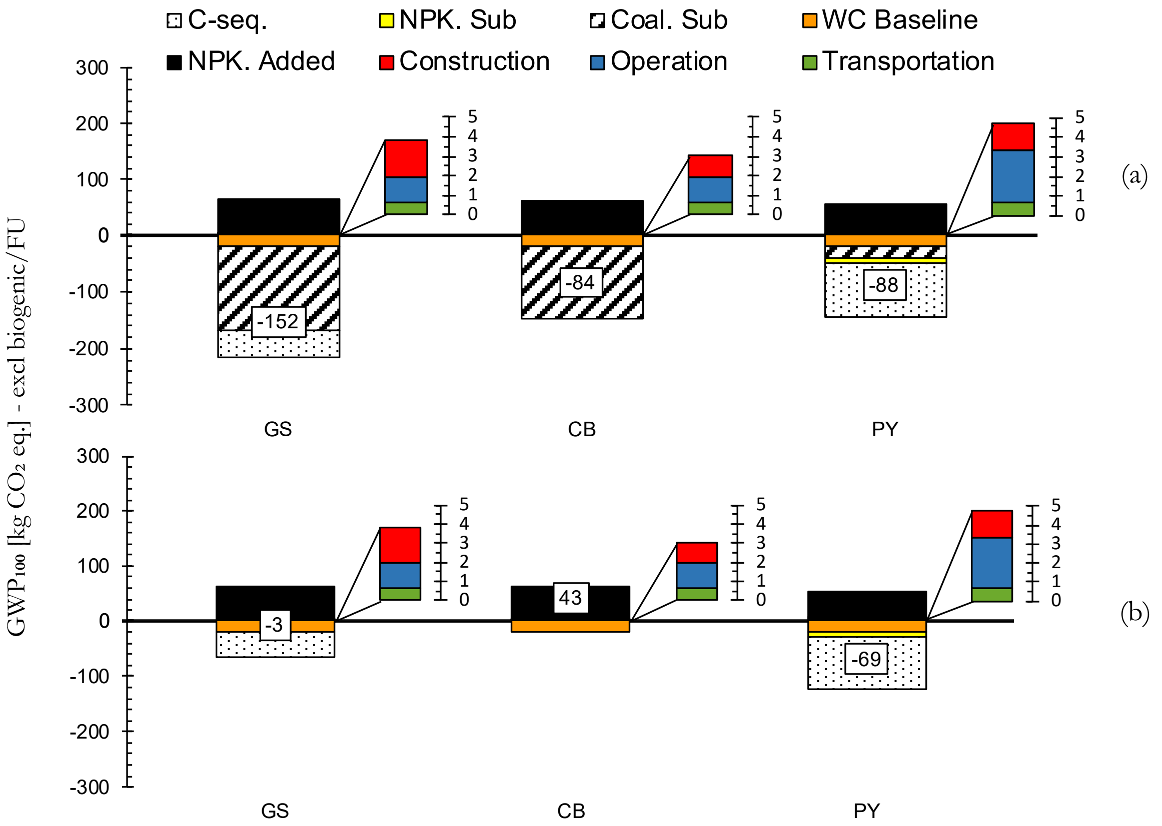

Figure 4.11: **Comparison of the GWP$_{100}$ impacts for the thermal treatment of the consequential scenarios; (a) coal replacement included, (b) coal replacement excluded.**

4.4.5 Sensitivity analysis

Based on the results from the previous section, a sensitivity analysis was conducted to evaluate the effect from varying the following parameters;

- The variation in methane oxidation rate in the baseline scenario,
- The change of moisture content (MC) in the feedstock,
- The substitution of coal for energy production, and;
- The availability of nitrogen in biochar.

Based on the assumption for methane oxidation percentage in section (4.2.4), two alternative scenarios were modelled with 46% oxidation of CH_4 and the case where no oxidation occurs (i.e. 0% oxidation of CH_4), representing various degrees of mismanagement of the composting process (i.e. insufficient turning frequency). In contrast, a well-managed composting process should mitigate the release of CH_4 (98% oxidation of CH_4) (as was modelled in the baseline scenario). Based on the data presented in Table 4.3, at 0% oxidation of methane the GWP_{100} from WC process will rise to 83 compare to 20 kg CO_2 eq./FU when 98% of CH_4 was being oxidised; this in return will improve the net carbon credit from all thermal processes as shown in Figure 4.13 (a). At a lower CH_4 oxidation rate the thermal processes will linearly improve their net carbon footprint.

The initial assessment of the MC from the collected GM showed that the moisture level ranged from 59% up to 67% from the same winery. This is mostly likely because different wineries have different pressing standards and different ways of storing the pressed GM afterwards (i.e. the GM could be stored covered or uncovered).

The sensitivity model accounted for the effects on the number of dryers, drying performance the solid content in GM (this impact the NPK presence), carbon sequestration and energy output. It was found that varying the MC caused a significant changes in energy and resource consumption, and biochar and energy outputs, and this affected the overall carbon balance as shown in Figure 4.13 (b). At the lower MC (59%), the overall GWP_{100} resulted in an increase in the carbon credit for all scenarios; the carbon balance in GS case reduced by about − 70% and a much greater reduction resulted from the PY and CB cases (− 138% and − 107% increase in the carbon credit respectively). In contrast, at 75% MC there was a reduction of the overall carbon credit; for the CB scenario the carbon credit become a carbon burden of 7 kg CO_2 eq./FU (108% increase, mostly due to the addition of NPK fertiliser), followed by the PY scenario with 85% increase and 77% with the GS scenario. On the other hand, the tested range of moisture content from 59% to 75% is within the recommended level for composting (see Table 4.1), thus, no major effects on the composting process is to be expected.

The moisture level in the feedstock plays a significant factor in process chain of the thermal treatment, this is fundamentally to do with ratio of moisture to the total solid content in GM. For instance, a feed with a high moisture content (i.e. 75%) will require more recycled feed to be burned to provide heat in order to dry the feed down to 20% MC, in contrast, if the moisture content in the feed is low (i.e. 59%) less heat for drying is needed to achieve 20% MC at the throughput; this represented by the illustrative examples in Figure 4.12. This in turn will have an impact on the net carbon credit of the thermal treatments as shown in Figure 4.13 (b)

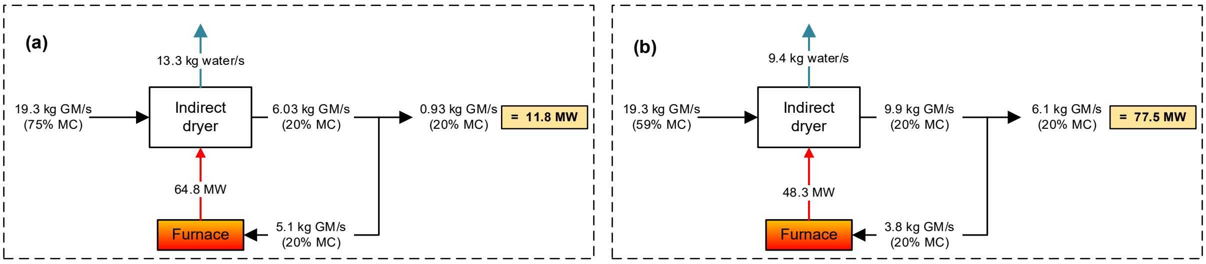

Figure 4.12: **Illustrative example of the effects of MC in fresh GM in relation to the net energy output from the drying process; (a) GM with high MC (75%) and (b) GM with low MC (59%). Note: CV is 12.7 MJ/kg of GM @ 20% MC.**

The third sensitivity analysis investigated the significance of choice of substituted energy system for the scenarios that included generation of electricity and heat. In the first set of results, the displaced electricity and heat were assumed to replace coal. The results in Figure 4.13 (c) show the results if this was not the case and no other energy source was replaced, (using the 67% MC data). It can be seen that the carbon credit for all the scenarios is reduced, and the CB scenario actually becomes a carbon burden (43 kg CO_2 eq./FU). For all three scenarios, the addition of NPK contributes the majority of the carbon burden, and carbon sequestration in biochar is the main contributor to the carbon credit (see Figure 4.13).

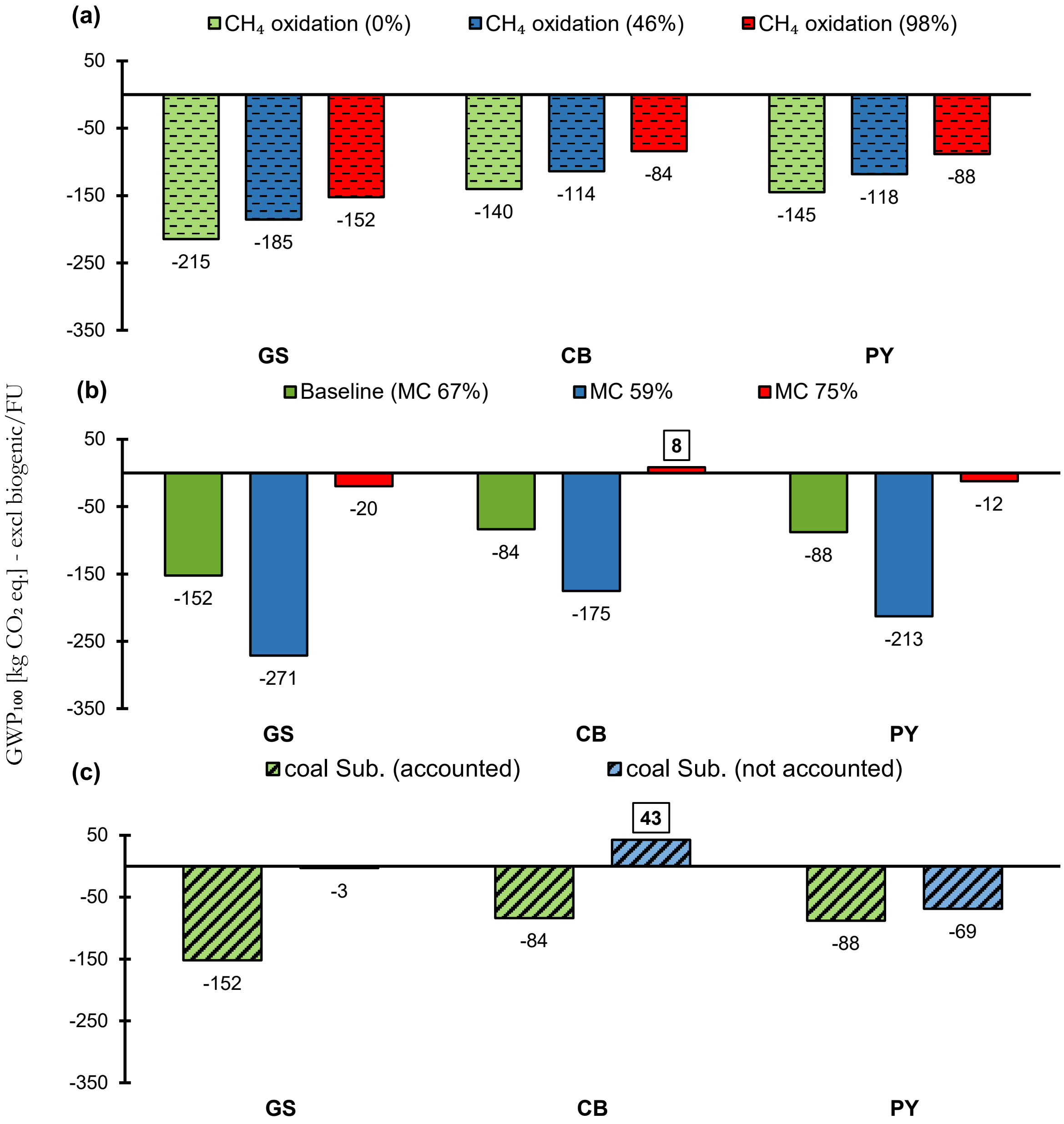

Figure 4.13: **Sensitivity analysis for the consequential scenarios; (a) the effect of CH_4 oxidation during composting on the net carbon footprint @ (67% MC with coal substitution), (b) the effect of the MC variation in the feedstock on the net carbon footprint @ (98% CH_4 oxidation with coal substitution), and (c) the effect of coal substitution on the net carbon footprint @ (67% MC and 98% CH_4 oxidation).**

The analysis also extended to assess the effect of N-CAN addition as a fertiliser based on the nitrogen available in biochar assuming an availability range of ± 10%. The effect of N-CAN addition on the GWP_{100} was found to be ± 0.29 and ± 0.78 kg CO_2 eq./FU for the GS and PY scenarios. Thus, the contribution of nitrogen availability can be neglected.

4.4.6 Discussion

The GS scenario has the highest carbon credit provided that the electricity and gas displace coal-fired energy generation. As there are hospitals and schools in the Marlborough region that currently use coal as a fossil fuel, this energy could be used to displace those energy sources. In addition, the gasification scenario produces biochar that can be used for soil improvement (increase water retention and reduce nutrient leaching) and provides long-term carbon storage. These advantages are only applicable if first mover for coal replacement is available. In contrast, if replacement of coal is not an option then pyrolysis provides the best carbon credits solution.

The CB and PY are relatively similar in term of their carbon credits. The PY scenario additionally provides soil improvement and long-term carbon storage through production of biochar (provided the feedstock moisture content is kept low). The benefit of the CB scenario is solely due to the displacement of coal-fired energy generation. For both these scenarios, their carbon credits are remarkably reduced if there is no displacement of coal-fired energy generation; in the case of the CB scenario, the system becomes a net carbon emitter of (+43 kg CO_2 eq./FU) that is a bit worse than the composting scenario (+20 kg CO_2 eq./FU). In the absence of coal substitution, the PY system has the best carbo footprint amongst the other thermal treatments

To avoid higher moisture levels in the feedstock, regulations and standards could be introduced that require vineyards to manage this feedstock in order to minimise moisture levels. Analysis of the influence of the moisture content of the fresh GM on the final carbon shows that at 75% MC or above all the thermal treatment systems will be net carbon emitters for the scenarios where there is displacement of coal-sourced heat and power (appendix 4.4.5, Figure 4.14 a). In contrast, when coal displacement is excluded from the analysis, the GS treatment option will become a carbon emitter at a MC of 68% or higher (as shown in appendix 4.4.5, Figure 4.14 b). However, the PY treatment option has a higher threshold at 75%. The GS will lose 98% of its carbon credit value which associated with heat and power replacement while the PY will lose only 22% of its carbon credit that accounted for heat replacement. The CB system will continue to be a net carbon emitter regardless of the moisture content. An alternative option is to reduce the feedstock moisture content using a mechanical press as pre-treatment step; which will reduce the load on drying (based on the mass and energy balance in Figure 4.12). However, such a process results in leachate which will then need to be treated.

The GM leachate is high in nutrients which makes it a potential source for environmental damage as shown in Table 4.11. Some parameters from Seddon sewage treatment plant and typical brewing influent were used to draw a prospective comparison with the GM pressed leachate. The numbers suggest that the leachate would need to be treated prior to discharge into local waterways, if regional wastewater plant unable to handle the BOD load (e.g. the wastewater generated from pulp and paper plant is normally treated on-site due to the high BOD loading [not modelled in this study]). The size and technology of the treatment plant is based on the available land area and expected loading rate generated by mechanical pressing.

Table 4.11: **GM leachate characteristics (waterborne material)**

Parameter		Fresh GM	Winery wastewater			SSTP* [47]	BWW* [48]
			Range	(mean)			
COD	[g/L]	154 ± 17.9	0.32 – 269	(15.55)	[49]		2 – 32.5
BOD_5	[g/L]	85	0.125 – 130	(8.86)	[49]	0.002	1.2 – 3.6
TOC	[g/L]	53	0.4 – 2.5	(1.35)	[49]		
TS	[g/L]	32.2 ± 14.8	1.6 – 80	(11.17)	[49]		
TSS	[g/L]	16.2 ± 7.1	0 – 30.3	(0.760)	[49]	0.003	0.2 – 3
TN	[g/L]	3.26	0.0019 – 0.07		[50]	0.00137	0.025 – 0.45
NH_4^+	[mg/L]	581	-			-	5 – 21.6
Dissolved							
CL^-	[mg/L]	41 ± 0.48	-			-	
NO_2^-	[mg/L]	2634 ± 370	-			-	
NO_3^-	[mg/L]	46 ± 31	-			-	
SO_4^{2-}	[mg/L]	549 ± 51	-			-	
PO_4^{3-}	[mg/L]	1680 ± 19	-			-	2 – 35

*SSTP: Seddon sewage treatment plant, BWW: Brewery wastewater

4.5 Conclusion

This study was conducted to explore the carbon footprint associated with repurposing of grape marc. A comparative approach was used to assess the effectiveness of three thermal treatment options: (combustion, gasification and pyrolysis) against a well-managed windrow composting process. It was found that pyrolysis had the best carbon footprint when it substituted for composting at -69 kg CO_2 eq. per tonne of fresh grape marc, when no first mover coal replacement was available. However, when a first mover coal replacement advantage was available, gasification had the best carbon footprint when it substituted for composting at -152 kg CO_2 eq. per tonne of fresh grape marc.

The carbon footprint is highly sensitive to the moisture content of the fresh grape marc; at 75% MC, there is no carbon credit for any of the thermal treatments (for the scenarios where the generated heat and power displace coal-fired heat and power); when coal displacement does not take place, the critical MC reduces to 68% for the GS and 75% MC for the PY treatment options, while the CB will always be a carbon emitter at any MC level. The oxidation of methane during composting makes a potentially big difference to the carbon footprint of composting (20 – 83 kg CO_2 eq./FU), and this is reflected in a change in net carbon footprint of the thermal treatments where they are assumed to displace composting. It is important to note that this change is due to management of the composting process and nothing to do with the thermal processes themselves. Indeed, all the thermal treatments have improved carbon footprints when compared to a mismanaged composting process (with or without coal displacement of generated heat and power), and all the thermal treatments require less land area than the windrow composting process.

4.6 Appendix

4.6.1 *Composting facility capital investment and O&M cost*

The economics for composting is highly variable which require a conceptual design before commencing the process. Here a rough estimation of the capital cost to build a composting facility with variation margin of ± 30% is shown in Table 4.12 based on the conceptual design in appendix (4.6.4). The cost estimation for the facility was based on a similar design from literature; here 18% of the cost is contributed toward excavation and hard filling of the processing area. The leachate system has been included which is common in modern windrow composting plants, the system assumed to retrieve leachate (if any) during composting to be used for maintaining the moisture level of the windrow. The number of windrow turners was assumed according to their turning capacities and turning time (i.e. 70,000 tonnes of GM can be turned within 5 hours). Operation and maintenance cost (O&M) are included.

Table 4.12: Breakdown of capital investment for composting facility.

Item	Unit/Quantity	Cost/unit		Estimated cost			
Site preparation							
Excavation (m^3) [a]	150020	NZD	8.10	NZD	1,215,158		
Hard filling (m^3) [b]	30004	NZD	43.70	NZD	1,311,170		
Leachate system [c]	8	NZD	165,000	NZD	2,544,246		
Building [c]	1	NZD	825,000	NZD	1,590,154		
Equipment							
Windrow turner [c]	3	NZD	330,000	NZD	1,225,799		
Front end loader [c]	3	NZD	297,000	NZD	1,103,219		
Screener [c]	2	NZD	330,000	NZD	817,199		
Sub-total						NZD	9,806,947
General Conditions							
Engineering					10%	NZD	980,695
Overhead					20%	NZD	1,961,389
Contingency					15%	NZD	1,471,042
Total capital						**NZD**	**14,220,073**

a: the area is (485.5×206) m^2 with depth of 1.5 m, cost source [51]
b: 20% of the excavation volume, cost source [51]
c: estimated based on R, van Haaren et al [52]

Table 4.13: Breakdown of the annual O&M cost based on 70,000 tonne of fresh GM

Item	Unit/Quantity	Working hours	Fuel (L/Mg)	Electricity (kWh/Mg)	Unit cost		Sub-total	
Windrow turner	3		0.54		NZD	1.00	NZD	113,400
Front-end-loader	3		0.40		NZD	1.00	NZD	84,000
compost screener	2			0.8	NZD	0.15	NZD	16,800
Composting facility	1			0.13	NZD	0.15	NZD	1,365
Labours	8	2080*			NZD	35.00	NZD	582,400
Maintenance	5% of capital						NZD	711,004
Total O&M							**NZD**	**1,508,969**

*5 days/wk x 52 wk/yr x 8 ppl
Fuel and Electricity consumption is per Mg of fresh GM.

4.6.2 Grape marc (GM) properties

Table 4.14: Grape marc characteristics

Moisture content (MC)	0.67 ± 0.012	(This value depends on the pressing efficiency)
Average bulk density	683 kg/m^3 Void 320 kg/m^3 dw[a]	23%
Average particle size	≥ 6 ± 0.25 mm	(Based on GM skin)
GM composition	Seeds: 23.7% Skin: 74.0% Stalks: 2.3%	
Ultimate analysis	C: 0.475 w/dw N: 0.014 w/dw H: 0.047 w/dw O: 0.432 w/dw Ash: 0.032 w/dw C/N: 33.46 HHV[b]: 17.50 MJ/kg-od[d] LHV[c]: 16.47 MJ/kg-od **$C_{38}H_{46}O_{26}N$**	 (calculated) (based on ultimate analysis)
Proximate analysis	VM[e]: 0.673 w/dw FC[f]: 0.277 w/dw Ash: 0.024 w/dw FC/VM: 0.41	

a: dry weight, b: High heating value, c: Low heating value, d: oven dried @ 105 °C, e: Volatile matter, f: Fixed carbon

4.6.3 Sensitivity analysis breakdown

Table 4.15: Breakdown of the sensitivity analysis results for MC effect (incl. coal offset)

		GS	**CB**	**PY**
MC 59%	Transportation	0.676	0.655	0.712
	Operation	1.3	1.3	2.7
	Construction	3.2	2.0	1.4
	NPK. Added	59.9	59.9	49.8
	WC Baseline	-20.8	-20.8	-20.8
	Coal. Sub	-237.2	-218.9	-33.6
	NPK. Sub	-	-	-10.1
	C-seq.	-78.8	-	-203.6
	Total	**-272**	**-175.2**	**-212.7**
MC 75%	Transportation	0.658	0.655	0.664
	Operation	1.3	1.3	2.7
	Construction	0.8	0.2	0.4
	NPK. Added	59.9	59.9	51.0
	WC Baseline	-20.8	-20.8	-20.8
	Coal. Sub	-49.7	-33.5	-5.1
	NPK. Sub	-	-	-9.0
	C-seq.	-12.2	-	-32.6
	Total	**-20**	**8.4**	**-12.1**
MC 67%	Transportation	0.668	0.655	0.688
	Operation	1.3	1.3	2.7
	Construction	1.9	0.9	1.0
	NPK. Added	59.9	59.9	50.4
	WC Baseline	-20.8	-20.8	-20.8
	Coal. Sub	-149.1	-126.5	-19.3
	NPK. Sub	-	-	-9.5
	C-seq.	-46.7	-	-94.1
	Total	**-152**	**-83.6**	**-88**

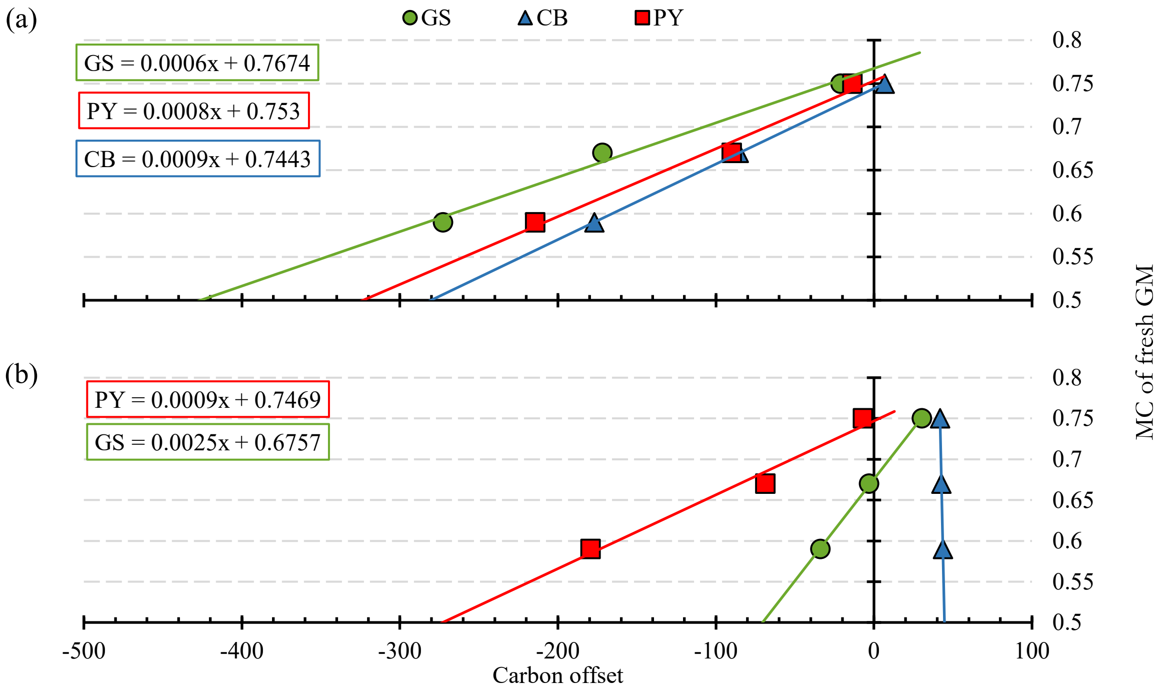

Figure 4.14: MC sensitivity results showing the breakeven points for (a) accounted coal replacement, (b) excluding coal replacement.

4.6.4 *CAD design of the composting facility*

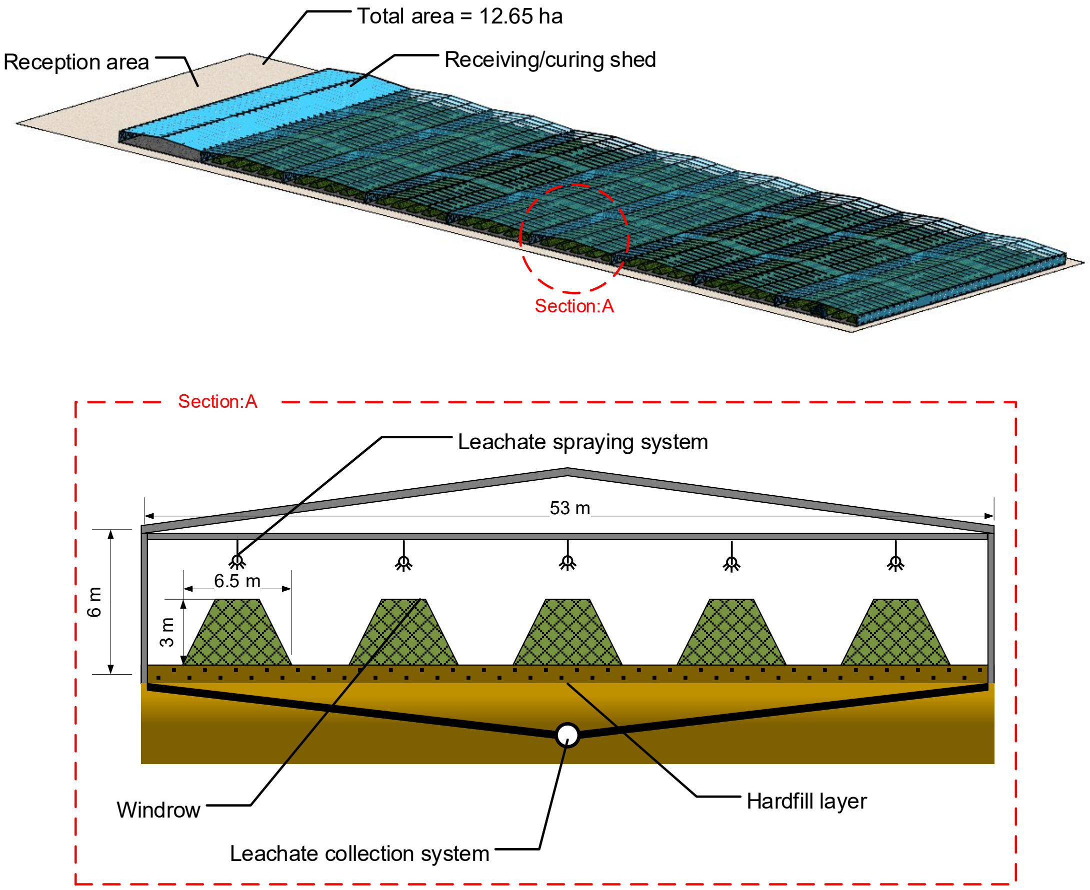

Figure 4.15: CAD design of the windrow composting facility with processing capacity of 70,000 tonnes annually.

4.6.5 Raw data and calculations

Table 4.16: Mass balance for the composting process

		Input (kg/t raw GM)	Output (kg/t raw GM)
Total GM		**1000**	**328.0**
Solid balance			
Biodegradable volatile solids	(BVS)	133.17	--
Non-biodegradable volatile solids	(NBVS)	186.40	186.40
Ash		10.42	10.42
Sub-total		**330.00**	**196.83**
Water balance			
Water in GM	(WGM)	670.00	--
Water produced	(WP)	32.15	--
Water in compost	(WC)	--	131.22
Water vapour	(WV)	38.89	609.82
Sub-total		**741.04**	**741.04**
Air balance			
Air	(due to turning)	5241.98	5319.86
Total		**6313**	**6258**

Notes:

- The biodegradable fraction (ks) is 0.6 of the volatile matter (VM) shown in Table 4.14.
- Water produced is the water of reaction during biodegradation.
- Water vapour is at the start of the process based on the average annual temperature of (13 °C) and relative humidity (RH) of (75%) in Blenheim (Figure 4.16), the saturated vapour pressure is 0.115 kg of water/kg of dry air @ 55 °C. The output water vapour represents the evaporated amount when the windrow is maintained at 55 °C.

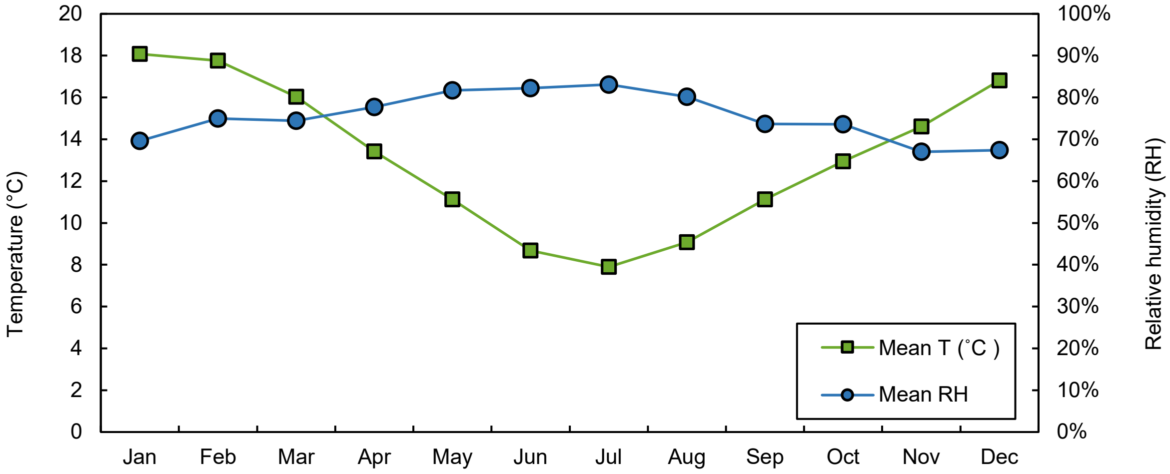

Figure 4.16: Annual climate conditions in Blenheim; annual mean 13 °C and 75% RH [53]

Table 4.17: **Breakdown of the composting biological air emissions in section 4.2.4**

Components flow	Emissions (kg/t raw GM)	Assumptions/comments	References
Non-degradable C	93.537		
C - lost	63.288	48% of BVS	
C - lost as CH_4	1.709	2.7% of degradable C	[20, 24]
CH_4 oxidised	1.675	98% CH_4 oxidised	[32]
C - lost as CO_2	61.579		
N – lost	0.0341	The conversion occurs during the nitrification/denitrification at the curing stage. Only 1.8% of 1.42% N in BVS converts to N_2O.	[21, 26, 54]
CH_4 emitted	0.0456	$(1.709 - 1.675) \times (16/12)$	
CO_2 emitted	225.558		
N_2O emitted	0.0536		
GWP_{100} effect	**Mg CO_2 eq. /day**	**GWP_{100} factor**	
GWP_{100} (CH_4)	1.2759	28	
GWP_{100} (N_2O)	14.1954	265	
Total GWP_{100}	**15.348**		

Table 4.18: **Breakdown of the air emissions for composting machinery**

Pollutant	Front-end-loader	Windrow turner
HC (kg/Mg)	0.00373	0.02
CO (kg/Mg)	0.01278	0.05
NOx (kg/Mg)	0.05170	0.08
PM_{tot} (kg/Mg)	0.00359	--
SOx (kg/Mg)	0.00445	--
CO_2 (kg/Mg)	1.12	1.51

4.6.6 Supplementary data

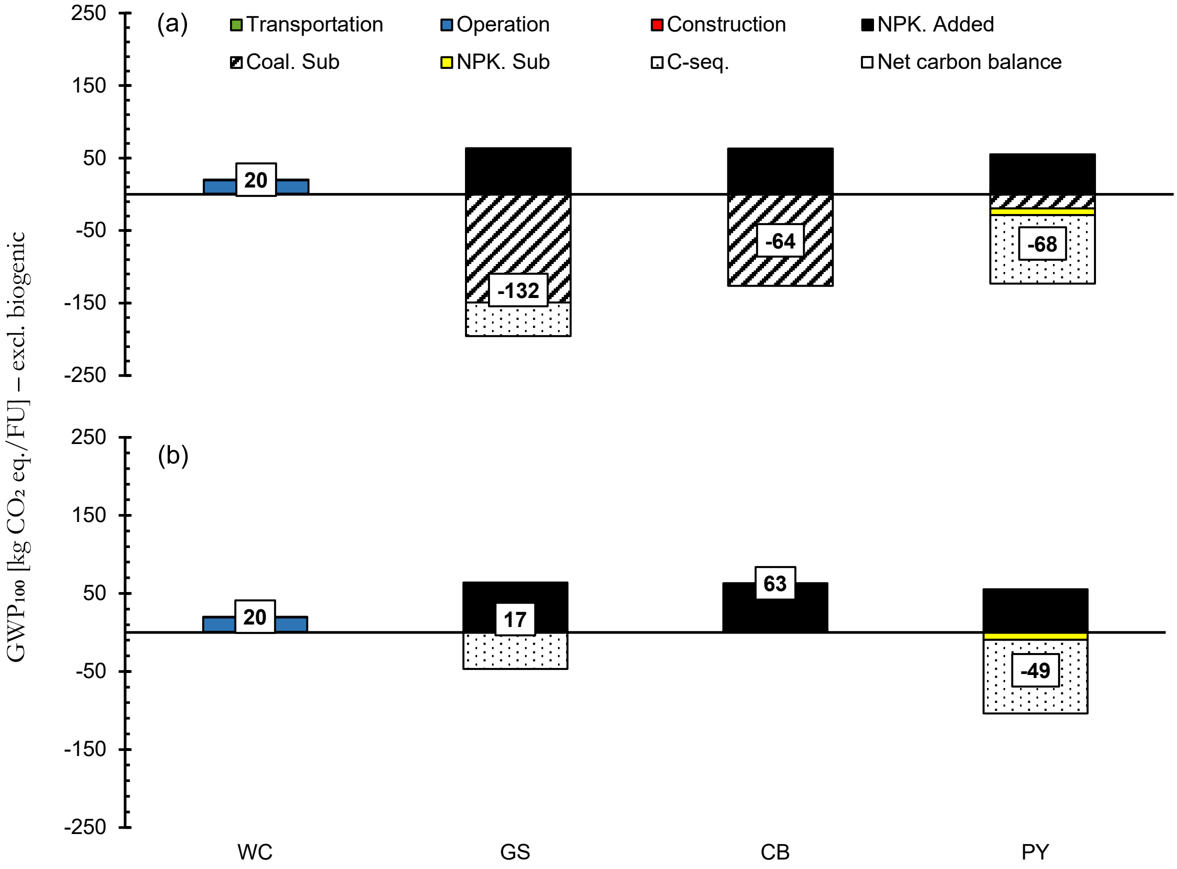

Figure 4.17: Comparison between all the four scenarios (a) the scenarios with coal replacement (b) the scenarios without coal replacement.

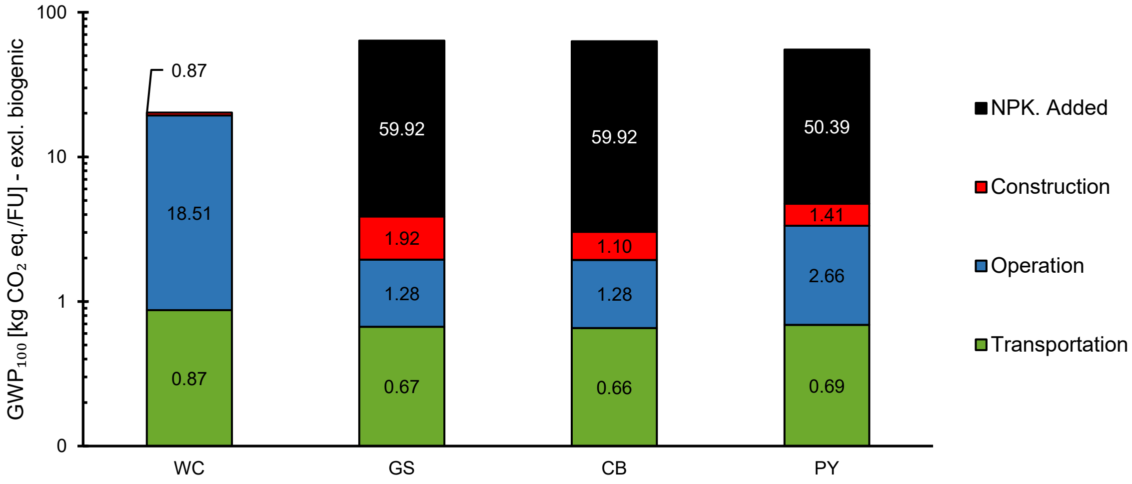

Figure 4.18: Breakdown of the carbon emitters for all the scenarios.

4.6.7 Thermal treatments (improved scenarios)

In this section, assessment of the carbon footprint for the improved thermal treatment scenarios (combustion 3, gasification 3&6 and pyrolysis 3&6). This covers, transportation, construction and maintenance and system substitution in comparison to the previously discussed thermal treatments in this report.

Note: the original scenarios in this report are labelled as CB.1, GS.1 and PY.1

4.6.7.1 Transportation impacts

The transportation of solid residues (i.e. char, biochar and ash) increase their carbon footprint due to the increase in produced weight (distances still the same) as shown in Figure 4.19. The CB.3 scenario had only a slight increase compare to CB.1. The GS and PY scenarios are shown much greater impacts.

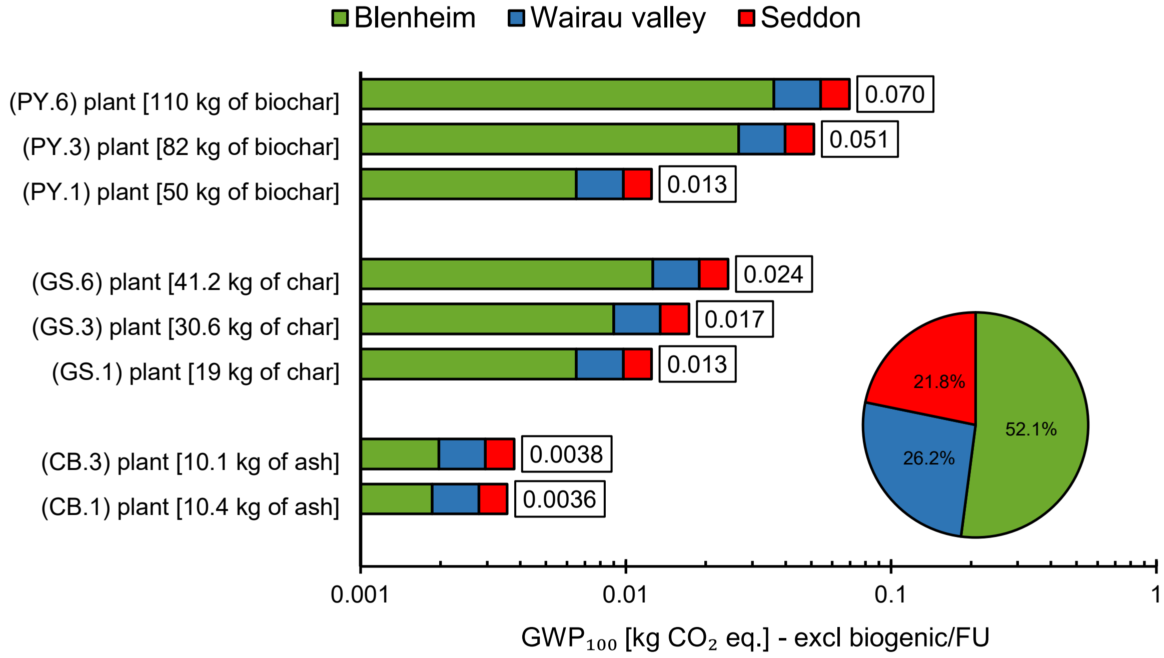

Figure 4.19: **Breakdown of the GWP_{100} due to transportation of the solid residue from each thermal treatment plant back to the original region; (CB.1, GS.1 and PY.1) are the processes prior to the improvement. The pie chart represents the portion of solid residue by region (Blenheim 6.6km, Seddon 17.4km and Wairau Valley 44.7km)**

4.6.7.2 Construction and maintenance impacts

Combustion scenarios

The CB.3 plant has about half the carbon footprint of the CB.1 this is mainly due to reduced number of dyers from 12 to 1 dryer. The impact from the drying plant in CB.3 is roughly 75% less than the CB.1.

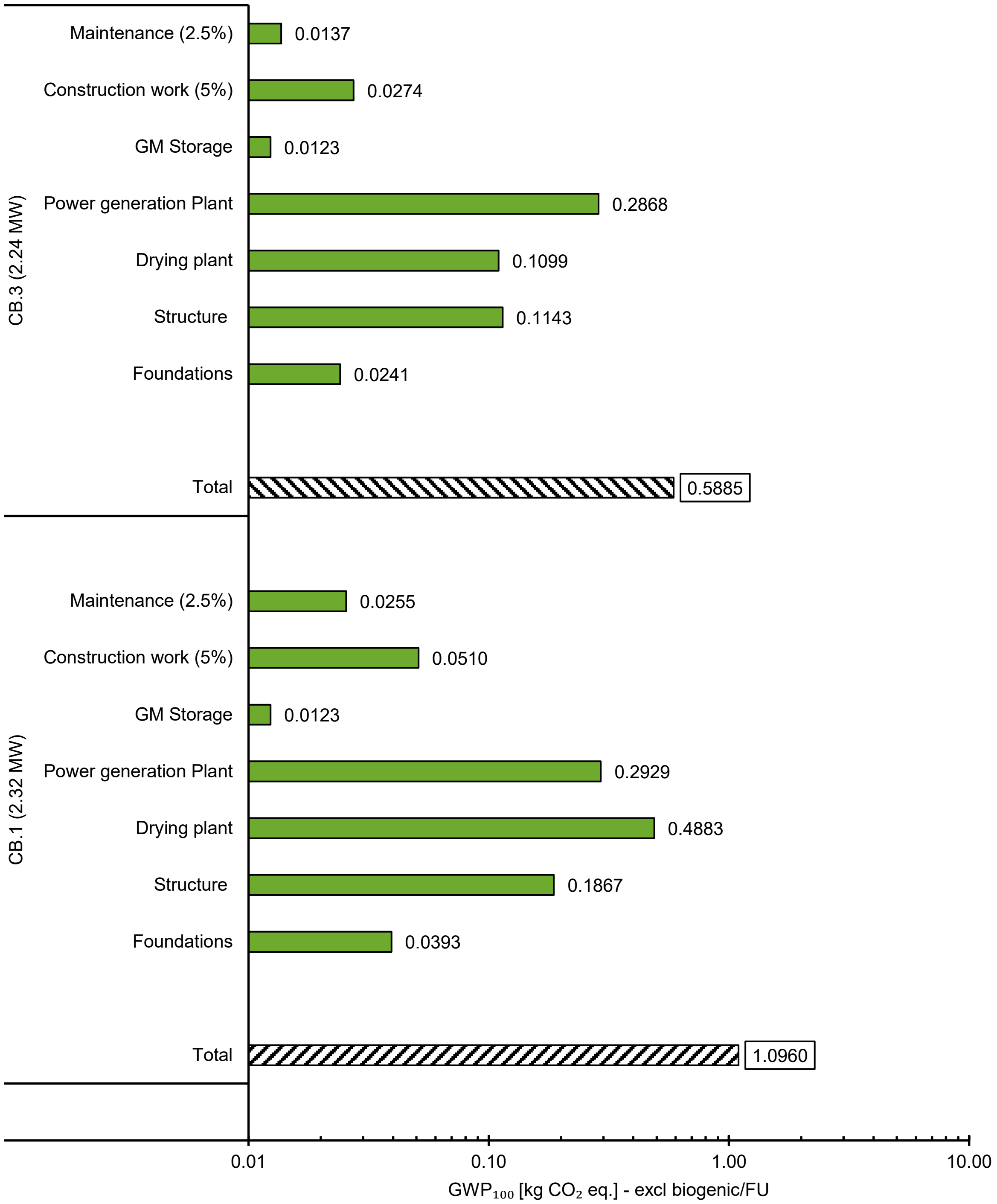

Figure 4.20: Breakdown of the GWP_{100} of the combustion plants 1 and 3 due to construction over 50 years of the life time of the plants

Gasification scenarios

The gasification scenarios (GS.3 and GS.6) have significantly improved their carbon footprint compared to the GS.1 plant. This reduction GWP_{100} is mainly associated with reduced size of the drying plant (Figure 4.21

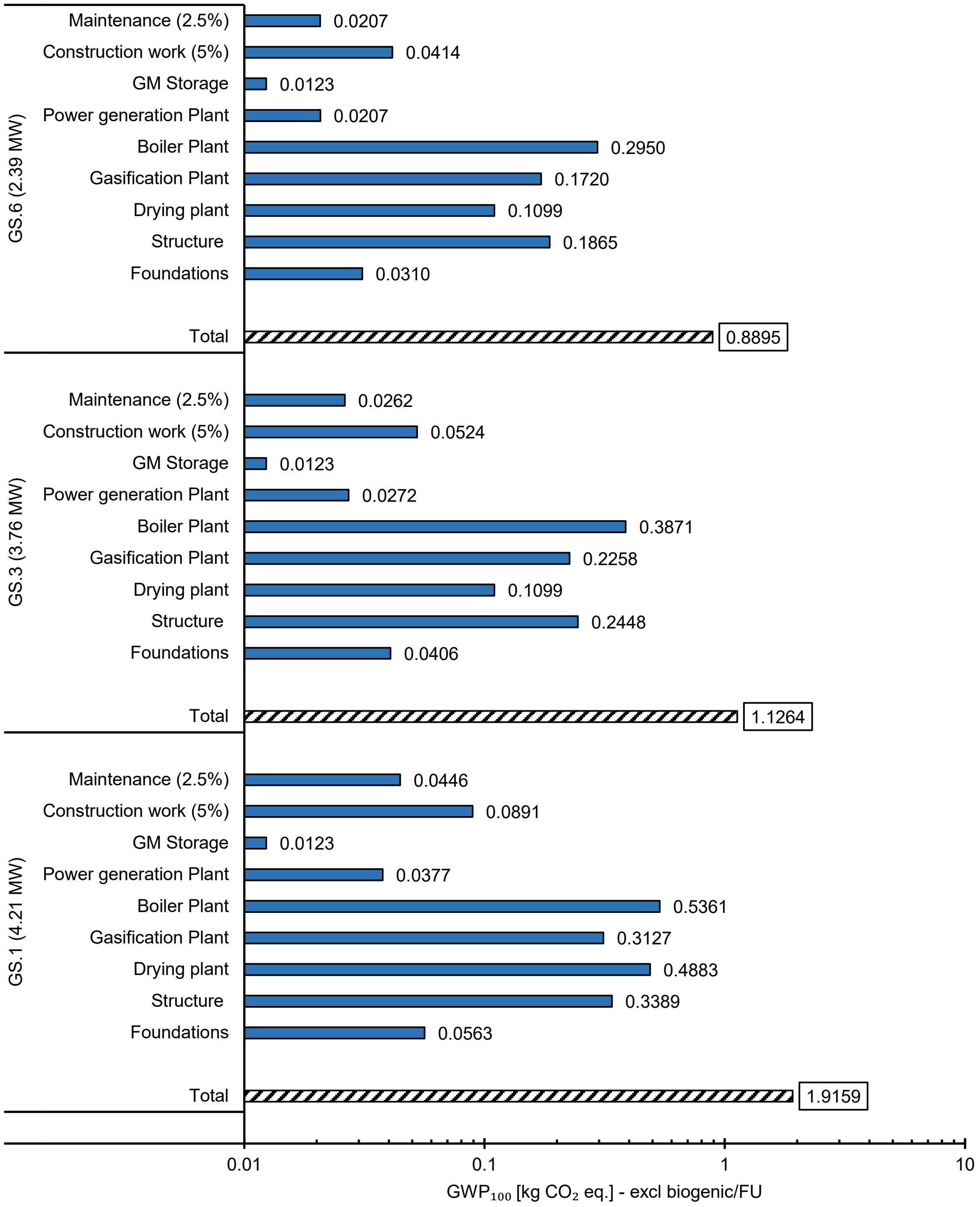

Figure 4.21: **Breakdown of the GWP_{100} of the gasification plants 1, 3 and 6 due to construction over 50 years of the life time of the plants.**

Pyrolysis scenarios

In Figure 4.22, the improved pyrolysis cases increased their carbon impacts due to the significant increase in the GWP_{100} of the pyrolysis plant.

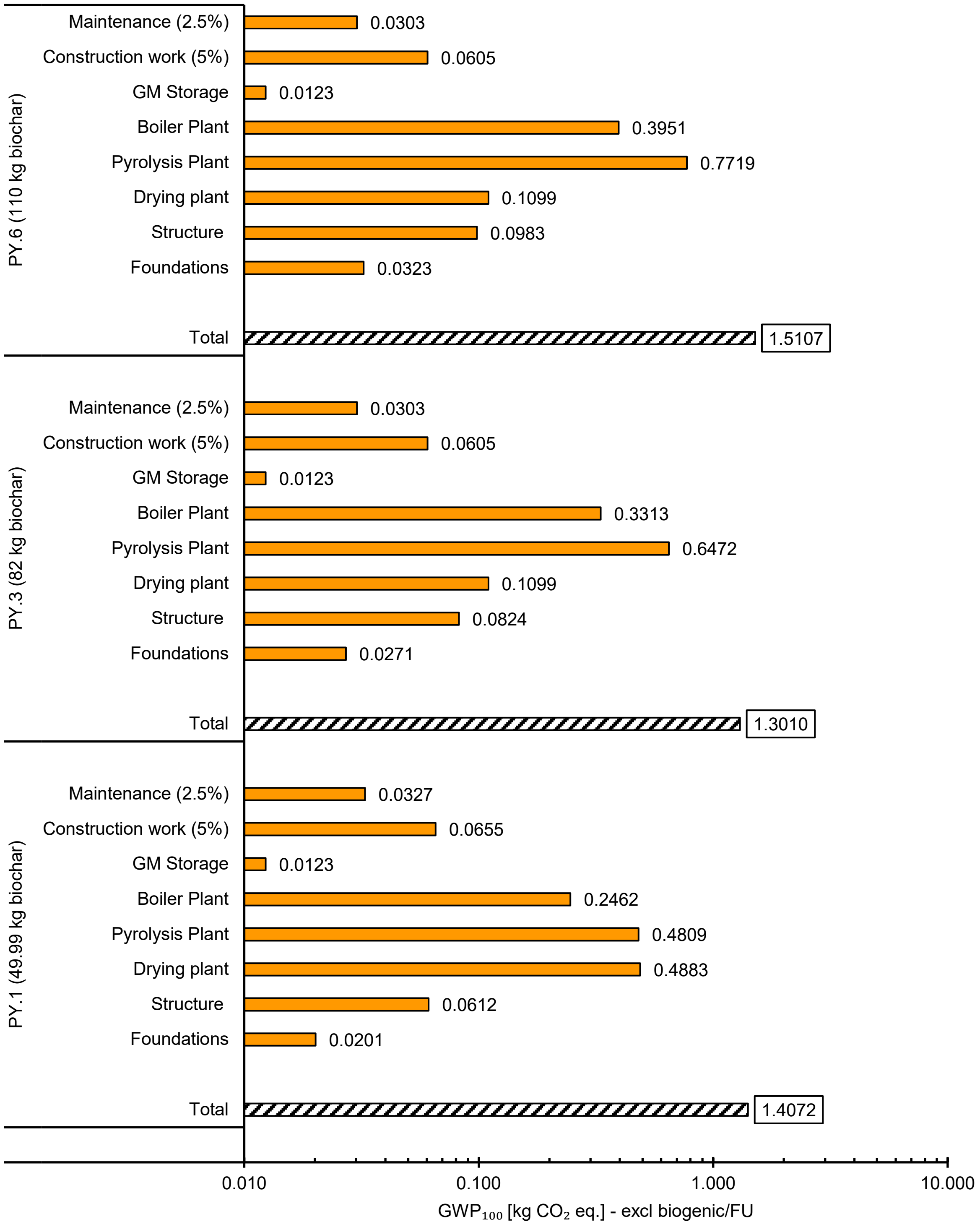

Figure 4.22: **Breakdown of the GWP_{100} of the combustion plants 1 and 3 due to construction over 50 years of the life time of the plants**

4.6.7.3 *The combined impact of the thermal treatment scenarios*

All the improved thermal treatment scenarios improve their carbon credits compared with their originals as shown in Figure 4.23. Although PY.6 has the lowest cola replacement credit (Table 4.19), it has the largest carbon sequestration value. When coal displacement excluded the combustion scenarios become carbon emitters, the gasification cases improve their credits as the production of char increase similar trend happens with pyrolysis with the increase of the biochar production (Figure 4.24)

Overall PY.6 gives the best carbon footprint results in comparison with the rest of the thermal treatments.

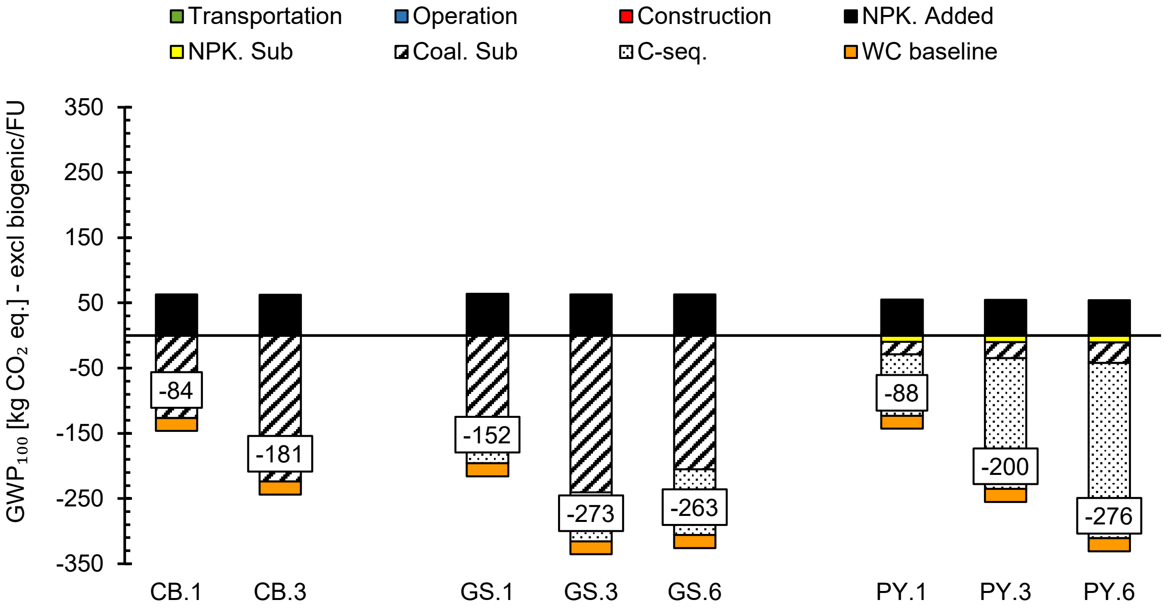

Figure 4.23: **Comparison of the GWP_{100} impacts for the thermal treatment scenarios (including coal replacement)**

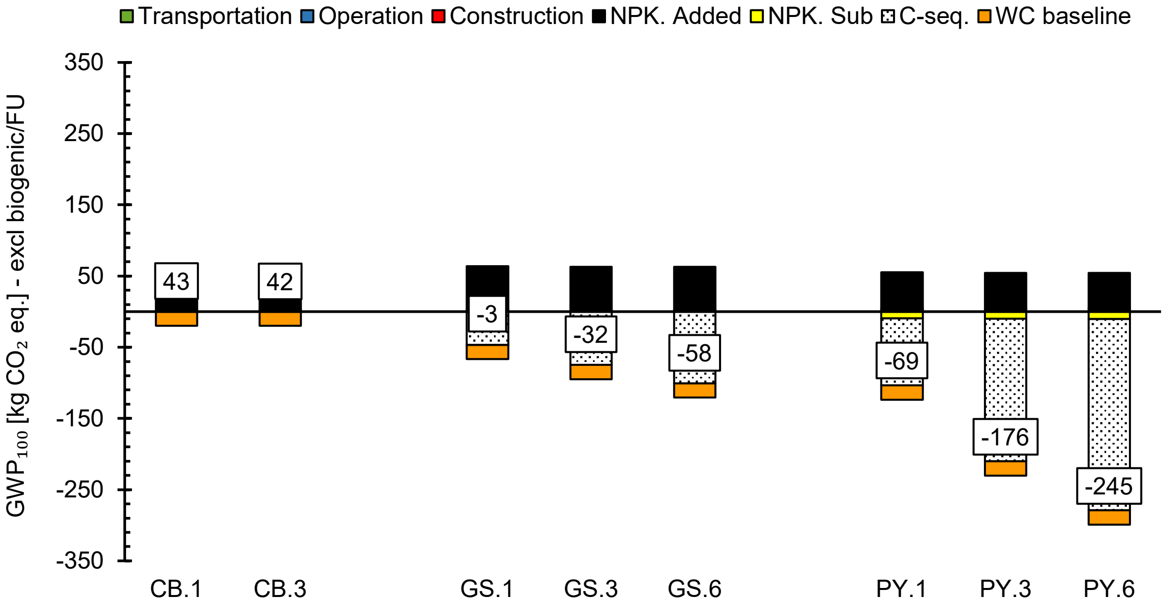

Figure 4.24: **Comparison of the GWP_{100} impacts for the thermal treatment scenarios (coal replacement is excluded).**

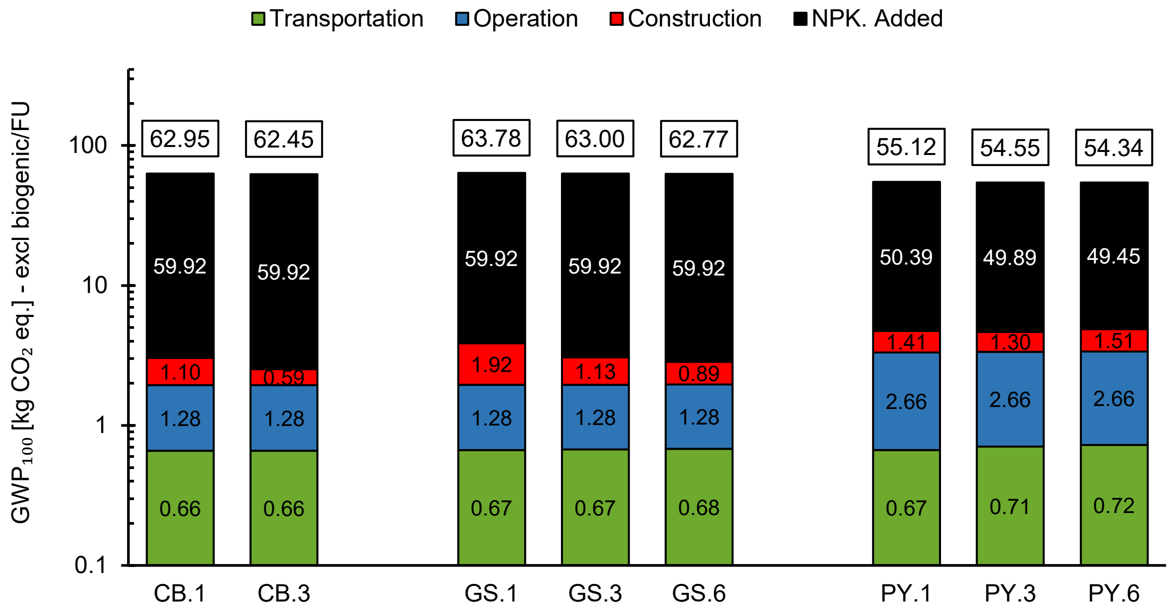

Figure 4.25: Comparison of the GWP$_{100}$ impacts for the thermal treatment scenarios excluding the carbon benefits.

Table 4.19: Breakdown of the GWP$_{100}$ of the thermal treatment scenarios,

	CB.1	CB.3	GS.1	GS.3	GS.6	PY.1	PY.3	PY.6
Transportation	0.659	0.659	0.668	0.672	0.679	0.668	0.706	0.725
Operation	1.280	1.280	1.280	1.280	1.280	2.656	2.656	2.656
Construction	1.096	0.588	1.916	1.126	0.890	1.407	1.301	1.511
NPK. Added	59.918	59.918	59.918	59.918	59.918	50.388	49.889	49.452
Sub-total	62.953	62.446	63.782	62.997	62.767	55.119	54.552	54.343
WC baseline	-20	-20	-20	-20	-20	-20	-20	-20
NPK. Sub	-	-	-	-	-	-9.530	-10.029	-10.466
Coal. Sub	-126.454	-223.776	-149.135	-240.765	-205.296	-19.341	-24.720	-31.621
C-seq.	-	-	-46.650	-74.746	-100.639	-94.126	-200.300	-268.696
Net carbon balance (Incl. coal replacement)	-83.50	-181.33	-152.00	-272.51	-263.17	-87.88	-200.50	-276.44
Net carbon balance (excl. coal replacement)	42.95	42.45	-2.87	-31.75	-57.87	-68.54	-175.78	-244.82

4.7 References

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