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Title:

Energy Recovery Alternatives for the Sustainable Management of Olive Oil Industry Waste in Australia: Life Cycle Assessment

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Abstract

Over the last two decades, the olive oil industry in Australia has been growing at an annual rate of 9%. Nevertheless, the highly polluting solid waste and wastewater generated by the industry poses significant challenges for the environmental sustainability of the industry. This paper analysed five alternatives for managing this waste stream using life cycle assessment methodology. The options included manufacturing briquettes as solid fuel for home heating; pellets for domestic or industrial water heating; pyrolysis and composting. The functional unit used in this study is the processing of 1 Mg of olive solid waste at the mill. Emissions were categorised into eight impact categories: ozone layer depletion potential (ODP), global warming potential (GWP100), eutrophication potential (EP), acidification potential (AP), human toxicity (HTP), fossil fuel depletion potential (FDP), ionising radiation potential (IRP), and photochemical oxidant formation potential (POFP). The study showed that although composting (current best practices - CBP) can achieve significant environmental benefits, using the olive waste to produce energy products may achieve better results, especially when displacing electricity from the main grid. The production of pellets for use in domestic hot water boilers (PHWH) is the option that is likely to deliver the highest environmental benefits. For example, GWP100 and ODP of the PHWH were estimated to be -1057 kg CO_2-Eq, -1.5×10^{-5} kg CFC-11-Eq compared to -12.4 kg-CO_2-Eq and 5.3×10^{-8} kg CFC-11-Eq achieved by the CBP, respectively. Future energy scenario and transportation distances were identified as significant parameters affecting the performance of the options. Sensitivity analysis showed that the expected change in the future Australian energy mix to cleaner energy sources is unlikely to have a significant effect on the performance of the alternatives. The results also showed little sensitivity to transportation distances of the energy product to the end user. This paper is the first to evaluate options for energy utilisation of olive solid waste using life cycle assessment and compare it to industry current best practices (composting). Although the paper focuses on the Australian olive oil industry, the results are also relevant to other countries and regions were olive solid waste is generated in relatively moderate quantities but distributed over large geographic area.

Keywords: *LCA, energy from waste, waste management, olive husk, renewable energy*

NOTATION

AP: acidification potential (AP)
BHH: Briquette manufacturing and use for home heating in a domestic solid fuel stove
CBP: Industry current best practice – composting
EP: eutrophication potential (EP)
FDP: fossil fuel depletion potential (FDP)
GWP100: global warming potential
HTP: human toxicity
IRP: ionising radiation potential
ODP: ozone depletion potential (ODP)
PHWH: Pellets manufacturing and use in domestic biomass water heater
PIB: Pellets manufacturing and use in industrial boiler
POFP: photochemical oxidant formation potential
PYRO: Pyrolysis in mobile units and use of bio-oil and char as energy substitutes

1. Introduction

The olive oil industry can be traced back thousands of years. Traditionally, the Mediterranean region has been the main producer of olive oil. Even so, during the last century, the olive oil industry has expanded beyond the Mediterranean region to new territories. In Australia, the olive industry has been growing at an annual rate of 9% for the past two decades. In 2012, Australian olive oil production was nearly eighteen thousand ($18x10^3$) m^3 and it is expected to reach twenty five thousand ($25x10^3$) m^3 by 2015 (Boundary Bend Limited 2011). Various types of olive mills are used to extract the oil from the fruit, for example: traditional olive press, 2-phase, and 3-phase modern mills. However, most Australian producers use the modern 2-phase olive mills because it produces less wastewater (Nair and Markham 2008). The solid waste, also known as olive husk and olive cake, generated from the process has high moisture content as shown in Table 1.

Table 1. Characteristics of the waste generated from the Australian olive oil industry (adapted from Nair & Markham (2008) and Kotronarou & Méndez (2003)).

Parameter (per 1000 kg olives)	2-Phase	3-Phase
Wastewater (kg)	190-210	700 - 1700
Wet solid waste (kg)	700 – 800	300 - 600
Moisture content in solid waste (%)	52-55	42-49

Nair and Markham (2008) estimated that the Australian olive oil industry generated more than 62,500 Mg of solid waste and $3.5x10^5$ m^3 of wastewater annually. Both the solid and liquid wastes are classified as highly polluting material. Consequently, responsible environmental management of these waste streams is essential for the sustainable growth of the industry. At the moment, composting is promoted as the best industry practice for managing this waste stream (AOA 2013).

The Australian olive husk, when dried to 5% moisture content, has a reasonable calorific value with its lower heating value (LHV) estimated to be around 20 $MJ.kg^{-1}$ (Dally and Mullinger 2002). Furthermore, olive husk has very low sulphur content (Caputo et al. 2003). As a result, it is an attractive biomass source for energy utilisation. Nevertheless, the high moisture content, the spread of the production over a wide geographical area, and the relatively short period of production, are factors that pose economic and logistic challenges to the effective utilisation of olive husk as an energy stoke (El Hanandeh 2013). Therefore, processing the waste on-site to produce higher energy density products which can be economically transported over longer distances is very important. Several methods are available to improve the energy density of biomass material. These methods include among others: briquetting, pelleting and pyrolysis.

Briquetting is a simple low technology option that can be used to increase the energy density of biomass, thus making it easier and more economical to transport. Biomass briquettes can be used as a substitute to coal or wood in most solid fuel stoves and burners. These stoves are usually used for cooking and home heating. Al-Widyan et al (2002) reported that olive waste briquettes have a density of more than twice the original olive husk. Nevertheless, Yaman et al (2000) reported that briquettes made from olive husk alone have a low shatter index and compressive strength and as a result are not durable. Yaman et al (2000)demonstrated that the mechanical properties of the briquettes can be improved by mixing paper mill waste with olive husk. However, paper mill waste is not readily available in the olive growing region of Australia and transporting it over long distance may be economically and environmentally inefficient. On the other hand, waste paper is readily available and was reported to enhance the mechanical properties of biomass briquettes from agricultural waste (Demirbas and Sahin 1998, Olorunnisola 2007, Yuhazri et al. 2012).

Pelletizing is another method of upgrading biomass fuel. Unlike briquettes, pellets are smaller in size and have a smaller diameter. They also require higher pressure and heat to produce. However, compared to briquettes, pellets are suitable for a wider range of applications. Traditionally, pellets are produced from woody biomass such as sawdust, wood chips and forestry residue (Lehtikangas 2001). Pellets can also be prepared from a wide range of agricultural and waste biomass material (Nilsson et al. 2011). Nowadays, olive cake pellets are produced on a commercial scale and marketed as a viable energy source in Europe. Miranda et al. (2010) studied the emissions from pellets made from different mixes of olive cake and oak biomass and concluded that pellets made of 100% olive cake have higher emissions of aromatic compounds at lower temperatures than pellets made from mixes of olive cake and oak.

Pyrolysis is a process in which organic material undergoes thermal decomposition in the absence of oxygen. The process yields an array of compounds: gaseous (syngas), liquid (bio-oil) and solid (biochar); all of which have significant heating value. Bio-oil and biochar have higher energy density than the original biomass and therefore are more economical to transport. El Hanandeh (2013) analysed the potential of treating the olive waste from the Australian olive oil industry in mobile pyrolysis units. After comparing different utilisation scenarios of the end products of the pyrolysis process, he concluded that utilising the bio-oil as a substitute to heavy fuel oil in an industrial boiler and co-combusting the biochar in a coal-fired power station would yield the maximum carbon offset. Nevertheless, the study did not include life cycle impacts other than greenhouse gas (GHG) emissions.

This study aims to evaluate energy utilisation options of the waste from the olive oil industry in Australia and compare it to the industry current best practices (composting). The environmental impacts of four potential scenarios for energy utilisation of the olive waste are assessed and compared to the industry current best practices using life cycle methodology. The objectives of this study are to:

1- Assess the environmental impacts of the current best practices using life cycle approach.
2- Assess the environmental impacts of alternative management options to the current best practices, and
3- Suggest an alternative to improve the sustainability of the olive oil industry in Australia.

2. Methods

2.1. Life cycle assessment

Life cycle assessment (ISO 14040: 2006) is a standardized method for the assessment of the environmental impacts of a product or service throughout all stages of its life; thus eliminating phase shifting of environmental burdens (ISO 2006). The goal of this study is to evaluate the environmental performance of options for using the waste from the Australian olive oil industry as energy stoke and compare it to the current industry best practices (composting). The intended audience of the study are the olive oil industry and industry associations, policy makers and academics. This study focuses on the treatment of the waste generated from olive oil processing; therefore, olive oil production and olive farming stages are excluded as they are the same for all options considered. Composting of olive waste was evaluated in this study because it is the current industry practice and is used as the baseline. Emissions due to manufacturing, transportation and processing of the olive waste into final energy product or compost are included. Avoided emissions due to the use of the final product to displace traditional energy sources or synthetic fertiliser are included as credits (negative values). The manufacturing of capital goods, such as agricultural machinery and transport trucks, is not included in the scope of this study. The functional unit chosen for this study is the treatment of 1 Mg of olive solid waste (56% moisture content) at the olive mill site. The system boundary of the study is illustrated in the system diagrams (fig 1 -5). Life cycle inventory (LCI) data were collected from different sources in the literature, the European Life Cycle Database (ELCD) (Joint Research Centre 2013), the U.S. Life Cycle Inventory (NREL) and the Australian National Life Cycle Inventory (AusLCI 2013). The impact categories considered in this study are global warming potential (GWP100), ozone depletion potential (ODP), eutrophication potential (EP), acidification potential (AP), fossil fuel depletion potential (FDP), human toxicity (HTP), ionising radiation potential (IRP) and photochemical oxidant formation potential (POFP). These impact categories were chosen based on the Best Practice Guide to Life Cycle Impact Assessment in Australia (Grant and Peters 2008). OpenLCA software was used to conduct the LCA analysis (GreenDelta 2014). The ReCiPe Midpoint (H) life cycle impact assessment (LCIA) method was used for the characterisation of emissions into the relevant impact categories except for the AP category for which the CML 2001 method was used as suggested by Bengtsson and Howard (2010).

2.2. Management Alternatives for the waste generated from the olive oil industry

Five alternatives are compared; four of which are for the energetic utilisation of the waste generated from olive oil processing in addition to the current best practices scenario:

i) *Briquette manufacturing and use for home heating in a domestic solid fuel stove (BHH)*
ii) *Pellets manufacturing and use in domestic biomass water heater (PHWH)*
iii) *Pellets manufacturing and use in industrial boiler (PIB)*
iv) *Pyrolysis in mobile units and use of bio-oil and char as energy substitutes (Pyro)*
v) *Industry current best practice – composting (CBP)*

2.2.1. Briquette manufacturing and use for home heating in a domestic solid fuel stove (BHH)

Space heating and cooling accounts for nearly 38% of the energy used in the Australian household (Riedy et al. 2013). According to the Australian Bureau of Statistics (ABS), more than 77% of Australian homes have a heater (ABS 2010). Gas and electricity are the main sources of energy used for space heating. Wood heaters, although their popularity has declined over time, are also used, especially in rural Australia. Table 2 shows the breakdown of home heating methods used by Australian households which have home heaters installed.

Table 2. Breakdown of the type of heater used by Australian households adapted from ABS (2010, 2012)

Heater type	Energy source	Share (%)	Typical Efficiency (%)
Gas heater non-flued (not ducted)	Gas	20	85
Gas flued (ducted)	Gas	12	70
Reverse cycle air-conditioning (not ducted)	Electricity	20	85
Electric heater (not ducted)	Electricity	17	95
Wood stove	Wood	10	60

Olive grows in the temperate regions of Australia. Olive harvesting and processing coincide with the colder months of the year when space heating is usually required. The waste generated from olive oil processing can be used to manufacture briquettes for burning in solid fuel burners. All solid fuel stoves sold in Australia must conform to AS/NZ 4013:1999 which set strict regulations on installing solid fuel stoves and limits on the PM_{10} and CO emissions (Standards Australia 1999a, b). Solid fuel stoves compliant with the standards are therefore, a safe, clean and efficient method of space heating.

The average efficiency of solid fuel stoves compliant with AS/NZ4012:1999 and AS/NZ 4013:1999 that are currently available in the market is 62% (AHHA 2014). Therefore in this study, it is assumed that solid fuel stoves with an efficiency of 60% are installed. Briquettes made of 20% waste paper and 80% olive husk (by weight) is used as the solid fuel. It is further assumed that the energy displaced corresponds to the average of Table 2. Figure 1 shows the system diagram for this alternative. Table 3 shows the emission factors for burning dry olive waste for energy during the briquette manufacturing process. Table 4 shows the emission factors for burning olive waste briquettes in an AS/NZ 4013 compliant solid fuel stove. Negative values indicate avoided emissions.

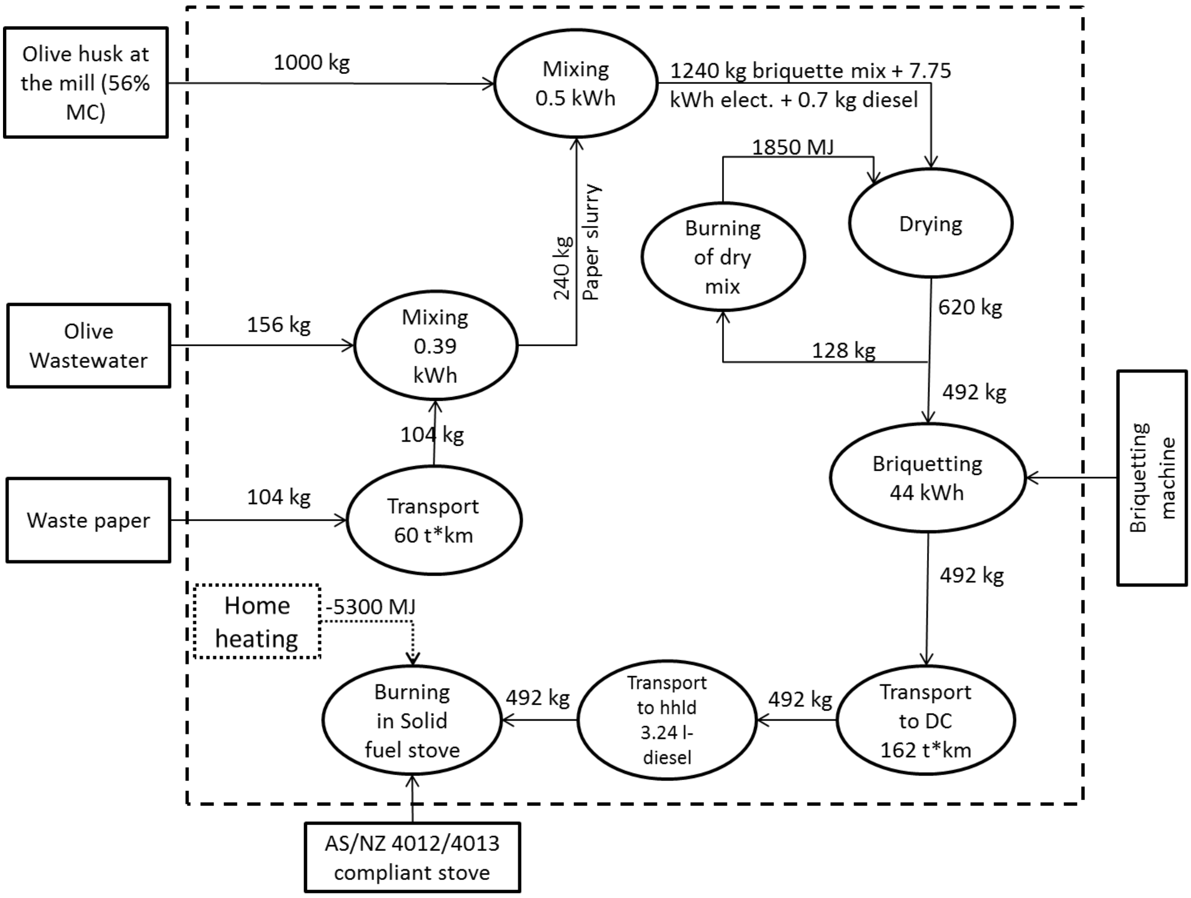

Figure 1. System diagram of the briquetting alternative (BHH)

Table 3. Emissions from burning dry olive cake (kg per Mg dry olive cake @ 12% MC)

Emission	Emission factor	Data Source
Ash	68	
CO	103	Estimated based on Al-Widyan et al. (2006)
NO_x	1.07	
SO_2	0.945	
PM_{10}	1.17	Estimated based on EF of biomass combustion Nussbaumer et al. (2008)

Table 4. Emissions from burning briquettes in an AS/NZ 4013:1999 compliant solid fuel stove (kg per Mg of solid fuel)

Emission	Emission Factor
Ash	40
CO	62.5
NO_x	21.75
SO_2	0.225
PM_{10}	4
VOC	5

2.2.2. Pellets manufacturing and use in domestic biomass water heater (PHWH)

Water heating accounts for 21% of the energy usage and 23% of the GHG emissions in the Australian household (Riedy et al. 2013). Table 5 shows the breakdown of the energy sources used for water heating in Australian households.

Table 5. Major energy sources used for water heating in Australian households (adapted from Riedy et al. (2013))

Energy Source	Share
Natural gas	48%
Electricity	45%
LPG	3%
Solar	4%

Domestic biomass boilers are available in several sizes and can use a variety of biomass sources such as pellets which can be manufactured from the solid waste generated by the olive oil processing industry. In this study, it is assumed that the boiler has an efficiency of 85% and complies with the AS/NZ4013 emission standards as shown in Table 4. As these boilers will be new installations, it is assumed that the energy displaced corresponds to Table 5. Due to their high efficiency, the heat output is expected to be at least 12.8 GJ/Mg pellets thus displacing 6.87 GJ of electricity from the grid mix and 135 kg of natural gas. Figure 2 shows the system diagram for pellet manufacturing.

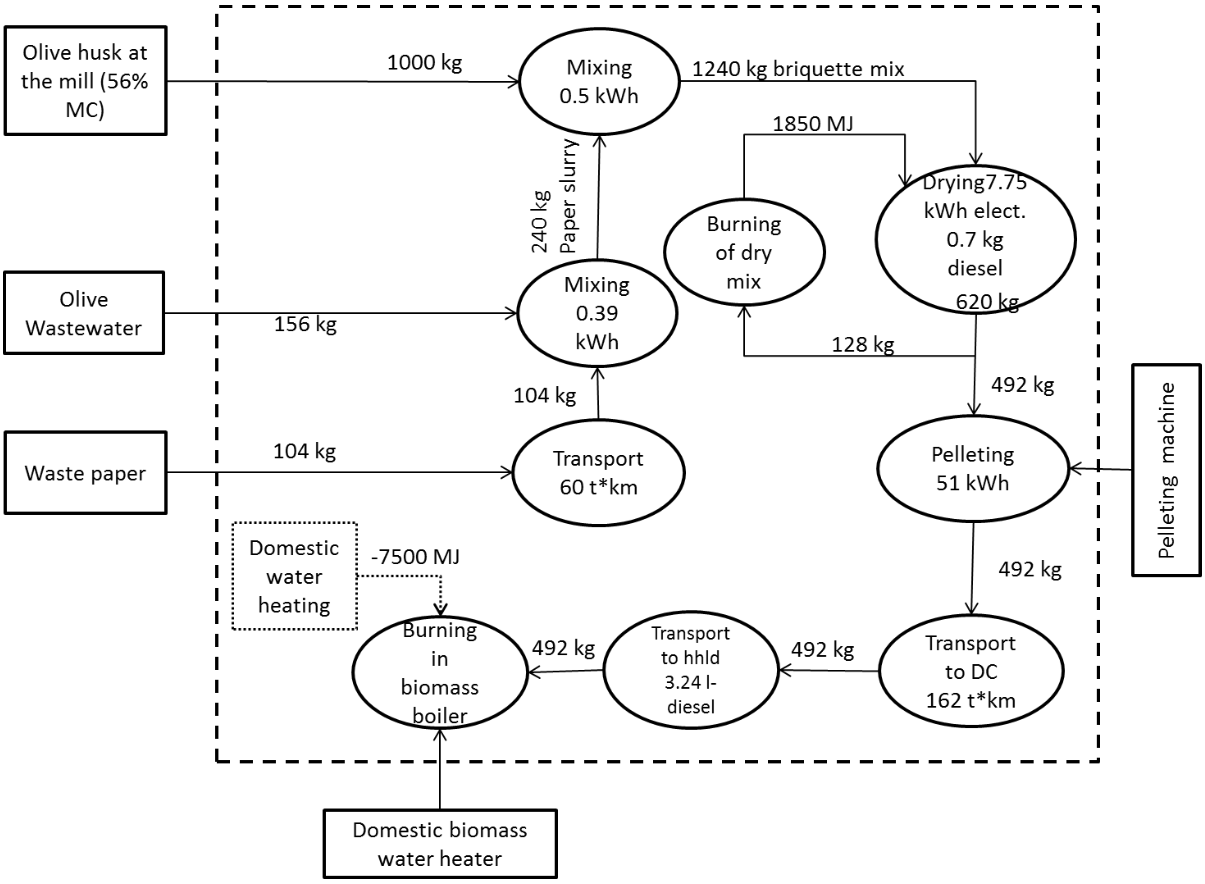

Figure 2. System diagram PHWH alternative.

2.2.3. Pellets manufacturing and use in industrial boiler (PIB)

This option is similar to the PHWH option except that pellets are combusted in a biomass industrial boiler displacing energy from a boiler using diesel fuel, and transported directly from the mill to the end user. Figure 3 shows the system diagram for this option.

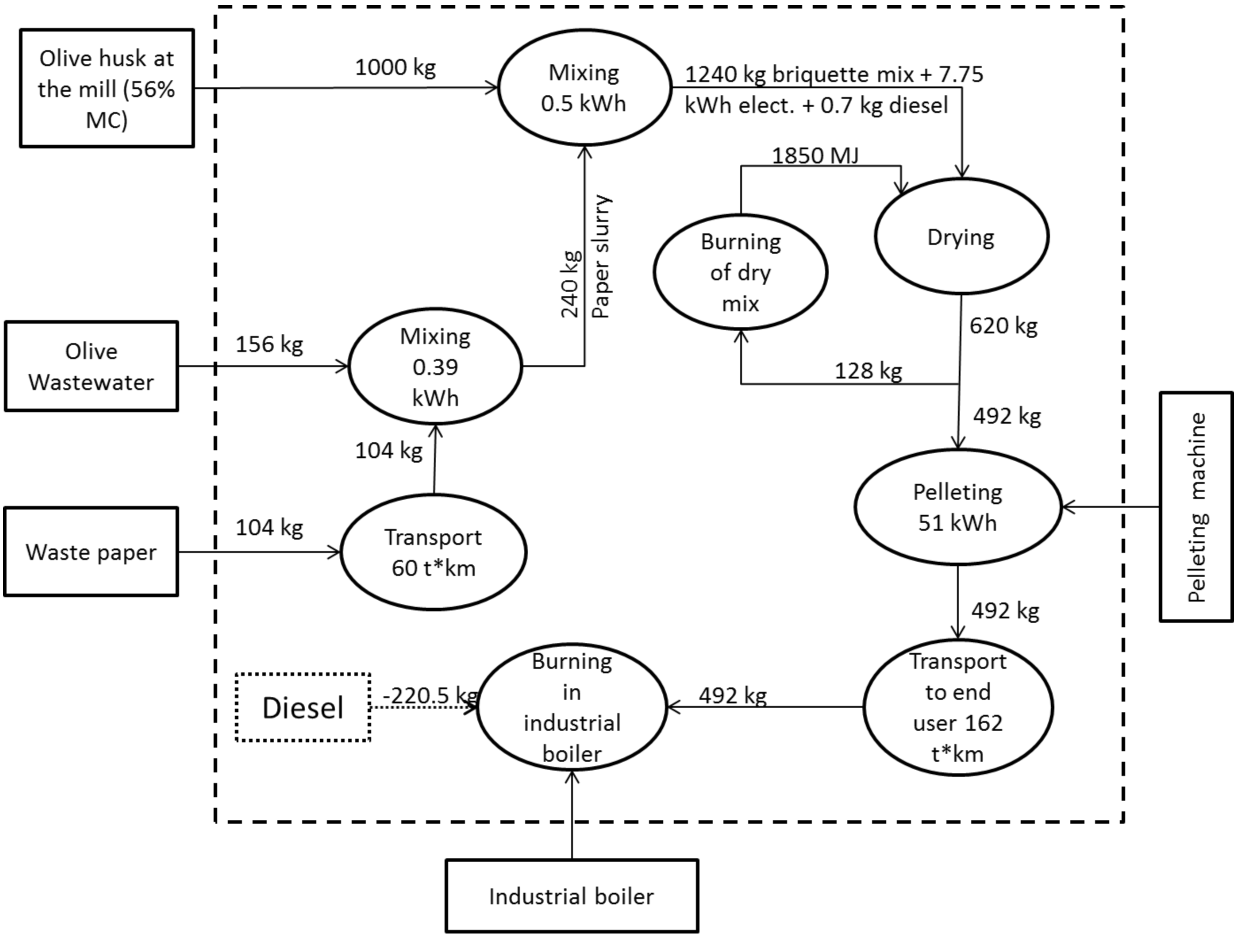

Figure 3. System diagram of the PIB alternative

2.2.4. Pyrolysis in mobile units and use of bio-oil and char as energy substitutes (Pyro)

This option follows El Hanandeh's (2013) study in which a system of mobile pyrolysis units was optimised for maximum GHG offset. El Hanandeh (2013) found that processing olive husk in fast pyrolysis mobile units would yield the maximum carbon offset. In this study, other environmental impacts are included. Figure 4 shows the system diagram for this alternative. Table 6 presents a summary of the LCI data for this option.

The process of pyrolysis will produce two energy co-products; biochar and bio-oil. Although, both products in this scenario are used to generate energy, the displaced energy as a result of the utilisation of each product differs. This raises the issue of allocating the environmental burdens of the process to the final products. In this study the energetic content of the product is the most important characteristic. Therefore, burdens are allocated to each product based on its energy value (43% biochar and 57% bio-oil).

Unlike the other alternatives, this scenario does not use wastewater. So, wastewater must be treated or dealt with separately. This may affect the validity of the comparison with the other systems. To account for this, the system is expanded to include the treatment of the wastewater. The common method of treating the wastewater from olive oil processing is to deposit it in evaporative ponds. This process does not add additional burdens that are not included in the other alternatives. Consequently, the overall performance of this alternative is independent of the wastewater treatment.

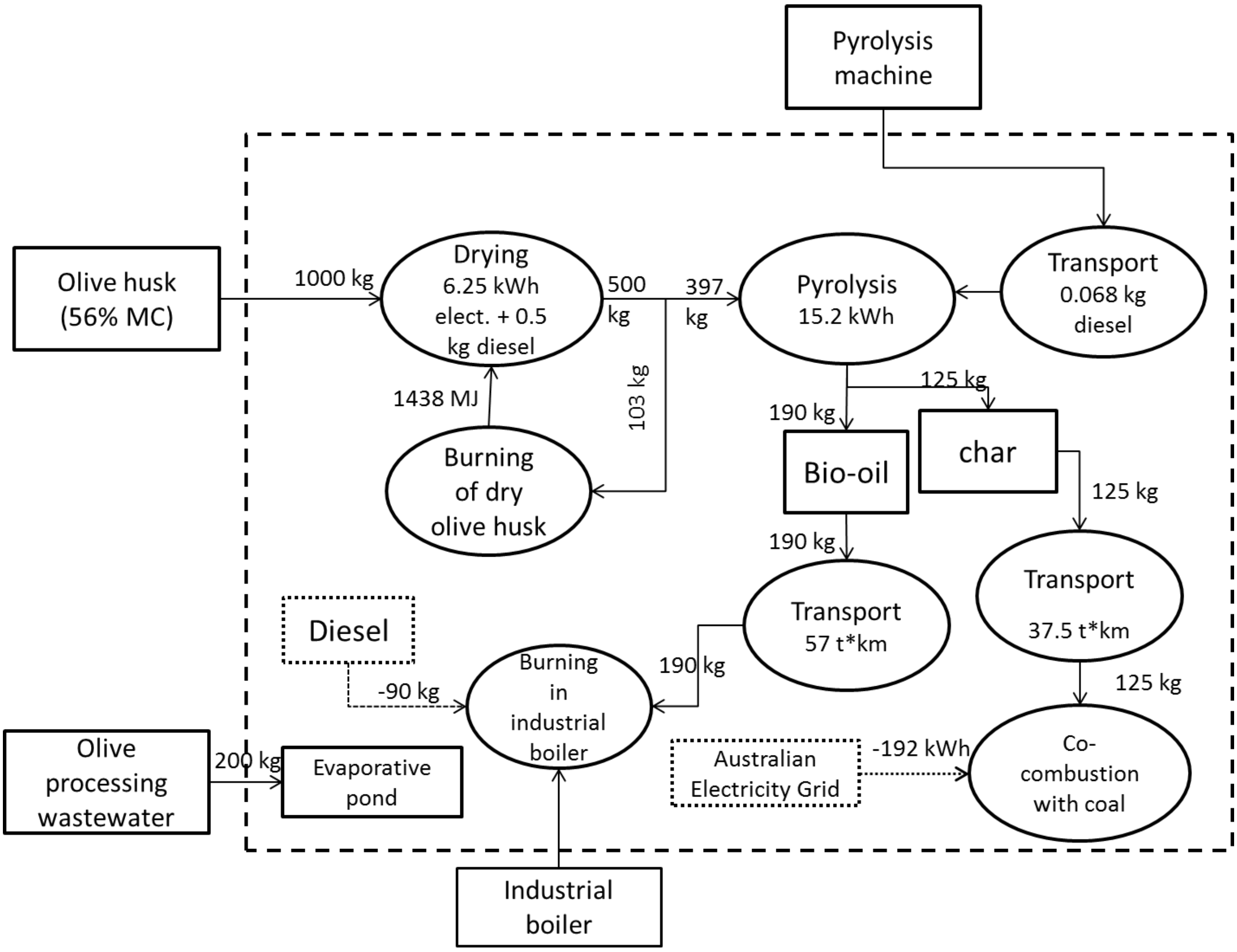

Figure 4. System diagram of the Pyro alternative

Table 6. Pyrolysis products utilisation emissions (kg per Mg olive solid waste MC 12%)

Product		
Biochar @ LHV 22 MJ/kg	315	Estimated based on El Hanandeh (2013)
Bio-oil @ LHV 19 MJ/kg	480	Jacobson et al. (2013)
Emissions		
Ash	22	Steele et al. (2012);Department of Ecology (NA)
CO	1.614	
NOx	3.114	
SOx	1.877	
PM	1.034	

2.2.5. Current best industry practices (CBP)

Composting is now viewed as the best industry practice. This alternative is included as a benchmark to compare the performance of all alternatives against it. Nair and Markham (2008) investigated several options for composting the waste generated by the Australian olive oil industry. In this study, one of the most promising options is used as a reference point. Figure 5 illustrates the system diagram describing this option.

Table 7 presents a summary of emissions during the composting process.

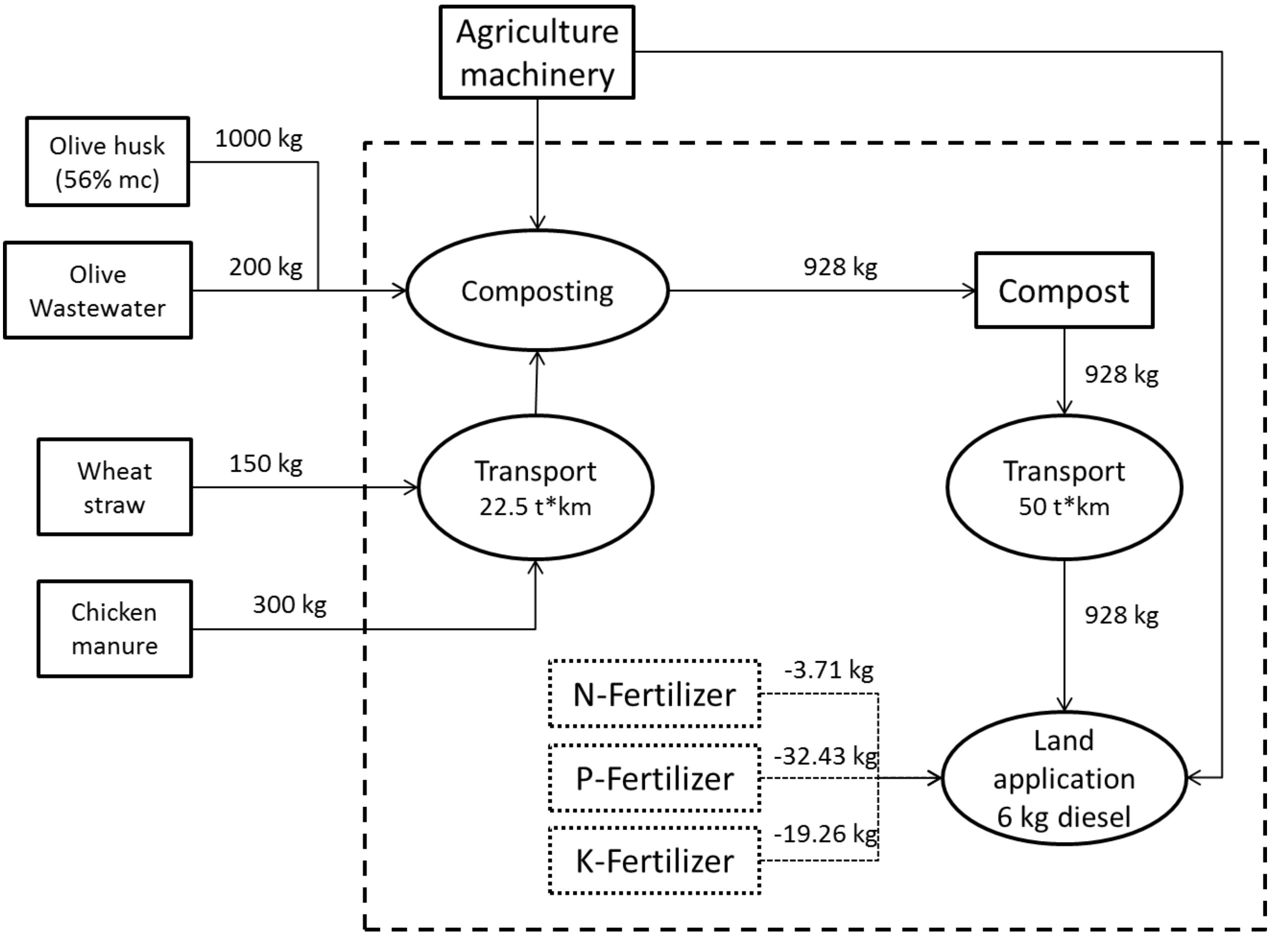

Figure 5. System diagram of the CBP

Table 7. Emission factors for composting (kg per Mg olive solid waste adapted from Hellebrand (1998))

Emission	Emission factor
Ammonia	0.306
CO	0.264
CH_4	11.228
NO_x	0.128

3. Results and Discussion

The results (**Figure 6**) show that using pellets as fuel in a domestic water heater (PHWH) is the only option that consistently delivers avoided impacts in all the impact categories considered in this study. Using briquettes for home heating (BHH option) also performs well. As shown in **Figure 6**, BHH results in avoided impacts in all impact categories except the AP. The pyrolysis option (PYRO) also performs well as it delivers avoided impacts in all categories except for the AP and POFP. When considering individual impacts, **Figure 6** suggests that PHWH is likely to deliver the maximum environmental benefits in seven out of the eight impact categories; namely: GWP, ODP, EP, FDP, POFP, IRP and AP. Composting (CBP), on the other hand, is the best performer in the HTP impact category. While using briquettes for home heating (BHH) ranked second in four impact categories (EP, GWP100, FDP and ODP), PYRO scored third place or better in six impact categories. In contrast, PYRO outperforms BHH in the AP category. The results, therefore, suggest that PHWH, BHH and PYRO alternatives are most likely to out-perform the current best practices (CBP) in most of the impact categories considered in this study.

Avoided emissions from the displaced energy as well as the efficiency of the system being substituted are the main factors in determining the overall performance of the scenario. This can be clearly seen by comparing the two scenarios which use pellets (PIB and PHWH). In both cases, the manufacturing process is the same however the end use differs. In the first scenario, pellets substitute diesel while in the second pellets substitute an array of energy sources in a domestic water heater as shown in Table 5. The PHWH scenario, despite the extra transportation requirements, has consistently outperformed the PIB. This can be attributed to: first, the majority of substituted energy in the PHWH case is electricity (45%) which is predominantly generated from burning coal; and second, the fact that the domestic water heater has an efficiency of 70-85% compared to 25-30% efficiency in the case of electricity generation in coal-fired power stations. These results in principle, are consistent with the findings of Parsons (2010) who compared different home heating alternatives in the temperate region of Queensland and found that burning wood obtained from sustainable sources in modern wood burners result in better environmental performance than electric heating.

The electricity grid mix differs significantly between Australian states; this in turn means that the actual environmental benefit will depend on where the end product is actually used. For example, New South Wales (NSW) relies mainly on black coal to generate electricity whereas in Victoria , where coincidently 48% of the Australian olive oil is produced, brown coal is the main source for electricity generation. Clearly, the energy utilisation of the olive waste products in Victoria will yield more environmental benefits than in NSW. Another point to be raised here is the effect of future changes to the current electricity grid mix; for example a shift to cleaner energy sources through the legislated renewable energy target scheme or other schemes may reduce the environmental benefits gained from the utilisation of biomass products as energy substitutes in the future.

Using pellets in a domestic water heater (PHWH) is the alternative that is likely to deliver best results. The results can be further improved if the biomass boiler were to provide space heating as well as hot-water. However, this type of boiler is not common in Australia despite the fact that they are available and are used in New Zealand and Europe. A survey on the cost of installing domestic biomass boilers has revealed that they are considerably more expensive than the conventional gas and electric systems. Yet another issue with the biomass boiler is fuel storage space requirements which may be limited especially in urban areas. Therefore, the adoption of this alternative is likely only if there are policy incentives to promote it; for example receiving credits under the renewable energy target scheme. Cellura et al. (2013) compared the option of using pellets in a biomass boiler for home heating and hot water production to a system of micro-generation of heat and electricity and concluded that the latter option had lower environmental impacts. Although, the micro-generation option was not considered in this study, it confirms that alternatives which displace electricity from the grid are preferable from an environmental perspective.

Using briquettes for home heating (BHH) ranked second in terms of its overall environmental performance. This finding is consistent with the findings of Kattan and Ruble (2012) who concluded that using briquettes made from olive solid waste for home heating in Lebanon would result in the lowest CO_2 emissions when compared to electric, diesel and LPG systems. Stolarski et al. (2013) measured the emissions of greenhouse gases (GHG) from home heating systems using different fuels in Northern Poland and concluded that wood briquettes produced the lowest GHG emissions; 12 times lower than burning hard coal. However, neither study included the life cycle emissions from the production and transportation stages or impact categories other than GHG emissions. Nevertheless, their results support the notion that the use of briquettes for home heating is an environmentally responsible option. Although, it is suggested that briquettes are a cheaper alternative to conventional fuels (Kattan and Ruble 2012, Stolarski et al. 2013), the high cost of the biomass boiler is likely to inhibit its adoption (Stolarski et al. 2013).

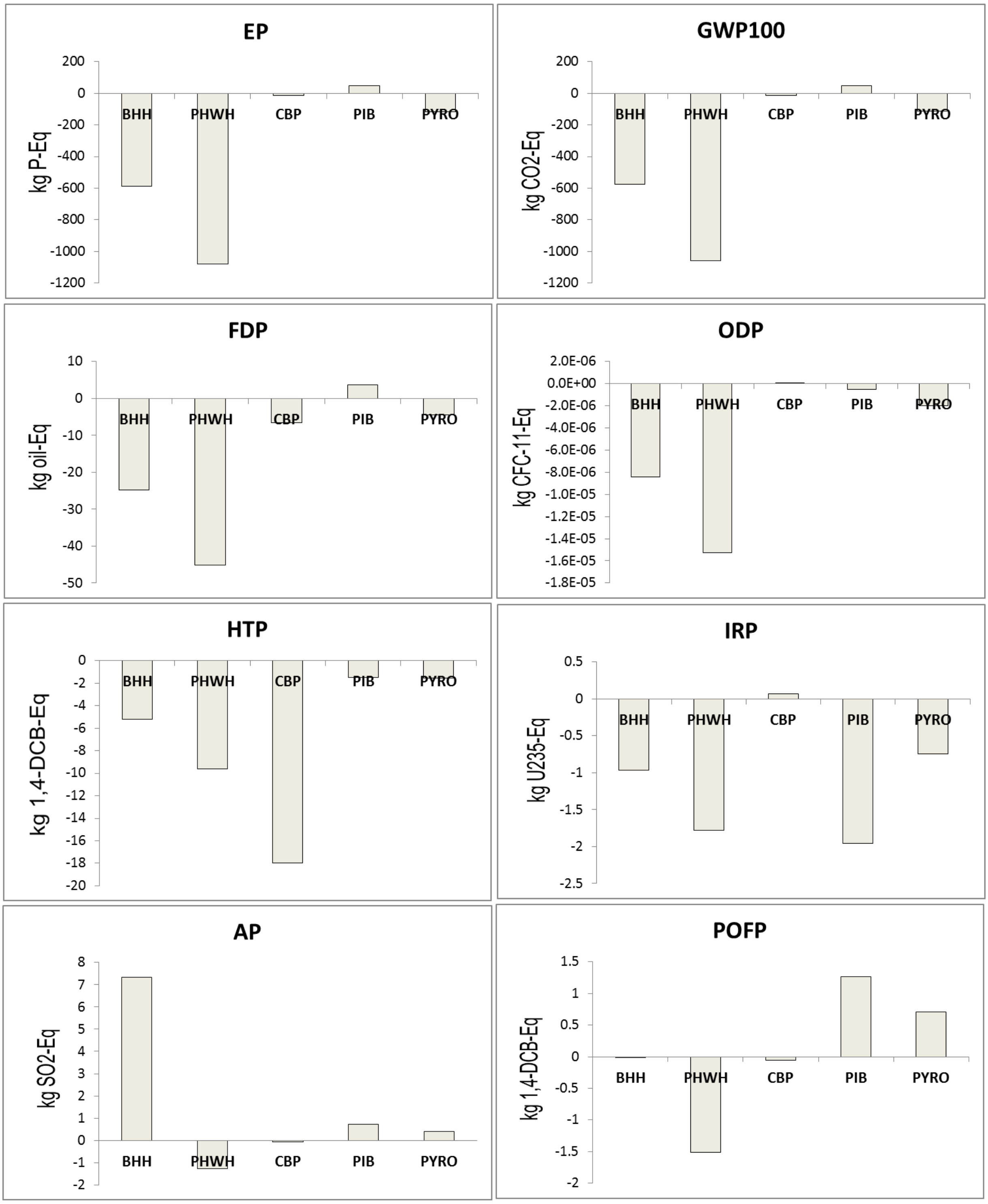

Figure 6: Performance of the scenarios for each impact category per Mg olive waste

4. Sensitivity Analysis

Choice of secondary data sources and assumptions made in the LCA study, such transportation and energy, may affect the outcome of the LCA analysis (Cellura et al. 2011). In this study, the results highlighted that avoided emissions due to main grid energy displacement play an important role in the environmental performance of the alternatives. To test the sensitivity of the performance of the alternatives to future cleaner energy scenario, the analysis was repeated by simulating the 2020 most likely scenario for the Australian grid mix: 25% renewables (15% wind energy, 2% solar, 7% hydro, 1% biomass), 71% coal and 4% natural gas (Reputex Carbon Analytics 2013). As expected, the results (Figure 7) show that the benefits will be reduced in all impact categories. Nevertheless, none of the impact categories is likely to change sign with the exception of POFP. However, Grant and Peters (2008) suggested that the POFP has low significance in Australia as the number of smog incidents are rare and the health effects associated with this impact are low. Therefore, the change in sign in this impact category may not be very significant to the overall results. Consequently, potential future change in the Australian grid mix is unlikely to have an effect on the ranking of the alternatives.

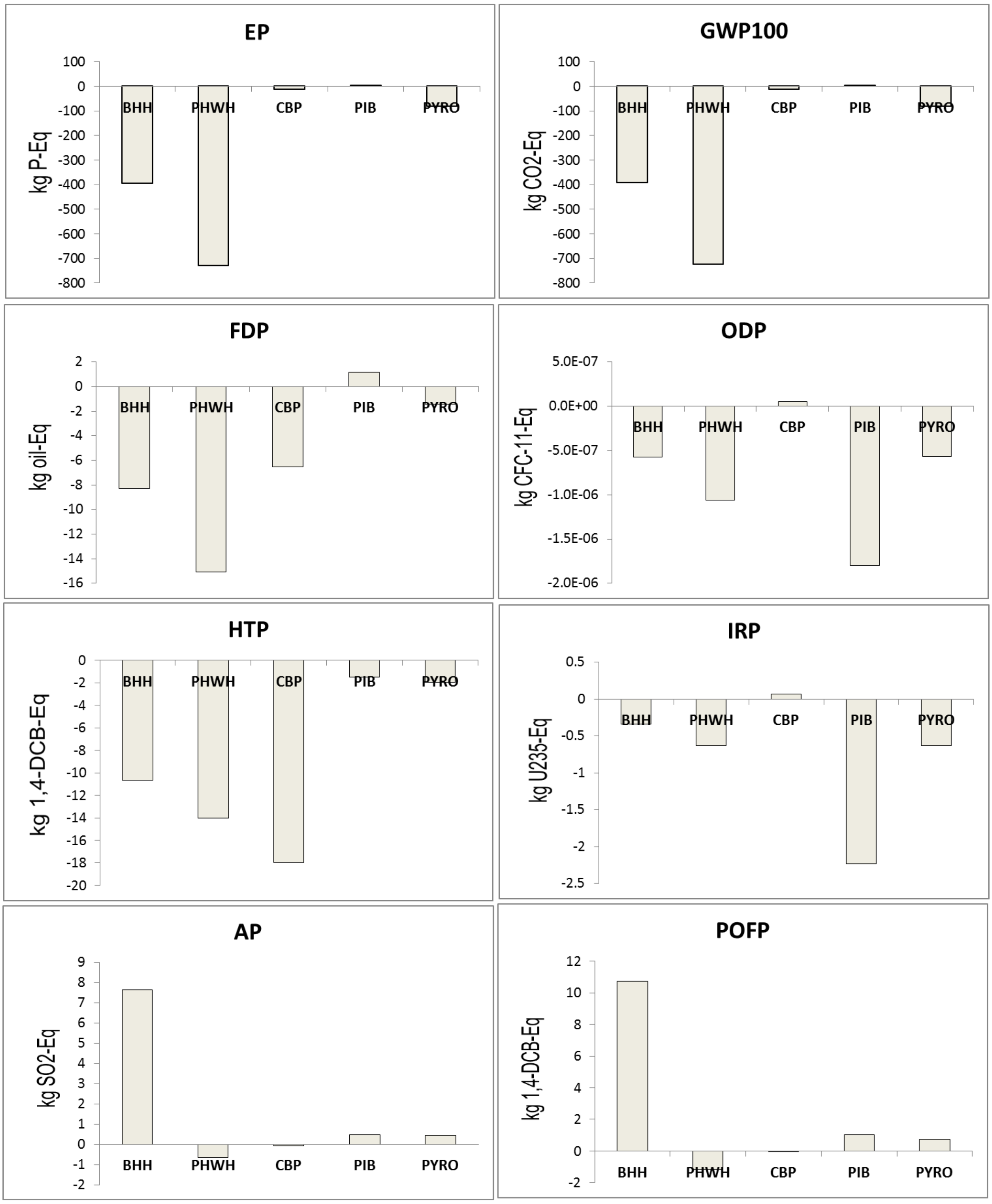

Figure 7. Performance of alternatives under clean energy scenario (25% renewables, 71% coal and 4% natural gas).

In this study, it was assumed that the average transport distance of products to the energy market is 300 km. Closer inspection of the results suggested that transportation of end products to the end-user may play a significant role in the performance of the alternatives under the GWP, POFP and AP impact categories. Therefore, the sensitivity of the results to changes in transportation distances was tested by assuming longer transportation distances from the production site to the utilisation site. The results (Figure 8) show that the performance of the energy based alternatives (BHH, PHWH, PIB and PYRO) was unaffected by the transportation distances as none of the impact categories changed sign. However, longer transportation distances have greater effect on the CBP alternative, especially in the GWP, POFP and AP impact categories where a change in sign has occurred signalling added environmental burdens.

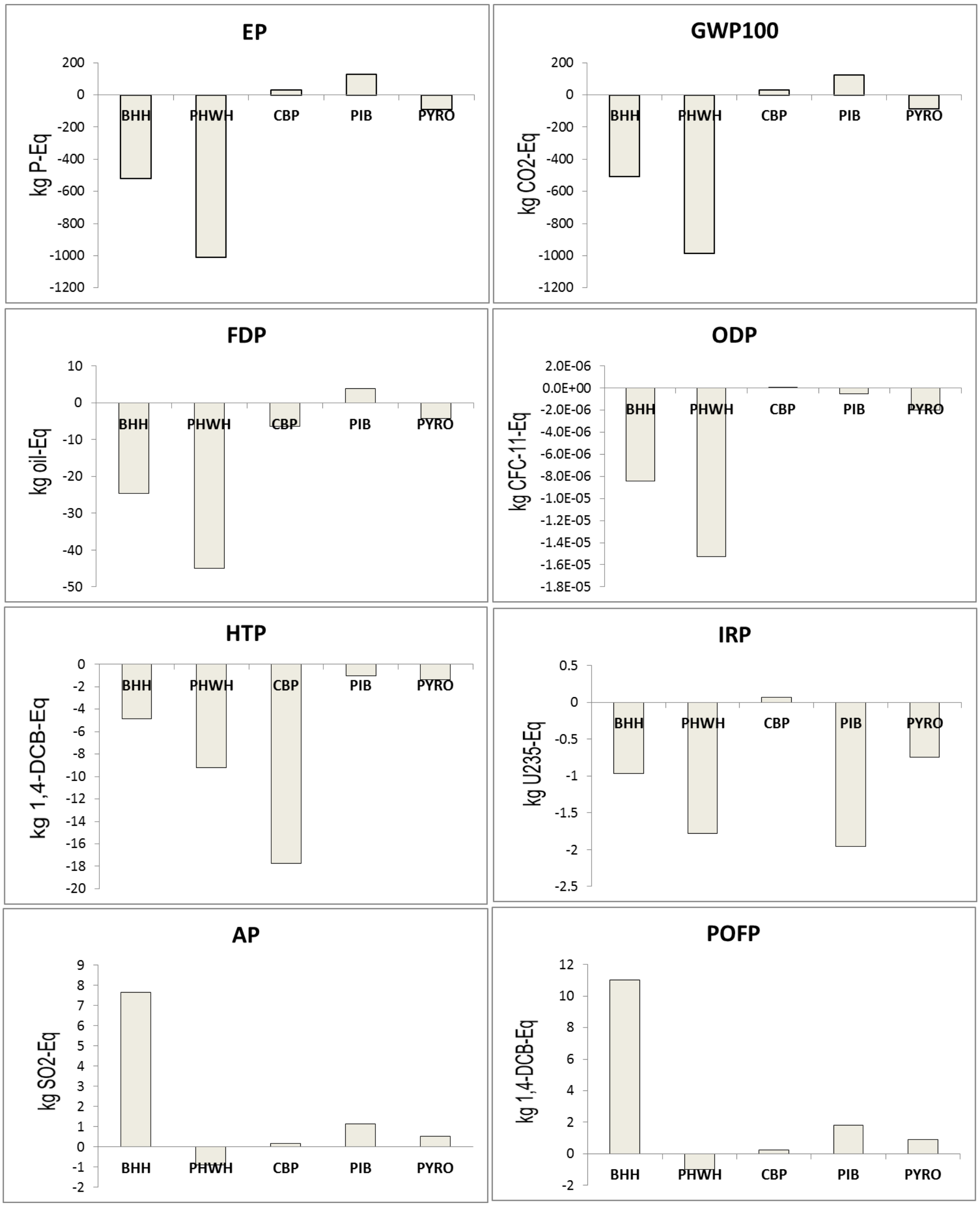

Figure 8. Performance of alternatives under the longer transportation distances scenario (1000 km to energy market and 300 km to compost land application)

According to Grant and Peters (2008) the HTP impact category may be omitted if the system is dominated by energy products. The GWP and other energy related impact categories correlate strongly with the HTP and may be used as a proxy indicators. Under the current Australian energy regime, this correlation holds true for the energy utilisation alternatives considered in this study as can be seen from Figure 6. The results further suggest that this correlation may continue to be valid under future energy scenarios as evident from Figure 7. Furthermore, it was also observed that the GWP100, FDP and EP are highly correlated as evident from figures 6-8. Therefore, the GWP100 may be used as a proxy indicator of the system's performance in the EP and FDP impact categories.

Under the current Australian energy regime, BHWH, BHH and PYRO are likely to out-perform the current industry best practices (CBP). The expected shift to cleaner energy sources is unlikely to have a major impact on the overall environmental performance of the alternatives considered in this study. The CBP has shown greater sensitivity to transportation distances than the energy-based alternatives.

5. Conclusions

Life cycle assessment methodology was used to compare five alternatives for managing the waste generated by the olive oil industry in Australia. Using the waste to manufacture pellets for domestic water heating is the alternative that is likely to deliver the highest environmental benefits. Briquette manufacturing for use in domestic stoves for space heating ranked second. The current best practices of the industry which promotes composting of the waste ranked fourth in the GWP, EP and FDP and fifth in the ODP and IRP being outperformed by three of the four energy alternatives considered in this analysis. The source of the energy displaced by the product plays a significant role in the performance of the energy alternatives. The likely change in the Australian energy mix by 2020 may have insignificant impact on the overall performance of the alternatives. This work focused solely on the environmental performance of the alternatives. It is recommended that the economic and technical feasibility of the alternatives considered in this work and/or other energy utilisation alternatives should be evaluated and perhaps an update to the industry best practice may be promoted. Further research is needed to evaluate the environmental, economic and social impacts of more advanced energy utilisation alternatives and the potential use of other agricultural waste streams in close proximity of the olive oil production regions.

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