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Environmental Impact Assessment of Solid Waste to Energy Technologies and Their Perspectives in Australia

Behnam Dastjerdi [1], Vladimir Strezov [1,*], Ravinder Kumar [1,2] and Masud Behnia [1,3]

[1] School of Natural Sciences, Faculty of Science & Engineering, Macquarie University, Sydney, NSW 2109, Australia
[2] College of Science and Engineering, James Cook University, Townsville, QLD 4811, Australia
[3] CTR, Building 500, Stanford, CA 94305-3035, USA
* Correspondence: vladimir.strezov@mq.edu.au; Tel.: +61-2-9850-6959

Abstract: The study assessed the environmental impacts of landfilling, anaerobic digestion and incineration technologies and investigated the effect of the replaced source of electricity on the environmental impacts of these waste to energy (WtE) technologies. Data published in the national pollutant inventories and ReCiPe impact assessment method were employed in this study. The study showed that electricity generation through incineration had the highest impacts on human health and ecosystems, followed by landfilling. Compared to the electricity of the Australian national grid, electricity generated from all three WtE technologies have a lower environmental impact. The results revealed that global warming and fine particulate matter formation with more than 97.6% contribution were the main impact factors for human health, while terrestrial acidification, global warming and ozone formation were contributing to more than 99% of the impacts to ecosystems. Global warming was the most impactful category on human health and ecosystems from incineration with over 85% contribution to both endpoint categories. Incineration revealed significantly higher avoided global warming impacts to human health and ecosystems than landfilling from the treatment of one tonne of solid waste by replacing electricity from brown coal, black coal or the Australian power grid. The growing share of renewable energy in the Australian power grid is expected to decrease the grid GHG emissions and the effect of the avoided impacts of replaced electricity. The results revealed that if the GHG emissions from the Australian power grid (757 kg CO_2 eq/MWh) decrease to break-even point (621 kg CO_2 eq/MWh), incineration loses the climate advantage over landfilling.

Keywords: environmental impact assessment; waste to energy technologies; national pollutant inventories; human health; power grid emissions

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1. Introduction

The world is currently facing global warming due to high levels of greenhouse gas (GHG) emissions mainly originating from fossil fuel consumption, while the consequent extreme climate change impacts threaten life throughout the planet [1,2]. The increase in GHG emissions can be mainly attributed to industrial and economic development [3]. Another concerning aftermath of socio-economic development is the increase in waste generation [4]. Together with the development and growth in population, waste generation has been estimated to increase significantly in the near future [5]. The world is facing the dual challenge of sustainable waste management and decreasing the over-dependence on fossil fuels to generate energy [6–8]. The conversion of waste to energy, fuels and other useful materials, with an emphasis on sustainability, has a specific role in the circular economy [9]. In this regard, waste to energy (WtE) technologies are considered a viable and promising solution for the generation of energy while effectively managing the staggering amount of waste generated [10].

Different types of WtE technologies, such as pyrolysis, gasification, incineration and anaerobic digestion (AD) have been designed to generate energy from various types of wastes [11]. However, similar to conventional energy generation from fossil fuels, WtE and renewable technologies also lead to GHG emissions and other environmental impacts, such as acidification, ecotoxicity and human toxicity [12]. It is possible that renewable technologies might result in higher impacts in some environmental categories compared to fossil fuel-based energy generation technologies [13]. In addition, individual WtE technologies might require more materials compared to fossil-fuelled plants, thus, leading to additional environmental impacts [14]. Therefore, it is imperative to study the environmental impacts of WtE technologies to estimate their potential to create a sustainable environment.

Life cycle assessment (LCA) is a powerful tool to compare the performance of WtE technologies to evaluate their environmental impacts [14,15]. The LCA tool is beneficial for the decision-makers to select the most sustainable WtE technology and identify potential steps or factors for improvements [12,16]. Several studies conducted an LCA of WtE technologies to assess their environmental impacts [17,18]. Dong et al. [16] compared the energy efficiency and environmental impacts of commercial plants of WtE technologies, including pyrolysis, gasification, and incineration for municipal solid waste (MSW) management using LCA. The results showed that the incineration plant proved a better sustainable technology than pyrolysis and gasification to produce a relatively high amount of energy from MSW with the lowest emissions [19]. The enhanced performance of the incineration plant was credited to the use of an effective combined heat and power cycle that helped to achieve surplus heat production of nearly 6% [19].

The environmental impacts of incineration and landfilling have been compared in numerous LCA studies in different regions of the world. The results of the majority of the LCA studies showed that incineration of MSW has lower net emissions compared to landfilling [20,21]. Anshassi et al. [22] investigated the life cycle of landfilling and incineration of MSW and identified the electricity grid offsets as the most significant factor for calculating net GHG emissions. The share of renewable energy in the power grid is significantly increasing and this would reduce GHG emissions from the grid [23]. By increasing the share of renewable energy in the power grid, its GHG emissions reach a certain point where incineration loses the climate advantage over landfilling [23]. Currently, fossil fuels are the primary source of energy across the world. However, in recent years the share of renewable sources in the grid, especially solar and wind energy, has been rapidly growing [24]. Over time the presumption about avoided emissions by electricity substitution would change and consequently, the results of the current LCA studies would not be applicable for an extended time. Therefore, investigating the influence of change in the energy mix over time on the environmental impacts of different WtE technologies becomes important. It is also necessary to develop a method to estimate the change in the energy mix when incineration becomes no longer beneficial for climate mitigation. This level of GHG emissions on the grid is the break-even point (BEP) for incineration and landfilling.

Electricity generation is the most significant source of GHG emissions in Australia. More than 70% of electricity in Australia is generated from fossil fuels [25]. The Australian government has a plan to reach a net zero emission economy by 2050 [26]. The main part of this plan is to decrease the GHG emission intensity from electricity generation, by 90% from the 2005 level [26]. The change in energy mix in Australia will influence the net emissions from waste treatment scenarios. In 2018–19 Australia produced a total waste of approximately 74.1 million tonnes (Mt), including 22.9 Mt of masonry materials, 14.3 Mt of organics, 12.5 Mt of ash, 7.8 Mt of hazardous waste (mainly contaminated soil), 5.9 Mt of paper and cardboard, 5.6 Mt of metals and 2.5 Mt of plastics [27]. Although recycling has been practised in Australia at a considerable level, there are limited WtE technologies adopted in Australia, which left landfilling with landfill gas recovery (termed as landfilling from now on) as the most used option for waste management. There are potentially different types of WtE technologies that could be adopted, depending on the types of generated waste and level of emissions from the grid so that sustainable management could be achieved [12,28].

The national pollutant inventories have high potential to provide the required data for conducting an environmental assessment [29]. Laurent et al. [30] and Dastjerdi et al. [12] reviewed 222 and 101 published LCA studies of solid waste management systems, respectively. The results of their evaluations showed that between 60 and 70% of the studies utilised commercial databases, between 10 and 20% employed the data reported in the literature, a few studies used the data from a facility as a case study and the rest of the studies did not mention the dataset. Environmental assessment studies on various WtE technologies based on the national pollutant inventories could offer a realistic perspective about the contribution of these technologies to the impact on human health and ecosystems and uncover the major contributor pollutants for each environmental impact category. To the best of our knowledge, no study has been conducted to assess the environmental impact of WtE technologies using national pollutant inventories and examining the potential of renewable energy sources to assess the prioritising of incineration and landfilling technologies for solid waste treatment. Therefore, this study aims to investigate the role of the replaced source of energy in avoided environmental impacts of WtE technologies and the influence of the alteration in the power grid mix on the avoided global warming impacts of the landfilling and incineration technologies. Furthermore, this study investigates the environmental impacts of landfilling, AD and incineration employing national pollutant databases.

2. Materials and Methods

2.1. Environmental Impact Assessment of Waste to Energy Technologies

Landfills throughout Australia with published data in national databases were selected to assess the environmental impacts of electricity generation. The Australian Government Clean Energy Regulator publishes a list of power plants with GHG emissions over 25 kt CO_2 eq. The annual amount of electricity generation and GHG emissions of each of the facilities in the list can be extracted from the NGER website [31]. The generated electricity in this study refers to the net electricity which can be exported to the grid and includes generation and consumption of the facilities. National Pollutant Inventory (NPI) is a governmental website which provides the level of pollutants emitted by different industry sectors and facilities [32]. In this study, environmental impact assessment was conducted on landfills with reported data on both NGER and NPI. In this case, 36 landfills were considered for environmental impact assessment since sufficient data of pollutant emission are required for a comprehensive environmental impact assessment. The detailed data of emissions of all 36 landfills is presented in the Supplementary Material in Table S1. Data related to direct pollutant emissions of the AD power station operating in Australia (EarthPower facility) was adopted for AD technology from NPI [32]. The EarthPower facility accepts source-separated food waste with no more than 5% contamination by weight [33]. The annual amount of electricity generation and GHG emissions of the EarthPower facility were extracted from a study conducted by Opatokun et al. [34]. Since there are no operating incineration power plants in Australia, the related data for incineration were extracted from European governmental and facility's websites for one incineration power plant located in the UK [35,36]. The data related to the Cory Riverside Energy incineration power plant with about 30% energy efficiency for electricity generation was employed in this study because in the temperate climate of Australia electricity is more desirable than heat as a final product from an incineration facility. [37–39]. Currently, an incineration power plant is under construction in Western Australia [40] with technical specifications and calorific value of the treatable waste similar to the Cory Riverside Energy incineration power plant [41]. Table 1 shows the reported direct emissions of selected pollutants and electricity generation from 36 landfills, one incineration power plant and one AD facility.

Table 1. Emissions of reported pollutants and electricity generation from WtE technologies.

Criteria Air Pollutants (kg/MWh)	Landfill	AD	Incineration
CO_2	58.25	0	5.95×10^{2}
NOx	1.36	0.88	1.24
SO_2	9.42×10^{-2}	0.30	2.37×10^{-2}
CO	3.64	2.04	2.22×10^{-2}
CH_4	0	0.82	0
PM_{10}	2.26×10^{-2}	3.96×10^{-2}	0
$PM_{2.5}$	2.12×10^{-2}	1.40×10^{-2}	0
VOCs	0.46	0.82	0
Arsenic	7.26×10^{-6}	7.61×10^{-7}	0
Antimony	0	1.28×10^{-7}	0
Beryllium	0	3.65×10^{-8}	0
Cadmium	9.93×10^{-6}	4.57×10^{-8}	6.26×10^{-9}
Chromium	6.11×10^{-5}	8.83×10^{-6}	4.13×10^{-4}
Chlorine	0	0	3.18×10^{-2}
Fluoride	0	2.53×10^{-5}	0
Copper	1.49×10^{-5}	3.65×10^{-6}	0
Lead	1.10×10^{-5}	4.57×10^{-6}	0
Manganese	2.08×10^{-4}	0	0
Mercury	9.66×10^{-7}	2.53×10^{-7}	5.42×10^{-9}
Nickel	1.32×10^{-4}	6.39×10^{-6}	0
Ammonia	0	0	2.66×10^{-3}
Formaldehyde (methyl aldehyde)	0.15	0	0
PAHs (B[a]peq))	9.37×10^{-6}	2.98×10^{-7}	0
Dioxins and furans (TEQ)	7.28×10^{-10}	0	0
Benzo(a)anthracene/(a)pyrene/(b)fluoranthene/(g,h,i)perylene/(k)fluoranthene	0	0	2.49×10^{-8}
Benzo(b)naphtho(1,2-d)thiophene	0	0	3.20×10^{-8}
Hydrogen chloride	0	0	2.13×10^{-2}
Hydrogen fluoride	0	0	2.65×10^{-7}
Dibenzo[a,h]pyrene-7,14-dione	0	0	4.15×10^{-8}
Fluoranthene	0	0	7.94×10^{-7}
Indeno(1,2,3-cd)pyrene	0	0	2.49×10^{-8}
Naphthalene	0	0	2.95×10^{-7}
Polychlorinated biphenyls	0	0	8.45×10^{-8}
Electricity generation (MWh)	755,063	32,850	534,828

OpenLCA software was employed for environmental impact assessment. The four stages of LCA study recommended by the International Standard Organization (ISO) guidelines, including goal and scope definition, life cycle inventory and assumptions, life cycle impact assessment (LCIA) and interpretation of the results [42,43] were carried out. The goal of this LCA study in the first part was to assess the environmental impacts of electricity generation from landfilling, AD, and incineration. One MWh of electricity generation was considered as a functional unit (FU) in this part of the study. In the second part, the environmental impacts of landfilling and incineration were compared based on treatment of one tonne of solid waste. Incineration and landfilling were employed for management of solid waste while the AD process was considered for management of food waste. The system boundary included all emissions from operating processes within the power plant required for electricity generation. Emissions related to waste collection and transport were excluded from this study. The data related to direct emissions to air, soil and water of each facility were imported manually to the OpenLCA software. The method adopted by Strezov and Cho [13] for forming the data inventory was followed in this study. ReCiPe 2016 midpoint and endpoint hierarchistmethods were applied for life cycle impact assessment [44]. The ReCiPe 2016 was applied in several LCA studies and is considered as one of the most popular impact assessment methods [12]. The midpoint and endpoint impact assessments on WtE technologies were achieved employing OpenLCA software and ReCiPe 2016 [44] midpoint and endpoint hierarchist methods. The average levels of environmental impact for landfilling technology were calculated by dividing the cumulative amount of emissions from all landfilling facilities for a specific impact category with the cumulative electricity generated by all landfilling facilities, as shown Equation (1).

$$LAE_j = \frac{\sum_{i=1}^{n} EIC_{ij}}{\sum_{i=1}^{n} Eg_i} \quad (1)$$

where LAE_j (landfilling average emissions) is the average level of environmental impact of electricity from landfilling for impact category type j (unit of impact category type j/MWh), EIC_{ij} is the amount of emission in impact category type j for facility i (unit of impact category j), and Eg_i represent the electricity generation from facility i (MWh).

Ten midpoint impact categories including global warming, fine particulate matter formation, freshwater ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, marine ecotoxicity, ozone formation (human health), ozone formation (terrestrial ecosystems), terrestrial acidification and terrestrial ecotoxicity were assessed. The cumulative results of the assessment of endpoint categories including global warming (human health), human carcinogenic toxicity, human non-carcinogenic toxicity, fine particulate matter formation, ozone formation (human health) based on disability adjusted life year (DALY) units were calculated as impacts to human health. Cumulative results of the assessment of 7 other endpoint categories with species loss over time (species.yr) unit were calculated as impacts to ecosystems. The results for midpoint and endpoint impact categories for three WtE technologies were calculated based on the data presented in Table 1. The relevant pollutants for each impact category have specific weights determined by the life cycle impact assessment method to estimate a normalised unit for each impact assessment category [30].

2.2. Comparing Net Environmental Impacts of Incineration with Landfilling

Incineration and landfilling can be employed to manage different types of solid waste. AD technology can only be employed for decomposable organic waste. Therefore, the study further focuses on the comparison of incineration and landfilling on treating 1 tonne of mixed solid waste to determine the impact of the energy mix change on the greenhouse gas emissions and mitigation of the two technologies. The environmental impact assessment was conducted by setting 1 tonne of solid waste as the functional unit for incineration and landfilling. Treatment of one tonne of solid waste generates a different amount of electricity through incineration (0.798 MWh/t) and landfilling (0.037 MWh/t) [35,45]. The characteristics of Australian solid waste including the moisture content, ash content and heating value were adopted from national reports and literature [46,47]. The generated electricity in waste treatment processes can replace the electricity from the power grid. By replacing the generated electricity, those emissions from the power grid can be avoided. The amount of avoided emissions is related to the amount of electricity generated through waste treatment and the intensity of the emissions from the power grid. It is anticipated that the avoided emissions by replacing electricity from the power grid would be zero in the future with a higher share of renewable energy in the grid [48].

The Australian grid vastly relies on fossil fuels. However, in the long-term period, renewable energy will grow and occupy a more significant share of the power grid [49]. Wind and solar power stations generate about 6.57 and 0.34% of electricity to the Australian grid, respectively. NGER [31] reported GHG emissions and electricity generation values for wind and solar energy power stations, while direct pollutant emissions data for these technologies were not available on NPI [32]. The total GHG emissions of electricity on the grid were calculated with Equation (2).

$$TGE = \sum_{i=1}^{n} (EI_i \times FTE_i \times TE) \quad (2)$$

where *TGE* is the total global warming impact (kg CO_2 eq), EI_i stands for emission intensity for technology type *i* (kg CO_2 eq/MWh), FTE_i represents the share (fraction) of technology type *i* from total electricity on the grid (dimensionless), and *TE* is total electricity supplied on the grid power (MWh)

Table 2 shows the number of power stations connected to the Australian grid, the annual amount of generated electricity and GHG emissions based on the technology from July 2017 to June 2018. Seven fossil fuel-based technologies (black coal, brown coal, waste coal mine gas, coal seam methane, natural gas, diesel and kerosene) and seven renewable energy-based technologies (hydro, wind, landfill gas, solar, sewage gas, biofuel (refuse-derived fuel) and bagasse) are employed to generate electricity in Australia. The annual Australian electricity supplied to the power grid was calculated by adding the amount related to all 14 electricity generation technologies together. Based on the data released by NGER (2018), the total amount of electricity provided to the grid for 2017/2018 was about 229,727 GWh. Table 2 also shows that black coal-fired power plants generated the largest electricity share of 55%, following by brown coal with about 16% and natural gas with a 13.5% share of the power grid. The greenhouse gas emissions of 1 MWh of electricity from the Australian power grid was calculated at 757 kg CO_2 eq [31].

Table 2. Selected power plants connected to the power grid for each technology and annual electricity generation and GHG emissions per technology from July 2017 to June 2018 [31].

Primary Fuel	Number of Power Plants Connected to Grid	Electricity Generation (MWh)	Total Emissions (t CO_2 eq)	Emission Intensity (t CO_2 eq/MWh)	Percentage of Total Electricity Generation
Black coal	17	1.26×10^8	1.12×10^8	8.83×10^{-1}	55%
Brown coal	3	3.61×10^7	4.41×10^7	1.22×10	15.7%
Gas	76	3.10×10^7	1.59×10^7	5.12×10^{-1}	13.5%
Hydro	57	1.57×10^7	4.05×10^5	2.58×10^{-2}	6.83%
Wind	57	1.51×10^7	2.48×10^4	1.64×10^{-3}	6.57%
Waste coal mine gas	11	1.69×10^6	9.55×10^5	5.63×10^{-1}	0.73%
Coal seam methane	7	1.50×10^6	8.27×10^5	5.50×10^{-1}	0.65%
Landfill gas	49	9.04×10^5	5.35×10^4	5.91×10^{-2}	0.39%
Solar	15	7.87×10^5	2.65×10^3	3.37×10^{-3}	0.34%
Bagasse	3	5.26×10^5	1.94×10^4	3.69×10^{-2}	0.23%
Sewage	1	6.43×10^4	4.25×10^3	6.61×10^{-2}	0.03%
Biofuel (refuse-derived fuel)	1	1.85×10^4	3.69×10^4	2.00×10	8.04×10^{-3}%
Diesel	10	1.14×10^4	1.28×10^4	1.12×10	4.97×10^{-3}%
Kerosene	1	9.74×10^3	1.39×10^4	1.42×10	4.24×10^{-3}%
Total	308	2.30×10^8	1.74×10^8	7.57×10^{-1}	100%

The main products of WtE technologies are energy and energy carriers. An increase in the share of renewable energies with lower emissions in the energy mix would decrease the environmental impacts of electricity from the grid. Therefore, the substitution of electricity would offset a smaller amount of impacts which results in lower environmental desirability of the WtE technologies. The environmental performance of a WtE technology is positively correlated with electricity generation per unit of mass and negatively correlated with emissions per unit of generated energy. As seen in Equation (3), a power grid with higher emissions can offset a larger part of emissions from WtE technologies.

$$NE_{ij} = \left(TAE_{ij} - AE_j\right) \times AEG_i \tag{3}$$

where NE_{ij} stands for the net emission for technology type *i* and impact category type *j* per tonne of feedstock (unit of impact category type *j*/t), AE_j represents the average level of environmental impact on impact category type *j* per one MWh of electricity from the primary source (power grid or coal) (unit of impact category type j/MWh), TAE_{jj} is the average level of environmental impact on impact category type j per one MWh of electricity from technology type i (unit of impact category type j/MWh), AEG_i represents the average amount of electricity generation per one tonne of feedstock processed through technology type i (MWh/t).

The zero value for NE_{ij} in Equation (3) means 1 MWh of electricity from technology type i has the same impact on impact category type j as the primary source (power grid or coal). The positive value of NE_{ij} shows that substitution of electricity from power grid with electricity from technology type i does not compensate for the entire emissions of impact category type j for processing one tonne of waste. The comparison between environmental impacts of electricity generation through a specific type of technology and power grid can determine the level of environmental benefit of replacing one MWh of electricity. Both energy generation and capability of treating waste are considered as the main criteria for comparing WtE technologies.

Break-even point (BEP) is a specific level of GHG emissions from the power grid where the net GHG emissions for processing 1 tonne of waste through incineration and landfilling is the same. BEP was calculated with Equation (4) by considering the net GHG emissions from the treatment of 1 tonne of waste through incineration and landfilling (kg CO_2 eq/t) as equal, while the emissions from the power grid (kg CO_2 eq/MWh) are considered as a variable.

$$(AEG_L \times TAE_L) - (AEG_L \times BEP) = (AEG_i \times TAE_i) - (AEG_i \times BEP)$$

$$(AEG_i \times BEP) - (AEG_L \times BEP) = (AEG_i \times TAE_i) - (AEG_L \times TAE_L)$$

$$BEP \times (AEG_i - AEG_L) = (AEG_i \times TAE_i) - (AEG_L \times TAE_L)$$

$$BEP = \frac{(AEG_i \times TAE_i) - (AEG_L \times TAE_L)}{(AEG_i - AEG_L)} \tag{4}$$

where BEP represents the level of GHG emissions for one MWh of electricity from the power grid, for which at that level the net GHG emissions for technologies type i and L are equal (kg CO_2 eq/MWh), AEG_i represents the average amount of electricity generation per one tonne of feedstock processed through incineration (MWh/t), TAE_i is the average level of GHG emissions for generation of one MWh of electricity from incineration (kg CO_2 eq/MWh), $\mathrm{AEG_L}$ represents the average amount of electricity generation per one tonne of feedstock processed through landfilling (MWh/t), $\mathrm{TAE_L}$ is the average level of GHG emissions for generation of one MWh of electricity from landfilling (kg CO_2 eq/MWh).

The global warming category was the only available data across all energy resources on the power grid. Therefore, the calculation of BEP was conducted on the GHG emissions to assess the consequences of the possible changes in the Australian power grid from replacing fossil fuels with renewable energy. The required changes in the share of energy sources in the power grid to decrease the average GHG emissions from the current values to the estimated BEP values was calculated by employing Equations (5) and (6). These equations can be utilised to calculate the required change in share of the two energy sources to alter the average GHG emissions. For instance, by replacing a fraction of the share of black coal in the grid with wind energy, the average GHG emissions from the grid would decrease. It also can be calculated for the ratio of the share of three energy sources. The results for three energy sources can be shown in ternary graphs. Equation (6) can be employed for finding all ratios of the share of the three energy sources when the average GHG emissions from the grid are at a specific level. In order to find these ratios, the fraction of the two energy sources was calculated when the fraction of the third energy source was considered zero. The connecting line between two calculated points on the sides of the triangle illustrates all the possible ratios for the specific GHG emissions.

$$\sum_{i=1}^{n} FS_i = 1$$
$$FS_1 + FS_2 + \sum_{i=3}^{n} FS_i = 1$$
$$FS_1 + FS_2 = 1 - \sum_{i=3}^{n} FS_i \tag{5}$$

where FS_i stands for a fraction of electricity from the energy source type i from total electricity on the power grid, FS_1 and FS_2 are the fractions of two energy sources that can replace each other, for instance, wind energy and black coal.

$$AG = \sum_{i=1}^{n} (FS_i \times ES_i)$$
$$AG = (FS_1 \times ES_1) + (FS_2 \times ES_2) + \sum_{i=3}^{n} (FS_i \times ES_i)$$
$$AG - \sum_{i=3}^{n} (FS_i \times ES_i) = (FS_1 \times ES_1) + (FS_2 \times ES_2) \tag{6}$$

where the AG is the average amount of GHG emissions from the power grid (kg CO_2 eq/MWh) and ES_i is emission intensity for energy source type i (kg CO_2 eq/MWh). FS and ES for each technology can be found in Table 2. The fractions of the two energy sources (FS_1 and FS_2) to determine when AG is equal to BEP was obtained by replacing the numerical values of BEP, ES_i and FS_i in Equations (5) and (6).

3. Results

This section presents the results of the environmental impact assessment of midpoint and endpoint level impact categories for three WtE technologies for the generation of one MWh of electricity. Midpoint and endpoint impact are two different levels of LCIA and either of the levels has advantages and disadvantages. Assessment of the net emissions of incineration and landfilling for treating one tonne of waste to produce electricity and its integration into the Australian power grid are presented. In the last section, the possible changes in the Australian power grid and the impact of the changes on net emissions of incineration and landfilling are discussed.

3.1. Midpoint Impact Assessment of Waste to Energy Technologies

A midpoint impact assessment focuses on evaluation of single environmental issues of concern. The impact categories with a value equal to zero for all three technologies were excluded while the results for the relevant 10 midpoint impact categories were presented. The results of the 10 impact categories for the considered WtE technologies are shown in Table 3, with the values illustrated in bold font representing the highest environmental impact levels, while the italic font demonstrates the lowest level of environmental impacts for each impact category. The highest environmental impacts in the eight categories, including freshwater ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, marine ecotoxicity and terrestrial ecotoxicity are related to landfill gas, which is attributed to atmospheric emissions of nickel, hexavalent chromium, lead, arsenic III and copper. The impact analysis in open LCA software also showed that the high value of environmental impacts in fine particulate matter formation and ozone formation (human health and terrestrial ecosystems) impact categories are attributed to emissions of acidic gasses of sulphur dioxide and nitrogen oxides.

Table 3. Results of midpoint impact assessment of electricity generation per MWh basis for three WtE technologies.

Impact category	Unit	Landfill	Anaerobic Digestion	Incineration
Fine particulate matter formation	kg PM2.5 eq	**0.21**	0.20	0.14
Freshwater ecotoxicity	kg 1,4-DCB	$\mathbf{9.62 \times 10^{-4}}$	1.39×10^{-5}	5.01×10^{-6}
Global warming	kg CO_2 eq	58.3	27.95	$\mathbf{5.95 \times 10^{2}}$
Human carcinogenic toxicity	kg 1,4-DCB	**0.17**	3.80×10^{-3}	1.55×10^{-5}
Human non-carcinogenic toxicity	kg 1,4-DCB	**2.63**	0.28	3.63×10^{-4}
Marine ecotoxicity	kg 1,4-DCB	$\mathbf{4.65 \times 10^{-2}}$	1.23×10^{-3}	1.83×10^{-5}
Ozone formation, human health	kg NO_x eq	**1.32**	0.88	1.24
Ozone formation, terrestrial ecosystems	kg NO_x eq	**1.32**	0.88	1.24
Terrestrial acidification	kg SO_2 eq	0.62	**0.62**	0.47
Terrestrial ecotoxicity	kg 1,4-DCB	**96.30**	3.13	1.75×10^{-2}

Incineration technology exhibited the highest level of global warming impact at 592 kg CO_2 eq/MWh, almost 10 times higher than that of landfill gas at about 58 kg CO_2 eq/MWh which has the second highest level of global warming impact. The high GHG emissions of incineration are related to carbon dioxide emitted during combustion of petroleum-based materials, such as plastics in solid waste. Incineration exhibited the lowest environmental impacts for fine particulate matter formation, freshwater ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, marine ecotoxicity and terrestrial acidification. The lowest emissions for the global warming category were related to the AD process. The biogenic source of carbon in feedstock utilised in the AD process can partly explain the level of impact in the global warming category. The absence of digestion in incineration compared to landfilling and AD technologies avoid methane emissions. Fugitive methane in landfills is one of the main sources of GHG emissions in the landfilling treatment. Among the three WtE technologies, incineration showed the minimum environmental impacts for fine particulate matter formation at 0.143 kg $PM_{2.5}$ eq/MWh and terrestrial acidification at 0.474 kg SO_2 eq/MWh. The best results for both ozone formation (human health and terrestrial ecosystems) and global warming impact categories were related to the AD process at 0.883 kg NO_x eq/MWh and 27.9 kg CO_2 eq/MWh, respectively. The detailed results of the midpoint impacts for all 36 landfills can be found in the Supplementary Material in Table S2.

3.2. Endpoint Impact Assessment of Waste to Energy Technologies

Endpoint impact assessment focuses on the impacts on human health and ecosystem quality. The translation of emissions into a limited number of endpoint scores utilising characterisation factors is useful for comparing the technologies at a higher level. Table 4 shows the results of the evaluations of environmental impact of WtE technologies on human health and ecosystems, while Figure 1 compares the aggregated endpoint impacts of the studied WtE technologies on human health and ecosystems.

The results revealed that the highest impacts to both ecosystems and human health were related to incineration. Incineration emitted at least 10 times higher GHG emissions which resulted in higher ecosystem and human health impacts. Landfill gas had the second-highest values in both human health and ecosystem impact categories. The level of damage to ecosystems by incineration is almost four times higher than landfill gas. The incineration impact on human health is approximately 3.5 times more than landfill gas. The high level of environmental impacts by incineration compared to the other two technologies result from the significantly larger amount of GHG emissions. The AD process showed the lowest impacts on both ecosystems and human health categories, followed by landfill gas.

The values of global warming and fine particulate matter formation have over 97.6% contribution to the human health impacts. The contribution of the endpoint categories was significantly different across the technologies with global warming responsible for 85.8% of impacts to human health by incineration. Fine particulate matter formation contributes to 14% of human health impact by incineration. The major contributors to impacts on ecosystems were the global warming, terrestrial acidification and ozone formation categories. Global warming makes over 86.5% of the contribution to the damage to ecosystems. Therefore, global warming is the most influential impact category in both ecosystem and human health endpoint impacts. Employing carbon capture technology and improving the pollution control system in incineration power plants could reduce GHG emissions and alleviate the ecosystem and human health impacts.

Table 4. Results of endpoint impact assessment of electricity generation per MWh basis for three different WtE technologies and contribution of each impact category to ecosystems and human health impacts in percentage.

Impact category	Unit	Landfill		Anaerobic Digestion		Incineration	
Global warming, human health	DALY	5.28×10^{-5}	28.62%	*1.26×10^{-8}*	0.01%	**5.52×10^{-7}**	85.80%
Human carcinogenic toxicity	DALY	**7.46×10^{-7}**	0.40%	1.26×10^{-8}	0.01%	*4.61×10^{-11}*	0.00%
Human non-carcinogenic toxicity	DALY	**4.48×10^{-7}**	0.24%	6.31×10^{-8}	0.05%	*8.26×10^{-11}*	0.00%
Fine particulate matter formation	DALY	**1.29×10^{-4}**	70.05%	1.25×10^{-4}	99.93%	*9.02×10^{-5}*	14.02%
Ozone formation, human health	DALY	**1.25×10^{-6}**	0.68%	*8.03×10^{-7}*	0.64%	1.12×10^{-6}	0.17%
Global warming, terrestrial ecosystems	species.yr	1.59×10^{-7}	34.04%	*7.82×10^{-8}*	24.15%	**1.67×10^{-6}**	86.51%
Terrestrial acidification	species.yr	1.29×10^{-7}	27.58%	**1.32×10^{-7}**	40.70%	*1.00×10^{-7}*	5.21%
Terrestrial ecotoxicity	species.yr	**8.35×10^{-10}**	0.18%	3.56×10^{-11}	0.01%	*1.99×10^{-13}*	0.00%
Ozone formation, terrestrial ecosystems	species.yr	**1.79×10^{-7}**	38.20%	*1.14×10^{-7}*	35.14%	1.59×10^{-7}	8.28%
Global warming, freshwater ecosystems	species.yr	4.35×10^{-12}	0.00%	*2.14×10^{-12}*	0.00%	**4.55×10^{-11}**	0.00%
Freshwater ecotoxicity	species.yr	**1.03×10^{-12}**	0.00%	9.64×10^{-15}	0.00%	*3.14×10^{-15}*	0.00%
Marine ecotoxicity	species.yr	**3.86×10^{-12}**	0.00%	1.30×10^{-13}	0.00%	*1.73×10^{-15}*	0.00%

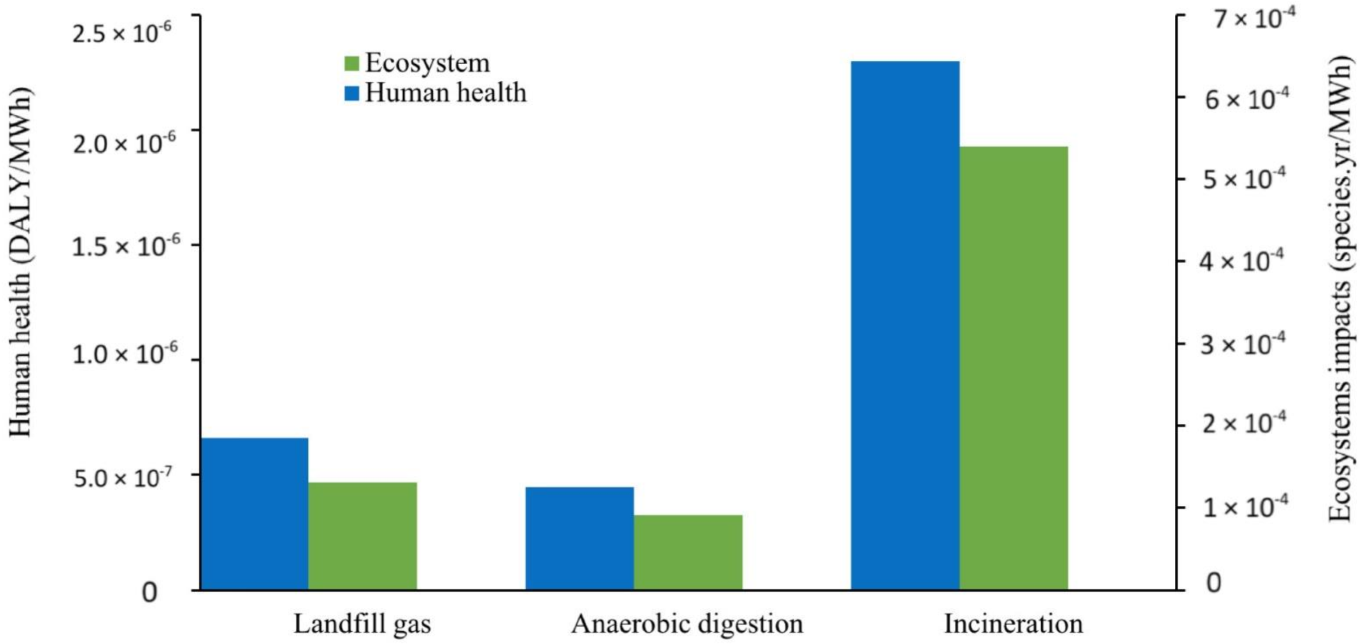

Figure 1. Results of impact assessment of electricity generation per MWh basis for three different WtE technologies on ecosystems and human health.

3.3. Net Environmental Impacts of Landfilling vs. Incineration

The main product of WtE technologies is energy. Incineration can be compared to landfilling based on treating 1 tonne of solid waste as a functional unit. Furthermore, a comparison between the two WtE technologies, incineration and landfilling, based on net emissions provides a more realistic outcome. The Riverside incineration power plant reported a generation of 0.798 MWh of electricity per tonne of solid waste [35]. In comparison, 1 tonne of solid waste in landfill can generate about 0.037 MWh of electricity [45]. The net environmental impacts for incineration and landfilling were calculated by reducing avoided emissions by replacing electricity from WtE technologies with brown coal, black coal and the Australian power grid from the direct emissions from the technologies by employing Equation (3).

3.3.1. Net Environmental Impacts by Replacing Electricity from Black Coal or Brown Coal

The net environmental impacts of WtE technologies depend on several factors, including direct emissions, feedstock and avoided environmental impacts by product replacement. The amount of avoided impacts is related to the source of the replaced product. Considering electricity as the main product of landfill and incineration, Equation (3) can be employed to calculate the net environmental impacts. This section assumed that electricity from incineration or landfill would replace black coal or brown coal.

The electricity generation from black coal and brown coal has very high environmental impacts. The environmental burdens in different impact categories for generation of one MWh electricity from black coal and brown coal was adopted from the results of a study conducted by Strezov and Cho [10]. The detailed midpoint and endpoint impacts of black coal and brown coal can be found in the supplementary material in Tables S3 and S4. Table 5 shows the net environmental impacts of incineration and landfill for treating one tonne of solid waste considering the avoided impacts by replacing electricity from black coal and brown coal.

Table 5. Net environmental impacts in midpoint categories from treatment of one tonne of solid waste through incineration and landfill considering avoided impacts by replacing electricity from black coal and brown coal.

Impact Category	Unit	Landfill Gas Electricity Replacing Black Coal	Incineration Electricity Replacing Black Coal	Landfill Gas Electricity Replacing Brown Coal	Incineration Electricity Replacing Brown Coal
Fine particulate matter formation	kg $PM_{2.5}$ eq	$\mathbf{-2.91 \times 10^{-2}}$	-0.68	-3.22×10^{-2}	*−0.75*
Freshwater ecotoxicity	kg 1,4-DCB	-1.20×10^{-4}	-3.35×10^{-3}	$\mathbf{5.99 \times 10^{-6}}$	-6.34×10^{-4}
Freshwater eutrophication	kg P eq	-5.18×10^{-7}	-1.12×10^{-5}	$\mathbf{-3.15 \times 10^{-7}}$	-6.78×10^{-6}
Global warming	kg CO_2 eq	**−30.37**	-2.27×10^{2}	−43.10	-5.01×10^{2}
Human carcinogenic toxicity	kg 1,4-DCB	$\mathbf{5.11 \times 10^{-3}}$	-2.23×10^{-2}	-1.59×10^{-3}	*−0.17*
Human non-carcinogenic toxicity	kg 1,4-DCB	$\mathbf{5.19 \times 10^{-2}}$	−0.98	4.21×10^{-3}	*−2.01*
Marine ecotoxicity	kg 1,4-DCB	$\mathbf{1.17 \times 10^{-3}}$	-1.20×10^{-2}	4.63×10^{-4}	-2.71×10^{-2}
Marine eutrophication	kg N eq	-5.55×10^{-6}	-1.20×10^{-4}	$\mathbf{-3.03 \times 10^{-7}}$	-6.54×10^{-6}
Ozone formation, human health	kg NO_x eq	$\mathbf{-7.37 \times 10^{-2}}$	−1.66	-8.11×10^{-2}	*−1.81*
Ozone formation, terrestrial ecosystems	kg NO_x eq	-1.82×10^{-2}	*−0.46*	$\mathbf{-5.64 \times 10^{-3}}$	−0.19
Terrestrial acidification	kg SO_2 eq	-4.41×10^{-2}	*−1.07*	$\mathbf{-3.15 \times 10^{-2}}$	−0.79
Terrestrial ecotoxicity	kg 1,4-DCB	**0.35**	−69.25	−0.62	*−90.16*

The results of all 12 midpoint impact categories revealed the higher benefits of incineration compared to landfilling. In seven impact categories, including fine particulate matter formation, global warming, human carcinogenic toxicity, human non-carcinogenic toxicity, marine ecotoxicity, ozone formation (human health) and terrestrial ecotoxicity, the incineration of solid waste with substitution of electricity from brown coal had higher level of avoided impacts. The higher environmental impacts of electricity generation from brown coal for the seven impact categories resulted in higher avoided impacts by its substitution. The highest avoided emissions in the other five impact categories were related to incineration with substitution of its generated electricity with electricity from black coal.

Table 6 presents the results for treating one tonne of solid waste through incineration and landfilling for the endpoint impact categories. The results for environmental impacts in all 13 endpoint impact categories suggested that incineration of solid waste had higher avoided emissions. Landfilling of solid waste with the substitution of its electricity with black coal had the highest environmental impacts in nine endpoint impact categories, while incineration of solid waste with substitution of its electricity with electricity from brown coal showed the highest level of avoided impacts in the same group of nine endpoint impact categories. In three endpoint impact categories, the avoided impacts of replacing electricity from black coal was less than the direct impacts from landfilling.

Table 6. Environmental impacts in endpoint categories from treating one tonne of solid waste through incineration and landfilling considering avoided impacts by replacing electricity from black coal and brown coal.

Impact Category	Unit	Landfill Gas Electricity Replacing Black Coal	Incineration Electricity Replacing Black Coal	Landfill Gas Electricity Replacing Brown Coal	Incineration Electricity Replacing Brown Coal
Global warming, human health	DALY	$\mathbf{-2.84 \times 10^{-5}}$	-2.14×10^{-4}	-3.87×10^{-5}	*-4.37×10^{-4}*
Human carcinogenic toxicity	DALY	$\mathbf{2.44 \times 10^{-8}}$	-6.94×10^{-8}	2.07×10^{-9}	*-5.51×10^{-7}*
Human non-carcinogenic toxicity	DALY	$\mathbf{1.03 \times 10^{-8}}$	-1.36×10^{-7}	-4.50×10^{-9}	*-4.55×10^{-7}*
Fine particulate matter formation	DALY	$\mathbf{-1.85 \times 10^{-5}}$	-4.31×10^{-4}	-1.93×10^{-5}	*-4.47×10^{-4}*
Ozone formation, human health	DALY	-1.65×10^{-8}	*-4.59×10^{-7}*	$\mathbf{-1.73 \times 10^{-9}}$	-1.40×10^{-7}
Global warming, terrestrial ecosystems	species.yr	$\mathbf{-8.66 \times 10^{-8}}$	-6.65×10^{-7}	-1.20×10^{-7}	*-1.38×10^{-6}*
Terrestrial acidification	species.yr	$\mathbf{-2.11 \times 10^{-8}}$	-4.78×10^{-7}	-2.26×10^{-8}	*-5.10×10^{-7}*
Terrestrial ecotoxicity	species.yr	$\mathbf{-5.74 \times 10^{-12}}$	-7.90×10^{-10}	-1.72×10^{-11}	*-1.04×10^{-9}*
Ozone formation, terrestrial ecosystems	species.yr	-1.90×10^{-9}	*-5.63×10^{-8}*	$\mathbf{-4.17 \times 10^{-10}}$	-2.44×10^{-8}
Global warming, freshwater ecosystems	species.yr	$\mathbf{-2.32 \times 10^{-12}}$	-1.71×10^{-11}	-3.32×10^{-12}	*-3.87×10^{-11}*
Freshwater ecotoxicity	species.yr	-6.90×10^{-14}	*-2.31×10^{-12}*	$\mathbf{1.76 \times 10^{-14}}$	-4.44×10^{-13}
Freshwater eutrophication	species.yr	-3.52×10^{-13}	*-7.58×10^{-12}*	$\mathbf{-2.11 \times 10^{-13}}$	-4.55×10^{-12}
Marine ecotoxicity	species.yr	$\mathbf{8.36 \times 10^{-14}}$	-1.28×10^{-12}	9.65×10^{-15}	*-2.87×10^{-12}*

Figure 2 shows the overall avoided impacts to human health and ecosystems by treating one tonne of solid waste through incineration and landfilling when the electricity produced replaces the current black coal and brown coal use. Treating solid waste through both WtE technologies had higher avoided impacts compared to their direct environmental impacts from incineration and landfilling process. The direct emissions from the incineration of one tonne of solid waste is higher than the direct emissions from the landfilling of the same amount of waste. However, because incineration can generate over 21 times more electricity compared to landfilling from the same amount of solid waste, the avoided emissions for incineration are significantly higher. Considering generated electricity replacing electricity from black coal, the avoided impacts to human health and ecosystems for incineration were approximately 14 and 11 times more than landfill gas, respectively. The changes in the source of replaced electricity avoided from black coal to brown coal for incineration increase the avoided impacts to human health and ecosystems by about 37 and 60%, respectively. The same change in electricity substitution for landfilling increases the avoided impacts to human health and ecosystems by 24 and 30%, respectively.

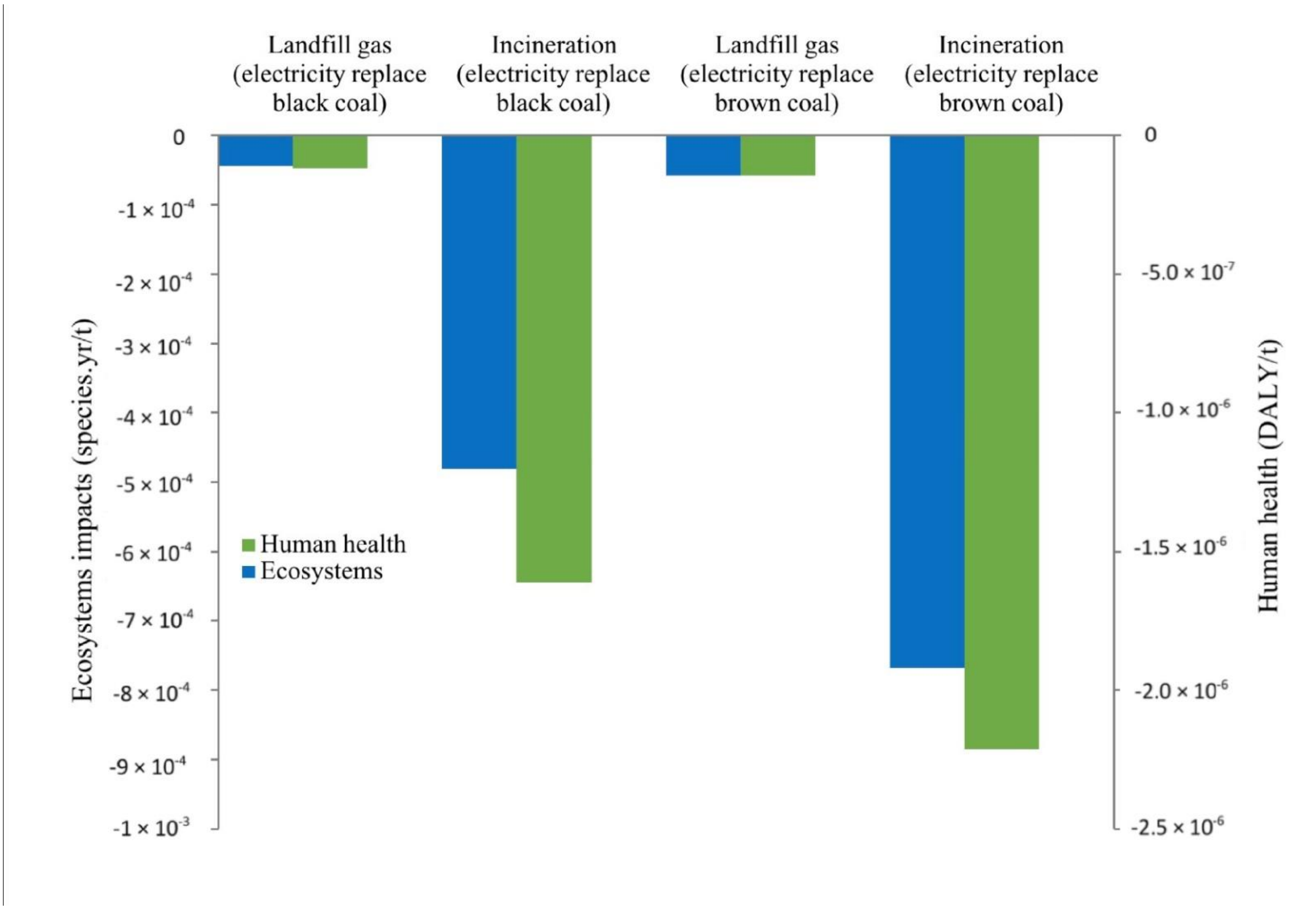

Figure 2. Avoided impacts to human health and ecosystems from treating one tonne of solid waste through incineration and landfilling considering avoided impacts by replacing electricity from black coal and brown coal.

3.3.2. Net Global Warming Impact by Replacing Electricity from the Australian Power Grid Considering Anticipated Changes

In this section, it was assumed that the generated electricity from landfill gas or incineration would replace electricity from the grid. The sensitivity of the results related to GHG emissions was assessed based on the potential variation of the energy sources contributing to power generation in Australia. The results of Section 3.1 showed that the global warming impact for incineration and landfilling were approximately 595 and 58 kg CO_2 eq per MWh, respectively. Considering electricity substitution by employing Equation (3), the net GHG emission for incineration and landfill were approximately −129 and −26 kg CO_2 eq/t, respectively. The calculated values for net emissions showed that incineration had a lower impact on global warming than landfilling; however, the environmental impact from the power grid is dependent on the changes in the energy mix. The results of research conducted on the evaluation of environmental impacts of several waste management scenarios showed that incineration of one tonne of solid waste compared to landfilling had a significantly lower impact on global warming [45]. By replacing fossil sources with renewable sources in the energy mix, the average GHG emissions of the power grid would decrease and eventually, the emission level would reach BEP. Equation (4) was employed to calculate a BEP of GHG emissions of the power grid for treating one tonne solid waste. The results showed that the BEP of the power grid for the global warming impact for incineration and landfilling is when the GHG emissions are approximately 621 kg CO_2 eq/MWh. This means a change in the energy mix that reduces

GHG emissions from the power grid to 621 kg CO_2 eq/MWh will result in the same net global warming impact from incineration and landfilling (−21 kg CO_2 eq/t).

As shown in Table 7, replacing black coal and brown coal with cleaner energy sources could reduce the power grid GHG emissions to the BEP. By replacing 15.5% of the power grid related to black coal or 11.2% related to brown coal with solar, the GHG emissions from the grid are expected to decrease to 621 kg CO_2 eq/MWh. The required replacement share of the power grid for wind is just about 0.1% below the solar values to reach the calculated BEP value, because the GHG emissions from wind and solar are relatively low with the difference of about 1.74 kg CO_2 eq/MWh. The GHG emissions from the grid could reach the BEP level by replacing 36.61% of the power grid related to black coal with natural gas. However, replacing all of the current share of brown coal from the grid (15.7%) with natural gas is not sufficient to reach the calculated BEP. An additional 6.6% of the power grid related to black coal should be replaced with natural gas to reach the BEP level.

Table 7. The minimum solar, wind and natural gas required to replace black coal and brown coal to reach to BEP of global warming of the power grid equal to 621 kg CO_2 eq/MWh (one percent of electricity on the grid is equal to about 2,297,270 MWh).

Energy Sources in the Power Grid	Current Share in the Power Grid	Wind Replaces Black Coal	Wind Replaces Brown Coal	Solar Replaces Black Coal	Solar Replaces Brown Coal	Natural Gas Replaces Black Coal	Natural Gas Replaces Brown Coal and Black Coal
Black coal	54.99%	−15.42%	0	−15.45%	0	−36.61%	−6.56%
Brown coal	15.70%	0	−11.14%	0	−11.15%	0	−15.70%
Natural gas	13.50%	0	0	0	0	36.61%	22.26%
Wind	6.57%	15.42%	11.14%	0	0	0	0
Solar	0.34%	0	0	15.45%	11.15%	0	0
Other sources	8.89%	0	0	0	0	0	0
Total	100.00%	0	0	0	0	0	0

In a number of studies, the electricity mix of other countries was considered as an alternative for the local energy mix [50]. Perez et al. [51] evaluated the effect of the energy mix in two extreme states of the power grid where 100% is either based on fossil fuel or renewable energies. Goulart Coelho and Lange [52] conducted a sensitivity analysis of the variation in the contribution of hydroelectricity to the grid. The results of these studies were in line with the current findings.

Figure 3 shows the type and ratio of variation in the energy mix, which could change the incineration and landfill priorities for treating solid waste. Ten ternary diagrams illustrate all possible combinations of five energy sources on the Australian power grid. Any variations in the energy mix will change the net emissions of WtE technologies. In each ternary diagram, it was assumed that three energy sources could replace each other's share on the grid, while the share of the other 11 energy sources remain intact. The blue line in each ternary diagram represents the BEP, illustrating all possible ratios of the three energy sources on the grid with the same GHG emissions to treat one tonne of solid waste through incineration and landfilling. All combinations of the three energy sources in the power grid in orange areas have GHG emissions higher than 621 kg CO_2 eq/MWh. Red lines in ternary diagrams represent all possible mixes of energy sources in which 1 MWh of electricity generation from incineration and the power grid have equal impacts on the global warming category at 595 kg CO_2 eq/MWh. In the orange areas, incineration of one tonne of solid waste has lower net GHG emissions compared to landfilling. In the orange and yellow regions, net GHG emissions for both technologies are negative. In the yellow and green areas of the ternary graphs, landfilling for one tonne of solid waste has a lower amount of net GHG emissions than incineration.

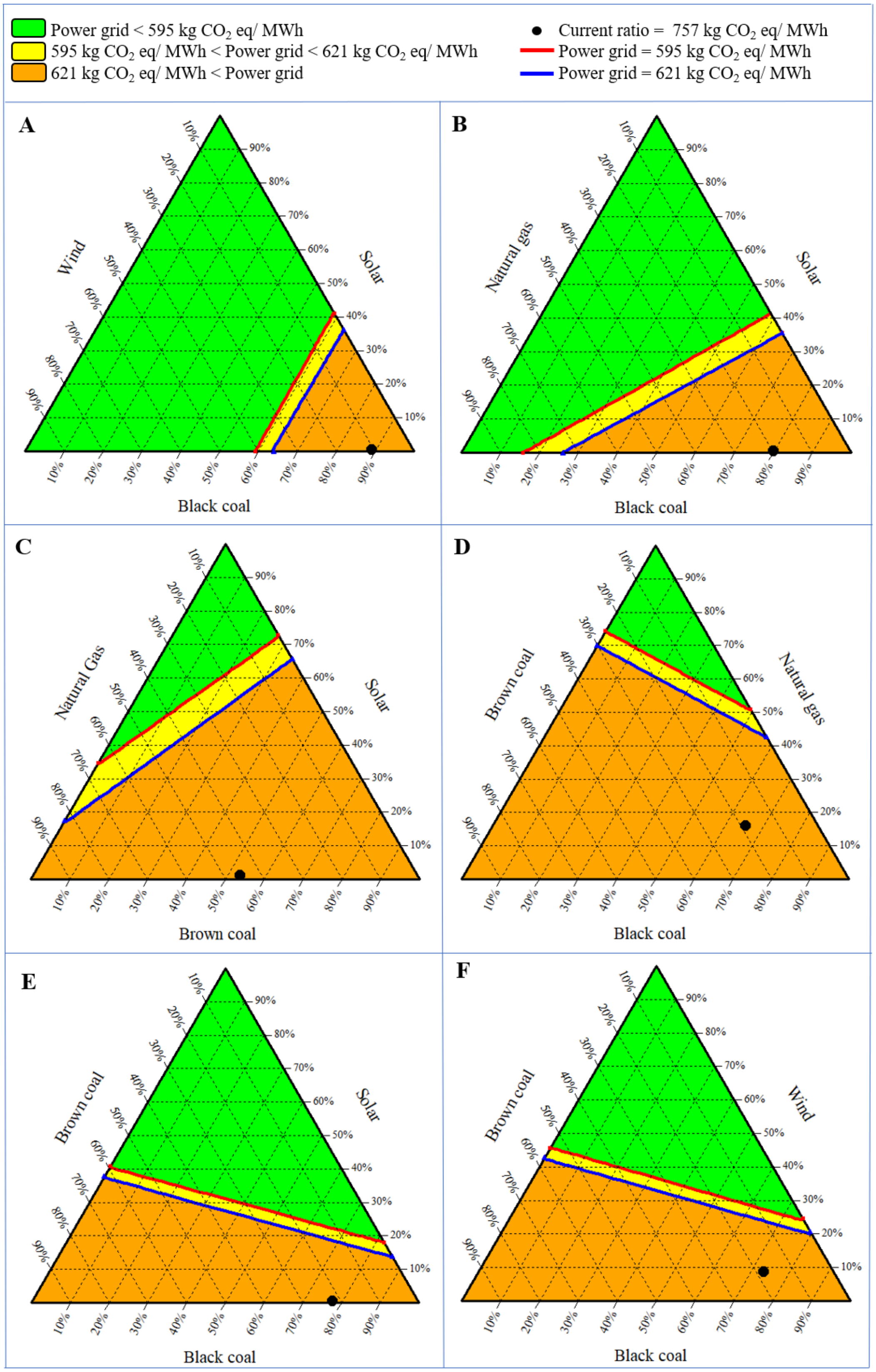

Figure 3. *Cont.*

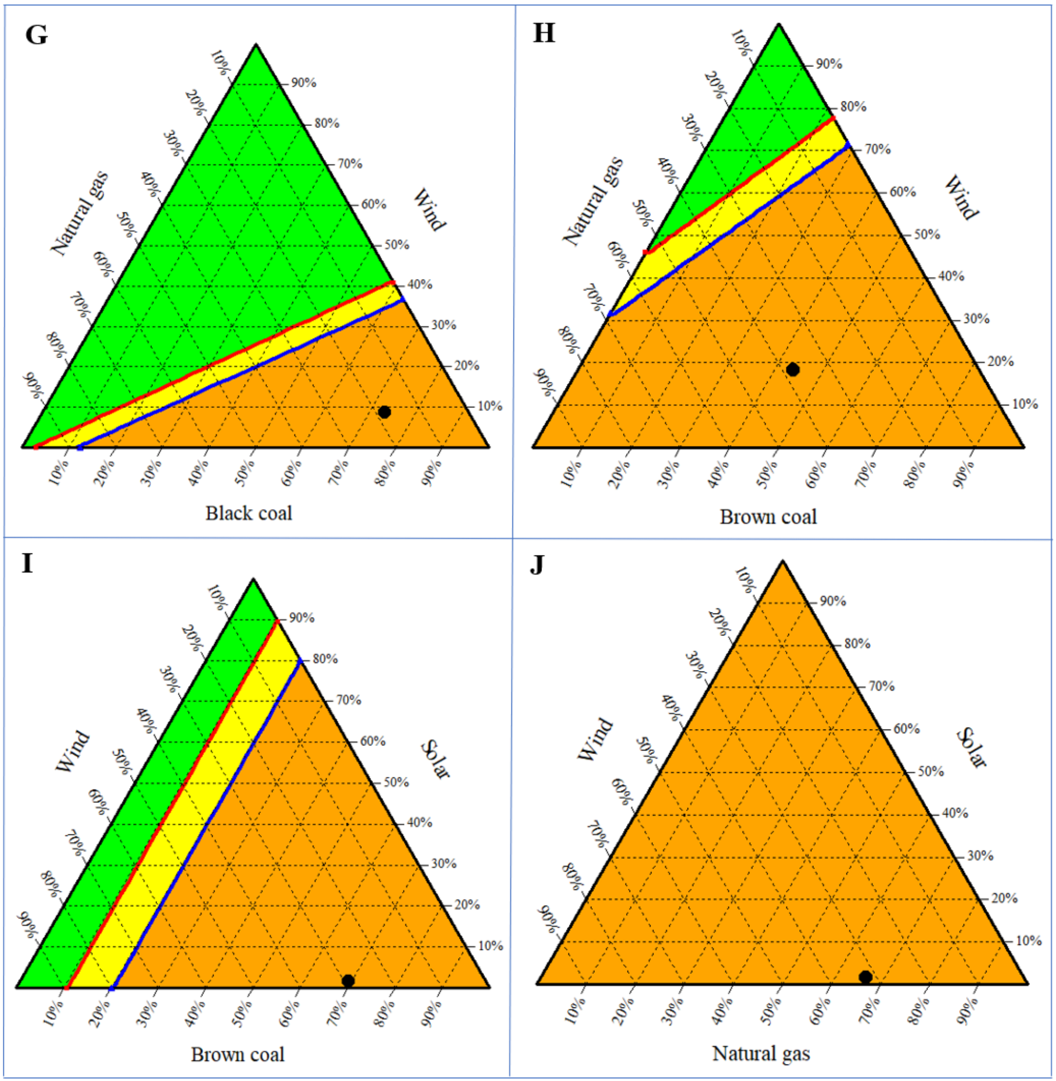

Figure 3. The environmental desirability of incineration and landfilling based on changes in level of impact on global warming category by substitution of black coal, brown coal, natural gas, wind and solar in Australian power grid. Percentage in each ternary graph represents the combined share of three energy sources from the power grid. The combined share of three energy sources from the Australian power grid for each ternary graph is equal to (**A**) 61.9%; (**B**) 68.8%; (**C**) 29.5%; (**D**) 84.2; (**E**) 71%; (**F**) 77.3%; (**G**) 75.1%; (**H**) 35.8%; (**I**) 22.6%; (**J**) 20.4%.

The general trend in the results is consistent with those of Demetrious et al. [17], Ferdan et al. [53], Gehrmann et al. [54], Kourkoumpas et al. [38], Ramos et al. [55], Ripa et al. [56], Zhou et al. [57]. However, employing the NPI for environmental impact assessment in this study leads to the estimation of a lower amount of emissions for WtE technologies compared to the majority of other studies. The system boundary defined by the NPI could be the main reason for this difference. The NPI considered direct emissions from facilities and excluded the emissions from the construction of infrastructure, manufacturing of equipment, and the collection and transport of waste [58]. The results showed that data inventories, such as the NPI, can be employed to estimate the direct environmental impacts of the WtE process. Expanding the system boundary by including environmental impacts of the use of products, complementary treatment for residuals, construction of infrastructure, manufacturing of equipment, and collection and transport of waste could change the priority of the WtE technologies.

4. Conclusions

The study employed pollutant emissions data from Australian and European emission databases to evaluate and compare the environmental impacts of WtE technologies considering anticipated changes in electricity supply. The results of the study suggest that global warming and fine particulate matter formation are two impact categories with the major contributions that impact human health. The main contributors to impacts on ecosystems are the global warming, terrestrial acidification and ozone formation categories. The level of environmental impact of fine particulate matter formation and terrestrial acidification categories for incineration are lower than landfill gas and anaerobic digestion (AD). Furthermore, the environmental impact of the ozone formation category for incineration is slightly higher than AD technology. However, the results for endpoint impact categories showed the electricity generated through the incineration process had the highest environmental impacts in both the human health and ecosystem categories. The comparison between the results from midpoint and endpoint impact categories highlighted the significant influence of the global warming category. Assuming electricity from WtE technologies replaces electricity from brown coal and black coal, the avoided impacts to human health and ecosystems for treating one tonne of solid waste through incineration would be significantly higher than landfilling. A variation in the mix of energy on the power grid, including the substitution of black coal and brown coal with natural gas, wind and solar energies may change the level of environmental benefits of WtE technologies. The global warming impact of treating one tonne of solid waste through incineration (−129 kg CO_2 eq/t) was lower than landfilling (−26 kg CO_2 eq/t). If the average GHG emissions from the power grid (757 kg CO_2 eq/MWh) decrease to 621 kg CO_2 eq/MWh, incineration and landfilling would have an equal amount of net GHG emissions. A further reduction in the average GHG emissions from the power grid below 595 kg CO_2 eq/MWh would result in unfavourable global warming benefits from electricity generation through incineration. The emissions from the substitution source are crucial and the growing share of the renewable energies in the power grid could change the priority of waste treatment methods.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142315971/s1, Table S1: Atmospheric emissions and electricity generation of 36 landfill facilities (the expressed values are total annual amounts); Table S2: Results of midpoint impact assessment and the amount of electricity generation for 36 different landfill facilities (the expressed values are total annual amounts); Table S3: Environmental impacts in midpoint categories for electricity generation from landfill gas, incineration, black coal and brown coal per MWh basis; Table S4: Environmental impacts in endpoint categories of electricity generation from landfill gas, incineration, black coal and brown coal per MWh basis.

Author Contributions: B.D.: conceptualization, methodology, data curation, writing—original draft. V.S.: writing—review and editing, conceptualization, supervision. R.K.: writing—review and editing. M.B.: supervision. All authors have read and agreed to the published version of the manuscript.

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