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Comparative analysis of the environmental impacts of Australian thermal power stations using direct emission data and GIS integrated methods

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ABSTRACT

This study integrates National Pollutant Inventory emission data and geographical information system (GIS) to analyse the environmental impacts of 197 Australian thermal power stations. ReCiPe 2016 hierarchist method was used to investigate mid and endpoint impacts and found that 93.3% of the total midpoint impacts of fossil fuel sources were attributed to global warming impacts due to high CO_2 emissions, whereas those of renewable energy technologies were driven by global warming and terrestrial ecotoxicity impacts with contribution rates of 46.2% and 47.8%, respectively. Brown coal had the highest mid and endpoint impacts per MWh electricity, whereas sewage gas and landfill gas performed the lowest midpoint and endpoint impacts, respectively. Total endpoint impacts of fossil fuel sources were in the order of brown coal > black coal > diesel > natural gas, while sewage gas > bagasse > landfill gas for renewables. It is estimated that total CO_2 emissions from Australian electricity generation can be reduced by 30% when renewable electricity generation increases from 17.1% to 50% of the total electricity mix. Since the majority of coal power stations are located in high population areas, the potential impacts in these areas could be a concern.

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1. Introduction

Despite the growing concerns about the adverse environmental impacts of electricity generation, Australian electricity generation is still dominated by fossil fuel sources, which contributed to 34% of the country's total CO_2 emissions in 2019 [1]. Pollutants emitted from power stations can cause a range of issues on human health, and threaten natural habitats. Emissions of acidic gases cause acid rain, while emissions of particulate matter (PM), NO_x and VOCs can create urban smog and cause respiratory malfunction in humans [2]. In addition, emissions of trace metals can seriously affect water quality [3].

A recent review on the environmental impacts of five electricity generation technologies showed that black and brown coal-fired electricity generation had the highest emissions of CO_2 and SO_2, whereas diesel electricity had relatively high NO_x and particulate matter (PM) emissions than other fossil fuel sources [4]. High emissions were associated with power stations without emission control measures, such as selective catalytic reduction (SCR) or PM filters [5]. In contrast, power generation with high generation efficiency and good quality of fuel sources led to low emissions [6]. Coal electricity presented the most significant global warming potential (GWP), while natural gas performed the lowest GWP among four fossil fuel sources (black coal, brown coal, diesel and natural gas) [4].

Emissions of pollutants from power stations and their consequent impacts can be reduced by substituting fossil fuel sources with renewables, or by adopting emission control technologies such as carbon capture and storage (CCS) [7]. CCS technologies were reported to contribute to around 47–86% reductions in GWP compared to conventional power stations [4] by capturing CO_2 from power stations and preventing its release into the atmosphere [8]. However, the increase in acidification, eutrophication and human toxicity impacts by the application of CCS due to the emissions of other pollutants during the CCS processes could be a concern [9]. Electricity generation using wood biomass was found to decrease GWP by 86% than coal-fired electricity, but other impacts including acidification, ozone layer depletion and PM formation were higher

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Abbreviations

CCS	Carbon capture and storage
FGD	Flue gas desulphurisation
GHG	Greenhouse gas
GIS	Geographic information system
GWP	Global warming potential
HELE	High efficiency low emission
LCA	Life cycle assessment
LGA	Local government area
NPI	National pollutant inventory
PM	Particulate matter
SCR	Selective catalytic reduction
WtE	Waste to energy

than or comparable to fossil fuel electricity in some cases [4]. Landfill gas is another renewable source which can produce electricity, while reducing the amount of landfilled waste [10]. Although reduction potential of global warming impacts of landfill gas electricity varied depending on the applied waste-to-energy (WtE) technologies (e.g. incineration, anaerobic digestion), landfill gas electricity showed great reductions in GWP when compared to conventional landfilling without energy recovery [11].

Pollutant emissions and their impacts can vary according to fuel types and power generation technologies, while individual pollutants can pose different health risks and threats to the environment. Therefore, optimising the power generation systems towards low impact generation systems should be preceded by full understanding of various environmental impacts of power generation processes.

Life cycle assessment (LCA) is one of the highly regarded tools for quantifying the environmental impacts resulting from the pollutant emissions, and to compare the impacts at a midpoint or endpoint levels [12]. However, LCA lacks in reflecting geographical variations of the environmental impacts and is unable to combine different types of datasets, such as climatic or demographic data of a specific region [3]. To complement these shortcomings, geographical information system (GIS) has been applied in some environmental studies. GIS is a tool that enables integration, analysis and display of spatial data, providing flexibility of being combined with different types of datasets [13]. Attempts have been made to integrate geographical factors into environmental impact studies. Vandepaer et al. [14] estimated long-term marginal electricity supply mixes that reflect changes in electricity demand based on large geographical coverage (40 countries), while Abdul-Manan et al. [15] conducted a regionalised LCA to evaluate life cycle GHG emissions of different hybrid engine options in the transport sector. Wu et al. [16] found the differences in carbon footprint of battery electric vehicles according to 31 provinces in China by conducting a regionalised LCA where the differences in regional electricity mix of the 31 provinces were considered. Despite the advantages of using GIS in conjunction with LCA, the integrated approach in impact assessment studies is very scarce, especially for fossil fuel electricity generations, with exception to the study by Mutel et al. [17] who demonstrated spatial distribution of the environmental impacts of US electricity generations.

The results of LCA are affected by a number of factors including data quality, system boundaries and electricity generation technologies [18]. Ross and Cheah [19] pointed out the importance of data quality in order to reduce uncertainties in LCA studies. In Australia, there is a national scale database for reporting and monitoring pollutant emissions, named National Pollutant Inventory (NPI), which reports 93 substances as emissions to air, water and soil based on facilities. Despite the wide range of NPI emission data and their public availability, the NPI data has been underutilised in research areas, particularly for analysing emissions from power stations [20]. To date, many previous studies have used industrial or commercially available LCA databases [21] which may not adequately reflect site-specific parameters. Also, surprisingly low number of studies have examined the environmental impacts of power generations using reliable country-specific data, such as NPI, which has constrained the comparison of the impacts of different types of fuel sources. Strezov and Cho [22] analysed mid and endpoint impacts of Australian thermal power generation technologies using the NPI emissions data, and concluded that brown coal electricity is the most impactful fuel source on per MWh basis. However, the study was limited to a small number of power stations where the implications of the impacts on Australian population and geographical impact analysis were not included. In this context, this study aims to investigate the environmental impacts of all Australian power stations based on eight fuel sources by integrating GIS method into impact assessment with utilising the NPI database, which is believed to be the first attempt. The study objectives include (1) comparison of the environmental impacts of eight fuel sources, (2) identification of significances of various impacts, and (3) visualising geographical variations of the impacts in relation to Australian population.

2. Methods

2.1. Data collection

In order to quantify the environmental impacts of power generations, currently operating Australian power stations for eight different fuel sources were selected based on the data from Australian Government Clean Energy Regulator [23] which reports annual electricity generations and total greenhouse gas (GHG) emissions as carbon dioxide equivalent according to primary fuel sources. The GHG emissions data were used as CO_2 equivalent emissions for impact assessment. As classified by NGER [23], five fossil fuel sources, namely black coal, brown coal, natural gas, diesel and coal seam methane, and three renewable sources, landfill gas, sewage gas and bagasse were selected in this study. The number of power stations and their technical parameters are summarised in Table 1. Among three sewage gas power stations, NGER only reported one power station (Werribee biogas facility), therefore the electricity data for the other two power stations were obtained from Sustainability Victoria [24], while the GHG emission data were obtained from AEMO [25].

All pollutants emitted from the power stations to air, water and soil were collected from the National Pollutant Inventory (NPI) [26] database which were later used to assess the potential environmental impacts of power stations. Both NGER and NPI data were selected for the period of July 2017 to June 2018. Since NPI reports aggregated emission data for Bluewaters A and B, and Callide A and B black coal power stations, the total annual electricity and GHG emission data were also aggregated for these power stations. Among 269 power stations reported by NGER, NPI emission data were only available for 197 power stations, therefore 197 power stations were analysed in this study. Geographical locations (longitude and latitude) of all 197 power stations were also collected from the NPI database, while population (number of people per local government area) and geographical boundary of local government areas were obtained from Australian Bureau of Statistics [27], both of which were used to explore the geographical variations of the environmental impacts of power stations. Based on the NPI emissions data as well as impact factors given to each

Table 1
Selection of power stations and their technological parameters.

Fuel source	Number of power stations analysed in this study	Average annual electricity generation per power station (GWh)	Total electricity generation in 2017−18 (GWh)	Average installed capacity (MW)	Average generation efficiency (%)
Fossil fuels					
Black coal	14	8422.0	126,330.1	435.5	37.8
Brown coal	3	12,020.4	36,061.3	463.0	27.9
Natural gas	76	422.4	32,943.9	75.7	34.3
Diesel	48	3.4	161.4	34.4	34.9
Coal seam methane	6	213.9	1283.4	158.4	34.6
Renewables					
Landfill gas	44	19.7	864.7	3.1	45.6
Sewage gas	3	24.4	73.3	n.a	n.a
Bagasse	3	175.5	526.4	n.a	n.a
Total	**197**		**198,244.5** [i]		

i. Total electricity generations from the selected 197 power stations account for about 76% of the total national electricity generation in 2017−18 ′(261,139.7 GWh).
*Source [30,32].

pollutant, a total of 12 midpoint and 14 endpoint impacts were estimated. Impact factors and other parameters based on which the impacts were estimated are presented in supplementary Table S1.

For sensitivity analysis, data for Australian electricity mix with total electricity generation for the period of July 2017 to June 2018, and projected electricity mix in 2030 were collected from CSIRO and Energy Networks Australia [28], DEE [29] and Department of Industry, Science, Energy and Resources [30]. Since detailed data for renewable energy sources were not available, percentage shares of landfill gas, sewage gas and bagasse to total electricity mix were estimated based on the amount of electricity generated from each fuel source accounted for total electricity generation. The percentage share was then applied to estimate the contribution rate of each fuel source to total impacts of electricity generation which was calculated as multiplying impact values by the percentage share of each fuel source (e.g. value of global warming impact of black coal * percentage share of black coal). Australian power stations do not have CCS or other advanced emission control technologies, but utilise either fabric filters or electrostatic precipitator for controlling pollutant emissions [31]. Graphical methodology and research processes of this study are presented in Fig. 1.

2.2. Goal and system boundaries

The goal of this study was to investigate the environmental impacts of Australian power stations. System boundaries included analysing point source emissions from power stations during the process of electricity generation in order to uncover commonly emitted pollutants from power stations, to identify the most polluting fuel source, and to estimate the environmental impacts of power stations. The impacts were expressed as per MWh of electricity, which was the functional unit of this study. The impacts were further analysed to provide an overview of geographical variations of the impacts, and to discover areas with higher impacts. System input included pollutant emissions including CO_2 emissions and electricity generation of each power station, while system output included midpoint and endpoint environmental impacts of power stations.

2.3. Environmental impact assessment

In this study, analysis was performed in two series. Pollutant emissions and electricity generation data were imported into OpenLCA, the open access LCA software. The emissions were analysed using ReCiPe 2016 midpoint and endpoint hierarchist method because ReCiPe is considered as one of the best impact assessment methods that includes both midpoint and endpoint impacts with the wide range of impact categories (12 midpoint categories and 14 endpoint categories) [33]. NPI emissions data were grouped into three categories, emissions to air, soil and water which were then imported into OpenLCA as emissions to air, soil (unspecified) and water (ocean or river) with selecting low population density. The

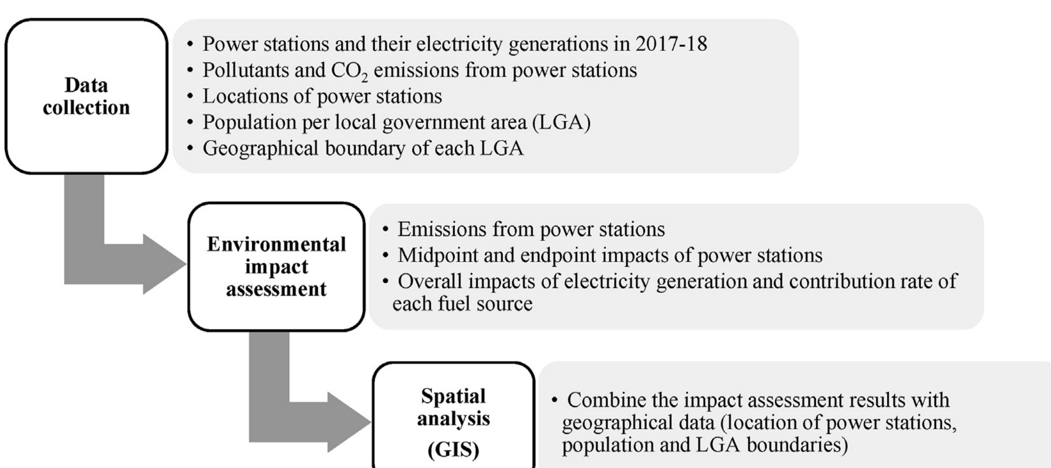


Fig. 1. Graphical methodology and research processes of this study.

type of water was determined based on the location of each power station, with the locations also derived from NPI. Pollutants reported by NPI were matched to pollutants considered in the ReCiPe method for recognition by the OpenLCA software. For example, metals with compounds from NPI were imported as corresponding metals in the OpenLCA, arsenic from the NPI was considered as the less polluting arsenic III compound in the OpenLCA, chromium as chromium III, and polychlorinated dioxins and furans (TEQ) as dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin. Although NPI reports the emissions of particulate matter as $PM_{2.5}$ and PM_{10}, PM_{10} emissions also include the emission of $PM_{2.5}$, therefore the emission value of $PM_{2.5\text{-}10}$ was calculated by subtracting $PM_{2.5}$ from PM_{10}, and imported into OpenLCA as $PM_{2.5}$ and $PM_{2.5\text{-}10}$.

Impact assessment was conducted based on 12 midpoint impact categories which were global warming, human carcinogenic toxicity, human non-carcinogenic toxicity, ozone formation (human health), fine particulate matter formation, freshwater ecotoxicity, freshwater eutrophication, marine ecotoxicity, marine eutrophication, ozone formation (terrestrial ecosystems), terrestrial acidification and terrestrial ecotoxicity. While midpoint method analyses the cause (emission)-result (impact) pathways based on the 12 categories, endpoint method analyses the potential damages on human health and ecosystems based on the same categories.

2.4. Spatial analysis

As a second series of the analysis, endpoint impacts obtained through the first series of analysis were summed up and grouped into two, impacts on human health and on ecosystems, and integrated with the locations of 197 power stations. Greenhouse gas emissions were also integrated with the location data, and then these integrated datasets were imported into Geographical Information System (GIS) to investigate spatial variations of the impacts. In order to discover areas where higher populations are potentially at risk due to the impacts of electricity generation, populations of 563 local government areas (LGAs) were spatial-joined with geographical boundary of each corresponding LGA in GIS which were used as a base map where the integrated impact datasets were overlaid on.

3. Results

3.1. Emissions of major pollutants

Table 2 summarises average emissions of major pollutants from eight fuel sources, classified as primary air pollutants, air toxics and metals. Among all fuel sources, bagasse electricity had the highest emissions in six out of 20 pollutants which included the highest particulate matter (PM_{10}) emissions, dioxins and furans, polycyclic aromatic hydrocarbons (PAHs), and three metals, arsenic, copper and lead. Brown coal was by far the highest emitter of CO_2, while having the lowest NO_x emissions. When zero emission values were excluded, natural gas had the lowest metal emissions, particularly in cadmium, copper, mercury and nickel emissions. Sewage gas power stations had no metal emissions with the lowest air toxics emissions among all studied fuel sources.

Fig. 2 illustrates the locations of 197 power stations and their CO_2 emissions on a national scale. Total annual emissions of power stations (Fig. 2-a) appeared to have low overall emissions (range 1 emissions, see Fig. 2-a) with only few power stations in the east coast areas having high annual CO_2 emissions, however, considerably larger number of power stations were in the range 2–3 CO_2 emissions when the emissions per MWh electricity were considered (Fig. 2-b).

* Ranges 1–8 represent the intensity of CO_2 emissions, with one being the lowest emission range and eight being the highest.

3.2. Midpoint environmental impacts of electricity generation from eight fuel sources

Midpoint impacts are designed to understand the mechanisms of potential environmental impacts caused by pollutant emissions, and to reflect the relative importance of pollutants and their contributions to each impact category [34]. The midpoint impact assessment conducted for 197 Australian power stations found the highest total midpoint impacts in brown coal among eight fuel sources followed by black coal, diesel and natural gas, mainly due to their high global warming impacts resulting from CO_2 emissions (see Table 3). Although brown coal had the highest impact in only one impact category (global warming) out of 12, its considerably high global warming impact (about 39% higher than black coal and 69.5% higher than diesel) led to the highest total midpoint impact of brown coal. However, as presented in Fig. 3, which estimates contribution rate of each fuel source to 12 impact categories, brown coal was the second largest contributor to total global warming impacts of national electricity mix. Considering 46.6% of share of black coal in the national electricity mix in 2017–18, whereas only 13.8% share of brown coal, the differences in their percentage shares resulted in different contribution rates of the two fuel sources to total global warming impact.

Table 3 presents average values of 12 midpoint impact categories based on fuel sources. Among all eight fuel sources, bagasse had the highest impacts in four out of 12 categories, which were human non-carcinogenic toxicity, freshwater eutrophication, marine ecotoxicity and terrestrial ecotoxicity. Despite the lowest global warming impact of bagasse, its significantly high terrestrial ecotoxicity impact made bagasse electricity have the highest total midpoint impacts among three renewable sources. However, when the share of bagasse to total electricity mix was considered, all four highest impacts decreased considerably due to its small share (0.2%, Fig. 3). Black coal and diesel both had the highest impacts in three out of 12 categories. In case of black coal, emissions of chromium (VI), and dioxins and furans were major contributors to freshwater ecotoxicity, while sulphur dioxide and ammonia contributed to terrestrial acidification. High $PM_{2.5}$ emission of diesel led to the highest PM formation impact, while emission of NO_x contributed to both ozone formation impacts of diesel. Large share of black coal (46.6% of total electricity mix) exacerbated its already high impacts which left black coal having the highest impact in 11 out of 12 impact categories. Natural gas had the lowest impacts in two out of 12 categories (see Table 3) with the lowest overall midpoint impact among four fossil fuel sources, however when its share (20.6%) was considered, its overall impacts increased from 13.7% to 17.5% to the total impact of national electricity mix (Fig. 3).

In order to understand geographical variations of global warming impacts, and to discover the relationship between the impacts and populations, the average global warming impacts of each fuel source were combined with a national-scale population map, and presented according to the local government areas. As illustrated in Fig. 4, the global warming impacts exhibited variations across the power stations, with the highest impact found in natural gas power station (point A in Fig. 4). Locations of the majority of coal and renewable power stations coincided with areas where most populations reside (east coastal areas), thus their high global warming and human toxicity impacts could be a concern in these areas.

i) 12 midpoint impacts of each fuel source were estimated as multiplying the impact values presented in Table 3 by the share (%) of each fuel source in 2017–18 electricity mix (numbers in brackets

Table 2
Emissions of major pollutants from electricity generation.

	Black coal	Brown coal	Natural gas	Diesel	Coal seam methane	Landfill gas	Sewage gas	Bagasse
Primary air pollutants (kg/MWh)								
CO_2	8.83E+02	1.23E+03	6.86E+02	7.24E+02	5.60E+02	6.20E+01	5.60E+01	4.19E+01
NO_x	1.84E+00	1.48E+00	1.81E+00	7.19E+00	3.98E+00	1.76E+00	2.58E+00	1.85E+00
SO_2	2.78E+00	2.95E+00	5.75E-03	8.14E-03	3.41E-03	2.18E-01	1.08E+00	9.98E-02
VOC	8.08E-03	1.55E-02	7.31E-02	2.74E-01	1.96E-01	4.14E-01	3.09E-01	9.75E-02
CO	1.07E-01	5.15E-01	7.68E-01	1.37E+00	7.82E-01	3.55E+00	5.61E+00	3.18E+00
$PM_{2.5}$	3.39E-02	5.25E-02	3.01E-02	3.30E-01	1.45E-02	2.75E-02	2.01E-05	1.81E-01
PM_{10}	3.76E-02	5.37E-02	1.57E-03	7.02E-03	7.00E-04	1.29E-03	2.01E-05	7.22E-02
Air toxics (mg/MWh)								
Benzene	0	0	3.55E+01	5.11E+01	3.29E+02	0	0	1.57E+00
Formaldehyde	0	0	1.58E+04	0	3.87E+04	1.76E+05	0	4.21E+02
Dioxins and furans	7.55E-05	8.43E-05	5.77E-06	3.27E-06	4.69E-06	9.21E-04	0	9.25E-04
PAHs	2.47E+00	6.80E-01	1.29E+01	1.13E+02	5.50E+00	2.02E+01	5.64E-02	2.02E+03
Toluene	2.90E-03	0	4.59E+01	3.38E+01	3.02E+02	0	0	6.06E-02
Xylene	2.90E+00	1.66E+00	2.14E+01	3.31E+01	1.37E+02	0	0	5.44E-02
Metals (mg/MWh)								
Arsenic	2.53E+00	6.18E+00	1.04E+00	2.77E+01	1.01E+00	1.30E+00	0	3.57E+01
Cadmium	5.00E+00	9.47E+00	2.59E+00	2.23E+01	3.60E+00	4.13E+00	0	8.89E+00
Chromium VI	4.48E-01	6.76E+00	1.51E+00	1.52E+01	7.57E-01	1.15E+02	0	1.94E+01
Copper	1.20E+01	2.02E+01	2.17E+00	0	3.07E+00	1.13E+01	0	1.58E+02
Lead	1.42E+01	9.99E+00	3.33E+00	6.53E+01	1.98E+00	5.56E+00	0	1.88E+02
Mercury	4.22E+00	2.80E+01	7.68E-01	5.46E+00	1.16E+00	1.12E+00	0	2.11E+00
Nickel	1.56E+01	4.01E+01	4.20E+00	2.15E+01	7.53E+00	8.72E+00	0	3.21E+01

i. PM_{10} represents particulate matter emissions of between $PM_{2.5}$ and PM_{10}.

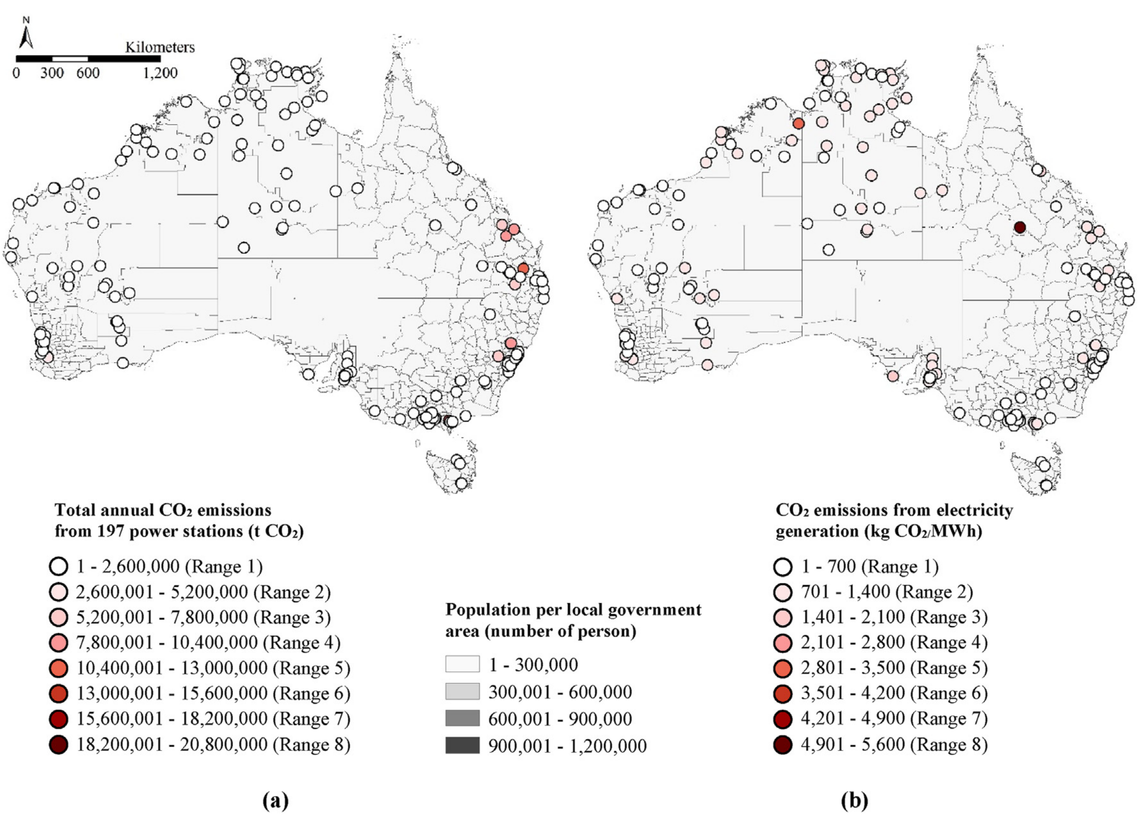


Fig. 2. CO_2 emissions from power stations; (a) Total annual CO_2 emissions of 197 power stations; (b) CO_2 emissions per MWh of electricity.

denote the percentage share of each fuel source).

ii) Percentage share was calculated based on total electricity generation data of black coal, brown coal, natural gas and diesel, derived from CSIRO and Energy Networks Australia [28], and Department of Industry, Science, Energy and Resources [30]. Share of diesel was assumed to be the share of oil. Since the shares of coal seam methane, landfill gas, sewage gas and bagasse electricity were not available, their shares were estimated based on the proportion of electricity generation of each fuel source to total electricity generation in the year of 2017–18.

i) Values in red and blue denote the highest and the lowest values in each impact category, respectively.

Table 3
Midpoint impacts of electricity generation from eight fuel sources (per MWh electricity).

Midpoint impact category	Unit	Blackcoal	Browncoal	Natural gas	Diesel	Coal seam methane	Landfill gas	Sewage gas	Bagasse
Global warming	kg CO_2 eq	882.7	1227.2	686.4	724.2	560.7	62.0	56.0	41.9
Human carcinogenic toxicity	kg 1,4-DCB	3.49E-02	2.00E-01	1.28E-01	3.01E-01	8.98E-02	8.40E-01	1.40E-06	6.99E-01
Human non-carcinogenic toxicity	kg 1,4-DCB	3.83	2.57	0.21	3.16	0.29	1.11	1.10E-08	10.49
Ozone formation, Human health	kg NO_x eq	1.99	1.48	1.83	7.02	3.99	1.76	2.18	1.89
Fine particulate matter formation	kg $PM_{2.5}$ eq	1.05E+00	1.08E+00	2.33E-01	1.10E+00	4.53E-01	2.96E-01	5.14E-01	4.00E-01
Freshwater ecotoxicity	kg 1,4-DCB	5.89E-03	9.00E-04	2.89E-04	1.95E-04	5.85E-04	6.55E-04	1.58E-08	5.81E-03
Freshwater eutrophication	kg P eq	1.41E-05	3.01E-05	0	0	0	0	0	1.50E-04
Marine ecotoxicity	kg 1,4-DCB	1.41E-01	3.62E-02	6.73E-03	1.06E-02	5.22E-03	4.48E-02	6.93E-07	1.65E-01
Marine eutrophication	kg N eq	5.71E-04	1.37E-05	0	0	0	0	0	0
Ozone formation, Terrestrial ecosystems	kg NO_x eq	1.99	1.49	1.84	7.02	3.99	1.76	1.98	1.89
Terrestrial acidification	kg SO_2 eq	3.88	3.49	0.67	2.53	1.44	0.89	1.69	0.85
Terrestrial ecotoxicity	kg 1,4-DCB	122.0	112.3	5.6	24.3	10.3	89.5	2.7E-06	380.8

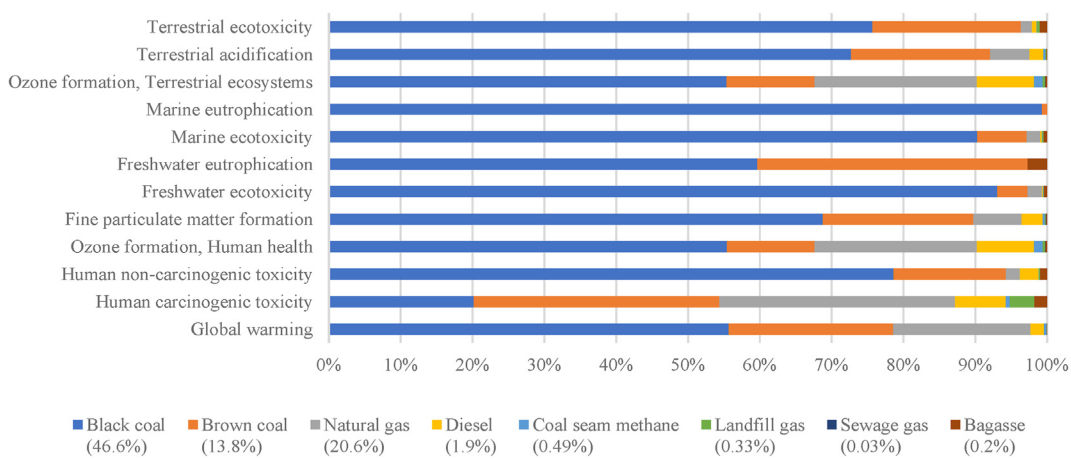


Fig. 3. Contribution rate of fuel sources to each midpoint impact category.

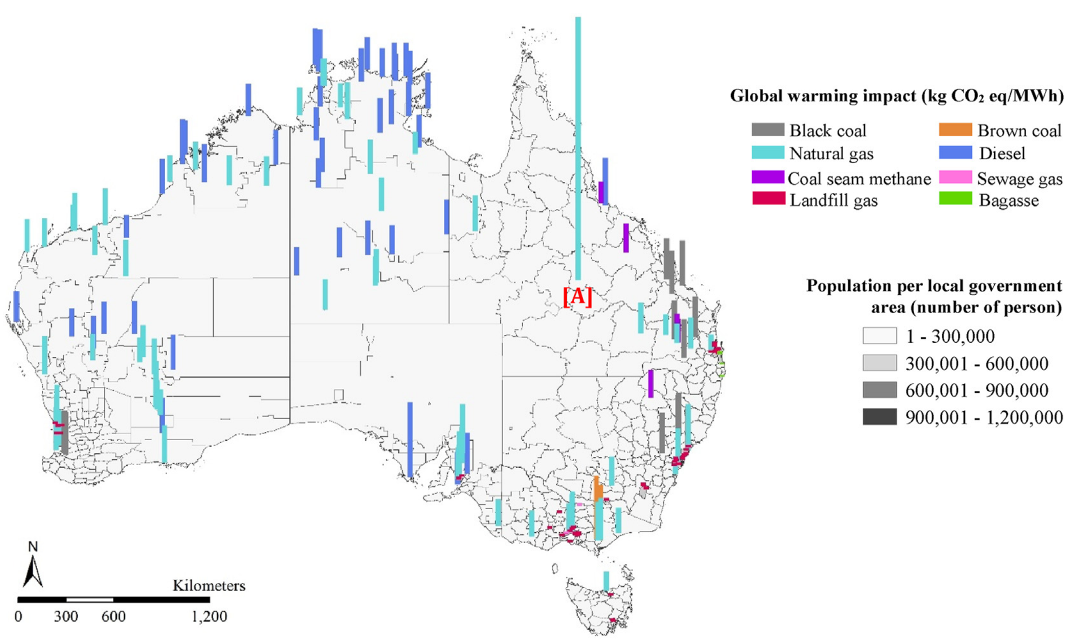


Fig. 4. Global warming impact of 197 power stations.

ii) For full details about impact factors and parameters that are used to estimate each impact category, please see ReCiPe2016 midpoint column in Table S1 in supplementary material.

* Bars illustrate global warming impact of each power station, expressed as kg CO_2/MWh. Longer bars indicate higher impacts, while the types of fuel sources are differentiated by colours. This

figure is drawn based on the impact assessment results presented in Table 3.

3.3. Endpoint environmental impacts of electricity generation from eight fuel sources

ReCiPe method also considers endpoint impacts to estimate final damages on human health and ecosystems caused by pollutant emissions. Endpoint impacts on human health reflect years of a person being disabled due to a disease or an accident, and is expressed as disability adjusted life years (DALY), whereas impacts on ecosystems estimate species loss over time, and is expressed as species.yr [33]. Table 4 presents average endpoint impacts on human health and ecosystems according to eight fuel sources, where among them, brown coal exhibits the highest impacts on both categories, followed by black coal and diesel, while landfill gas shows the lowest total endpoint impacts. Despite the five highest impacts of bagasse electricity out of 14 impact categories, it had the second lowest total endpoint impact due to the significantly low impacts from other categories. In contrast, brown and black coal both had the highest impacts in three categories, where the highest total endpoint impact of brown coal was mainly driven by its relatively high global warming and fine particulate matter formation impacts with the contribution rates of 62% and 37%, respectively. When the percentage share of each fuel source to total electricity mix was considered, black coal had the highest impacts in both endpoint categories, followed by brown coal and natural gas, while total endpoint impacts of renewable sources were almost negligible (Fig. 5).

As presented in Fig. 6, the total endpoint impacts expressed on per MWh of electricity varied across the power stations with some of diesel and natural gas power stations in Western Australia exhibiting higher total endpoint impacts than brown or black coal power stations. Also, more impactful power stations, including brown and black coal power stations, were mostly located in highly-populated areas, while majority of diesel and gas power stations were located in remote and less populated areas with relatively low generation capacity. Multi-source renewable energy systems that integrate biogas, solar and wind as proposed by Zhang et al. [35] could be a useful alternative for remote areas for increasing energy security, while reducing the adverse impacts of fossil electricity generation systems.

i) Total human health impacts are a sum of five categories shown in Table 4, whereas total ecosystem impacts are a sum of nine categories. For details, see Table 4.

3.4. Sensitivity analysis

3.4.1. Emission reduction scenarios

Sensitivity analysis was performed to address choices and assumptions made throughout the analysis, and to confirm how these choices affect the assessment results. Total CO_2 emissions from electricity generations of eight fuel sources were selected as parameters to examine whether emissions reduction target in 2030 could be met. First, five scenarios were developed based on percentage shares of the eight fuel sources to total electricity generation in 2017–18 and projected shares in 2030. Since the projected shares in 2030 for renewable energy sources were not available, landfill gas, sewage gas and bagasse were combined, and expressed as 'renewables' in the scenarios. Coal seam methane electricity was excluded in this sensitivity analysis due to data availability. Projected electricity mix for the year of 2030, derived from CSIRO and Energy Networks Australia [28], and Department of Industry, Science, Energy and Resources [30] were used as baseline scenario, while total electricity generation (MWh) remained the same as the year of 2017–18. Scenario S1-a and S1-b considered further 5% and 10% increases in renewable electricity generations than the projected generation in 2030, respectively. Scenario S2-a and S2-b assumed 5% and 10% increases in total electricity generation in 2030 than in 2017–18, while percentage shares in electricity mix remained the same as baseline scenario. The scenarios were developed based on the information about the projected share of renewable electricity and demand for electricity in 2030, reported by Refs. [28,29,36,37] where 48–50% share of renewable electricity and about 275,000 GWh of electricity generation in 2030 were projected.

Electricity mixes and descriptions of the scenarios are summarised in Table 5. Based on these scenarios, total annual CO_2 emissions from different electricity generation systems were estimated and presented in Fig. 7 as per million tonnes of CO_2 emissions (Mt CO_2). Total CO_2 emissions were estimated to decrease by 30% (baseline scenario), compared to 2017–18 emissions (from 199.4 Mt to 138.9 Mt of CO_2) which further decreased by 32.4% when renewable electricity generation increased by 10% (S1-b) than the projected generation in 2030 (from 199.4 Mt to 134.8 Mt). However, when only 5% increase in the renewable electricity generation was achieved (S1-a), total annual CO_2 emissions were slightly higher than the baseline scenario (from 138.9 Mt to 139.5 Mt) due to the increased electricity generation from black and brown coal in order to meet the demand for electricity. Projected CO_2 emissions in increased total electricity generation scenarios (S2-a and S2-b) were slightly higher than the baseline, S1-a and S1-

Table 4
Endpoint impacts of electricity generations from eight fuel sources (per MWh electricity).

Endpoint impact category	Unit	Black coal	Brown coal	Natural gas	Diesel	Coal seam methane	Landfill gas	Sewage gas	Bagasse
Global warming, Human health	DALY	8.21E-04	1.13E-03	6.47E-04	6.75E-04	5.23E-04	5.75E-05	5.24E-05	3.89E-05
Human carcinogenic toxicity	DALY	1.02E-07	6.89E-07	4.26E-07	9.01E-07	2.97E-07	2.79E-06	4.68E-12	2.23E-06
Human non-carcinogenic toxicity	DALY	4.56E-07	5.78E-07	4.84E-08	4.91E-07	6.52E-08	2.53E-07	2.51E-15	1.71E-06
Ozone formation, Human health	DALY	1.90E-06	1.35E-06	1.71E-06	6.53E-06	3.63E-06	1.60E-06	1.98E-06	1.74E-06
Fine particulate matter formation	DALY	7.09E-04	6.81E-04	1.50E-04	7.05E-04	2.85E-04	1.86E-04	3.19E-04	2.82E-04
Total impacts on human health		**1.53E-03**	**1.81E-03**	**7.99E-04**	**1.39E-03**	**8.13E-04**	**2.48E-04**	**3.74E-04**	**3.27E-04**
Freshwater ecotoxicity	species.yr	3.34E-12	6.12E-13	2.00E-13	1.11E-13	4.06E-13	4.17E-13	1.07E-17	3.59E-12
Freshwater eutrophication	species.yr	9.51E-12	9.02E-12	0	0	0	0	0	1.51E-10
Global warming, Freshwater ecosystems	species.yr	6.74E-11	9.40E-11	5.34E-11	5.57E-11	4.27E-11	4.74E-12	4.29E-12	3.21E-12
Marine ecotoxicity	species.yr	1.16E-11	5.28E-12	7.07E-13	8.99E-13	5.48E-13	4.72E-12	7.38E-17	1.63E-11
Marine eutrophication	species.yr	6.93E-13	9.06E-14	0	0	0	0	0	0
Global warming, Terrestrial ecosystems	species.yr	2.47E-06	3.41E-06	1.95E-06	2.04E-06	1.56E-06	1.74E-07	1.52E-07	1.17E-07
Ozone formation, Terrestrial ecosystems	species.yr	2.70E-07	1.92E-07	2.43E-07	9.25E-07	5.15E-07	2.27E-07	2.45E-07	2.47E-07
Terrestrial acidification	species.yr	9.13E-07	7.22E-07	1.44E-07	5.49E-07	3.04E-07	1.89E-07	3.40E-07	1.93E-07
Terrestrial ecotoxicity	species.yr	2.50E-09	1.41E-09	6.43E-11	2.32E-10	1.19E-10	1.02E-09	3.12E-17	4.06E-09
Total impacts on ecosystems		**3.65E-06**	**4.32E-06**	**2.34E-06**	**3.51E-06**	**2.38E-06**	**5.90E-07**	**7.37E-07**	**5.61E-07**

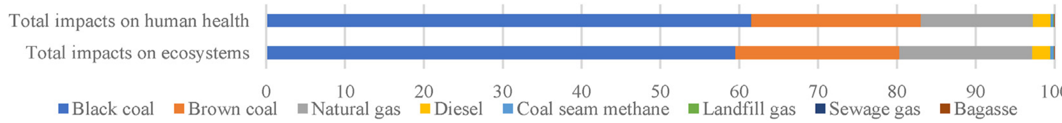


Fig. 5. Contribution rate of fuel sources to total endpoint impacts on human health and ecosystems.

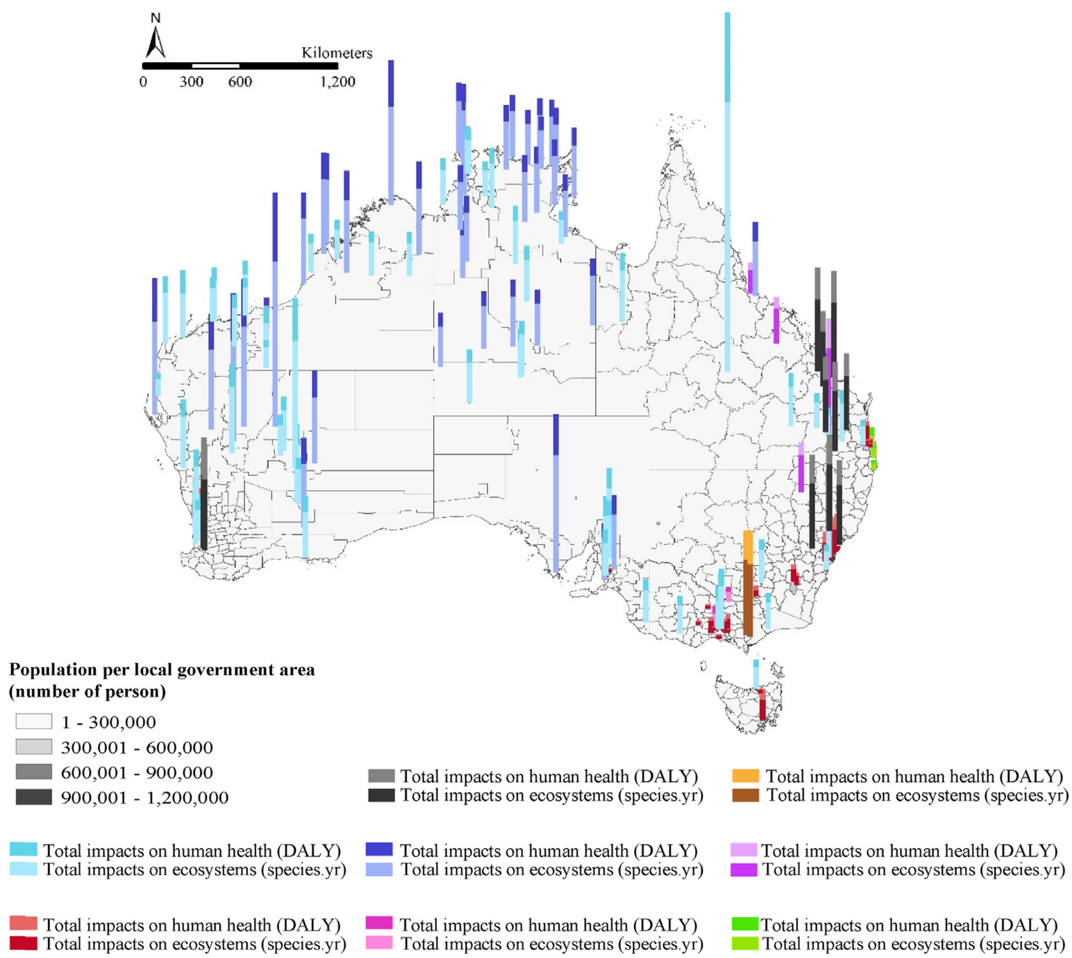


Fig. 6. Total endpoint impact of electricity generation and population per local government area.

b scenarios with total CO_2 emissions of both scenarios increased with the amount of electricity increases. This scenario analysis confirms that the emission reduction target of 131 Mt CO_2 from the electricity sector in 2030 [29] may not be able to be met without stricter regulations of CO_2 emissions.

Projected electricity mix in 2030 was also applied to estimate potential changes in total endpoint impacts. As shown in Fig. 8, total human health impacts are projected to decrease by 9.1%, and total impacts on ecosystems decrease by 14.4% in 2030 compared to the impacts in 2017–18 when the projected 2030 electricity mix was applied with total electricity generation remained the same as the 2017-18 level. Contribution rates of renewables to total endpoint impacts are projected to be much higher in 2030 than in 2017–18 in both impacts due to the increased electricity generations from renewable sources. Despite the decrease in percentage share of black coal in 2030, its contribution rates to both endpoint impacts will still be the highest although the contribution rates will become very similar to those of renewables in 2030.

3.4.2. Comparison of impact assessment results by two assessment methods

Impact assessment results can differ according to the applied assessment methods, and differences in the results can be found in overall impacts or in some specific impact categories. Impact factors represent the relative importance of individual pollutant which impacts are estimated accordingly, and the factors vary across the methods to a large extent which cause differences in impact assessment results. In this regard, CML-IA baseline method was applied to perform a new set of impact assessment for examining differences in the assessment results. Detailed information about the impact factors, and inclusion and exclusion of each pollutant to impact categories are summarised in Table S1 in the supplementary material. The two CML-IA baseline and ReCiPe 2016 midpoint methods were used to analyse the environmental impacts of 197 power stations, while other parameters that might affect the assessment results remained identical. Fig. 9 illustrates impact assessment results of the two methods with similar trends

Table 5
Description of emission reduction scenarios used in sensitivity analysis.

			Black coal	Brown coal	Natural gas	Diesel	Renewables	Total
Share (%) to total electricity mix in 2017–18			46.6	13.8	20.6	1.9	17.1	
Electricity generation in 2017–18 (GWh)			121,702.3	36,008.4	53,881.7	4904.5	44,642.8	261,139.7
Share (%) to total electricity mix in 2030			32.0	8.0	8.9	1.5	49.6	
Electricity generation in 2030 (GWh)			83,564.7	20,891.2	23,110.9	4021.6	129,551.4	261,139.7
Scenario[iii]	**Baseline**	**Share (%)**	32.0	8.0	8.9	1.5	49.6	
		Electricity generation (GWh)	83,564.7	20,891.2	23,110.9	4021.6	129,551.4	261,139.7
		Description	Projected electricity share in 2030 and total electricity generation remains same 2017-18 level					
	S1-a	**Share (%)**	23.7[i]	13.8[i]	8.9	1.5	52.1	
		Electricity generation (GWh)	61,941.0	36,037.3	23,110.9	4021.6	136,029.0 [ii]	261,139.7
		Description	5% increase in renewable electricity with total electricity generation is same as baseline					
	S1-b	**Share (%)**	21.2	13.8	8.9	1.5	54.6	
		Electricity generation (GWh)	55,466.1	36,037.3	23,110.9	4021.6	142,503.9	261,139.7
		Description	10% increase in renewable electricity with total electricity generation is same as baseline					
	S2-a	**Share (%)**	32.0	8.0	8.9	1.5	49.6	
		Electricity generation (GWh)	87,742.9	21,935.7	24,266.4	4222.6	136,029.0	274,196.7
		Description	Projected share in 2030 remains same and 5% increase in total electricity generation in 2030					
	S2-b	**Share (%)**	32.0	8.0	8.9	1.5	49.6	
		Electricity generation (GWh)	91,921.2	22,980.3	25,421.9	4423.7	142,506.5	287,253.7
		Description	Projected share in 2030 remains same and 10% increase in total electricity generation in 2030					

i) Since average electricity generation capacity of renewables was much lower than fossil fuel sources, when increases in renewable electricity generation were considered (S1-a and S1-b), deficiencies in total electricity generation were assumed to be supplied by black and brown coal in order to maintain the amount of total electricity generation.
ii) Increase in renewable electricity generation in S1-a and S1-b was calculated based on total electricity generation of renewables (increasing total renewable electricity from 129,551.4 GWh to 136,029 GWh and to 142,503.9 GWh for 5% and 10% increase scenarios, respectively).
iii) 2030 projection scenarios were developed based on [28,29,36,37].

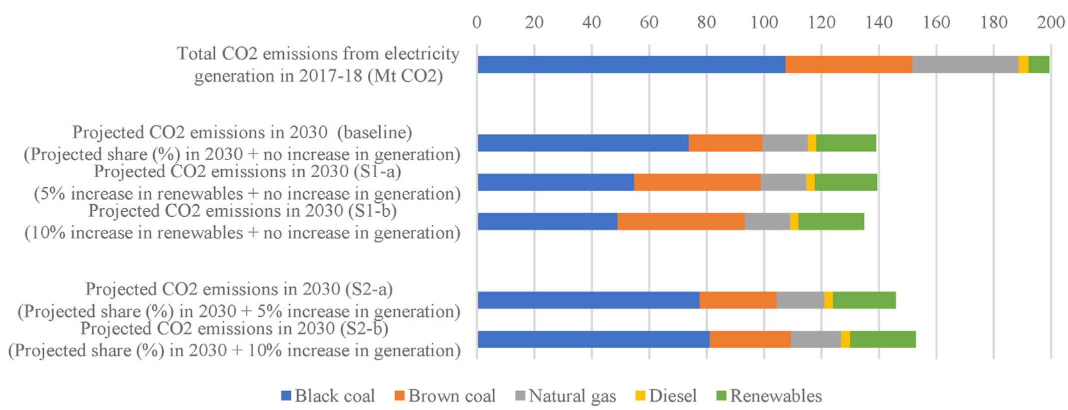


Fig. 7. Projected changes in national electricity mix and corresponding changes in CO_2 emissions in 2017–18 and 2030.

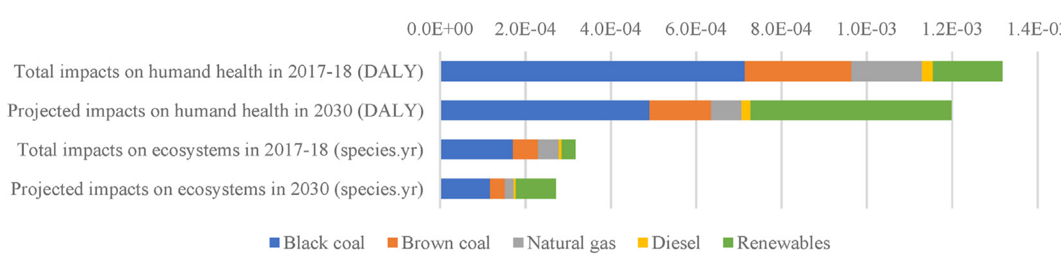
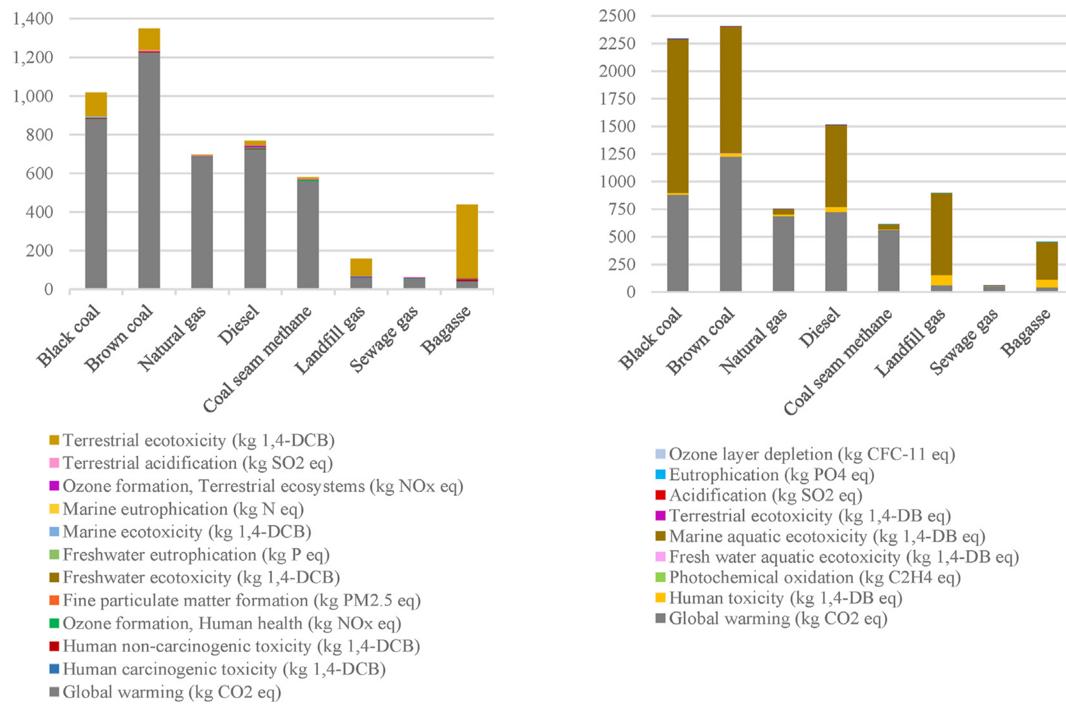


Fig. 8. Estimated endpoint impact reductions in 2030.

in overall midpoint impacts observed in both methods. Overall, brown coal had the highest total midpoint impact, followed by black coal, diesel and natural gas in both methods. However, total midpoint impact of landfill gas electricity was higher than coal seam methane in CML-IA baseline method (Fig. 9-b), whereas it was much lower than coal seam methane in ReCiPe 2016 midpoint method (Fig. 9-a). This was due to much higher marine aquatic ecotoxicity impact in CML-IA baseline method that was mainly estimated by the emissions of metals, including cobalt, nickel, mercury and cadmium, with much higher impact factors considered in CML-IA method than in ReCiPe 2016. Among renewable fuel sources, the impacts were in the order of bagasse > landfill gas > sewage gas in ReCiPe 2016 method, whereas they were in the order of landfill gas > bagasse > sewage gas in CML-IA method due to significant differences in the estimates of terrestrial ecotoxicity and marine ecotoxicity impacts from the two methods.



(a) **(b)**

Fig. 9. Midpoint impact comparison based on assessment methods; (a) ReCiPe 2016 midpoint method; (b) CML-IA baseline method.

4. Discussion

4.1. Environmental impact assessment of Australian power stations

Australia has set up its emission reduction target for 2030 that is 26–28% below the 2005 emission levels [29]. Although emissions from the electricity sector have declined by 13.9% since 2005 [38], electricity is still the largest contributor to the country's total CO_2 emissions. This study found that total CO_2 emissions from electricity generation was around 199.4 Mt during the period of 2017–18, and 96.4% of which was resulting from the use of fossil fuels.

Total midpoint impacts were in the order of brown coal > black coal > diesel > natural gas for fossil fuel sources when the impacts per MWh electricity were considered, which was in disagreement with some cases found in previous studies due possibly to the integration of methane emissions into greenhouse gas emissions of this study. NGER does not separately report methane emissions, but they integrate the emissions of carbon dioxide, methane, nitrous oxide and hydrofluorocarbons, and reports them as carbon dioxide equivalent, therefore the emission of methane was not individually analysed but included as a carbon dioxide emission in the impact assessment. Considering many of the impact assessment methods (e.g. ReCiPe 2016, CML-IA, IMPACT 2002+) separately analyse methane emissions for estimating global warming impact with impact factors between 28 and 34 (see Table S1), while the impact factor of carbon dioxide is 1, reporting methane emission as carbon dioxide equivalent can result in differences in global warming impact values depending on the applied assessment method.

The results in this study found that the global warming impacts of black coal and diesel were slightly lower than average impact values reported in the previous studies, whereas the impact of natural gas was about 7–74% higher than the previous studies (Fig. 10). This could be due to the gas leakage in some of Australian

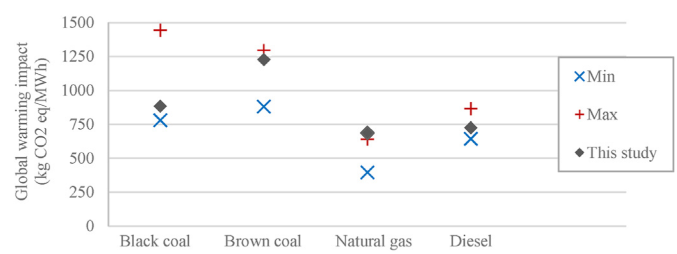


Fig. 10. Global warming impact comparison with previous studies. *Source: [7–9,39–55].

gas power stations such as Barcaldine power station in Queensland which had about five times higher greenhouse gas emissions (expressed as CO_2 eq) than other gas power stations. When this high-emission power station was excluded, the average global warming impact from gas power stations decreased from 686.4 to 620 kg CO_2 eq/MWh.

Total endpoint impacts on human health were mainly attributed to global warming and fine particulate matter formation impacts. Total impacts of fossil fuel sources on ecosystems were dominated by global warming and terrestrial acidification impacts with average contribution rates of 71% and 15%, respectively, whereas those of renewable sources were mainly attributed to ozone formation impacts on terrestrial ecosystems and acidification with average contribution rates of 39% and 37%, respectively.

As seen in the electricity mix analysis, black coal electricity dominated the overall impacts of Australian electricity mix in 2017–18, indicating small reductions in emissions or the share of black coal electricity could result in considerable environmental benefits for Australian electricity. Substituting 10% (which is equivalent to 12,170 GWh electricity) of black coal electricity with natural gas is estimated to reduce the total endpoint impacts of national electricity mix by 3.1%, while substituting 10% of black coal electricity with bagasse is estimated to reduce the total impacts by 5%. A recent government report by AEMO [56] emphasised the need for improving electricity generation efficiency to mitigate the potential impacts of electricity generation, while meeting the increasing demand for electricity. Application of supercritical CO_2 thermodynamic cycle to conventional thermal power stations is suggested to increase the power generation efficiency by utilising the waste heat resulting from the power generation process [57]. Adopting high efficiency, low emission (HELE) technologies to conventional power stations is estimated to reduce CO_2 emissions from the power station by 8% [58].

Due to the characteristics of Australian populations where the majority of populations reside along the coastal areas, the potential human health impacts in these areas could be more significant than less-populated areas. According to Mazaheri et al. [59], emissions from coal power stations are major sources of ambient air pollution in the Sydney Greater Metropolitan Region which can cause premature deaths and decrease in life expectancy. Although it is expected that the electricity generation from renewable sources, such as solar PV and wind will significantly increase for next decades, fossil fuels will likely dominate the national electricity market in 2030 in order to meet the increasing demand for electricity [60]. A study by Lu et al. [61] found that de-carbonising electricity generation through complete transition to renewable energy systems could be possible by the support of energy storage systems in Australia, which was estimated to reduce the country's total GHG emissions by 80%, while maintaining the balance between the renewable electricity generation and the demand for electricity. As such, efforts to reduce the impacts of conventional fossil fuel-based power generations along with increasing electricity generations from renewables will be critical for mitigating adverse impacts of electricity generations.

Australian environmental protection license states that power stations should apply readily available technologies for controlling emissions at the time when the power stations were commissioned [62]. Considering that the majority of Australian coal fired power stations have been operating more than 25 years [32], and there is no obligation for the power stations to adopt more advanced emission control measures, Australian coal fired power stations have no retrofitted or updated emission control measures, such as selective catalytic reduction (SCR) or flue gas desulphurisation (FGD), which are known to reduce NO_x and SO_2 emissions, respectively [62]. By adopting these advanced emission reduction technologies, the potential environmental impacts of Australian electricity generations, particularly the impacts on ecosystems and human health including particulate matter formation impact, could be reduced.

4.2. Factors affecting the impact assessment results and recommendations

Although the quality of emission data used in this study was relatively reliable, NPI data have a number of limitations. Technical report and methods for estimating the emissions, and facility-specific data such as changes in electricity generation efficiency, or updated emission control measures are unknown, thus uncertainties may be present in the NPI emission data. Since the efficiency and application of emission control measures greatly affect the emissions, changes in these factors should be reflected in the NPI data.

As a sensitivity analysis, this study compared the impact assessment results of two different assessment methods, ReCiPe 2016 midpoint and CML-IA baseline, in order to confirm how choices of the methods affect the results. ReCiPe 2016 method estimates the impacts based on 12 categories, while CML-IA considers nine categories, with higher weightings (impact factors) given to metal emissions in the CML-IA method (for details, see Table S1 in supplementary material). Arsenic (III), one of the major pollutants in the ReCiPe methods is excluded in CML-IA method, while antimony is considered only in CML-IA for estimating toxicity impacts. The differences found in the assessment methods have limited comparisons of impacts of different fuel sources, and even when the same impact category from two different methods are considered, impact values vary greatly due to significantly different impacts factors assigned to individual pollutant. For instance, ReCiPe 2016 method considers discharges of dioxins and furans, copper and mercury as major pollutants for estimating marine ecotoxicity, whereas CML-IA considers discharges of cobalt, nickel and mercury for the same impact with much higher impact factors.

Lack of reflection of geographical variations of the impacts is another aspect that should be improved in environmental impact assessment studies. Some impacts such as global warming and ozone layer depletion potential have an influence on a global scale, whereas human health impact can have an influence on much smaller geographical scale. Also, areas where power stations are densely located may have synergetic impacts, in which cases, integrated method that applies GIS into impact assessment could be beneficial to assess the synergetic impacts. The integrated methods facilitate site-specific impact analysis of a particular power station on various geographical scales. However, very limited number of studies have employed the integrated methods for environmental impact assessment, and most of which is for identifying optimal locations of biofuel power stations based on the geographical distribution of feedstock and infrastructures required for the feedstock supply to power stations [63].

GIS integrated impact assessment methods enable the aggregation of different types of datasets (e.g. air emissions, average annual temperature) which can be particularly efficient when a large volume of datasets are required for an analysis. A study by Ma et al. [64] discovered factors that affect air quality by analysing the location of power stations, population and annual precipitation using GIS and other modelling processes. Data that are imported into GIS can be updated with more recent data, or overlaid with different types of data, which facilitates trend analysis and cumulative impact analysis [65]. It should be noted that the environmental impacts can have influences on various geographical scales (e.g. continental, regional) [13], and certain types of data (e.g. average age of population in a selected area) could be affected by the scale [17], thus geographical scales should be carefully selected based on the purpose of a study to avoid misinterpretation of assessment results.

5. Conclusions

This study for the first time integrated GIS into environmental impact assessment to estimate the potential environmental impacts of 197 Australian power stations using National Pollutant Inventory (NPI) emission data. The impact assessment conducted by analysing point sources emissions from the power stations found that total CO_2 emissions from electricity generation was 199.4 Mt during the period of July 2017 to June 2018, contributing 34% of the country's total CO_2 emissions. Fossil fuel electricity had high CO_2, SO_2 and NO_x emissions, while renewable electricity had relatively higher emissions of air toxics and metals, especially in bagasse electricity.

Total endpoint impacts were in the order of brown coal > black coal > diesel > natural gas for fossil fuel sources, while sewage gas > bagasse > landfill gas for renewables. When the percentage share of each fuel source in 2017–18 electricity mix was considered, black coal appeared to be the most impactful fuel source due to its highest share (46.6%) to total electricity mix. The national-scale map which presented the relationship between the total endpoint impacts and Australian populations found that some of natural gas and diesel power stations exhibited higher impacts than brown or black power stations, implying targeted impact mitigation programs should be necessary. Also, the majority of coal power stations were located in the areas with higher populations, thus potential health risks in the populations could be significant. Regionalised impact assessment studies using GIS integrated methods could be beneficial when assessing the impacts on populations or certain areas.

Comparison of impact assessment results of the two different methods, ReCiPe 2016 midpoint and CML-IA baseline methods, found differences in impact categories and impact factors used to estimate various environmental impacts. Global warming was found to be the major impact in the ReCiPe 2016 method, whereas the total impacts estimated by the CML-IA method was mostly driven by marine aquatic ecotoxicity due to its much higher impact factors given to metal emissions. Therefore, direct comparison of impact assessment studies conducted using different assessment methods are not recommended.

In the projected national electricity mix scenarios, total CO_2 emissions from electricity generations were estimated to decrease by 30% in 2030 compared to the emissions in 2017–18 (from 199.4 Mt to 138.9 Mt CO_2) through the increased shares of renewable electricity by 49.6%. However, when the renewable electricity generation was assumed to increase by 5% than the projected 2030 level (total 52.1% shares of renewable sources in 2030), the total CO_2 emissions were slightly higher than the 2030 emission projections (from 138.9 Mt to 139.5 Mt CO_2) due to the increased electricity generation from coal to meet the demand for electricity. Therefore, stricter regulations for emission reductions and larger share of renewable electricity generations would be necessary to meet the country's emissions reduction target of 131 Mt CO_2 in 2030.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2021.120898.

CRediT author statement

Hannah Hyunah Cho: Conceptualization, Data curation, Formal analysis, Writing – original draft. Vladimir Strezov: Conceptualization, Resources, Validation, Writing – review & editing, Supervision.

References

[1] DEE. Quarterly update of Australia's national greenhouse gas inventory: June 2019. Canberra, Australia: Australian Government Department of the Environment and Energy; 2019.
[2] Tang M, Mudd GM. The pollution intensity of Australian power stations: a case study of the value of the national pollutant inventory (NPI). Environ Sci Pollut Control Ser 2015;22:18410–24. https://doi.org/10.1007/s11356-015-5108-0.
[3] Weldu YW, Assefa G, Jolliet O. Life cycle human health and ecotoxicological impacts assessment of electricity production from wood biomass compared to coal fuel. Appl Energy 2017;187:564–74. https://doi.org/10.1016/j.apenergy.2016.11.101.
[4] Cho HH, Strezov V. A comparative review on the environmental impacts of combustion-based electricity generation technologies. Energy Fuel 2020;34(9):10486–502. https://doi.org/10.1021/acs.energyfuels.0c02139.
[5] Smylie M, Chan LM, Rao S. Estimates of emissions for small-scale diesel engines. California: HARC Project H-10. Novato; 2003.
[6] Dong Y, Jiang X, Liang Z, Yuan J. Coal power flexibility, energy efficiency and pollutant emissions implications in China: a plant-level analysis based on case units. Resour Conserv Recycl 2018;134:184–95. https://doi.org/10.1016/j.resconrec.2018.03.012.
[7] Modahl IS, Askham C, Lyng K-A, Brekke A. Weighting of environmental trade-offs in CCS—an LCA case study of electricity from a fossil gas power plant with post-combustion CO2 capture, transport and storage. Int J Life Cycle Assess 2012;17:932–43. https://doi.org/10.1007/s11367-012-0421-z.
[8] Petrescu L, Cormos CC. Environmental assessment of IGCC power plants with pre-combustion CO 2 capture by chemical & calcium looping methods. J Clean Prod 2017;158:233–44. https://doi.org/10.1016/j.jclepro.2017.05.011.
[9] Petrescu L, Bonalumi D, Valenti G, Cormos AM, Cormos CC. Life Cycle Assessment for supercritical pulverized coal power plants with post-combustion carbon capture and storage. J Clean Prod 2017;157:10–21. https://doi.org/10.1016/j.jclepro.2017.03.225.
[10] Ayodele TR, Ogunjuyigbe ASO, Alao MA. Life cycle assessment of waste-to-energy (WtE) technologies for electricity generation using municipal solid waste in Nigeria. Appl Energy 2017;201:200–18. https://doi.org/10.1016/j.apenergy.2017.05.097.
[11] Erses Yay AS. Application of life cycle assessment (LCA) for municipal solid waste management: a case study of Sakarya. J Clean Prod 2015;94:284–93. https://doi.org/10.1016/j.jclepro.2015.01.089.
[12] Cui X, Hong J, Gao M. Environmental impact assessment of three coal-based electricity generation scenarios in China. Energy 2012;45:952–9. https://doi.org/10.1016/j.energy.2012.06.063.
[13] Antunes P, Santos R, Jordao L. The application of Geographical Information Systems to determine environmental impact significance. Environ Impact Assess Rev 2001;21(6):511–35. https://doi.org/10.1016/S0195-9255(01)00090-7.
[14] Vandepaer L, Treyer K, Mutel C, Bauer C, Amor B. The integration of long-term marginal electricity supply mixes in the ecoinvent consequential database version 3.4 and examination of modelling choices. Int J Life Cycle Assess 2019;24(8):1409–28. https://doi.org/10.1007/s11367-018-1571-4.
[15] Abdul-Manan AF, Won HW, Li Y, Sarathy SM, Xie X, Amer AA. Bridging the gap in a resource and climate-constrained world with advanced gasoline compression-ignition hybrids. Appl Energy 2020;267:114936. https://doi.org/10.1016/j.apenergy.2020.114936.
[16] Wu Z, Wang C, Wolfram P, Zhang Y, Sun X, Hertwich E. Assessing electric vehicle policy with region-specific carbon footprints. Appl Energy 2019;256:113923. https://doi.org/10.1016/j.apenergy.2019.113923.
[17] Mutel CL, Pfister S, Hellweg S. GIS-based regionalized life cycle assessment: how big is small enough? methodology and case study of electricity generation. Environ Sci Technol 2012;46:1096–103. https://doi.org/10.1021/es203117z.
[18] Turconi R, Boldrin A, Astrup T. Life cycle assessment (LCA) of electricity generation technologies: overview, comparability and limitations. Renew Sustain Energy Rev 2013;28:555–65. https://doi.org/10.1016/j.rser.2013.08.013.
[19] Ross SA, Cheah L. Uncertainty quantification in life cycle assessments: exploring distribution choice and greater data granularity to characterize product use. J Ind Ecol 2019;23(2):335–46. https://doi.org/10.1111/jiec.12742.
[20] Zuo A, Wheeler SA. Maximising the use of national pollution data: views from stakeholders in Australia. J Clean Prod 2019;222:455–63. https://doi.org/10.1016/j.jclepro.2019.03.029.
[21] Wang J, Wang R, Zhu Y, Li J. Life cycle assessment and environmental cost accounting of coal-fired power generation in China. Energy Pol 2018;115:374–84. https://doi.org/10.1016/j.enpol.2018.01.040.
[22] Strezov V, Cho HH. Environmental impact assessment from direct emissions of Australian thermal power generation technologies. J Clean Prod 2020;270:122515. https://doi.org/10.1016/j.jclepro.2020.122515.
[23] NGER. Electricity sector emissions and generation data 2017–18. Canberra, Australia: Australian Government Clean Energy Regulator; 2019.
[24] Sustainability Victoria. Bioenergy in the goulburn valley. 2010. https://www.solarchoice.net.au/wp-content/uploads/ResourceSmart-BioEnergy-in-the-Goulburn-Valley.pdf. . [Accessed 16 January 2020].
[25] AEMO. Review of emission factors for use in the CDEII. Australian Energy Market Operator 2014.
[26] NPI. National pollutant inventory. Canberra, Australia: Australian Government Department of the Environment and Energy; 2019. http://www.npi.gov.au/npidata/action/load/download-result/criteria/destination/ALL/source-type/ALL/subthreshold-data/Yes/substance-name/All/year/2018. [Accessed 15 January 2020].
[27] ABS. Australian Bureau of Statistics. 2016 census DataPacks. 2016. https://datapacks.censusdata.abs.gov.au/datapacks. [Accessed 6 August 2020].
[28] CSIRO, Energy Networks Australia. Electricity network transformation roadmap: final report. 2017.
[29] DEE. Australia's emissions projections 2019. Canberra, Australia: Australian Government Department of the Environment and Energy; 2019.
[30] Department of Industry. Australian energy Statistics, table O. Science, energy

and Resources. 2020. https://www.energy.gov.au/publications/australian-energy-update-2019. [Accessed 8 July 2020].

[31] Australian Energy Council. Considerations for retrofitting emissions control systems in Australian coal power plants. Project No PS114792. Available at:. 2020. https://www.energycouncil.com.au/media/dtyjfcdh/addendum-and-report.pdf. [Accessed 28 February 2021].

[32] AEMO. Technical parameters and operating costs. Australian energy market operator. Available at:. 2019. https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/Inputs-Assumptions-Methodologies/2019/GHD-AEMO-revised—2018-19-Costs_and_Technical_Parameter.xlsb. [Accessed 28 February 2021].

[33] Huijbregts MA, Steinmann ZJ, Elshout PM, Stam G, Verones F, Vieira M, Zijp M, Hollander A, van Zelm R. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 2017;22(2):138—47.

[34] Bare JC, Hofstetter P, Pennington DW, De Haes HAU. Midpoints versus endpoints: the sacrifices and benefits. Int J Life Cycle Assess 2000;5(6):319.

[35] Zhang K, Zhou B, Li C, Voropai N, Li J, Huang W, Wang T. Dynamic modelling and coordinated multi-energy management for a sustainable biogas-dominated energy hub. Energy; 2020, 119640. https://doi.org/10.1016/j.energy.2020.119640.

[36] Brinsmead TS, Hayward J, Graham P. Australian electricity market analysis report to 2020 and 2030. 2014. CSIRO Report No. EP141067.

[37] Department of Environment, Land, Water and Planning. Victorian renewable energy target, 2018-19 progress report. Land, Water and Planning, Melbourne, Australia: The State of Victoria Department of Environment; 2019.

[38] Department of Industry, Science, Energy and Resources. Quarterly update of Australia's national greenhouse gas inventory: march 2020. Canberra, Australia: Australian Government Department of Industry, Science, Energy and Resources; 2020.

[39] Agrawal KK, Jain S, Jain AK, Dahiya S. Assessment of greenhouse gas emissions from coal and natural gas thermal power plants using life cycle approach. Int J Environ Sci Technol 2013;11:1157—64.

[40] Atilgan B, Azapagic A. An integrated life cycle sustainability assessment of electricity generation in Turkey. Energy Pol 2016;93:168—86.

[41] Bicer Y, Khalid F. Life cycle environmental impact comparison of solid oxide fuel cells fuelled by natural gas, hydrogen, ammonia and methanol for combined heat and power generation. Int J Hydrogen Energy 2020;45:3670—85.

[42] Brizmohun R, Ramjeawon T, Azapagic A. Life cycle assessment of electricity generation in Mauritius. J Clean Prod 2015;106:565—75.

[43] Korre A, Nie Z, Durucan S. Life cycle modelling of fossil fuel power generation with post-combustion CO2 capture. International Journal of Greenhouse Gas Control 2010;4:289—300.

[44] Natividad Perez-Camacho M, Curry R, Cromie T. Life cycle environmental impacts of biogas production and utilisation substituting for grid electricity, natural gas grid and transport fuels. Waste Manag 2019;95:90—101.

[45] Navajas A, Mendiara T, Goñi V, Jiménez A, Gandía LM, Abad A, García-Labiano F, de Diego LF. Life cycle assessment of natural gas fuelled power plants based on chemical looping combustion technology, vol. 198. Energy Conversion and Management; 2019.

[46] Nie Z, Korre A, Durucan S. Life cycle modelling and comparative assessment of the environmental impacts of oxy-fuel and post-combustion CO2 capture, transport and injection processes. Energy Procedia 2011;4:2510—7.

[47] Orfanos N, Mitzelos D, Sagani A, Dedoussis V. Life-cycle environmental performance assessment of electricity generation and transmission systems in Greece. Renew Energy 2019;139:1447—62.

[48] Ozturk M, Dincer I. Comparative environmental impact assessment of various fuels and solar heat for a combined cycle. Int J Hydrogen Energy 2019;44:5043—53.

[49] Santoyo-Castelazo E, Gujba H, Azapagic A. Life cycle assessment of electricity generation in Mexico. Energy 2011;36:1488—99.

[50] Schreiber A, Zapp P, Markewitz P, Vögele S. Environmental analysis of a German strategy for carbon capture and storage of coal power plants. Energy Pol 2010;38:7873—83.

[51] Singh B, Strømman AH, Hertwich EG. Life cycle assessment of natural gas combined cycle power plant with post-combustion carbon capture, transport and storage. International Journal of Greenhouse Gas Control 2011;5:457—66.

[52] Somorin TO, Di Lorenzo G, Kolios AJ. Life-cycle assessment of self-generated electricity in Nigeria and Jatropha biodiesel as an alternative power fuel. Renew Energy 2017;113:966—79.

[53] Strazza C, Del Borghi A, Costamagna P, Gallo M, Brignole E, Girdinio P. Life cycle assessment and life cycle costing of a SOFC system for distributed power generation. Energy Convers Manag 2015;100:64—77.

[54] Tang L, Yokoyama T, Kubota H, Shimota A. Life cycle assessment of a pulverized coal-fired power plant with CCS technology in Japan. Energy Procedia 2014;63:7437—43.

[55] Zainorizuan MJ, Usapein P, Chavalparit O, Yee Yong L, Alvin John Meng Siang L, Mohamad Hanifi O, Siti Nazahiyah R, Mohd Shalahuddin A. Life cycle assessment of producing electricity in Thailand: a case study of natural gas power plant. MATEC Web of Conferences 2017;103.

[56] AEMO. Australian energy market operator. Electricity Statement of Opportunities. A report for the National Electricity Market; 2019.

[57] Wang D, Xie X, Wang C, Zhou Y, Yang M, Li X, Liu D. Thermo-economic analysis on an improved coal-fired power system integrated with S-CO2 Brayton cycle. Energy; 2020, 119654. https://doi.org/10.1016/j.energy.2020.119654.

[58] Wang C, Zhang L, Zhou P, Chang Y, Zhou D, Pang M, Yin H. Assessing the environmental externalities for biomass-and coal-fired electricity generation in China: a supply chain perspective. J Environ Manag 2019b;246:758—67. https://doi.org/10.1016/j.jenvman.2019.06.047.

[59] Mazaheri M, Scorgie Y, Broome R, Morgan G, Jalaludin B, Riley M. Health benefits of reducing Australian coal-fired power stations emissions. Environmental Epidemiology 2019;3:264—5. https://doi.org/10.1097/01.EE9.0000608816.02465.cb.

[60] De Rosa L, Castro R. Forecasting and assessment of the 2030 Australian electricity mix paths towards energy transition. Energy 2020;205:118020. https://doi.org/10.1016/j.energy.2020. 118020.

[61] Lu B, Blakers A, Stocks M, Cheng C, Nadolny A. A zero-carbon, reliable and affordable energy future in Australia. Energy 2020:119678. https://doi.org/10.1016/j.energy.2020. 119678.

[62] Environmental Justice Australia. Controlling toxic air pollution from coal-fired power stations in New South Wales. 2018 [Carlton, Australia].

[63] Viana H, Cohen WB, Lopes D, Aranha J. Assessment of forest biomass for use as energy. GIS-based analysis of geographical availability and locations of wood-fired power plants in Portugal. Appl Energy 2010;87:2551—60. https://doi.org/10.1016/j.apenergy.2010.02.007.

[64] Ma J, Ding Y, Cheng JC, Jiang F, Tan Y, Gan VJ, Wan Z. Identification of high impact factors of air quality on a national scale using big data and machine learning techniques. J Clean Prod 2020;244:118955. https://doi.org/10.1016/j.jclepro.2019.118955.

[65] Eedy W. The use of GIS in environmental assessment. Impact Assessment 1995;13(2):199—206.