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Aggregating local, regional and global burden of disease impact assessment: detecting potential problem shifting in air quality policy making

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Abstract
Purpose Quantitative risk assessment (QRA) has been applied widely in environmental decision-making. Despite its advantage in taking locally specific details into consideration, problem shifting may occur due to its relatively narrow focus. To achieve a broader perspective, we propose that the combined use of QRA and life cycle assessment (LCA) may be beneficial. The feasibility and effectiveness of a hybrid approach of QRA and LCA were evaluated by considering alternative future air quality scenarios.
Methods Future air pollution emission scenarios based on different state-based environmental agency policies in Victoria, Australia, were considered to explore ways to reduce problem shifting. QRA was used to estimate human burden of disease (BoD) for the local population due to particulates and tropospheric ozone under 'Low Impact' and 'Most Likely' scenarios. To detect potential problem shifting, LCA was performed for other associated impact categories such as climate change potential. Disability-adjusted life years (DALYs) were used as a common metric to facilitate direct comparisons and aggregation between results of QRA and LCA.
Results and discussion While the 'Low Impact' scenario was developed to project a scenario with reduced human health impacts (among other environmental impacts), the overall assessment revealed that BoD impacts may suffer a net increase under this scenario. The QRA suggested about 0.74 kilo DALYs (kDALYs) were saved annually; however, the LCA indicated that more impacts were expected, over 8 kDALYs per year. Hence, it was projected that reducing local impact by improving local air quality would shift more problems elsewhere. Therefore, using QRA alone that focuses on local impacts could result in an inappropriate scenario being preferred and improper policies being set.
Conclusions The outcomes of this study revealed the importance of applying a broad perspective in environmental decision-making. QRA appeared to be a suitable tool to assess local BoD impacts caused by ambient air pollutants. However, by also including LCA, impacts could be more comprehensively assessed. Combined use of QRA and LCA enables the analyst to account for locally specific considerations while reducing potential problem shifting to more distant receptors.

Keywords Quantitative risk assessment · Life cycle assessment · Burden of disease · Particulate matter · Tropospheric ozone · Climate change · Human toxicity · Electric vehicles

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1 Introduction

Quantitative risk assessment (QRA) is an environmental management tool increasingly used by government agency decision-makers. It is applied to assess potential burden of disease

(BoD) impacts related to specific activities, primarily by considering the potential effects of microbial and chemical environmental contaminants to human health. The application of QRA takes locally specific factors into account in order to assess local risks to specific groups of people. QRA has been applied in many areas of government agency decision-making (Bichai and Smeets 2013; Fann et al. 2011).

An important limitation of QRA is that in most cases, hazards must be individually assessed. The outcome is usually a separate numerical measure of risk for each assessed hazard. When applied in product or process development, an additional limitation is that impacts that are not specifically local, such as those that may occur at earlier or later life cycle stages of a product or process, are commonly overlooked. Consequently, BoD impacts may simply be shifted outside of the focus of a study when proposing measures to reduce specific local impacts. To prevent such problem shifting, a broader environmental management perspective is required.

Life cycle assessment (LCA) offers wider perspectives. Many types of impacts on human health and the environment due to thousands of substances can be assessed with LCA. In comparison to QRA, however, LCA incorporates locally specific details poorly, or not at all. Often, global or regional average data, simplified modelling for pollutant fate and cause-effect analysis are used in impact assessments (Kobayashi et al. 2015b). The limitations of LCA in this regard have been discussed, and improved methods with increased geographical resolution have been proposed for some of the impact categories including air pollution, toxicity, eutrophication, water consumption and land use (Azevedo et al. 2013; de Baan et al. 2013; Fantke et al. 2015; Pfister et al. 2009; Saad et al. 2013; van Zelm et al. 2016; Verones et al. 2013). Some impact assessment tools, such as USEtox for toxicity, offer flexibility in specifying user data for various parameters including biophysical conditions for fate analysis and affected population for exposure assessment (Fantke et al. 2015). In the case of air pollution, for example, van Zelm et al. (2016) divided the world into 56 regions, where each region may be a single country or multiple countries. Characterisation factors for each region were then derived by considering regionally specific parameters such as the background concentrations, the population exposure to pollutants and the severity of BoD effects of pollutants (van Zelm et al. 2016). While characterisation factors with higher resolutions (e.g. state and city scale) can be derived following similar methods and implemented in LCA tools, the availability of local data and required workloads could be obstacles in practice.

LCA tends to be more suited to globally or regionally affected impact categories such as global warming. For these differences in their approaches, QRA and LCA have been considered complementary (De Haes et al. 2006; Owens 1997; Sleeswijk et al. 2003). The similarities and differences between these tools have been studied to seek potential integration of the two (Cowell et al. 2002; Udo de Haes et al. 2006), and their combined use has been attempted previously (Heimersson et al. 2014; Kobayashi et al. 2015a).

BoD impacts associated with air pollution generally are highly site dependent. The fates of pollutants are influenced by the local climate which may significantly vary even within a single country. The number of population affected and characteristics such as demography are locally varying factors. For these reasons, the necessity of site-dependent approach for impact assessment of air pollution in LCA has long been recognised (Moriguchi and Terazono 2000; Spadaro and Rabl 1999). However, currently, commercially available LCA methods lack capacity to include the local specifics. Hence, to improve environmental decision-making, we considered using QRA for BoD impacts due to local air pollution in combination with wider impact assessment with LCA.

To quantify the extent of BoD impacts, disability-adjusted life years (DALYs) have been useful units (Gao et al. 2015; Kobayashi et al. 2015a). DALYs are calculated as the sum of severity weighted years lived with disability and those lost due to premature mortality (Murray and Acharya 1997). Therefore, not only is the number of fatal cases accounted for, but also the number of cases affected by nonfatal health outcomes as well as the severity and duration of these health effects (Murray and Lopez 1996). Although modelling cause-effect chains from environmental releases to DALYs adds to the amount of model uncertainty, an important advantage of DALYs over traditional LCA midpoint indicators is that they facilitate the accumulation of diverse BoD end-points. DALYs have already been used in QRA and LCA separately to varying degrees. Accordingly, DALYs appear to be advantageous as a common metric to merge results of QRA and LCA approaches (Kobayashi et al. 2015b).

Urban air quality assessment and management is an important focus of government agency decision-makers in developed countries. In many parts of the world, air pollution and associated BoD impacts are expected to be more intense in the future unless emissions are further controlled (WHO 2013). Particulate matter with a diameter less than 2.5 μm ($PM_{2.5}$) or less than 10 μm (PM_{10}) and tropospheric ozone are often the main urban air pollution concerns in developed regions (EPA VIC 2013).

Particulate matter in the atmosphere can originate through human activities or from natural sources. It can also be formed in the air from other pollutants such as sulphur dioxide, nitrogen oxides, ammonia and non-methane volatile organic compounds. The potential for morbidity as well as mortality from respiratory and cardiovascular disease due to exposures to particulates has been widely recognised (Lim et al. 2012; WHO 2006).

Tropospheric ozone, on the other hand, is not directly emitted. It is formed as a result of chemical reactions of precursor pollutants, such as nitrogen oxides and volatile organic compounds, in the presence of sunlight (Leighton 1961). Studies have demonstrated adverse BoD effects due to exposure to ozone, including those related to lung function and airway inflammation (WHO 2006). The impacts of particulates and tropospheric ozone are relatively local and have traditionally been assessed with QRA (WHO 2006).

Interventions to reduce locally impacting air quality pollutants can paradoxically increase other emissions. For example, when local pollution prevention is achieved using alternative hardware, such as electric passenger vehicles instead of conventional passenger vehicles, its production and operation may induce other emissions elsewhere. Such emissions may include air quality pollutants that lead to global warming or destruction of the stratospheric ozone layer which affect global population, as well as pollutants to other compartments such as water- and soil-affecting local and regional population. A more comprehensive assessment of BoD impacts associated with local air quality policy would require consideration of local, regional and global impacts. We propose that the combined use of QRA and LCA may be beneficial in this regard. The feasibility and effectiveness of a hybrid approach of QRA and LCA using DALYs were evaluated by considering alternative future air quality scenarios.

2 Methods

The Environmental Protection Agency for the Australian state of Victoria (EPA VIC) has previously identified potential alternative future scenarios for air quality by 2030 for the Port Phillip Region which includes cities of Melbourne and Geelong (between longitudes 144°E and 145°E and latitudes 37°S and 38.5°S) (EPA VIC 2013; Walsh et al. 2013). That study was conducted to forecast trends in air quality and to support policy and strategy development to control air pollution. Projected ambient concentrations of pollutants in 2030 for each scenario were estimated and compared to current air quality standards. However, the potential BoD impacts were not considered in their study.

For this paper, further analysis of the two scenarios considered by the EPA VIC referred to as ‘Low Impact’ and ‘Most Likely’ was undertaken. The ‘Most Likely’ scenario formed the base case scenario, and the following changes were proposed for the ‘Low Impact’ scenario:

- Domestic use of wood heaters: All wood heaters will comply with the Australian Standard for the particulate emissions from wood-burning residential heating appliances (AS/NZS 4013) (PM_{10} emission should be less than 4 g/kg of dry wood).
- Residential lawn mowers: All 2-stroke lawn mowers will be replaced with 4-stroke lawn mowers to reduce the operational emissions.
- Passenger vehicles: 50% of conventional vehicles (CVs) will be replaced with electric vehicles (EVs).
- Light vehicles: 30% exhaust and evaporative emissions will be reduced through better maintenance (no technology improvement).
- Domestic use of charcoal briquettes for heating and cooking: All briquettes will be replaced with natural gas.
- A power station: Anglesea power station is a 150-MW brown coal-fired power station which provides electricity to a local aluminium smelter. It contributes a considerable amount of sulphate particles to the region (Alcoa 2013; EPA VIC 2013). Ninety percent of SO_2 emissions will be reduced by applying desulphurisation technology.

BoD impacts related to the alternative scenarios were evaluated using QRA and LCA approaches to assess the potential for a combined measure of local, regional and global impacts. Local BoD impacts due to ambient particulates and ozone concentrations were calculated for each scenario using QRA. Regional and global BoD impacts associated with other emissions causing other impacts, including human toxicity and global warming, were estimated using LCA. DALYs were used in both QRA and LCA. Finally, the results of QRA and LCA were numerically aggregated to assess the overall BoD impacts for each scenario.

2.1 Quantitative risk assessment

To assess the local BoD risks associated with ambient particulates and ozone concentrations, a traditional risk assessment approach was applied. It is generally composed of four steps: (1) hazard identification where potential stressors to human or ecological system are investigated, (2) dose-response assessment where the relationship between exposure to each stressor and its effect is determined, (3) exposure assessment where frequency, duration and intensity of exposure to each hazard are examined and (4) risk characterisation in which risks from exposure to each stressor are analysed. The details of each step are provided in the subsequent sections.

2.1.1 Hazard identification

The future air quality was previously analysed by EPA VIC with the aid of an air pollution model (TAPM-CTM version 2.061) developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (EPA VIC 2013). The model disaggregates the region into 3 × 3 km squares and takes emissions of pollutants and weather information (winds, temperature, sunlight, clouds, etc.) as inputs to predict ambient air quality. It takes the movement and chemical reactions of pollutants into account. The detailed steps required to run the TAPM-CTM can be found in the study of Cope and Lee (2009), and the technical background of chemical transport model used in TAPM-CTM is provided in the work of Cope et al. (2009). The emissions in 2030 were projected based on the emission estimates in the base year, 2006, by considering trends in population, industry and transport. As uncertainties are involved in future emission predictions, multiple scenarios were studied. Since the effects of climate change were expected to be small in this study period and significant time lags between greenhouse gas emissions and their effects were expected, a single greenhouse emission scenario (the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios A2) (IPCC 2000) was considered. For weather data, due to significant weather variation from year to year in the region, 10 years of weather details (2025–2034 for 2030) obtained from climate projections undertaken by CSIRO was considered. Synoptic-scale patterns including troughs, cold fronts and sea breezes were taken into account. The results indicated that $PM_{2.5}$ and tropospheric ozone were the primary pollutants in 2030. These pollutants have been identified to cause adverse effects to human health such as cardiovascular and respiratory diseases (Ostro 2004; WHO 2003).

2.1.2 Dose-response assessment

Dose-response factors were calculated using breathing rate and concentration response factors which take relative risks, base incidence rates and background concentrations of pollutants into account. To be consistent with the method applied by Gronlund et al. (2015), which was used in the LCA of this study, cardiopulmonary mortality and lung cancer mortality were considered as health effects due to $PM_{2.5}$. Since no relative risks (RRs) specifically derived from the target population of this study were available, RRs reported in the US-based study (Pope et al. 2002) were used. In line with the method used by Gronlund et al. (2015), no effect for population under 29 years of age was assumed. For ozone, acute mortality was considered as a health effect and a single RR for all age groups reported by WHO (2004) was applied in order to be consistent with the method used in the LCA (van Zelm et al. 2008). The associated annual mortality rate for each cause in 2013 for Australia (IHME 2016) was used as the base mortality rate in the calculations.

2.1.3 Exposure assessment

The yearly dose of pollutants for the whole region was estimated using the population exposure data provided by EPA VIC (2013), which is based on matching the population distribution with the pollutant concentration distribution for each square in the 3 × 3 km geographical grid. The age distribution of the population in the region was estimated by assuming the trends of the annual population change for each 5-year age group between 1991 and 2011 (ABS 2014) persisting to 2030. It was also assumed that there is no significant difference in age distribution between geographical grids. To be consistent with the LCA methods used, age distribution was considered in the calculation of impacts due to $PM_{2.5}$ only.

2.1.4 Risk characterisation

To quantify the health impacts in DALYs, DALYs per each health outcome incidence were considered. For $PM_{2.5}$, YLL values for Australia provided by van Zelm et al. (2016) were used. For ozone, DALY values reported in Dutch study (Knol and Staatsen 2005) were used due to unavailability of local values. The equations and parameter values used for the QRA are shown in Online Resource 1.

2.2 Life cycle assessment

LCA for wood heaters, lawn mowers, passenger vehicles, charcoal briquettes and the use of desulphurisation technology at the Anglesea power station were performed to quantify BoD impacts associated with the two investigated scenarios. Data for the LCA model was entered in dialogue with the original authors of the QRA at the EPA VIC (Bannister 2014) so as to create a consistent data set. For the reduction of emissions related to light vehicles (defined as commercial vehicles less than 4.5 t), it was assumed that the only necessary input was manual labour for better maintenance of engine tuning and correct tyre inflation pressure; therefore, no LCA was conducted for this element of the 'Low Impact' scenario. The goal of this LCA study was to evaluate the BoD impact difference between the two future scenarios, 'Most Likely' and 'Low Impacts'. By carrying out LCA, global and regional BoD impacts can be realised in addition to local impacts which are assessed by QRA. This provides more holistic view of BoD impacts and helps to improve decision-making by avoiding potential problem shifting.

The LCA was performed using GaBi LCA software (thinkstep 2013) and the ReCiPe method (Goedkoop et al. 2013) using endpoint indicators for the 'hierarchist' cultural perspective, which is based on the most common policy principles (Goedkoop et al. 2013). GaBi professional database (thinkstep 2013) was used as main background datasets, and ecoinvent v.2 (Swiss Centre for Life Cycle Inventories 2014) was used as a supplementary dataset. As the focus of this study is the BoD impacts, the following impact categories were included: climate change potential (CCP), human toxicity potential (HTP), ionising radiation potential (IRP), ozone depletion potential (ODP), particulate matter formation potential (PMFP) and photochemical oxidant formation potential (POFP). Since the impacts related to local ambient concentrations of particulates and tropospheric ozone were included in QRA, the impacts due to the local emissions of these pollutants and the precursor substances such as sulphur oxides and nitrogen oxides were disregarded in the LCA to avoid double counting. These include impacts of PMFP and POFP due to emissions from wood combustion of 'Wood heaters', emissions from petrol combustion of 'Lawn mowers', tailpipe emissions from CVs ('Passenger vehicles'), emissions from briquettes and natural gas combustion ('Briquettes') and reduced amount of SO_2 by 'Desulphurisation'.

The regional and global BoD impacts due to particulate matter were estimated based on midpoint results of the ReCiPe method which are expressed in mass of PM_{10} equivalent. To be consistent with the QRA, these were converted to the equivalents of $PM_{2.5}$ using the ratio of $PM_{2.5}/PM_{10} = 0.65$ as suggested for cities in developed countries including Australia (Ostro 2004). The characterisation factor (1.2 × 10–3 DALYs/kg of $PM_{2.5}$ emitted) (Gronlund et al. 2015) was then applied to estimate the BoD impacts in DALYs. The inventory data used in the LCA are provided in Online Resource 1.

2.2.1 Wood heaters

For wood heaters, the LCA functional unit was the process of heating residential houses in the region for a year. The number of houses included in the LCA was the same as the number of wood heaters in the region estimated by EPA VIC and used in the QRA, which was 490,433 (Bannister 2014). It was assumed all wood heaters would be replaced with newer heaters to be compliant with the Australian and New Zealand standard AS/NZS4013 in the 'Low Impact' scenario. It was also assumed that the replacement would not occur unless regulations were set, and hence, for the 'Most Likely' scenario, there would be no hardware changes. Since the result of this study showed that the contribution of wood heaters to the overall BoD impact was small, the error caused by this assumption is expected to be insignificant. The amount of wood used per household was projected to be unchanged from current use. The production of wood heaters, operational emissions due to wood burning, electricity requirements for a heated air blower and the heaters' end-of-life phase were included for the 'Low Impact' scenario, while only operational emissions were included for the 'Most Likely' scenario. Data for operational emissions were taken from a study done by Solli et al. (2009) and provided in Online Resource 1 (Table S7). For this comparable LCA, substances were included only when the amount of emissions differed between newer and older heaters. These include non-methane volatile organic compounds (NMVOC), carbon monoxide polycyclic aromatic hydrocarbons and $PM_{2.5}$. The emissions of NMVOC and PM2.5 during operation phase were not included in the LCA, however, as they were considered in the QRA. Impacts due to transportation of the new heaters were excluded due to a lack of data and the expectation that they would make a relatively small contribution to the total impact (Parsons 2010). A recovery rate of 90% for steel and no recycling of glass were assumed (Sustainability Victoria 2014; Worldsteel 2012).

2.2.2 Lawn mowers

All separate houses were assumed to have lawn areas to be maintained. The functional unit was to maintain residential lawn areas in the region for a year. The time spent for lawn mowing per household per year was estimated by EPA VIC to be 22.5 h (Bannister 2014). The life span of a typical lawn mower is assumed to be 250 h of operation (Lan and Liu 2010). It was also estimated by EPA VIC that 27% of lawn mowers had 2-stroke engines, and these were to be replaced with 4-stroke mowers in the 'Low Impact' scenario (Bannister 2014). Other types of mowers would be replaced with equivalent mowers at the rate of 9% per year by considering their life span. In the 'Most Likely' scenario, all the mowers were expected to be replaced with the same type as previously owned at the same rate of 9% per year. Since the impacts of the replacement of mowers other than 2-stroke mowers would be identical in the two scenarios, only the impacts due to replacement of 2-stroke mowers were included. Due to the lack of data availability and for the similarity in types and amounts of material required in construction for 2- and 4-stroke mowers, the inventory data of 4-stroke mowers were used for production and end-of-life phases of 2-stroke mowers. Data used for operation phase including emissions and fuel consumptions were specific to 2-stroke. Operational emissions of carbon monoxide, carbon dioxide, methane and non-methane hydrocarbons were included following Priest et al. (2000). The values used are shown in Online Resource 1 (Table S10). As the result of this study suggests, the contribution of lawn mowers to the overall impact are negligibly small; hence, the influence of errors caused by assuming the 2-stroke inventory as the same as 4-stroke is expected to be insignificant.

The production, operation and end-of-life phases of lawnmowers were included. The transport phase was excluded based on the assumption of relatively insignificant impacts and the lack of data (Lan and Liu 2010). The inventory data for 4-stroke mower production were principally adopted from Lan and Liu (2010) and supplemented with data from other studies (East Penn Manufacturing 2013; Hawkins et al. 2013; Sullivan and Gaines 2012). Fuel consumptions and emissions during the operation phases for both 2- and 4-stroke mowers were estimated from data provided by Priest et al. (2000). For end-of-life treatment, all plastics and paper were assumed to be disposed to landfill. A recovery rate of 90 and 95% for steel and aluminium, respectively, was adopted (Boin and Bertram 2005; Worldsteel 2012). Although a high recycling rate was expected for lead acid batteries (Sullivan and Gaines 2012), due to the lack of data and relatively insignificant impacts (Premrudee et al. 2013), their disposal and recycling were not considered. Similarly, impacts of the disposal of engine lubricating oils were not considered.

2.2.3 Passenger vehicles

The LCA endpoint results for both kinds of passenger vehicles (CV and EV) were calculated by multiplying the midpoint results reported by Hawkins et al. (2013) by midpoint-to-endpoint factors of the ReCiPe method (Goedkoop et al. 2013) for production and end-of-life phases. The results were aggregated excluding components that are identical between CV and EV. The operation phases for EVs included the electricity usage for charging the vehicles assuming associated emissions of power plants were not considered by EPA VIC in their air quality model. Detailed justifications for this assumption are provided in Online Resource 1. The operation phase of CVs included petrol production and tailpipe emissions. For CVs, impacts were determined by applying the Euro 5 emission standard (EUR-Lex 2014) by considering the commitment of Australian Government to improve the standards for light-duty vehicles based on Euro 5 and Euro 6 (EPA VIC 2013). Operational emissions that were considered by the associated process data set of GaBi include ammonia, benzene, carbon dioxide, carbon monoxide, methane, nitrogen oxides, nitrous oxide, NMVOC, particulate, sulphur dioxide, toluene and xylene (thinkstep 2013). The LCA output of PMFP and POFP due to these operational emissions was excluded as it is considered in QRA. Victoria's electricity mix (Hall 2012) was considered for EV charges. Fifty percent of the CVs (about two million vehicles) were replaced by 2030 with EVs in the 'Low Impact' scenario as estimated by EPA VIC (Bannister 2014). The life spans of vehicles and batteries were based on driving 150,000 km (Hawkins et al. 2013). The functional unit was two million vehicles driven for 1 year. The distance driven per vehicle per year was estimated from the total distance driven in the region and the number of vehicles registered (ABS 2012b), assuming no significant changes in 2030.

2.2.4 Briquettes

Approximately 5900 t (about 130 TJ) per year of briquettes, which are charcoal manufactured from brown coal, were predicted by EPA VIC to be consumed for residential heating and cooking in the 'Most Likely' scenario (Bannister 2014). These would be replaced with natural gas of equivalent energy content in the 'Low Impact' scenario. Therefore, the functional unit was to generate 130 TJ of energy per year. The production processes for natural gas and brown coal briquettes were included in the 'Low Impact' and the 'Most Likely' scenarios, respectively. The emission data during operation were taken from studies of Singh et al. (2014) and shown in Online Resource 1 (Table S12). The substances considered by Singh et al. (2014) were carbon dioxide, carbon monoxide, methane, nitrogen oxides, NMVOC, particulate matter and sulphur dioxide for both scenarios. For 'Most Likely' scenario, ash was also included. In the current study, the impacts due to nitrogen oxides, NMVOC, particulate matter and sulphur dioxide were excluded from the LCA as they were considered in the QRA. Since detailed emission data for brown coal charcoal combustion were not available, data for wood charcoal were used. As the BoD impacts associated with briquettes were found to be insignificant compared to the overall impacts, errors due to this inaccuracy are expected to be insignificant.

2.2.5 Desulphurisation

Circulating fluidised bed flue gas desulphurisation (CFB-FGD) was assumed to be applied due to the relatively small size of the power plant to reduce SO_2 emissions in the 'Low Impact' scenario. Inventory data from a LCA study of CFB-FGD for a 2 × 300 MW coal-fired power plant (Feng et al. 2014) was downscaled for this LCA. A linear relationship was assumed for operational inventory data, and a power law ($y = x^{0.6}$) was used for capital inventory data. The life span of the system was assumed to be 30 years, and the operation time per year was estimated to be 6667 h (Alcoa 2013; Feng et al. 2014). The functional unit was the annual operation of CFB-FGD. Transport phase and assembly of the FGD system were not considered due to their expectedly low impacts and insufficient data availability (Feng et al. 2014; Strezov and Herbertson 2006). Since operational emissions other than SO_2 would be the same for both scenarios and the impacts due to operational SO_2 emission were included in QRA, emissions during operational phase were not considered in the LCA. Recovery rate of 90% for steel was taken into account for end-of-life phase, while disposal of iron was not included due to lack of data and significantly small amount used in the system.

2.3 Sensitivity analysis

The LCA in this study showed that impacts due to passenger vehicles were significant and those of other items were negligible compared to passenger vehicles. Therefore, sensitivity analysis for the LCA was focused on assumptions used for passenger vehicles. Hawkins et al. (2013) showed the high influence of the choice of electricity source for battery charging, average life span and energy efficiency of a vehicle; therefore, sensitivity analysis was performed for these variables.

For QRA, since the result of this study suggested that the contribution of impacts due to tropospheric ozone was negligibly small, sensitivity analysis was carried out only for the impacts of particulates. The parameters considered were population exposure to $PM_{2.5}$, relative risks and base mortality rate.

2.3.1 Type of electricity source for EV charging—LCA

The current electricity mix of Victoria was assumed to be used in 2030. However, it may change in the future. To determine the influence of types of electricity source to charge EVs, LCA was performed with different types of electricity source. In addition to the current Victoria mix, current Victoria renewable energy only mix and electricity solely from wind, natural gas and brown coal were assessed. More realistic assessment can be achieved by considering mix of multiple energy sources with various electrical dispatch orders; however, only the simple energy supply options were considered here to observe the influence of different type of energy sources.

2.3.2 Passenger vehicle average life span—LCA

As the technology advances, passenger vehicle life span may be extended, especially for EV which is still relatively immature. Hence, the average life span was varied between 100,000 and 300,000 km to examine the influence of this uncertain factor.

2.3.3 Electric vehicle energy efficiency—LCA

The energy efficiency assumed in the LCA was 0.623 MJ/km following Hawkins et al. (2013). However, the uncertainty of this assumption is large (Hawkins et al. 2013). Global warming potential, particulate matter formation potential and human toxicity potential were chosen to be examined, as the effect of other impact categories was found to be negligibly small and due to the lack of data (Hawkins et al. 2013). Energy efficiency between 0.3 and 0.9 MJ/km was used for sensitivity analysis.

2.3.4 Population exposure—QRA

The population exposure data used in the QRA involves the estimation of pollutant concentrations and exposed population in each square of the 3 × 3 km geographical grid for 2030 based on the future scenarios considered. These future predictions require numerous assumptions and hence contains uncertainties. A sensitivity analysis of the QRA was performed by varying the population exposed to the contaminants by ±25 and ±50%.

2.3.5 Relative risk—QRA

In the QRA, RRs from studies of Pope et al. (2002) were used. Large sample size, wide geographical distribution of population and strict control for confounders were considered in their study; however, derivation of RRs generally contains uncertainties. To assess the effect of selected RR values to the overall results, BoD impacts were recalculated with lower and upper bounds of 95% confidence level of RRs provided by Pope et al. (2002).

2.3.6 Base mortality rate—QRA

IHME (2016) provided lower and upper bounds of 95% confidence intervals for the mortality rate in their report. These numbers were applied in the QRA to analyse the effect of uncertainties involved in the estimations of mortality rates.

3 Results

Compared to the 'Most likely scenario', local BoD impacts due to $PM_{2.5}$ were reduced by 740 DALYs (0.74 kilo DALYs, kDALYs) per year under the 'Low Impact' scenario. On the other hand, a slight increase in impact due to ambient ozone was estimated (0.0043 kDALYs per year). This is due to the increase in estimated population exposure to ozone in the 'Low Impact' scenario. Since ozone is formed through a long sequence of chemical reactions, its ambient concentration is strongly affected not only by the precursor emissions but also other factors such as winds and sunlight. This makes the estimated ozone concentration more complex and less intuitive. The results of the LCA suggested that BoD impacts were projected to be greater for most of the engineering interventions assumed under the 'Low Impact' scenario. Figure 1 illustrates the differences in BoD impacts between the 'Low Impact' and 'Most Likely' scenarios. Negative numbers represent the reductions, and the positive numbers indicate greater impacts in the 'Low Impact' scenario. The only categories where net reduction was expected under the 'Low Impact' scenario were briquettes and ambient concentrations of particulates. For all other categories, greater impacts were projected from the 'Low Impact' scenario, generally due to extra hardware production and operations involved. Despite the improved air quality due to reduction of ambient $PM_{2.5}$ and hence the reduced BoD impacts by the interventions suggested in the 'Low Impact' scenario, the achieved benefit was estimated to be small compared to the impacts added by the changes. It can be seen that the replacement of passenger vehicles was the main element that makes the 'Most Likely' scenario to outperform the 'Low Impact' scenario. The impacts estimated for non-operation and operation phases of each intervention for each midpoint impact category are

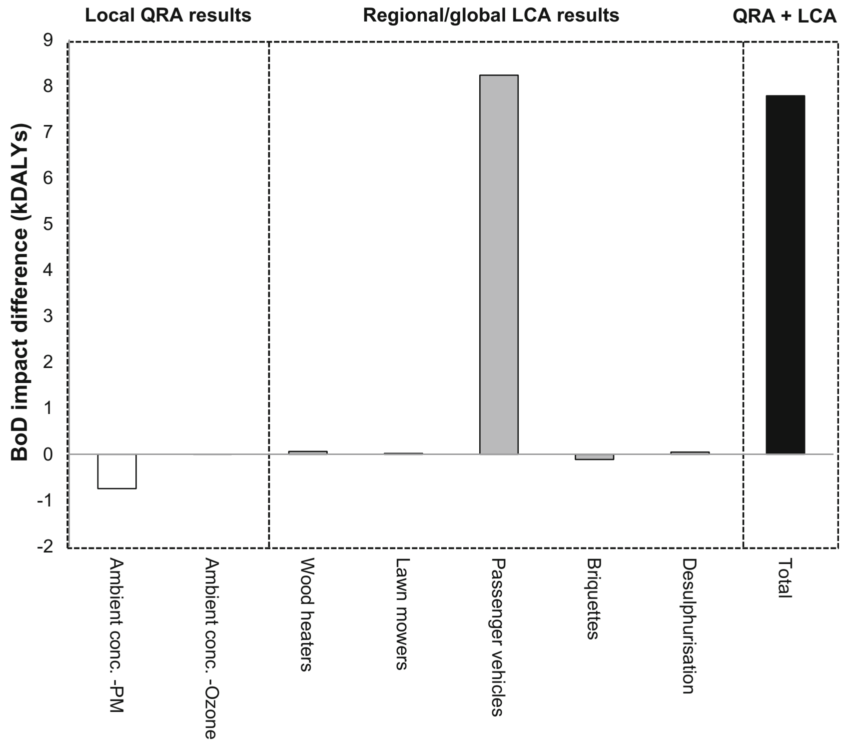

Fig. 1 Difference in BoD impact between 'Low Impact' and 'Most Likely' scenarios

provided in Online Resource 1 (Table S14). It should be emphasised that the specific populations projected to share the health burdens identified by the QRA and LCA were not identical. An effort to reduce burdens of a local population by improving the local air quality was projected to increase burdens in a broader population in this study.

By far, the largest contribution to the overall difference between the two scenarios was made by the change to passenger vehicles. This is because the numbers of vehicles and corresponding mass of hardware to be replaced are very large and the vehicle life spans (about 10 years) are relatively short compared, for example, to those of wood heaters and desulphurisation system (30 years). The impacts during non-operation and operation phases of passenger vehicles are shown in Table 1. In both phases, the uptake of EVs was found to cause more impacts than CVs.

Although EVs generate no tailpipe emissions, their impacts during the operation phase are high. The PMFP is the largest single cause of the difference between the two scenarios. This is partially because the PMFP, due to tailpipe emissions of CVs, is not included in this LCA as it is accounted in the QRA. An additional factor is that the current Victorian electricity mix, which depends heavily on fossil fuel combustion and particularly brown coal, was assumed to be used to charge EVs. For the same reason, CCP in the 'Low Impact' scenario was similarly high as the 'Most Likely' scenario.

For the non-operational phase, the projected difference between the two scenarios was mostly contributed by CCP, HTP and PMFP. The impacts in these impact categories in the 'Low Impact' scenario originated with energy-intensive production of lithium battery (Delucchi et al. 2014). For the category of HTP in particular, lithium battery caused about 70% of the impact in this LCA. BoD impacts estimated for each process for each midpoint impact category are provided in Online Resource 1 (Table S15). In the study of Hawkins et al. (2013), which this LCA was based on, European studies for inventories of battery productions were used. Majeau-Bettez et al. (2011) estimated that if batteries were produced in China, for instance, associated CCP would be increased by 10 to 16%.

Hawkins et al. (2013) reported that battery production contributes over 35% of CCP of the whole production of an EV. Since the LCA in this study only accounted differences between the scenarios, other vehicle components that are potentially CCP intensive in their production were excluded when they were common to both EVs and CVs. Vehicle body and door productions are such examples. Consequently, the relative contribution of battery production to the total CCP of EV is higher in this study. Similarly, HTP is significantly higher for EVs compared to CVs. The cause of this is mainly metal requirements for battery production such as copper and nickel (Hawkins et al. 2013; Majeau-Bettez et al. 2011). However, battery technology by 2030 may well have evolved to lower polluting options (Peled et al. 2015).

Overall, the largest contributions due to change in 'passenger vehicle' were made by PMFP in operational phase (36%), HTP in non-operational phase (26%), CCP in non-operational phase (19%) and PMFP in non-operational phase (13%).

Table 1 BoD impacts in non-operation and operation phases of passenger vehicles for 'Low Impact' and 'Most Likely' scenarios in kDALYs per year estimated with LCA

		'Low Impact' (EV)		'Most Likely' (CV)		Diff[a]	
		Non-operation	Operation	Non-operation	Operation	Non-operation	Operation
Impacts (kDALYs)	CCP	1.9	7.4	3.8E-01	7.1	1.6	2.6E-01
	HTP	2.3	4.7E-01	2.2E-01	2.1E-01	2.1	2.5E-01
	IRP	3.0E-03	1.2E-04	1.3E-03	2.2E-04	1.7E-03	-9.6E-05
	ODP	1.5E-02	2.9E-06	4.4E-05	3.3E-05	1.5E-02	-3.0E-05
	PMFP	2.7	5.5	1.6	2.5	1.1	2.9
	POFP	1.5E-04	3.8E-04	5.5E-05	1.4E-04	9.6E-05	2.4E-04
	Total	7.0	13	2.2	9.9	4.8	3.5
Contributions	%	34%	66%	18%	82%	58%	42%

CCP climate change potential, *HTP* human toxicity potential, *IRP* ionising radiation potential, *ODP* ozone depletion potential, *PMFP* particulate matter formation potential, *POFP* photochemical oxidant formation potential

[a] Diff = difference = 'Low Impact'–'Most Likely'

Although the contribution of HTP which is known to contain higher uncertainty is relatively significant, since impact categories with more robustness contribute nearly 70% of the total, the results of this LCA can be considered reliable.

The second most significant impact category for the difference between the two scenarios was the ambient concentration of particulates. The efforts to reduce BoD impacts due to air quality in the 'Low Impact' scenario were predicted to be more effective for particulates than ozone in this study.

The result of this study showed that strong burden shifting may be caused when trying to reduce local BoD impacts. An attempt to reduce local BoD impacts due to air pollution caused much higher BoD impacts mainly as a consequence of energy consumption and production of lithium batteries required for EVs. This burden shifting can easily be overlooked when only impacts due to local air quality are considered. Therefore, more holistic approaches should be considered when making policy changes so as to ensure that BoD impacts are truly reduced, not just shifted.

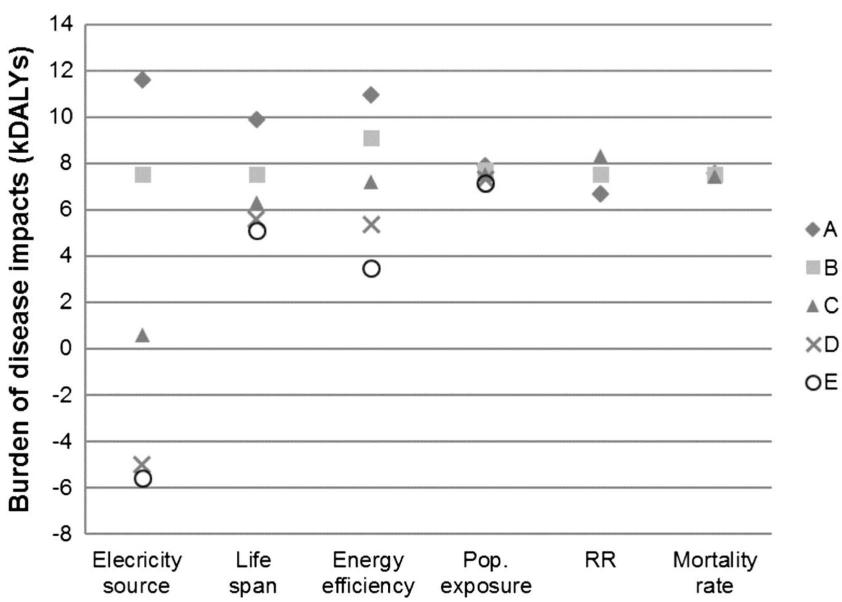

Fig. 2 Results of sensitivity analysis in estimations of disease burden impacts by parameter. Scenarios: Electricity source: A-Brown coal, B-Victoria mix, C-Natural gas, D-Victoria renewable mix, E-Wind; Vehicle life span: A-100,000km, B-150,000km, C-200,000km, D-250,000km, E-300,000km; Vehicle energy efficiency: A-0.9MJ/km, B-0.75MJ/km, C-0.6MJ/km, D-0.45MJ/km, E-0.3MJ/km; Population exposure: A-+50%, B-+25%, C-default value, D–25%, E–50%; Relative risk (RR): A-upper bound of 95% CI, B-mean values, C-lower bound of 95% CI; Mortality rate: A-upper bound of 95% CI, B-mean values, C-lower bound of 95% CI

4 Sensitivity analysis

The results of the sensitivity analysis are shown in Fig. 2. The values are the differences between total impacts of the 'Low Impact' and 'Most Likely' scenarios when different values were selected for each parameter. Negative numbers indicate that impacts would be improved and positive numbers indicate that the impacts would be greater in the 'Low Impact' scenario.

The result favoured the 'Low Impact' scenario when renewable energy sources such as Victoria's renewable electricity mix and wind energy were used for EV charging. More than 4 kDALYs per year were projected to be saved in the 'Low Impact' scenario. For fossil fuel-based energy sources, brown coal and Victoria's current mix caused significantly more impacts in the 'Low Impact' than 'Most Likely' scenario. With natural gas powered electricity, the 'Most Likely' scenario was also superior, though only by about 1 kDALY per year, compared to 12 kDALYs per year for brown coal and 8 kDALYs per year for Victoria mix. The difference between the best case (wind energy) and the worst case (brown coal) was around 17 kDALYs per year. For this wide range of projected impacts, it is crucial that the future electricity sources are carefully considered in policy making.

The variations caused by the chosen vehicle life span and energy efficiency of EVs were not sufficient to alter the scenario preference for BoD impacts in this study. However, the ranges between the results with highest and lowest assumed values were not insignificant, about 5 kDALYs per year for life span and 7 kDALYs for energy efficiency. While individual parameter selection did not affect the overall conclusion, some combinations of these value choices can alter the conclusion. Since EVs are relatively immature products and the associated technologies are still rapidly advancing (Hawkins et al. 2013), these uncertainties should also be considered in decision-making.

The influence of uncertainty in QRA was not considered significant. This is because the contribution of the particulate induced impact to the total impact is relatively small. Among the parameters assessed, the RR was found to be the most influential within the chosen range of uncertainty. However, it was still only about 1.6 kDALYs difference between lowest and highest values applied, which is not significant enough to alter the favour of scenario.

5 Discussion and conclusions

5.1 Limitations of the study

There were several key limitations to note in this study. They are discussed in the following sub-sections.

5.1.1 Population demography

Population demography may play an important role when evaluating BoD impacts. Sensitivity to pollution may vary depending on age and health conditions (WHO 2006). For example, Gronlund et al. (2015) showed the DALYs per kg of $PM_{2.5}$ inhaled of 78 for the total WHO world standard population as opposed to that of 110 for US population. The reason for this difference is that the WHO standard population is younger than the US population (Gronlund et al. 2015).

In Victoria, the number of people aged over 65 years old will grow significantly in the coming years (EPA VIC 2013). However, the projection for population demography for 2030 was not available; it was estimated by considering the past trend, as described in the method section. Also, a single population demography prediction was used for all the geographical grids in the study region. Since errors introduced by this uncertainty are likely to be insignificant in comparative studies like this where the targeted populations are identical, the effect of this inaccuracy should be insignificant. In addition, the contribution to overall impacts made by local air pollution was found to be small, so the influence to the overall results is expected to be minimal.

5.1.2 Impacts of particulates and tropospheric ozone outside the region

In the QRA, only regional impacts due to particulates and tropospheric ozone were considered while population outside of the study region can also be affected. Tang et al. (2015) showed that the impacts to outside of a chosen region for a study were significant in Europe while they were relatively insignificant for Japan. The rationale for this difference was not explicitly explained; however, it is likely that emissions from an isolated island region such as Japan are less impacting on other regions. Australian cities including those in Victoria are also isolated from other densely populated cities. As such, the errors due to focusing on a specific region are expected be minimal.

5.1.3 Uncertainty analysis

The importance of accounting uncertainties associated with LCA and QRA has been acknowledged (Hauck et al. 2014; Spruijt et al. 2016). When a number of assumptions are associated in a study, uncertainty analysis using probability distributions improves the robustness of the results. However, due to the limited data availability for probability distribution function for each parameter, only sensitivity analysis for limited number of parameters was performed. The results of the sensitivity analysis suggested that the uncertainties of the main parameters in this study are unlikely to significantly affect the final conclusion except for the selection of electricity source for EV charging, for which probability distribution cannot be defined. Therefore, performing uncertainty analysis with point estimates should be sufficient for his study.

5.1.4 Use of pollutant concentration data from previous studies

In the QRA of this study, BoD impacts were calculated by using ambient concentrations of pollutants which were previously estimated by EPA VIC. The disadvantage of using such data from previous studies is the limitation of breaking down the results for further analysis. For example, in the case of the current study, only the overall results which are the ambient concentrations of each pollutant were available. In other words, the contributions of each proposed change to the estimated ambient concentrations were not known. For the purpose of this study, which was to demonstrate the combined use of LCA and QRA to detect potential problem shifting while taking local details into account, the use of overall concentration data was adequate; however, depending on study objectives, the ability to determine the contributions of each change may be necessary.

5.2 The potential for hybridisation of health burden assessments

5.2.1 Consideration for the integration of LCA and QRA

In this study, parameters in QRA have been selected to be consistent with those used in the LCA where possible. These include the health effects and age of population who are potentially exposed. In reality, LCA practitioners do not always carefully examine the impact assessment methods used in LCA tools. In such cases, methodological inconsistency between QRA and LCA approaches could occur and the results of the two become directly incomparable. For example, type of health effects considered in the impact assessment may differ, depending on LCA methods (Kobayashi et al. 2015b). Selections of health effects in QRA also varies among studies (Hänninen et al. 2014; Kim et al. 2011). In this study, only cardiopulmonary and lung cancer mortalities due to $PM_{2.5}$ and acute mortality due to ozone were considered to follow the LCA methods applied. Some QRA studies also include morbidity due to cardiovascular and/or respiratory diseases (Kim et al. 2011). There is greater flexibility in QRA to select type of health effects to be included when the knowledge on cause-effect relationships between pollutants and health effects advances. It could take some time for LCA tools to be updated with these new findings.

It has been pointed out that the fundamental difference between LCA and QRA that needs to be carefully considered when integrating these two approaches was the use of functional unit in LCA and the use of absolute amount in QRA (De Haes et al. 2006). Harder et al. (2015) indicated that when QRA is combined with LCA, it may cause misinterpretation of the results, depending on the functional unit chosen. The purpose of this study was to compare the two alternative future scenarios in terms of BoD impacts during 2030. As such, QRA was carried out to quantify the BoD impacts due to air pollution in 1 year (2030), and the functional unit of LCA was chosen to be the operation of each intervention defined in each scenario for the same 1 year. Since pollutant emission rates and resulting ambient concentrations could vary depending on the season and other factors such as weather conditions, the use of shorter time period for functional units may cause misconception.

5.2.2 Implications for analysts

The current ReCiPe method uses the mass of PM_{10} equivalent emissions as a midpoint indicator, and health effects due to PM_{10} are considered to quantify BoD impacts of potential particulate matter formation at the endpoint level. The use of PM_{10} in this regard may underestimate the BoD impacts as the smaller particles cause greater effects to BoD (WHO 2005). Another concern with ReCiPe method, and the LCA method in general, is that it does not account the location of emissions. Exposed population and the degree of their exposure to pollutants vary depending on the location of the pollutant release as well as emission height (Humbert et al. 2011). This also potentially influences the estimation of BoD impacts. For this reason, QRA appeared to be a more suitable tool to assess local BoD impacts caused by ambient pollutants, including particulate matter and ozone.

Similarly, other local details such as more precise number of population exposed and its demography can be accounted with QRA. Behaviour of the people (e.g. time spent outside) and geographical variations of exposed population can also be considered when desired. Since DALY values and relative risks are known to be locally dependent, the impact estimation can be improved by using locally derived values. Currently, relative risks used in LCA tools are mostly from studies in Europe and the USA. These may not be relevant for population in different culture with different habits such as smoking.

For larger regional scales, on the other hand, LCA is more useful than QRA to evaluate impacts. The use of global or regional average values in the calculation which may be insufficient for locally affected impacts is adequate for global impacts. LCA provides more comprehensive impact assessment and helps to prevent problems shifting to other locations or other types of impacts rather than being fully contained in the broader system.

The ability to combine the outcomes of QRA and LCA for air quality was introduced in this study, although it has been examined for water (Kobayashi et al. 2015a), sludge (Heimersson et al. 2014) and transportation of hazardous materials (Clark and Besterfield-Sacre 2009). Here, we demonstrated that the use of QRA and LCA, where applicable, would enhance comprehensiveness of an impact assessment. DALYs, as a common metric between the two approaches facilitates, direct aggregation of local, regional and global BoD impacts to assist more straightforward quantitative comparison of alternative scenarios.

DALYs have been used increasingly in LCA and more traditionally in QRA, and the advantages of using DALYs as a common metric between LCA and QRA have been demonstrated (Heimersson et al. 2014; Kobayashi et al. 2015a). While there are many valuable benefits of DALYs, it should also be addressed that some general assumptions and value choices are unavoidable when quantifying BoD impacts using DALYs (Goedkoop et al. 2013; Mathers 2008). It is mainly due to the limited understanding between cause and effects and difference in personal preference for severity of health effects. It is important to note that additional uncertainties are introduced.

5.2.3 Further improvements for analysis

For the QRA aspects of this study, only ambient concentrations of fine particulates and ozone were considered for local air quality-related impacts. While most of the proposed changes under the 'Low Impact' scenario would only affect the outdoor air quality directly, the indoor air quality may be influenced by ambient air pollutions especially in this study area where the usage of air conditioner in households is relatively low (ABS 2012a). In addition, the use of wood heaters, for example, may also cause indoor air pollution. Since people tend to spend more time indoors, future assessments of the BoD impacts should also include indoor emissions. Furthermore, the importance of including indoor air quality as an impact category in LCA has been recognised (Skaar and Jørgensen 2013) and implemented in the 2015 release of the UseTox model (version 2.0). Alternatively, since the indoor emissions and the rate of population exposure are locally dependent, impacts due to indoor emissions may be better assessed using QRA when associated data is obtainable. The results can then be aggregated with LCA results in a similar manner, as the QRA for ambient air pollutions was demonstrated in the current study. However, this was not included in the QRA of this study because although TAPM-CTM does not consider indoor air quality, it does provide a very detailed, locally tailored, regional air quality model for the fate and exposure assessment. Depending on the type of wood heaters used, installation and maintenance of heaters, size of rooms/houses, efficiency of ventilation system, number of inhabitants in household and duration of exposure, the indoor concentrations and degree of BoD impacts vary. Since indoor emissions of modern wood heaters are limited when operated properly (Chafe et al. 2015) and this study only accounts the difference between the two emission scenarios, the influence of disregarding indoor air quality in this study is expected not to affect the conclusion of the study.

Human toxicity potential is another impact category that could be locally dependent. The approaches used in current LCA tools are generic and contains many uncertainties (Kobayashi et al. 2015b). Since the number of substances potentially contributing to human toxicity is vast and the availability of data necessary to assess BoD impacts such as relative risk is limited, it may often not be feasible to include important local details in an assessment. Nonetheless, applying QRA when possible would further improve the accuracy of a study, and certain key components, such as acrolein and formaldehyde, could account for a significant amount of the indoor air risk along with fine particulates (Logue et al. 2012).

5.2.4 Implications for policy makers

Comparing the total impacts of the two scenarios indicates that the 'Most Likely' scenario outperforms in terms of BoD impacts despite the improved local air pollutant emissions in the 'Low Impact' scenario. This conclusion was shown to be robust in 24 of the 26 sensitivity analyses applied in this work. The extensive global impacts could have been overlooked if QRA alone was applied, focusing only on the local impacts. In such cases, an improper scenario could be preferred and inappropriate policies may be set. For instance, EV may be promoted for its zero tailpipe emissions without consideration of impact caused by electricity requirement for battery charging, resulting in significantly higher overall BoD impacts. As others have identified previously, the current study revealed the importance of having a broader perspective when making environmental policies (Philp et al. 2013). Specifically for CCP impacts, the recognised need to address this transfer of impacts is one of the reasons for the success of the Paris Agreement (UNFCCC 2016). Individual nations will have to respond by decreasing carbon emissions, which may take the form of a carbon tax, a cap-and-trade approach or other measures. Current Australian policy is based on the idea of an auction for climate reduction subsidies. Various groups consider this response inadequate to meet the government's stated goals, but the country has nevertheless signed on to the Paris Agreement. To achieve the goals, it is important that governments at local level also cooperate to reduce emission.

5.2.5 Further improvements for policy making

The use of DALYs or, more generally, the use of LCA endpoint approaches can aid decision-makers to directly compare various types of environmental impacts and/or impacts of alternative scenarios as demonstrated in this study. However, when seeking further data, analysis is often subjected to additional uncertainties as mentioned earlier. Nonetheless, the degree of uncertainty associated with endpoint results can be numerically addressed. Quantification of uncertainty provides more information to decision-makers and stakeholders. In this regard, probability analysis would potentially be useful. This approach takes ranges of values defined as a probability density function (PDF) as input data and provides a PDF outcome rather than a point estimate for decision-makers. From this PDF output, valuable information such as probability of getting certain values and the degree of variability and uncertainty are obtainable (see, e.g. Kobayashi et al. (2015b)). While this requires more data and could be more complex to analyse the results, the benefit of providing more comprehensive characteristics of results should aid by improving decisions made.

Additional endpoint impacts, such as ecosystem quality and resource depletion, are generally required for policy making. These impacts were disregarded in the current study as the focus was on demonstrating the importance of applying a more holistic approach to assess BoD impacts. However, some LCA studies such as those of wood heaters (Solli et al. 2009), lawn mowers (Lan and Liu 2010) and passenger vehicles (Hawkins et al. 2013) suggest that the impacts to ecosystem quality and resource depletion could be significant. Moreover, to determine the overall preferred scenario, other aspects including economic and social impacts also need to be considered (Singh et al. 2012).

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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