The Centre for Australian Weather and Climate Research
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Exploring the co-benefit of electric vehicle uptake and ozone pollution reduction in Sydney - Final report

Martin Cope and Sunhee Lee

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1. INTRODUCTION

Interest in the uptake and externalities of electric vehicle use has been gathering pace over the last decade, driven by concerns of future oil availability and security, urban sustainability and climate change (CSIRO 2008). The Jamison Report[1] concluded that a transition from internal combustion to electric drive cars is likely to dominate the future of the motor vehicle. A recent economical modelling study into the economic viability of electric vehicles for the NSW Metropolitan region (DECC 2009) concluded "that the plug-in electric vehicle market in NSW is both economically and financially viable. However the economic and financial returns accrue over the longer term". The study also concluded that there was the potential to generate large savings in greenhouse gas and air pollution emissions.

Albrecht et al. (2009) looked into the uptake of electric vehicles (EVs) in Australia and concludedfor Sydney that a five per cent uptake of EVs for daily commuting could lead to a 3.6 million kilometre reduction in travel by liquid fuelled vehicles in Sydney. They also concluded that the maximum benefit would be obtained by acquiring electricity for the EVs from renewable energy. In unpublished work[2] Simpson (2009) concluded that an Australian fleet of one million EVs would reduce toxic air pollutant emissions by 150000 - 300000 tonnes per year. Jacobson (2009) reviewed solutions to global warming, air pollution and energy security and ranked renewable energy powered electric vehicles amongst the most promising solutions.

Given the likely pace of change in the electric vehicle market, it is important that the environmental externalities are identified and quantified. In this report we present the results of a modelling study which investigated how ozone pollution in the Greater Metropolitan Region of Sydney NSW, Australia would respond to the replacement of Sydney's internal combustion engine (ICE) passenger vehicle fleet with a fleet of electric vehicles. A brief description of the modelling methodology is provided in the next section, and a summary of the modelling outcomes is provided in the following section.

2. HOW OZONE IS MODELLED IN THIS STUDY

The methodology used for modelling ozone air pollution is identical to that described in Cope et al.(2009) with the emissions, weather and air pollution transport for the Sydney regionsimulated with a chemical transport model (CTM). This model is nested inside a larger scale model which simulates the weather over the Australian continent. This model is in turn nested in a global climate model (GCM) which has been used to simulated current and future global climates- the latter for various scenarios of global warming.

The results presented below have been generated by this system of models for a global climate forced by an A2 greenhouse gas emission scenario (a high end CO_2 emissions growth scenario). The A2 family of emissions scenario is summarised in the IPCC Special Report on Emission Scenarios (http://www.grida.no/climate/ipcc/emission/index.htm) as follows. "The family represents a differentiated world. Compared to the A1 storyline it is characterized by lower trade flows, relatively slow capital stock turnover, and slower technological change. The A2 world "consolidates" into a series of economic regions. Self-reliance in terms of resources and

[1] http://www.mynrma.com.au/cps/rde/xchg/mynrma/hs.xsl/jamison_report.htm
[2] http://sustainability.curtin.edu.au/local/docs/0907_Environmental_Attributes_EVs_Australia.pdf

less emphasis on economic, social, and cultural interactions between regions are characteristic for this future. Economic growth is uneven and the income gap between now-industrialized and developing parts of the world does not narrow, unlike in the A1 and B1 scenario families."

Modelling was undertaken for decadal periods covering the years 1996–2005 and 2051–2060. Fig.1shows the modelled 99thpercentile 1–h ozone concentration for each of the decades. Note that ozone precursor emissions were held fixed at 2000 business-as-usual levels (other than temperature-related differences) for both decades and thus the differences between the two plots inFig.1can be used to characterise the 'climate penalty'- that is the increase in ozone concentration resulting from climate change alone for a 'do nothing' emission control strategy.

The chemical transport modelling used emissions from the Sydney Greater Metropolitan Region (GMR) on-road mobile source inventory (DECCW 2007), while industrial, commercial and domestic emissions were taken from the Metropolitan Air Emissions Inventory (Carnovale et al. 1996). Note that an updated inventory of commercial, domestic and industrial emissions is now available; however this inventory was not used in the current study because the electric vehicle scenarios discussed below were compared to a base case scenario generated using the earlier inventory (Cope et al. 2009). Emissions from natural sources (NO_x from bacterial activity in soils; VOC emissions from plants) were also modelled (see Azzi et al. 2005 and references therein). Table 1 shows emission totals for the major source groups in the inventory used by Cope et al. (2009) and in this study.

The environmental impacts of the modelled ozone for the emission scenarios considered in this study were quantified by two methods.

1. Through the calculation of exceedence frequencies of the National Environment Protection Measure (NEPM) Ambient Air Quality Standards (AAQS) for ozone[3]- being 100 ppb for a 1–h average and 80 ppb for a 4–h average.

2. Through the calculation of relative changes in population exposure using a similar methodology to that discussed in Cope et al. (2009) and CSIRO and Orbital (2008).

[3]http://www.environment.gov.au/atmosphere/airquality/standards.html

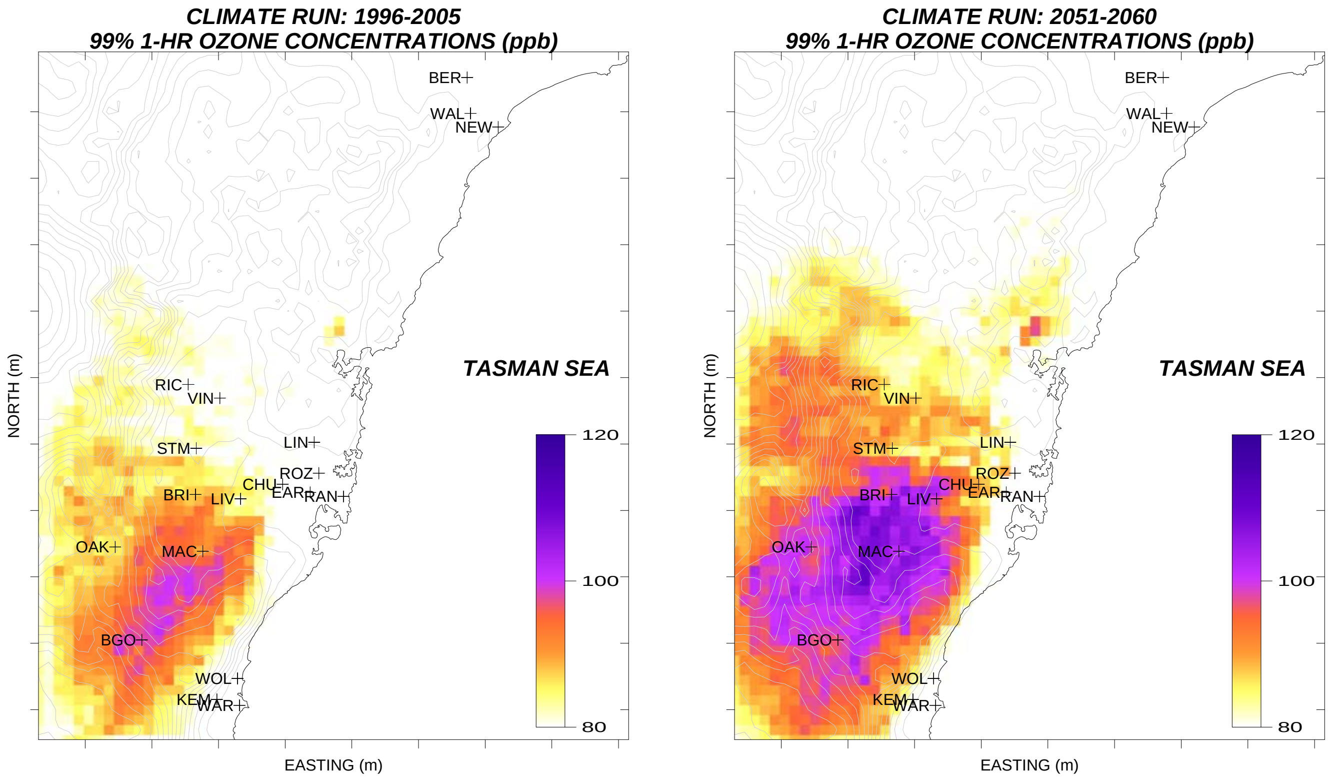

Fig.1. The spatial distribution of 99th percentile 1–hour ozone concentrations for (left) the decade 1996–2005; right- for the decade 2051–2060.

2.1 The passenger vehicle emission scenarios

The base case emissions scenario considered in this study is based on a 2006 passenger vehicle fleet which is powered predominately by petrol-fuelled internal combustion engines. The study used two electric vehicle emission scenarios. The first considers a 100% replacement of the ICE passenger vehicle fleet with electric vehicles (EVs) in which the vehicle batteries are re-charged from renewable energy sources. It is assumed that the upstream air pollution emissions associated with the renewable energy is small and thus does not need to be considered when modelling ozone pollution in the GMR. This scenario (henceforth called EV+Renewable) leads to a 34% reduction in total oxide of nitrogen emissions (NO_x) emissions, a 41% reduction in volatile organic carbon (VOC) emissions and a 65% reduction in carbon monoxide (CO) emissions.

Table 1. Daily anthropogenic and biogenic/natural precursor emissions for the Greater Metropolitan Region used for the 2006 base case.

	NO_x		**VOC**		**CO**	
	(t/day)	(%)	(t/day)	(%)	(t/day)	(%)
Petrol vehicle exhaust	155	34	129	32	1712	65
Diesel vehicle exhaust	80	17	5	1	71	3
Petrol vehicle evaporative	0	0	38	9	0	0
Commercial-domestic and surface industrial	66	14	232	57	137	5
Elevated industrial	159	35	2	1	732	28
Natural	1–1.4	N/A	600	N/A	0	N/A

In the second EV scenario we assume that the electrical energy for battery recharging is supplied by coal-fired power stations located in the GMR (EV+Coal Power). The approach for determining the additional amount of power at the power station (and hence the additional atmospheric emissions) is summarised in Arar (2010) and may be estimated as follows.

$$E = Qev \times VKT \times {}^{1}/_{CE} \qquad (1)$$

Where *E* is the electrical energy requirements of the EV fleet (kw-h), *Qev* is the fleet average energy consumption per vehicle (kw-h km^{-1}), *VKT* is the fleet total vehicle kilometres travelled, and *CE* is the centralised efficiency i.e. the efficiency of the electrical transmission network.

In order to calculate the electrical energy requirements for the Sydney passenger vehicle fleet we take *Qev* = 20 kw-h/100 km (DECC 2009). The annual *VKT* for Sydney has been estimated using Australian Bureau of Statistics data which gives a per capital passenger vehicle VKT = 7.61×10^3 for 2002-2003 for Australia. Taking the Sydney population to be 4.5×10^6 gives an annual VKT of 6.34×10^{10} km. Finally we prescribe a centralised efficiency of 0.945 for the NSW electricity grid[4]. Thesenumbers give an estimated annual electrical energy demand of 7.25×10^6 MW-h per annum for EV battery charging.

For the EV+Coal scenario, we have assumed that the electrical energy will be provided by eight coal-fired power stations located in- or close to the Sydney Greater Metropolitan Region: RedBank, Wallerawang, Mt Piper, Liddell, Munmorah, Vales Point, Bayswater and Eraring. In total these power stations provide 1.02×10^8 MW-h/annum of electrical energy to the grid (personal communication, Nick Agapides DECCW, 2010) and thus the EV electrical energy requirements is about 7% of the combined power station annual output. For the EV+Coal scenario we have spatially distributed the additionally energy requirements between the eight power stations according to relative contribution that each power station makes to the total generated electric energy of 1.02×10^8 MW-h.

The associated increase in the emissions of NO_x, CO and VOCs from the eight power stations was then estimated using power station-specific ratios of emission per MW-h for each pollutant (personal communication, Nick Agapides DECCW, 2010). As would be expected (given that assumption of a linear relationship between annual emissions and power station electrical output), the pollutant emissions from the coal-fired power station group is calculated to increase by about 7%. These emissions were assigned a diurnal distribution using an uncontrolled EV battery charging scenario in which the charging demand ramps up after 5 pm in the evening and continues through the night before declining by 5 am the following morning (personal communication, Paevere, CSIRO Sustainable Ecosystems, 2010). The impact on ozone production for the EV+Coal scenario is considered in the following sections.

[4] http://www.moxy.com.au/Wiki/index.php?title=NSW_Electricity_Network&action=annotate

3. THE MODELLED OZONE CHANGES IN 2051-2060

3.1 How EV uptake changes the NEPM AAQS ozone statistics

Fig.2 shows the modelled change in the yearly average number of exceedence days for the NEPM 1–h and 4–h ozone AAQS. Results are shown for the 1995–2005 and 2051–2060 climatologies with base case emissions (i.e. the 2006 ICE passenger vehicle emissions scenario); for the 2051–2060 climatology with the EV+Renewable scenario, and for the EV+Coal scenario.

The figure shows that the average exceedence frequency increases by 45–75% between 1996–2005 and 2051–2060 for the base case emission scenario. As mentioned previously this outcome is the defined as the climate penalty and results entirely from a warming climate and a do-nothing policy for ozone precursor emissions. Further discussion of climate penalty outcomes can be found in Cope et al. (2009).

Replacement of the ICE vehicle fleet with the EV fleet powered by renewable energy sources is modelled to result in a 56–62% reduction in ozone exceedences. Although this more than offsets the climate penalty, it can also be seen that 7–8 exceedences of the ozone AAQS are still predicted to occur within the GMR as a result of ozone generation from other anthropogenic and natural precursor sources.

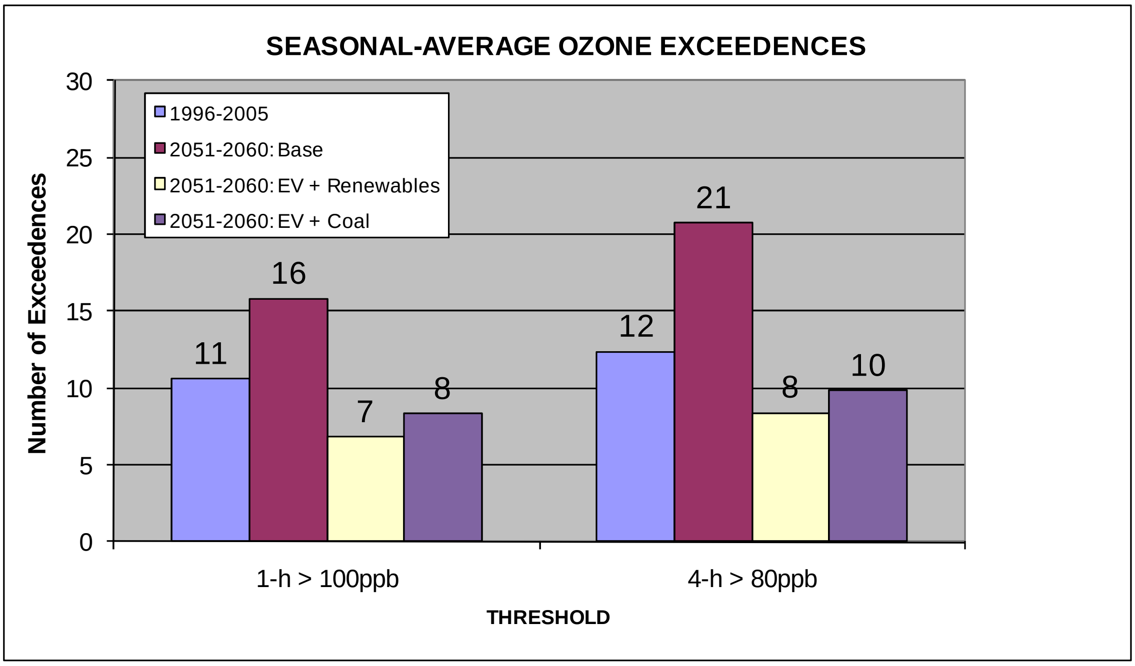

Fig.2. The average number of days per year when 1–hour ozone > 100 ppb and 4–hour ozone > 80 ppb.

If the electrical demand of the EV fleet is met by coal-fired power stations then it can be seen that the increased level of emissions associated with the power station output (see Section 2.1), increases the number of exceedences of the 1- and 4–h standards by 22 and 17% respectively compared to the option of powering the electric vehicles by renewable energy.

Fig.3 shows the modelled spatial distribution of 1-h ozone AAQS exceedences in the GMR for the three 2051–2060 scenarios. Fig.4 shows the spatial distribution ofexceedencesfor the 4-h AAQS. Both of the figures show that a significant reduction occurs in the spatial area over which two or more exceedences of the ozone AAQS is predicted to result. For example the exceedencearea shrinks to zero in the case of the 1–h standard for the EV+Renewable scenario (worst case cell has a peak of 1.6 days per year- decadal average- down from 2.9 days per year), while the EV+Coal scenario still leads to a significant improvement (worst case cell reduced to 2.0 days per year down from 2.9 days per year). With respect to the 4-h standard the maximum number of predicted exceedences reduces from 4.3 days per year for the 2051–2060 base case to 2.1 days for the EV+Renewable scenario, and to 2.5 days per year for the EV+Coal fired scenario.

So this analysis indicates that the 1-h AAQS for ozone would be achieved in the case of the EV+Renewable scenario, and would just be out of compliance in the case of the EV+Coal scenario. On the other hand, neither scenario is predicted to achieve the more stringent 4-h standard, although the EV+Renewable scenario is only marginally out of compliance.

Considering Fig.3 again, it can be seen that the regions with the highest number of exceedences for the two EV scenarios are predicted to occur slightly closer to the metropolitan Sydney. This is likely a consequence of a reduction in NO_x emissions in the Sydney region following replacement of ICE passenger vehicles with EV vehicles.Nitric oxide in the emissions acts to reduce ozone concentrations close to source areas by rapidly converting ozone into nitrogen dioxide. Reducing NO_x emissions thus serves to reduce the magnitude of the O_3 to NO_2 conversion, leading tomodest increases in ozone concentrations in the urban areas.

3.2 How EV uptake changes population morbidity

We have used the approach developed for Cope et al. (2009) and further refined in the Ethanol and Health Study (CSIRO and Orbital 2008) to investigate the relationship between ozone population exposure and the EV emission scenarios. The approach is know as the baseline increment method and involves three steps.

1. Determine the baseline health impact associated with ozone from previous research. In the case of ozone this was taken from the original Ambient Air Quality NEPM Impact Statement and updated by the Ethanol study team to be representative of 2006. The data suggest that ozone health effects in Sydney are dominated by morbidity outcomes and thus our methodology will be based on this endpoint. Here we follow the approach of Anderson et al. (2004) who recommends the use of daily 8–h maximum ozone concentration to describe the morbidity outcomes of ozone exposure.

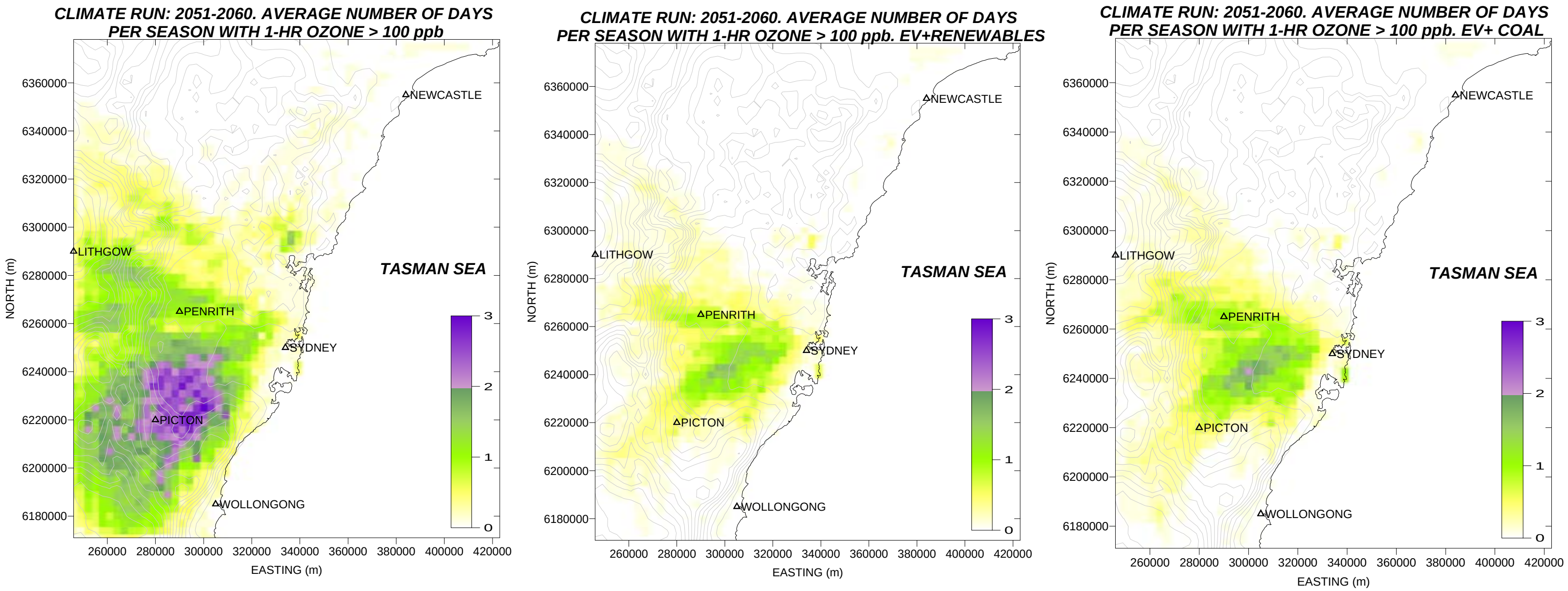

Fig.3. The spatial distribution of the yearly average exceedence frequency of the 1–h ozone NEPM AAQS of 100 ppb. Left- internal combustion engine passenger vehicles; centre- electric vehicles with batteries charged from renewable sources; right- batteries charged using coal-fired power stations.

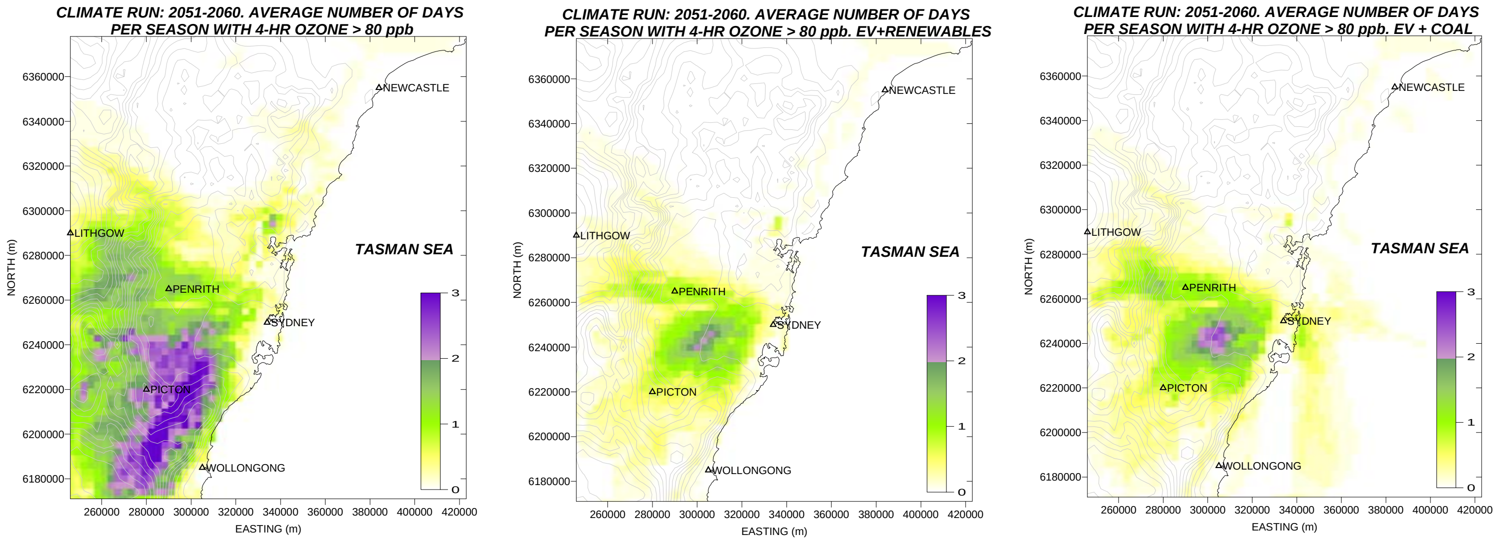

Fig.4. The spatial distribution of the yearly average exceedence frequency of the 4–h ozone NEPM AAQS of 80 ppb. Left- internal combustion engine passenger vehicles; centre- electric vehicles with batteries charged from renewable sources; right- batteries charged using coal-fired power stations.

An important parameter in the calculation of ozone health impact is the baseline concentration below which minimal health effects are observed. Bell et al. (2006) undertook a meta-analysis of health effects based on 98 US cities and concluded that the threshold may occur close to the background concentration. In this regard Duc and Azzi (2009) derived a median background ozone concentration (based mainly on night-time observations) in the range 16–21 ppb for Sydney. However it is not clear whether this would be the most appropriate threshold concentration to use given that the maximum population exposure is likely to occur during daytime conditions. Cope et al. (2009) used a 60 ppb threshold concentration; while a zero concentration threshold was used in the Ethanol and Health Study (CSIRO and Orbital 2008). For the current study we have used a threshold concentration of 40 ppb however note that there is some uncertainty associated with this choice.

2. Determine the increment or decrement to the baseline exposure- which we define here as the population-weighted ozone concentration and estimate the baseline exposure using the 1996–2005 modelling from Cope et al. (2009). The increments or decrements to the baseline exposure can then calculated using the modelling results for the 2051–2060 vehicle emission scenarios.

3. The increment or decrement may then be applied to the baseline health impact to estimate the change in health impact resulting from the modelled changes in population exposure. Note that we have not undertaken this step for the current study; rather the results are presented as percentage changes.

Using the approach described above, we have calculated that the population exposure in the GMR will increase by 53% between 1996–2005 and 2051–2060 as a result of the climate penalty. In the case of the EV+Renewable scenario, the population exposure is modelled to increase by 42%, and thus is a 9% reduction in impact relative to the 2051–2060 climate penalty result for the ICE fleet scenario. Although this is a positive result it nevertheless suggests that the turnover of the Sydney passenger vehicle fleet from ICE to EV powered vehicles would not be sufficient to totally offset the climate penalty. In the case of the EV vehicles recharged from coal fired power station energy the population exposure is modelled to increase by 48%, and thus results in only a 5% reduction relative to the climate penalty result for the ICE fleet.

Fig.5 shows the spatial distribution of population exposure change (expressed as a percentage) for the three 2051–2060 scenarios relative to the 1996–2005 base case scenario. Note that the population exposure is calculated only at grid points of non-zero population, and that population growth is not considered in this study.

It can be seen that the climate penalty scenario leads to increases in the exposure for the majority of the populated regions in the GMR. Although some of the largest increases are modelled to occur within metropolitan Sydney, this result must be interpreted with caution. It is likely that some of this changemay be the result of days where the daily maximum 8–h ozone has increased from just below the 40 ppb threshold to just above it thus leading to large relative changes in population exposure even though the absolute levels of the exposure aresmall.

The EV+Renewable scenario leads to smaller positive and sometimes negative changes in population exposure outside of metropolitan Sydney. However, large relative increases in exposure are again predicted for the metropolitan region. As noted above, this is likely due to an increase in the number of daily maximum 8–h ozone concentrations which now lie above the 40 ppb threshold. Although climate warming (and hence increased ozone generation) will be responsible for some of this change, another contributor is the reduction in nitric oxide emissions associated with the replacement of ICE passenger vehicles with zero emission EVs. As discussed in the previous section, a reduction in nitric oxide emissions within urban areas can lead to higher ozone concentrations and increased ozone exposure.

The EV+Coal scenario leads to a smaller reduction in exposure compared to the EV+Renewable scenario. Thus regions outside of Sydney which showed a 20-40% reduction in exposure for the EV+Renewable scenario now show little reduction. Areas on the edge of the Sydney region which showed less than 10% change for the EV+Renewable scenario, now show increases of around 20% in population exposure.

These results suggest that powering electric vehicles from coal-fired power stations rather than a renewable energy source reduces the effectiveness of the gain made by the replacement of ICE vehicles (and the subsequent reduction in ozone precursor emissions) by about 50% in the case of the population exposure metric, and by about 20% in the case of the NEPM AAQS exceedence metrics. This likely occurs because the increased emissions of NO_x and CO associated with the increase in power generationinteract with biogenic and other anthropogenic VOC emissions, leading to increases in the background ozone concentrations and hence the total ozone concentrations within the Sydney urban plume. Warmer temperatures associated with the modelled A2 climate scenario probably amplify this effect through increasing VOC emissions from vegetation, and through speeding up the process of photochemical transformation which lead to ozone generation.

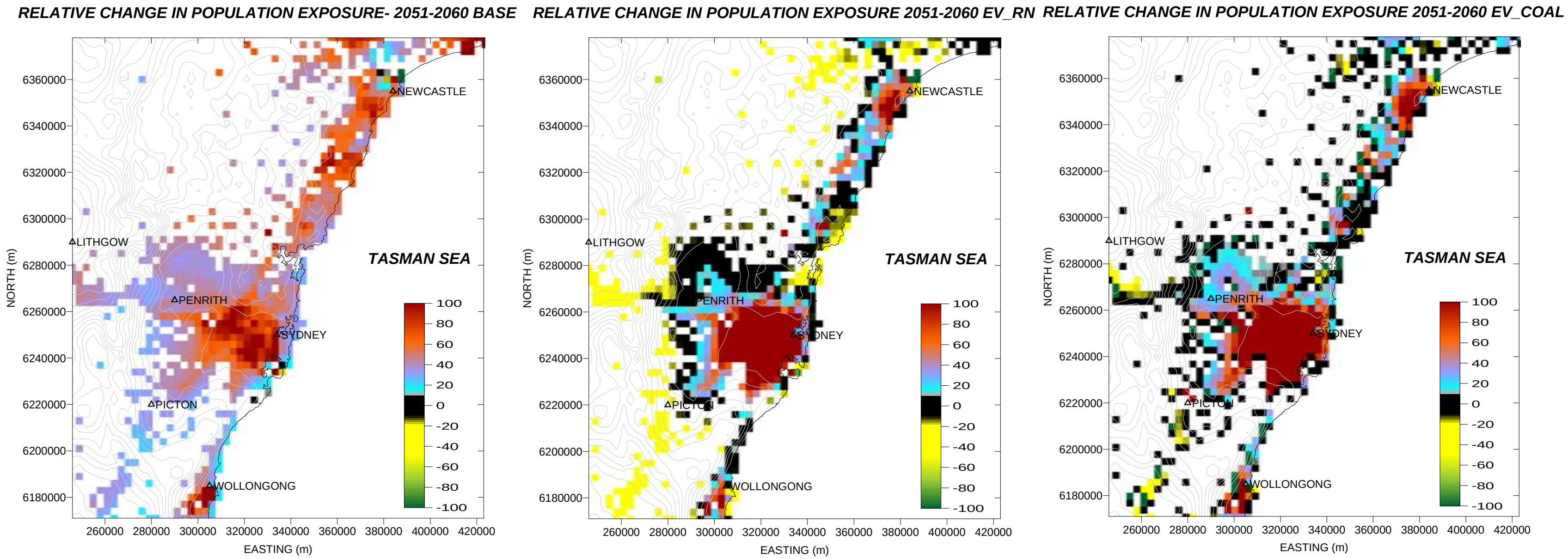

Fig.5. The percentage relative change in population exposure (relative to 1996–2006) for (left) 2051–2060 ICE passenger vehicles; (centre) 2051–2060 EV passenger vehicles powered by renewable energy; (right) 2051–2060 passenger vehicles powered by coal-fired power stations.

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