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## Original Article

# Implications of Australia's Population Policy for Future Greenhouse Gas Emissions Targets

Corey J. A. Bradshaw\* and Barry W. Brook

### Abstract

*Australia's high per capita emissions rates makes it a major emitter of anthropogenic greenhouse gases, but its low intrinsic growth rate means that future increases in population size will be dictated by net overseas immigration. We constructed matrix models and projected the population to 2100 under six different immigration scenarios. A constant 1 per cent proportional immigration scenario would result in 53 million people by 2100, producing 30.7 Gt CO<sub>2</sub>-e over that interval. Zero net immigration would achieve approximate population stability by mid-century and produce 24.1 Gt CO<sub>2</sub>-e. Achieving a 27 per cent reduction in annual emissions by 2030 would require a 1.5- to 2.0-fold reduction in per-capita emissions; an 80 per cent reduction by 2050 would require a 5.8- to 10.2-fold reduction. Australia's capacity to limit its future emissions will therefore depend primarily on a massive technological transformation of its energy sector, but business-as-usual immigration rates will make achieving meaningful mid-century targets more difficult.*

**Key words:** demography, fertility, dependency ratio, emissions, climate change

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### 1. Introduction

Australia is the world's sixth-largest country (land area=7.69 million km<sup>2</sup>), yet it has a 2014 human population of only 23.5 million, making it the 51st largest national population in the world (worldbank.org), or approximately 0.3 per cent of the planet's total human population. Despite this relatively small population, Australia has one of the highest per capita greenhouse gas emissions rates in the Organisation for Economic Co-operation and Development, because of its heavy reliance on coal-fired and gas-fired electricity generation, an expansive fossil-fuelled transport network, and large agricultural sector (International Energy Agency 2014). Australia is also a major producer of fossil fuels, having exported approximately 11,600 petajoules (PJ) of primary energy in 2013, of which ~80 per cent was coal and ~10 per cent was natural gas (abs.gov.au). When combusted, this equates to approximately 1.3 per cent of the world's total anthropogenic greenhouse gas emissions (Brook 2012a).

In 2007, Australia committed to reducing its greenhouse gas emissions by ratifying the Kyoto Protocol (United Nations 1998) and signing the second commitment period (2013–2020) (Bradshaw et al. 2013). Australia's current pledge is to reduce its emissions by 5 per cent of its year 2000 National Greenhouse Gas Inventory (NGGI) total by 2020 (dfat.gov.au). In the Clean Energy Act 2011, the government of the day had set a reduction target of 80 per cent of 2000 emissions by 2050, but that was repealed (Commonwealth of Australia 2011). Since

then, a 26 to 28 per cent reduction below 2005 emissions (equivalent to 21 to 23 per cent below 2000 emissions) by 2030 has been set (Australian Government 2015). After 2030, Australia's official commitment is still undecided. How Australia will manage to achieve the 2030 target, and any longer-term goals such as an 80 per cent reduction by 2050 has been the subject of many studies, mainly focused on increasing efficiency and penetration of renewable electricity generation (Beyond Zero Emissions 2010; Seligman 2010; Elliston et al. 2012; Palmer 2012; Trainer 2012; Australian Energy Market Operator 2013; Denis et al. 2014); however, few have considered the direct impact of an increasing Australian population on meeting these targets (although see Brook 2012a).

As a wealthy nation (that is, world's sixth-highest per capita gross domestic product=US\$67,463; [worldbank.org](http://worldbank.org)), Australia's demography is typical of economically developed nations in that its intrinsic fertility is below replacement (average number of children born to a woman who survives to the end of her reproductive life=1.78; replacement=2.1) (CIA World Factbook 2011). As such, its current population growth is dictated mainly by net overseas migration (Turton & Hamilton 1999). Accumulated greenhouse gas emissions are strongly related to population size (Shi 2003), so it stands to reason that any policies to reduce national emissions should also incorporate population projections in their assessments. However, a critical overview of the contribution of population growth to achieving both its short-term and longer-term emissions-reduction targets is lacking or obsolete (Foran & Poldy 2002).

We address this gap by producing a comprehensive demographic model of the Australian population with projections to 2100, assuming various rates of future net overseas immigration. Based on these projections, we forecast business-as-usual and zero-immigration emissions trajectories to calculate the per capita reductions required to meet the 2020 emissions-reduction target (5 per cent), the median 2030 target (27 per cent reduction of

2005 emissions) and a putative 2050 target of an 80 per cent reduction (from 2000). We ask broadly how effective population policies can be in mitigating Australia's future greenhouse gas emissions (both cumulative outcomes and annual rates), and explore the sensitivity of this conclusion to net immigration policy. We also quantify the major economic outcomes—in terms of child, aged and health care costs—of the changing population age structures under various immigration scenarios.

## 2. Methods

### 2.1. Demographic Data

We obtained life table data (age-specific mortalities and fertility from 0 to 100+ years of age) for the Australian population from the Australian Bureau of Statistics <<http://www.abs.gov.au>>. We converted the aggregated 5-year age class births per 1000 women into age-specific fertilities ( $m_x$ ) by dividing the 5-year classes equally among their constituent years and accounting for breeding female mortality within each of the 5-year classes (Bradshaw & Brook 2014). The Australian Bureau of Statistics also provides age-specific ( $x$ ) yearly population estimates ( $n_x$ ) from 1971 to 2014. These estimates are obtained by adding to the estimated population at the beginning of each census period the components of natural increase and net overseas migration ([www.abs.gov.au](http://www.abs.gov.au)). All age-specific population size, mortality and fertility data we derived are available online at DOI:10.4227/05/55679E714245D.

### 2.2. Leslie Matrix

We defined a pre-breeding, 100 ( $i$ ) $\times$ 100 ( $j$ ) element, Leslie projection matrix ( $\mathbf{M}$ ) for women only, multiplying the subsequent population vector by the 2014 stage-specific sex ratio to estimate total population size at each forecast time step (Bradshaw & Brook 2014). Fertilities ( $m_x$ ) occupied the first row of the matrix (ages 15–49 years), survival probabilities ( $1 - M_x$ ) were applied to the sub-

diagonal, and the final diagonal transition probability ( $\mathbf{M}_{i,j}$ ) represented survival of the 100+ stage. Complete R code (R Core Team 2014) for the scenario projections is available from the authors upon request.

### 2.3. Immigration

We obtained net overseas migration data from 2004 to 2013 for women and men and their 5-year age class structure from the Australian Bureau of Statistics. We applied the average age structure to a migration vector constructed for each of the migration scenarios (Figure S1 and see following discussion) and added this to the population vector for each yearly iteration of the projections.

### 2.4. Projection Scenarios

For each projection, we multiplied the  $N_x$  vector by  $\mathbf{M}$  for 86 yearly time steps (2014 to 2100). All projections were deterministic. We applied a broad range of immigration scenarios to examine the effects of various immigration policies on long-term population change and their associated emissions profiles (compared with Turton & Hamilton 1999; Foran & Poldy 2002) (Table 1). *Scenario 1* was a business-as-usual projection with all matrix elements (that is, demographic rates) kept constant at 2014 values and with the average immigration ( $215,000 \text{ year}^{-1}$ ; Section 3) added to the  $n_x$  vector at each time step (in reality, we randomly sampled immigration from the yearly values between 2003 and 2014 for each time step, which approximates adding the average, but more realistically incorporates year-to-year variability in immigration rates.) *Scenario 2* was identical to scenario 1 except that we held immigration at a constant proportion of total population size (1 per cent; Section 3). *Scenario 3* was as scenario 1 except that we increased the immigration rate linearly such that it became twice the average by 2100 (again, randomly sampling from 2003 to 2014 and applying a linearly increasing multiplication factor). This scenario is an arbitrary immigration scenario where immigration doubles in response to an

increasing number of environmental refugees, for example. *Scenario 4* simulated a zero-immigration policy (no net overseas migration), whereas *Scenarios 5* and *6* simulated fixed annual net immigration at 20,000 and 100,000, respectively (Table 1).

It is arguably unrealistic to assume that the demographic rates (survival, fertility) would remain stable from 2014 to 2100 especially noting recent trends. We therefore repeated all scenarios assuming a continuous (linear) increase in average age of (female) breeding (increasing average age of primiparity) by allocating 50 per cent of the fertility in the youngest reproductive age class (15–24 years) evenly across the older breeding classes (25–49 years), following a linear change function from 2014 to 2100 (Bradshaw & Brook 2014) (Table 1). According to the Australian Treasury's 2015 Intergenerational Report (Commonwealth of Australia 2015a), life expectancy is predicted to increase from 93.6 to 96.6 years for woman from 2015 to 2055. This represents a 3.2 per cent increase in average survival, so we also conservatively estimated a 3.2 per cent reduction in mortality across all age classes achieved linearly by 2100 (Table 1).

### 2.5. Dependency

For all scenario-based projections, we calculated the yearly total population size (females and males; male  $n$  calculated as the stage-dependent sex ratio [males:females] multiplied by the female  $n$  vector) and the proportion of the population <15 or >65 years old. The proportion in the 15- to 65-year classes relative to the remainder represents the 'dependency ratio', which is a metric of the population generally considered to be dependent on the productivity of employed society (Bongaarts 2009; Kwok et al. 2013).

The dependency ratio is only a crude measure of the potential costs to society because it assumes that the different components (for example, <15- and >65-year classes) impart the same costs. In reality, different age classes have different 'costs' to 'economically productive' society. For

**Table 1 Summary Parameters of Population Projection Scenarios (Scenarios 1–6, Main Text; Scenarios 7–12, Supporting Information)**

Scenario	Demographic rates	Net immigration rate	Projected population in 2100 (millions)
1	All constant (2014 values)	Randomly sampled between 2003 and 2014 values (mean = 215,000 year <sup>-1</sup> )	52.9
2	All constant (2014 values)	1% total population year <sup>-1</sup>	87.1
3	All constant (2014 values)	As scenario 1, but increasing linearly to twice mean by 2100	68.1
4	All constant (2014 values)	No net immigration	23.4
5	All constant (2014 values)	20,000 year <sup>-1</sup>	26.2
6	All constant (2014 values)	100,000 year <sup>-1</sup>	37.1
7	Linear increase in ♀ age at primiparity to 2100; 3.2% reduction in mortality by 2100; others constant at 2014 values	Randomly sampled between 2003 and 2014 values (mean = 215,000 year <sup>-1</sup> )	53.1
8	Linear increase in ♀ age at primiparity to 2100; 3.2% reduction in mortality by 2100; others constant at 2014 values	1% total population year <sup>-1</sup>	87.6
9	Linear increase in ♀ age at primiparity to 2100; 3.2% reduction in mortality by 2100; others constant at 2014 values	As scenario 1, but increasing linearly to twice mean by 2100	67.6
10	Linear increase in ♀ age at primiparity to 2100; 3.2% reduction in mortality by 2100; others constant at 2014 values	No net immigration	23.5
11	Linear increase in ♀ age at primiparity to 2100; 3.2% reduction in mortality by 2100; others constant at 2014 values	20,000 year <sup>-1</sup>	26.2
12	Linear increase in ♀ age at primiparity to 2100; 3.2% reduction in mortality by 2100; others constant at 2014 values	100,000 year <sup>-1</sup>	37.2

See Section 2 for more details.

Australia, research commissioned by the Ministerial Taskforce on Child Support for the House of Representatives Committee on Family and Community Affairs estimated the derived costs of children in 2007 based on 10 subcomponents: housing, energy, food, clothing and footwear, household goods and services, child care, health services, transport, leisure and personal care (Henman et al. 2007). While costs vary among living standards, household types, age of the child, number of children in the family and labour force status of the primary carer, the average was approximately A\$8500 child<sup>-1</sup>year<sup>-1</sup> (Henman et al. 2007). To estimate the per capita cost of aged care, we used the ~1 per cent of the 2014–15 gross domestic product spent on government-funded aged care ( $0.01 \times A\$1.56 \times 10^{12} = A\$1.56 \times 10^{10}$ ) (Commonwealth of Australia 2015a). In that year, there was an estimation of 3,221,185

Australians aged >65 years, which equates to a cost of A\$4843 per ‘aged’ person.

Similarly, a rapidly inflating cost of health care is a commonly argued outcome of an ageing society (Productivity Commission 2005; Armstrong et al. 2007; Commonwealth of Australia 2015a; Australian Institute of Health and Welfare 2016), despite evidence to the contrary from Australia (Coory 2004) and elsewhere (Getzen 1992; Reinhardt 2003). We therefore obtained per capita health care costs (2008–09) for 10 five-year age groups (0–4, 5–9 ... 85+ years) from the Australian Institute of Health and Welfare (Figure 3.1 in Australian Institute of Health and Welfare 2016) and isolated the ‘dependent’ component of the health care costs as earlier for all projections.

Assuming that the per capita ‘costs’ of children <15 and adults >65 years old do not change in terms of the proportion of the

gross domestic product, the ratio of the total costs (child, aged and health care) of these age groups relative to the per capita gross domestic product should remain invariant over the projection interval. Australia's per capita gross domestic product in 2014 was A \$66,409 per person with an estimated population of 23,490,736 in that same year.

## 2.6. Emissions

We sourced Australia's annual NGGI emissions data from the National Greenhouse Emissions Information System <<http://ageis.climatechange.gov.au>> from 1990 to 2012. These represent the national accounting data for the Kyoto targets to 2020 and 2050. However, the NGGI includes emissions only from energy (fuel combustion and fugitive emissions from fuels), industrial processes (mineral products, chemical industry, metal production etc.), agriculture (enteric fermentation from ruminant animals, manure management, fertilizer use, prescribed burning etc.) and waste (solid waste disposal, wastewater handling etc.) for all years. Emissions from land use change and forestry (Land Use, Land Use Change and Forestry—LULUCF) data from the National Greenhouse Emissions Information Systems are only available for 1990 and 2008 onwards (that is, land use change in the base year (1990) and deforestation, afforestation and reforestation during the first commitment period (2008–2012)). We therefore sourced the LULUCF net emissions (that is, not sequestration—this is only available as a relative value from the 1990 baseline) from the *Australian LULUCF Emissions Projections to 2030* report (Commonwealth of Australia 2013).

Using the per capita total (NGGI + LULUCF) emissions for 2012, we projected the emissions to 2030 and again to 2050 (under the assumption of 'freezing' technology and structural change that underpin emissions), for two of the population scenarios listed earlier: (i) scenario 2: constant proportional (1 per cent) immigration, and (ii) scenario 4: zero net overseas migration. We then tallied the total emissions produced from 2015 to 2030 and again from 2015 to 2050 (that is, summing

over all projected years) for each projection scenario and target. We then estimated the reduction in per capita emissions (from unspecified actions) required to meet the 2030 and 2050 targets under the various emissions scenarios, using (a) only the NGGI values and (b) the NGGI+LULUCF values.

When people move permanently to Australia from elsewhere, their average emissions in their country of origin should ideally be subtracted from the new, average emissions they will produce once living in Australia. This difference therefore represents the net emissions the growing Australian population will contribute to the world carbon budget (Turton & Hamilton 1999). While ideally, the country of origin for each net overseas migrant each year would provide a better approximation of the net global emissions from Australia, these data were not available. We did, however, have access to the Australian residents' region of birth (excluding Australia) from 2000 to 2010 (excluding 2001–2004) from the Australian Bureau of Statistics. These data included the percentage of residents born in Oceania, North-West Europe, Southern and Eastern Europe, North Africa and Middle East, South-East Asia, North-East Asia, Southern and Central Asia, Americas and Sub-Saharan Africa from 2000 to 2010. The interannual variation in these percentages was small (average coefficient of variation = 9.2 per cent), so we took the mean proportion across years for each region as an index of the region of origin for annual net overseas migrants.

For each of these regions, we sourced the per capita emissions of their constituent countries (see Table 2 for full country listing) from the World Bank (2010 estimates, [worldbank.org](http://worldbank.org)) and took their population-weighted (that is, by country) average per capita emissions as the regional average. We then multiplied the weighted-average immigrant proportion by the regional per capita emissions rate and summed them over all source regions to provide an immigration-weighted 'average' per capita emissions rate (year<sup>-1</sup>) for an immigrant prior to arriving in Australia (Table 2). Multiplying this value by the number of annual net overseas migrants for each scenario projection,

we subtracted this product from the total emissions estimated for each projection scenario to determine net Australian emissions (Section 3).

Finally, emissions calculations and targets typically include only those produced within national jurisdictions and exclude any exported potential emissions (for example, exported fossil fuels, typically called ‘Scope 3’ emissions) (Centre for Integrated Sustainability Analysis 2008). Australia is a major producer of coal and gas, exporting over 11,500 PJ of fossil fuel energy in 2013 alone (Australian Bureau of Statistics). To compare the net national emissions with those arising from exported fossil fuels, we also compiled the fossil fuel exports (in PJ) from 1990 to 2013 (excluding 1993

and 2007) from the Australian Bureau of Statistics for the major fossil fuel exports: bituminous (black) coal, natural gas, liquid petroleum gas, and crude oil and feedstocks. These four types represented between 98.7 and 98.9 per cent of the total fossil fuel energy exported between 2009 and 2013. For each source, we estimated the CO<sub>2</sub>-e emissions arising from the CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O components using the fuel combustion emissions factors (Table S1) provided in the Australian *National Greenhouse Accounts Factors* report (Commonwealth of Australia 2014), and expressed these values per capita from 1990 to 2013.

Finally, we calculated the potential emissions avoided from the export of uranium from

**Table 2 Mean Percentage of Resident Country of Birth (Excluding Australia) of Immigrants to Australia by World Region from 2000 to 2010 (Excluding 2001–2004) (Source: Australia Bureau of Statistics: <Http://abs.gov.au>). The Per Capita Greenhouse Gas Emissions (t CO<sub>2</sub>-e person<sup>-1</sup>) are the Average Per Capita Emissions<sup>†</sup> (2010) Weighted by the 2010 Population of the Countries Included in Each Region (ISO3 Country Codes Given in the Table footnote<sup>‡</sup>). The Weighted (w) Average Per Capita Greenhouse Gas Emissions of Immigrants Prior to Their Arrival in Australia is Therefore the Sum of the Products of the Proportion Immigrating and Their Country Population-weighted Region-of-origin Emissions (Source: <http://www.worldbank.org>)**

Region of origin	I <sub>2000-10</sub> (%)		t CO <sub>2</sub> -e person <sup>-1</sup> §		w t CO <sub>2</sub> -e person <sup>-1</sup>
Oceania <sup>¶††</sup>	11.2	×	3.0291	=	0.3401
North-west Europe <sup>‡‡</sup>	29.2	×	8.0309	=	2.3464
Southern and Eastern Europe <sup>§§</sup>	16.1	×	5.6587	=	0.9105
North Africa and Middle East <sup>¶¶</sup>	5.6	×	5.9082	=	0.3317
South-east Asia <sup>†††</sup>	12.6	×	2.0435	=	0.2584
North-east Asia <sup>‡‡‡</sup>	9.5	×	7.0330	=	0.6707
Southern and Central Asia <sup>§§§</sup>	7.1	×	1.6159	=	0.1151
Americas <sup>††††</sup>	4.1	×	8.1496	=	0.3374
Sub-Saharan Africa <sup>‡‡‡‡</sup>	4.4	×	0.8309	=	0.0366
Average (weighted average)			4.7000		(5.3468)

<sup>†</sup>Notes: Carbon dioxide emissions are those stemming from the burning of fossil fuels and the manufacture of cement (including carbon dioxide produced during consumption of solid, liquid and gas fuels and gas flaring).

<sup>‡</sup>See <http://wits.worldbank.org/wits/wits/witshelp/content/codes/country\_codes.htm> for full country names of ISO3 codes.

<sup>§</sup>A population-weighted (2010 estimate) average per capita emissions over all countries included in each region of origin.

<sup>¶</sup>Excluding Australia.

<sup>††</sup>FJI, FSM, KIR, MHL, NCL, NZL, PNG, PYF, SLB, TON, VUT.

<sup>‡‡</sup>BEL, BLR, CHE, CZE, DEU, DNK, EST, FIN, FRA, FRO, GBR, GRL, IRL, ISL, LTU, LUX, LVA, NLD, NOR, POL, SWE.

<sup>§§</sup>ALB, AUT, BGR, BIH, CYP, ESP, GRC, HRV, HUN, ITA, MDA, MKD, MNE, PRT, ROU, SRB, SVK, SVN, TUR, UKR.

<sup>¶¶</sup>MAR, ARE, BHR, DJI, DZA, EGY, IRN, IRQ, ISR, JOR, KWT, LBN, LBY, MLT, OMN, PSE, QAT, SAU, SYR, TUN, YEM.

<sup>†††</sup>BRN, IDN, KHM, LAO, MMR, MYS, PHL, SGP, THA, TLS, VNM.

<sup>‡‡‡</sup>CHN, JPN, KOR, MNG, PRK, RUS.

<sup>§§§</sup>AFG, AZE, BGD, BTN, GEO, IND, KAZ, KGZ, LKA, MDV, NPL, PAK, TJK, TKM, UZB.

<sup>††††</sup>ABW, ARG, ATG, BHS, BLZ, BMU, BOL, BRA, BRB, CAN, CHL, COL, COM, CPV, CRI, CUB, CYM, DMA, DOM, ECU, GRD, GTM, GUY, HND, HTI, JAM, KNA, LCA, MEX, NIC, PAN, PER, PRY, SLV, SUR, TTO, URY, USA, VCT, VEN.

<sup>‡‡‡‡</sup>BDI, BEN, BFA, BWA, CAF, CIV, CMR, COD, COG, ERI, ETH, GAB, GHA, GIN, GMB, GNB, GNQ, KEN, LSO, MDG, MLI, MOZ, MWI, NAM, NGA, RWA, SDN, SEN, SLE, SOM, STP, TGO, TZA, UGA, ZAF, ZMB, ZWE.

Australia for 2013–2014 as an ‘offset’ of the exported fossil fuel emissions described earlier. Our rationale was that Australia’s exported emissions should be corrected for the emissions avoided by the combustion of Australia’s exported uranium. Australia exported 2607.6 PJ of uranium in 2013–2014 (Department of Industry and Science 2015). We assumed an equivalent proportion of fossil fuel-based exports for that year (black coal: 0.75, brown coal: 0.04, gas: 0.16, oil: 0.05, and liquid petroleum gas: 0.01) to calculate a uranium emissions offset based on the fuel combustion emissions factors in Table S1.

### 3. Results

#### 3.1. Projection Scenarios

Assuming a constant (average) net overseas migration of 215,000 people year<sup>-1</sup> with this age structure and under constant demographic rates (2014 survival and fertility), Australia’s population would reach 36.4 million by 2050 and 52.9 million by 2100 (scenario 1, Table 1, Figure 1). Migrants to Australia have a weighted mean age of 25.5 years based on the data from 2004 to 2013, and most (62 per cent) are between the ages of 15 and 34 years (Figure S1). If net immigration remained at a constant 1 per cent of total population size, these figures would rise to 41.0 million by 2050 and 87.1 million by 2100 (scenario 2, Table 1, Figure 1). Linearly doubling the immigration rate to twice the 2014 average by 2100, Australia’s population would achieve 38.6 million by 2050 and 68.1 million by 2100 (scenario 3, Table 1, Figure 1).

To put these projections into context, a simple estimate of the final population size in 2100—if the population grew at the average rate it did between 1971 and 2014 (1.36 per cent, increasing 1.88 times)—is 75.9 million. If the population grew at the average rate it did between 2006 and 2014 (1.73 per cent), then the final population in 2100 would be 104.2 million (4.4× today’s population) (Figure 1).

At the other extreme, under a future scenario of zero net overseas migration from 2014 onwards, Australia’s population would rapidly level off, peaking at 25.6 million in 2040, followed by a slow decline to 23.4 million by 2100 (scenario 4, Table 1, Figure 1). With a modest net overseas migration of 20,000 people year<sup>-1</sup>, the total population would peak at 26.5 million in 2052 and reach 26.2 by 2100 (that is, essentially stable) (scenario 5, Table 1, Figure 1). Finally, an average of 100,000 net overseas migrants per year would result in a steady increase in total population to 37.1 million by 2100 (scenario 6, Table 1, Figure 1). For all scenarios, assuming a rise in life expectancy and later age of first childbirth in woman would alter the 2100 population projections by <1 per cent (scenarios 7–12, Table 1, Figure S2).

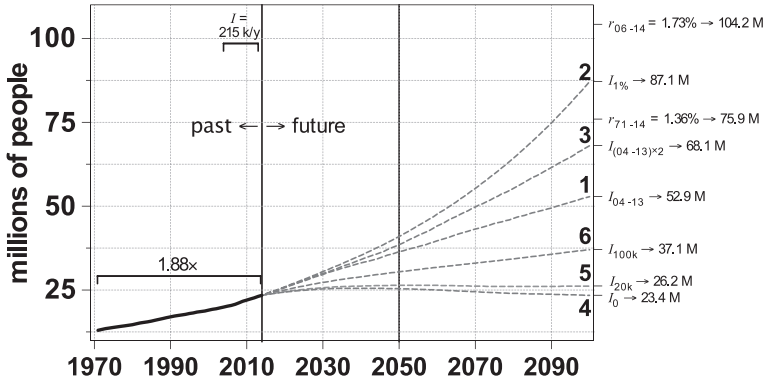
#### 3.2. Dependency Ratios

The dependency ratio varied little (coefficient of variation of 3 to 9 per cent) under all immigration scenarios (Figure 2). Under a zero net-migrant future (scenario 4), the overall dependency ratio would fluctuate between 0.48 and 0.72 (that is, 48 to 72 ‘dependants’ per 100 working adults between the ages of 16 and 64 years) (Figure 2), compared with 0.48 in 2014. As the number of net overseas migrants increases, the dependency ratio trajectory to 2100 flattens (for example, with a constant 1 per cent immigration rate, dependency ratio fluctuates between 0.48 and 0.56.)

When the dependency ratio is expressed in terms of ‘costs’ as outlined in Section 2 (child, aged and health care), the ratio is even more stable. Indeed, under the most extreme zero-migration scenario (scenario 4), the cost dependency ratio only fluctuates between 0.09 and 0.13 (that is, dependants will ‘cost’ the economy between 9 and 13 per cent of what it produces as measured by gross domestic product) (Figure 2). As for the raw dependency ratio, even this small variation stabilizes further as immigration rate increases (Figure 2).



**Figure 1** Australia's population trajectory from 1971 to 2014 (it grew 1.88 times over this period) and scenario-based projections of its future population from 2015 to 2100. Scenario 1: business-as-usual population growth (constant 2014 age-specific vital rates) and net overseas migration ( $I_{04-13}$  = average of 215,000 year<sup>-1</sup> from 2004 to 2013); scenario 2: as scenario 1 except with constant (1 per cent of total population size) immigration ( $I_1\%$ ); scenario 3: as scenario 1 except with a linear increase in immigration rate to twice the average by 2100 ( $I_{(04-13) \times 2}$ ); scenario 4: zero net overseas ( $I_0$ ); scenario 5: fixed annual net immigration of 20,000 ( $I_{20k}$ ); scenario 6: fixed annual net immigration at 100,000 ( $I_{100k}$ ). Also shown as reference points are the projected final populations at constant, a constant growth rate observed between 1971 and 2014 (1.36 per cent,  $r_{71-14}$ ) and between 2006 and 2014 (1.73 per cent,  $r_{06-14}$ )



### 3.3. Emissions

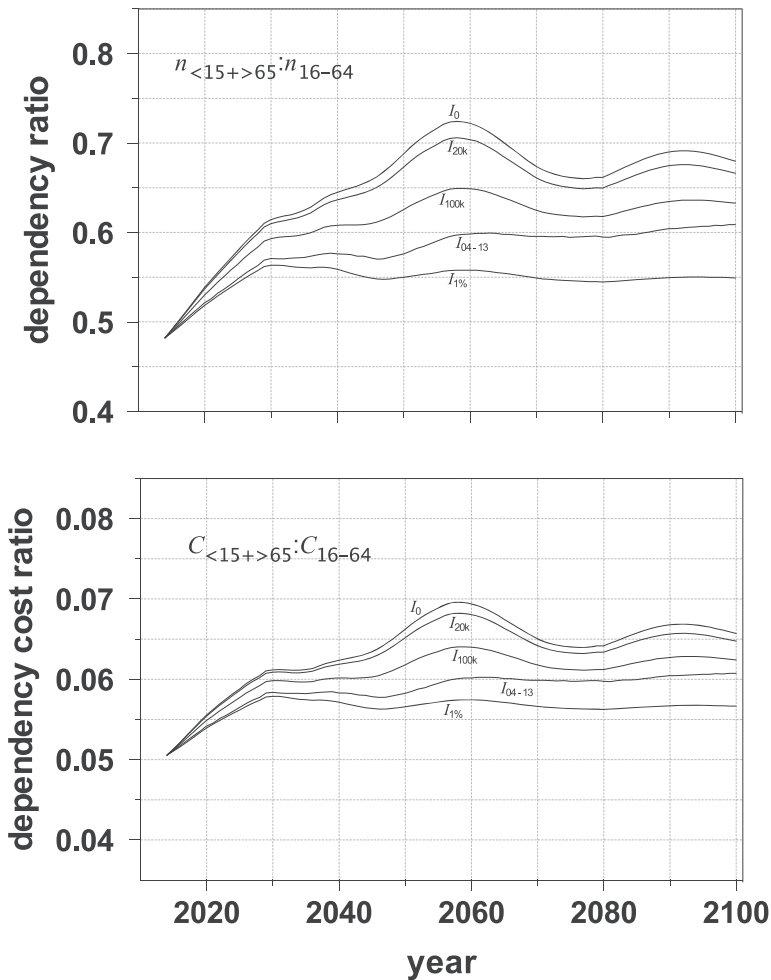
Under a 1 per cent immigration policy (constant 1 per cent overseas migrants per year; scenario 2), Australia will emit a total of 30.66 gigatonnes (Gt) CO<sub>2</sub>-e (NGGI + LULUCF) between 2015 and 2050, reaching a maximum rate of 1.09 billion tonnes (t) year<sup>-1</sup> (Gt) by 2050 (Figure 3). After subtracting the avoided global emissions in source countries as people move to Australia, the total net emissions would be 30.60 Gt CO<sub>2</sub>-e or a difference of only 0.06 Gt (that is, 60 million t, representing a net difference of 0.2 per cent) (Figure 3). Removing all net overseas migration would reduce cumulative emissions to 2050 by 21 per cent to 24.12 Gt CO<sub>2</sub>-e (Figure 3).

Total per capita emissions (NGGI + LULUCF) have averaged 29.6 t CO<sub>2</sub>-e person<sup>-1</sup> between 1990 and 2012 or 25.2 t CO<sub>2</sub>-e NGGI person<sup>-1</sup> (Figure 3). Based on NGGI emissions only, Australia would have to achieve between 1.62 (zero immigration) and 1.95 (1 per cent immigration) times reduction in per capita emissions to meet the 2030 median target of 27 per cent reduction on 2005 emissions, equating to an average per capita emissions rate of between

12.5 and 15.0 t CO<sub>2</sub>-e person<sup>-1</sup> year<sup>-1</sup> in 2030 (Figure 3). If Australia introduces an 80 per cent reduction target for 2050, there would have to be between a 6.3 (zero immigration) and 10.2 (1 per cent immigration) times reduction in per capita emissions, equating to an average per capita emissions of between 2.4 and 3.9 t CO<sub>2</sub>-e person<sup>-1</sup> year<sup>-1</sup> in 2050 (Figure 3). Including LULUCF emissions in the calculation, the reduction would have to be between 5.8 and 9.4 times by 2050, or 2.8 and 4.6 t CO<sub>2</sub>-e person<sup>-1</sup> in 2050 (Figure 3). This calculation is based on an 80 per cent reduction in *total* emissions (NGGI + LULUCF) by 2050 (that is, not just NGGI).

Expressed as a percentage reduction in per capita emissions, under the no-migration scenario, there would be 25.4 million people by 2050 who would have to achieve an average emissions rate of 3.85 t CO<sub>2</sub>-e person<sup>-1</sup> year<sup>-1</sup> (NGGI) under an 80 per cent reduction scenario. This represents a required reduction of 83.5 per cent (23.30 to 3.85 t CO<sub>2</sub>-e NGGI person<sup>-1</sup> year<sup>-1</sup>). Under the business-as-usual scenario (scenario 1: 36.4 million people by 2050), the required reduction would be 88.4 per cent (23.30 to 2.71 t CO<sub>2</sub>-e NGGI person<sup>-1</sup> year<sup>-1</sup>).

**Figure 2** Dependency ratios based on (top panel) population size ( $n$ ) and (bottom panel) cost ( $C$ ). The size ratio is the sum of the number of people <15 and > 65 years old divided by the number of people between 16 and 64 years old ( $n_{<15+>65}:n_{16-64}$ ) and represents the average proportion of 'dependants' per working adult. We calculated the yearly size ratio for each projection scenario:  $I_0$  = zero immigration;  $I_{20k}$  = 20,000 net overseas migrants year<sup>-1</sup>;  $I_{100k}$  = 100,000 net overseas migrants year<sup>-1</sup>;  $I_{04-13}$  = average net overseas migrants year<sup>-1</sup> observed between 2004 and 2013 (215,000);  $I_{1\%}$  = constant proportional immigration (1 per cent of total population size year<sup>-1</sup>). The cost ratio is the sum of the costs of children <15 (A\$8500 per child), the costs of people >65 (A\$4843 aged per person) and the age-specific costs of health care (Section 2) versus the total gross domestic product of the population estimated as constant per capita amount of A\$66,409 per person

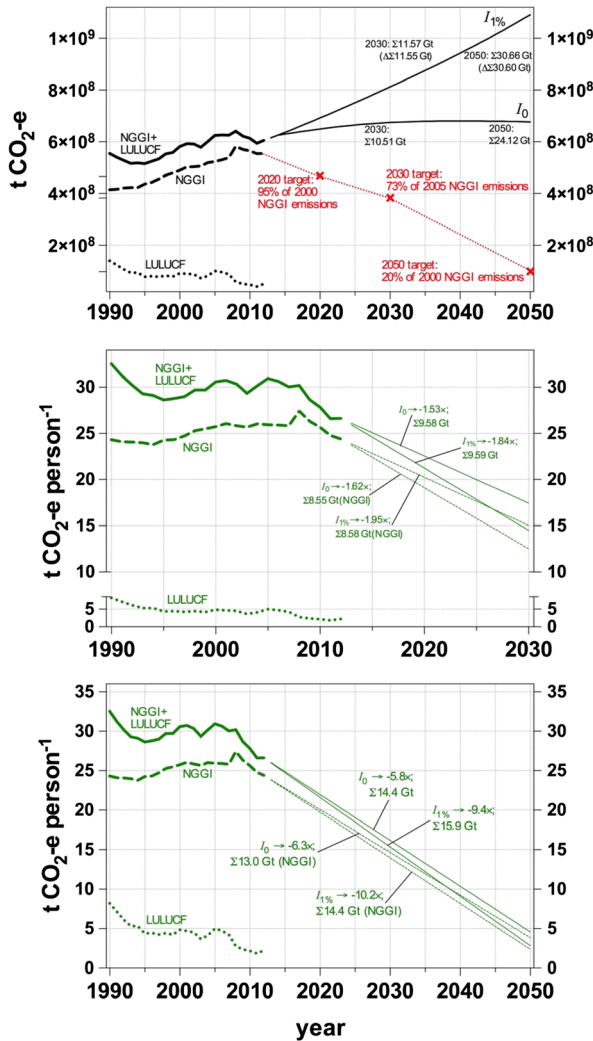


For fossil fuel export emissions not considered in any national accounts or targets, Australia has steadily (and almost linearly) increased its total fossil fuel exports from 3394 PJ in 1990 to 11,510 PJ in 2013 (increasing 328.2 PJ year<sup>-1</sup>; Figure 4). This equates to 497.7 PJ person<sup>-1</sup> in 2013. Expressed in terms of CO<sub>2</sub>-e, this represents a rise from 289.4 megatonnes (Mt) CO<sub>2</sub>-e in 1990 to 953.1 Mt

CO<sub>2</sub>-e of exported emissions in 2013 (increasing 27.1 Mt year<sup>-1</sup>) or 17.0 to 41.2 t CO<sub>2</sub>-e person<sup>-1</sup> over the same period (increasing 0.99 t year<sup>-1</sup>; Figure 4). Based on these values, Australia today exports around 55 per cent more CO<sub>2</sub>-e per capita than it produces domestically (NGGI + LULUCF). However, the 'saved' emissions from uranium export in 2013–2014 amounts to 213.0 Mt CO<sub>2</sub>-e or

**Figure 3** Australia’s historical (1990 to 2013) and projected greenhouse gas emissions to 2030 and 2050. *Top panel:* total emissions (t CO<sub>2</sub>-e) from the National Greenhouse Gas Inventory (NGGI) and Land Use, Land Use Change and Forestry (LULUCF) sectors. Shown are the emissions from both categories separately and combined and the total projected under constant average per capita emissions assumptions for the zero-immigration ( $I_0$ ) and constant proportion immigration ( $I_{1\%}$ ) scenarios. For each scenario, we provide the total cumulative emissions ( $\Sigma$ ) in Gigatonnes (Gt) and total net emissions ( $\Delta\Sigma$ ); the latter removes the emissions that would have been produced by migrants in their countries of origin (Section 2). Also shown are the emissions targets for 2020 (5 per cent reduction of 2000 NGGI emissions), 2030 (median 27 per cent reduction of 2005 NGGI emissions) and 2050 (a putative 80 per cent reduction of 2000 NGGI emissions). *Middle panel:* per capita NGGI and LULUCF emissions from 1990 to 2013 (t CO<sub>2</sub>-e person<sup>-1</sup>) and the required linear declines to achieve the 2030 target under the two immigration scenarios considered ( $I_0$ ,  $I_{1\%}$ ).

We calculated the target as a median 27 per cent reduction in NGGI emissions only (solid lines) and NGGI + LULUCF emissions together (dashed lines). For each immigration scenario–target combination, we provide the times by which per capita emissions would have to decline to achieve the 2030 target ( $-x\times$ ) and the total cumulative emissions (Gt) from 2015 to 2030 ( $\Sigma$ ). *Bottom panel:* per capita NGGI and LULUCF emissions from 1990 to 2013 (t CO<sub>2</sub>-e person<sup>-1</sup>) and the required linear declines to achieve the 2050 target under the  $I_0$  and  $I_{1\%}$  immigration scenarios. We calculated the target as an 80 per cent reduction in NGGI emissions only (solid lines) and NGGI + LULUCF emissions together (dashed lines). For each immigration scenario–target combination, we provide the times by which per capita emissions would have to decline to achieve the 2050 target ( $-x\times$ ) and the total cumulative emissions (Gt) from 2015 to 2050 ( $\Sigma$ )



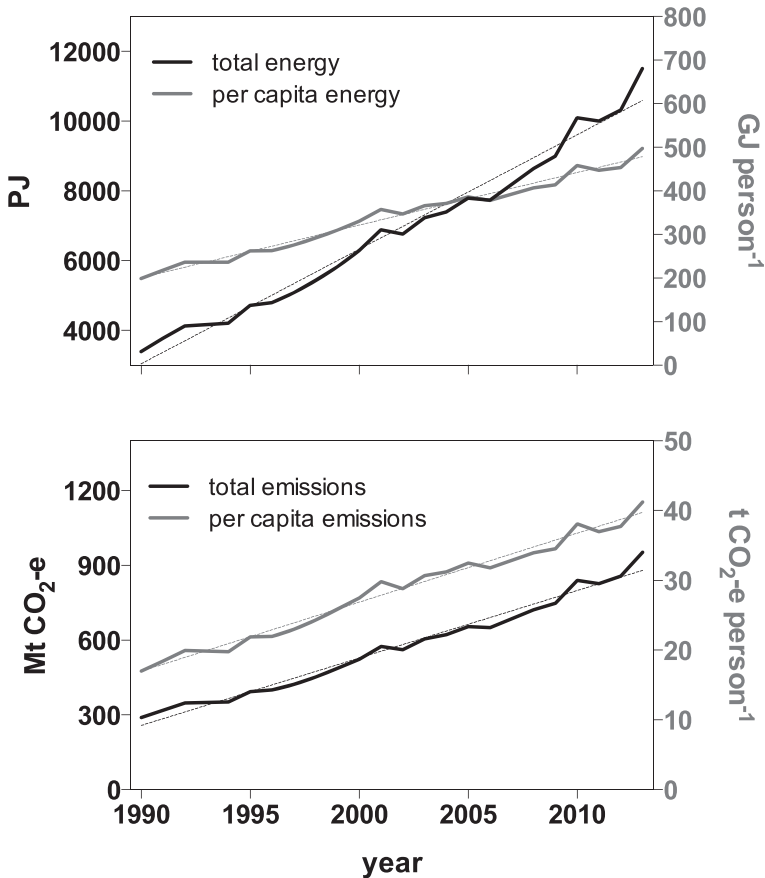
9.1 t CO<sub>2</sub>-e person<sup>-1</sup>. Offsetting the exported fossil fuel emissions by this amount equates to 740.1 Mt CO<sub>2</sub>-e and 32.1 CO<sub>2</sub>-e person<sup>-1</sup> or 21 per cent more CO<sub>2</sub>-e per capita than Australia produces domestically (NGGI +LULUCF).

**4. Discussion**

It is clear from our demographic modelling and the available data on net overseas migrants that Australia's future population is entirely contingent on its immigration policies. This differs from Australia's demographic situation even

20 years ago when net overseas migration accounted for only 39 per cent of the total population growth (Shu et al. 1996). The current demographic state of the Australian population is such that if all net immigration were halted today, the population would stabilize by the mid-2040s and decline only slightly thereafter, achieving nearly the same population size that it is today by mid-century. In fact, a modest rate of net overseas immigration of around 20,000 people year<sup>-1</sup> would guarantee stability at around 26.5 million after 2050. Given that most of the world's countries must grapple with controversial and complicated

**Figure 4** Australia's fossil fuel exports (bituminous coal, natural gas, liquid petroleum gas, and crude oil and feedstocks) and CO<sub>2</sub>-e emissions from 1990 to 2013 (data from the Australian Bureau of Statistics; <<http://abs.gov.au>>). Values are expressed in total and per capita exported energy (in petajoules, PJ) and CO<sub>2</sub>-e emissions from CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O by-products of combusted fuels (see Table S1 for conversion factors) (Commonwealth of Australia 2014). Lines of least-squares best fits are shown for each trajectory as thin dashed lines (*total energy* = 328.2 × year – 650,104; *per capita energy* = 12.05 × year – 23,783; *total emissions* = 27.06 × year – 53,590; *per capita emissions* = 0.9894 × year – 1,952)



family planning policies to even achieve reductions in population growth rate (Bradshaw & Brook 2014), let alone total population size, Australia is in an unusual socio-political situation in this regard. While many Western European countries have an intrinsic demographic profile like Australia's (that is, slightly declining populations in the absence of net immigration) (Coleman & Rowthorn 2011; Bradshaw & Brook 2014), the ability of those countries to moderate net immigration is perhaps more difficult given their geopolitical proximity to many other jurisdictions. Australia is a large island with vigilant border controls and so has a greater potential control over its future immigration and, hence, its total population size and greenhouse gas emissions. Japan is perhaps the only other developed country with this similar demographic, economic and island status (Coleman & Rowthorn 2011) (although Japan's per capita emissions are currently about one half of Australia's).

Whether Australians choose to limit their future population growth is entirely another matter. The country's natural systems have already suffered severe degradation of ecosystems from forest loss and fragmentation because mainly of past agricultural expansion (Bradshaw 2012), lowered rainfall in some areas because of deforestation (Pitman et al. 2004), increasing salinization of agricultural land (Pannell 2001; Clarke et al. 2002; Lambers 2003) and freshwater (Nielsen et al. 2003) systems because of deforestation, the world's highest mammal extinction rate (Woinarski et al. 2015), extensive economic and environmental problems associated with introduced animals and weeds (Bradshaw et al. 2007; Bradshaw et al. 2013; Gallagher & Leishman 2014; Krull et al. 2014) and declining health of its coral reefs (De'ath et al. 2012; Hughes et al. 2015). In this context, any policy that seeks an even larger Australian population would need to be carefully focused on how to achieve this goal sustainably, while mitigating (and, in some situations, reversing) these threatening processes. Given the rising environmental damage globally from a large and growing human population (Bradshaw & Brook 2014), Australia has the rare option to

limit this damage by adjusting its immigration policies accordingly.

The argument that Australia's ageing population will represent an increasing economic burden to the country (Commonwealth of Australia 2015a) is also demonstrably false, in terms of both total dependency and cost dependency ratios, such that it should not be invoked as an argument to inflate Australia's population unnecessarily further. There is, however, some argument that a too steeply declining population (as opposed to a stable one) would reduce the *future* value of the working population with fewer young people to replace the employed population. On the other hand, the crude metric of dependency ratios does not consider the important economic contributions of post-employed persons and the anticipated increase in 'participation rates' of older people (Commonwealth of Australia 2015a), nor do they include the essential contributions to society of unpaid work involved in child rearing (Folbre 2004). Even economic analyses suggest that declining fertility would increase, not decrease, Australia's future living standards (Booth & Tickle 2003). As such, the notion that ageing populations will push future societies to an economic breaking point is difficult to support on the basis of population structure alone.

Based on current population policies, the projected growth in the Australian population will make its already challenging future emissions-reduction goals even more difficult to achieve. In addition to the rising pressure of Australia's population on its ecosystems, the country's future greenhouse gas emissions are also partially tied to its immigration policy. As immigrants adopt Australian lifestyles, they inevitably increase their emissions by accessing emissions-intensive electricity and transported goods and perhaps also by becoming more intensive consumers themselves. As an example, immigrants to the USA increase their average emissions fourfold after settlement in that country (Kolankiewicz & Camarota 2008). In Australia, average per capita emissions from immigrants' countries of origin are only 42 per cent of Australia's (Turton & Hamilton 1999).

Because Australia already has one of the highest per capita emissions in the world, as well as a massive global footprint (Bradshaw et al. 2010) in terms of external emissions arising from its exported fossil fuels, it has a challenging road ahead regardless of its future choices on migration policy. This contrasts previous work (Turton & Hamilton 1999) stating that modifying population and immigration policies would have large effects on Australia's future emissions profile. With a 2020 target of 5 per cent reduction in emissions (relative to 2000), a 27 per cent reduction by 2030 (relative to 2005) and potentially an 80 per cent reduction by 2050, Australia has no credible mechanisms in place to achieve these goals. With a now-defunct carbon-pricing scheme (Schiermeier 2014), a weak and ambiguous renewable energy target (Roelfsema et al. 2014; Simpson & Clifton 2014), a demonstrably ineffectual action plan for future emissions reductions (Lubcke 2013; Shahiduzzaman et al. 2015) and legal impediments to building nuclear energy capacity (Hong et al. 2014; Heard et al. 2015), it seems unlikely that Australia will be able to achieve either of these two targets without substantial policy changes across population, energy, agriculture and environmental sectors.

Given that Australia has less than 14 years to meet the 2030 target, and less than 34 years to meet the putative 2050 target, and that a reduction in per capita emissions of 83.5 per cent would still be required even under the extreme scenario of no net migration, a possible solution would be to plan a large (>40 per cent) penetration of nuclear energy (Hong et al. 2014; Brook & Bradshaw 2015), supported by various renewable sources, to replace its ageing and polluting electricity generators (International Energy Agency 2014; Heard et al. 2015). Even with the rapid construction of nuclear energy to replace its entire coal-fired and gas-fired baseload capacity (as France achieved >75 per cent nuclear penetration in 20 years) (Hong et al. 2015), electricity production accounts for only about 33 per cent of Australia's total emissions (Commonwealth of Australia 2015b). Thus, even a complete decarbonization of the nation's electricity

production would not be enough to meet a 2050 target of 80 per cent reduction. Most of the transport industry would have to be decarbonized as well (Loftus et al. 2015), fuelled by a mix of synthetic products from a nuclear-derived surplus of heat and electricity and battery electric 'plug-in' vehicles (Brook 2012b), and current domestic gas use would have to be electrified (Heard 2013). Massive gains in efficiency might also be needed, depending on deployment rates.

Irrespective of these challenges, any increase in Australia's population will make these targets even more difficult, such that a business-as-usual projection (scenario 1) would require a fivefold greater reduction in per capita emissions to reach a 2050 target of 80 per cent reduction compared with the zero-immigration scenario and produce ~10 per cent more emissions (Figure 3). More population growth driven by immigration will hamper Australia's ability to meet its future climate change mitigation commitments and worsen its already stressed ecosystems, unless a massive technological transformation of Australia's energy sector is immediately forthcoming. This general conclusion mirrors the sustainability issues of population at the global scale—while reducing population size over the next few centuries is essential for limiting the deleterious effects of consumption on our planet's ecosystems, more immediate (decadal-scale) improvements in sustainability will need to originate from technological and social innovation (Bradshaw & Brook 2014; Brook & Bradshaw 2015).

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## Author contributions

C.J.A.B. and B.W.B. conceived and designed the models. C.J.A.B. sourced and analyzed the data. C.J.A.B. and B.W.B.

contributed the analysis tools. C.J.A.B. and B.W.B. wrote the article.

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## SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher’s web site.

**Table S1.** Solid fossil fuel combustion emission conversion factors for carbon dioxide

equivalents (CO<sub>2</sub>-e) for carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) (Commonwealth of Australia 2014)

**Figure S1.** Average age structure of immigrants to Australia from 2004 to 2013

**Figure S2.** Australia's population trajectory from 1971 to 2014 and scenario-based projections of its future population from 2015 to 2100. Scenario 7: business-as-usual population growth (increasing survival and age at first reproduction—Section 2) and net overseas migration ( $I_{04-13}$  = average of 215,000 year<sup>-1</sup> from 2004 to 2013); scenario 8: as scenario 7

except with constant (1 per cent of total population size) immigration ( $I_{1\%}$ ); scenario 9: as scenario 7 except with a linear increase in immigration rate to twice the average by 2100 ( $I_{(04-13)\times 2}$ ); scenario 10: zero net overseas ( $I_0$ ); scenario 11: fixed annual net immigration of 20,000 ( $I_{20k}$ ); scenario 12: fixed annual net immigration at 100,000 ( $I_{100k}$ ). Also shown as reference points are the projected final populations at constant, a constant growth rate observed between 1971 and 2014 (1.36 per cent,  $r_{71-14}$ ) and between 2006 and 2014 (1.73 per cent,  $r_{06-14}$ )