Options for Change in the Australian Energy Profile

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Abstract Climate change is occurring largely as a result of increasing CO₂ emissions whose reduction requires greater efficiency in energy production and use and diversification of energy sources away from fossil fuels. These issues were central to the United Nation climate change discussions in Durban in December 2011 where it was agreed that a legally binding agreement to decrease greenhouse gas emissions should be reached by 2015. In the interim, nations were left with the agreement reached at the analogous 2009 Copenhagen and 2010 Cancun meetings that atmospheric CO₂ levels should be constrained to limit the global temperature rise to 2 °C. However, the route to this objective was largely left to individual nations to decide. It is within this context that options for reduction in the 95 % fossil fuel dependency and high CO₂ emissivity of the Australian energy profile using current technologies are considered. It is shown that electricity generation in particular presents significant options for changing to a less fossil fuel dependent and CO₂ emissive energy profile.

Keywords Energy profile · CO₂ emissions · Electricity · Efficiency · Fossil fuels · Renewable energy · Nuclear electricity

INTRODUCTION

Over the past 150 years the increasing use of energy largely derived from fossil fuels has underpinned an impressive rise in global prosperity (Crutzen 2002; Steffen et al. 2004, 2007; Lincoln 2005, 2006), albeit unevenly distributed over a growing population which is likely to reach 9300 million by 2050 (United Nations 2011). The consequent human-induced changes in the biosphere are such that the later part of the Holocene epoch has been renamed

the Anthropocene by Crutzen (Crutzen 2002; Steffen et al. 2007, 2011). Human-induced changes in climate, biodiversity, and the nitrogen cycle have reached levels at which deleterious impacts are either already occurring or are anticipated together with seven other similarly induced changes which are causes for concern (Rockström et al. 2009). These changes have resulted either directly or indirectly from increasing use of fossil fuels. The accompanying rise in atmospheric CO₂ levels from the pre-Industrial Revolution level of ~270 ppm by volume to >380 ppm today (IPCC 2007; Quadrelli and Petersen 2007) has coincided with a rise in global temperature of ~0.8 °C superimposed on natural variability such that the last decade was the warmest in the past 150 years (Brohan et al. 2006; Hansen et al. 2006; UKMO 2011). This is largely attributable to increasing absorption of terrestrial infrared radiation by a growing CO₂ atmospheric concentration with lesser absorptions arising from increasing CH₄ and N₂O concentrations in concert with the major absorption arising from H₂O (Raupach et al. 2007; Allen et al. 2009; Matthews et al. 2009; Meinshausen et al. 2009; Solomon et al. 2009).

Against this background, resolutions to minimize anthropogenic climate change were sought at the United Nations sponsored climate conferences in Copenhagen, Cancun, and Durban in 2009, 2010, and 2011, respectively (Editorial 2009; Tollefsen 2009, 2010, 2011; Jacobs 2012). An agreement to negotiate a new treaty requiring all nations to meet yet to be quantified greenhouse gas emissions reductions by 2015 was reached in Durban. The Kyoto Protocol was extended for a period to be finalized at the next meeting in Doha in late 2012, and the non-binding agreement reached at the Copenhagen conference setting 2 °C as the desirable upper limit to global warming was retained. However, nations were largely left to decide their

own energy and CO₂ emission policies coincident with a growing global interest in improving energy production and use efficiency and the adoption of non-fossil fuel energy sources (Hoffert et al. 2002; Pacala and Socolow 2004; Lincoln 2009; Hedberg et al. 2010).

In Australia, significant concerns about climate change and energy policy are evident in two governmental reports (Garnaut 2011; Steffen 2011) which preceded the introduction of a tax of US\$24 per ton of CO_{2-e} from July 2012 which will increase by 2.5 % annually until 2015 when it will be replaced by an emissions trading scheme (Syed and Penney 2011). This is part of a governmental plan to decrease CO_{2-e} emissions by ≥ 5 and 80 % of 2000 emissions (556 Mt) by 2020 and 2080, respectively (AG 2010a, 2011a). (Herein, CO₂ emissions refer specifically to CO₂, and CO_{2-e} emissions refer to all greenhouse gas CO₂ equivalences except that of H₂O.)

Within this context, the options available to decrease the particularly high fossil fuel dependency and CO₂ emissivity of the Australian energy profile are examined with an emphasis on currently available technology. Australian energy use and CO₂ emissions are first discussed in a global comparison. This is followed by an examination of the Australian energy profile for the financial year 2008–2009, which is the latest year for which a complete data set is available, and which is used as a convenient reference point. Within this profile, Australian electricity is dominantly derived from coal which together with natural gas and oil accounts for 38 % of all fossil fuel primary energy domestic use and 54 % of the CO₂ emissions from fossil fuels. As electricity generation is generally considered central to minimizing CO₂ emissions and climate change [ECF (European Climate Foundation) 2010; Greenblatt et al. 2011; Hayward et al. 2011; Williams et al. 2012], an emphasis is next placed on options for change in Australian electricity

generation. These options progressively decrease fossil fuel dependence and show how the 2008–2009 CO₂ emissions would decrease by up to 71 % with changes in primary energy usage for electricity generation, and could be decreased to zero with carbon capture and sequestration, CCS (IPCC 2005). The options chosen are broadly in accord with Australian governmental policy (AG 2008, 2011a; Syed and Penney 2011) with the exception of the use of nuclear power. A reduction in the CO₂ emissivity of the non-electricity energy sector is also considered at both the current and the more advanced technological levels.

AUSTRALIAN ENERGY USE AND CO₂ EMISSIONS IN A GLOBAL CONTEXT

Australian national primary energy use and CO₂ emissions are small by comparison with those of the five largest national primary energy users, the Organization for Economic Cooperation and Development, OECD, and the world as seen from Table 1 (IEA 2010). However, on a per capita basis Australian energy use and CO₂ emissions are high by comparison with the other entries in Table 1 except for those of the United States. While a decrease in the 1.35 % Australian contribution to global CO₂ emissions will have little impact on climate change which is dominantly caused by the emissions of others, this latter fact is also true for the larger emitters and emphasizes the need to reduce CO₂ emissions globally.

THE AUSTRALIAN ENERGY PROFILE

The Australian energy profile for the financial year 2008–2009 is shown in Fig. 1 as a flow-chart constructed

Table 1 The five largest national, Australian, OECD and world primary energy uses and CO₂ emissions from combustion in 2008

Country	Primary energy use ^a		CO ₂ emissions	
	Total PJ and (%) ^b	Per capita (GJ)	Total in Mt and (%) ^b	Per capita (t)
United States	95 614.8 (18.46)	314.0	5595.92 (19.05)	18.38
PR China	89 220.7 (17.37)	66.9	6550 (22.29)	4.92
Russian Fedn.	28 753.3 (5.55)	202.8	1593.83 (5.42)	11.24
India	25 998.8 (5.02)	22.2	1427.64 (4.86)	1.25
Japan	20 759.8 (4.27)	162.6	1151.14 (3.92)	9.02
Australia	5447.4 (1.06)	253.2	397.54 (1.35)	18.48
OECD	227 008.3 (44.20)	190.8	12 630 (42.99)	10.61
World	517 865.3 (100.0)	77.4	29 381 (100.0)	4.39

^a Primary energy is the initial energy form prior to some of it being converted into electricity, refined oil products, or other energy forms before it reaches the end user

^b Total and percentage of world primary energy usage converted from IEA data [IEA (International Energy Agency) 2010] on the basis that 41.868 PJ = 1 Mtoe and CO₂ emissions (PJ = petajoule = 10¹⁵ joule, GJ = gigajoule = 10⁹ joule, Mtoe = million tonnes of oil equivalent energy. CO₂ emissions in megatonnes, Mt, and tonnes, t)

TOTAL AUSTRALIAN DOMESTIC ENERGY PRODUCTION 2008-09
17 769 PJ (-90 PJ stock changes/discrepancies)

Fig. 1 The Australian energy profile for the financial year 2008–2009 in which all quantities are rounded to the nearest PJ. Domestic production and imports are shown to the left for a total of 19 583 PJ once –90 PJ in stock changes and discrepancies are accounted for. Total exports of 13 810 PJ and the domestic energy supply of 5773 PJ composed of 5470 PJ from fossil fuels of which 2413 PJ were used in

electricity generation, 162 PJ (together with 7 PJ electricity) in fuel treatment, transformation, and refining, and 2895 PJ was supplied to end users together with 303 PJ from renewable energy sources. The productive domestic end use was 2364 PJ after the loss of 1865 PJ in supply and 1544 PJ in end use

from governmental data (AG 2011b). Domestically produced energy and imports are shown to the left and exports and domestic end use are shown to the right. Of the total domestic primary energy production, including U_3O_8 and renewable energy, 78.0 % was exported which makes Australia one of the larger energy exporters. Energy was imported as crude oil, refined petroleum and natural gas, and represented 9.7 % of the total energy input. The domestic primary energy usage was 5773 PJ which grew from 2695 PJ for the financial year 1974–1975 (AG 2009), and since 2000–2001 has continued to grow at ~1.6 % per annum although it remained largely unchanged in 2008–2009 due to the global economic downturn.

The energy of all types lost in supply to the domestic end user was 1865 PJ in 2008–2009 (Fig. 1). Of this loss, electricity generation, supply, and transmission was responsible for 1696 PJ, and fuel treatment, conversion, and refining for 169 PJ. The primary energy contents of oil and refined products, natural gas, coal and by-products, and liquid petroleum gas, LPG were 1779, 822, 195, and 99 PJ, respectively, after stock changes and discrepancies were accounted for and by-products from fuel refining were

included, amounted to a fossil fuel total of 2895 PJ being delivered to the end users. Bagasse and wood, liquid and gas biofuels, and solar water heating contributed another 194, 9, and 8 PJ, respectively, to give a total of 3908 PJ including electricity at 802 PJ. This is equal to the sum of the end use loss of 1544 PJ and the productive end use of 2364 PJ shown in the lower right segment of Fig. 1. The total domestic fossil fuel energy use of 5470 PJ was the sum of 2895 PJ end use, 162 PJ used in fuel treatment, transformation and refining, and 2413 PJ used in electricity generation. This total is larger than the 5447.4 PJ attributed to Australia in 2008 in Table 1; a variation which arises from small differences in time periods and estimations between agencies.

The overall efficiency of energy use was 41 % when end use efficiencies in all usage except transport were set at 80 and at 25 % for all forms of transport on the assumption that estimates by the Lawrence Livermore National Laboratories, LLNL, of the analogous end use efficiencies in the United States (LLNL (Lawrence Livermore National Laboratory) 2008) are applicable to Australia. A notable aspect of Fig. 1 is that 95 % of the energy used

domestically came from fossil fuels which is a high proportion by comparison with the 2008 world average of 81 % [IEA (International Energy Agency) 2010]. This is largely because Australian coal is plentiful and moderately priced for electricity generation and also because nuclear power, which contributed 13.5 % of global electricity in 2008 [IEA (International Energy Agency) 2010], is not used in Australia.

ELECTRICITY GENERATION 2008–2009

Ninety-three percent of Australian electricity was generated from fossil fuels in 2008–2009 as shown in Fig. 2 and discussed below (AG 2008–09, 2011b). Of this, electricity generation from black coal, brown coal, natural gas, oil and refined products and LPG, biofuels and combined bagasse and wood with primary energy contents of 1361, 649, 368, 35, 15, and 18 PJ, respectively, lost 1565 PJ from a total energy input of 2446 PJ. The electricity generated from each of these sources was 516, 205, 140, 10 (including 0.1 PJ generated from LPG), 5 and 6 PJ, respectively, to give a total of 881 PJ, or 245 TWh (TWh = terawatt hour = 10^{12} watt hour). Another 44 PJ came from hydroelectricity in addition to 14

and 1 PJ, respectively, from wind and solar generated electricity to give a total of 940 PJ (261 TWh). Of this, 131 PJ were lost in generation, supply and transmission to leave 809 PJ (225 TWh) of which 7 PJ (2 TWh) were used in fuel refining industries to leave 802 PJ (223 TWh) for end users. It is clear from these data that electricity generation offers significant opportunities to decrease fossil fuel primary energy consumption and CO₂ emissions.

OPTIONS FOR CHANGE IN ELECTRICITY GENERATION

In Fig. 3, five cumulative options for change in electricity generation are shown which progressively decrease the 2008–2009 CO₂ emissions from 202 to 58 Mt while continuing to provide 940 PJ of electricity prior to subtraction of 131 PJ used in generation, supply, and transmission. The options chosen to decrease fossil fuel use and CO₂ emissions are within the capacity of current technology and are used to illustrate a range of possible outcomes. In practice, it is likely that there will be variations of these options as cost and technological considerations come into play [ECF (European Climate Foundation) 2010;

AUSTRALIAN ELECTRICITY 2008-09

Fig. 2 The sources and efficiencies of electricity generation and supply, and end use in Australia in the financial year 2008–2009. In the *left-hand column* the primary energy (2413 PJ to give 871 PJ of electricity) in the fossil fuels used is shown in *black*, that in the biofuels/bagasse and wood (33 PJ to give 10 PJ of electricity) is shown in *green* as is the 59 PJ of electricity generated from hydro/wind/solar sources. The efficiency of electricity generation from each combustible fuel is shown on the *arrows* leading to the *first blue*

column to give 881 PJ of electricity at an average efficiency of 36 %. Addition of the 59 PJ from the other renewable sources gives a total of 940 PJ of electricity generated. The *second blue column* shows the 809 PJ of electricity remaining after losses of 1565 PJ of primary energy and 131 PJ of electricity used in generation, supply, and transmission to give an overall efficiency of 32.5 %. The *final column* shows the use of 7 PJ of electricity for refining leaving 802 PJ for end users on the grid. All energy quantities are rounded to the nearest PJ

OPTIONS FOR CHANGE IN AUSTRALIAN ELECTRICITY GENERATION 2008-09

Fig. 3 Five cumulative options for change in Australian electricity generation to decrease fossil fuel use by 53 % and CO₂ emissions by 71 % while retaining an electricity output of 940 PJ (261 TWh) based on the year 2008–2009. *Option 1: Current profile*. This is the BAU option leading to increasing CO₂ emissions as electricity use grows. *Option 2: Efficiency increased to 50 %*, increases the efficiency of electricity generation from combustible fossil and renewable fuels to 50 % and results in decreased fossil fuels use while retaining the same renewables use and decreasing CO₂ emissions by 29 %. *Option 3: Natural gas only fossil fuel*, requires the replacement of other fossil

fuels with natural gas while retaining the same renewables use and decreasing CO₂ emissions by 46 % cumulatively. *Option 4: Renewable electricity at 20%*, increases the use of renewable resources to 20 % while retaining them in the same proportions as in *Option 1*. This decreases natural gas use with a cumulative CO₂ emissions decrease of 62 %. *Option 5: Nuclear electricity at 20 %*, generates 20 % of electricity as nuclear electricity while retaining the same renewables use and decreasing natural gas use with a cumulative CO₂ emissions decrease of 71 %

Greenblatt et al. 2011; Hayward et al. 2011]. The actual 2008–2009 electricity generation is summarized as *Option 1: Current profile*, and is the “business as usual”, or BAU, case. A CO₂ emission total of 202 Mt is calculated for this option from the CO₂ emission factors: black coal, 88.2 kt/PJ, brown coal, 92.7 kt/PJ, natural gas and LPG, 51.2 kt/PJ, oil and refined products, 72.9 kt/PJ (AG 2010b). [This is slightly less than the governmental estimate of 206 Mt (AG

2010c)]. When all greenhouse gas emissions were included according to the Kyoto Protocol accounting method, CO_{2-e} emissions amounted to 545 Mt in 2008–2009, or 564 Mt when land use, land use change, and forestry emissions were included (AG 2010c). Electricity from renewable sources amounted to 70 PJ or 7.5 %.

Option 2: Efficiency increased to 50 %, entails the replacement of older plants and upgrading of others to

increase the efficiency of electricity generation from 36 to 50 % which is within the capacities of current technologies (Carcasci and Facchini 2000; Buhre et al. 2005; Bugge et al. 2006; Beér 2007). This decreases primary energy input from fossil fuels from 2413 to 1729 PJ (to give a total of 1762 PJ when combustible renewable fuels are included) and CO₂ emissions from 202 to 145 Mt when the efficiency of electricity production from each fuel is raised to 50 % and the amount of each fossil fuel is adjusted to provide the same relative proportion of primary fossil fuel energy as used in *Option 1*. The primary energy inputs of biofuels, bagasse and wood are retained at 15 and 18 PJ, respectively, and together with electricity sourced from hydro, wind, and solar generate 76 PJ of renewable electricity or 8.1 % of total electricity.

Substitution of coal and oil by natural gas retains a primary fossil fuel energy input of 1729 PJ in *Option 3: Natural gas only fossil fuel*, and decreases CO₂ emissions to 89 Mt, and is consistent with governmental modeling which indicates a shift to natural gas in electricity generation as CO₂ emissions costs grow (Syed and Penney 2011). Increasing the use of renewable energy from 8 to 20 % by 2020 is a governmental target (AG 2008). A route to achieving this is shown in *Option 4: Renewable electricity at 20%*, through which the input from biofuels, bagasse and wood primary energy is raised from 33 to 83 PJ and the electricity contribution from hydro, wind, and solar electricity is increased from 59 to 147 PJ to retain the same relative usage ratios of renewable energy as in *Option 1*. This increases electricity from renewable resources to 188 PJ or 20 %. Consequently, the primary energy required from natural gas decreases to 1500 PJ and CO₂ emissions to 77 Mt.

While there are currently no plans to use nuclear electricity in Australia, the generation of 20 %, or 188 PJ, of electricity from this source would further decrease the use of natural gas to 1124 PJ and CO₂ emissions to 58 Mt as shown in *Option 5: Nuclear electricity at 20 %*, or 29 % of the 2008–2009 emissions in *Option 1* when the small “whole of life” nuclear electricity CO₂ emissions are set to zero. This 20 % contribution is chosen as it is in the mid-range for the 29 countries generating nuclear electricity in 2010 [IAEA (International Atomic Energy Agency) 2012]. The efficiency of nuclear electricity generation through conventional light water reactors is ~35 % and the total primary energy used consequently rises to 1746 PJ while primary fossil fuel energy usage drops from 2413 to 1124 PJ and CO₂ emissions drop from 202 to 58 Mt, or to 47 and 29 %, respectively, of the amounts shown in *Option 1*.

Carbon capture and sequestration, CCS, could further lower or eliminate CO₂ emissions for any of the five options considered above. However, CCS itself consumes additional electricity and is not yet practiced in Australia,

and globally is largely in the planning stage (IPCC 2005; Hansson and Bryngelsson 2009; Haszeldine 2009; Syed and Penney 2011). Application of CCS to accommodate the decreased 2008–2009 CO₂ emissions of 59 Mt resulting from the implementation of Options 2–5 presents a major challenge. A prominent, but relatively small, example of CCS is that of the Sleipner natural gas field in the North Sea where 1 Mt of CO₂ separated from natural gas is sequestered in porous sandstone between 550 and 1500 m below the seabed annually (Service 2004). This came about largely because the cost of CCS is smaller than the Norwegian tax of US\$55 per ton of CO_{2-e}. It is possible that the analogous Australian tax of US\$24 (Syed and Penney 2011) may similarly encourage further consideration of CCS. However, in the United States, where about 65 Mt CO₂ is used annually in enhanced oil recovery, it is estimated that current amine-based CCS technologies are likely to increase electricity costs by up to 30 % (Bhown and Freeman 2011).

Inevitably, the cost of electricity generation through different technologies will influence future choices (Greenblatt et al. 2011; Hayward et al. 2011; Syed and Penney 2011). Two European studies show that fossil fuel and nuclear technologies are considerably cheaper options than renewable alternatives for electricity generation even when global warming abatement costs are taken into account for fossil fuels (RAE 2004; Fredga and Mäler 2010). An Australian study shows fossil fuel technologies to hold a similar advantage in the absence of CCS, but the cost of wind generated electricity is less than that from fossil fuels when CCS is introduced (Syed and Penney 2011). According to this study, hydroelectricity is cheaper than any other form of electricity, and photovoltaic and solar thermal electricity is more expensive than that derived from fossil fuels with CCS.

COMBINED AUSTRALIAN FOSSIL FUEL USE AND CO₂ EMISSIONS

Fossil fuel use outside the electricity sector amounted to 3057 PJ in 2008–2009. The sectorial usage was: agriculture 89 PJ, mining 370 PJ, commerce and services 83 PJ, transport 1394 PJ, residential 155 PJ, manufacturing and construction 739 PJ, fuel treatment, transformation, and refining 163 PJ, and other use 64 PJ (AG 2011b). The combined CO₂ emissions from these sectors amounted to 171 Mt. Assuming the LLNL estimated efficiencies of 25 % to apply to the transport sector and 80 % to the others [LLNL (Lawrence Livermore National Laboratory) 2008], a modest efficiency improvement in fossil fuel usage to 30 and 85 %, respectively, would decrease the 2008–2009

usage from 3057 to 2726 PJ and CO₂ emissions from 171 to 152 Mt assuming a similar fossil fuel mix and usage pattern (AG 2010c). (The CO₂ emissions from fuel treatment, transformation, and refining are subsumed into those of the electricity and other sectors.) When these decreases are combined with the maximum decreases in fossil fuel use from 2413 to 1124 PJ and in CO₂ emissions from 202 to 58 Mt, or zero with CCS, for electricity generation for *Option 5* of Fig. 3, the overall decrease in fossil fuel use is from 5470 to 3851 PJ and in CO₂ emissions from 373 to 211 Mt, or 153 Mt with CCS. On this basis and an Australian 2008–2009 population of 20.8 million, the per capita decrease in primary fossil fuel energy consumption is from 263 to 185 GJ and a decrease in CO₂ emissions from 17.9 t (which differs from the 18.48 t in Table 1 due to differences in time periods and estimation methods) to 10.1 t which further decreases to 7.4 t with CCS.

Energy consumption in the Australian transport sector, 1409 PJ (fossil fuels 1394 PJ, biofuels 6 PJ and electricity 9 PJ; AG 2011b) is dominated by road transport (1070 PJ) which in turn is dominated by small passenger vehicles (653 PJ). Qualitatively, gains in new vehicle fuel efficiency over a decade during which most of the fleet is replaced will slow the growth of fossil fuel use and CO₂ emissions as the population increase. As global production of oil has leveled out at about 75 barrels per day since 2005, growing demand is likely to increase the price (Murray and King 2012). Consequently, some transfers from individual passenger vehicles to public transport and transfers of long distance freight transport from road to rail and coastal shipping are likely to further slow fossil fuel usage and CO₂ emissions growth. The use of ethanol and biodiesel fuels and electric and hybrid passenger vehicles is in its infancy in Australia, as is the adaptation of other alternative energy sources for transport (Jacobson 2009; Fredholm and Nordén 2010; Graham 2011). However, growth in their usage is expected to moderate increases in fossil fuel consumption. In the non-transport sectors there is a growing emphasis on improving energy use efficiency in areas ranging from plant operation, domestic appliances, air conditioning, roof-mounted solar panels and water heating, lighting, and insulation to building design.

AUSTRALIAN ENERGY USE, EMISSIONS, AND TIMESCALES

The potential decreases in fossil use and CO₂ emissions discussed above for 2008–2009 are all technologically possible, but the timescale for their achievement is subject to a range of factors. However, on the basis of Australian governmental plans to decrease 2020 CO_{2-e} emissions by $\geq 5\%$ in comparison with 2000 CO_{2-e} emissions of 556 Mt,

a consideration of timescale becomes particularly relevant (AG 2011a). Under a BAU scenario, Australian CO_{2-e} emissions will grow from 564 Mt in 2008–2009 to 690 Mt by 2020 and 1000 Mt by 2050 (AG 2010a, 2011a) coincident with projected population increases to 25.7 and 35.9 M, respectively (AG 2010d). A decrease of 5, 15, and 25 % by comparison with 2000 CO_{2-e} emissions of 556 Mt requires decreases to 528, 473, and 417 Mt, respectively.

As shown in Fig. 3, the combined *Options 2–5* deliver a 144 Mt decrease in CO₂ emissions from 2008 to 2009 electricity generation which becomes 202 Mt if CCS is fully deployed. Addition of the proposed modest decrease in CO₂ emissions of 19 Mt from the other sectors results in emission decreases of 163 and 221 Mt without and with CCS, respectively, to give corresponding CO_{2-e} emissions of 401 and 343 Mt. On this basis and the BAU assumption that electricity generation increases linearly along with fossil fuel consumption in the other sectors, the 690 Mt CO_{2-e} emissions in 2020 decrease proportionately to 491 and 420 Mt (with CCS), which correspond to 12 and 24 % decreases of by comparison with the 2000 CO_{2-e} emissions of 556 Mt. While only 8 years remain to implement these or similar emission reduction strategies in the energy production and use sectors, it appears that the lower end of the $\geq 5\%$ target is achievable. Clearly, major innovations are required to reach the 2050 target of an 80 % decrease compared with the 2000 CO_{2-e} emissions as is discussed below.

LONGER TERM EMISSION REDUCTIONS

While current technology has the potential to substantially decrease Australian CO₂ emissions from electricity generation, CO_{2-e} emission decreases in other sectors are less certain and this poses a problem in attaining an overall 80 % decrease by 2050. A major improvement in energy production and use efficiency and the form in which energy is delivered will be required. A recent assessment of the efficiency of energy use concluded that sophisticated improvements in design in the construction, industrial, and transport sectors could contribute up to a 73 % saving in energy use (Cullen et al. 2011). Substantial improvements in efficiency are incorporated in several plans for CO_{2-e} decreases coincident with a growing consensus that increased use of electricity in combination with CCS is likely to make a major contribution to emissions decreases. Thus, the Californian intention to decrease CO_{2-e} emissions by 80 % by 2050 in comparison with those of 1990 requires a per capita decrease from 14.62 t in 1990 to 1.56 t in 2050, or from a total of 470 Mt in 2005 to 85 Mt in 2050 when population growth is taken into account (Greenblatt et al. 2011; Williams et al. 2012). It is proposed that the Californian energy profile should be “decarbonized” through

increasing the electricity component of energy used in transport and other sectors in concert with a major use of CCS, nuclear power, and low-carbon fuels and hydrogen. The uses of biofuels and substantial improvements in energy use efficiency are also envisaged as important components of this decarbonization. It is further estimated that most renewable energy sources will become competitive with a CO_{2-e} tax of US\$30 per ton.

The European Climate Foundation similarly concluded that decarbonization through increased proportionate use of electricity, alternative fuels and increased efficiency offered a route to achieving a decrease by comparison with 1990 CO_{2-e} emissions of 80–95 % by 2050 [ECF (European Climate Foundation) 2010]. To achieve the extent of decarbonization envisaged in the transport sector in particular, advanced alternative energy sources are required (Jacobson 2009; Fredholm and Nordén 2010) as exemplified by advanced solar energy storage and hydrogen generation (Cook et al. 2010) and biofuels for aviation (Graham 2011) which are unlikely to make significant global contributions for at least a decade. Consequently, fossil fuels will remain major sources of Australian and world energy for much of the twenty-first century [Lincoln 2005; ECF (European Climate Foundation) 2010; AG 2011a; Greenblatt et al. 2011; Hayward et al. 2011; Syed and Penney 2011] and as a result there appears little alternative to a major utilization of CCS.

CONCLUSIONS

Substantial options exist for improving efficiency and reducing CO₂ emissions in Australian electricity generation either as indicated in Fig. 3 or through variations of them using current technologies. While it is probable that the lower end of the ≥ 5 % CO_{2-e} emission decrease by comparison with 2000 set as a governmental target for 2020 is achievable, a decrease of 80 % by 2050 presents a very major challenge (AG 2011a). It is likely that a substantial increase in electricity as a proportion of energy supply, CCS, the adoption of new fuels, and much improved efficiency in energy use and production will be major factors in meeting this challenge. It also appears inevitable that nuclear electricity will have to be given further consideration as part of the future Australian energy profile to achieve the 2050 CO_{2-e} emission target.

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