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Nuclear power can reduce emissions and maintain a strong economy: Rating Australia's optimal future electricity-generation mix by technologies and policies

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HIGHLIGHTS

- Nuclear power is essential for reducing greenhouse-gas emissions at lower cost.
- Physical and economic limits of renewables at high penetrations hamper their growth.
- Large-scale fossil fuels are required if nuclear power is not permitted in Australia.
- Well-balanced information is a prerequisite for defining an optimal future mix.

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ABSTRACT

Legal barriers currently prohibit nuclear power for electricity generation in Australia. For this reason, published future electricity scenarios aimed at policy makers for this country have not seriously considered a full mix of energy options. Here we addressed this deficiency by comparing the life-cycle sustainability of published scenarios using multi-criteria decision-making analysis, and modeling the optimized future electricity mix using a genetic algorithm. The published 'CSIRO *e-future*' scenario under its default condition (excluding nuclear) has the largest aggregate negative environmental and economic outcomes (score = 4.51 out of 8), followed by the Australian Energy Market Operator's 100% renewable energy scenario (4.16) and the Greenpeace scenario (3.97). The *e-future* projection with maximum nuclear-power penetration allowed yields the lowest negative impacts (1.46). After modeling possible future electricity mixes including or excluding nuclear power, the weighted criteria recommended an optimized scenario mix where nuclear power generated >40% of total electricity. The life-cycle greenhouse-gas emissions of the optimization scenarios including nuclear power were <27 kg CO_2-e MW h^{-1} in 2050, which achieves the IPCC's target of 50–150 kg CO_2-e MW h^{-1}. Our analyses demonstrate clearly that nuclear power is an effective and logical option for the environmental and economic sustainability of a future electricity network in Australia.

1. Introduction

The use of nuclear energy for electricity generation is currently prohibited in Australia under the Environmental Protection and Biodiversity Conservation Act 1999 [1] as a result of public misperceptions and political ideologies [2]. But what would Australia's future electricity-generation mix look like if nuclear power were permitted to compete? Australia's greenhouse-gas emissions from public electricity and heat production have increased from 130 megatonnes (Mt; 23% of national greenhouse-gas emissions) in 1990, to 203 Mt (36%) in 2010 [3]. While total renewable energy electricity generation including hydropower increased slightly during the same period (15.6 terawatt hours [TW h] in 1990 to 21.7 TW h in 2010), total electricity generation has grown from 155 to 252 TW h over this time, and fossil-fuel sources (mostly coal power) have provided the majority of the remainder of electricity generation [4]. This means that the proportion of renewable electricity in Australia has actually declined from 0.19 in 1960, to <0.07 in 2008 [5]. Although electricity and heat consumption—and its associated greenhouse-gas emissions—decreased between

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2010 and 2012 [3], it is expected that energy consumption will increase on average over the long term [6] as demand grows from emerging technologies like plug-in electric vehicles in the transport sector, and the expanding human population size. Detailed analyses of historical data [7] and future forecasts [8,9] suggest that energy efficiency and renewable energy will be insufficient to reduce national greenhouse-gas emissions from the electricity sector substantially. Although the German government (and a few other countries including Japan, Italy, Belgium, and Switzerland) have announced plans to phase out nuclear power and increase the share of renewable energy in their electricity consumption to up to 80% by 2050, the reality to date is that these pathways have allowed a higher fossil-fuel (mostly coal) penetration share into the national electricity grid to fill the reduced the nuclear share [10–12]. However despite its environmental and economic benefits as a practical and scalable ‘zero-emission’ option [13,14], the legislated exclusion of nuclear power in Australia means that most detailed published scenarios have, to date, disregarded the role of nuclear power in Australia’s electricity sector.

Australia’s Commonwealth Scientific and Industrial Research Organisation (CSIRO) developed the *e-future* web tool [15], underpinned by an integrated assessment model, to explore Australia’s future electricity scenarios based on different conditions, including electricity demand, energy source price, technology costs, the inclusion/exclusion of nuclear power and the type of backup power required [15]. In addition, the Australian Energy Market Operator (AEMO) published a government-commissioned report on 100% renewable energy scenarios, all of which were based on the expectation of increased electricity consumption [16]. The World Wildlife Fund (WWF) [17] and Greenpeace [18] have also published 100% renewable-energy scenarios, but in contrast these rely heavily on limiting electricity consumption via increased energy efficiency and intermittent renewable resources. Others have attempted to model the supply of renewable electricity-based consumption assuming current demand [19], or used other assumptions [20].

Although renewable energy is often touted as a ‘zero-carbon’ option, the life-cycle processes of all current energy sources confer non-negligible carbon emissions [14]. Moreover, no electricity-generating source is perfectly safe [21], or exempt from any environmental impacts or social reluctance [22]. The potential loss of life due to severe accidents of the current technology for commercial nuclear power (Generation II and III) is 1.07×10^{-5} fatalities GWe y^{-1} including latent fatalities, whereas coal power records 1.2×10^{-1} fatalities GWe y^{-1}, and biomass records 1.49×10^{-2} fatalities GWe y^{-1} [21]. The installation, operation and maintenance of wind power or photovoltaics can also result in accidents leading to fatalities or injuries [23]. Therefore, all electricity-generation options must be considered objectively and transparently, and contrasted with balanced scientific methods using quantitative information. Future technological development and political decisions that can influence a future electricity mix should be founded on objective assessment of the evidence.

In contrast to any previously published scenarios for Australia’s future energy mix, we included nuclear power to propose a range of plausible sustainable future electricity-generation mixes. We also implemented an innovative weighting tool to optimize decadal mixes based on diverse socio-political perspectives. First, we analyzed the adverse environmental and economic impacts of previously published Australian scenarios based on the following sustainability criteria: (1) levelized cost of electricity with additional costs, (2) greenhouse-gas emissions, (3) air pollutants, (4) land transformation, (5) freshwater consumption, (6) safety costs, (7) solid-waste generation, and (8) material requirements. We then chose optimal future (2050) electricity-generation mixes based on six extreme socio-political perspectives using a ‘genetic’ simulation algorithm: (1) equally valued, (2) environmentalist, (3) economic realist, (4) anti-nuclear, (5) economic only, and (6) greenhouse-gas emissions reduction only. We then explored the influence of currently non-commercial technological possibilities (carbon capture and storage, and the maximum limits of renewable energy) and alternative political decisions (permitting nuclear power, carbon pricing and minimum renewable energy penetration of total electricity generation).

This is a novel approach to a situation that has been previously characterized by: (i) largely narrative or single (fixed) scenario themes and (ii) an a priori exclusion of nuclear power for reasons beyond engineering or economic practicality. As such, this is arguably the first genuine attempt, using these two methodologies, to optimize the future electricity-generation mix for Australia, and indeed few such examples exist for any country. Moreover, our use of weights to model explicitly a wide range of future electricity generation mixes and capture modified by a suite of different socio-political perspectives, technological changes and policy measures, makes this a particularly distinctive contribution to the sustainable-energy literature.

2. Methods

2.1. Assumptions

The demand profile we used followed the Australian Energy Projections to 2040–50, published by the Bureau of Resources and Energy Economics [8]. Gross national electricity generation in 2010 was 252 TW h, and increased 1.1% year^{-1} until 2050. We did not assume the early forced closure of any operating power plants. The life cycle of power plants followed the Australian Energy Technology Assessment [24]. The constructed years of currently operating renewable energy generators with >10 kW of peak capacity and fossil-fuel generators with >20 MW of capacity followed the information from Geoscience Australia [25,26]. Fossil fuels included gas, gas with carbon capture and storage, black coal, black coal with carbon capture and storage, brown coal, and oil; renewable sources included rooftop photovoltaic, large-scale photovoltaic (solar photovoltaic farms), solar thermal, onshore wind, offshore wind, hot-dry-rock geothermal, biomass, biogas, ocean and hydro power, backup power included biogas, biomass, gas, gas with carbon capture and storage, and oil.

We reviewed technological barriers (carbon capture and storage), physical barriers (intermittent renewable energy sources), and political barriers (nuclear power) to model future electricity generation mixes objectively. Despite nuclear power being a technologically and economically proven system in many countries [13], the construction or operation of a nuclear power plant is legally prohibited in Australia. However, we assumed the first nuclear power could be permitted by a change of legislation by around 2020 and nuclear power could be utilized in full scale after 2030. We also assumed that carbon capture and storage could be employed commercially from 2030 [27]. Although high penetration of intermittent renewable energy (photovoltaic, wind, solar thermal and ocean power) can cause economic and physical problems [28–32], we optimistically assumed that advanced grid (smart grid) technologies, coupled to storage and backup systems, could stabilize the impacts without electricity loss or additional economic cost. The maximum limits of renewable energy sources followed the median or maximum values of the High Penetration Renewables Studies prepared by CSIRO [32]. We also ignored the physical limits of inter-state transmissions; therefore, renewable energy systems could be distributed nationwide without electricity loss or additional economic costs.

2.2. Multi-criteria decision-making analysis

We assessed life-cycle sustainability of published scenarios and proposed desired scenarios using multi-criteria decision-making analysis (MCDMA). MCDMA is a widely used methodology to evaluate energy systems or grids using a range of environmental, social and economic indicators based on indicator weightings [33–35], but it has never been applied to scenarios describing the Australian electricity mix. Here we used the weighted sum approach with the Delphi method for the criteria selection [36]. We selected the cost and sustainability indicators for the MCDMA carefully based on the guidelines of the International Atomic Energy Agency in cooperation with the United Nations Department of Economic and Social Affairs (UNDESA), the International Energy Agency (IEA), Eurostat and the European Environment Agency (EEA) [37], which are relevant to the context of Australia. These were: (1) levelized cost of electricity (which is the minimum cost of electricity at which an electricity producer can sell and still secure an economic return), including carbon pricing between 2013 (\$23 tonne CO_2-e^{-1}) and 2050 (\$140 tonne CO_2-e^{-1}) [24], and additional costs [31], (2) greenhouse-gas emissions [38], (3) air pollutants Australian Academy of Technological Sciences and Engineering, 2009 [22,39–48], (4) land transformation [39,46,49–53], (5) freshwater consumption [41,48,50,54–59], (6) safety costs [21,60,61] (the probability of severe accidents and the impact of them), (7) solid-waste generation [41,48,62–69], and (8) material requirements [46,48,59,65,70–72].

We acknowledge that sustainability indicators can be different among countries, particularly the levelized cost of electricity, due to specific economic conditions and technological expertise. For example, South Korea requires a capital investment of <US\$4000 kW^{-1} to build a nuclear power plant [35], whereas the first-of-a-kind European Pressurized Reactor (unit 3) at Olkiluoto nuclear power plant in Finland required US\$7200 kW^{-1} (US\$1.35/€) [73]. Therefore, to ensure the objectivity and transparency of this analysis, we applied the country-specific economic values (levelized cost of electricity) reported in the recent Australian Energy Technology Assessment report prepared by the Bureau of Resources and Energy Economics in Australia [24]. According to the United Nations, radionuclides releases during normal operation of nuclear reactors or from spent nuclear fuels would not cause major public health issues [74]. The hazard posed by the radioactive-material releases from nuclear-related accidents to the general public is also small compared to many other energy-related emissions and accidents [75], although it carries the burden of high public concern, which we represent via our 'social weightings' (see below). Although all other power plants emit some amount of radioactive substances during life-cycle processes [76,77], we could not source any objective information about these. Therefore, here we only considered spent-fuel management (additional cost of between \$1.3 and \$4.06 MW h^{-1}) [78] and decommissioning costs (additional cost of between 10% and 15% of the capital investment) [79] of nuclear power plants as additional costs (i.e., a process that a priori de-emphasizes nuclear power). For all criteria, we applied the median value of each indicator (Appendix A).

Particular socio-economic weightings are important for defining 'optimal' future electricity generation mixes in Australia, based on qualitative, but potentially influential, community attitudes. We proposed six diverged weightings: (i) all indicators equally valued, (ii) environmentalist, (iii) economic realist, (iv) anti-nuclear, (v) economic only, and (vi) greenhouse-gas emissions reduction only (the breakdown of relative weights is shown in Table 1). Environmentalists tend to put more weight on technologies favouring overt environmental outcomes. Economic realists are most concerned about electricity costs (levelized cost of electricity), followed by emissions and safety. The most prominent of the concerns of anti-nuclear organizations are radioactive contamination of land and water, and the risk of severe accidents [80]. Since a completely anti-nuclear perspective would entirely negate the use of nuclear power, here we excluded nuclear power for the completely anti-nuclear perspective, rather than try to capture this position in the weightings.

To implement the weighting sets within the optimization algorithm proposed, we normalized the maximum negative sustainability impact values to 1 and the minimum to 0; all other values were interpolated linearly. For each criterion i, we then multiplied weighting (0 = negligible; 1 = most important) with the sustainability impact values, as follows:

$$I = \sum_{(i=0\to n)} S_i \cdot W_i \tag{1}$$

where S_i is the sustainability value of criterion i (for n criteria) and W_i is a weighting applied to S_i (Appendix B).

2.3. Optimization

To define desired future electricity-generation mixes that reflect the six socio-political perspectives, we considered three different optimization algorithms: (i) a random optimization algorithm, (ii) a simulated annealing algorithm, and (iii) a genetic algorithm [81]. Due to the large number of permutations (18 different types of power plants could generate between 0% and 100% of the total electricity generation), choosing an appropriate algorithm is important to avoid local optimization traps and excessive processing time.

To obtain a globally optimized set using a random optimization that includes the actual best combination, all possible permutations would need to be compared, which makes random optimization too time-consuming and unrealistic. For example, only three different penetration levels of each of 18 power plants would lead to 387,420,489 different combinations. A simulated annealing algorithm is a widely accepted method to obtain a globally optimized solution [82]. The algorithm generates a single set randomly, and then compares this with a second random sample. If the second set is closer to the desired answer than the first, the second set is accepted. However even if the second set is not closer than the first, the second set can be accepted with a certain probability to avoid a locally optimized answer. The chance of accepting an incorrect answer reduces as the process is progressed. However, since MCDMA does not provide a 'correct' answer by comparing two sets, it can still lead to an incorrect answer.

A genetic algorithm, by contrast, solves these issues. It is a replicated, natural evolutionary process using binary or continuous (real) values [82]. The algorithm compares many sets simultaneously, so it is more suitable than a simulated algorithm for MCDMA. Using such a genetic algorithm, we defined optimized decadal scenarios for each socio-economic perspective through to 2050. For each decade we replaced power plants that reached the end of their lifespan, and tailored the additional increased electricity consumption with an optimized generation mix derived from a genetic algorithm. This process first involves drawing 1000 generation sets randomly (replaceable and additional electricity generation mixes), followed by using the generation mixes ranked in the lower half (lower scores = higher sustainability) of the MCDMA range as the 'parents' (crossover) for the next generation mix ('offspring'). For the crossover process, we created 500 parent couples at random from the selected best (lowest MCDMA scores) mixes, with each couple then generating two offspring by swapping their electricity generation quantities between a couple. The total amount of electricity generation and the minimum or maximum limits of electricity generation options must be kept by the mutation process. Finally, we used the generated offspring group as a parent

Table 1

Multi-criteria decision-making analysis weightings to represent ‘social’ values for or against different indicators of sustainability in electricity generation systems. Different weightings (perspectives) on each sustainability criterion can range between 0 (negligible) to 1 (important). The proposed weights (‘social’ values) given below are arbitrary, but representative of different plausible community or socio-economic mind-sets.

Indicators	Equal	Environmentalist	Economic realist	Anti-nuclear[a]	LCOE[b]	GHG
Levelized cost of electricity	1	0.2	1	0.2	1	0
Greenhouse-gas emissions	1	1	0.6	0.2	0	1
Air pollutants	1	0.8	0.2	0.2	0	0
Land transformation	1	1	0.4	0.8	0	0
Water consumption	1	1	0.2	0.6	0	0
Safety costs	1	0.4	0.6	0.8	0	0
Solid waste	1	0.6	0.2	0.2	0	0
Material consumption	1	0.4	0.2	0.2	0	0

[a] The anti-nuclear perspective did not include nuclear power.

[b] LCOE: levelized cost of electricity.

population for the next generation. We repeated these series of procedures for 100 iterations (‘evolved’ generations). The lowest MCDMA-scored electricity mix that resulted from the last generation therefore represents an optimized additional electricity generation mix for a particular perspective for that decade. We then evaluated the greenhouse-gas emissions and levelized cost of electricity that arose as a consequence of each optimized future electricity mix, according to the different perspectives (Appendix B).

2.4. Published scenarios

We compared and contrasted eleven published future electricity generation mixes in 2050 from six organizations (Appendix C). Using the *e-future* tool developed by CSRIO, three scenarios were created (default without nuclear power, default with nuclear, and maximum nuclear power, which set high demand, high energy-source price, and low nuclear power costs, to obtain the highest nuclear penetration) [15]. We included WWF’s 100% renewable energy scenarios that either include or exclude transport [17], and the Australian Energy Market Operator’s (AEMO) two 100% renewable energy scenarios for the National Electricity Market [16]. In addition, we used two low-cost scenarios from Elliston [19], Greenpeace’s Energy Revolution scenario [18], and a scenario from Seligman [20].

It is important to note that each scenario had diverse electricity consumption predictions and simulation conditions, so we did a standardized comparison of those mixes by dividing the aggregate MCDMA score by the total electricity generation of each scenario (i.e., MCDMA score per unit energy delivered). Additionally, we assumed that the final generation mix of each scenario was maintained until 2050 if the target year of a scenario was earlier than 2050 (WWF’s 100% renewable energy scenario excludes transport, Elliston’s scenarios, Greenpeace’s scenario, and Seligman’s scenarios are included).

Each previously published scenario had different objectives and placed often divergent emphasis on the metrics of economic and environmental sustainability. We thus examined the sensitivity analyses of the sustainability indicators’ weightings. For the weighted sensitivity analysis, we changed each selected indicator’s weighting (e.g., greenhouse-gas emissions) from 0 to 1, while holding the other indicators at 0.5. We then duplicated the procedure for all the other indicators.

2.5. Optimized scenarios

To define desired future electricity-generation mixes, we followed the median values from the High Penetration Renewables Studies by CSIRO [32] for the maximum technological and economical limits of renewable energy penetration (the ‘renewable energy limits’, which were derived by a sophisticated analysis of a range of physical and economic scaling criteria). The minimum renewable energy component of the total electricity generation was 20% and the minimum backup electricity share (the renewable energy target) was 20% during the entire simulation period.

We modeled scenarios with and without nuclear power, and with and without carbon capture and storage, with the goal of revealing the consequences of renewables-only future mixes. For renewable energy sources, we applied 20% of the renewable energy target as a minimum value and the maximum values of the renewable energy limits. We also examined the impact of carbon pricing (including or excluding carbon pricing), the renewable energy target (0% or 20%) and the physical and economic maximum renewable energy limits (the median values from the High Penetration Renewables Studies by CSIRO or the maximum values) [32].

2.6. Limitations

Our analysis focused on a sustainability assessment of Australia’s published electricity generation mixes and recommendations of optimal combinations according to alternative socio-economic perspectives. However, due to the lack of appropriate information about the life-cycle assessment of electricity generation technologies in Australia, we were obliged to apply information from published international peer-reviewed articles or reports. Although MCDMA requires balanced and objective approaches across all electricity-generation options, here we added decommissioning and spent-fuel management costs [83] only to nuclear power, to provide the most conservative criteria for ranking within the anti-nuclear (non-exclusion) viewpoints.

3. Results

3.1. Published scenario analyses

The life-cycle sustainability of the eleven published scenarios (Appendix C), based on MCDMA with equal weightings ($w = 1$) for all indicators, is shown in Table 2. The *e-future* scenario with maximum nuclear power penetration had the lowest (i.e., most ‘sustainable’) score (1.46 out of 8) and the *e-future* default scenario without nuclear power had the highest (4.51). Although the *e-future* scenario with maximum nuclear power penetration had a similar renewable energy share to the *e-future* default scenario, nuclear power replaced virtually all the coal-power share, and reduced greenhouse-gas emissions across the entire electricity grid in 2050 by 194.3 kg MW h^{-1}. However, the higher fossil-fuel penetrations of *e-future* scenarios limited the reduction in greenhouse-gas emissions. Since the other scenarios did not include any fossil-fuel generators, their life-cycle greenhouse-gas emissions were <35 kg CO_2-e MW h^{-1}. However, none of the existing

Table 2
Published scenario comparison using multi-criteria decision-making analysis with equal weights ($w = 1$). Note that carbon pricing is not considered here. Each sustainability criterion can range between 0 (least negative impact) to 1 (most negative impact).

	Greenhouse-gas emissions (kg CO_2-e MW h^{-1})	Total score	Levelized cost of electricity	Greenhouse-gas emissions	Air pollutants	Land use	Freshwater consumption	Safety	Solid waste	Material requirements
e-Future default without nuclear	296.9	4.51	0.04	1.00	1.00	0.12	0.09	1.00	1.00	0.26
e-Future default with nuclear	105.0	2.11	0.07	0.30	0.21	0.03	0.64	0.27	0.49	0.10
e-Future maximum nuclear	102.6	1.46	0.00	0.29	0.04	0.00	0.59	0.27	0.27	0.00
WWF (including transport)[a]	32.9	1.94	1.00	0.04	0.09	0.05	0.00	0.00	0.00	0.76
WWF (excluding transport)[a]	30.4	2.71	0.94	0.03	0.07	0.06	0.60	0.02	0.00	0.99
AEMO (Scenario 1)[b]	35.8	3.93	0.88	0.05	0.62	0.68	0.38	0.07	0.57	0.68
AEMO (Scenario 2)[b]	32.2	4.16	0.59	0.04	0.79	1.00	0.36	0.08	0.8	0.49
Elliston (low cost 5%)[c]	22.6	2.41	0.70	0.00	0.01	0.21	0.51	0.02	0.14	0.82
Elliston (low cost 10%)[c]	22.0	2.46	0.70	0.00	0.00	0.23	0.53	0.03	0.16	0.81
Greenpeace (Revolution)	30.2	3.97	0.94	0.03	0.16	0.48	1.00	0.13	0.23	1.00
Seligman's energy scenario	32.6	1.90	0.84	0.04	0.06	0.05	0.18	0.02	0.00	0.71

[a] World Wildlife Fund's 100% renewable energy scenarios [17].
[b] Australian Energy Market Operator's (AEMO) 100% renewable energy scenarios [16].
[c] Elliston's (2013) renewable energy scenarios [19].

published scenarios had the lowest or highest scores across all the indicators.

Fig. 1 presents the results of the sensitivity analysis of the previously published scenarios. Here we did not consider carbon pricing for the levelized cost of electricity criterion. The published scenario analyses clearly demonstrated that none had the lowest negative impact score regardless of the socio-political perspective (weighting sets). We therefore needed to choose weighting sets carefully to reflect various socio-political perspectives to create optimized future electricity generation mixes according to socio-economic sentiment.

3.2. Electricity-generation mixes by technology options

Fig. 2 presents the influence of different technology options on future electricity generation mixes in Australia. Three sets of technology options (i) including both nuclear power and carbon capture and storage, (ii) including only carbon capture and storage (excluding nuclear power), or (iii) excluding both nuclear power and carbon capture.

3.2.1. Optimized future electricity generation mixes

The optimized scenarios including both nuclear power and carbon capture and storage recommended that nuclear power should supply >40% of total electricity generation for all scenarios (except the anti-nuclear scenario) in 2050 (Fig. 2a). Appendix E details the decade-by-decade forecast of the alternative future electricity mixes of the scenario sets presented in Fig. 2a. The economic-only scenario required the largest share of nuclear power (>75%), and the greenhouse-gas emissions reduction-only scenario required the lowest contribution (but still >40%). The equally valued, environmentalist and economic-realist scenarios required that nuclear

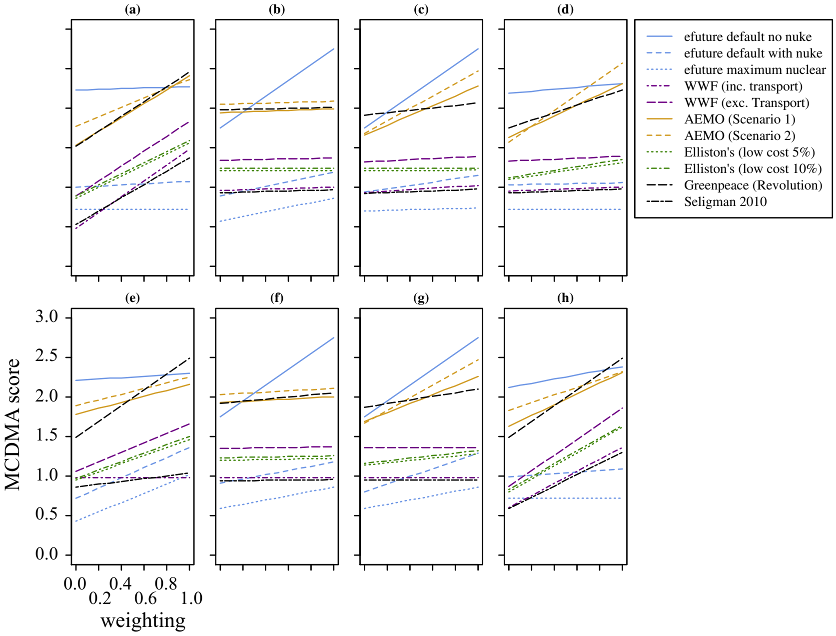

Fig. 1. Sensitivity analyses of the published future electricity scenarios for Australia, using multi-criteria decision-making analysis without carbon pricing. Sequentially, each selected indicator's weighting was changed from 0 to 1, while holding the other indicators at 0.5. The selected indicators shown in each panel are: (a) levelized cost of electricity, (b) greenhouse-gas emissions, (c) air pollutants, (d) land transformation, (e) freshwater consumption, (f) safety costs, (g) solid-waste generation, and (h) material requirements.

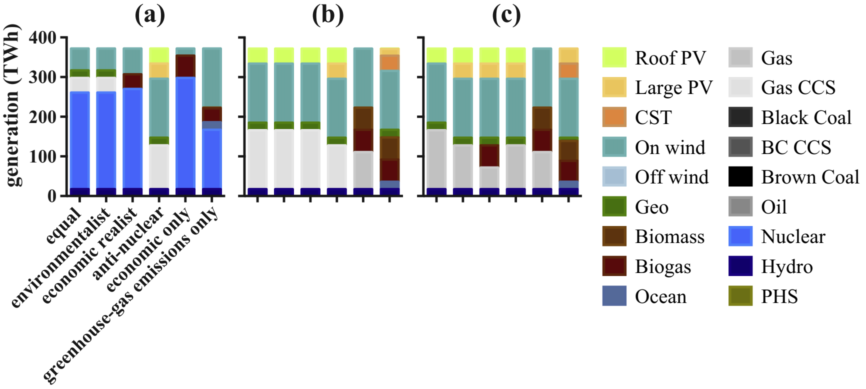

Fig. 2. Forecast of alternative future electricity mixes by types of electricity-generation sources for Australia in 2050 by 'technology options'. Each panel represents a different technology option: (a) including both nuclear power and carbon capture and storage, (b) including only carbon capture and storage, and (c) excluding both nuclear power and carbon capture and storage. *All scenarios include carbon pricing in their levelized cost of electricity, median values of renewable energy penetration limits (economic and physical) and a 20% renewable energy target (minimum renewable energy penetration). *Each column represents the different socio-political perspectives (described in Table 1).

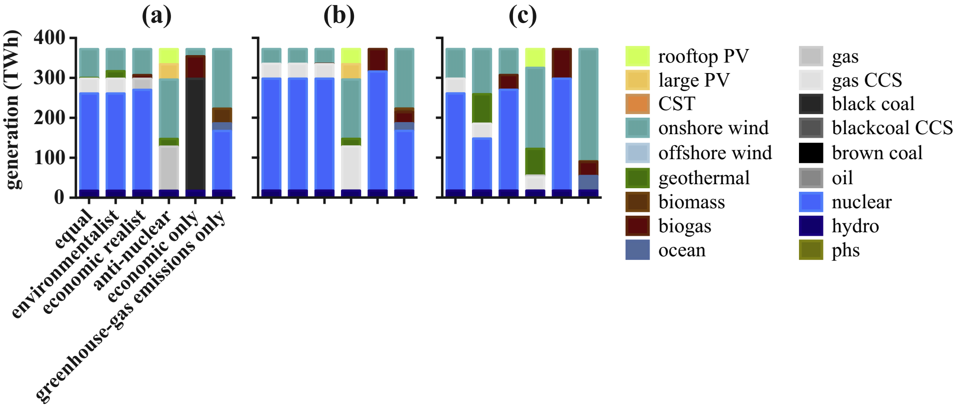

Fig. 3. Forecast of alternative future electricity mixes by type of electricity-generation source for Australia in 2050 and by 'policy option', including both nuclear power and carbon capture and storage. Each panel represents a different policy option: (a) excluding carbon pricing (includes the Government-mandated 20% renewable energy target and median values of renewable energy penetration limits), (b) a 0% renewable energy target (includes carbon pricing and median renewable energy limits), and (c) maximum values of renewable-energy penetration limits (including carbon pricing and the 20% renewable energy target). *The base-condition scenario is Fig. 2a including both nuclear power and carbon capture and storage with carbon pricing, a 20% renewable-energy target and median renewable energy limits. *Each column represents the different socio-political perspectives (described in Table 1).

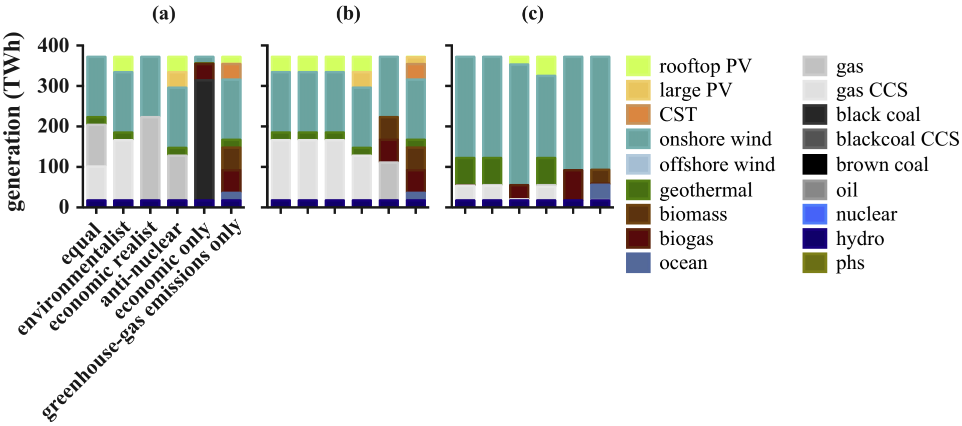

Fig. 4. Forecast of alternative future electricity mixes by type of electricity generation source for Australia in 2050 according to six alternative 'policy options'; in this case, carbon capture and storage was permitted, but not nuclear power*, as enforced by current Australian legislation. Each panel represents a different 'policy option': (a) excludes carbon pricing (including a government-mandated 20% renewable energy target and median renewable energy limits), (b) a 0% mandated renewable energy target (including carbon pricing and median values of renewable energy penetration limits), and (c) maximum values of renewable energy penetration limits (including carbon pricing and the 20% renewable energy target). *The base-condition scenario is Fig. 2b includes only carbon capture and storage (excluding nuclear power) with carbon pricing, a 20% renewable energy target and median renewable energy limits. *Each column represents the different socio-political perspectives (described in Table 1).

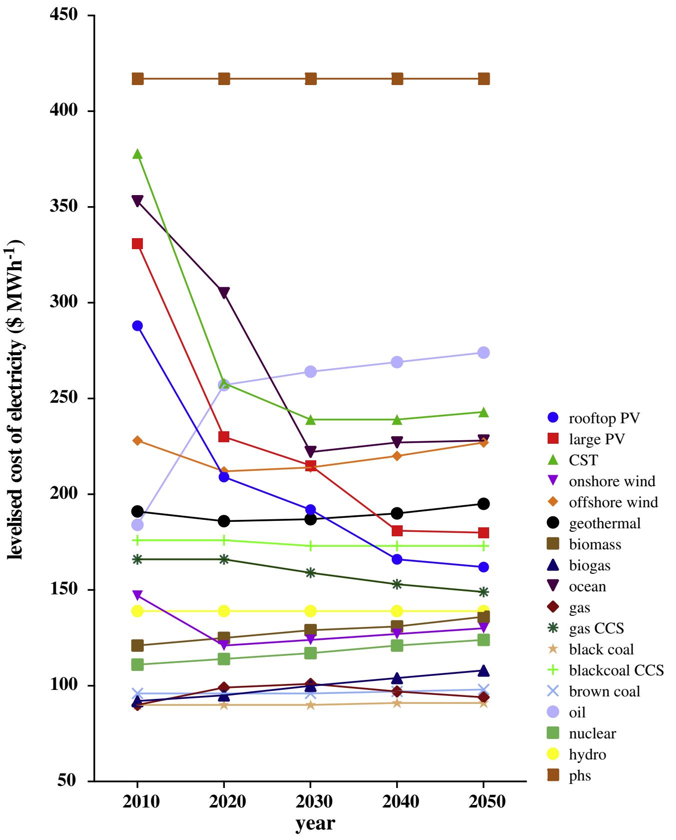

Fig. A.1. Levelised cost of electricity (median values) without carbon pricing from 2010 to 2060 for the current potential electricity generation sources in Australia.

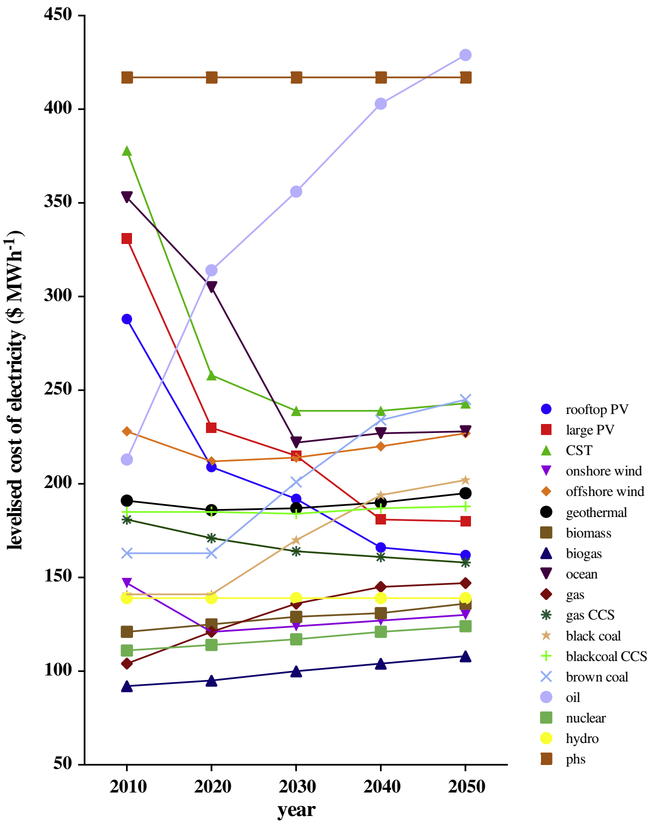

Fig. A.2. Levelised cost of electricity (median values) with carbon pricing from 2010 to 2060 for the current potential electricity generation sources in Australia.

power supply between 65% and 68% of total electricity. By contrast, fossil fuels (gas power with carbon capture and storage) supplied about 30% of the electricity consumption in the anti-nuclear scenario (highest). Renewable sources also expanded across all scenarios, supplying about 70% of total electricity consumption in the anti-nuclear scenario, and <60% in the greenhouse-gas emissions reduction-only scenario. The other scenarios relied on about 25% renewables for their electricity consumption. Of the component renewable technologies, onshore wind power and bioenergy provided >45% of renewable energy penetration.

All scenarios with nuclear power (i.e., except the anti-nuclear) emitted <50 kg CO_2-e MW h^{-1} (the lowest IPCC guideline) in 2050 [84]. The anti-nuclear scenario emitted the highest greenhouse gases per unit energy produced (60.1 kg CO_2-e MW h^{-1}), and the greenhouse-gas emissions reduction-only scenario emitted the lowest (14.0 kg CO_2-e MW h^{-1}). The anti-nuclear scenario also had the highest levelized cost of electricity ($150.4 MW h^{-1}), whereas the economic-only scenario had the lowest ($122.6 MW h^{-1}), followed by the economic-realist scenario ($124.1 MW h^{-1}). On the contrary, the economic-only (>75% nuclear power) and the economic realist scenarios (>65% nuclear power) emitted only 15.9 and 14.4 kg CO_2-e MW h^{-1}, respectively, and had the lowest and the second-lowest levelized cost of electricity, respectively.

3.2.2. Nuclear-free scenarios

Optimizations based on the nuclear-free scenarios (including only carbon capture and storage) typically required a contribution of between 25% and 40% fossil-fuel sources (gas with carbon capture and storage) (Fig. 2b). The economic-only and the greenhouse-gas emissions reduction-only scenarios did not employ carbon capture and storage. All these scenarios increased renewables >18% above the same scenarios with nuclear power. Renewables supplied 100% of the electricity consumption of the greenhouse-gas emissions reduction-only perspective, >74% of the economic-only scenario and >70% of the anti-nuclear scenario. The renewable energy shares of the other three scenarios were 60%.

Despite the higher renewable energy share, all scenarios excluding nuclear power emitted more greenhouse gases (due to a dependence on fossil-fuel backup sources), and had higher levelized cost of electricity (due to renewables), compared to the scenarios that included nuclear. These nuclear-free scenarios emitted between 10.2 (greenhouse-gas emissions reduction-only) and 121.4 kg CO_2-e MW h^{-1} (economic-only) more greenhouse gases than the same scenarios with nuclear power. None of the scenarios (excluding the greenhouse-gas emissions-reduction-only scenario) emitted greenhouse gases below the lowest IPCC guidelines [84]. In cost terms, the economic-only scenario required $9.5 MW h^{-1} (lowest) more than the same scenario with nuclear power, and the greenhouse-gas emissions-weighted scenario required $19.2 MW h^{-1} (highest) more.

3.2.3. Carbon capture and storage

Although the scenarios excluding nuclear power appeared to emit lower greenhouse-gas emissions than the current condition, gas power with carbon capture and storage provided a noticeable share of electricity (between 25% and 40%) in 2050. However, carbon capture and storage remains economically and technologically unproven [85] and there are safety concerns regarding the long-term security of the geological CO_2 reservoirs [86,87]. Therefore, here we modeled the same nuclear-free scenarios without carbon capture and storage to examine the worst-case scenario (Fig. 2c). Note that we excluded the economic-only and the greenhouse-gas

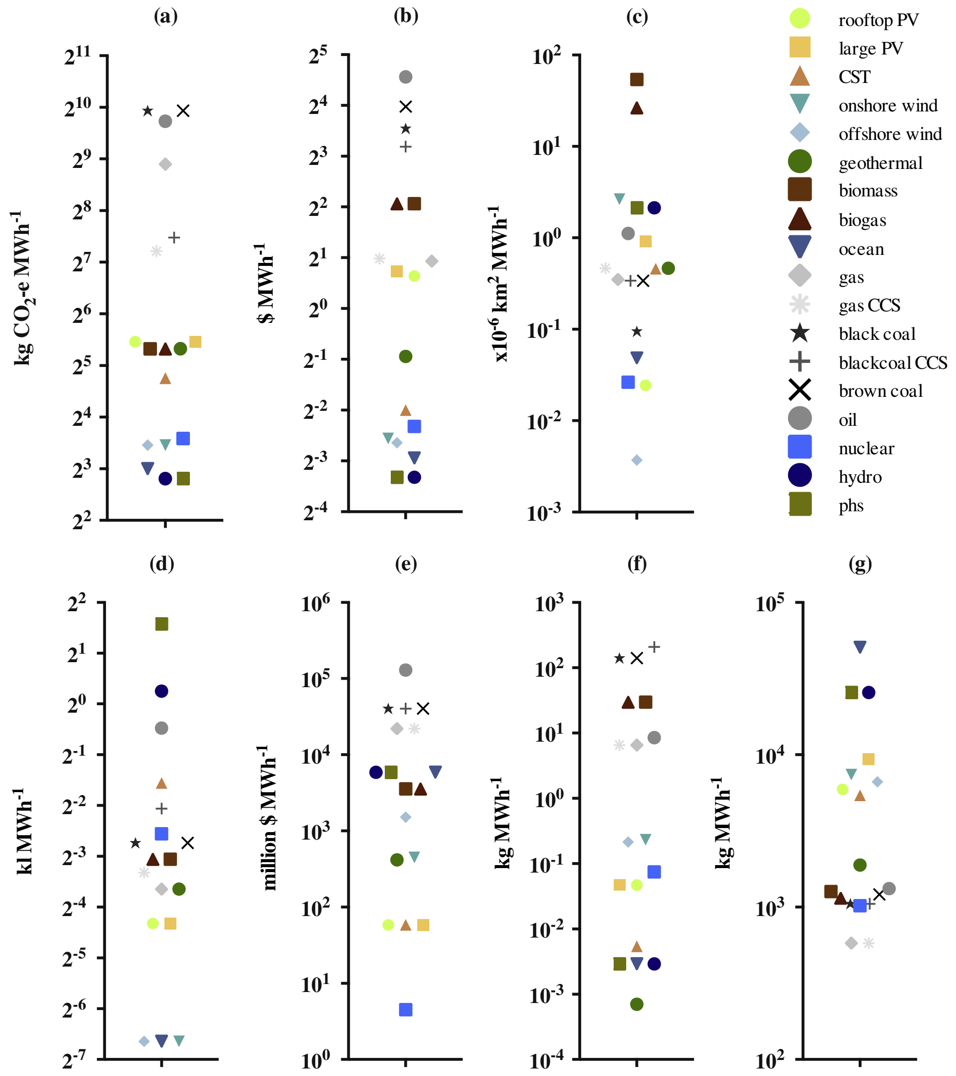

Fig. A.3. Cost and sustainability indicator values (median values) for multi-criteria decision-making analysis, by electricity-generation source: (a) greenhouse-gas emissions, (b) air pollutant damage costs, (c) land transformation, (d) freshwater consumption, (e) safety costs, (f) solid-waste generation, and (g) material requirements.

emissions reduction-only scenarios for this analysis, because neither scenario had carbon capture and storage penetration in any conditions.

Compared with the nuclear-free scenarios including carbon capture and storage, the environmentalist and economic-realist scenarios reduced fossil-fuel shares from 40.1 to between 29.8% and 14.8% in 2050, respectively via renewables. All nuclear-free scenarios without carbon capture and storage were the least costly compared to those that included it, due to the higher system cost of implementing carbon capture and storage. However as a result, all scenarios experienced increased total greenhouse-gas emissions, despite increased renewable shares. The economic-realist scenario emitted 92.3 kg CO_2-e MW h^{-1} of greenhouse gases, the anti-nuclear and the environmentalist scenarios emitted 158.1 kg CO_2-e MW h^{-1}, and the equally valued scenario emitted 202.3 kg CO_2-e MW h^{-1}.

For scenarios without nuclear or carbon capture and storage, renewable energy is required to take up the full burden of replacing fossil fuels to reduce emissions. However, renewables were not able to supply 100% of electricity consumption while maintaining low costs. Traditional fossil fuels thus generated >15% of the total electricity consumption in these cases.

3.3. Electricity generation mixes by policy options

The physical (intermittency and distribution) and economic (high electricity cost) limits of renewable energy sources are critical barriers to higher renewable penetrations. However renewables-friendly policies (carbon pricing, and a renewable energy target) also can increase renewable-energy penetration. Here, we analyzed the influence of the policy barriers and opportunities (Fig. 3).

3.3.1. Carbon pricing

Carbon pricing did not affect the total share of ‘zero-emission’ options (renewables and nuclear power) in the nuclear scenarios, except the economic-only scenario (Fig. 3a). Interestingly, carbon pricing did not invoke carbon capture and storage for any scenario that included nuclear power. The economic-only scenario without carbon pricing emitted 746.4 kg CO_2-e MW h^{-1} of life-cycle greenhouse gases, mainly from traditional coal (>75%), whereas the scenario with carbon pricing emitted about 15.9 kg CO_2-e MW h^{-1}. The other scenarios with nuclear power emitted <47.3 kg CO_2-e MW h^{-1}, regardless of the implementation of carbon pricing.

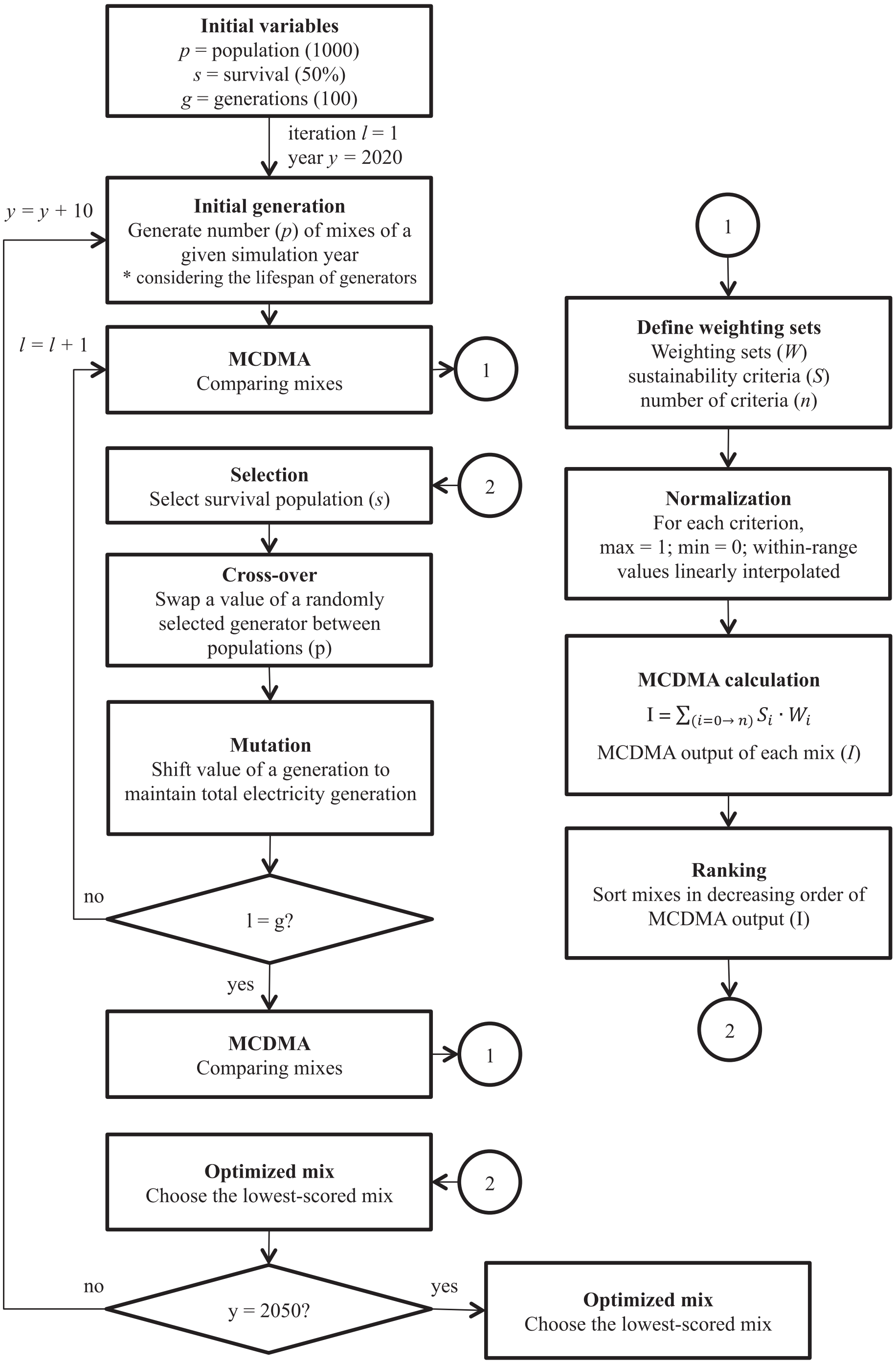

Fig. B.1. Detailed flow chart describing the optimization of Australia's energy system using a genetic algorithm, underpinned by a multi-criteria decision-making analysis

Carbon pricing affected the emissions from the scenarios without nuclear power because renewables failed to supply 100% of electricity generation, and fossil fuels (with or without carbon capture and storage, depending on scenario) filled the remainder (Fig. 4a). The equally valued (172.4 kg CO_2-e MW h^{-1}), economic-realist (268.9 kg CO_2-e MW h^{-1}), anti-nuclear (158.1 kg CO_2-e MW h^{-1}), and economic-only scenarios (786.9 kg CO_2-e MW h^{-1}) without carbon pricing had higher emissions than the highest IPCC guidelines.

3.3.2. Renewable energy target and limits

The renewable energy target did not exert a noticeable influence in any scenario (Fig. 3b). Onshore wind power scored better according to MCDMA than fossil fuels (except for levelized cost of electricity), so total renewable shares (mostly onshore wind) on each scenario exceeded the renewable energy target (20%). The physical and economic limits of renewable energy penetration shifted the shares within 'zero-emission' options (nuclear power and renewables) when nuclear power is permitted (Fig. 3c). For example, wind power generated about 75% of the total electricity consumption of the greenhouse-gas emissions reduction-only scenario with maximum renewable energy limits, while the identical scenario with the median renewable energy limits required about 40% wind power and nuclear to supply the remainder. However, renewable energy limits affected scenarios without nuclear power more (Fig. 4c). Onshore-wind power supplied >70% of the total

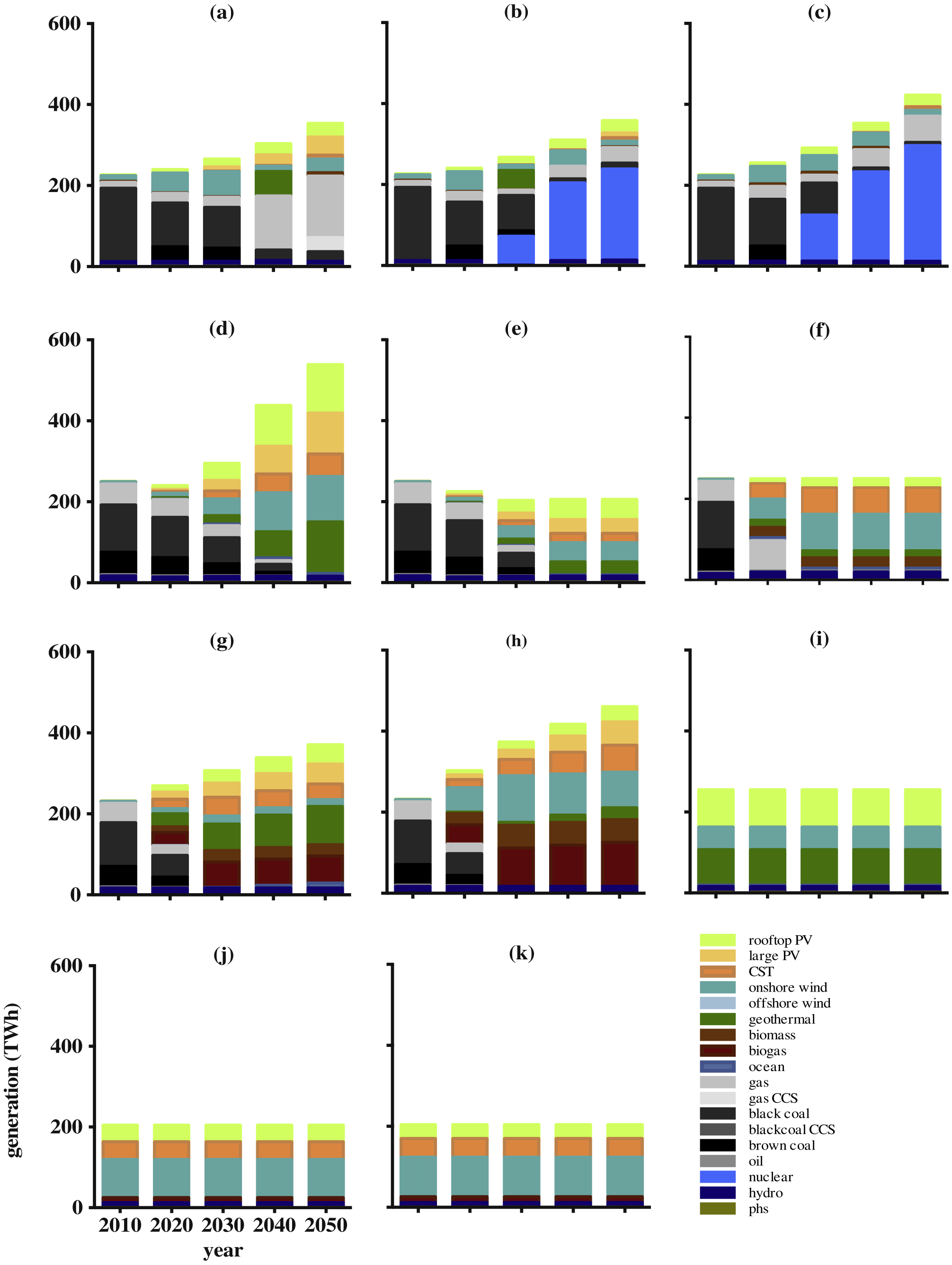

Fig. C.1. Electricity generation mixes of published future scenarios for Australia in the year 2050: (a) *e-future* default without nuclear power [15], (b) *e-future* default with nuclear power [15], (c) *e-future* maximum nuclear power [15], (d) World Wildlife Fund (WWF)'s renewable scenario (including transport) [17], (e) WWF's renewable scenario (excluding transport) [17], (f) Greenpeace's Energy Revolution [18], (g) Australian Energy Market Operator's (AEMO) renewable scenario (case 1) [16], (h) AEMO's renewable scenario case 2 [16], (i) Seligman's energy scenario [20], (j) Elliston's scenario (low cost 5%) [19], and (k) Elliston's scenario (low cost 10%) [19]. *For those scenarios whose final year is earlier than 2050 (World Wildlife Fund's 100% renewable energy scenario excludes transport, Elliston's scenarios, Greenpeace's scenario, and Seligman's scenarios), the electricity generation mix of the last scenario year is applied through to 2050.

electricity generation of the scenarios (without nuclear power) with maximum renewable limits.

4. Discussion

In those future Australian energy scenarios in which nuclear power is permitted, lower emissions and costs inevitably result. While total system emissions of the nuclear-free scenarios that included carbon capture and storage were reduced, these scenarios were substantially more costly than those without carbon capture and storage. Moreover, most scenarios that used neither nuclear power nor carbon capture and storage emitted a large amount of greenhouse gases (>150 kg CO_2-e MW h^{-1}), and at the extreme end of the spectrum, the anti-nuclear scenario resulted in both the highest electricity cost and the worst emissions intensity. By contrast, the scenarios with nuclear power emitted negligible emissions (<26.6 kg MW h^{-1}) for less cost (<\$132.6 MW h^{-1}) compared to any other scenario. It is essential to remember that these comparisons include the other components of the MCDMA such as

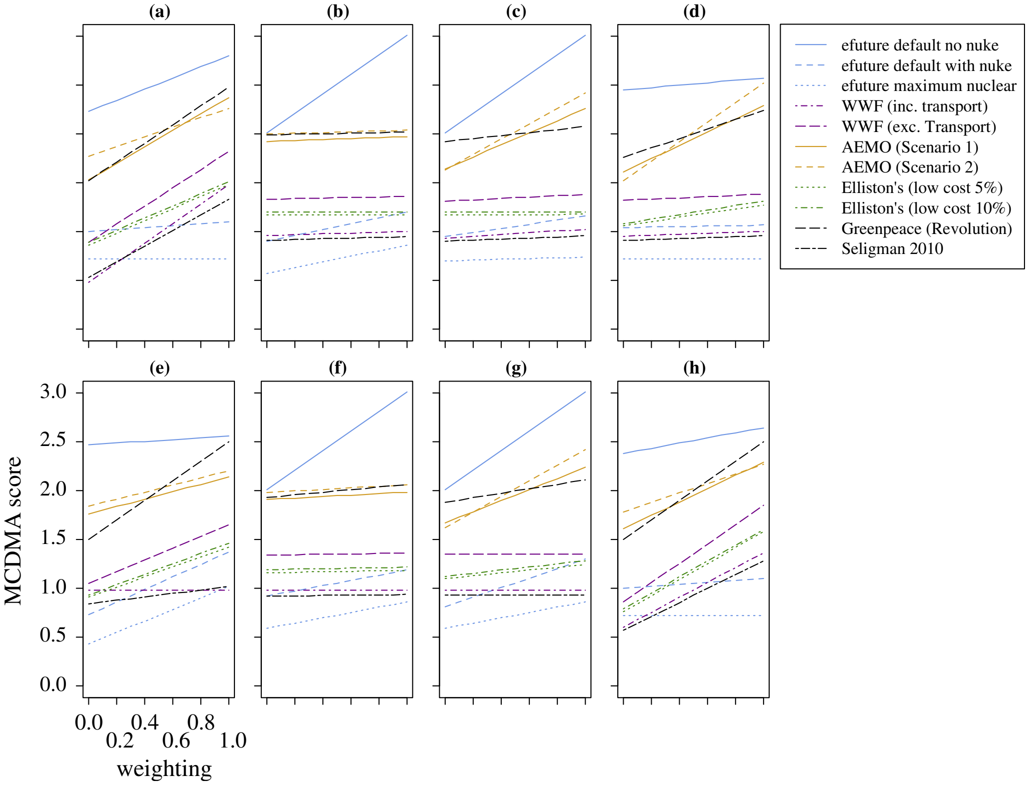

Fig. D.1. Sensitivity analyses of the published future electricity scenarios for Australia, using multi-criteria decision-making analysis with carbon pricing. Sequentially, each selected indicator's weighting was changed from 0 to 1, while holding the other indicators 0.5. The selected indicators shown in each panel are: (a) levelized cost of electricity, (b) greenhouse-gas emissions, (c) air pollutants, (d) land transformation, (e) freshwater consumption, (f) safety costs, (g) solid-waste generation, and (h) material requirements.

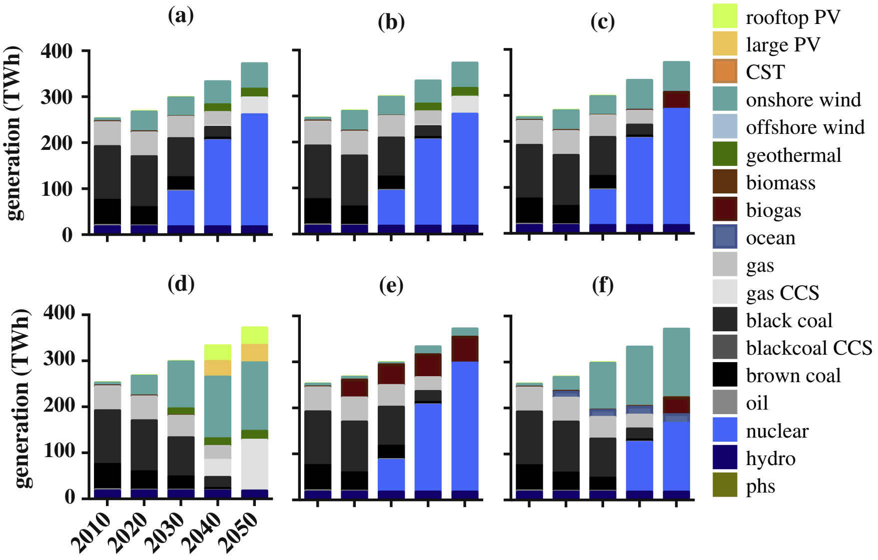

Fig. E.1. Decade-by-decade forecast of alternative future electricity mixes (Fig. 2(a)) by types of electricity generation sources for Australia between 2010 and 2050, under the assumption of median renewable energy limits (economic and physical) and a 20% renewable energy target. Each panel represents a different 'social weighting' for the indicators shown in Table 1: (a) all equally valued, (b) environmentalist, (c) economic realist, (d) anti-nuclear, (e) economic only, and (f) greenhouse-gas emissions reduction-only perspectives.

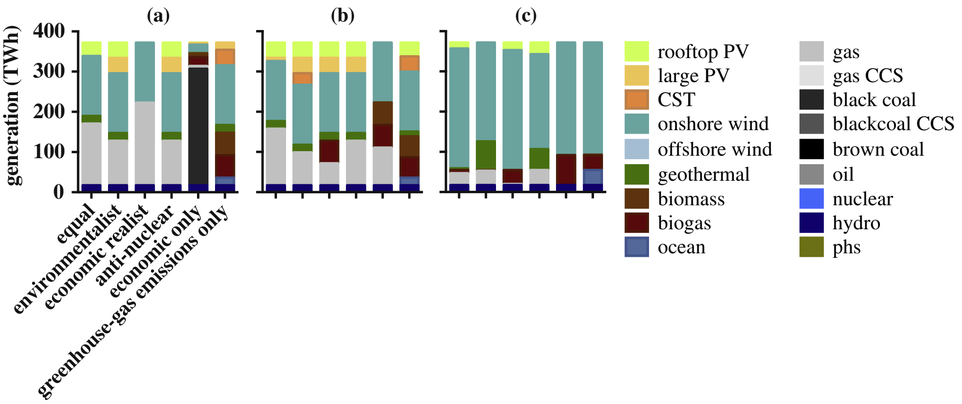

Fig. F.1. Forecast of alternative future electricity mixes by types of electricity generation sources for Australia in 2050 by 'policy options', exclude both nuclear power and carbon capture and storage. Each panel represents a different 'policy option': (a) excludes carbon pricing (includes 20% renewable energy target and median renewable energy limits), (b) a 0% renewable energy target (includes carbon pricing and median renewable energy limits), and (c) maximum renewable energy limits (includes carbon pricing and 20% renewable energy target). The base-condition scenario is Fig. 2c excludes both nuclear power and carbon capture and storage with carbon pricing, a 20% renewable energy target and median renewable energy limits. Each column represents the different socio-political perspectives (described in Table 1).

safety, land use and other concerns associated with each electricity-generation source.

Higher technological and economic renewable limits could increase wind power penetration to >70% of total electricity consumption. However, generating 70% of electricity consumption from wind power is economically and practically unrealistic, due to increasing grid-management and supply–demand problems once intermittent renewable energy sources reach high penetration [88]. Additionally, since both wind and nuclear, which had the highest electricity generation for all scenarios, emit <12 kg CO_2-e, the changes within the options did not affect the greenhouse-gas emissions noticeably. Therefore, to minimize the influences of political or economic changes, or technological failure to meet policy goals, nuclear power appears to be an essential future requirement for Australia, and indeed for any developed nation.

Having examined objectively a wide range of published future electricity-generation scenarios for Australia that cover various socio-economic perspectives, we reached four main conclusions: (i) nuclear power is essential for reducing greenhouse-gas emissions for the lowest cost, (ii) wind power has a lower MCDMA score than fossil fuels (with carbon pricing), but its physical and economic limits at high penetrations hamper ultimate growth, (iii) massive fossil-fuel generation (with/without carbon capture and storage) is required if nuclear power is not permitted in Australia, and (iv) a perspective based on well-balanced information is a prerequisite for defining an optimal future electricity-generation mix that is able to balance the trade-off between lower cost and greater reductions in greenhouse-gas emissions. We emphasize that although we have applied the approach to the Australian situation as a detailed case study, it can be easily tailored to any other nation using local and context-specific sustainability criteria.

An energy-development pathway emphasizing or preferring renewable energy a priori cannot solve the spectrum of economic, environmental and social challenges facing Australia's electricity-generation future. Our approach provides for future electricity-generation mixes tempered by socio-political perspectives, and is the first transparent and objective analysis of Australia's future energy mix that allows for fair competition among all viable technologies. Despite the uncertainties, our analyses demonstrate clearly that nuclear power, along with some renewable penetration, can reduce greenhouse-gas emissions to the level required to meet climate change-mitigation goals, for the lowest relative cost. For a strong economy that simultaneously mitigates climate change, nuclear power should be considered as an essential component in Australia's future electricity-generation mix.

Appendix A. Indicator values for multi-criteria decision-making analysis (MCDMA)

See Figs. A.1–A.3.

Appendix B. Flow chart of the energy-system optimization process

See Fig. B.1.

Appendix C. Published scenarios

See Fig. C.1.

Appendix D. Sensitivity analysis of the published scenarios with carbon pricing

See Fig. D.1.

Appendix E. Detailed future electricity mixes by year

See Fig. E.1.

Appendix F. The impact of policy options on future electricity scenarios without both nuclear power and carbon capture and storage

See Fig. F.1.

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