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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.