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Global zero-carbon energy pathways using viable mixes of nuclear and renewables

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HIGHLIGHTS

- A proper mix of nuclear power and renewables achieves sustainable energy future.
- A high nuclear share provides cost and land effectiveness compared to nuclear-free.
- Only-renewable mix will increase negative economic and environmental impacts.
- A deployment of advanced reactor technologies is essential to overcome limitations.

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ABSTRACT

What are the most viable global pathways for a major expansion of zero-carbon emissions electricity sources given the diversity of regional technical, socio-political and economic constraints? We modelled a range of zero-emissions energy scenarios across nations that were designed to meet projected final energy demand in 2060, and optimised to derive the best globally aggregated results in terms of minimising costs and land use (a surrogate for environmental impacts). We found that a delayed energy transition to a zero-emissions pathway will decrease investment costs (−\$3,431 billion), but increase cumulative CO_2 emissions (additional 696 Gt). A renewable-only scenario would convert >7.4% of the global land area to energy production, whereas a maximum nuclear scenario would affect <0.4% of land area, including mining, spent-fuel storage, and buffer zones. Moreover, a nuclear-free pathway would involve up to a 50% greater cumulative capital investment compared to a high nuclear penetration scenario (\$73.7 trillion). However, for some nations with a high current share of renewables and a low projected future energy demand (e.g., Norway), pursuit of a higher nuclear share is suboptimal. In terms of the time frame for replacement of fossil fuels, achieving a global nuclear share of about 50% by 2060 would be a technically and economically plausible target if progressing at a pace of the average historical growth of nuclear power penetration in France from 1970 to 1986 (0.28 MWh person^{-1} year^{-1}). For effective climate-change mitigation, a high penetration of nuclear in association with a nationally appropriate mix of renewables achieves far superior cost and land effectiveness compared to a renewables-only future to reduce emissions.

1. Introduction

The emissions of greenhouse gases from fossil fuels, which currently supply >80% of the world's energy consumption (358 exajoules [EJ] in 2011), must be reduced substantially and urgently for effective climate-change mitigation [1–3]. Globally, fossil-fuel consumption emitted about 31 gigatonnes of carbon dioxide (Gt CO_2) in 2011, with coal accounting for the largest share of emissions (44%) by providing 29% of total primary energy supply [1]. To avoid dangerous global temperature rise and the risk of additional feedbacks in the climate system, recent work suggests society should target a total cumulative global emissions of <1 trillion tonnes of CO_2 (270 Gt C) by 2100, with the long-range goal of reducing atmospheric CO_2 to <350 ppm (ppm) [4,5]. In this context, a large expansion of zero-emission sources such as nuclear power (2% of the global final energy consumption in 2011) and renewable resources (17%, including hydroelectric power and traditional fuels such as animal products and wood), as well as

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on-going efficiency improvements, will be needed to replace existing fossil-fuels.

Energy efficiency in both production and consumption, combined with widespread deployment of various renewables (principally wind, solar and engineered geothermal), are widely touted by environmental advocacy organisations as the only appropriate pathway for replacing global consumption of fossil fuels, and even nuclear power [6–9]. However, it is unlikely that energy efficiency alone will have much impact on greenhouse-gas emissions because of increasing energy demand associated with the economic growth of developing countries, continued growth of the human population [10–12], and the well-documented 'rebound effect' (Jevon's paradox) in more developed economies whereby gains in efficiency are offset by increased consumption or new uses for energy [13,14]. Decreased energy prices due to conservation technologies can also increase energy consumption, thus the effectiveness of energy efficiency technologies will be limited [14].

Although there is a theoretical potential for renewable energy resources to supply global energy demand [15,16], the real-world limitations of renewables, such as economic cost, land transformation, intermittency, scalability, energy storage, long-distance transmission and geographical distribution, put serious constraints on the plausibility of high renewable penetration [17–21]. Nuclear power is a viable, large-scale, low-emissions option [17–19,22]; however, after the Fukushima-Daiichi nuclear accident associated with the Tohoku earthquake and tsunami in Japan in March 2011, the governments of Germany, Switzerland, Italy and Belgium announced plans to phase out nuclear power or reduce their nuclear penetration. This involved pathways that allowed a higher share of fossil fuels to fill a reduced nuclear-power share, resulting in an increase in emissions intensity [23–25]. Given these limits and policies, four prominent climate scientists recently urged decision makers to pursue an increased penetration of nuclear power to reduce greenhouse-gas emissions from the energy sector, and to mitigate other negative sustainability impacts such as air pollution [26]. Brook [3] also argued that nuclear-fission energy is a proven, scalable and economically attractive option for decarbonizing energy sectors [27–29], and showed how the technology could supply half of global final energy demand by 2060. In a follow-up analysis, Brook and Bradshaw [10] also demonstrated that from the perspective of minimising humanity's footprint on biodiversity and land conservation, increasing nuclear power penetration would have major benefits for global ecosystem integrity.

Here we evaluate the possibilities, barriers and solutions towards global pathways of zero-emissions energy mixes by 2060. We used regional and economic breakdowns to compare a range of future energy mixes with different shares of nuclear power (ranging from 0% to 100%) among nations and economic groups and a portfolio of renewable sources. Based on this objective and transparent analysis, we show that a >50% global penetration of nuclear power is technically and economically viable, and desirable to mitigate anthropogenic climate disruption and other negative environmental and economic phenomena.

2. Assumptions and methodology

2.1. Demand assumptions

For energy demand, we applied the 'new-policies scenario' from the *World Energy Outlook* report prepared by the International Energy Agency (IEA) [2]. The IEA report considers both energy production- and demand-side management to model future energy demand until 2035. The new-policies scenario is the main scenario of the IEA, and it includes full implementation of a range of energy-related polices that have been announced or planned in recent years. We extended that time frame by simple forward (linear) projection of the increasing or decreasing rate of the scenario through to 2060 (694 EJ in 2060). We assumed a highly electrified future energy system by 2060, because electricity can be transformed readily into other forms of energy including heat, mobility, light, etc. [30]. Beyond this convenience, a highly electrified future energy system is desirable on environmental, social and health grounds [31]. In our scenario, electricity constitutes >88% (185,132 TW h, including about 10% electricity loss) of the global final energy consumption, whereas the non-energy use of resources, such as oil and coal products, remains at the current level (34 EJ) through to 2060.

We also compared three different deployment pathways: early, linear and late deployment of zero-emission sources (including both nuclear and renewables) to quantify the impact of the delayed transition on capital investment and greenhouse-gas emissions. The early-deployment pathway assumes a complete phase-out of fossil fuels for energy by 2050, excluding non-energy use of fossil resources. Although both the linear- and late-deployment pathways also assume the complete phase-out of fossil-fuels for energy by 2060, the former reduces fossil-fuel consumption linearly from 2011 to 2060, whereas the latter relies heavily on fossil fuels through to 2030 (>58% of the final energy consumption) due to the delayed action arising from some combination of political inertia, explicit anti-nuclear or fossilfuel-friendly policies [23–25], insufficient awareness of the socio-economic risks posed by climate-change impacts [32], and/or delayed technological improvement and inertia of energy systems [21,33].

Because there is no scientific consensus or real-world deployment data on 'optimal', high-penetration renewable energy mixes, here we assumed a fixed, balanced renewable-energy portfolio that included 20% from bioenergy, 20% from concentrated solar thermal, 20% from photovoltaic, 20% from wind power, 10% from hydroelectric power and 10% from geothermal. Although a high bioenergy share is unlikely and undesirable from an environmental perspective, this actually remains a key assumption in most '100% renewable energy' scenarios that have been released, including the Greenpeace Energy [R]evolution 2012 [34] and the 2012 Australian Energy Market Operator assessment for Australia [35]. In both of these published, refereed examples, bioenergy contributes >20% of total energy supplied. We also assumed that the energy derived from traditional renewable resources (e.g., animal products and woods) could in the future be converted to more sustainable systems such as wind, solar, geothermal or advanced bioenergy without additional costs. We assumed that renewable energy could track energy consumption by the use of smart grids with some combination of plug-in electric vehicles, storage and geographically distributed networks. However, we did not include in our analysis the cost of commercial-scale electricity storage (e.g., pumped-hydro or compressed-air storage) and its land use, nor the additional transmission cost, land use or smart-grid facilities required for geographically distributed networks. In terms of low-emissions fossil fuels, some have touted carbon-capture-and-storage as a potentially important technology [36]. However, we did not consider its deployment in our scenarios due to its unresolved safety issues (involving leakage and seismic disturbance), environmental concerns, and unproven technological maturity and cost implications (e.g., it would, *a priori*, require a strong carbon price) [37].

2.2. Sustainability assessment

We used the capital investment per unit power capacity of each system (2005 US$ kW^{-1}) and capacity factors from the IEA's *Energy Technology Perspectives* [38] to account for the required cumulative capital investment (overnight costs) of each system and an entire energy network (Appendix A) between 2011 and 2060. We extended the cost-reduction timeframes by simple (linear) forward projection of the cost trend of each system by 2060. We only considered the cost for power plant construction, but not the additional costs such as fuels, management, decommissioning, large-scale energy storage, transmission and required backup utility for intermittent sources. The current average capacity factor of renewables without hydropower is 0.22, but the average capacity factor of our analysis was about 0.46 due to assumed improvements in on-site energy storage (e.g., via solar thermal heat) and wider use of utility-scale chemical storage or synfuels conversion.

We calculated greenhouse-gas (carbon dioxide equivalents: CO_2-e) emissions from fossil-fuel combustion, but not the life-cycle (embodied) emissions from fossil fuels or alternative resources including nuclear and renewable energy resources because this is tied intimately to the carbon intensity of the underpinning future economy. We also calculated cumulative greenhouse-gas emissions per unit electricity generated by dividing the cumulative emissions by the cumulative electricity generated between 2011 and 2060, and emissions per capita by dividing the cumulative emissions by the average population size between 2011 and 2060. To calculate the required land area converted for renewable energy systems (excluding bioenergy and hydroelectric power), we only considered the land area for power plants. For bioenergy, we included land area for power plants together with bio-crop cultivation area, and for hydroelectric power, we included land area for power plants as well as the drainage watershed area. For nuclear power, we included the land area for power plants and related actions including uranium mining, nuclear spent-fuel storage and buffer zones (non-residential area surrounding nuclear facilities for security and safety reasons) [6,39–42]. Although some renewable energy systems can be installed in urban areas or offshore such that they have lower land-transformation impacts, the required minimum land area is not sufficient to provide the entire energy consumption from renewable energy sources in many European and Asian countries. Moreover, even if power plants were located in remote areas like mountains or offshore, environmental impacts on the surrounding ecosystems due to the land changes, road building, transmission lines, water use, and so on, would need to be considered carefully [9,43,44]. We calculated the carbon-abatement intensity (kg $\$^{-1}$) that examines the effectiveness of the capital investment to reduce the greenhouse-gas emissions compared to the *status quo* mix with the new-policies demand scenario by 2060. A mix with the higher carbon-abatement intensity requires less capital investment while reducing the same quantity of greenhouse-gas emissions, or reduces more greenhouse gases while requiring the same amount of capital investment.

2.3. Modelling

We modelled future electricity mixes using a combination of two different methods: (*i*) generating 101 mixes by allocating an equal share of nuclear to all nations ranging from 0% to 100% at 1% increments, and (*ii*) generating an additional 1000 mixes by allocating a randomly drawn nuclear share (0%, 25%, 50%, 75%, and 100%) to each country. This combination allows extreme cases (the former) along with uniformly distributed future electricity mixes (the latter). We also considered a set of limitations to examine critical cases, including (*i*) the maximum nuclear-penetration limits following the historical experience of one nation (France) between 1970 and 1986 (0.28 MWh person^{-1} year^{-1}), (*ii*) the minimum nuclear energy share (current nuclear penetration share will remain until 2060) and (*iii*) the minimum renewable energy share (assuming current renewable penetration shares will remain a static proportion) in 2060. We applied the maximum nuclear penetration limits to the final energy consumption of either each nation or the entire world in 2060. Although we acknowledge that the life cycle of renewable infrastructure is typically <30 years (except hydroelectric power), here we assume that currently installed renewable power plants remain until 2060 for applying the minimum renewable energy share limits. Some ageing nuclear power plants also need to be replaced, but we do not consider the replacement costs because recent experience in the U.S. has shown that the life cycle of older nuclear power plants can usually be extended for two decades at <10% of the installation costs [45,46]. We then applied all possible combinations of the three limitations to model the future electricity mixes.

We also selected five geographic and/or economic national groupings, comprised of countries at approximately the same wealth and development stages, as well as 16 individual countries, to examine the impact of each country's penetration share of nuclear power or renewable energy on the economic and environmental sustainability of the future global energy network. The economic groupings include the European Union and Organization for Economic Co-operation and Development (EU/OECD), Brazil, Russia, India, China, South Africa (BRICS), the Association of Southeast Asian Nations (ASEAN), the Organization of Petroleum Exporting Countries (OPEC), and other nations (OTHER). To select a representative sample of individual countries for our analysis, we examined a range of characteristics to maximise the variation in possible energy mixes. These characteristics included: (*i*) the current major electricity sources (nuclear, renewable or fossil fuels), (*ii*) population density (high or low), and (*iii*) projected future energy consumption (high or low) (see Appendix B for selection detail). Our final selection comprised Australia, Brazil, Canada, China, Denmark, France, Germany, India, Indonesia, Japan, South Korea, New Zealand, Norway, Russia, Sweden, and USA.

3. Results

3.1. Capacity analysis

With higher shares of renewable energy sources came an increase in potential peak power supply due to the low capacity factors of renewable systems, whereas a higher nuclear share reduced the total required installed capacity. The 100% nuclear-share mix would require a nuclear power capacity of 24.9 TW in 2060, whereas the nuclear-free mix would require renewable power capacities of 45.4 TW. Using the average growth of nuclear penetration in France from 1970 to 1986 (0.28 MWh person^{-1} year^{-1}) [1] as the maximum growth rate of nuclear power penetration for each country with sufficient capacity for nuclear power [47], we estimated that the global maximum nuclear share could be as much as 49.2% (12.2 TW of nuclear and 23.1 TW of renewable capacities) of the total electricity generation in 2060 (>88% of total final energy consumption). Although the high-nuclear pathway is ambitious, it is feasible compared with the average penetration growth rate of nuclear capacity in the historical energy development of countries like South Korea and Sweden. The peak growth rate was 0.33 MWh person^{-1} year^{-1} in 2005 when the economic capacity (GDP) was <40% of France. South Korea recorded a higher person^{-1} year^{-1} nuclear-penetration growth rate in 1986 and 1987 when the national economic capacity was <20% of France. Sweden recorded 0.44 MWh person^{-1} year^{-1} of the average growth rate between 1970 and 1991. Therefore, it is clear that the economic and technical capacity of a country is not a consequential barrier, and that deployment rates are largely dictated by socio-political considerations [48]. Global maximum nuclear penetration could increase to 58% by applying the average growth rate of nuclear penetration (0.28 MWh person^{-1} year^{-1}) to global electricity generation in 2060. The maximum limit of global nuclear would be about 97.6% of the total electricity consumption in 2060 should the current minimum renewable penetration share remain fixed until 2060. On the contrary when the current nuclear penetration share remains until 2060, the maximum renewable penetration would be limited to 98.6% (1.4% of nuclear penetration) in 2060.

3.2. Greenhouse-gas emissions

Compared to the early-deployment pathway (cumulative emissions of 428 Gt between 2011 and 2060), the late-deployment pathway of large-scale zero-carbon energy sources would emit an additional 698 Gt CO_2 from final energy consumption by 2060. Unlike the new-policies scenario, none of the modelled heavy mitigation pathways (early, linear and late) would exceed the maximum likely range (between 0% and 95% confidence interval) of emissions considered in the IPCC RCP2.6 scenario (cumulative fossil-fuel emissions between 513 and 1503 Gt CO_2 between 2012 and 2100). Our modelled scenarios could not be compared directly with the IPCC RCP2.6 scenario due to the different time frames. However, since our modelled scenarios assumed earlier and deeper decarbonisation from the global energy sector than RCP2.6, these pathways would likely result in <1.7 °C of global mean surface temperature increase by 2100 compared to the average surface temperatures between 1986 and 2005 based on recent climate-model forecasting (see Fig. 1).

EU/OECD countries would emit the largest cumulative CO_2 between 2011 and 2060 (347.7 Gt CO_2 from final energy consumption based on the linear-deployment pathway), and ASEAN countries would emit the lowest (18.2 Gt CO_2) (Fig. 2). EU/OECD under the late-deployment pathway would emit even more CO_2 (509.7 Gt CO_2) than the cumulative global emissions of the early-deployment pathway (428.2 Gt CO_2). Although final energy consumption of BRICS in 2060 (328.2 EJ) would be twice that of EU/OECD (152.2 EJ), the current lower energy consumption of BRICS and the early decarbonisation of the energy sector (120.4 EJ in 2011) would result in lower cumulative emissions (263.0 Gt CO_2, based on the linear-deployment pathway). ASEAN and OPEC are also projected to continue their rapid economic and energy-demand growth (>335% of energy-demand increase for ASEAN in 2060 compared to 2011, and >262% for OPEC), the cumulative emissions of these groups would still be lower than the other

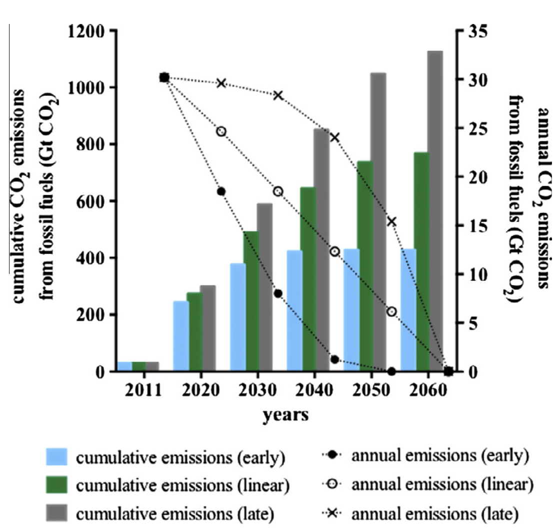

Fig. 1. Global cumulative greenhouse-gas (CO_2) emissions (bars – left *y*-axis) and annual greenhouse-gas (CO_2) emissions (lines – right *y*-axis) from fossil-fuel combustion of three different deployment pathways (early deployment, linear deployment and late deployment) between 2011 and 2060.

groups because of the former's current low energy consumption (17.2 EJ for ASEAN in 2011, and 24.9 EJ for OPEC). China would emit the most cumulative CO_2 from the final energy consumption based on the linear-deployment pathway (163 Gt CO_2) by 2060, followed by USA (148 Gt CO_2). The other major growing economies, Brazil, India and Russia, would emit 11, 36, and 44 Gt CO_2, respectively. Australia's electricity sector would emit >52% of the nation's cumulative CO_2 emissions due to their high reliance on fossil fuels (>93% of total electricity generation in 2011). For the other nations with high shares of zero-emission sources (including nuclear power and renewables) such as Norway, Sweden, France, and Brazil, the electricity-generation sectors would emit <11% of each nation's cumulative CO_2 emissions.

In terms of the cumulative per-capita emissions from aggregate final energy consumption over the period 2011 to 2060, the USA would emit between 243 (early-deployment pathway) and 639 t person^{-1} (late-deployment pathway), followed by Australia (222–583 t CO_2 person^{-1}) and Canada (218–571 t CO_2 person^{-1}), whereas China would emit <174 t CO_2 person^{-1} (minimum 66 t CO_2 person^{-1}) (Appendix C). Despite their projected growth in energy consumption, Brazil (<74 t CO_2 person^{-1}) will likely have much lower emissions than many other countries including China due to its high current renewable-energy dependency (>87% of national electricity consumption in 2011). India (<38 t CO_2 person^{-1}) also will emit less CO_2 due to its low per-capita energy consumption. Because of its high dependency on fossil fuels, Australia would have the highest cumulative per-capita emissions from electricity generation (118–309 t CO_2 person^{-1}), followed by USA (102–269 t CO_2 person^{-1}). France (<22 t CO_2 person^{-1}), Norway (<25 t CO_2 person^{-1}) and Sweden (<13 t CO_2 person^{-1}) would emit much less cumulative per-capita CO_2 because of their current high shares of zero-emission electricity generation (nuclear and renewables).

3.3. Land use

Renewable energy sources require more land area than conventional energy systems (nuclear and fossil fuels) to generate the same quantity of electricity due to the diffuse and variable (daily to seasonal to yearly) natural flows of energy that must be harnessed [9] (Fig. 3a). The global nuclear-free energy mix would require >7.4% (11,026,835 km^2) of Earth's total land area. As a point of comparison, the total land area of Australia – the world's sixth largest country – is 7,682,300 km^2. By comparison, the 100% nuclear energy mix would only transform <0.4% of the Earth's total land area, including land for power plants, uranium mining, mid- and long-term spent-fuel storage, and buffer zones. A different mix of renewables could potentially reduce its land footprint (e.g., a mix of 40% wind, 40% photovoltaic, 10% hydroelectric and 10% bioenergy would claim about 2.2% of the Earth's total land area, excluding large-scale energy storage, backup power plants, material mining area, and fuel storage for bioenergy), and efficient land use and advanced technologies could further reduce the land area required (e.g., lower bioenergy penetration, land sharing and offshore wind power) (Appendix E). However, relying on one or two intermittent sources of total electricity demand to reduce required land area is not technically and economically feasible [21], and it is axiomatic that nuclear power would claim less land area than any scalable renewable system due to its extremely high energy density and inherent energy storage properties as a fuel [40].

A country with a relatively low population density and large land area, such as Australia or Canada, would not have as pronounced land-related conflicts between its energy and other sectors. However, renewable energy alone would not able to serve many Asian countries with high population densities (and

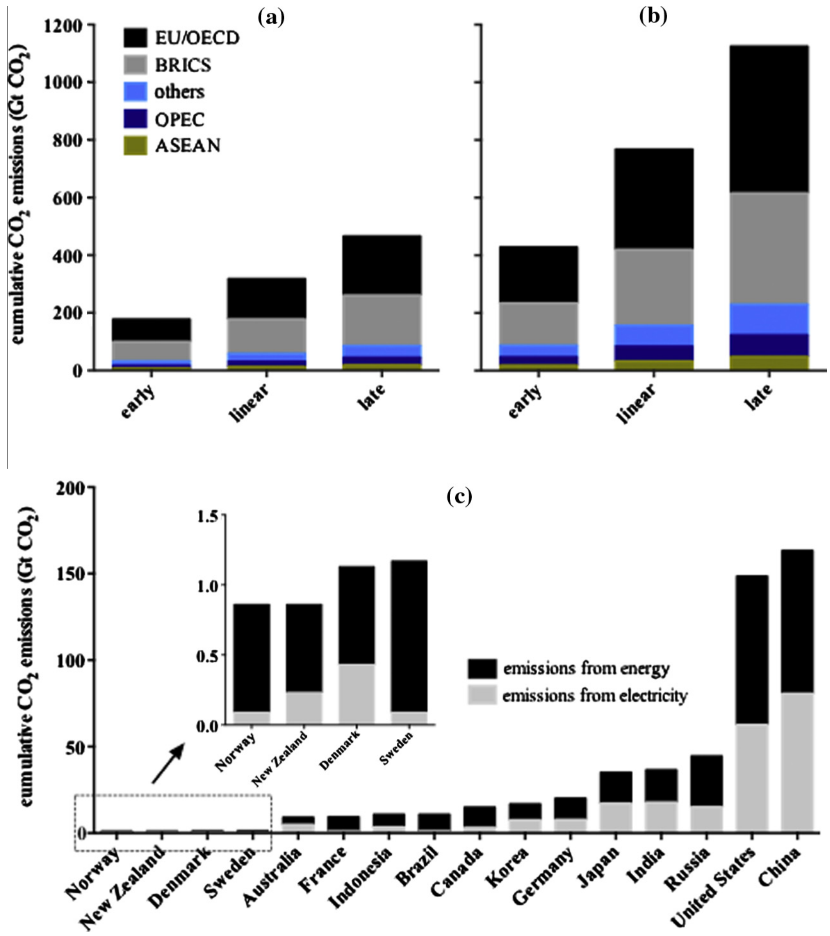

Fig. 2. Projected cumulative greenhouse-gas (CO_2) emissions from fossil-fuel combustion for (a) electricity and (b) energy consumption (including electricity consumption) of economic groups (EU/OECD, BRICS, OPEC, ASEAN, and OTHER) following three different deployment pathways (early, linear and late) between 2011 and 2060, and (c) cumulative emissions of 16 selected countries (Australia, Brazil, Canada, China, Denmark, France, Germany, India, Indonesia, Japan, South Korea, New Zealand, Norway, Russia, Sweden, and USA) based on the linear-deployment pathway (grey area indicates CO_2 emissions from electricity and the sum of grey and black area indicates CO_2 emissions from final energy consumption).

continued economic growth) such as China, India, Indonesia, Japan [17] and South Korea [18,19], due to their limited available land area (Fig. 3b). In terms of total required land (% of a nation's total land area) to generate projected future energy demand from only renewable energy resources in 2060, South Korea would require the highest proportion (>110%), followed by Japan and India (>50%), Germany (>28%), Indonesia (>18%) and France (>13%). There is no definitive maximum land area that can be transformed, but higher land transformation will increase environmental and social conflicts (e.g., land competition between food and energy, biodiversity and habitat issues, and carbon sequestration of natural forest) [9,44,49]. Moreover, the required land use for nuclear power of a highly populated country can be reduced because the present measured resources of uranium are largely located in Australia and Canada that have lower population density [50]. Note that the above calculations are conservative because we have not considered the minimum distance between wind power stations, transmission lines, material mining area for renewable technologies, fuel storage for bioenergy and affected ocean area for offshore wind power stations.

3.4. Cost analysis

Our sensitivity analysis shows that increasing the global nuclear share of electricity generation would lead to lower cumulative capital investment (Fig. 4). The nuclear-free mix based on the linear-deployment pathway would require a cumulative capital investment of $109,631 billion, and the maximum nuclear mix would require $73,753 billion. China would need 28.8% of global cumulative capital investment; India and USA would require 14.0% and 9.6%, respectively. In terms of the total capital investment for cumulative electricity generation between 2011 and 2060, the maximum nuclear scenario (97.6% of nuclear share) based on the linear-deployment pathway would require \$29.00 MWh^{-1}, and the minimum nuclear scenario (1.4% of nuclear share) would require \$42.40 MWh^{-1}. The 100% renewable scenario would require an additional \$0.80 MWh^{-1} compared with the minimum nuclear scenario; and 100% nuclear scenario would require an additional \$0.80 MWh^{-1} compared with the maximum nuclear scenario. Applying the maximum observed nuclear growth rate (0.28 MWh $person^{-1}$ $year^{-1}$) to each country would lower the global minimum capital investment to \$35.70 MWh^{-1}. However, applying the maximum growth rate of nuclear penetration to the global electricity consumption (58% of a global nuclear share) could further decrease the capital investment to \$34.50 MWh^{-1}. Note that we are only (conservatively) considering the average growth rate of nuclear penetration in France from 1970 to 1986 (0.28 MWh $person^{-1}$ $year^{-1}$), but the peak growth rate was 0.93 MWh $year^{-1}$ $person^{-1}$ in 1985 [1].

Given the current high share of renewables in the Norwegian electricity network (>97% from hydroelectric power) and projected low energy growth (−0.3% per annum), increasing the nuclear

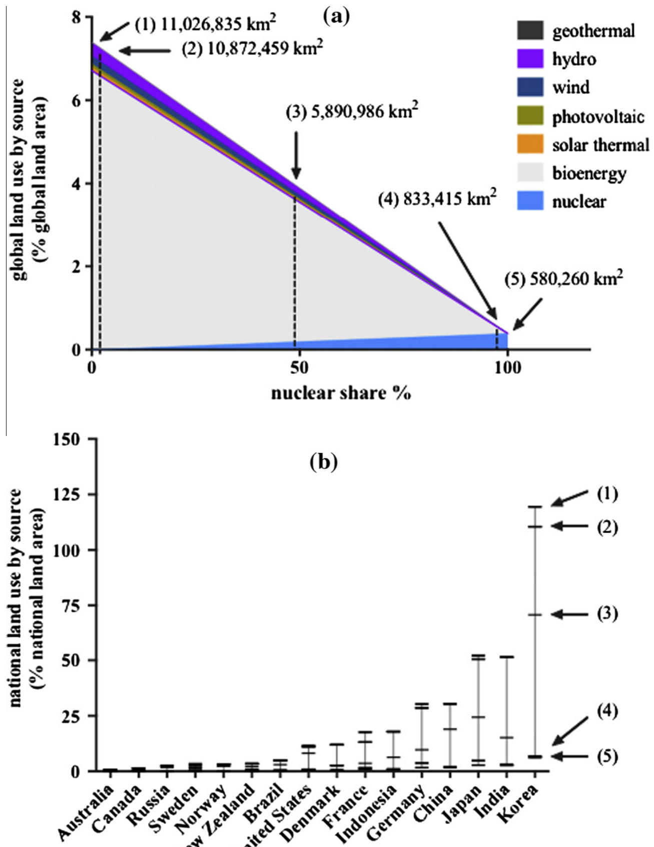

Fig. 3. (a) Global land use per total land area by energy source, and (b) 16 selected countries' (Australia, Canada, Sweden, Norway, New Zealand, Brazil, United States, Denmark, France, Indonesia, Germany, China, Japan, India, and South Korea) land use compared to the national land area for energy production in 2060. (1) 100% renewables, (2) 1.4% nuclear with 2011 nuclear share, (3) 49.2% nuclear with the maximum growth rate of nuclear penetration for each nation, (4) 97.6% nuclear with 2011 renewable shares, and (5) 100% nuclear mixes.

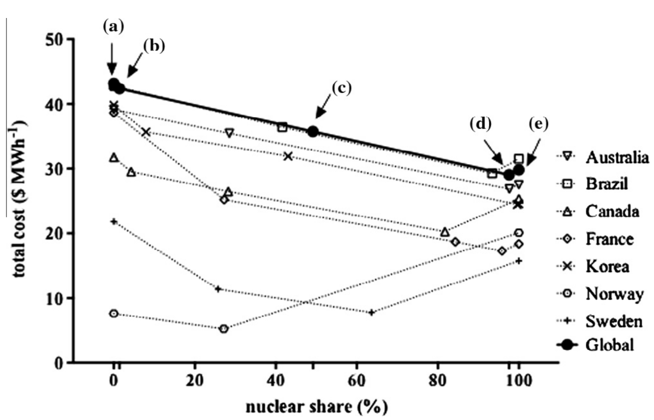

Fig. 4. The global and seven chosen countries' (Australia, Brazil, Canada, France, South Korea, Norway, and Sweden) cumulative capital investment costs per electricity generation ($ MWh^{-1}) between 2011 and 2060 by percentage nuclear share. (a) 0% nuclear share, (b) minimum nuclear share while maintaining current nuclear capacity, (c) maximum nuclear share without international cooperation (0.28 MWh $person^{-1}$ $year^{-1}$), (d) maximum nuclear share while maintaining current renewable capacity, and (e) 100% nuclear share.

power share to >27% of electricity generation in 2060 would increase cumulative capital investment in that country. Sweden, also with abundant hydro resources, would have the lowest capital investment cost with a nuclear share of 65%. However in Brazil, despite its high dependency on large hydroelectric power in 2011 (>85% of national total electricity consumption), rapid energy-demand growth (2.5% per annum) would eliminate the cost-saving effect of the current renewable penetration share, and nuclear power would be a better option to reduce the cumulative capital investment. France would face the greatest difference in capital investment by nuclear share in 2060. France's nuclear-free pathway would require \$38.6 MWh^{-1}, whereas the maximum nuclear scenario (about 96% of the electricity generation) would require less than half of that investment (\$17.30 MWh^{-1}). We acknowledge that some of the current nuclear power plants in France are ageing and need to be replaced before 2060. However, the additionally required capital investment for replacing aged renewable energy capacity (which have shorter operational life-spans than nuclear) with new renewable plants would be higher than the impact of replacing nuclear power plants (Appendix F). Globally, replacing current renewable energy capacity for 100% renewable energy future would require \$10.80 MWh^{-1}. Norway would require the highest additional capital investment (additional \$26.80 MWh^{-1}, and total \$34.50 MWh^{-1}), and France would require the least (additional \$6.40 MWh^{-1}, total \$45.00 MWh^{-1}). On the contrary, replacing ageing nuclear power plants with new nuclear power plants would add a maximum of \$6.80 MWh^{-1} in France in the 100% nuclear scenario. Globally, only \$0.40 MWh^{-1} is required.

Reducing the nuclear share in growing economies such as BRICS countries (Brazil, China, India, Russia and South Africa) and in currently high energy-consuming nations such as the USA, would affect the required global capital investment relatively more than in other nations. For example, a 0% nuclear share in China would increase the required global capital investment by between \$0.03 (compared to the minimum global nuclear-share mix, \$42.40 MWh^{-1}) and 3.5 MWh^{-1} (compared to the maximum global nuclear-share mix, \$29.10 MWh^{-1}). On the contrary, a 100% nuclear mix in China would decrease the required investment by \$3.40 MWh^{-1} compared to the minimum global nuclear-share mix. Unlike China, a nation like France, which represents only a small fraction of future cumulative electricity consumption, would not have much effect on the required global capital investment (<\$0.40 MWh^{-1}). In the case of the OECD as a whole, a 90% nuclear share would result in lower capital investment than the 100% nuclear share due to the relatively higher renewable share in 2011 and the lower energy demand in 2060 compared with other countries. A 90% nuclear share in the OECD would reduce global investment by \$2.40 MWh^{-1} compared to the minimum global nuclear-share mix, and a 0% nuclear share of the OECD would increase the cost by between \$0.70 and 3.30 MWh^{-1} compared with the minimum and the maximum global nuclear-share mixes, respectively.

3.5. Carbon-abatement intensity

Either lower cumulative capital investment or lower cumulative greenhouse-gas emissions increases the system-wide carbon-abatement intensity (Fig. 5). Despite lower capital investment, the longer one waits to deploy new technology at a large scale (given the assumed time-by-cost reduction relationships), the carbon-abatement intensity of an early-deployment scenario is higher than the same scenario with late deployment (>61%). A mix with a higher nuclear-penetration share has a higher carbon-abatement intensity compared to a mix with a lower nuclear-penetration share based on the same demand scenario due to the higher capital investment of renewables. The maximum nuclear mix (97.6% of nuclear share) has the highest carbon-abatement intensity (20.21 kg $\$^{-1}$ based on the linear deployment scenario), and the nuclear-free mix has the lowest (13.60 kg $\$^{-1}$).

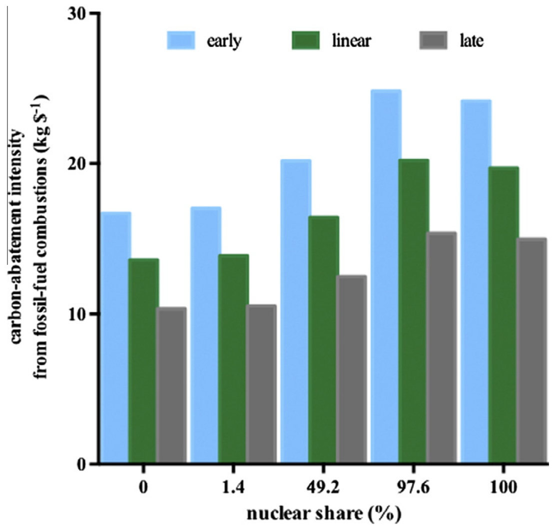

Fig. 5. Carbon-abatement intensity of three different deployment pathways (early, linear and late) from energy mixes based on high rates of fossil-fuel combustion to increasing nuclear-penetration shares.

3.6. Limitations and solutions

Using France's average growth rate of nuclear power penetration (0.28 MWh person^{-1} year^{-1}) as the global nuclear-penetration target by 2060, we analysed the potential limitations and solutions for reaching a global nuclear share of 49.2% in association with a renewable mix share of 51% by 2060. First, to generate cumulative electricity from nuclear power between 2011 and 2060 (1,146,603 TWh), about 30,480,456 tonnes of mined uranium would be required. In 2011, nuclear-fission energy consumed 68,000 tonnes of mined uranium to generate 2558 TWh [51], and the global known recoverable uranium resource is estimated at 5,327,200 t as of 2011 at current market prices [51]. Although a major expansion of global uranium supply is plausible from lower-quality ores and marine sources (about 4,290,000,000 t) [52] should fuel prices rise, we argue that Generation IV reactor technologies coupled with full fuel recycling (to extract over 100 times the energy from the actinides compared to earlier-generation technology) is a more sustainable and feasible approach to achieving rapid and sustainable nuclear expansion, especially because nuclear waste becomes a zero-carbon fuel rather than a management problem [3]. Second, after the Fukushima-Daiichi incidents, safety matters associated with nuclear reactors again rose to prominence as a major concern of the general public. However, a recent report provided by the World Health Organisation concluded that the public health risk caused by the radiation from the Fukushima-Daiichi reactor accidents has been, and will remain, negligible [53]. Amongst 20,115 emergency workers involved in management and clean-up of the accident, only 0.8% were exposed to >100 millisieverts (mSv), and it has consequently been deemed unlikely that any detectable elevated cancer risk (leukaemia or thyroid) will result from this expose [53]. From the survey of 110,000 clean-up workers of the Chernobyl accident who were exposed to a much higher radiation dose, leukaemia were detected from only about 0.1% of the workers [54]. In addition, statistical data show that current nuclear power plants are safer (between 0.000414 and 0.00726 fatalities GWyr^{-1}) than most other energy systems, including fossil-fuels (coal: 0.12 fatalities GWyr^{-1}) and renewables (e.g., biomass: 0.0149 fatalities GWyr^{-1} and offshore wind: 0.00641 fatalities GWyr^{-1}), in terms of total deaths per unit electricity generation (including eventual deaths arising from radiation exposure) [55]. Note that advanced reactor systems – including the Generation III + reactors currently commercialised and Generation IV reactors with inherent feedback systems – can vastly reduce the probability of rare accidents occurring [56].

4. Discussion

In this scenario analysis, we evaluated a range of sustainability issues (total required capacity of power plants, greenhouse-gas emissions, land requirements, and capital investment) associated with zero-emission energy sources (nuclear power and renewables), with the primary goal of achieving a global carbon-free energy network by 2060. All of our visualised mitigation pathways achieved lower cumulative CO_2 emissions compared with the IPCC RCP2.6 warming scenario [4]. However, a scenario following an early-deployment pathway will emit less than half the cumulative amount of CO_2 compared to one following a late-deployment pathway. Because neither nuclear nor renewables emits CO_2 during electricity generation, replacing a zero-emission baseload (dispatchable) source (nuclear) with other intermittent zero-emission sources (e.g., photovoltaic and wind power) is an inefficient approach that will delay the deployment of the total share of zero-emission sources and increase capital investment. Moreover, it is inevitable that a higher nuclear share would reduce the required land area required for development, even including mining, spent-fuel storage and buffer zones, and even when compared to an optimised renewable energy mix that includes some land-sharing with other resources [44].

Each nation will therefore need a different optimised mix to reduce greenhouse-gas emissions from electricity generation, while avoiding unnecessary additional and negative economic and environmental impacts. A rapidly developing nation with high energy demands in the future compared to 2011, such as Brazil, China, and India, and developed nations now relying mainly on fossil fuels, such as Australia, USA and most other OECD countries, would require a much higher nuclear share to reduce the cumulative capital investment and land transformation while curtailing greenhouse-gas emissions from the energy sector. From this global-scale perspective, we have shown that a global nuclear share of almost 50% is economically and technically plausible within a half-century time frame. The carbon abatement-intensity analysis shows that a scenario with a higher nuclear-penetration share is an economically more effective pathway for reducing the equivalent amount of greenhouse-gas emissions compared to a scenario with a lower nuclear-penetration share. However, to overcome potential barriers and limitations to the rapid expansion of nuclear power (including fuel supply, spent-fuel management, proliferation and safety issues), there is a need for strong international cooperation (technology, and human and physical infrastructure transformation) [57–59], coupled with concerted efforts to increase public acceptance [60], and a medium- to long-term emphasis on deployment of advanced reactor technologies (Generation IV and smaller modular reactors) [3,56,61]. Whether this is achievable within the next few decades in many countries remains open for debate and difficult to resolve in a simulation modelling exercise like this.

5. Conclusion

Nuclear power is not the only zero-carbon electricity-generation solution for all nations; however, neither can renewables be the sole solution for almost any nation, regardless of the economic, social and environmental conditions. Each country must plan and evaluate economically and environmentally appropriate energy mixes that can serve particular national or regional issues. Although some European countries (Germany, Italy, Belgium, and

Italy) have recently begun decommissioning their existing nuclear-generating capacity without replacement, our analysis clearly shows that nuclear power is an important component for mitigating climate change of both economically developed and developing countries. A future pathway for the global energy mix that emphasises only renewable resources and opposes the large-scale deployment of nuclear power will inevitably increase negative economic and environmental impacts. Given this reality and the results of our analysis, a high penetration of nuclear power associated with nationally or regionally optimised mixes of renewables will ultimately be the only feasible pathways towards effective decarbonisation of the global energy sector.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2015.01.006.

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