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Energy transitions and national security: the potential application of integrated assessment models

Llewelyn Hughes, Thomas Longden and Yeliz Simsek

Introduction

In the 2023 *National Defence: Defence Strategic Review* (DSR), the Australian Government confirmed '[c]limate change is now a national security issue' that 'has the potential to significantly increase risk in our region'. The DSR further states that climate change 'could lead to mass migration, increased demands for peacekeeping and peace enforcement, and intrastate and interstate conflict'.[1]

The implications of climate change for Australian national security were also addressed in the 2018 report from the Foreign Affairs, Defence and Trade References Committee of the Australian Senate.[2] In summarising submissions to the inquiry, the committee noted climate change will directly impact the environment across different timescales. It proposed increasing the capability to respond to climate risks, providing additional funding for international climate adaptation and disaster risk mitigation measures, and building capacity within government by providing ongoing funding for climate science and research organisations, amongst other recommendations.

A key issue for governments planning how to respond to climate change is uncertainty. The most recent summary of the state of the global climate released by the United Nations Intergovernmental Panel on Climate Change (IPCC) confirms it is unequivocal humans have warmed the atmosphere, ocean and land, leading

1 Defence, *National Defence: Defence Strategic Review*, Australian Government, Canberra, 2023, p 41. https://www.defence.gov.au/about/reviews-inquiries/defence-strategic-review

2 Foreign Affairs Defence and Trade References Committee 2018, *Implications of climate change for Australia's national security*, Australian Senate, Canberra ACT, 17 May 2018. https://www.aph.gov.au/Parliamentary_Business/Committees/Senate/Foreign_Affairs_Defence_and_Trade/Nationalsecurity/Final_Report

to widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere.[3] Yet it also shows a large range of uncertainty around climate futures depending on the effect of future emissions on additional warming. There is also uncertainty about the potential for low-likelihood, high-impact tipping points in which the climate system or a climate subsystem crosses a critical threshold, leading to potentially abrupt and irreversible changes in natural systems.[4] The resilience of human systems to climate impacts is also uncertain, depending on factors such as state capacity, the structure of political institutions, and the extent and ways in which international assistance is delivered.[5]

A second source of uncertainty lies in the transition pathways countries take when decarbonising. Governments are pursuing different levels of near and long-term climate ambition. In the Indo-Pacific, for example, governments have adopted nationally determined contributions (NDCs) and net-zero targets with different levels of ambition. Japan has committed to reduce greenhouse gas emissions by at least 46 per cent by 2030 relative to 2013 and to reach net zero by 2050. China has committed to peak CO_2 emissions in 2030 and reach net zero in 2060, and India has committed to reduce the intensity of emissions by 33–35 per cent by 2030 and to reach net zero by 2070. In addition, the technologies used to decarbonise differ across countries depending on domestic resources, technology costs and policy choices.

The implications of climate change for national security in the Indo-Pacific are profound. One strategy for assessing the possible effects that decarbonisation trajectories have in the Indo-Pacific, including the effect of different policy settings on future climate changes, is integrated assessment modelling. Integrated assessment models (IAMs) are quantitative models designed to study future change, including the effect of policies on climate pathways. Broadly speaking, IAMs are used to understand the impact of climate change on different factors of interest, the economic impact of climate mitigation policies, or a combination of both.[6]

3 Intergovernmental Panel on Climate Change (IPCC), *AR4 Climate Change 2007: Mitigation of Climate Change*, IPCC, 2007. https://www.ipcc.ch/report/ar4/wg3/

4 IPCC, '2023: summary for policymakers', in Core Writing Team, Hoesung Lee and José Romero (eds), *Climate change 2023: synthesis report* , IPCC, Geneva Switzerland, 2023, pp 1–34, doi: 10.59327/IPCC/AR6-9789291691647.001. PDF access via https://www.ipcc.ch/report/sixth-assessment-report-cycle/

5 Joshua W Busby, *States and Nature: The Effects of Climate Change on Security*, 1st edn, Cambridge University Press, 2022.

6 John Weyant, 'Some contributions of integrated assessment models of global climate change', *Review of Environmental Economics and Policy,* 2017, 11(1): 115–37; Robert S Pindyck, 'The use and misuse of models for climate policy', *Review of Environmental Economics and Policy*, 2017, 11(1): 100–114. There are limitations of IAMs identified that potentially weaken their utility in modelling potential climate futures. For a trenchant critique see Pindyck (2017).

In this paper, we assess the potential application of IAMs to the practice of strategic foresight in long-term national security strategy. We propose that IAMs are a potentially useful additional tool as an input for considering the implications of decarbonisation trajectories in the Indo-Pacific. We pay particular focus to testing the implications of assumptions about the availability and costs of different technologies on the composition of energy supply and demand in the region. IAMs also provide a way of considering the strategic implications of what will be a decades-long transition to net zero nationally, regionally and globally.

In the next section we discuss the low-carbon energy transition as a national security challenge, before outlining the function, characteristics and applications of IAMs in section three. In section four we then introduce possible applications of IAMs in strategic foresight for the purposes of defence planning. We conclude by offering a number of policy recommendations.

Climate change, energy transition and national security

Climate change risks can emerge from direct physical impacts, defined as the 'adverse physical impact of hazards related to climate change'.[7] Physical risks manifest through threats to national integrity caused by phenomena such as sea level rise, loss of life through extreme weather, disruptions to critical infrastructure and mass migration.[8] The most recent assessment of the state of the climate from the IPCC records that as the world continues to warm loss and damage will increase, and some human and natural systems will no longer be able to effectively adapt.[9] Reflecting this, research focuses on the relationship between environmental security, and more narrowly climate change, and human security, defined as the ability for people to 'meet their most essential needs and to earn their own living'.[10] Scholars note that climate change is being increasingly securitised as an issue, including in Australia, with complex implications. For instance, domestic pressure to enhance climate adaptation may have the

7 Priyadarshi R Shukla and Jim Skea (eds), Climate Change 2022: Mitigation of Climate Change – Working Group III contribution to the sixth assessment report of the Intergovernmental Panel on Climate Change, IPCC, Geneva Switzerland, 2023. https://www.ipcc.ch/report/ar6/wg3/

8 Joshua W Busby, 'Who cares about the weather? Climate change and US national security', *Security Studies*, 2008, 17(3): 468–504.

9 IPCC, '2023: summary for policymakers'.

10 Florian Krampe, Anders Jägerskog and Ashok Swain, 'The environment and human security', in *Routledge Handbook of Environmental Security*, Routledge, London, 2021, pp 250–59.

potential to reduce emphasis on the need for continued mitigation or support for improving the adaptive capabilities of other states in the Indo-Pacific region.[11]

A particularly challenging physical risk is sea level rise, which will continue for millennia. Extreme sea level events may become 20 to 30 times more frequent by 2050. One billion people are exposed to this risk.[12] In addition to the implications for human security, sea level rise and extreme weather events also have implications for existing energy-related infrastructure. In an assessment of the implications of sea level rise and extreme events for Europe's coastal energy infrastructure, Brown, Hanson and Nicholls find there are 158 major oil/gas/liquid natural gas tanker terminals in Europe's coastal zones, as well as 71 operating nuclear reactors, concluding that adapting coastal energy infrastructure to rising sea levels will be a crucial issue for governments and industry in the coming decades.[13] Militaries and military operations also generate large greenhouse gas (GHG) emissions, leading to pressure to decarbonise military forces through future force design.[14]

National security implications from climate change also emerge from the interaction of energy-related risks faced by states and decarbonisation policies. A core concern historically for governments has been potential vulnerability to politically induced shocks in fuel supplies.[15] For example, the geopolitical leverage of exporters of energy commodities will change as a result of the energy transition.[16] Under the International Energy Agency's net-zero emissions scenario for the energy sector, fossil fuel use falls as a share of total energy supply from 80 per cent in 2020 to just over 20 per cent in 2050. Oil demand falls from 90 million barrels a day in 2020 to 72 million barrels a day in 2030, and 24 million barrels a day in 2050.[17]

11 Matt McDonald, *Ecological Security: Climate Change and the Construction of Security*, Cambridge University Press, Cambridge, 2008; Matt McDonald, 'After the fires? Climate change and security in Australia', *Australian Journal of Political Science*, 2021, 56(1): 1–18; Maria Julia Trombetta, 'Environmental security and climate change: analysing the discourse', *Cambridge Review of International Affairs,* 2008, 21(4): 585–602.

12 IPCC, '2023: summary for policymakers'.

13 Sally Brown, Susan Hanson and Robert J Nicholls, 'Implications of sea-level rise and extreme events around Europe: a review of coastal energy infrastructure', *Climatic Change*, 2014, 122(1): 81–95.

14 Duncan Depledge, 'Low-carbon warfare: climate change, net zero and military operations', *International Affairs*, 2023, 99(2): 667–85.

15 Llewelyn Hughes and Austin Long, 'Is there an oil weapon?: security implications of changes in the structure of the international oil market', *International Security,* 2015, 39(3): 152–89.

16 Christian Downie, 'Geopolitical leverage in the energy transition: a framework for analysis and the case of Australia', *Energy Research & Social Science*, November 2022, 93, Article 102826, pp 1–6. https://doi.org/10.1016/j.erss.2022.102826

17 International Energy Agency (IEA), *Net zero by 2050 – a roadmap for the global energy sector*, IEA, Paris, May 2021, p 57. https://www.iea.org/reports/net-zero-by-2050

The low-carbon energy transition thus will have a large impact on the role of energy security in the foreign policy behaviour of import-dependent states in the Indo-Pacific, as well as Australia's relationship with the region. Policies such as the electrification of transport and industrial and other processes that currently use liquid and gaseous fuels, for example, coupled with the decarbonisation of electricity systems, will 'make energy supply, energy mix and energy trade less dependent upon assumptions of fossil resource availability'.[18] The potential of hydrogen as an energy carrier also has geopolitical consequences as new patterns of trade and investment emerge.[19] Reflecting this, Bordoff and O'Sullivan argue 'the transition will reconfigure many elements of international politics that have shaped the global system since at least World War II'.[20]

A core challenge in analysing these changes is uncertainty. In addition to uncertainties around the nature and extent of physical climate risk, there are also large uncertainties about the mix of technologies different countries will use to decarbonise their economies. There is also uncertainty about the pace of transition. Although many governments have committed to net-zero targets, for example, policies being used in the near to medium term to support transition continue to be developed. There is also the risk of an implementation gap, in which governments make long-term commitments but do not put in place the policies required to meet those commitments. The longer that governments delay the low-carbon energy transition, the longer risks associated with traditional fossil fuels will continue to be an important part of energy security concerns.

A potential solution to understanding this uncertainty for national security and defence planning is the use of IAMs. IAMs incorporate both economic and natural processes contributing to greenhouse gas emissions and allow for the characterisation and analysis of future uncertainty.[21] In the next section we discussed the function characteristics and applications of IAMs. We then move on to discuss possible applications of IAMs for national security planning.

18 A Cherp, J Jewell, V Vinichenko, N Bauer and E De Cian, 'Global energy security under different climate policies, GDP growth rates and fossil resource availabilities, *Climatic Change*, 2016, 136, pp 83-94. First published 1 November 2013. https://doi.org/10.1007/s10584-013-0950-x

19 International Renewable Energy Agency (IRENA), *Geopolitics of the energy transformation, the hydrogen factor*, IRENA, Abu Dhabi, January 2022. https://www.irena.org/publications/2022/Jan/Geopolitics-of-the-Energy-Transformation-Hydrogen

20 Jason Bordoff and Meghan L O'Sullivan, 'Green upheaval: the new geopolitics of energy', *Foreign Affairs*, January/February 2022, 101: 68, p 69.

21 M Granger Morgan and Hadi Dowlatabadi, 'Learning from integrated assessment of climate change', *Climatic Change*, November 1996, 34(3-4): 337–368.

The function, characteristics and applications of IAMs

There are numerous quantitative models that enable scenario analyses of the links between emissions from a range of economic sectors, GHG concentrations, the impact of GHG emissions on temperature and climate change, as well as the effect of technological changes and public policies on climate outcomes. If a model has most of these elements, it offers an 'integrated assessment of climate change' and is typically referred to as an IAM. There are over 20 global-scale models that can be classified as either benefit–cost or detailed process IAMs.[22]

The Dynamic Integrated Climate and Economy model is an example of an early benefit–cost IAM, which compares the optimal climate mitigation policy trajectory using an assessment of abatement costs and climate change damages.[23] A key question is whether emissions reductions should occur in the near-term, based on an assessment of the present value of future damages from climate change. Other examples of benefit–cost IAMs are the Framework for Uncertainty, Negotiation, and Distribution (FUND) and the Policy Analysis of the Greenhouse Effect (PAGE) models.[24]

Detailed process IAMs disaggregate key factors using detailed regional and sectoral representations, motivated by informing analysis of optimal emissions pathway and associated policies to achieve them. Topics include the assessment of the impacts of delayed policy action and how technological changes impact sectoral emissions.[25] Other detailed process IAMs utilise projections of the physical impacts of climate change, such as changes in crop growth, and temperature-related mortality.[26]

22 John Weyant, 'Some contributions of integrated assessment models of global climate change', *Review of Environmental Economics and Policy*, 2017, 11(1): 115–37.

23 William D Nordhaus, *Managing the Global Commons: The Economics of Climate Change*, MIT Press, Cambridge MA, 1994, p 31.

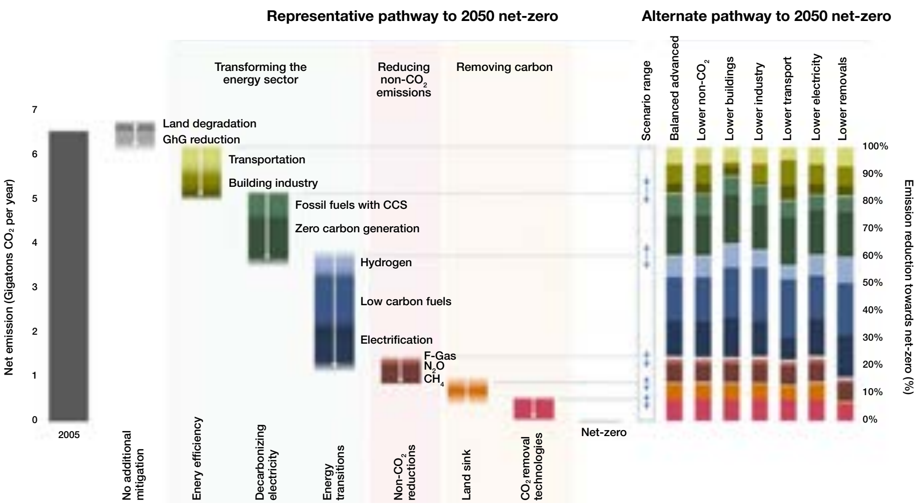
24 Daiju Narita, Richard SJ Tol, and David Anthoff, 'Economic costs of extratropical storms under climate change: an application of FUND', *Journal of Environmental Planning and Management*, 2010, 53(3): 371–84.

25 Keywan Riahi, Elmar Kriegler, Nils Johnson, Christoph Bertram, Michel Den Elzen, Jiyong Eom, Michiel Schaeffer, Jae Edmonds, Morna Isaac, Volker Krey, Thomas Longden, Gunnar Luderer, Aurélie Méjean, David L McCollum, Silvana Mima, Hal Turton, Detlef P van Vuuren, Kenichi Wada, Valentina Bosetti, Pantelis Capros and Ottmar Edenhofer, 'Locked into Copenhagen pledges – implications of short-term emission targets for the cost and feasibility of long-term climate goals', *Technological Forecasting and Social Change*, January 2015, 90(Part A): 8-23, https://doi.org/10.1016/j.techfore.2013.09.016;
Jiyong Eom, Jae Edmonds, Volker Krey, Nils Johnson, Thomas Longden, Gunnar Luderer, Keywan Riahi and Detlef P van Vuuren. 'The impact of near-term climate policy choices on technology and emission transition pathways', *Technological Forecasting and Social Change*, January 2015, 90(Part A): 73–88. https://doi.org/10.1016/j.techfore.2013.09.017

26 John Weyant, 'Some contributions of integrated assessment models of global climate change', *Review of Environmental Economics and Policy*, 2017, 11(1): 115–37.

Detailed process IAMs have been used to set renewable energy and/or emission targets. The European Commission has a suite of models that inform policy development with analysis of environmental, economic and social impacts, including cost-effectiveness analysis. These include the POLES-JRC, PRIMES and PRIMES-TREMOVE models, which are respectively, a global energy model, an EU energy-system model and a transport model.[27] The results from these models have informed the 2020 and 2030 emissions targets. The Global Change Assessment Model (GCAM) and Office of Policy – National Energy Modelling System (OP-NEMS) were used to assess the possible pathways to net-zero emissions in the US by 2050. A key contribution of GCAM was to illustrate how the pathways may differ based on assumptions that include lower industrial emissions, lower CO_2 removal technologies and land use change, and lower non-CO_2 reductions.[28]

Figure 1: Emissions reductions pathways to achieve 2050 net-zero emissions in the United States



Source: United States Department of State and United States Executive Office of the President, *The long-term strategy of the United States: pathways to net-zero greenhouse gas emissions by 2050*, US Department of State and US Executive Office of the President, Washington DC, 2021. https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf

27 European Commission, *Modelling tools for EU analysis,* Directorate-General for Climate Action website, 2023. https://climate.ec.europa.eu/eu-action/climate-strategies-targets/economic-analysis/modelling-tools-eu-analysis_en

28 United States Department of State and United States Executive Office of the President, *The long-term strategy of the United States: pathways to net-zero greenhouse gas emissions by 2050* [pdf], US Department of State and US Executive Office of the President, Washington DC, 2021. https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf

IAMs have had an important role as part of the IPCC reporting process, in which they have been given a chapter in each report.[29] These chapters contain a model comparison where numerous scenarios are compared to summarise the literature on how IAMs have modelled climate policy and technology assumption-sensitivity analyses.[30] A key concern has been the need to better highlight the complexities and uncertainties associated with the underlying model formulations, and the role of key model inputs and parameters, such as the impact of assumptions on economic growth and technological change.[31] This led to a literature that focuses on model diagnostics, which can be based on hindcasting or model comparison exercises.[32]

Often, IAMs are calibrated to aggregated national or regional data, such as the International Energy Agency's World Energy Outlook. Some modelling initiatives have focused on improving the representation of key segments of a sector using facility-level data. Examples include a focus on the number of coal electricity generation facilities that are in planning, permitting or construction and the possible need for early retirement of these facilities to achieve climate policy targets.[33]

A key advantage of IAMs is they can be used to conduct 'what if' assessments of potential future economic and climate outcomes, while taking into account uncertainty. IAMs can also be used to place bounds on the range of estimated costs, even where substantial uncertainties remain.[34] While transitioning away from coal is a common finding of the modelling of emissions reduction

29 Contribution of Working group III to the Fourth Assessment Report of the IPCC, *Climate Change 2007: Mitigation of Climate Change*, IPCC, Geneva, 2007; IPPC, *AR4 Climate Change 2007: Mitigation of Climate Change*, IPCC, Geneva, 2014; IPPC, *AR6 Climate Change 2007: Mitigation of Climate Change,* IPCC, Geneva, 2022.

30 Weyant, 'Some contributions of integrated assessment models of global climate change'.

31 Karen Fisher-Vanden and John Weyant. 'The evolution of integrated assessment: developing the next generation of use-inspired integrated assessment tools', *Annual Review of Resource Economics,* 2020, 12: 471–87.

32 Valeria Jana Schwanitz, 'Evaluating integrated assessment models of global climate change', *Environmental Modelling & Software*, December 2013, 50: 120–31. https://doi.org/10.1016/j.envsoft.2013.09.005

33 RY Cui, N Hultman, MR Edwards, L He, A Sen, K Surana, H McJeon, G Iyer, P Patel, S Yu and T Nace, 'Quantifying operational lifetimes for coal power plants under the Paris goals', *Nature Communications*, 2019, 10(1): 4759; Ryna Yiyun Cui, Nathan Hultman, Diyang Cui, Haewon McJeon, Sha Yu, Morgan R Edwards, Arijit Sen, Kaihui Song, Christina Bowman, and Leon Clarke, 'A plant-by-plant strategy for high-ambition coal power phaseout in China', *Nature Communications*, 2021, 12(1): 1468; Morgan R Edwards, Ryna Y Cui, Matilyn Bindl, Nathan Hultman, Krinjal Mathur, Haewon McJeon, Gokul Iyer, Jiawei Song, and Alicia Zhao. 'Quantifying the regional stranded asset risks from new coal plants under 1.5 C', *Environmental Research Letters*, 2022, 17(2): 024029.

34 Weyant, 'Some contributions of integrated assessment models of global climate change'.

policies,[35] the mix of energy sources that a given country transitions towards is uncertain. Modelling provides a tool to understand the potential shares of gas, biomass, solar, wind and nuclear energy. Future fuel mixes will be determined by technological costs, available resources and trade, hence the ability to model these dynamics is a key strength of IAMs.

The GCAM, which we focus on in this paper, is an IAM developed at the Pacific Northwest National Laboratory in the United States that incorporates the interaction of five systems: the economy, the energy system, the climate system, water and agriculture and land use. As such, it allows for analysis of the interaction of physical and socioeconomic systems in a single computational platform that is not highly demanding of computational power. Key outputs from scenario analyses using GCAM are:

- energy – energy demand and flows, technology deployment, energy prices
- agriculture and land use – prices and supply of all agricultural and forest products, land use and land use change
- water – demand and supply for agricultural, energy and household water use
- GHG emissions – 24 GHG and short-lived species: CO_2, CH_4, N_2O, halocarbons, carbonaceous aerosols, reactive gases and sulphur dioxide.

In climate research, GCAM has been used to address a wide variety of research questions about human-climate interactions from the global to the national in scope, including the future impact of climate on global agricultural yields, water demands associated with long-term electricity plans under different developmental pathways in India, and the implications of uncertainty regarding the renewable-energy resource base for projections of the global role of wind and solar power projections globally.

The key characteristics of GCAM are as follows.

Transparency and open access

GCAM is fully documented and available online, supporting transparency and open access. This is a useful characteristic given a key issue with IAMs as analytic tools lies in the importance of assumptions in determining model outcomes.

35 Cui et al., 'Quantifying operational lifetimes for coal power plants under the Paris goals'; Ryna Yiyun Cui, Nathan Hultman, Di-Yang Cui, Haewon Mcjeon, Leon Clarke, Jia-Hai Yuan and Wen-Jia Cai, 'A US–China coal power transition and the global 1.5°C pathway', *Advances in Climate Change Research*, April 2022, 13(2): 179–186. https://doi.org/10.1016/j.accre.2021.09.005

Wide coverage of fuels and sectors

GCAM models demand and supply of coal, gas, bioenergy, nuclear, solar, wind and hydroelectricity.

Traded fuels

Fossil fuels (i.e. coal, gas, and oil) are traded across regions in the model, allowing modelling of import demands of fuels under different scenarios.

Policy-based scenarios

GCAM allows the modelling of different 'what if' policy scenarios, such as emissions reduction targets, technological subsidies or restrictions.

Uncertainty analysis

The model runs using a dynamic recursive process, which approximates a decision-maker that is unable to foresee future changes. This contrasts with another class of IAMs called intertemporal optimisation models, which assume agents in the model have full information about the future when they make decisions.

GCAM offers a potentially useful tool for long-term scenario analysis, as it enables the flexible assessment of future scenarios concerning key areas of interest to Australia's interests related to energy, land, water, climate and socioeconomic factors in the Indo-Pacific region, including the potential role of feedback loops and compounding effects. The open-source nature of the GCAM IAM also allows for the development of additional modules to increase resolution of assessments in the Indo-Pacific. At present, geographic and sectoral coverage of the model in the Indo-Pacific is as follows: Australia/New Zealand, China, India, Indonesia, Japan, South Korea, Taiwan, and the rest of South-East Asia and the Pacific.

Potential use of IAMs in the interaction of energy transitions and national security

IAMs have already been used to examine the implications of climate change for energy security, although with a particular focus on Europe. Guivarch and Monjon find a nonlinear relationship between energy transition and energy security, and suggest low cost and wide availability of low-carbon power generation technologies will rapidly reduce European reliance on the import of fuels for power generation while increasing the robustness of the energy system.[36] In an

36 Céline Guivarch and Stéphanie Monjon, 'Identifying the main uncertainty drivers of energy security in a low-carbon world: the case of Europe', *Energy Economics*, May 2017, 64: 530–41. https://doi.org/10.1016/j.eneco.2016.04.007

assessment of the energy-security implications of long-term climate scenarios for China, India, the European Union and the United States, Jewell et al. compared results from six different IAMs and found climate policies lower energy trade globally and reduce energy-related imports of major economies,[37] suggesting there are energy security co-benefits from the introduction of more stringent policies. Related, McCollum et al. found across multiple IAMs that energy-system resilience increases along with a reduction in oil imports as climate-change mitigation policies increase in stringency.[38] They also found, however, that energy-efficiency policies are unlikely to improve energy independence, and that there may be an increased concentration in regions exporting oil and gas as countries decarbonise, with negative implications for energy security. Taken together, these studies suggest national security concerns associated with fossil fuel import dependence may fall in the long-run; however, there are potential nonlinearities and complexities emerging from the substitution of coal for gas in the short to medium term, coupled with the potential for increased market concentration in fossil fuel markets. Supply chains in the energy sector will also grow in complexity as the range of technologies used to supply energy services increase.

IAM's have also been used to examine the economic and emissions implications of a European embargo of Russian fossil fuel imports,[39] technology requirements for achieving net-zero carbon dioxide emissions in North America by 2050,[40] and the implications of an increased use of bioenergy for food security globally.[41] Factors relevant to climate risk and a sample of research using IAMs is shown in Table 1.

37 Jessica Jewell, Aleh Cherp, Vadim Vinichenko, Nico Bauer, Tom Kober, David McCollum, Detlef P van Vuuren and Bob van der Zwaan, 'Energy security of China, India, the EU and the US under long-term scenarios: results from six IAMs', *Climate Change Economics*, 2013, 4(4): 134001. https://doi.org/10.1142/S2010007813400113

38 David McCollum, Nico Bauer, Katherine Calvin, Alban Kitous and Keywan Riahi. 'Fossil resource and energy security dynamics in conventional and carbon-constrained worlds', *Climatic Change*, 2014, 123: 413–426. https://doi.org/10.1007/s10584-013-0939-5

39 Li-Jing Liu, Hong-Dian Jiang, Qiao-Mei Liang, Felix Creutzig, Hua Liao, Yun-Fei Yao, Xiang-Yan Qian et al. 'Carbon emissions and economic impacts of an EU embargo on Russian fossil fuels', *Nature Climate Change*, 2023, 13(3): 290–296. https://doi.org/10.1038/s41558-023-01606-7

40 M Browning, J McFarland, J Bistline, G Boyd, M Muratori, M Binsted, C Harris, T Mai, G Blanford, J Edmonds and AA Fawcett, 'Net-zero CO_2 by 2050 scenarios for the United States in the energy modeling forum 37 study', *Energy and Climate Change*, December 2023, 4, p 100104. https://doi.org/10.1016/j.egycc.2023.100104

41 Tomoko Hasegawa, Ronald D Sands, Thierry Brunelle, Yiyun Cui, Stefan Frank, Shinichiro Fujimori and Alexander Popp, 'Food security under high bioenergy demand toward long-term climate goals', *Climatic Change,* 2020,163: 1587–1601.

Table 1: Climate risk and integrated assessment modelling approach

Factor relevant to climate risk	How can this factor be addressed with IAMs?
Natural resources	Natural resources are a core energy security concern of governments. IAMs are widely used models for developing scenarios of the future of resources including the phasing out of fossil fuels,[i] stranded assets,[ii] renewable energy integration and low-carbon transition,[iii] innovative technology substitution, and the effect of shocks (such as the Russo–Ukraine War).[iv]
Energy and infrastructure	Energy is a broad and significant topic for national security as well as IAMs. Most IAMs include energy sectors demand-supply representation including residential, industry, transport and agriculture. The role of specific technologies (such as wind technology),[v] or the impact of climate change and transition-related security risks on particular sectors (such as steel and cement) can be studied.[vi]
Climate transition policies	To address climate change and its risks, several global, regional and sectoral strategies including different policy portfolios are studied since the Paris Agreement. IAMs are useful tools for decision-makers to see the future impacts of policies, including understanding the synergies and trade-offs between different policies in terms of national security.[vii]
Displaced population, migration	IAMs typically use population as a key assumption, and population change due to climate change and transition risks can be reflected in the model. Most IAMs allow users to define new pathways with different population and urbanisation projections.[viii] Most IAMs also have the flexibility to allow creation of a new region by disaggregating a combined area, including detailed subnational representation. For instance, the GCAM-USA model was created to represent US economic, energy, and water systems for 51 state-level regions (50 states plus the District of Columbia) and to explore the climate impacts at a subnational level.[ix]
Water	Water is a significant topic for national security as well as energy and food. Not only including residential and industrial usage in the models, but also modelling water resources in the energy context (hydro energy, hydrogen etc.) gained importance to develop successful strategies and prioritise water use in case of scarcity.[x]
Food, agriculture, land use	Land use is an essential input for IAMs. Depending on the complexity of the model, land use can be modelled to understand future changes in a specific land of a region in terms of agriculture, water and energy use.[xi] Furthermore, changes in agriculture sector and food security could be examined by IAMs to understand the impact of climate change and transition-related security risks.[xii]

i Cui et al., 'A US–China coal power transition and the global 1.5°C pathway', 2022 (fn 35); Cui, et al., 'A plant-by-plant strategy for high-ambition coal power phase-out in China', 2021 (fn 33); Greg Muttitt, James Price, Steve Pye, and Dan Welsby, 'Socio-political feasibility of coal power phase-out and its role in mitigation pathways', *Nature Climate Change*, 2023, 13(2): 140–47.

ii J-F Mercure, Hector Pollitt, Jorge E Viñuales, Neil R Edwards, Philip B Holden, Unnada Chewpreecha, Pablo Salas, Ida Sognnaes, Aileen Lam, and Florian Knobloch, 'Macroeconomic impact of stranded fossil fuel assets', *Nature Climate* Change, 2018, 8(7): 588–593.

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IAMs may also provide a useful input into strategic foresight practices. In a report on the design and implementation of scenario analysis in defence planning by the Australian Defence Science and Technology Organisation (DSTO) of the Department of Defence, Nguyen and Dunn describe procedures for identifying a problem and synthesising scenarios for analysis.[42] Leigh notes the use of strategic foresight processes lead to a more 'focused, innovative and creative government' in Australia.[43] Elsewhere, Durst et al. document the foresight processes used by the German Federal Armed Forces,[44] which includes environmental planning, impact uncertainty analysis and explorative scenario construction. Davis recommends strategic planning in the United States should prioritise capabilities attuned to a proper treatment of uncertainty and make recommendations for use in analyses.[45] Dreyer and Stang review practices used by governments in foresight activities, recommending proper identification of target audiences, maintaining close ties with senior decision-makers, establishing programs rather than single projects, and using scenario-based analysis.[46] In a review for the Swiss Federal Commission for Nuclear, Biological and Chemical Protection and the Federal Office for Civil Protection, Kohler summarises different forecasting techniques, and notes that 'foresight can help to prioritize which areas would profit from more data collection and resilience'.[47]

Amongst other potential uses, IAMs could be used to assess how decarbonisation trajectories affect the energy-security risks faced by states in the Indo-Pacific region, including Australia. It is possible, for example, that energy-security risks for governments in the region will increase if thermal coal rapidly exits power-generation systems but is replaced by gas. In addition, coal, gas and oil will continue to play a role as countries in the region chart trajectories towards net-zero emissions, but the range of technologies that are available to support decarbonisation are likely to influence the pace with which these fuels exit

42 Minh-Tuan Nguyen and Madeleine Dunn, *Some methods for scenario analysis in Defence strategic planning*, Defence Science and Technology Organisation, 2009.

43 Andrew Leigh, 'Thinking ahead: strategic foresight and government', *Australian Journal of Public Administration*, June 2003, 62(2): 3–10. https://doi.org/10.1111/1467-8497.00320

44 Carolin Durst, Michael Durst, Thomas Kolonko, Andreas Neef, and Florian Greif. 'A holistic approach to strategic foresight: a foresight support system for the German Federal Armed Forces', *Technological Forecasting and Social* Change, 2015, 97: 91–104.

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46 Iana Dreyer and Gerald Stang with Carole Richard, 'Foresight in governments – practices and trends around the world', in Antonio Missiroli (ed), *EUISS Yearbook of European Security*, EU Institute for Security Studies, May 2013, 1368, no 1: 7–32. https://www.iss.europa.eu/content/euiss-yearbook-european-security-2013

47 Kevin Kohler, *Strategic foresight: knowledge, tools, and methods for the future*, Center for Security Studies (CSS)/ETH Zurich, September 2021. https://doi.org/10.3929/ethz-b-000505468

the market. Regional governments will use increasing amounts of low-carbon technologies to support electrification and the decarbonisation of electricity systems, which leads to greater complexity in supply chains supporting the provision of energy services. Analysis of scenarios using IAMs could be used to support assessments of how the strategic behaviour of states in the Indo-Pacific may change in response to shifts in the structure of supply chains supporting energy systems regionally and globally.

A second example is the implications of China's economic and military rise for the future trajectory of climate change regionally and globally. China is the largest global emitter of GHG emissions globally. But it has committed to achieving carbon neutrality by 2060 and to peak CO_2 emissions by 2030. In addition to being a large emitter of GHGs, China also dominates the supply chains for key technologies involved in the low-carbon energy transition. The International Energy Agency records that China held 79 per cent of the world's polysilicon production capacity in 2021, 97 per cent of global production capacity for solar-wafer manufacturing, and 85 per cent of solar-cell production. China also holds an important share of production for raw materials used in solar manufacturing.[48] Strategic competition between China and the United States has potential implications not only for climate policies, but also for the costs of low-carbon technologies relative to more emissions-intensive substitutes. Assessing the implications of a more fragmented world for trade and investment in key low-carbon technologies aligns with the capabilities of IAMs.

Conclusion and discussion

IAMs are an important tool climate scientists use to assess the future impacts of climate change and the impact of public policies. These include – but are not limited to – policies designed to transition to low-carbon economies, on climate futures and other important factors, such as the structure of energy supply and demand within countries, regionally or globally. A benefit of IAMs is their ability to conduct 'if-then' analysis, in which the effect of climate transition policies can be assessed in terms of their future implications for energy supply and demand using a robust quantitative framework. A second benefit of IAMs is the ability to address future uncertainty using scenario-based analyses; although, it is important to note that outputs are affected by key assumptions used as model inputs. State responses to climate risks are also crucial in understanding the national security implications of climate change, and vary across countries. It

48 International Energy Agency (IEA), *Solar PV global supply chains: an IEA special report*, IEA, Paris, July 2022. https://www.iea.org/reports/solar-pv-global-supply-chains

is thus crucial to additionally take into account heterogeneity in individual and collective human behaviour in interpreting and improving climate modelling.[49]

In the European and North American contexts, IAMs have been used to assess issues such as the energy-security implications of low-carbon energy transition. Yet their application to analysing future scenarios in the Indo-Pacific related to national security issues is limited. IAMs thus represent a potentially useful tool for use in strategic foresight exercises, complementing other approaches, such as the use of horizon scanning, trend analysis, the use of the Delphi method or expert surveys in forecasting, and other approaches.[50] Carrying out assessments using IAMs requires an investment in human capital to enable capabilities development, including through working with the research sector. Understanding the future implications of climate change, and the effect of strategic issues such as the economic and military rise of China for the future of climate change mitigation in the Indo-Pacific, warrants consideration of such an approach in order to inform long-term decision-making.

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49 Brian Beckage, Frances C Moore and Katherine Lacasse, 'Incorporating human behaviour into Earth system modelling', *Nature Human Behaviour*, 2022, 6(11): 1493–1502. https://doi.org/10.1038/s41562-022-01478-5

50 Kohler, *Strategic foresight: knowledge, tools, and methods for the future*.