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The Potential Role of Nuclear Energy in National Climate Change Mitigation Strategies

Final Report of a Coordinated Research Project

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THE POTENTIAL ROLE OF NUCLEAR ENERGY IN NATIONAL CLIMATE CHANGE MITIGATION STRATEGIES

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FINAL REPORT OF A COORDINATED RESEARCH PROJECT

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2021

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For further information on this publication, please contact:

Planning and Economic Studies Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Email: Official.Mail@iaea.org

Printed by the IAEA in Austria
November 2021

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: The potential role of nuclear energy in national climate change mitigation strategies : final report of a coordinated research project / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2021. | Series: IAEA TECDOC series, ISSN 1011–4289 ; no. 1984 | Includes bibliographical references.
Identifiers: IAEAL 21-01453 | ISBN 978-92-0-135621-5 (paperback : alk. paper) | ISBN 978-92-0-135521-8 (pdf)
Subjects: LCSH: Nuclear energy — Environmental aspects. | Climate change mitigation. | Climatic changes.

FOREWORD

In 2015, at the 21st session of the Conference of the Parties to the United Nations Framework Convention on Climate Change in Paris, 196 Parties adopted a new legally binding treaty on climate change. This treaty — the Paris Agreement — seeks to limit global warming to well below 2°C compared with pre-industrial levels, and preferably to 1.5°C. Nuclear energy could play a significant role in reaching these ambitious targets. The IAEA supports its Member States in better understanding the potential contribution of nuclear energy to climate change mitigation in various ways. It also provides information to broader audiences engaged in energy, environmental and climate policy making.

The inclusion of nuclear power in low carbon energy supply is a complex matter, with political, economic, financial and social dimensions. A key aspect involves the economic and environmental performance of nuclear power considering a country's or region's broader energy system, including its geological energy resources, the amount and quality of renewable energy sources, the level of technological development, the availability of energy technologies and human capacity to operate them, among other factors. It is therefore sensible to conduct rigorous assessments of energy systems to better understand how climate change mitigation targets can be achieved and to what extent nuclear power can play a role.

The IAEA has supported Member States to improve their energy planning for decades with a range of analytical tools, including computer models, and associated capacity building and training. The scope of these tools ranges from the compilation of energy statistics through energy demand projections and environmental impact assessments to complex energy system and macroeconomic modelling, specified according to the characteristics of the countries in which they are applied. Hundreds of experts are trained annually and a considerable pool of knowledge has accumulated as a result. Some of the IAEA's energy models can also be used to explore how nuclear energy could contribute to reducing greenhouse gas emissions.

Many Member States have indicated interest in such assessments and requested related support. In response, the IAEA has conducted many studies and released a range of publications about the role of nuclear energy in sustainable development and mitigating climate change. The IAEA also initiated a coordinated research project entitled Assessments of the Potential Role of Nuclear Energy in National Climate Change Mitigation Strategies to support research teams in interested Member States in conducting national studies on the prospects of nuclear energy in their energy systems.

This publication presents the outcomes of this project. It provides information on the possible role of nuclear power in managing the climate change challenge, presents brief descriptions of the analytical tools applied in the national studies, provides concise summaries of the analysis and results produced by participating research teams and summarizes the general insights from across the national studies. This publication demonstrates an array of possibilities to undertake rigorous quantitative analyses and provide scientific advice to support policy making on links between nuclear energy and climate change. It is expected that the methods and results presented here will also encourage additional in depth studies on this topic.

The IAEA wishes to thank all the research teams in participating Member States for their contributions. The IAEA officer responsible for this publication was H. Turton of the Division of Planning, Information and Knowledge Management.

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1. INTRODUCTION

In August 2021 the Intergovernmental Panel on Climate Change (IPCC) issued a sobering assessment highlighting the speed, intensity and pervasiveness of recent changes to the Earth's climate [1]. Climate change is occurring across all world regions, with many changes unprecedented in thousands of years and, in some cases, irreversible for centuries or longer. Without “immediate, rapid and large-scale reductions in greenhouse gas emissions, limiting warming to close to 1.5°C or even 2°C will likely be beyond reach” [2].

1.1. BACKGROUND

Based on the increasing evidence accumulated over the past three decades by the IPCC [1, 3], climate change is widely considered as one of the major threats to human well-being and socioeconomic development, including the ecological foundations and natural resource base underpinning modern civilization, as well as the geophysical environment in general. It has dominated the global environmental and energy policy agenda over the past two decades and has become a major global political issue in recent years.

Increasing temperatures in most regions of the world, changing precipitation patterns and shifts in other climate variables are driven by increasing concentrations of greenhouse gases (GHGs) in the atmosphere. A major anthropogenic source of GHGs, particularly of carbon dioxide (CO_2) emissions, is the fossil fuels burned by the energy sector and other industrial activities. Driven by economic development aspirations, energy demand is projected to increase extensively in the twenty-first century. Without a profound transformation of the global energy system to reduce GHG emissions drastically over the coming decades, current trends in energy production and use may well lead to what Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) [4] calls “dangerous anthropogenic interference with the climate system”.

A turning point in global climate policy was marked by the Paris Agreement [5] under the UNFCCC in 2015. It is the first universal and legally binding global accord to mitigate climate change. The mitigation target in this agreement is specified in Article 2 as:

> “Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change” (Ref. [5], p. 3).

The Paris Agreement commits Parties to provide information about their planned actions to tackle climate change in the form of nationally determined contributions (NDCs). The NDCs should cover intended efforts in various components of the Agreement, including mitigation. As of 2020, there are no established firm and legally binding commitments in terms of implementation between Parties because the Agreement commits countries to declare, report and review but not to achieve pledged outcomes.

Article 4 of the Paris Agreement [5] requires each Party to communicate NDCs concerning the GHG emission reduction targets they intend to achieve by pursuing domestic mitigation measures and stipulates that successive NDCs should exceed the Party’s earlier contributions. This reporting procedure is linked to the earlier process of communicating intended nationally determined contributions (INDCs). Almost all Parties to the UNFCCC submitted INDCs in 2015. For most of the 190 countries that have ratified the Agreement (as of mid 2021), INDC submissions also served as first NDCs. For the next round of submissions, Parties were requested to communicate new or updated NDCs in 2020, and a significant number had already submitted revised first or second NDCs by the end of the year. Progress on all components of the Paris Agreement, including mitigation, will be reviewed every five years in a so-called ‘global stocktake’ starting in 2023.

The Paris Agreement is expected to continue giving impetus to policies on climate change mitigation and the low carbon energy transition. The challenge is daunting. Energy related GHG emissions account for around two thirds of total GHG emissions [6]. According to projections of the International Energy Agency (IEA), IPCC and others, global demand for electricity could easily double between 2018 and 2050 [6]. Over the same period, total direct CO_2 emissions from the power sector need to be cut by almost 90% to achieve the goal of limiting the global increase in temperatures to 2°C, and more for 1.5°C. To reach these goals, it is necessary to send strong signals for decarbonization of electricity systems through a combination of measures such as pricing of GHG emissions, direct regulation and support instruments to reduce investment risks for low carbon technologies.

While there is a broad consensus that electricity is a key component of cost effective mitigation [7], emissions from electricity generation are growing rapidly, accounting for more than one third of the increase in total GHG emissions since 1990. Although there are recent signs of some investments slowly shifting towards low carbon sources, which made up 50% of total new electricity capacity in recent years, current policy and investment trends still risk locking in high emissions in the future. As the IEA observes “[o]ver 95% of power sector investment was made by companies operating under fully regulated revenues or long-term contractual mechanisms to manage the revenue risk associated with variable wholesale market pricing” (Ref. [8], p. 136) and “over 95% of power investments are incentivised by regulations and contracts” (Ref. [9], p. 71). As a result of these current energy market arrangements and only limited carbon pricing, today’s low carbon investments (RESs, nuclear energy) must rely on government support to reduce the investment risk, ensure timely investments and avoid the lock-in in fossil fuel intensive assets.

To realize the goals of the Paris Agreement, stronger policies are needed for transforming the power sector. Rapid decarbonization and investment in low carbon technologies require incentives, appropriate market and regulatory frameworks and targeted policies. The effectiveness of alternative support mechanisms for low carbon investment, including for nuclear power projects, also needs to be assessed in light of increasing ambition in mitigation of climate change under different national policy and electricity market circumstances.

The Paris Agreement does not itself impose specific policy or regulatory measures — such as a price on carbon — but it does recognize the important role of providing incentives for emission reduction activities, including tools such as domestic policies and carbon pricing. It also describes how countries can pursue voluntary cooperation in the implementation of their NDCs.

Nuclear energy is a low carbon technology that has demonstrated its ability and potential to massively contribute to reducing energy related GHG emissions. This is outlined in a series of successively updated reports that since 2000 present the latest information about the diverse array of linkages between climate change and nuclear power [10]. The latest edition was published in 2020 [6]. The potential contribution of nuclear power to achieve the mitigation target specified in the Paris Agreement was also highlighted by other IAEA publications [11] and recently reaffirmed at the 2019 International Conference on Climate Change and the Role of Nuclear Power, which concluded that:

> "Action is urgently needed, making use of all possible technologies to reduce emissions and rapidly move to the decarbonization of the energy sector. In most scenarios developed by relevant international organizations, nuclear power contributes to the decarbonization of electricity supply to achieve climate goals by 2050… Taking into account the expected growth in world population and energy demand…in order to decarbonize the energy sector, nuclear power has a significant role to play" (Ref. [12], p. 8).

This conclusion also reflects the open time frame of the Paris Agreement, which implicitly supports technologies that can deliver low carbon energy and thus GHG mitigation benefits for several decades, such as nuclear energy.

In a broader context, nuclear energy can also promote the implementation of several Sustainable Development Goals adopted by the United Nations (see Refs [13, 14]). In 2017, the International Ministerial Conference on Nuclear Power in the 21st Century concluded that:

> "for many countries, nuclear power is a proven, clean, safe and economical technology that will play an increasingly important role in achieving energy security, reducing the impact of volatile fossil fuel prices and mitigating the effects of climate change and air pollution. For many countries, nuclear power will have an important role to play in achieving the Sustainable Development Goals and meeting the targets in the Paris Agreement. Governments should ensure that their national energy policies support their development and climate goals" (Ref. [15], p. 5).

Due to the fast growing demand for energy, in particular electricity, in emerging economies and developing countries and the mounting pressure to reduce GHG emissions, an increasing number of countries are considering expanding their nuclear reactor fleets or adding nuclear power to their electricity generation portfolios. To support Member States in this regard, the IAEA provides information and assistance to consider nuclear power and other technologies to reduce GHG emissions, supports sustainable energy planning (including updates to NDCs under the Paris Agreement), provides guidance on establishing and expanding nuclear power programmes, assists with the development of low carbon advanced reactor and fuel technology, and evaluates new roles for nuclear energy to replace high carbon sources. The IAEA also helps Member States to use nuclear science and technology to enhance natural carbon sinks and to adapt to and monitor climate change [16].

In addition to providing information, the IAEA also recommends conducting in-depth analysis on whether, and if so to what extent, nuclear energy might contribute to GHG emissions reductions. After the adoption of the Paris Agreement, France and the United States of America also expressed interest in Agency research supporting Member States' assessments of the role of nuclear energy in national mitigation strategies. These recommendations have generated considerable interest in other Member States.

In response, the IAEA initiated the Coordinated Research Project (CRP) on Assessments of the Potential Role of Nuclear Energy in National Climate Change Mitigation Strategies to explore these issues further [17]. This built upon an earlier CRP completed in 2009 on Greenhouse Gas Mitigation Strategies and Energy Options, which analysed the potential role of different energy options, with a special focus on nuclear energy, under different designs and implementation mechanisms for a future international climate change agreement (prior to the definition of the Paris Agreement).

Commencing soon after the adoption of the Paris Agreement, the most recent CRP was designed to align with the international process and needs of Member States. Its value and relevance became progressively apparent over the course of the project from 2016 to 2019, as the international community increasingly recognized both the need for more ambitious and urgent climate action as well as the potential of nuclear energy to contribute to mitigation — both reinforced by the 2018 IPCC Special Report on Global Warming of 1.5°C [3]. By the concluding meeting of the CRP, during the week of the UN Secretary General's Climate Action Summit, an increasing number of countries had adopted net zero emission targets for 2050, while around 13 countries had included nuclear power in their NDCs submitted under the Paris Agreement (with the number rising to 19 countries by mid 2021).

1.2. OBJECTIVE

The objective of this publication is to provide a comprehensive summary and synthesis of the national case studies conducted under the IAEA CRP on Assessments of the Potential Role of Nuclear Energy in National Climate Change Mitigation Strategies. It seeks to share the findings, methodological approaches, experiences and lessons learned to improve general understanding of the role of nuclear energy in climate change mitigation and assist other Member States in designing their own energy–climate assessments using IAEA or other analytical tools to objectively evaluate the feasibility and potential of nuclear energy in meeting domestic mitigation targets and international climate change commitments.

The objective of the publication reflects the goal of the CRP itself to support Member States in national level evaluations of the potential role of nuclear energy in GHG mitigation in preparation of their NDCs and long term low GHG emissions development strategies under the Paris Agreement. Similarly, the CRP sought to assist Members States to develop and apply analytical frameworks — comprising IAEA analytical methodologies and Member States' own models and tools — for the assessment of support mechanisms (i.e. domestic policies, carbon pricing) recognized under the Paris Agreement in order to identify key barriers and develop approaches to address investments in low carbon technologies, including nuclear energy. These objectives contribute, in turn, to the overall goal of IAEA Subprogramme 1.3.2 (Energy-Economy-Environment Analysis) to support Member States' understanding of the potential roles of nuclear energy in achieving Sustainable Development Goals and mitigating climate change.

1.3. SCOPE

The publication describes the role of nuclear energy in climate change mitigation and the range of analytical frameworks suited for assessing and developing mitigation strategies, both in general terms and based on detailed country-by-country summaries of each CRP study. It is intended for a variety of analysts, stakeholders and decision makers, with the aim to strengthen the scientific basis of energy and climate change mitigation strategy and policy development. The publication and the related CRP may thereby ultimately support countries define and achieve ambitious commitments in the UNFCCC process to protect the Earth's climate.

1.4. STRUCTURE

Section 2 presents a short history of the debate on nuclear energy in the UNFCCC. It also provides a review of recent scientific literature on issues related to the role of nuclear energy in climate change mitigation.

Section 3 then presents the national frameworks for analysis and the modelling tools used in the national studies. It contains short descriptions of methods and models which can be used for assessing the prospects for adding or increasing nuclear electricity generation capacities and the impacts on GHG emissions, the main research question of this project. Most national teams used well-established IAEA models, including modified and extended versions, while others applied tools from other international sources (e.g. IEA, Stockholm Environment Institute) and yet others use their own models and analytical tools. This methodological diversity offers the opportunity to examine the extent to which the choice of methodology influences the results. Outcomes of the model simulations are summarized to capture impacts of nuclear power on key energy system features and on GHG or CO_2 emissions from either the entire energy system or the electric power sector alone.

The central element of this publication is Section 4, which includes summaries of the main results of ten participating national research teams. Sources of the short summaries include final reports to the IAEA on the objectives, methods, results and conclusions of the national projects, presentations at the final CRP meeting, other reports and publications prepared by the research teams and supplementary material provided by them for this publication.

Finally, Section 5 presents the main conclusions and outlook emerging from the analysis of the national study teams in order to provide general insights into the potential contribution of nuclear energy to climate change mitigation, observations about the operation of various analytical frameworks and methodologies in the national assessments, opportunities and prospects for future work and the ways the IAEA might support additional work on this issue.

1.5. SUMMARY

Research teams from 12 Member States participated in this CRP. Researchers from Armenia, Chile, Croatia, Ghana, Lithuania, Pakistan, Poland, South Africa, Turkey and Viet Nam prepared final reports with case studies on the role of nuclear power in their respective national energy–climate programmes. Research teams from Australia and Ukraine shared their experiences in technical issues under so-called research agreements, an arrangement that does not require submission of a final report.

Table 1 lists the ten countries that contributed final reports presented in this publication, the titles and themes of their studies and selected socioeconomic, energy and emissions indicators. As shown in the table, the Member States participating in this CRP differ considerably in virtually all considered characteristics. They comprise small, medium and large countries, with populations ranging from about 3 million to more than 212 million. The participating Member States also include a mix of lower middle, upper middle and high income countries covering an annual per capita income range from US $1500 up to US $19 100, equating to total economic output between US $12 and 771 billion (in 2018 international dollars). Total CO_2 emissions from fuel combustion span from about 5 to 428 gigatonnes (Gt), or between half and eight tonnes per capita (and around 0.2 to 1.2 kg CO_2 per dollar of economic output), reflecting their different levels of development, economic structures, energy intensities and fuel mixes (and associated energy–climate challenges). Total power generation extends across two orders of magnitude, and between 0.4 and 4.5 megawatt-hour (MW·h) per capita, and the contribution of nuclear power in the three countries currently operating nuclear power plants (NPPs) ranges between 7 and 27% of electricity generation.

TABLE 1. COUNTRY STUDY TITLES, THEMES AND MAIN INDICATORS IN 2018
(data sources: Refs [18, 19, 20])

Country	National study title (and main theme)	Additional (non-climate) themes	Population (million)	GDP[a] (current US $ billion) (per capita (US $ thousand))	CO_2 emissions[b] (Mt[c]) (per capita (t))	CO_2 emissions[b] per unit of GDP[a] (kg/US $)	Total electricity generation (TW·h[d]) (per capita (MW·h[e]))	Share of nuclear in power generation (%)
Armenia	Assessments of the Potential Role of Nuclear Energy in Armenian Climate Change Mitigation Strategies	Energy import dependence, supply security	3.0	12.5 (4.2)	5.4 (1.8)	0.43	7.8 (2.6)	26.6
Chile	Evaluation of the Potential Contribution of Nuclear Power for Meeting National Targets of Greenhouse Gas Reduction	Environmental impacts of different nuclear technologies	18.7	298.3 (15.9)	85.7 (4.6)	0.29	82.3 (4.4)	n.a.[f]
Croatia	Evaluation of Climate Change Mitigation Options in Power Generation (Case Study Croatia)	Role in national energy planning, depleting hydrocarbon reserves	4.1	61.0 (14.9)	15.3 (3.7)	0.25	13.6 (3.3)	n.a.[f]
Ghana	Potential Role of Nuclear Energy in Aiding Ghana's Climate Change Strategy	Fast growing economy and demand for electricity	29.8	65.6 (2.2)	14.7 (0.5)	0.22	12.3 (0.4)	n.a.[f]
Lithuania	Modelling of Least-Cost Long-Term Greenhouse Gas Emission Reduction Strategies for Lithuania	Road transport model, power sector integration and isolation	2.8	53.5 (19.1)	11.1 (4.0)	0.21	3.5 (1.3)	n.a.[f]

Pakistan	Potential Role of Nuclear Energy in Climate Change Mitigation Strategies of Pakistan	Large share of imported energy, supply security	212.2	314.6 (1.5)	194.1 (0.9)	0.62	149.2 (0.7)	7.0
Poland	Assessing the Potential Contribution of Polish Nuclear Power Programme in Meeting National Targets of Greenhouse Gas Reduction	Model development, assessment of official energy strategies, energy sector transformation	38.0	587.1 (15.5)	305.7 (8.1)	0.52	170.0 (4.5)	n.a.[f]
South Africa	The Potential Role of Nuclear Power and Other Low Carbon Electricity Generation Options in Achieving South Africa's Mitigation Ambitions	Aging coal power fleet, support national energy planning process	57.8	368.3 (6.4)	428.0 (7.4)	1.16	256.1 (4.4)	4.5
Turkey	Assessments of the Potential Role of Nuclear Energy in National Climate Change Mitigation Strategies	Transfer of emission charges to support low carbon sources	82.3	771.4 (9.4)	374.1 (4.5)	0.49	304.8 (3.7)	n.a.[f]
Viet Nam	Assessment of Low Carbon Options (Technologies and Policies) for Power Sector Development in Viet Nam up to 2035	Fast growing electricity demand, multi-criteria assessment of supply options	95.5	245.2 (2.6)	226.5 (2.4)	0.92	240.9 (2.5)	n.a.[f]

[a] GDP: gross domestic product.
[b] CO_2 emissions: CO_2 emissions from fuel combustion.
[c] Mt: megatonne.
[d] TW·h: terawatt-hour.
[e] MW·h: megawatt-hour.
[f] n.a.: not applicable.

The diverse national circumstances across CRP participants and their different starting points in the climate change mitigation process have the potential to provide a wider range of insights applicable to both developed and developing Member States about possible decarbonization strategies, including the role of nuclear energy.

The low carbon nature of nuclear energy has long been demonstrated by numerous studies over the past four decades since global climate change emerged and became increasingly prominent in scientific and political agendas. Over this time, an increasing number of countries have decided to include nuclear power in their national electricity supply portfolios, often independent of climate change concerns, motivated by factors ranging from scarce or expensive domestic fossil energy resources to high dependence on imported energy and energy supply security. At the same time, the role of nuclear energy has been influenced by concerns regarding possible severe accidents and radioactive waste, and more recently the emergence and rapid development of renewable energy technologies, which have received substantial financial support for research, development and deployment.

The importance of these factors is reflected in recent scientific literature (reviewed in Section 2). While there is little disagreement across studies that nuclear energy is a low carbon technology, results of model based studies, single issue analyses and comprehensive reviews diverge considerably about its role in international and national GHG emission reduction endeavours. This ongoing debate about nuclear energy and its contribution to climate protection highlights the timeliness of this CRP, which provides a valuable complement to the broader literature.

The recent scientific literature also illustrates the very diverse range of methodological concepts and tools used to analyse the role of nuclear energy and other low carbon options in mitigation. Synthesizing results emerging from different theoretical and methodological frameworks can provide complementary, stronger and more reliable insights for policy making. At the same time, there is no clear association in the literature between the choice of analytical tool and the conclusions regarding the potential role of nuclear energy in climate change mitigation. Differences in conclusions appear to be driven by assumptions and judgments, taking the form of explicit constraints on nuclear power, parameter specifications for technology costs and performance, or weightings assigned to the wide range of criteria against which energy technologies are assessed and compared.

Reflecting the broader literature, the CRP brings together a diversity of complementary analytical frameworks and contexts. The national studies in the CRP have approached the topic by applying different analytical tools that frame key energy system features while considering the most important constraints and challenges for nuclear energy and formulating policy relevant questions about its role in climate change mitigation strategies in their national contexts. Nevertheless, they all focus on the quantitative assessment of economic costs (total energy systems costs, price of electricity) and environmental benefits (lower GHG emissions) of including nuclear power in the electricity generation mix. The tools applied in the CRP are based on two main modelling approaches widely used in energy–climate studies. Most teams applied bottom-up models of energy systems, which include detailed descriptions of current and possible future energy supply technologies. These models estimate the least cost energy system configuration (i.e. the combination of technologies and fuels) to satisfy a given demand for energy services under different scenarios representing economic, natural resource and environmental constraints, and different policy objectives and mechanisms. A smaller number of CRP teams applied top-down models, which examine the performance of the energy sector in the broader context of the national economy. These models calculate impacts and feedbacks of policy triggered changes in relative prices and incomes across different markets — describing economic behaviour based on microeconomic principles and representing primary factors of production (mostly capital, labour and natural resources) — to estimate the equilibrium between supply and demand.

These two approaches have strengths and weaknesses: bottom-up models tend to be rich in technology detail but have a limited representation of broader economic interactions, while top-down models account for these interactions but generally include only an aggregated representation of energy technologies. The selection of analytical framework by each CRP research team was determined by several factors, including the specific research questions of interest, with a majority of teams focusing on energy system impacts and technological factors (and thus employing technology rich bottom-up modelling tools). Nevertheless, many decisions about energy–climate policies, including the role of nuclear energy in climate change mitigation, require information on both the technological characteristics and feasibility of various options as well as their economy-wide impacts in term of gross domestic product (GDP), employment, household income, competitiveness and government budget. While this remains methodologically challenging, one CRP team employed an integrated bottom-up and top-down approach.

The overall conclusions from this CRP reveal that nuclear energy has a significant potential to contribute to climate change mitigation, although this varies considerably depending on national circumstances — including the size and level of development of the national economy, fossil fuel and renewable energy endowments, the energy intensity of the economy, the carbon intensity of the energy system and many others — reflecting some of the debate regarding nuclear energy in general and its suitability for climate change mitigation as seen in recent scientific studies. Appropriate policy targets and instruments can support investment in nuclear energy to unlock its mitigation potential.

The CRP studies find that the economic performance of nuclear power, especially its costs in absolute terms and relative to those of available low carbon alternatives, is a key factor (and potential policy target) in the decision concerning its role in climate change mitigation. Nuclear power is often more competitive if moderate construction costs or lower discount rates, reflecting alternative financing arrangements, can be achieved, even in the absence of mitigation targets. Nuclear power becomes increasingly attractive when constraints or charges are applied to GHG emissions (e.g. via emissions trading or carbon pricing regimes) relative to more GHG intensive technologies. The magnitude of the benefit and whether it is large enough for nuclear power to become competitive in the clean electricity supply portfolio depends primarily on the availability and costs of other low carbon technologies, predominantly new renewable energy sources (RESs) such as wind and solar power. In countries where the availability of cheap RESs is estimated to be low, or nearing the limit beyond which more intermittent supply would jeopardize grid stability, nuclear power is assessed to have a significant or even key role in climate change mitigation.

In addition to the availability of competing low carbon energy sources in the mitigation portfolio, other factors and objectives in national energy policies also influence the prospects for nuclear power. Fast economic growth (driving rapidly increasing demand for electricity), energy supply security and reducing import dependence, avoiding power shortages when hydropower plants are constrained by low water flows, enhancing grid flexibility and reserves or, more generally, diversifying and enhancing the security of the electricity supply are among the most important policy objectives besides climate change mitigation that support the use of nuclear energy despite its costs and other drawbacks.

Overall, studies in this CRP confirm that nuclear power can play an important role in responding to climate related challenges. Depending on specific national circumstances and priorities, such as those mentioned above, nuclear power can foster not only GHG emissions reductions but also other aspects of sustainable energy development.

2. THE ROLE OF NUCLEAR ENERGY IN CLIMATE CHANGE MITIGATION

The appropriateness and potential of nuclear energy in reducing GHG emissions in particular countries and in joint international efforts have been extensively debated ever since the UNFCCC entered into force. This section first summarizes the treatment of nuclear power in international climate policy instruments, including lessons for the Paris Agreement learned from negotiations around the eligibility of nuclear power in the implementation of flexibility mechanisms under its predecessor, the Kyoto Protocol. It is followed by a survey of recent scientific assessments (Section 2.2) and national and regional studies (Section 2.3) on this issue that are of particular relevance to the work and results of the national teams in this CRP. This survey serves to provide a balanced illustration of the cross-section of perspectives and methodological approaches. It includes studies asserting the indispensability of nuclear power in climate change mitigation through to publications claiming that the transition to zero carbon electricity is feasible without nuclear energy. The main conclusions are summarized in Section 2.4.

2.1. DEBATES ABOUT NUCLEAR POWER IN THE UNFCCC

In 1992, the international community adopted the UNFCCC with the objective of achieving stabilization of GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. The UNFCCC did not stipulate the role of specific mitigation technologies such as nuclear power, referring instead in broad terms to the application of technologies to reduce GHG emissions (Article 4.1c) and the commitments of developed country Parties (listed in Annex I) to adopt policies and measures taking into account the differences in “available technologies and individual circumstances” (Article 4.2a).

At the Third Conference of the Parties (COP 3), held in 1997 in Kyoto, Japan, Parties agreed to a protocol to the UNFCCC [4] that specified legally binding, albeit modest, GHG emission reduction targets for almost all Annex I countries [21]. Like the UNFCCC, the Kyoto Protocol itself did not promote or restrict the use of specific low carbon technologies; however, the Protocol introduced three flexibility mechanisms — elaborated below — to help reduce the costs of implementation. The eligibility of different technologies under these mechanisms was a topic of intense negotiation over several years.

As a brief aside, at the time of negotiating the implementation rules of the Kyoto Protocol in the late 1990s and early 2000s, the main options for reducing GHG emissions included increasing end use energy efficiency in all sectors and more widespread utilization of three main supply options: modern bioenergy, nuclear power and fossil fuels with CO_2 capture and storage (CCS). Although wind and solar energy had expanded significantly, they were not major contributors to GHG mitigation at that time, while hydropower was considered to have a relatively limited potential to deliver additional mitigation. Of the three supply options, only nuclear power was in widespread use, with several decades of operational experience in over 30 countries. Experience in China, France, the Republic of Korea, the Russian Federation, the USA and other countries in the past had demonstrated that deployment of nuclear power can be scaled up rapidly. However, nuclear power as a mitigation option was controversial. Some countries, e.g. France, the United Kingdom and the USA intended to include nuclear energy in their domestic energy portfolios and mitigate GHG emissions, others, e.g. Germany and Belgium, were phasing out nuclear power, and still others prohibited its use entirely (e.g. Austria and Italy).

In the lead-up to COP 3, numerous economic analyses indicated that flexibility in the location, time and nature of mitigation actions offered significant potential to reduce the economic costs of emissions reductions at the levels under discussion in the Kyoto agreement. Studies estimated that cost reductions from the flexibility mechanisms could be as large as 90% in an ideal case when all actions that reduced emissions below reference levels anywhere in the world could be credited and projects would be approved without delays and with zero transaction costs. This underpinned the rationale for establishing three flexibility mechanisms in the Protocol: (1) emissions trading and (2) joint implementation for countries with quantified emission limitation or reduction commitments (listed in Annex B to the Protocol) and (3) the clean development mechanism (CDM) between Annex I and non-Annex I countries to jointly support development and climate protection in developing countries.

The flexibility mechanisms provided the possibility for countries to meet their emissions abatement obligations under the Kyoto Protocol through activities undertaken beyond their national boundaries. Many country delegations and interest groups involved in the negotiations were sceptical about the use of flexibility mechanisms in general because they could potentially enable developed countries to largely avoid domestic abatement actions. In addition, questions arose about whether certain types of activities, including nuclear power projects, should be eligible under the mechanisms. Of particular focus was the eligibility of nuclear power under the CDM.

Eligibility of nuclear power (and some other options, including large scale hydropower and CCS) under the CDM was contested on the basis of Article 12 of the Kyoto Protocol, which left wide room for interpretation in stipulating that CDM projects should, among other criteria, assist developing countries in achieving sustainable development and reduce emissions beyond what would occur otherwise. Opponents (comprising developed countries prohibiting or phasing out nuclear energy, many smaller developing nations and powerful advocacy groups) argued that nuclear power was inappropriate for sustainable development and was already a commercial technology, so would not result in additional abatement. They also argued that supporting nuclear power under the CDM would crowd out other (in their view) more preferable technology options such as renewable energy.

In contrast, a number of large countries and interest groups such as the International Chamber of Commerce supported the inclusion of nuclear power in the CDM. They maintained that decisions about the appropriateness of technologies should be made by the host country rather than be imposed under an international agreement and argued that nuclear energy provided cost effective mitigation. Proponents also contemplated that prohibiting nuclear power or other technologies would establish a detrimental precedent for future international agreements and restrain technological innovation. News accounts in that period showed that Canada, China, France, India, Japan, the UK and the USA, among others, supported the eligibility of nuclear power projects in offset mechanisms.

Decisions on the eligibility of nuclear energy in the CDM, as well as several other contentious issues, were finally approved at COP 7 in 2001 in the Marrakesh Accords [22], which state that “Parties included in Annex I to the Convention are to refrain from using” emission reduction units (Decision 16/CP.7) and certified emission reductions (Decision 17/CP.7) “generated from nuclear facilities to meet their commitments” to reduce emissions. Although this is not necessarily an explicit ban, the decision eliminated any offset incentive for potential investors. Moreover, it became apparent by 2001 that nuclear projects would face extreme opposition from the soon to be established CDM Executive Board. However, in retrospect, it seems somewhat surprising that this outcome achieved the level of consensus required in the

UNFCCC decision process and that at least some of the major countries supporting nuclear projects as offsets did not find a way to prevent the de facto prohibition. It can be speculated that pressure to reach an agreement weakened support for nuclear energy in the face of persistent opposition, notably by the European Union (EU).

Ultimately, CDM as a whole achieved only a miniscule fraction of its anticipated potential due to several hindrances such as restricted project eligibility, high transaction costs, project delays (due to the CDM approval process, among others) and low allowance prices. In contrast to the exclusion of nuclear power from the CDM, it is notable that CCS has become an eligible technology. Box 1 presents the background.

BOX 1. CCS AS AN ELIGIBLE TECHNOLOGY IN THE CDM

Many governments publicly organized support and succeeded in keeping CCS, another controversial technology, as an option for the CDM at COP 6. Supporters of CCS formed the very visible Carbon Sequestration Leadership Forum in 2003 and, through persistent lobbying, were able to secure a declaration at COP 17 in Durban in 2011 that CCS projects with geological storage of CO_2 were eligible for CDM, albeit subject to a long list of criteria to be met for approving projects.

As of October 2020, this forum comprised 26 members (25 countries and the European Commission), including major developing countries such as Brazil, China, India, Mexico, South Africa and others. Ironically, CCS is still controversial in many member countries of the forum such as Germany where federal states can ban carbon storage projects and not a single CCS demonstration project is likely to be implemented in the coming years (see Ref. [23]).

Turning to the Paris Agreement, countries are free to specify technology details in their NDCs, and the Agreement neither defines criteria for low carbon energy technologies nor identifies any energy technology explicitly (except the promotion of universal access and sustainable energy in developing countries, in particular in Africa, through the enhanced deployment of renewable energy). Accordingly, all technologies, including nuclear, are available to countries for implementing their NDCs as a means of progressing towards the targets of the Paris Agreement. As of July 2021, 19 countries specifically mention nuclear power as part of their current NDCs/INDCs, including China, India, Japan, Jordan, Turkey, the UK and the USA (noting that EU countries — including 13 using nuclear power — do not submit separate NDCs but are instead covered by the NDC submitted by the European Commission, which does not mention nuclear power). Several additional countries mention nuclear energy in their long term low GHG emissions development strategies communicated under the Paris Agreement, including Mexico and six EU countries, while a number of other countries that currently use nuclear power (out of a total of 32) do not rule out the possibility of using this technology as part of efforts to strengthen climate actions. Furthermore, about 30 countries that are either considering or planning to include nuclear power in their energy mix are actively working with the IAEA (see Ref. [24]).

Although the Paris Agreement leaves technology choices to the Parties, some aspects of the Agreement still under negotiation could influence the conditions under which low carbon technologies, including nuclear power, can contribute to climate change mitigation going forward. These aspects include the specification of rules and procedures for new market based mitigation mechanisms, which may influence domestic policies and carbon pricing, including additional criteria related to the sustainable development goals.

The Paris Agreement defines two market based mechanisms based on ‘voluntary cooperation’ that have the potential to capitalize on the mitigation potential of nuclear power (see Ref. [25]). The first comprises Cooperative Approaches (under Article 6.2), which are expected to enable two or more Parties to exchange internationally transferred mitigation outcomes (ITMOs) under specific bilateral project or programme based agreements to reduce GHG emissions. The other mechanism is a somewhat revised version of the CDM called the Sustainable Development Mechanism (Article 6.4), which aims to contribute to mitigation and support sustainable development. However, the rules, modalities and procedures governing these mechanisms are still to be fully defined, and it remains to be seen if technological restrictions will be incorporated because of issues such as additionality, sustainability and transparent accounting.

2.2. NEW INQUIRIES INTO THE SCOPE FOR NUCLEAR ENERGY IN MITIGATING GHG EMISSIONS

Numerous analyses, including the Contribution of Working Group III to the Fifth Assessment Report of the IPCC (see Fig. 7.6 in Ref. [26]), confirm that nuclear power is among the lowest contributors to GHG emissions over the entire life cycle (‘from cradle to grave’), with emissions per unit of electricity similar to hydro- and wind power [6]. The potential future contribution of nuclear energy to climate change mitigation is also illustrated in international studies exploring long term scenarios of the global energy system [6], including the 2018 IPCC Special Report on Global Warming of 1.5°C [3]. Despite technical, economic, social and policy uncertainty, nuclear power is seen to have a significant potential across the vast majority of stringent mitigation scenarios. For example, in the full set of IPCC pathways compatible with the goal of limiting global warming to 1.5°C, average nuclear generation triples by 2050 from 2018 levels.

Nevertheless, ongoing interest and debates in the policy arena about the potential role of nuclear energy continue to generate further studies about the subject. A common difficulty faced in many such investigations is that nuclear energy provokes a range of social and political disagreements beyond the scope of the scientific, technological and economic methods used in many analyses. This is also reflected in recent publications.

Starting from the basics, the latest edition of a popular textbook on nuclear energy concepts, systems and applications [27] includes a chapter explaining the possible future role of nuclear energy in climate change mitigation. The chapter reflects many of the findings of the IPCC and others regarding the increasing global demand for energy and electricity, the urgent need for sustainable large scale power generation and the low contribution of nuclear power to CO_2 emissions, even when compared to RESs like solar and wind power. The chapter also notes that nuclear reactors can be utilized for large scale desalination in regions with increasingly scarce water resources and hydrogen generation for various applications in industry and transport. Yet public opposition to nuclear energy strongly influences government policies in some countries.

Other studies representing a cross-section of perspectives and methodological approaches are briefly reviewed below to illustrate the potential and some of the related challenges in more detail. Considering the urgency of reducing GHG emissions by around mid-century, one study [28] reviews the prospects for the main low carbon energy technologies (hydropower, wind, solar, coal with CCS), assesses past experience with and potential future properties of nuclear fission technologies and proposes that nuclear power could replace all coal power plants without CCS starting around 2025 or somewhat later. The study estimates the required nuclear capacity at about 1600 gigawatts (electrical) (GW(e)) during the period 2025–2065 and demonstrates that — with pressurized water reactors as the dominant light water technology — the uranium supply would be sufficient without fuel reprocessing. Looking beyond the imminent mitigation requirement, this study estimates that Tokamak fusion might be developed by the 2050s but the commercial potential of current concepts is limited owing to the scale and complexity of the technology. New concepts for fusion may arise but their development and commercialization might stretch out into the next century. Fast breeders and small modular reactors (SMRs) are considered as possible competitors in the long term utilization of fission energy. Molten salt thorium reactors are also potential contributors to safe and economical nuclear power that would at least provide baseload supply together with RESs. The proposed gradual substitution of all non-CCS coal power plants by nuclear plants from 2025 would reduce annual CO_2 emissions in 2065 by 11.8 Gt [29]. Unquestionably, building 1600 GW(e) of nuclear capacity would be next to impossible without public support. Yet the authors argue that it would be irresponsible not to use the mitigation potential of proven fission technologies to supply baseload electricity.

A different approach is taken in a recent review paper [30] that applies a three-way assessment framework to analyse the current performance of nuclear energy across three dimensions: energy, climate change and the environment. This review of recent literature seeks to reflect both positive (energy security and mitigating climate change) and negative (accident risk, spent nuclear fuel storage) characteristics of nuclear energy. The findings suggest that from energy supply and economic perspectives, nuclear power remains an important energy source for at least a few more decades in nuclear countries, reflecting recent decisions to extend the operating lifetimes of existing power plants and the numerous new builds currently under construction in many countries. Concerning the role in climate change mitigation, nuclear power is considered to be a major potential contributor to decarbonizing the global energy sector because GHG emissions from the entire life cycle of nuclear energy are similar to those of RESs. The review paper therefore suggests that keeping nuclear energy as part of the global decarbonization strategy is a meaningful solution. However, one needs to consider the risks of nuclear accidents and the challenges of managing high level radioactive waste. In this context, the authors maintain that fission based nuclear power should be gradually but systematically replaced by RESs and nuclear fusion in the future, despite lower risk of nuclear accidents due to steadily safer fission reactor technologies. They maintain that this will bring multiple advantages such as increasing global energy security and clean electricity production without long lived radioactive waste. Accordingly, the authors' advice to policy makers is to continue and intensify fusion electricity research and development efforts because it could be a major contributor to protecting the Earth's climate and solving other environmental issues.

The above study clearly shows the need for better understanding of how risks associated with nuclear accidents and radioactive waste and, more generally, with nuclear power are perceived by the public and influence their acceptance of this technology in the context of climate change mitigation. In this direction, a quantitative approach to risk perception concerning nuclear power is adopted by a recent survey based study [31]. Recognizing that public perception limits or even prevents the deployment of some energy technologies and that modellers struggle to incorporate these factors in integrated assessment and energy system models, the study compares how knowledge and ignorance of a particular technology affects judgments about the acceptability of the technology based on actuarial risk. This approach has the potential to provide guidance to energy modellers to select appropriate quantitative limits on nuclear power that accurately reflect public opposition rather than applying ad hoc limits or developing arbitrary nuclear-free scenarios. The authors conducted an experiment involving a large sample of US citizens (N = 1226) to distinguish public opposition due to the fear of nuclear power from opposition resulting from its actuarial risk (based on accident statistics). In this survey, respondents were provided with information about the actuarial risks of technologies and asked to select a mix of power generation technologies that cuts CO_2 emissions. All respondents received the same risk information but half of them were not informed about the type of technology (e.g. nuclear power). The differences are large and statistically significant. Respondents who were informed about the type of technology deploy 6.6 percentage points less nuclear power as a share of their preferred US low carbon power generation mix, equivalent to around 40% less nuclear power in 2050 or approximately 40 large reactors. The authors note that their methods could be applied to other technologies where gaps between actuarial and perceived risks might exist, such as CCS.

Returning to global scenario studies mentioned at the beginning of this section, a recent integrated assessment using one of the models in the IPCC Special Report on Global Warming of 1.5°C [3] provides additional insights by exploring the implications of reactor ageing and nuclear phase-out policies in the context of GHG emissions mitigation to 2100 [32]. Modelling with the World Induced Technical Change Hybrid (WITCH) model [33] — a dynamic optimization model combining a top-down optimal growth model with a detailed bottom-up representation of the energy sector — shows the potential for nuclear power to expand across scenarios in which deployment is not constrained. Expansion is higher in a scenario in which a global carbon tax is assumed and nuclear power partly replaces retired fossil fuel plants. However, if phase-out (NPP closure after 60 years operating time) or switch-off (immediate shutdown) policies are assumed in the OECD, the growth of nuclear power is lower and closer to a business as usual (BAU) trajectory. Not surprisingly, global nuclear generation goes to zero immediately in the global switch-off scenario and declines to zero in few decades under a global phase-out. In the constrained nuclear scenarios, RESs (mainly wind and solar photovoltaic (PV)) and, to a lesser extent, fossil sources with CCS fill the power generation gap. The calculated additional policy costs (GDP loss) of a nuclear phase-out are moderate because, based on the assumptions and parameters in the WITCH model, they are almost entirely compensated by innovation and technology benefits of RESs and energy efficiency improvements.

The possibility to replace nuclear power with other low emissions generation technologies (notably RESs) reported in the above analysis draws attention to the large number of studies concerned with the question of how and when electricity producers could achieve the target of generating 100% of their output from renewable sources (and whether this is possible or desirable). In a recent book about resource planning by electric utilities, a chapter explores various aspects of a target of 100% renewable energy [34]. The author observes that in the hasty and zealous propositions to achieve power sector decarbonization, it is often implied that future electricity systems must entirely be based on RESs. He warns that this is neither required nor necessary in the strict sense. A climate benign GHG free power system might well include non-renewable generation such as NPPs and thermal plants burning hydrogen or carbon neutral synthetic hydrocarbons (e.g. synthesized from hydrogen along with CO_2 directly captured from the air). The author explores different pathways utilities could follow to achieve a 100% carbon free end state and suggests, nonetheless, that the bulk of the electricity is likely to come from RESs, irrespective of how such a target is defined.

Combining RESs and other low carbon electricity generation technologies such as nuclear power has been a widely discussed topic in recent years. A study [35] reviews the prospects for new hybrid or integrated nuclear–renewable energy systems that have been recommended as an attractive option. Such hybrid systems include an NPP, renewable energy generation and industrial processes. After evaluating the challenges for renewable energy (scalability, commercialization, timeline, material input requirements, intermittency, land requirements, grid compatibility, technological barriers and ecological issues) and the difficulties faced by nuclear power (economic and financial issues, safety and security, waste disposal, additional research and technological development needs, public perception and opinion), the author investigates technical, economic, interconnection and other aspects of various hybrid nuclear–renewable energy systems. He identifies several advantages of the hybrid systems such as fostering the competitiveness of renewable energy and thus expanding its role in power generation, increasing the penetration of intermittent RESs by transforming the grid infrastructure to provide grid scale energy storage and dispatch, and initiating advanced integration via smart control and heat management technologies to increase energy conversion efficiency. Hybrid systems can potentially ease public fear and opposition associated with nuclear power by combining it with widely accepted RESs.

Another inquiry [36] into the joint contribution of RESs and low carbon non-renewable technologies to GHG mitigation investigates the role of ‘firm’ low carbon resources, comprising reliable sources of electricity available over extended periods any time (e.g. flexibly operated NPPs, hydropower plants with large reservoirs, coal and natural gas plants with CCS and flexible operation capabilities, geothermal, biomass and biogas fuelled power plants), as distinct from variable renewable energy resources and short duration energy storage, flexible demand (or schedulable loads) and other demand-side responses. The authors use the electric power system investment and operations model GenX (see Ref. [37]) to evaluate the role of firm low carbon resources in reducing GHG emissions from power generation in combined systems including variable renewable resources, battery energy storage, demand flexibility and long distance transmission. They assess more than 900 scenarios across a wide variation of CO_2 emissions constraints, technological uncertainties and region specific differences in demand and RES potentials. The authors conclude that firm low carbon technologies, including nuclear power, bioenergy and natural gas with CCS, are increasingly valuable with tighter emissions constraints since they reduce electricity costs in the overwhelming majority of cases. This implies that short term policies and investments need to consider technology options according to their performances in long term decarbonization instead of near term targets. Moreover, firm low carbon resources are especially valuable in regions where the availability of RESs is limited. These technologies also provide an effective hedge if further steep reductions in the cost of variable RESs are not achieved. The general insight is that firm resources foster achieving deep decarbonization of power generation at reasonable costs.

Such findings are not inconsistent with those of other studies that find that zero carbon electricity supply is *possible* without nuclear power or fossil generation with CCS, albeit at higher cost and with additional trade-offs (see Ref. [38]).

An increasing number of studies analyse the role of emerging and advanced nuclear technologies in addressing global climate change. For example, an in-depth review identifies several potential advantages of SMRs owing to their size, modularity and design features [39]. Although the reduced size of SMRs is not new either in terms of physical scale or power capacity, they offer economic and flexibility advantages that allow their application for various purposes (ranging from power generation to burning radioactive waste) in different power systems, grids or off-grid applications. The review examines different definitions of modularity (design, process intensification, manufacturing and construction) and concludes that different forms of modularity have both advantages and drawbacks that need to be addressed in order to exploit the full potential of SMRs. The review also shows that many modern SMR designs incorporate tested and well-proven features of early reactors while others introduce inherent and/or passive safety characteristics of Generation IV reactors. SMRs are considered by many experts a potential technology to reduce GHG emissions and to supply reliable baseload power. The review suggests that the licensing of such reactors by national regulators is expected to accelerate their acceptability and application in mitigating GHG emissions even in electric grids that are too small for traditional large reactors.

Beyond its merits in GHG emissions mitigation, many recent publications highlight the co-benefits of using nuclear power in combatting climate change in terms of human health and environmental protection. These studies identify, for example, considerable and diverse positive impacts on human health far beyond those of mitigating climate change (see Box 2).

2.3. RECENT NATIONAL AND REGIONAL STUDIES

In addition to the studies investigating the prospects for nuclear energy in climate change mitigation on a global or generalized basis, an increasing number of studies explore the issue in specific geographical contexts ranging from subnational regions to multinational unions. Insights relevant for the national studies in this CRP are concisely presented in this section.

Starting with the USA, a recent paper [40] proposes that the response to the global threat of climate change should be triaged — a term used in the medical field referring to procedures to prioritize patients, especially when vital resources are scarce — by identifying regions and countries where CO_2 emissions are high, increasing or beginning to increase along with the technologies that can have the greatest impact on global CO_2 emissions, while sustaining economic growth and development. According to the triage approach, the initial strategy for CO_2 mitigation should not prohibit a technology that has a proven record of reducing CO_2 emissions rapidly and at scale (i.e. nuclear power) and attribute 100% dependency on technologies with no precedent of such achievements (i.e. non-hydro RESs). The author emphasizes that RESs and associated technologies will be indispensable in a diverse low and zero carbon energy future but they have limits and nuclear power cannot neglectfully be rejected. The paper concludes that the US nuclear power sector needs to be incorporated in the US energy and climate policy in order to meet global GHG mitigation and national security objectives.

Another study of the US electric power industry observes that the availability of cheap natural gas and the increasing use of low cost RESs reduce electricity prices and may lead to the premature retirement of many NPPs that currently provide over 60% of the carbon free electricity in the country [41]. The authors use a Monte Carlo based model to assess the future economic viability of existing US NPPs by determining a break-even price of electricity required to cover the costs of the plants between 2015 and 2040 and combine these costs with forecasted revenues under different scenarios to determine a payment (they call it 'missing money payment') each NPP would need to receive above its revenues from power sales to break even through 2040. In their low natural gas price scenario, US NPPs are estimated to require an additional payment of 8–44 US $/MW·h (median results) on top of their electricity sales revenues in order to break even. Since, in the absence of this payment, NPPs would likely be replaced by new combined cycle gas turbine (CCGT) plants, the authors estimate the equivalent cost of avoided CO_2 emissions between 18–30 US $/t (median results) for multi-reactor nuclear plants and 47–97 US $/t (median results) for single-reactor plants. This indicates that keeping the existing NPP fleet running, especially multi-reactor plants, is a cost effective carbon mitigation strategy. The results also show that early retirement of US NPPs would considerably reduce the effectiveness of the recommended CO_2 regulations.

BOX 2. ANCILLARY BENEFITS OF USING NUCLEAR ENERGY IN CLIMATE CHANGE MITIGATION

The accident at the Fukushima Daiichi NPP triggered drastic reductions in nuclear power generation in Japan and Germany. A study analyses energy, electricity and CO_2 emissions data for these countries through 2017 [42] and finds that CO_2 emissions increased after the accident until 2013 but declined afterwards because total energy use decreased, and very high renewable energy generation was achieved. The authors assess the human health and CO_2 consequences of two post-Fukushima scenarios. In the first assumed case, Japan and Germany are assumed to reduce fossil fuel generation rather than nuclear output. The second scenario estimates the implications of shutting down the remaining nuclear power capacities in the USA and the rest of Europe. In the first scenario, it is estimated that Japan and Germany could have avoided 28 000 air pollution related deaths and 2400 megatonnes (Mt) of CO_2 emissions between 2011 and 2017, if fossil based and other non-nuclear generation had been reduced. Germany could prevent a further 16 000 deaths and 1100 Mt CO_2 emissions up to 2035 if coal based generation were reduced rather than nuclear power eliminated according to the phase-out plan. In the second scenario, the study estimates that over 200 000 additional air pollution related deaths and 14 000 Mt CO_2 emissions would occur by 2035 if the USA and the rest of Europe followed the German nuclear phase-out policy.

An extensive review [43] compares environmental impacts and risks to humans of nuclear, hydro, wind, solar and biomass electricity generation, including specific impacts of wind turbines on human and bird populations, the widely ignored or underestimated difficulties of biomass and concerns over biodiversity degradation. The authors find carbon intensity values for nuclear power and RESs similar to those presented in various IAEA reports (see Refs [6, 24, 44]): on life cycle basis, GHG emissions from nuclear power are similar to those from wind technologies and lower than even the lowest PV technology (thin film). Moreover, nuclear power performs well compared to RESs in terms of land and water use, critical raw material input and even against controversial criteria such as fatalities in operation or mortality per unit of electricity produced. The authors maintain that life cycle analyses are the most promising approach to developing objective criteria for energy technology choices but it is largely ignored by policy makers and their advisors.

A UK research team uses a detailed techno-economic energy systems model (UK The Integrated MARKAL-EFOM System (TIMES) — see Section 3 for a presentation of TIMES, also used in the South Arica study presented in Section 4.8), air pollutant emission inventories, a sophisticated air pollution model (Community Multi-scale Air Quality) and correlation data between air pollutant concentrations (fine particulate matter (PM2.5), nitrogen dioxide and ozone) and human health consequences to analyse ancillary benefits [45]. Among other scenarios, the study explores two nuclear power scenarios that meet the target of the UK Climate Change Act: one with a limited increase of nuclear electricity generation, and a second without any constraint on nuclear output. Modelling results estimate that in the latter case almost 50% more life years can be saved between 2011 and 2154 due to lower nitrogen dioxide emissions than in the scenario when nuclear power extension is constrained, subject to the considerable uncertainties of projecting to the middle of the twenty-second century.

Moving northward from the USA, the Canadian province of Alberta sources nearly 90% of its electricity from fossil fuels (mostly coal). In November 2015, the Government of Alberta announced the goal for zero emissions from coal fired electricity generation by 2030 [46] and to replace two thirds of the lost capacity with RESs. The implications are analysed in a recent study applying the load duration and screening curves method to calculate minimized costs of power generation to meet projected hourly load across a range of carbon tax scenarios [47]. Results show that wind and solar investments might replace a maximum of one third of the lost coal capacity but only 22% of the electricity generated from coal, while the rest would need to come from gas. The largest optimal capacity of intermittent RESs would require an implied price of carbon higher than 175 US \$/t CO_2, the level at which nuclear power would become more economical. The average and marginal costs of renewable and nuclear energy sources are about the same, but deployment of the latter can reduce CO_2 emissions by as much as 97% compared to only 56% with solar and wind.

Ambitious climate protection targets and policy initiatives in Europe have stimulated many studies at the level of the EU and its member countries. Some of them also include nuclear power as a mitigation option and provide useful background information to the national studies in this CRP.

One recent study aimed to identify optimal technological portfolios for achieving the EU’s goal to reduce GHG emissions by 80–95% relative to the 1990 levels by 2050 and the related Energy Roadmap for 2050 (see Ref. [48]) by charting cost efficient ways to reduce GHG emissions and energy consumption while increasing competitiveness and supply security [49]. The authors combine the Global Change Assessment Model (see Ref. [50]), a recursive dynamic partial equilibrium model with portfolio analysis and multi-objective optimization to derive optimal technological research and development portfolios. The model was restricted to allocate no more than 30% of the total budget to nuclear energy because it is not supported in several EU countries, while wind and PV were assumed to collectively receive at least 40% of the total budget to reflect energy technology preferences. In spite of these constraints, the results show that all three technologies — PV, wind and nuclear energy — need to be prioritized and subsidized in the optimal portfolio to maximize GHG emissions reduction and energy security. An analysis of inherent stochastic uncertainty indicates that having these three technologies with the largest shares in the budget portfolio is also the most robust arrangement concerning the double objective of GHG emissions reductions and energy security. This is a clear advice to policy makers regarding the priority of PV, wind and nuclear energy.

Another study arrives at rather different conclusions. It explores the techno-economic feasibility of reaching the EU's mitigation targets by 2050 with a politically driven nuclear phase-out [51]), rather than whether this would be *optimal* from an economic or energy security perspective. The authors use a combined short and long term simulation tool, the linear European long term energy system planning model (elesplan-m) (see Ref. [52]) that includes the main electricity generation, storage and transmission technologies considered in Europe. (This model is conceptually similar to the IAEA’s Model of Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) used by several research teams in the CRP but MESSAGE covers the entire energy supply system, not only electricity.) A techno-economically optimized decarbonization pathway for 18 interconnected European regions is simulated, assuming that nuclear power is phased out by 2040. The authors find that the EU's GHG reduction targets (reducing emissions from 1300 to 24 Mt CO_2-eq/year by 2050) can be achieved by large investments (€403 billion over the 34 years modelled) in RESs capacities to achieve a system based primarily on wind energy (1485 GW) and PV (909 GW), complemented by 150 GW hydropower and 244 GW gas generation capacity. Furthermore, 432

GW of storage and 362 GW of transmission capacity are required to distribute electricity in the modelled region temporally and spatially. The authors conclude that the energy transition from conventional to RESs based electricity supply is feasible in the EU even if nuclear power is phased out due to political decisions.

Decisions about the role of nuclear energy in climate change mitigation are difficult in the EU because its member countries have been following very different policies ranging from total prohibition to vigorous new builds. Three recent studies are summarized below from three EU countries.

The UK has even more ambitious climate protection targets than the EU (the target is to bring all GHG emissions to net zero by 2050) and a series of carbon budgets to support policy development over time. Recognizing that current approaches to energy systems modelling either ignore or are unable to consider fully the physical limits to the speed of changing infrastructure, authors of a recent study [53] develop and apply a new system dynamics model and framework to compare physically constrained scenarios that emphasize either CCS, the quickest plausible nuclear new build or the fastest physically possible construction rate of offshore wind capacities, albeit without accounting for grid stability. The results show that an ambitious nuclear extension programme is more costly than building up offshore wind capacities and, due to physical limits to the rate at which NPPs can be deployed, delays emissions mitigation. If nuclear new build or CCS programmes suffer delays or cancellations, offshore wind generation can also help meet the electricity and decarbonization targets without harming financial and employment levels.

Finland has set one of the most ambitious climate change mitigation targets in the EU by aiming to achieve carbon neutrality by 2035. This is a major challenge because carbon intensity of the Finnish power sector is already very low, while district heating, a crucial component of the energy system, still heavily depends on fossil fuels. A recent study [54] analyses the impacts of the necessary transitions in the electricity markets and district heating systems by adopting the MATLAB based linear programming model Enerallt, a multi-region power market and district heating model (see Ref. [55]). The model optimizes regional hourly electricity production in 24 hour intervals (representing the day-ahead market) accounting for interregional transmission capacities. The authors define a range of combinations of energy sources and technologies and develop 17 scenarios to assess the large scale transition to wind and nuclear power and heat pumps in district heating systems. The results indicate that increased shares of wind and nuclear power can counteract the impact of banning hard coal on electricity prices and improve the electricity trade balance.

Italy was among the nuclear energy pioneers in Europe but two referendums rejected its exploitation: the first one in 1987 after the Chernobyl accident, the second in 2011. However, some scientists have suggested reintroducing nuclear power as part of a transition towards a climate friendly and sustainable energy system while addressing high electricity prices, which considerably exceed the EU mean. A recent study [56] evaluates the pros (CO_2 and air pollutant emissions reductions, energy density, dispatchability, fuel availability and security of supply, safety and economics (despite high investment costs considerable benefits due to reduced electricity and fossil fuels, mainly natural gas, imports)) and cons (high initial investment costs, radioactive wastes, nuclear proliferation and public acceptance (the greatest barrier)) of nuclear power in the Italian context. The authors conclude that nuclear energy — together with RESs — could play an important role in decarbonizing the energy sector and accelerating the energy transition while providing advantages in terms of dispatchability and security of supply.

In recent decades, demand for energy and electricity as well as GHG and air pollutant emissions have been growing fastest in Asia. Many countries in the region consider introducing nuclear power or extending its use for various reasons, including climate protection.

A research team from Pakistan participated in this CRP (see Section 4.6), and a recently published paper [57] provides an interesting historical background to their results. The paper uses advanced statistical tools (autoregressive distributive lag model and vector error correction Granger causality analysis) to examine the links between nuclear energy, economic growth and CO_2 emissions in Pakistan between 1973 and 2017. The authors argue that the statistical analysis shows that nuclear energy correlates with CO_2 emissions in Pakistan and speculate on possible explanations for this outcome, including the very low share of nuclear power in the total energy mix (4.36%) (i.e. nuclear energy needs to cross a threshold level to mitigate emissions), the utilization of nuclear power to meet essential energy requirements (thus it does not displace existing fossil fuel generation) and the small capacity of existing NPPs (their construction causes larger CO_2 emissions relative to their power output than that of large capacity units). Nonetheless, the authors conclude that nuclear energy does play a role in forming an environmental Kuznets curve (the inverted U-shaped relationship between economic growth and CO_2 emissions). The study also finds positive association between nuclear energy and GDP that is attributed to the role of nuclear power in reducing electricity shortages and stimulating growth of other sectors providing goods and services to the nuclear industry (see national studies on the macroeconomic impacts of nuclear energy in another IAEA CRP in Ref. [58]).

Another study analyses options for electricity generation to 2050 for Malaysia using TIMES (see Section 3 for a summary of this model framework that was also used in the South African study of this CRP, see Section 4.8). The Malaysian study [59] examines optimized scenarios minimizing energy total system costs with different technology bundles: existing (mainly fossil) technologies; RESs (of which hydropower and PV have by far the largest potential), 2.0 GW(e) nuclear power capacity by 2030 (to simulate the government's former plan, cancelled in 2019) and a 8.57 GW PV capacity combined with 3.59 GW pumped heat electrical storage by 2030 (to generate electricity equivalent to the 2.0 GW(e) NPP). Except for the case with existing technologies, CO_2 emissions decline to virtually zero in all scenarios. The total system costs are lowest in the existing technologies scenario and only slightly higher in the PV plus storage (by 0.7%) and the nuclear (by 3%) scenarios. Without considering any other criteria of sustainability and energy security, the authors claim that "if Malaysia were to adopt a sustainable policy, then nuclear power would not be an ideal option as uranium fuel relies on continuous imports" (Ref. [59], p. 2844).

2.4. CONCLUSIONS

Nuclear energy in general and its role in climate change mitigation remain controversial issues not only in international and domestic politics and policy formulation but also in scientific studies. There is little disagreement in the scientific literature at large and in the studies reviewed here that nuclear energy is a low carbon technology. However, results of modelling studies as well as conclusions from individual assessments and comprehensive reviews widely diverge regarding whether nuclear power should be used in international and national efforts to reduce GHG emissions.

The methodological foundations of the quantitative studies reviewed in the two preceding sections are very diverse and include modelling concept and tools also used by the study teams in this CRP. The main benefit of this diversity is that stronger and more reliable insights for policy making arise from synthesizing results emerging from different theoretical paradigms framed in alternative quantitative approaches.

In the scientific literature and in the studies reviewed above, no clear association is apparent between the analytical tools (models and desk studies) and the conclusions regarding the potential role of nuclear energy in climate change mitigation. Differences in conclusions of modelling studies appear to be driven by assumptions and judgments taking the form of explicit constraints for nuclear power or implied by the parameters specified for different energy technologies, including their economic costs, technological performance and pollutant emissions. There is also considerable scope in desk studies for the analysts' judgements to influence the selection and weighting of criteria against which energy technologies are assessed and compared.

This concise review of recent studies on the topic demonstrates the still ongoing debates about nuclear power and its contribution to climate protection and hence the timeliness of this CRP. The model based assessments in the national studies presented in Section 4 are valuable additions to the scientific information on the subject.

3. NATIONAL FRAMEWORKS FOR ANALYSIS

This section presents short descriptions of the analytical frameworks and modelling tools developed and applied by the participating national research teams to project energy and electricity demand for the next few decades, assess technology options and supply portfolios — including the potential role of nuclear energy — to satisfy the projected demand and evaluate implications of those portfolios for CO_2 or broader GHG emissions. An overview of the modelling tools in Section 3.1 is followed by concise presentations of the two IAEA models used by the majority of the national teams (Sections 3.2 and 3.3) and other models and analytical frameworks applied by a few other teams (Section 3.4). The section concludes with a comparison of strengths and weaknesses of different analytical approaches (Section 3.5).

3.1. ANALYTICAL TOOLS FOR CLIMATE CHANGE MITIGATION ASSESSMENTS

A diverse array of analytical frameworks and modelling tools were used by the national research teams participating in this CRP. Most teams used the well-established and widely distributed IAEA models: the Model for Analysis of Energy Demand (MAED) and the MESSAGE. These teams implemented various features of these models and applied specific data and parameters to reflect particular and important characteristics of their countries' economies and energy systems. The remaining teams applied models adopted from other sources — in many cases drawing on extensive prior experience with these tools — which they combined in various ways to analyse economic, policy and environmental aspects of national energy and electricity strategies.

Table 2 presents an overview of the models and analytical tools used in this study. Some of them are discussed in more detail, while others are summarized briefly in this section.

TABLE 2. MODELS AND ANALYTICAL TOOLS USED IN THIS CRP

Country	Models and tools
Armenia	MAED[a], MESSAGE[b]
Chile	MAED[a], MESSAGE[b], Ministry of Energy Model
Croatia	MAED[a], MESSAGE[b] and PLEXOS Integrated Energy Model
Ghana	LEAP[c], MESSAGE[b]
Lithuania	MESSAGE[b]
Pakistan	MAED[a], MESSAGE[b]
Poland	Extended Input–Output Model for Sustainable Power Generation Poland Climate Change (Empower.pl.cc)
South Africa	South African The Integrated MARKAL-EFOM System TIMES — Energy extension to the South African General Equilibrium (SATIM—e-SAGE)
Turkey	MESSAGE[b]
Viet Nam	LEAP[c], multi-criteria analysis, cost–benefit analysis

[a] MAED: Model for Analysis of Energy Demand.

[b] MESSAGE: Model of Energy Supply Strategy Alternatives and their General Environmental Impacts.

[c] LEAP: Long-range Energy Alternatives Planning.

The MAED and MESSAGE have been extensively used in dozens of Member States to support national energy planning (see, for example, Refs [60, 61]) and sustainable energy assessments (see Refs [62, 63]). These models also support in-house activities as methodological foundations of internal and external publications and reports to United Nations activities such as UN-Energy (see Refs [64, 65]). Short summaries of these models are presented in Ref. [66]. Hardware and software requirement for using these models are presented in their user manuals cited below. The next two sections draw extensively on these publications.

3.2. PROJECTING ENERGY DEMAND WITH THE MAED

The MAED (see Ref. [67]) evaluates future energy demand based on medium to long term scenarios of demographic, socioeconomic and technological developments. The model relates systematically the specific energy demand for producing an identified range of goods and services to the corresponding social, economic and technological factors that affect this demand. Energy demand is disaggregated into a large number of end use categories; each one corresponding to a given service or to the production of certain goods. The nature and level of the demand for goods and services are a function of several determining factors such as population growth, number of inhabitants per dwelling, number of electrical appliances used in households, peoples' mobility and preferences for transport modes, national priorities for the development of certain industries or economic sectors, the evolution of the efficiency of certain types of equipment, market penetration of new technologies or energy forms, etc. The expected future trends for these determining factors, which constitute scenarios, are exogenously introduced.

An understanding of these determining factors permits the evaluation of the various categories of energy demand for each economic sector considered. The total energy demand for each end use category is aggregated into four main energy consumer sectors: industry (including agriculture, construction, mining and manufacturing), transportation, service and household. The model provides a systematic accounting framework for evaluating the effect on energy demand of socioeconomic and technological development, including changes in the economy and in the standard of living of the population. The main inputs and outputs of the MAED are presented in Fig. 1.

The starting point for using the MAED is the reconstruction of base year energy demand patterns of a given country. This requires compiling and reconciling necessary data from different sources, deriving and calculating various input parameters and adjusting them to establish a base year energy balance. This helps calibrating the model to the specific situation of the country. This is followed by the development of future scenarios of the social and economic evolution of the country and technological factors, e.g. the efficiency and market penetration potential of alternative energy forms.

The future scenarios are specific to a country's situation and objectives. The scenario assumptions can be subdivided into two subcategories:

- The first related to the socioeconomic system describing the fundamental characteristics of the social and economic evolution of the country;
- The second related to the technological factors affecting the calculation of energy demand, e.g. the efficiency and technical market penetration potential of each alternative energy form.

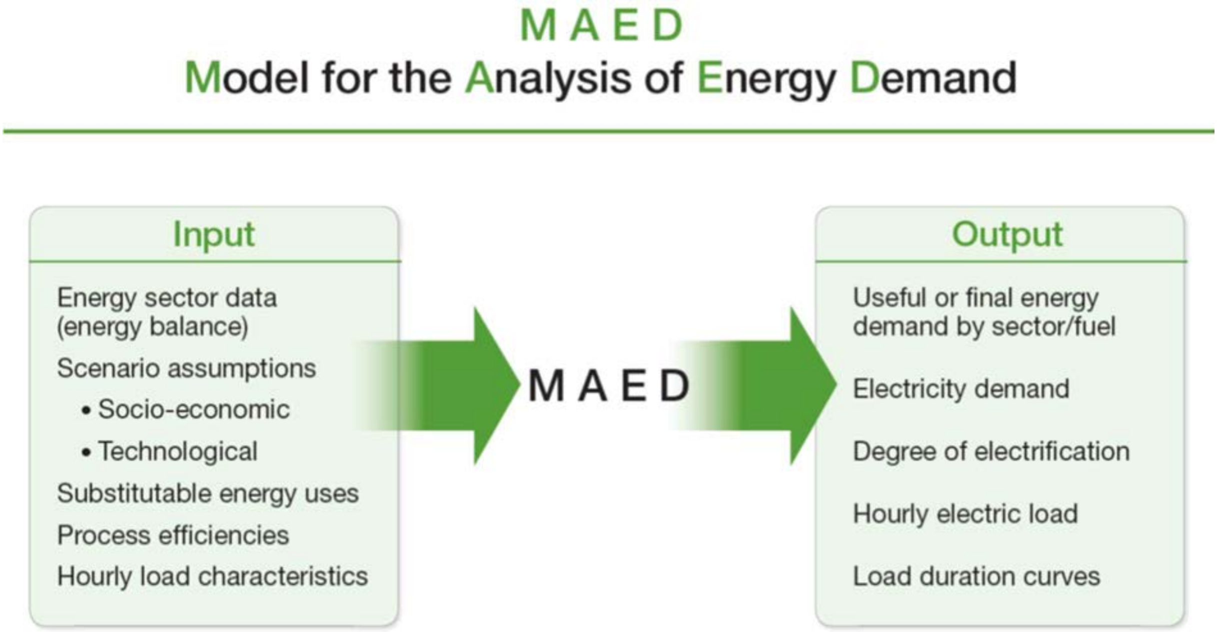

FIG. 1. Main inputs and outputs of the MAED. Source: Ref. [66].

The key to plausible and useful scenarios is internal consistency of assumptions, especially for social, economic and technological evolution. A good understanding of the dynamic interplay among various driving forces or determining factors is necessary. The model output, i.e. future energy demand, is just a reflection of these scenario assumptions. The evaluation of output and the modification of initial assumptions is the basic process by which reasonable results are derived.

The model focuses exclusively on energy demand for specified energy services. When electricity, fossil fuels and other energy forms are competing for a given end use category of energy demand, this demand is calculated first in terms of useful energy and then converted into final energy, taking into account market penetration and the efficiency of each alternative energy source, both specified as scenario parameters. Non-substitutable energy uses such as motor fuels for cars, electricity for specific uses (electrolysis, lighting, etc.) are calculated directly in terms of final energy. Energy demand is not only calculated annually (as for all other forms of energy) but also hourly. Such calculations serve as input data for further analysis of the energy supply by using energy systems models such as the MESSAGE described below.

Accordingly, aside from non-substitutable energy uses, demand for fossil fuels is not broken down in terms of coal, gas or oil in the MAED because the energy supply mix largely depends on the technological possibilities of supply and relative prices of these fuels, and these aspects are beyond the scope of the model. The substitution of fossil fuels by alternative energy forms (e.g. solar, wind, district heat) is nevertheless estimated due to the importance of structural changes in energy demand that may induce the introduction of these energy forms in the future. However, these substitutions are essentially regulated by policy decisions, therefore they need to be considered in formulating and writing the development scenarios.

3.3. EXPLORING ENERGY SUPPLY OPTIONS WITH THE MESSAGE

The MESSAGE (see Refs [68, 69]) is designed to formulate and evaluate alternative energy supply strategies consonant with user defined constraints on new investment limits, market penetration rates for new technologies, fuel availability and trade, environmental emissions, etc. It was originally developed at the International Institute for Applied Systems Analysis (IIASA) (see Refs [70, 71]). The IAEA added a user interface to facilitate its applications and extended the model. The underlying principle of the model is the optimization of an objective function — typically, minimizing the sum of energy system costs — under a set of constraints. MESSAGE uses projections of useful or final energy demand from consistently framed (compatible demographic, economic and policy scenarios) energy demand models such as the MAED to generate the energy supply system. Figure 2 shows the main inputs and outputs of the MESSAGE.

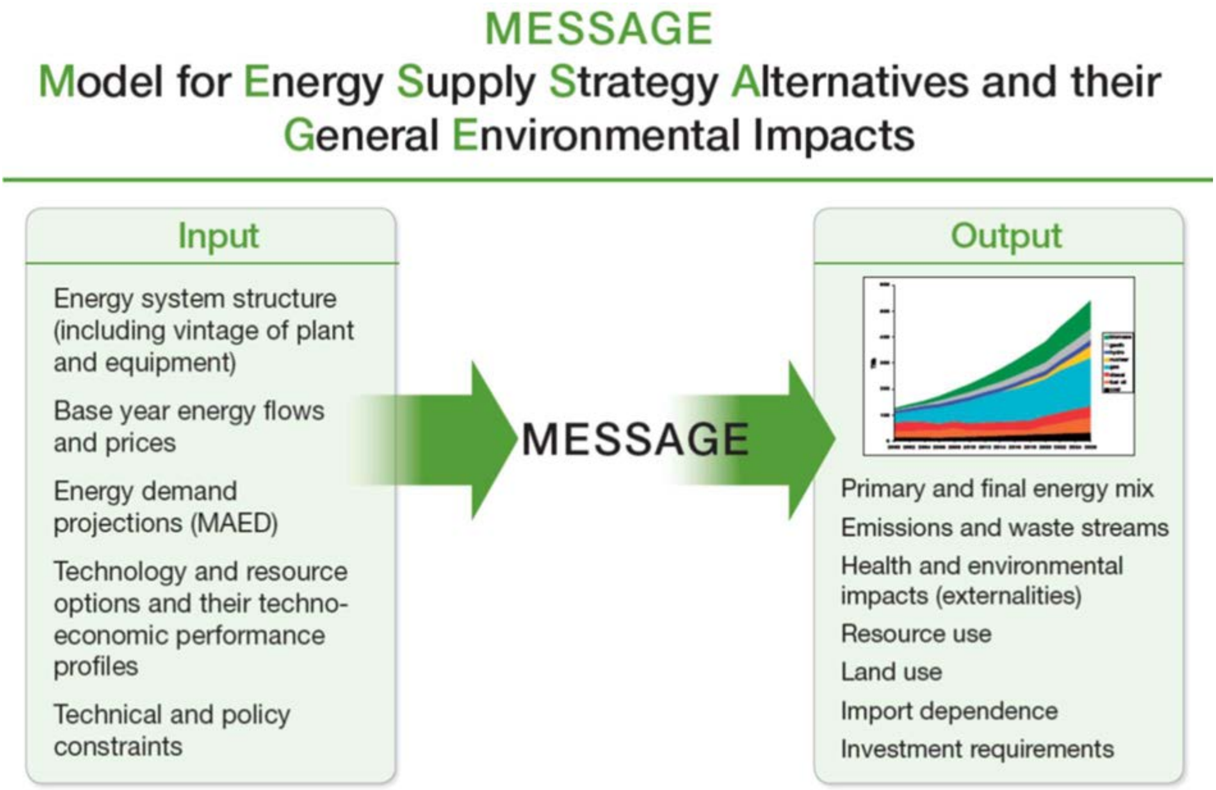

FIG. 2. Main inputs and outputs of the MESSAGE. Source: Ref. [66].

The core of the MESSAGE is the technical description of the modelled energy system. It includes the definition of the categories of energy forms considered (i.e. primary energy, final energy, useful energy (e.g. mechanical energy, light)), the energy forms (commodities) actually used (e.g. coal or district heat), as well as energy services (e.g. useful space heat provided by energy). Technologies are defined by their inputs and outputs, their efficiency and the degree of variability if more than one input or output exists, e.g. the possible production patterns of a refinery or a pass-out turbine. Economic characteristics include investment costs, fixed and variable operation and maintenance costs, imported and domestic fuel costs and estimates of levelized costs. The model outputs also include shadow prices measuring the sensitivity of the overall cost of the energy system to a unit change in a related constraint — e.g. the value to the energy system of one additional resource unit.

These energy carriers and technologies are combined to construct so-called energy chains where energy flows from supply to demand. The definitional limitations on supplying energy carriers are that they can belong to any category except useful energy, they have to be chosen in light of the actual problem and limits on availability inside the region or area, and that import possibilities have to be specified. The technical system provides the basic set of constraints to the model, together with demand that is exogenous to the model. Demand must be met by the energy flowing from domestic resources and from imports through the modelled energy chain(s).

The model takes into account the characteristics of existing installations, including their scheduled retirement at the end of their useful lives. During the optimization process, this determines the need to construct new capacities of various technologies. Knowing new capacity requirements permits the user to assess the effects of system growth on the economy.

The investment requirements can be distributed over the construction time of the plant and can be subdivided into different categories to reflect more accurately the requirements from significant industrial and commercial sectors. The requirements for basic materials and non-energy inputs during construction and operation of a plant can also be accounted for by tracing their flow from the relevant originating industries either in monetary terms or in physical units.

Assuring timely availability of some energy carriers entails considerable cost and management effort. For instance, electricity has to be provided to final consumers at exactly the same time when it is used. The MESSAGE simulates this situation by subdividing each year into an optional number of so-called ‘load regions.’ The parts of the year can be aggregated into one load region according to different criteria, e.g. sorted according to power requirements or aggregation of typical consumption patterns (summer/winter, day/night). The latter (semi-ordered) load representation creates the opportunity to model energy storage as the transfer of energy (e.g. from night to day, or from summer to winter). Including a load curve further improves the representation of power requirements and the utilization of different types of power plants and storage.

Environmental aspects can be analysed by keeping track of, and if necessary limiting, the amounts of pollutants emitted by various technologies at each step of the energy chains. This helps to evaluate the impact of the energy system on pollution to inform the design of environmental regulations and, vice versa, the impact of environmental regulations on energy system development.

The most powerful feature of the MESSAGE is that it provides the opportunity to define constraints between all types of technology related variables. The user can, among other options, limit one technology in relation to some other technologies (e.g. a maximum share of wind energy that can be handled in an electricity network), give exogenous limits on sets of technologies (e.g. a combined limit on all technologies emitting sulphur dioxide (SO_2), CO_2 or GHGs) or define additional constraints between production and installed capacity (e.g. ensure take-or-pay clauses in international gas contracts, forcing customers to consume or pay for a minimum share of their contracted level during summer months). The model is extremely flexible and can also be used to analyse energy and electricity markets and issues related to GHG emissions.

3.4. OTHER MODELS AND ANALYTICAL FRAMEWORKS

3.4.1. The energy planning model LEAP

Two national teams adopted a modelling tool used widely in the international energy community called, until recently, the ‘Long-range Energy Alternatives Planning’ (LEAP) system (see Ref. [72]). The LEAP system is an energy planning model developed by the US office of the Stockholm Environment Institute. It includes energy demand, transformation and supply. The model starts from the current energy status of a geographical area (a utility, city, region or country) and projects the future by simulating the interactions among energy system components under user specified assumptions. It is usually used to analyse national energy systems. The model was upgraded into an integrated energy planning and climate change mitigation assessment tool after the conclusion of the CRP described in this publication and was renamed ‘Low Emissions Analysis Platform’ with the same acronym (see Ref. [73]). It can be used to assess energy demand, production and consumption, and GHG and air pollutant emissions from various sectors of an economy.

The LEAP system allows sophisticated simulations and the adoption of complex data structures (see Ref. [74] for an overview of the LEAP structure). Yet, it lacks the ability of macroeconomic models to estimate economy-wide impacts of energy policies on GDP, total output, employment and others even though these types of models can be run in combination with the LEAP system. As a policy simulation tool, it can be used to find least cost configurations of energy supply.

The LEAP framework enables medium to long term modelling of energy requirements under various scenarios and the comparative assessment of the resulting emissions, environmental impacts as well as social costs and benefits. Diverse mitigation policies and management options can be modelled on their own or within an integrated framework. Model components include a database for baseline and historical data, a model to forecast future energy supply and demand, and an analytical device to compare options for strategic planning.

The energy component of the model includes demand analysis (end use energy consumption), transformation analysis (conversion and transportation of energy through the energy chain from extraction to final consumption), resource analysis (a database of resources used for the activities in various demand categories) and environmental analysis (GHG and other pollutant emissions from all devices specified in the demand analysis and all fuels considered in the transformation analysis). Additional functions include cost–benefit analysis (based on the social cost of resources) and non-energy related impacts (e.g. emissions from waste and refrigeration equipment). These components and functions can be combined into an integrated energy planning analysis.

The LEAP model can support a large variety of data and a high degree customization of the energy system under study. A unique hierarchical data structure is developed by the user to model a specific energy system. Data specified for so-called branches depend on the type, e.g. category, fuel or indicator branches, and on the defined properties of the given branch. The user needs to specify the model architecture and assumptions, the inclusion of components (e.g. energy suppliers, users and sectors) as well as the level of analysis anywhere between high level aggregated energy consumption to detailed end use data, depending on data availability.

Data requirements depend on the modules and components included in a study. They usually include macroeconomic variables (e.g. population, household size, production of energy intensive materials), energy demand data (e.g. fuel use by sector, usage breakdown by end use devices, technology costs and performance), energy supply data (e.g. capital and operation and maintenance costs, performance efficiency, capacity factor) and technology options (e.g. costs, performance, share of new or existing capital stock). The technology and environmental database contains baseline values of emission factors for hundreds of energy consuming and energy producing technologies but these can be customized by the user. It also includes information on the suitability, availability and cost effectiveness of these technologies.

The LEAP system uses annual time steps over a time horizon defined by the user (typically between 20 and 50 years). It supports a range of modelling methodologies from bottom-up end use accounting techniques to top-down macroeconomic modelling on the demand side and diverse accounting and simulation methodologies for modelling power generation and capacity expansion planning in the electricity sector on the supply side. This flexibility enables the user to incorporate data and results from more specialized models. The modelling capabilities of the LEAP system work at two levels: built-in calculations handle all energy, emissions and cost–benefit accounting at the first level, while the user can enter spreadsheet type expressions to specify data changing over time or to specify complex models for econometric and simulation methods for inclusion in the model's general accounting framework at the second level.

The LEAP model can simulate all sectors and all technologies in an energy system. It also includes a scenario manager for describing specific policy measures that can be combined in various packages to craft different integrated scenarios. These scenarios are internally consistent plots of the future development of the energy system over time. Results of a model run typically include fuel demands, costs, unit productions, GHG and air pollutants emissions, etc. Usually, these results are then used to compare implications of baseline scenarios without interventions with those of policy scenarios including various policies and measures.

3.4.2. Modelling tools for assessing macroeconomic impacts

In recent decades, three main types of models have been used to estimate the macroeconomic impacts of economic, energy and environmental policies and large scale investment projects. They include traditional input–output models (IOMs), econometric input–output models (IO-E) and computable general equilibrium (CGE) models. Two study teams examine wider implications of using nuclear energy for climate change mitigation on the national economy by looking beyond the energy systems: Poland (Section 4.7) and South Africa (Section 4.8). This section provides a generic introduction to this type of modelling tools. Details of model specifications are provided in the national sections and their underlying reference material.

IOMs describe the relationships between various sectors of an economy (national or regional). They include a system of linear equations that describe the relationships between the inputs and outputs of each economic sector. The models facilitate the assessment of changes in the inputs or outputs of one or several economic sectors and their subsequent impacts on the entire economy. Final demand is exogenously given in traditional IOMs. The system of linear equations is used to calculate primary and intermediate inputs required by the producers to meet this demand but they do not include price responses. IOMs are usually open, i.e. there is no feedback between primary inputs and final demand. Moreover, these models are often static, which means that they do not track the distribution of ensuing impacts of different activities over time.

Closed IOMs incorporate feedback linkages between primary inputs and household consumption by treating households as an industry that provides labour as its output and uses food, consumer goods and different kinds of services as input. This method allows to assess the trickling impacts of higher household consumption, induced by higher demand for labour, on the entire economy.

A wide range of IOMs are used in assessing the macroeconomic impacts of energy, economic and environmental policies. Although there are significant theoretical and analytical differences across the models, some important common features can be observed, particularly:

- No supply side constraints. IOMs assume that there are no constraints on the availability (supply) of productive resources (such as natural resources, capital and labour), implying that any amount of extra output can be produced in any economic activity (e.g. electricity generation from fossil fuel sources) without reducing the availability of these resources for other economic activities (e.g. steel production). This assumption implies that these resources have infinite elasticity[1] of supply, hence their prices remain unchanged (fixed) when their use increases to serve the increased economic activity.

- Fixed production/consumption functions. Most IOMs assume fixed (and linear) production and consumption functions, denoting a fixed relationship between each sector's inputs and outputs. This relationship represents a technology with constant returns to scale and does not allow substitution among inputs.

Some studies use integrated IO-E models that combine IOMs with macro-econometric models. Such models link the determination of final demand and income with interindustry flows in an IOM. As a result, they present a full synthesis of supply and demand in the economy as a whole. A typical IO-E model uses econometric models to estimate final demand (such as investment and savings, household consumption, government expenditures) over time, which in turn is used to drive the IOM (see Ref. [75]). The result is a dynamic structure in which the IOM starts in the base year, is updated in annual steps by taking into account changes in various macroeconomic variables such as labour force, wages and employment. Furthermore, the econometric part of the IO-E models can be tightly based on macroeconomic theories.

In a typical CGE model, an equations system describes producer and consumer behaviours. The equations usually take the form of Cobb–Douglas or constant elasticity of substitution (CES) functions. In CGE models, producers are assumed to choose input and output levels that would minimize their production costs given the costs of inputs (such as fuel, equipment and labour), prices of outputs and technological constraints of production processes. Household consumers are usually assumed to maximize their utility by purchasing the most satisfying basket of consumer goods and services (such as clothing, household equipment, health and beauty services) permitted by their budget constraints and the prices of consumer goods.

Some of the CGE models are static and assume that producer and consumer behaviours depend only on the current state of the economy, while other models are dynamic and describe changes in producer and consumer behaviours over time. In addition, CGE models apply two distinctive approaches to describe energy production. The top-down approach typically starts with a detailed description of the macro (and international) economy and then estimates the demand for various energy inputs by using highly aggregated production functions. The bottom-up approach, on the other hand, starts with a detailed description of the energy producing processes

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[1] An elasticity refers to the relative change in an economic variable in response to a unitary change in another.

or technologies and then determines the most cost efficient way of meeting energy demand in terms of the energy technologies employed and the level of inputs for energy production.

Input–output and IO-E models are used in many countries for assessing macroeconomic impacts of policy interventions in general and of energy–environment–climate policies in particular (see Section 2). They are attractive for policy analysis due to the simplicity of introducing policy variables relevant for the issues to be explored and the ability to simultaneously consider market and non-market based systems, underscored by possibilities of targeted factor substitution in response to price changes. Moreover, these models are considerably more transparent and easier to implement than CGE models.

3.4.2.1. Poland: the EMPOWER

The origin of the Extended Input–Output Model for Sustainable Power Generation Poland Climate Change (Empower.pl.cc) used in the Poland case study (Section 4.7) is the IAEA's Extended Input–Output Model for Sustainable Power Generation (EMPOWER) (see Refs [58, 76]). The main objective of this model is to assess macroeconomic impacts of building and operating NPPs but it can be applied to study the macroeconomic effects of any types of energy investments. Technically, the model would be applied exactly the same way for alternative energy technology options.

The methodological basis of the EMPOWER is an extended input–output framework that takes an input–output table as its primary database. The model is structured so as to allow the assessment of macroeconomic impacts in the construction as well as in the operational phase of NPPs separately and the application of four consecutive levels of economic feedback mechanisms in both periods, depending on the availability of data and the interests of the model's users. The simplest application of the model with minimum data requirements can estimate the macroeconomic impacts of the investment in constructing an NPP and requires only a recent input–output table of the economy and country specific investment costs of the plant. The EMPOWER is designed as a traditional impact assessment in input–output analysis in which a new industry is introduced (see Ref. [77]). The final demand approach is used to introduce new activities (construction or operation of new NPPs) in which the focus is on goods for final demand (which are not used to produce other goods) rather than on goods which serve as input to subsequent production processes and represent intermediate demand (see Ref. [78] for details).

The EMPOWER goes beyond the traditional static IOMs that do not take into account the implications of additional incomes resulting from introducing a new industry in the national economy and thus underestimate the short term impacts. It provides mechanisms to keep track of such income implications. It also accounts for changes in wages as a result of larger demand for labour which is missing from static IOMs and leads to overestimating employment effects. Yet another improvement in the EMPOWER over traditional IOMs is a more realistic representation of the price–quantity relationships by introducing elasticities between prices and demands for consumption, exports and labour. Finally, the EMPOWER allows to consider feedback effects from public–private partnerships if the government finances a certain part of the investment. In this sense, the EMPOWER is a reasonable compromise between quasi-realistic depiction of national economies on the one hand and difficult technical challenges (involved in a dynamic CGE, for example) on the other.

In the CRP, the Poland team modified the original EMPOWER for the implementation of Empower.pl, the model for Poland. The modifications do not change either the fundamental features of the model or the main principles of the software application and are largely technical. Names of files and sheets in the software are shortened. Some of the original files of the EMPOWER software were extended by adding new sheets. But neither the structure of the files and sheets nor its purpose has been changed, except the plData file in which several new sheets are added to enter Polish source data and to adjust them to the EMPOWER software requirements.

The Empower.pl.cc (see the model presentation in Ref. [79]) is an extended version of the Empower.pl that adds an energy block and a pollutant emissions block. It uses the Interdyme modelling package (see Ref. [80]). The quantities of emissions of various pollutants from different sectors are expressed as the sum of emissions resulting from the use of different fuels. By dividing sectoral emissions by sectoral outputs, coefficients are derived, which express emissions of different pollutants resulting from the use of a given fuel type in a given sector per unit of output of the sector. Assuming that the coefficients are constant, the emissions equation is rewritten so that sectoral emission coefficients are equal to the sum of emission coefficients of fuels.

Further decomposition of the emission coefficients results in an equation in which sectoral emissions of each pollutant are computed by multiplying the sum of the products of the emission coefficient (emission of a pollutant per unit of a fuel used in a sector) and the fuel use coefficient (amount of fuel per unit of input of the energy sector as the producer of a fuel used in a sector) and the direct input coefficient of products of an energy sector used in a sector by the output of the sector. This equation is then made dynamic and formulated for each pollutant, sector and fuel. By adopting the simplifying assumption that the emissions and the fuel use coefficients are constant at their base year level, sectoral emissions are calculated by multiplying the sectoral emissions of each pollutant in a given year with the sectoral output in that year. See Ref. [79] for the mathematical derivation of this calculation process.

3.4.2.2. South Africa: The integrated SATIM–e-SAGE model

The South African study (Section 4.8) applies the combination of an energy system model like the MESSAGE (see Section 3.3) and a CGE model. The energy system model — the South African The Integrated MARKAL-EFOM System (SATIM) (see Ref. [81]) — is a full sector energy system optimization model that utilizes TIMES modelling platform, a partial equilibrium linear optimization model.

TIMES is a model generator developed and maintained by the IEA Energy Technology Systems Analysis Program (ETSAP), an international programme that conducts energy and environmental studies based on long term energy scenarios (see Refs [82, 83]). TIMES combines a technical engineering and an economic approach and provides a technology rich, bottom-up model generator in which linear programming is used to determine the least cost energy supply system based on various types of user defined constraints (natural resource availability and environmental restrictions) over medium to long term time horizons.

Similarly to the MESSAGE, TIMES incorporates the entire energy chain from primary resources extraction (plus imports minus exports) to transformation, transport, conversion and distribution of energy (called producers) to the supply of energy services required by energy consumers (see Ref. [84]), usually calculated by an energy demand model or projection. Energy is delivered in various energy forms to the demand side that is arranged into industrial, agricultural, transport, commercial and residential sectors called consumers. The representation of mathematical, economic and engineering relationships between energy producers and consumers is the foundation of TIMES models.

Models built with the TIMES framework include technologies, commodities and commodity flows as basic elements (see Ref. [84]). Technologies (or processes) represent physical devices that convert commodities into other commodities. They include processes to obtain primary resources (e.g. mining or imports), conversion processes that generate electricity from fossil fuels and other sources or refineries supplying oil products, and end use appliances and devices such as stoves, lamps, heating/cooling systems and cars. Commodities include various types of energy carriers and services, materials, monetary flows and emissions that are produced or consumed by a technology. Finally, commodity flows map commodities (e.g. electricity generation by PV panels) to a particular technology to represent one input or one output of that technology. These three elements comprise the energy system of a country or region. Similarly to the MESSAGE, TIMES models also have a reference energy system that is the starting point for developing future scenarios. A reference energy scenario illustrates the future as it would unfold by seeking the optimal (least cost) energy supply portfolio in the absence of any intervention. Policy or regulation scenarios impose constraints on resources, flows or processes to achieve different kinds of political (e.g. energy security), economic (e.g. industrial competitiveness) or environmental (e.g. pollutant emissions) targets and the model calculates an alternative energy system capacity and supply portfolio that satisfies the prescribed end use energy demand at the minimal cost under the specified constraints.

The SATIM works in tandem with the Energy extension to the South African General Equilibrium (e-SAGE) model (see Ref. [85]) to provide a more consistent framework for analysing the development of the national economy and its sectors. The e-SAGE model is a recursive dynamic CGE model of the South African economy. The dynamics involve rebalancing the social accounting matrix describing the economy after it has been exposed to different types of ‘shocks’ due to assumed policy or regulatory interventions. The rebalancing is implemented by allowing prices to change and by adopting substitution mechanisms that represent behavioural responses to those price changes, while maintaining macroeconomic restrictions. The e-SAGE represents the operation of the South African economy by simulating direct and indirect linkages between industries, households, the government and foreign economies. It includes a number of industrial sectors, commodities, five factors of production (capital and four types of labour) and several representative household groups.

The recursive dynamics in e-SAGE comprise two components. The model is solved according to given levels of population, labour, capital and productivity provisions within a time period and it is updated in line with population growth, capital accumulation and technical change between periods, where the allocation of new capital is determined endogenously based on investment levels and the relative profit rates of different sectors in the preceding period. The special feature of the e-SAGE model is the additional calibration step involving the energy commodity flows in the economy. In this step, monetary flows representing energy commodity flows in the social accounting matrix are corrected to represent the actual physical flows (see Ref. [85] for details).

The SATIM describes the demand for energy services and the supply and transformation of energy throughout the economy. It includes five demand sectors (industry, agriculture, residential, commercial and transport) and two supply sectors (electricity and liquid fuels). The system is optimized to meet an estimated future demand for energy services at least cost. The e-SAGE model provides GDP and sectoral growth projections in the linked system. See Section 4.8 on how these models are specified and used in the South Africa study in this CRP.

3.5. STRENGTHS AND WEAKNESSES OF ANALYTICAL FRAMEWORKS

The range of methodologies applied in the CRP reflects the diversity of the economic frameworks and tools applied more broadly to analyse energy system development and climate change mitigation. This spectrum of economic models spans from relatively simple optimal growth (or welfare optimization) models through partial equilibrium — most importantly energy system — models all the way to various kinds of macroeconomic, including CGE, models (see Section 3.4.2 and Ref. [86]).

Across this spectrum, the dichotomy between so-called top-down macroeconomic models (which examine the national economy and the performance of the energy sector in this broader context), and bottom-up energy system models (which include a detailed description of the current and possible future energy supply and end use technologies) is of most relevance in the CRP, recalling that the majority of teams applied bottom-up energy system models (MESSAGE, LEAP, SATIM), while a small number of teams applied top-down macroeconomic models (Empower.pl.cc, e-SAGE)), including one team which combined top-down and bottom-up tools. The implications for policy insights of how these two modelling paradigms represent the relationships between the national economy and the energy system has been debated for decades (see Refs [87, 88]).

Bottom-up models of energy systems are typically formulated with mathematical programming to estimate the least cost configuration of the energy system (i.e. the detailed combination of specific technologies and fuels) that satisfies an exogenously specified demand for energy services under economic, natural resource and environmental constraints. As evidenced by the number of research teams applying such tools, bottom-up models are particularly well suited to the research questions in the CRP since they can assess impacts of particular technological changes or various kinds of policies such as carbon prices, GHG emission limits or efficiency standards.

The main limitation of bottom-up partial equilibrium models is that they are generally most suited to analysing changes that affect primarily one sector (i.e. energy) and are expected to have a relatively small effect on other sectors. Equally, their main shortcoming is that they do not account for economy-wide interactions (e.g. feedbacks from sectors beyond the energy market), so do not fully consider the required primary production factors (capital, labour and natural resources) or overall general equilibrium outcomes such as effects on income and saving. They also tend to lack microeconomic (behavioural) realism and, as a result, often underestimate barriers and costs associated with the deployment and diffusion of new technologies. Moreover, they focus on financial costs of investments and ignore key factors such as greater risks, intangible costs and longer payback periods of some technologies.

Top-down energy models, in comparison, examine the national economy and the performance of the energy sector in this broader context, accounting for impacts and feedbacks of policy triggered changes on relative prices and incomes across different markets. Relations between the energy sector and the broader economy are represented via the supply and demand of goods and services, and parameters are estimated by using econometric techniques applied to data on consumption, prices, incomes and factor costs. Top-down models can also describe economic behaviour based on microeconomic principles, and represent markets for primary factors of production as well as domestic and imported goods and services. Unlike the approach of bottom-up models, top-down models do not seek to determine optimal outcomes but instead the market equilibrium between supply and demand by price adjustments and the associated economic, social and environmental impacts. In the CRP, these features have been applied to assess specific questions related to the broader economic impact of different NPP investment plans and the feedback between energy demand and prices under different energy and climate policies.

Despite ongoing improvements, the main shortcoming of top-down models is that they generally do not include a high level of technological details of energy production, conversion and consumption. Like all economic sectors, the energy sector is represented in an aggregate way by smooth production functions that describe possibilities of substituting different inputs (represented by price elasticities of demand, supply and factor substitution). As a result, in typical top-down models it is difficult to include alternative assumptions about the future evolution and costs of individual energy technologies, particularly emerging technologies.

Since decisions about energy–climate policies, including the role of nuclear energy in climate change mitigation, require an understanding of both technological characteristics and economy-wide impacts in terms of GDP, employment and so on, neither bottom-up nor top-down models alone can provide comprehensive and reliable information. Accordingly, there have been many efforts to bridge the gap, including by linking bottom-up and top-down models: this strategy was applied by the South African team in this CRP (see Section 4.8.2). Yet, this remains a challenging area given the complex, heterogeneous and potentially inconsistent accounting methods of the different types of models. Other approaches include incorporating macroeconomic modules in bottom-up models, introducing more detailed and hierarchically nested production functions in top-down models, or using a single integrated framework in which bottom-up and top-down features are firmly integrated.

Observing the urgent need for and increasing ambition of climate protection measures under the Paris Agreement, robust advice on the feasibility, costs and benefits of alternative energy–climate strategies are of obvious importance to policy making. Despite the numerous improvements in modelling techniques, the dichotomy between bottom-up and top-down models is still not fully resolved.

While the above discussion has focused on the two main methodological approaches used in both the CRP and the broader literature on energy system development and climate change, it is important to recall that many other methods and tools are also routinely used to assess further aspects and complement these main approaches, as illustrated in Section 2 and by some of the CRP studies (see Section 4). Also, the discussion above serves as a general reminder that different modelling approaches have strengths and limitations, and — implicitly — that the most suitable methodology is determined by the specific research questions of interest. This is largely reflected in the choice of models applied by the CRP teams to assess different aspects of the role of nuclear energy and other technologies in climate change mitigation that are most relevant for their national circumstances. In addition to the insights provided by each individual model, the different models applied in the CRP can also provide complementary insights and identify more robust relationships.

4. POTENTIAL ROLE OF NUCLEAR ENERGY IN NATIONAL CLIMATE CHANGE MITIGATION STRATEGIES IN PARTICIPATING MEMBER STATES

Research teams from 12 IAEA Member States submitted research proposals and participated in the CRP on the Potential Role of Nuclear Energy in National Climate Change Mitigation Strategies. This section presents summaries of the national studies and their results based on the detailed final reports prepared by the national research teams. It is important to emphasize that the national studies generally analyse hypothetical cases framed as plausible future scenarios rather than actual or specific implementation plans.

This section contains case studies from ten research groups: Armenia, Chile, Croatia, Ghana, Lithuania, Pakistan, Poland, South Africa, Turkey and Viet Nam. Final reports were not available for two other participating teams (Australia and Ukraine). It is important to note at the outset that the future role of nuclear energy in climate change mitigation will depend on many factors. They include socioeconomic characteristics of the country in which a national nuclear programme is considered (population size, the size and development level of the national economy, energy intensity of the economy and carbon intensity of the energy sector, just to name a few) on the one hand and the level of national aspiration and international commitments to reduce GHG emissions and the costs and availability of natural energy resources and technologies to achieve them on the other. A large heterogeneity in terms of these factors can be observed across the participating Member States. As described in Section 3, to analyse the evolution and impact of these factors, most teams developed long term energy scenarios using IAEA models calibrated using country specific data. A few national teams also used other methodologies and tools to explore the prospects for nuclear power in GHG emissions reductions and in the broader context of national energy strategies.

Following the presentation of detailed summaries in this section, Section 5 synthesizes the overall results of the national studies and seeks to draw robust insights and conclusions against the background of the wide heterogeneity in national circumstances.

4.1. ARMENIA

This section provides a concise assessment of the potential role of nuclear energy in climate change mitigation strategies in Armenia. The study includes baseline and climate mitigation scenarios in line with the Paris Agreement in order to foster sectoral programmes to reduce GHG emissions in the electric power industry. The section is based on Refs [89, 90, 91].

4.1.1. Problem and situation assessment

The Paris Agreement was adopted in 2015 and entered into force in Armenia in 2017. Armenia needs to design a strategy and related mechanisms to achieve the declared INDC and to start preparations for future (mid-century) development strategies with low GHG emissions. The main sources of energy traditionally used in Armenia are oil products, natural gas, nuclear energy, hydropower and coal. Hydropower, solar and a very small amount of brown coal are the only currently exploited domestic energy sources.

One of the main directions for developing the Armenian energy sector is the establishment of an export oriented power system integrated into the regional electricity market. Thus, it is planned to create a regional hub for trade in electricity and power generation capacity. To achieve this goal, the governmental plan for the long term development of the country’s energy system includes a number of projects in power generation, transmission, interconnection and distribution. At the same time, a key role is designated for developing nuclear energy.

4.1.2. Methodology and assumptions

To explore GHG emissions for the period 2015–2050, several scenarios are constructed based on the expected activity in different sectors of the economy, taking into account the increase of population to 4.0–4.3 million by 2050 and the assumed average annual economic growth rate of 6.4% between 2015 and 2030 and 3% between 2030 and 2050. The MAED (see Section 3) is used to project electricity demand in three scenarios up to 2050. Based on the strategic guidelines of relevant government policies, the MESSAGE (see Section 3) is specified with the objective function to minimize GHG emissions over the mid-century time horizon subject to environmental criteria. Nuclear energy is a development priority for Armenia.

Three scenarios for energy demand, supply and GHG emissions are assessed for all GHG sources. The BAU scenario assumes the continuation of general practices at the national level. Economic development trends continue with the increasing use of fuel and energy resources, limited energy efficiency and the introduction of some RESs such as small hydropower, solar panels, heat pumps and biogas plants. The mitigation scenario includes certain measures to reduce GHG emissions by implementing energy saving policies and extending the use of alternative energy sources according to the government's strategy documents and actions to reduce GHG emissions but this scenario is largely based on CCGT plants. The nuclear scenario (also including the energy saving policies and the extended alternative energy sources in the mitigation scenario) assumes that — instead of the gas fired capacities in the mitigation scenario — the currently operating nuclear unit at the Arminian NPP will be replaced by two 1000 megawatt (electrical) (MW(e)) reactor units to enhance the country's energy independence and supply security and to contribute to GHG emissions reductions. These scenarios are analysed with the MESSAGE model.

The theory of experiment planning (see Ref. [92]) serves as the mathematical basis for a sensitivity analysis of the nuclear scenario. In addition, the process involves principles and approaches of multi-criteria analysis (MCA) and the MESSAGE software. The theory of experiment planning also makes it easy to formalize and take into account unquantifiable criteria. In the MCA framework, the objective is to minimize GHG emissions over the mid-century time horizon subject to criteria of estimated environmental values.

4.1.3. Results

Demand for electricity in the three scenarios as projected by the MAED is presented in Fig. 3. Least cost energy supply options in the three scenarios are simulated with the MESSAGE. The resulting electricity generation portfolios are presented in Fig. 4.

The nuclear scenario is much more expensive in terms of investment costs than the gas dominated mitigation scenario. However, the present value of the two scenarios is about the same, especially when taking into account the constantly growing fuel (gas) costs, tax on CO_2 emissions and other factors. Moreover, the nuclear scenario has more favourable environmental characteristics, i.e. lower GHG emissions.

According to the Armenian INDC [93], the total GHG emissions quota is 633 Mt CO_2-eq for the period 2016–2050. As a result, the average annual emissions quota is 18.086 Mt CO_2-eq. Figure 5 shows total GHG emissions in four scenarios (the nuclear MIN scenario is explained below).

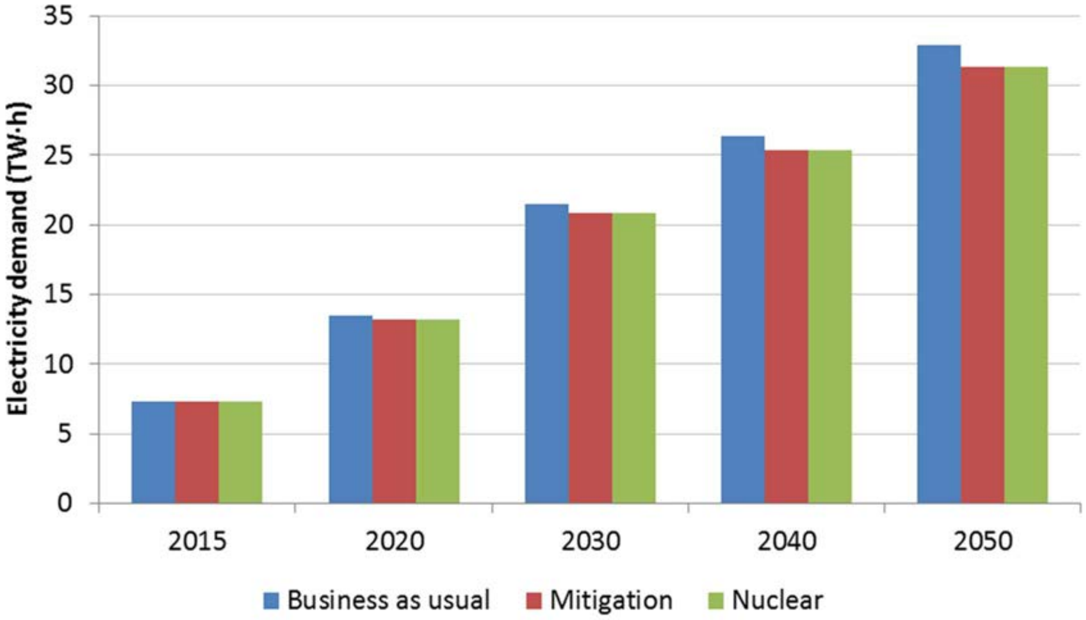

FIG. 3. Electricity demand in three scenarios. Data source: Ref. [90]. Note: TW·h — terawatt-hour.

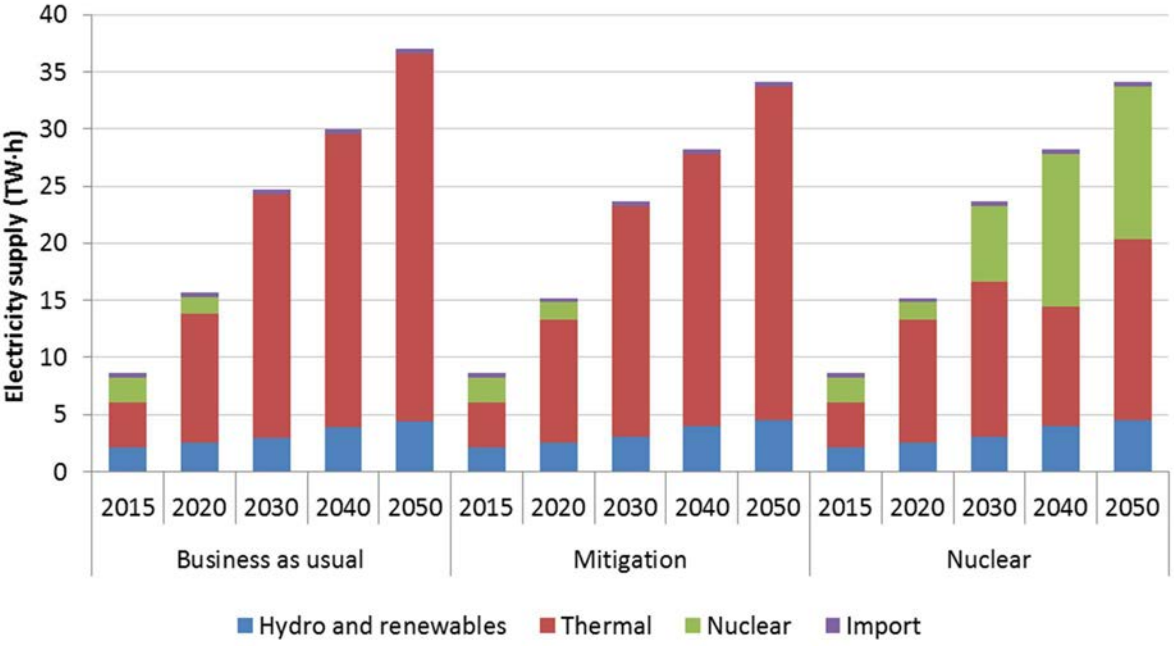

FIG. 4. Electricity generation structure in four scenarios. Data source: Ref. [90]. Note: TW·h — terawatt-hour.

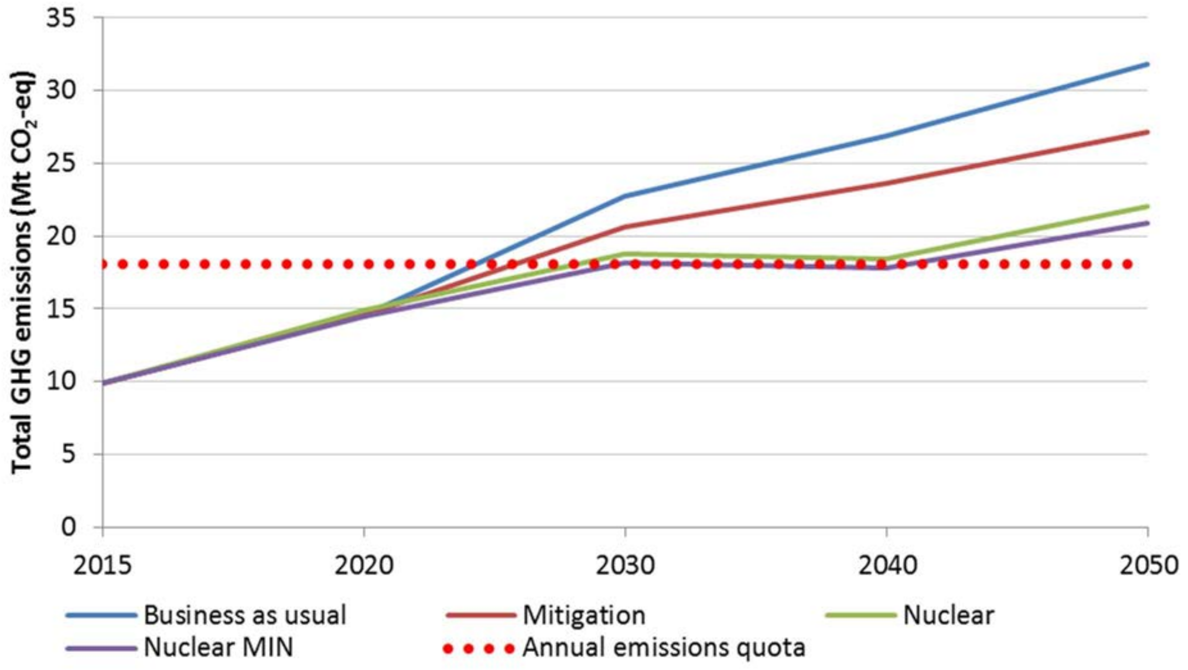

FIG 5. Total GHG emissions in four scenarios. Data source: Ref. [90]. Note: GHG — greenhouse gas, Mt CO_2-eq — megatonne carbon dioxide equivalent.

Emissions from the power generation sector affect total GHG emissions significantly. In the BAU scenario, emissions will exceed the annual quota between 2025 and 2050. Total emissions at 802 Mt CO_2-eq exceed the total quota by 27%. Emissions from electricity generation amount to 62% of total emissions. In the mitigation scenario, emissions exceed the annual quota between 2027 and 2050. Total emissions (724 Mt CO_2-eq) in this case are above the quota by 14%. Emissions from electricity generation contribute 62% of total emissions. In the nuclear scenario, emissions exceed the annual quota between 2030 and 2050. Total emissions at 631 Mt CO_2-eq almost exactly match the quota, while emissions from electricity generation produce only 56% of total emissions. This means that only the nuclear scenario is consistent with the INDC target, thus providing a base for developing the mid-century low GHG emissions policy for Armenia.

An expert assessment has identified a range of factors that influence GHG emissions in the study period, including factors supporting nuclear power. They include the discount rate (used in calculating the present value of all cost items throughout the analysed time horizon), electricity imports from environmentally benign sources (such as electricity from Georgia where 80% of the electricity is produced by hydropower plants), demand side management (to reduce electricity use through energy efficiency improvements), increasing electricity generation from hydropower and other renewable sources and delays in commissioning new NPP units (risks for all parties involved in an NPP project). A sensitivity analysis of these drivers was conducted through a series of experimental model runs with the MESSAGE.

Variants of selected emissions driver factors (their minimum and maximum values) were organized into a planning matrix and their combinations are defined as experiments. Each experiment is a model run of the MESSAGE with minimax values of factors as input data according to elements of the planning matrix. The result of each model run is the total GHG emissions over the study period of 35 years. On the basis of the obtained results and a statistical analysis, the lowest total emissions are achieved under conditions in which the discount rate is 6% or less, demand side management enables a 5% or greater reduction in consumption and the commissioning of NPPs proceeds according to the planned schedule without delay. These conditions are represented in the nuclear MIN scenario in which total GHG emissions in the 2016–2050 period are 4% below the emissions quota, as shown in Fig. 5.

This means that implementing the nuclear MIN scenario not only achieves the INDC target but also results in a small surplus that could potentially be sold in the carbon market or transferred to the 2050–2100 period. It is important to note, however, that this strategy can only be successfully implemented if the marginal values of the selected emissions drivers identified in the sensitivity analysis are achieved. The results of this sensitivity analysis thus provide further guidance for preparing the mid-century low GHG emissions energy development strategy for Armenia.

Fostering energy supply security is an important policy objective in Armenia. It has several components: sociopolitical safety (to satisfy energy needs at the required quality and quantity at acceptable costs), structural safety (a market oriented energy sector that guarantees vital, controllable and non-discriminative conditions for stable development of the society), financial and economic safety (reliably and stably functioning energy sector at least cost that ensures returns to cover current financial requirements, fulfilment of international and domestic obligations as well as stable development) and many others. It is obvious that in countries with a complete lack of their own fuel deposits like Armenia, ensuring energy security and independence is of paramount importance. In this regard, further development of the nuclear energy programme is of vital value for Armenia. Figure 6 shows the level of energy and electricity independence of Armenia in the case of future development of the national nuclear energy programme.

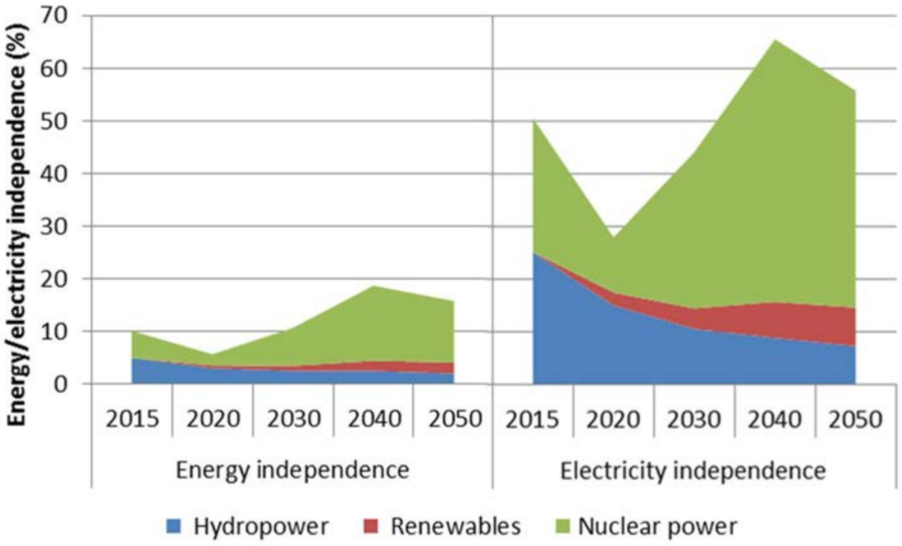

FIG. 6. Energy and electricity independence of Armenia under the continued nuclear energy programme. Data source: Ref. [90].

Figure 6 shows that sufficiently high level of energy independence and, consequently, energy safety can be reached by nuclear energy development. Moreover, implementation of the nuclear scenario reduces the need for gas imports drastically.

4.1.4. Conclusions and policy insights

Nuclear power can make a significant contribution to achieving Armenia's climate change mitigation target under the Paris Agreement. NPPs produce virtually no GHG emissions or air pollutants during their operation and very low emissions over their entire life cycle.

Among the assessed scenarios, only the nuclear scenario complies fully with Armenia's commitments under the Paris Agreement. On the basis of this study, it can definitely be argued that the implementation of Armenia's INDC is strongly supported by the development of nuclear energy. The main barrier for implementing the nuclear scenario is high investment costs, even for SMRs.

The government and the energy community have a clear understanding of the complex and multifaceted problems involved in the future development of nuclear energy. The upcoming decommissioning of two units (one operating, the other mothballed as of September 2020) of the Armenian NPP also increases the complexity. However, earlier assessments have shown that the process of decommissioning old units is greatly facilitated by the commissioning new units at the same NPP site.

Lessons from the energy crisis of the 1990s show that a reasonably high level of energy independence can ensure continued operation of critical social and economic systems under a wide range of emergency situations. Nuclear power fosters energy security and industrial development by reliably providing electricity at stable and predictable prices. The analysis shows that a sufficiently high level of energy independence and, consequently, energy security can be achieved by developing nuclear power. The energy independence indicators further justify that the inclusion of nuclear power in the energy policy of Armenia is correct.

4.2. CHILE

This section summarizes the analysis by the CRP team from Chile exploring the conditions under which nuclear energy could play a role in the projected energy market and in GHG emissions mitigation, based on Refs [94, 95]. The summary presents results from the IAEA tools MAED and MESSAGE as well as the model of the Ministry of Energy that were used to project demand and supply of energy and electricity in Chile.

4.2.1. Problem and situation assessment

Chile ratified the Paris Agreement in February 2017 and committed in its first NDC to reduce GHG emissions per unit of GDP by 30% by 2030 relative to the level in 2007, and up to 35–45% with international support (see Ref. [96]). Based on this commitment, Chile established the National Action Plan 2017–2022 that aims to respond to the challenges caused by the impacts of climate change over the short and medium term and implement its mitigation commitments [97]. In 2020, Chile submitted an updated NDC with a more ambitious goal of limiting GHG emissions (excluding land use) to 95 Mt CO_2-eq by 2030 (compared with about 123 Mt CO_2-eq under the emissions intensity target) [98].

The energy sector is the largest contributor to GHG emissions (77.4% of the total in 2013) [99] and the National Energy Policy 2050 proposes the development of a reliable, sustainable, inclusive and competitive energy sector [100]. The sector has also published an energy emissions mitigation plan in 2017 that establishes measures for electricity generation, transport, mining and industry, and the commercial, public and residential sectors.

The guidelines in the National Energy Policy seek to reduce GHG emissions by following different strategies such as increasing the contribution of renewable energy in the grid and supporting the implementation of low carbon technologies in the power generation sector, while boosting the market for low emission technologies (electromobility) in the transport sector. These sectors are the largest contributors to CO_2 emissions (electricity generation with 45.3% and transport with 28.9% in 2013) [101]. Electricity generation is currently dependent on fossil fuels, mainly coal (21%) and natural gas (20%), as well as hydropower (15%) and variable RESs such as solar and wind (17%) [102]. The solar energy industry, in particular, has been developing rapidly.

In addition to the strategies of the National Energy Policy, the Chilean government, with electricity generators, is analysing the conditions for a gradual retirement of coal fired power plants without CCS or other equivalent technologies [103] to achieve a low carbon electricity system by increasing the contribution of hydropower, variable renewable technologies (solar and wind) and energy storage. An agreement starting in 2020 is already in place to retire old coal fired plants and replace them with renewable energy. While this initiative will reduce dependence on fossil fuels, there are concerns that increasing reliance on intermittent renewable sources could affect the safety and resilience of the national electricity supply, if suitable energy storage systems are not available. Similarly, hydroelectric power is a mature technology in Chile with a large share in the electricity market but there is considerable uncertainty regarding its variability due to the impacts of climate change such as lower rainfall (in recent years by 10 to 37% less than 30 years ago) [104].

Chile is currently at an important point concerning climate action, with significant uncertainty regarding regulatory changes in the next law on climate change that could result in new guidelines for the evaluation of energy options. Against this backdrop, the potential role of nuclear power merits consideration.

Chile has been considering the introduction of nuclear power for over a decade. The country is participating in the IAEA's nuclear newcomers programme and has prepared several pre-feasibility studies. The government has also initiated a national energy agenda as a forum to discuss its future energy policy.

4.2.2. Methodology and assumptions

Two types of models are adopted in this study. The first exercise used the MAED and the MESSAGE and explored the possibility of including an NPP in the national electricity grid based on data from the National Energy Commission and from international sources. For this model, the system was divided into five geographical zones (according to population density, concentration of demand, availability of resources, development potential for RESs and technologies). Primary energy resources include coal, gas and diesel (all imported) as well as geothermal, solar, wind, hydropower and biomass. Costs of investment, construction projects and fuel prices, among other parameters, are specified according to April 2016 costs and prices. The national electricity system model in MESSAGE includes decreed interconnection projects up to 2018, generation projects awarded in supply tenders in 2016 and recent estimates of RESs potentials. The modelling framework has been applied to explore a range of scenarios from 2012 to 2053, including a BAU scenario and a nuclear energy scenario that evaluates the incorporation of conventional and SMR technologies in the electricity matrix considering the cost of nuclear electricity generation projected by the OECD NEA and IEA [105].

The second round of modelling used the model, data, assumptions and scenarios that the Ministry of Energy employed for developing its Long Term Energy Plan (PELP) [106]. The framework includes models of seven subsectors defined according to the national energy balance. Inputs include the costs of the technologies (investment and variable costs), their operational performance, and power and capacity factors, among others. The energy system represents energy chains designed to meet the electricity demand projected by the 2018–2022 PELP scenarios. In the CRP modelling, the inputs were supplemented with nuclear energy data from a national study.

The analysis sought to evaluate the impacts that different types of nuclear power technology (light water, heavy water and SMRs) could have in the Chilean electric matrix under the same assumptions used to develop the PELP. A total of six scenarios were considered, encompassing different assumptions for key factors driving energy sector development (including energy demand, costs of fossil fuels and RESs, costs of environmental externalities and willingness to exit coal use). Five of the scenarios correspond to the PELP scenarios, while the sixth assumes particularly favourable conditions for nuclear power (i.e. high willingness to exit coal use, high energy demand, high costs of environmental externalities and high costs of fossil fuels and RESs). However, this scenario also considers a cost increase of 12% for nuclear technologies to account for adaptation to local seismic conditions, that is, representing the costs of modifying the design conditions to accommodate a safe shutdown ground motion of 0.6g (instead of 0.3g).

4.2.3. Results

In the exploratory study with the MESSAGE, the BAU scenario of the power generation mix includes coal, gas, diesel, geothermal, solar, wind, hydropower and biomass. The nuclear scenario considers an NPP of 1300 MW(e) capacity in one of the five geographical zones. A sensitivity analysis of this scenario considers alternative assumptions for overnight construction costs of 7000, 5000 and 3000 US $/kW. The results show that at an overnight cost of 7000 or 5000 US $/kW nuclear power is too expensive and does not enter the cost minimizing generation mix, i.e. it is uncompetitive under the modelled market conditions. However, at an investment cost of 3000 US $/kW, a 1300 MW(e) unit is included in the optimal electricity supply mix in 2046.

A variant of the nuclear scenario considers the potential deployment of a maximum of four 335 MW(e) SMR units (in another zone). Since a large nuclear reactor is competitive at the investment cost of 3000 US $/kW, this cost is also considered as the basis for projecting the possibilities for SMR technology. The SMR nuclear scenario assumes an initial unit cost of 3000 US $/kW for the first reactor that decreases for subsequent reactors due to economies of serial deployment. Under these assumptions, SMRs become part of the generation mix in 2035 in two zones, one reactor in each. However, the installed SMR generation capacities are never fully utilized over the study period. The marginal costs of electricity in the nuclear and BAU scenarios practically overlap up to the late 2040s after which they are slightly lower in the nuclear scenario. That is, nuclear power decreases marginal electricity costs but this reduction is rather minor, due to the abundance of cheap RESs.

In general, adding nuclear power to the generation mix to replace fossil technologies can help reduce GHG emissions somewhat. Nonetheless, results in the case of Chile show that there is no significant reduction in CO_2 emissions in the nuclear scenario due to the high presence of low emissions sources (RESs) in the electric system.

Results calculated with the Ministry of Energy model show that none of the original five PELP scenarios are favourable to nuclear operation. In the specially defined additional nuclear energy scenario, the resulting levelized cost of electricity (LCOE) for the light water reactor ranges from about 80 to 130 \$/MW·h out to 2050. The LCOE results for SMRs are somewhat lower. They start in the range between about 97 to 122 \$/MW·h in 2018 and slowly decline to the range 87 to 110 \$/MW·h in 2050, remaining above the LCOE of wind and solar throughout. The ranges in both cases are determined by the number of units added. More units lead to lower levelized costs due to economies of scale and serial deployment.

The overall conclusion is that under current market and electricity regulation conditions nuclear power is not competitive in the 30 year period considered in the study. Apart from the high LCOE, this is mainly due to increasing requirements for flexible technologies that can operate in peak hours to accommodate the large amount or variable RESs (wind and solar) expected to enter the system. Flexible operation is not economically optimal for nuclear plants, with LCOE estimated to increase up to 55 US \$/MW·h with a reduction in operating time from 85% to 50%. Under these conditions, gas fired plants fuelled with liquefied natural gas (LNG), particularly CCGT plants, are more competitive than NPPs. It is important to note, however, that this modelling exercise was performed before the decarbonization plan was put in place, warranting further analysis given the resulting changes in market conditions.

4.2.4. Conclusions and policy insights

Nuclear energy is considered in many countries as an option to decrease GHG emissions from the electricity generation sector. It can also contribute to ensuring a stable and secure supply of energy. Therefore, it is advisable to continue considering and reviewing the potential role of nuclear energy in upcoming long term energy plans, with special attention given to environmental, social and economic issues in order to enable a more comprehensive analysis of the nuclear option in Chile. Since a large amount of variable RESs is expected to enter the power system in the next few years, clean baseload generation will be required in order to strengthen the system. Additionally, due to the new National Energy Policy and the national commitment to reduce GHG emissions, nuclear energy appears as a promising option that deserves further assessment. However, the most difficult barriers to the implementation of a nuclear programme in Chile are related to public opinion, investment costs and power system requirements, especially the need for load following capacities.

In Chile, as in other places in the world, the public's perception of the associated risks results in an aversion to any activities related to the nuclear industry. In contrast, the benefits and applications of nuclear technology are not well understood or appreciated. Nuclear energy is not viewed by society as a green or clean energy as opposed to solar and wind energy that are widely accepted socially. From the economic point of view, the analysis shows that the high investment costs of nuclear power can reduce its competitiveness. However, recognizing the value of other benefits of nuclear power (emissions mitigation, resilience in the electrical system, grid security) in broader policy measures, for example supporting access to financial instruments that provide an incentive for developing long term projects, could improve economics and foster NPP deployment.

4.3. CROATIA

The focus of this section is on the power sector of Croatia and the role of nuclear energy in achieving the country's international commitments to reduce GHG emissions. The main objective is to assess and compare different long term energy policies in exploring the transition of power generation towards low emission technologies. This section is based on Refs [107, 108, 109, 110].

4.3.1. Problem and situation assessment

Energy development guidelines for Croatia include three main components: (i) growing, flexible and sustainable energy production (decreasing import dependence, increasing domestic production, investing in energy production from domestic resources and ensuring an adequate energy mix with low CO_2 emissions), (ii) developing a connected energy infrastructure and fostering alternative energy supply sources, (iii) improving energy efficiency by measures to enhance energy consumption efficiency. The goals also include electrification (using electricity in final energy consumption) and clean generation (decreasing GHG emissions).

As a member country, Croatia aspires to implement the climate change mitigation goals of the EU. Total GHG emissions from energy sources amounted to 16.3 Mt CO_2-eq in 2016, which is 21.6% less than in 1990. In 2016, stationary energy sources contributed 60.7% to total GHG emissions (30.0% from energy production and transformation plants, 17.1% from non-industrial combustion furnaces and 13.6% from industry and construction). Road and off-road transport caused 37.5%, while fugitive emissions from fuels amounted to 1.8% of total emissions. After several years of decline, emissions increased slightly in 2015 and 2016 as a result of growing economic activities after the economic crisis.

At the time of the CRP, the EU had committed to a target for GHG emissions reductions under the Paris Agreement of at least 40% by 2030 relative to the 1990 level (which was increased to 55% in 2020, after the CRP). Commitments across member countries varied between -40 and 0%, the target for Croatia was -7% relative to the 2005 emissions. Based on IPCC recommendations, the EU plans require significantly higher (80–95%) reductions by 2050.

Croatia is the owner of 50% of the Krško NPP located in Slovenia. In this way, the country has an active nuclear energy programme and supports the extension of the Krško NPP operation up to 2043. The energy development strategy of 2009 for the period up to 2020 includes activities related to developing the national infrastructure needed for the preparation, construction and operation of an NPP. The required legal and regulatory framework has also been developed and significant progress has been made on managing spent nuclear fuel and the disposal of radioactive waste from the Krško NPP. This is a good basis for an eventual nuclear programme expansion that will depend on the competitiveness of nuclear power and the possible development of new types of reactors with smaller capacities and greater operational flexibility.

4.3.2. Methodology and assumptions

Energy scenarios in this study are assessed by the MAED for demand and by a combination of the MESSAGE (see Section 3) and the PLEXOS Integrated Energy Model (PLEXOS) for supply analysis up to 2050. The national energy and electricity demand scenarios are using the bottom-up approach in the MAED calibrated to 2015, the latest year for which data were available at the time of the study. The PLEXOS is primarily used for power system modelling and system expansion planning. The main features of the PLEXOS are detailed modelling of generation units, both hydro- and thermal power, in the sense of ramp-up rates, progressive start costs (depending on the time since the last shutdown and fuel type), providing different types of ancillary services as well as modelling transmission and distribution systems, energy storage and non-physical elements of the power system (power exchanges, energy markets, bilateral agreements, non-elastic models of supply and demand). Thus, the PLEXOS can capture dynamics of the power system that is of a great significance when integration of large shares of intermittent RESs is considered. However, the PLEXOS cannot model other energy sectors such as heating and cooling, therefore the MESSAGE is a more robust tool for modelling the entire energy system.

The supply scenarios in the MESSAGE minimize costs to customers based on assumptions about changes in prices of energy products and GHG emissions. The carbon price in the EU emissions trading system progressively discourages the use of fossil fuels compared to RESs. Energy development scenarios also include expectations about technological development, particularly in the energy sector, which will be crucial for the expansion of RESs and electromobility. A key parameter in the analysis is the magnitude of total GHG emissions reductions from the energy sector by 2030 and 2050 compared to the 1990 level. These targets are also compared to the 2005 level because statistical data are better for that year.

In addition to the reference pathway or BAU scenario (designated as scenario 0), two transition pathways (called scenario 1 and scenario 2) are analysed in which the speed of implementation of mitigation strategies differ. Both transition scenarios assume reaching the pre-2020 EU and Paris Agreement GHG mitigation goals and strong international cooperation, especially among EU member countries to do so, decreasing specific investment costs of RESs, establishing market mechanisms to create favourable conditions for a rapid expansion of RESs use and application of energy efficiency measures, improving energy efficiency through the entire chain of energy production, transmission, distribution and consumption. A fixed price of 0.74 €/GJ is assumed for nuclear fuel and 4.6 €/GJ for biomass. Assumed emission unit prices reach 34.3 €/t CO_2 in 2030, 51.1 €/t CO_2 in 2040 and 92.1 €/t CO_2 in 2050 in scenarios 1 and 2. Table 3 presents the main features of the three scenarios.

TABLE 3. MAIN CHARATERISTICS OF THE ENERGY DEVELOPMENT SCENARIOS *(data source: Ref. [109])*

Scenario feature	Scenario 0		Scenario 1		Scenario 2	
	2030	2050	2030	2050	2030	2050
Expected reduction in GHG emissions relative to 1990 (%)	32.8	49.3	37.5	74.4	35.0	65.0
Final energy consumption (PJ)	297.7	255.3	272.5	189.6	286.9	225.6
Final energy consumption relative to 2005 (%)	12.0	-3.8	2.6	-28.6	8.1	-15
Energy renovation of buildings (%/year)	0.1	0.1	3	3	1.6	1.6
Penetration of electric and hybrid vehicles in total road passenger transport (%)	2.5	30.0	4.5	85.0	3.5	65.0
Share of renewable energy sources in gross energy consumption (%)	35.7	45.5	36.7	65.6	36.6	53.2
Decarbonization of electricity generation with increased share of RESs relative to 1990 (i.e. the share of RESs in total electricity demand) (%)	60	82	66	88	61	83

Scenario 1 is specified to achieve GHG emissions reductions according to the pre-2020 obligations by 2030 and in line with expected commitments up to 2050. This includes an enormous rise in the price of GHG emissions (up to 92 $€_{2015}$/t CO_2-eq in 2050) and very strong measures to increase energy efficiency and the use of RESs. Scenario 2 assumes the same rise in GHG emissions prices up to 2050 as in scenario 1. This is also the main driver of the energy transition whereby emissions reductions are achieved by implementing a series of cost effective measures and by encouraging energy efficiency and RESs.

4.3.3. Results

Final electricity consumption in the three scenarios is shown in Fig. 7.

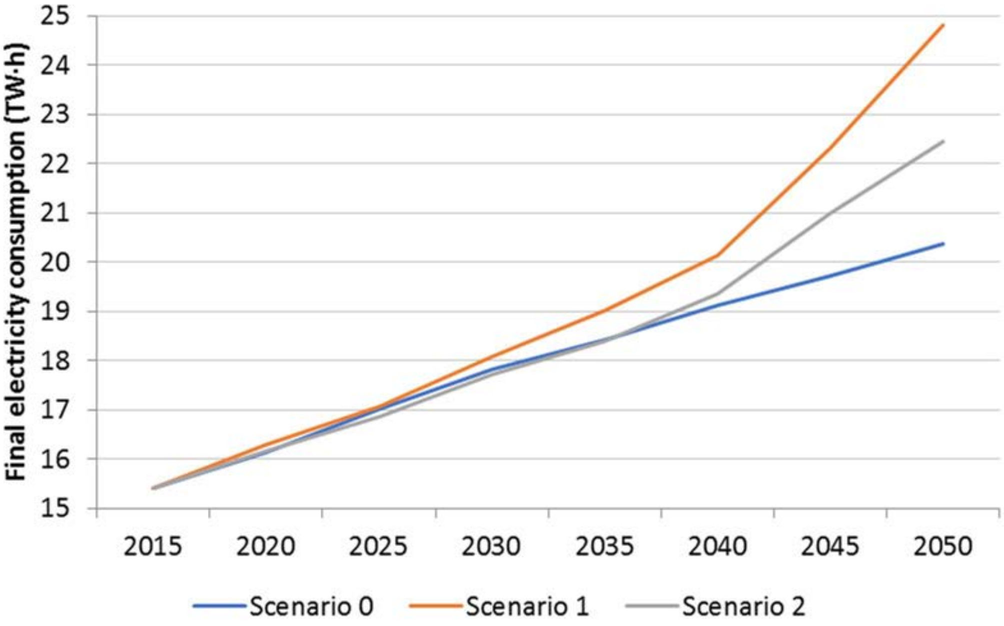

FIG. 7. Final electricity consumption in three scenarios. Data source: Ref. [109]. Note: TW·h — terawatt-hour.

The final electricity consumption in the three scenarios is supplied by a range of technologies according to the cost minimizing generation portfolio calculated by the MESSAGE/PLEXOS. The results are summarized in Fig. 8, which shows that electricity generation in domestic power plants is projected to increase and a significant change in the structure of electricity production is anticipated in all three scenarios. The share of RESs increases and that of thermal power decreases. By the end of the study period, the electricity demand can be satisfied by domestic generation but trade with adjacent power systems is also possible (i.e. net imports are close to zero). Despite the construction of new hydropower plants and the absolute increase in their output, their share under average hydrological conditions, which can vary significantly from year to year, declines from the 2017 level of 46.0% to 41.8–44.0% in 2030 and 32.3–35.1% in 2050 across the scenarios because other generation capacities are built and net imports keep decreasing. Similarly, total power generation in thermal power plants increases but its share in total production decreases from 43.3% in 2017 to 32.3 % in 2030 and to 12.3–26.0% in 2050 across the scenarios. The combined share of wind and PV electricity increases drastically from 10.7% in 2017 to 44.9% and 53.1% in 2050 in scenarios 1 and 2, respectively. Electricity imports fluctuate in the first five years but continually decline after 2019 and Croatia becomes a net electricity exporter in the early 2030s.

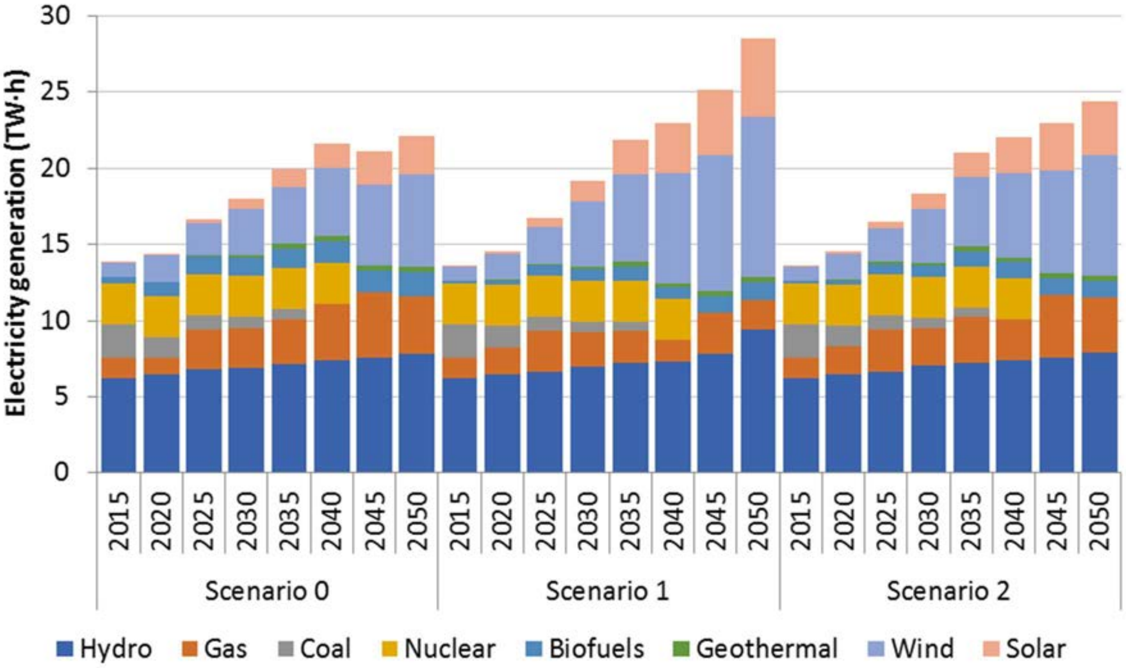

FIG. 8. Electricity generation in three scenarios. Data source: Ref. [109]. Note: TW·h — terawatt-hour.

The extension of the Krško NPP operating licence has a significant impact on the final level and structure of power generation capacities after 2040. Should the licence not be extended, output from the NPP must be replaced by new sources (practically wind and solar). All three scenarios are based on the conservative assumption that it will be necessary to invest in new low carbon electricity sources. Sensitivity analyses show that the nuclear option would only be competitive if smaller capacity units at lower construction costs (compared to the current costs of large NPPs in Europe) became available in the market. In this respect, it is necessary to monitor the development of new reactor technologies in the next decades, analyse the competitiveness of nuclear options and trace the development of announced projects in the Central European region (e.g. Slovenia, Hungary). In addition, pursuing complete decarbonization of all sectors could potentially boost nuclear energy with a view to the possibility of using it in other applications (e.g. cogeneration and hydrogen production).

GHG implications of the above three scenarios are presented in Fig. 9.

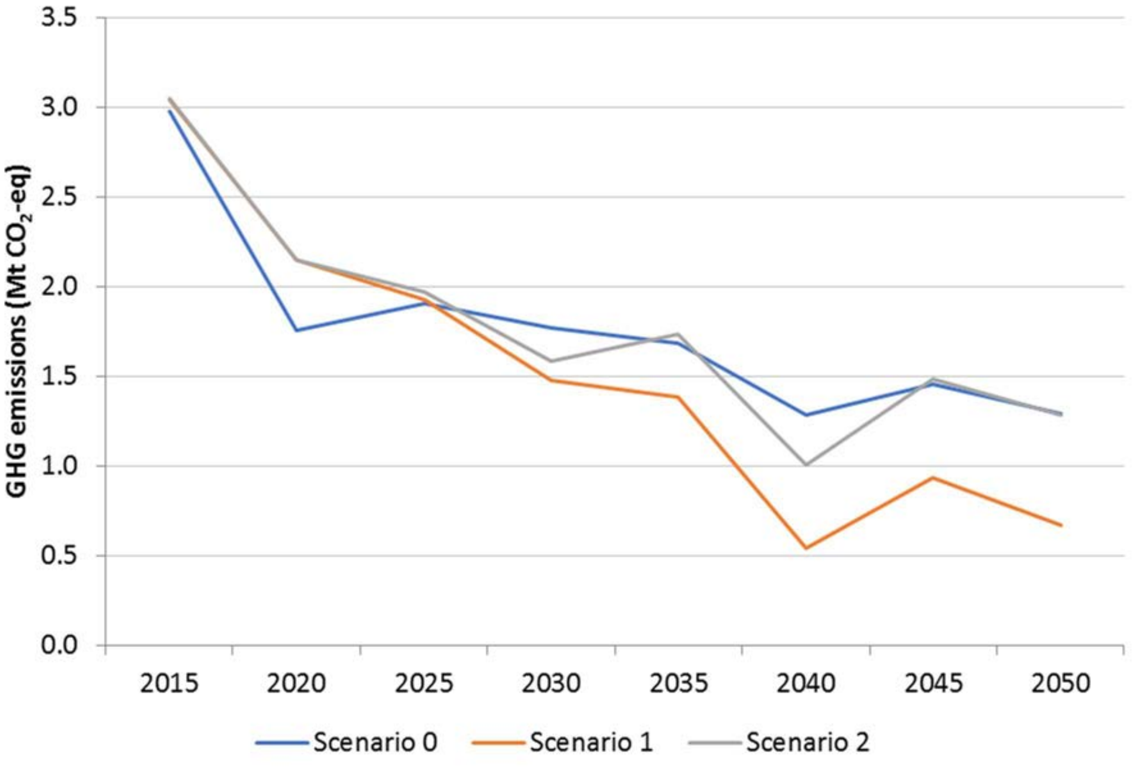

FIG. 9. GHG emissions projections from the power sector in three scenarios. Data source: Ref. [109]. Note: Mt CO_2-eq — megatonne carbon dioxide equivalent.

In scenario 1, emissions decrease by 37.5% by 2030 and by 74.4% by 2050 relative to 2005 emissions, while emissions in scenario 2 decline by 35.4% by 2030 and by 64.3% by 2050 relative to the 1990 level (note the difference between the reference years in scenarios 1 and 2). These trajectories reflect the price of GHG emissions (up to 92 $€_{2015}$/t CO_2-eq in 2050 in these two scenarios) and the different measures to increase energy efficiency and the use of RESs in each scenario. In scenarios 1 and 2, energy production and transformation are rapidly decarbonized, accounting for only around 22% of emissions in 2030, while transportation remains the dominant emission source with a share of around 40%. Croatia is most likely to fulfil its obligations to reduce GHG emissions from the sector outside the EU non-emissions trading system by 2030 and its expected commitments up to 2050 in scenarios 1 and 2.

4.3.4. Conclusions and policy insights

The energy policy of Croatia is determined by the availability of resources and infrastructure, the EU goals to reduce GHG emissions, security and quality of supply and economic competitiveness. These components are integrated into the accelerated transition scenario (scenario 1) in which Croatia increases energy efficiency, uses RESs intensively and reduces GHG emissions by about 75% in 2050 relative to the 1990 level and by 64.2% relative to 2016. The implementation of scenario 1 requires mobilization of the whole society, brings changes in all business entities, affects all customers and consumers, and requires large investments as well as technological and organizational arrangements. The moderate transition scenario (scenario 2) has less ambitious GHG emissions reductions targets. In this scenario, higher energy consumption and greater use of fossil fuels, especially natural gas, are foreseen, while the projected electricity consumption is lower than in scenario 1.

In both scenarios, the energy sector transition towards a low carbon economy is supported by electricity as an energy form that can replace fossil fuels in many applications. Despite the overall increase in energy efficiency and decrease in energy consumption, electricity demand is expected to increase, especially in the transport sector. Croatia has large potential of low carbon RESs in the form of hydropower, wind, solar, geothermal and biomass, which are competitive and can meet the projected electricity demand. However, the increased use of variable energy sources (wind and solar) necessitates a high degree of system flexibility as well as market mechanisms that enable compensation of the costs of system balancing energy sources required for meeting security of supply requirements in the short and long term. It is important to ensure a level playing field for all production and consumption options.

The competitiveness of fossil fired technologies in electricity generation mostly depends on fuel and emissions prices. The competitiveness of coal power plants is expected to decrease and the retention of existing facilities will depend on the technological possibilities to reduce CO_2 emissions, including CO_2 capture and geological disposal on the one hand, and their competitiveness on the market on the other. Natural gas and biomass power plants have the most important role in high efficiency cogeneration in electricity production (where such a need and possibilities exist) as technological options for maintaining operational and long term reserves in the system.

Concerning the role of nuclear energy, given the economic parameters of nuclear and other technologies used in the analysis, new NPPs are not part of the cost minimizing solutions in any of the scenarios. The existing nuclear capacity is assumed to operate until 2043 (60 years after its commissioning). Nonetheless, nuclear energy is one of the low carbon technologies and Croatia continues to examine possibilities of using this technology and prolonging the operation licence of the Krško NPP. It is necessary to monitor the progress of new technologies of small and flexible reactors and potential applications in cogeneration and hydrogen production as well as the development of new nuclear projects in neighbouring countries.

4.4. GHANA

The objective of the Ghana study in this CRP is to analyse the electricity generation system and the potential role of nuclear energy in the country's climate change strategy. This section presents results of an impartial analysis applying quantitative models. The section is based on Refs [111, 112, 113].

4.4.1. Problem and situation assessment

Demand for energy and electricity has been growing fast in Ghana in recent years. The country is considering the introduction of nuclear energy and is participating in the IAEA's nuclear newcomers programme (see Ref. [114]).

For over six decades now, the growth of the Ghanaian economy has been accompanied by increasing energy consumption across various economic sectors leading to a proportionate rise in the demand for electricity. Ghana's National Climate Change Policy [115] of 2013 claims that climate change and its impacts are a serious threat to the development of the national economy. The Government of Ghana recognizes that climate change must be incorporated into policies and sectoral activities to achieve sustainable growth. Limited resources coupled with an ever increasing demand for energy, and international commitments like the Paris Agreement, require other energy sources such as upscaling renewable energy and considering nuclear power in the energy mix.

Ghana submitted its INDCs to the UNFCCC in 2015 [116]: this did not include nuclear power in the country's mitigation strategies. In the review of the current draft of the nuclear energy policy, it is noted that the introduction of nuclear energy would be an additional option to support national climate change mitigation efforts.

4.4.2. Methodology and assumptions

The electricity demand and supply assessments are performed by using quantitative models. The LEAP system [117] (see Section 3) is used to project the electricity demand and its output serves as input to the MESSAGE (see Section 3) to analyse electricity generation and how nuclear power can play a role in emissions reductions.

The main drivers of energy demand include demographic factors such as population growth, changes in shares of urban and rural population, household size and sectoral activities such as cooking and space cooling; economic factors such as disposable income, changes in the structure of the economy (i.e. shares of industry, services and agricultural in total GDP); acquisition of energy consuming appliances; mobility needs and travel modes, fuel substitution, and energy intensity of the economy; and government policies such as the national electrification scheme, the one district one factory policy, the planting for food and jobs programme and the promotion of productive uses of electricity. Energy efficiency programmes reduce waste in energy use and contribute to reducing primary energy needs.

The electricity demand modelling covers the period 2018–2048. Two scenario groups are developed: the BAU and the accelerated economic growth (AEG) groups.

The BAU scenarios are based on the current average performance of the economy, while the AEG scenarios follow the objectives of the Ghana shared growth and development agenda, including the 'one district one factory' policy to improve economic conditions. The population is projected to increase at an average annual growth rate of 2.17% as projected by the Ghana Statistical Service. Total GDP in the BAU scenarios is estimated to increase at an average annual rate of 7.1%. Per capita GDP in 2020 is expected to reach US $1500 and then to increase to US $3341 in 2030. The AEG scenarios are based on the government's long term population policy objective of an annual population growth rate of 2.2%. Total GDP is assumed to increase at an average annual rate of 8.3% and reach a per capita income of about US $3000 in 2020.

The principle of the MESSAGE is to determine the mix of technology and fuel options that minimizes total energy supply costs subject to economic, technological and environmental constraints (see Section 3). This study also estimates the financial implications of various emissions reductions strategies. In modelling the electricity supply system of Ghana, 2018 is the base year. The discount rate of 12% used in procurement of power plants by the Bank of Ghana is used in all modelled cases except some sensitivity analyses. The reference electricity system reflects the current electricity configuration. The assessment considers all energy sources used in the base year for electricity generation and those yet to come online according to a 30 year plan (2018–2048). Several sensitivity analyses are conducted in the BAU and AEG scenario groups to explore the impacts of nuclear power on Ghana's energy system. A minimum 20% reserve margin is assumed for the electricity system. The study period spans from 2018 to 2048 but discussions in this report focus on the 2020–2048 period because most current power purchase agreements are scheduled to terminate in 2020.

The BAU reference scenario is modelled to estimate the impact of GDP growth on electricity demand, technology overnight costs, gas resource availability and unlimited imports. All potential power plants or new builds are included with no constraints except the limits on RESs such as solar and wind due to their limited potentials in Ghana. The major hydropower plant, the Akosombo Dam, is modelled according to its current inflow, which is lower than the historical inflows. The AEG reference scenario is specified to satisfy a faster growing energy demand caused by the faster growing economy but all model parameters are the same as in the BAU reference scenario.

A number of sensitivity cases are analysed in the BAU and AEG scenario groups. In the next section, results are presented for the following cases: BAU 6% DR in which a discount rate of 6% is applied to determine its impact on the electricity mix and if nuclear energy can play a role even at a high overnight cost. According to the CO_2 emissions mitigation target of 15% below projected baseline emissions defined in Ghana's INDCs, a 15% CO_2 emissions reductions relative to the pertinent baselines are imposed in the 15% INDC scenarios in both scenario groups.

4.4.3. Results

Electricity demand is projected for the following sectors: household, commerce and service, industry, aluminium smelting and agriculture. Total final electricity demand is estimated to increase from 18.542 TW·h and 19.10 TW·h in 2020 at an average annual growth rate of 5.1% and 8.1% to 53.58 TW·h and 96.98 TW·h in 2048 in the BAU and the AEG scenarios, respectively (see Fig. 10).

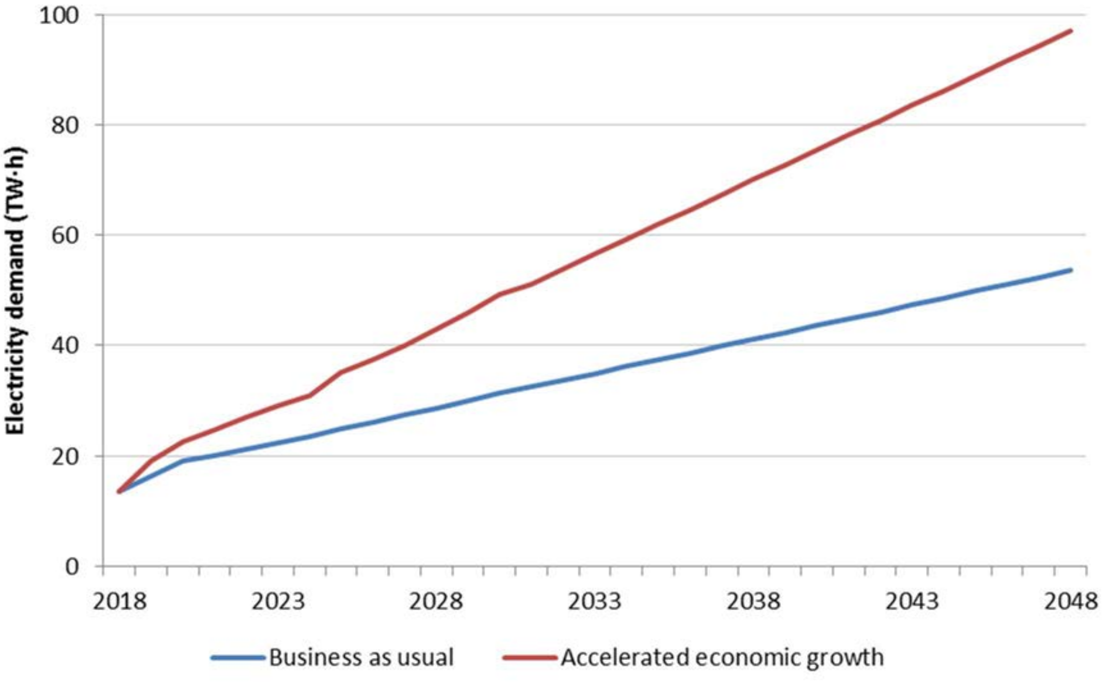

FIG. 10. Projections of final electricity demand in two scenario groups. Data source: Ref. [113]. Note: TW·h — terawatt-hour.

The energy sources considered in electricity generation in the MESSAGE include 12 technologies of which five — light cycle oil, heavy fuel oil, biomass, gasoline and distillate fuel oil — play a negligible role in the cost minimizing portfolios in all scenarios. Therefore, at most seven energy sources appear in the electricity supply portfolios below.

Figure 11 shows electricity generation by types of technology in five scenarios. Nuclear power is missing from both baseline scenarios due to the fixed overnight cost of 5000 US $/kW installed capacity and the high discount rate of 12%. All installed capacities of RESs are in non-grid generation in the baseline scenarios.

The BAU baseline scenario serves as the reference case. Total installed capacity reaches 10.80 GW in 2038 and 15.36 GW in 2048 in this scenario. Generation from gas technologies dominate the power mix at the beginning of the study period but they are outstripped by coal power after 2038.

One of the sensitivity cases in the BAU scenario group includes a reduction of the baseline 12% discount rate to 6%. Total installed generation capacity in the BAU 6% discount rate case increases from 4.82 GW in 2020 to 10.66 GW in 2038 and 15.23 GW in 2048. Installed capacities of oil and gas decline and nuclear power appears in the capacity mix as of 2029. Total generation in this scenario almost triples between 2020 and 2048 (see Fig. 11).

Unlike the BAU reference scenario without emissions limits, a 15% emissions reductions constraint is included in the BAU 15% INDC scenario. The entire electricity supply system requires a total installed capacity of 4.79 GW in 2020, 10.80 GW in 2038 and 15.29 GW in 2048. The total installed capacity in 2048 is somewhat lower than in the BAU reference case. Electricity generation (see Fig. 11) almost triples between 2020 and 2048. Coal fired generation starts in 2025 and dominates the generation portfolio with a 50% share in 2048 followed by gas, hydro and nuclear power in that year.

Reflecting the aim of developing into a middle level income economy in the long term, the AEG baseline scenario serves a much higher electricity demand by the middle of the 21st century compared to the BAU baseline case. All other parameters and specifications are the same in these two scenarios (see above). Total installed capacity in the AEG baseline scenario increases from 4.85 GW in 2020 to 20.55 GW in 2038 and 28.90 GW in 2048. In addition to coal, oil and gas fired plants dominate the capacity mix with an over 80% share. Based on this installed capacity, power generation in the AEG reference scenario increases from about 23 TW·h in 2020 to about 98 TW·h in 2048 (see Fig. 11).

The INDC 15% strategy is also applied in the AEG scenario group. Aside from applying a 15% emissions reduction constraint relative to the AEG reference case, all other parameters are held constant. Total installed capacity in the AEG 15% INDC scenario in 2020 is 4788.11 MW and it grows to 17 681.4 MW in 2048. The share of oil and gas capacities is 44% and that of coal is about 20%. A 700 MW nuclear plant is added to the capacity mix in 2029. Figure 11 also shows electricity generation in the AEG 15% INDC scenario for the period 2020 to 2048.

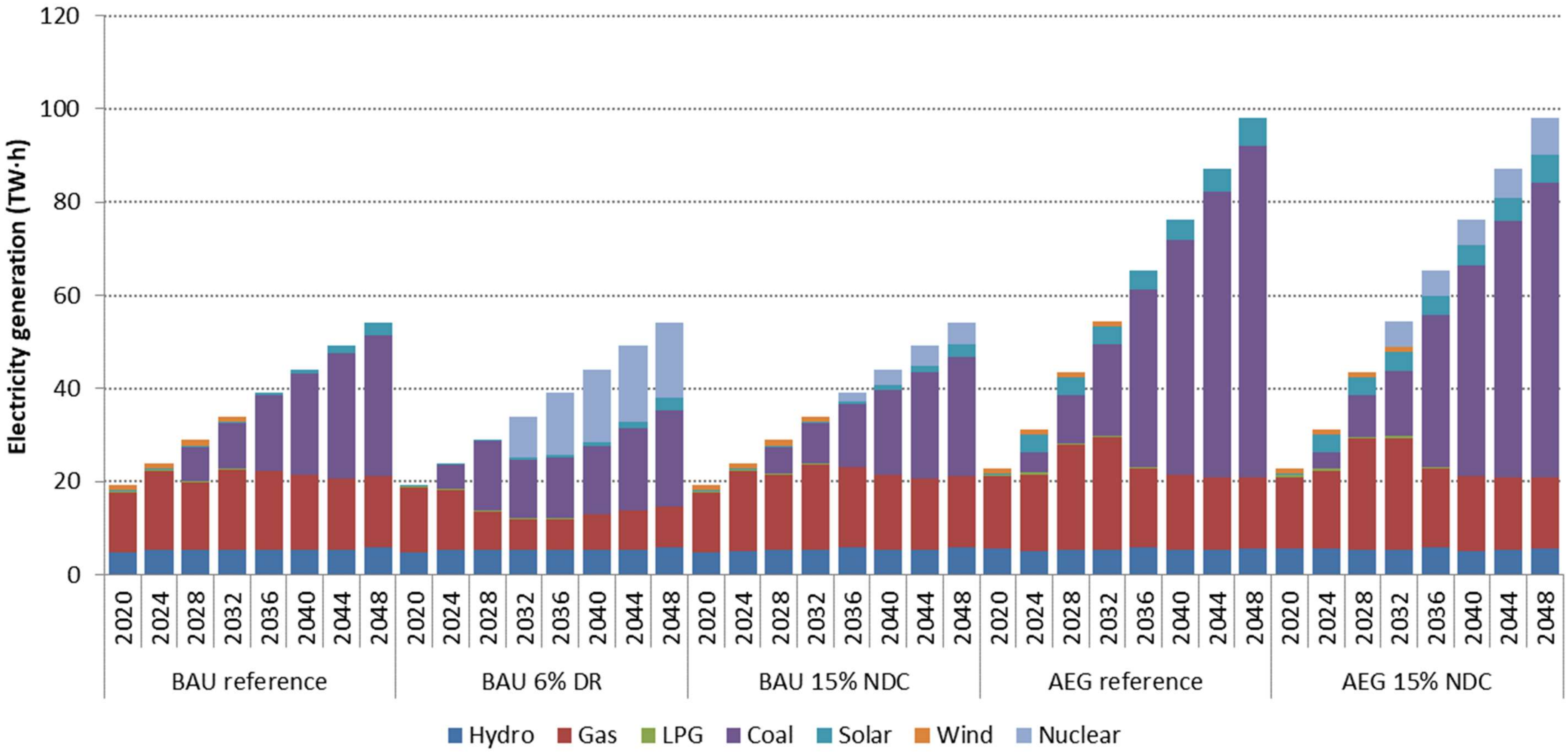

FIG. 11. Electricity generation projections in five scenarios. Data source: Ref. [113]. Note: TW·h — terawatt-hour, BAU — business as usual, DR — discount rate, INDC — intended nationally determined contribution, AEG — accelerated economic growth, LPG — liquefied petroleum gas.

It is not surprising that the widely diverging electricity demand projected in the two scenario groups and the various parameter specifications and emissions constraints in the modelled cases lead to very different CO_2 emissions pathways of the electric power sector in the five selected scenarios. They are presented in Fig. 12.

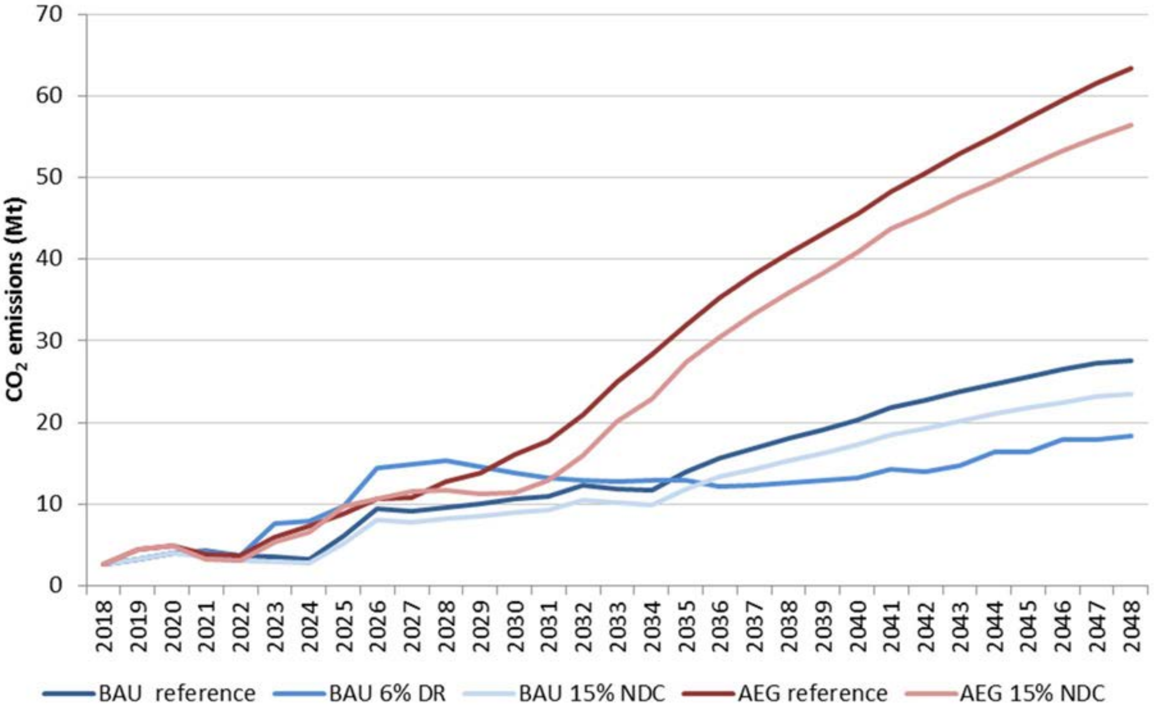

FIG. 12. CO_2 emissions from electricity generation in five scenarios. Data source: Ref. [113]. Note: Mt — megatonne, BAU — business as usual, DR — discount rate, INDC — intended nationally determined contribution, AEG — accelerated economic growth.

In the BAU reference scenario, CO_2 emissions from the entire electricity system are projected to rise from 3.95 Mt in 2020 to 27.62 Mt in 2048. The corresponding emissions factor increases from 0.21 kg CO_2/kW·h in 2020 to 0.51 kg CO_2/kW·h in 2048. Figure 12 also shows that CO_2 emissions in the BAU 6% discount rate scenario increase from 3.94 Mt in 2020 to 18.31 Mt in 2048. The resulting emissions factor increases from 0.20 kg CO_2/kW·h in 2020 to 0.34 kg CO_2/kW·h in 2048. The inclusion of nuclear power reduces CO_2 emissions by about 9.31 Mt relative to the BAU reference scenario in 2048.

In the BAU 15% INDC scenario, CO_2 emissions increase from 3.95 Mt in 2020 to 23.47 Mt in 2048 (see Fig. 12). The emissions reduction limitation relative to the BAU reference case without any constraints reduces CO_2 emissions below the BAU baseline over the entire time horizon and below the BAU 6% discount rate case until 2035 but the latter has a lower emissions path after 2035.

Not surprisingly, the almost twofold electricity demand and the resulting higher power generation in the AEG reference case relative to the BAU reference scenario significantly increases CO_2 emissions: from 4.89 Mt in 2020 to an astronomical 63.41 Mt in 2048 (Fig. 12).

The corresponding CO_2 emissions factor of power generation increases from 0.21 kg CO_2/kW·h in 2020 to 0.65 kg CO_2/kW·h in 2048. Both absolute emissions and the emissions factor grow slower in the AEG 15% INDC case relative to the AEG baseline (Fig. 12). Emissions increase from 4.89 Mt in 2020 to 56.48 Mt in 2048. The resulting emissions factor increases from 0.21 kg CO_2/kW·h in 2020 to 0.58 kg CO_2/kW·h in 2048.

4.4.4. Conclusions and policy insights

It is envisaged that Ghana's electricity demand will continue to grow and it is imperative to provide robust supply options to help the country develop. As the world moves from low to zero carbon emission technologies, Ghana needs to consider nuclear energy to support its economic growth while meeting its international climate protection obligations.

Although the results of this study show that no single electricity source can in itself reduce emissions in line with Ghana's INDC commitments in the absence of nuclear power, there are currently substantial competitive barriers to its deployment due to high overnight costs and the country's high discount rate of 12%. Therefore, without substantial reductions in capital costs, it is likely that nuclear power could only play a role in CO_2 emissions mitigation with strong market and policy support backed by strong political will and commitment. As illustrated by the results of the study, this includes not only direct climate change policy but also measures by the central government to shape the macro- and microeconomic parameters favourably to attract investment and improve access to cheaper financing to reduce the discount rate, to enable nuclear power to be competitive even at a high overnight cost. In other words, establishing a suitable investment environment can play a substantial role in unlocking the mitigation potential of nuclear power.

Cost assessments of Ghana's entire power system indicate that the inclusion of nuclear energy as a resilient low carbon baseload energy source decreases both the dispatch and average generation costs of electricity supply. A strong baseload electricity supply provided by nuclear power together with RESs at falling prices can satisfy even fast growing electricity demand.

The study shows that to reduce CO_2 emissions from the electricity sector, Ghana cannot continue to run it with a BAU attitude. Strong commitment, government policies and an enabling environment are needed in which nuclear can thrive and provide clean energy for the economy.

Ghana's first INDCs submitted in 2015 do not include nuclear power. This CRP study shows that nuclear energy could be recognized as an option in the country's climate change mitigation strategy and be incorporated in future mitigation commitments. Further, the results of the study are expected to contribute to Ghana's next strategic national energy plan that will consider nuclear power as a potential energy source, in contrast to the first plan.

4.5. LITHUANIA

The Lithuania study in the CRP illustrates the application of energy planning models to evaluate the role of renewable and nuclear energy in least cost decarbonization of power and heat generation in small countries. The section is based on Refs [118, 119].

4.5.1. Problem and situation assessment

Lithuania is a net energy importer. About 78% of the country's primary energy supply was imported in 2013. A key element of the energy strategy is the diversification of energy imports and resources. The long term goals are established in the National Energy Independence Strategy of 2012 [120] (revised in 2018). Despite the fast growing contribution of RESs, natural gas has still a large share in electricity generation. In order to end Gazprom's monopoly in the natural gas market of Lithuania, a large LNG import terminal has been operating in Klaipėda since 2014 and the Lithuania–Poland pipeline is expected to be completed by the end of 2021.

The Ignalina NPP used to provide about 70% of Lithuania's electricity and exported power to other republics of the Soviet Union. However, in solidary with the EU, Lithuania committed itself to decommission the Ignalina NPP upon accession. In 2019, Lithuania imported about 72% of its electricity, mostly from the Russian Federation and Sweden. The country is expected to remain a major electricity importer for some time in the future since low electricity import prices make major investments in new generation capacities unattractive.

GHG emissions in Lithuania dropped from almost 50 Mt CO_2-eq in 1991 to about 30 Mt CO_2-eq in 1992. Annual CO_2 emissions in the 2010s are about 20 Mt. Energy production and transport account for over 70% of total GHG emissions.

4.5.2. Methodology and assumptions

Numerous factors drive the future development of the energy sector in Lithuania. They include the current situation, the evolution of energy demand and its changes over time, the availability of local RESs, fuel prices and their fluctuations over time, import and export possibilities, environmental changes and requirements, the legal environment, requirements for energy security, technological progress, modernization options of existing technologies and other factors.

The MESSAGE (see Section 3) is used as the main tool for modelling least cost long term GHG emissions reductions strategies for Lithuania. The main emphasis is on the correct representation of economic sectors. The models of power and district heating sectors include fuel supply, fuel conversion to electricity and/or heat in power and heating plants, electricity exchange with foreign countries, supply and cross-border exchange of reserves, demand for electricity and heat, energy security, emissions accounting and support schemes for RESs and high efficiency technologies. The power system is modelled as a single region, while the district heating sector is split into physically isolated systems in order to represent the 11 most relevant systems and one additional system combining all others. Demand in each separate system is satisfied by a unique set of technologies.

Special attention is paid to GHG emissions reductions options (RESs and nuclear energy) in this model. In order to adequately evaluate the economic viability of these options, the intermittency of wind and solar power plants as well as required reserve capacities for NPPs are taken into account. A probabilistic approach is used to evaluate fluctuations in power generation from RESs. Reserve capacities are modelled by setting frequency containment (primary), frequency restoration (secondary) and replacement (tertiary) reserve demands, which are endogenously associated with the biggest operating capacity of the unit in the system. Reserves are supplied by power plant technologies that are technically able to provide these reserves, as well as by international power lines connecting Lithuania with neighbouring countries.

Fuel prices and fuel availability, prices and availability of electricity imports and exports, final demand and CO_2 emissions prices are estimated for the whole modelling period. Models are calibrated based on historical data. Fourteen different scenarios are prepared for the electricity and heat sector and a single one for road transport. Conclusions are drawn from the calculation results of different scenarios.

Three scenarios are considered on the demand side. Economic development and energy demand are assumed to increase by 2.6%/year up to 2030 and at 3.1%/year thereafter in the base scenario, by 4.6%/year and 3.6%/year in the respective periods in the fast growth scenario and at the annual rate of 2.8% and 1.7% in the slow growth scenario before and after 2030, respectively. Electricity demand is projected to grow slower, at annual rates of 2.2% in the base, 2.7% in the fast growth and 1.7% in the slow growth scenario up to 2030 and even slower at 1.1% in the base, 2.1% in the fast growth and 0.7% in the slow growth scenario after 2030.

Energy supply security is an important policy priority in Lithuania. Various combinations of minimum shares of domestic installed capacities and generation, and restrictions on imported electricity are defined in 14 scenarios modelled with the MESSAGE. All assume the base scenario of energy demand, moderate growth in fuel prices, CO_2 prices according to the new energy policy in the IEA World Energy Outlook 2013 [121], average electricity market prices, average investments in technologies, synchronous operation with the power system of continental Europe after 2025 and they exclude the option of new small NPPs. Electricity imports are distinguished according to their source: imports from the Scandinavian, Latvian and Polish electricity networks and from third countries that include Non-EU countries in which Nord Pool (a power trading market including 360 customers from 20 countries as of October 2020) does not operate trading markets. Scenarios for the electricity and heat sectors include electricity demand from the transport sector. Based on recent transport sector development trends, expert opinions and the national energy strategy, electricity demand in the transport sector is assumed to increase to 1.2 TW·h by 2050. The IPCC stationary and mobile combustion tier 2 approach is used for estimating future GHG emissions in the power and heat sectors in the MESSAGE. CO_2 emissions are calculated by multiplying the consumed fuel quantity by the corresponding CO_2 emission coefficient based on the carbon content of the fuel. Biofuels are considered carbon neutral. Other emissions like nitrous oxide, methane, nitrogen oxide pollutants, particulate matter and SO_2 are calculated by using technology specific emissions coefficients.

Long term emissions reductions targets for Lithuania are identified according to the national climate change policy. Lithuania’s target is to reduce its GHG emissions by 40% in 2030, 60% in 2040 and 80% in 2050 relative to the 1990 level.

The scenarios are clustered into four groups: basic, integration, isolation and green. Table 4 presents the most important specifications regarding electricity supply. Of the 14 scenarios, the results of four scenarios are discussed here that best represent possible developments, hence they are most important with a view to future energy and climate policies. They include I50 and G80b in the group of basic scenarios and Aa and Ab in the integration group.

TABLE 4. ELECTRICITY SUPPLY ASSUMPTIONS IN MODELLED SCENARIOS
(based on Ref. [119])

Factors	Basic scenario					Integration scenario			Isolation scenario			Green scenario		
	I50	I100	G50	G80	G80b	Aa	Ab	Ac	Aa	Ab	Ac	Aa	Ab	Ac
RES[1] level	Not specified					30% (2030), 55% (2050)						35% (2030), 65% (2050)		
VNPP[2] existence	Not specified				No	Yes	No		Yes	No		Yes	No	
Share of locally produced electricity in total electricity demand	Not specified		2020(30%), 2050(50%)	2020(50%), 2050(80%)		2020(30%), 2050(50%)	Not specified		2020(50%), 2050(80%)	Not specified				
Possible share of imported electricity in total electricity demand	Not specified		2020(70%), 2050(50%)	2020(50%), 2050(20%)		2020(70%), 2050(50%)	Not specified		2020(50%), 2050(20%)	Not specified				
Possible share of imported electricity from third countries in total electricity demand	Not specified		2020(35%), 2050(10%)	0%		2020(35%), 2050(10%)	Not specified		0%			Not specified		
Share of possible electricity production by local generators with guarantied availability	50%	100%	50%			Not specified	50%	100 %	Not specified	50%	100%	50%		100%
Links with IPS/UPS[3] for electricity import	Used					Used			Not used			Used		

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[1] RES: renewable energy source.
[2] VNPP: Visaginas nuclear power plant.
[3] IPS/UPS: Integrated Power System/Unified Power System.

4.5.3. Results

Total electricity demand is projected to steadily increase in all three scenarios (see Fig. 13). By the middle of the 21st century, it is estimated to increase to above 21.1 TW·h in the fast growth, to about 17.7 TW·h in the base and to more than 15.2 TW·h in the slow growth scenario.

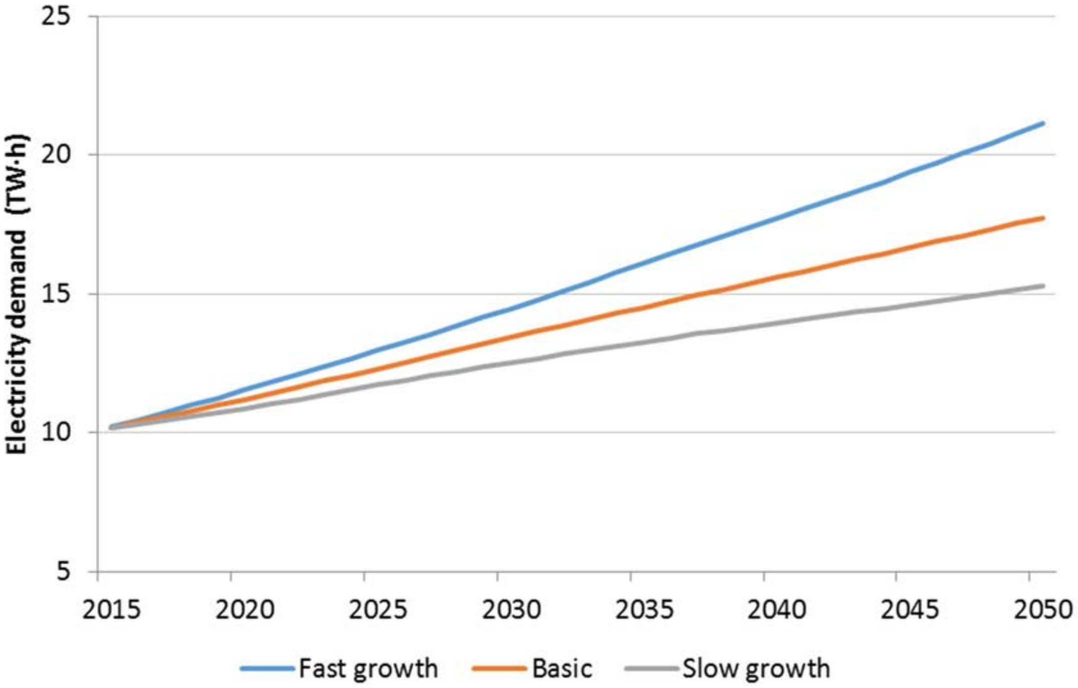

FIG. 13. Electricity demand projections. Data source: Ref. [119]. Note: TW·h — terawatt-hour.

Electricity supply scenarios show a diverse range of possibilities to satisfy demand. Generation portfolios under the four most important scenarios are presented in Fig. 14.

As Fig. 14 shows, local generation covers 59.6% of final electricity demand in scenario basic I50, 99.5% in basic G80b, 135.9% in integration Aa and 118.5% in integration Ab in 2050. The model is free to choose whether to build an NPP in basic scenarios (excluding basic G80b). In the basic G50 scenario, nuclear power is introduced in 2040 but it produces a meagre 0.2 TW·h in that year and only 1.4 TW·h in 2050. Nuclear power is introduced in 2030 in scenario basic G80 and it generates the largest amount of electricity in 2050 but still only 2.2 TW·h. The model is forced to build a 1350 MW(e) NPP in 2025 in the integration Aa, isolation Aa and green Aa cases. In all three scenarios, it generates annually 5.0–5.2 TW·h electricity between 2020 and 2030. Thereafter generation drops and produces only 0.7 TW·h in 2050 in the green Aa case, largely due to increasing generation targets for RESs. Similarly, in scenarios integration Aa and isolation Aa, generation drops after 2040 and the NPP produces only 3.6–3.8 TW·h in 2050. This means that on average only 30–32% of the installed capacity is utilised. Electricity generation from RESs reaches 79.8% in the basic I50, 49.3% in the basic G80b, 81.8% in the integration Aa and 94% in the integration Ab scenario by 2050. Heat generation from RESs for district heating by 2050 reaches 80% in the basic I50, 64.2% in the basic G80b and 93.8% in all other scenarios.

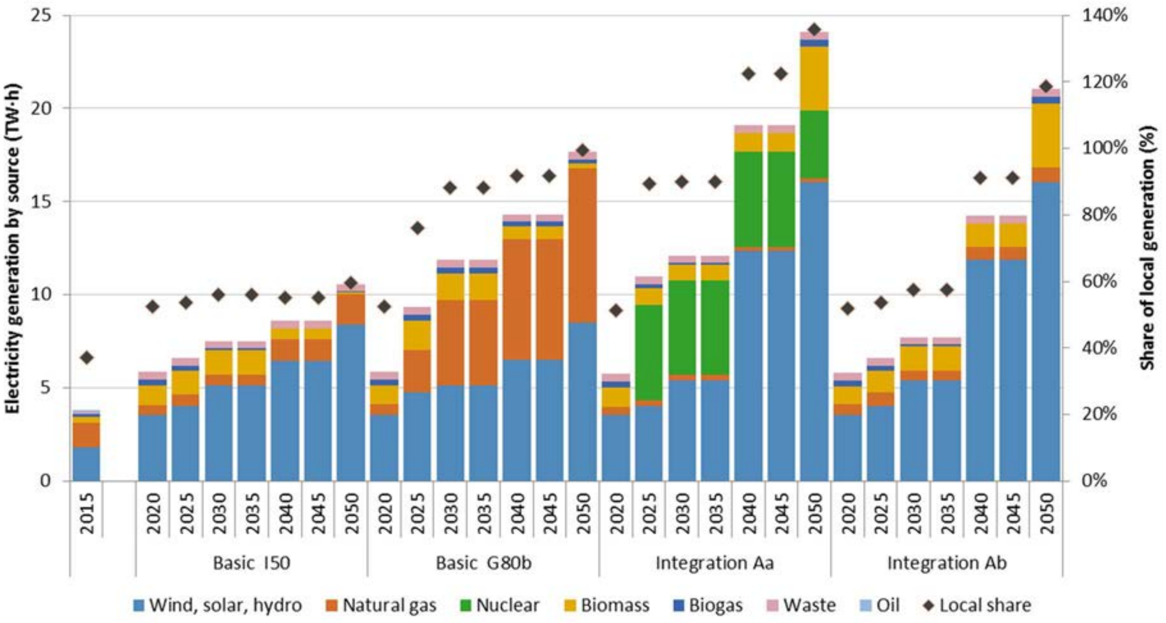

FIG. 14. Electricity generation (columns, left axis) and shares of final electricity generated locally (rhombuses, right axis) in four scenarios. Data source: Ref. [119]. Note: TW·h — terawatt-hour.

Total discounted costs of the development and operation of the Lithuanian energy sector during the study period indicate that the implementation of practically all scenarios is more expensive than those in the basic group, except the rather flexible integration Ab and green Ab scenarios. Total discounted costs over the modelling period amount to €50 billion in the basic I50, €50.8 billion in the G80b; €51.1 billion in the integration Aa and €50.5 billion in the integration Ab scenario. Wholesale electricity prices relative to those in basic I50 scenario are somewhat higher in all other basic and integration cases while considerably higher in the isolation and green scenario groups. They are higher by 21% in the basic G80b and by 17% in the integration Aa and integration Ab scenarios compared with the basic I50 scenario.

CO_2 emissions from electricity and heat production are presented in Fig. 15. Note that emissions from heat generation are also included because it is not straightforward to divide emissions from combined heat and power plants between the two types of output. Heat related emissions amount to a small fraction in the total anyway.

The biggest reductions in CO_2 emissions in electricity and heat production are achieved in the integration Aa scenario in which emissions decline from 2.2 Mt in 2013 to 0.51 Mt in 2050. Emissions in the basic G80b scenario strongly increase to 3.4 Mt CO_2 in 2050 mainly due to the extensive use of CCGT cogeneration. CO_2 emissions in 2050 from electricity and heat generation amount to 1.0 Mt CO_2 in the basic I50 and 0.69 Mt CO_2 in the integration Ab scenario.

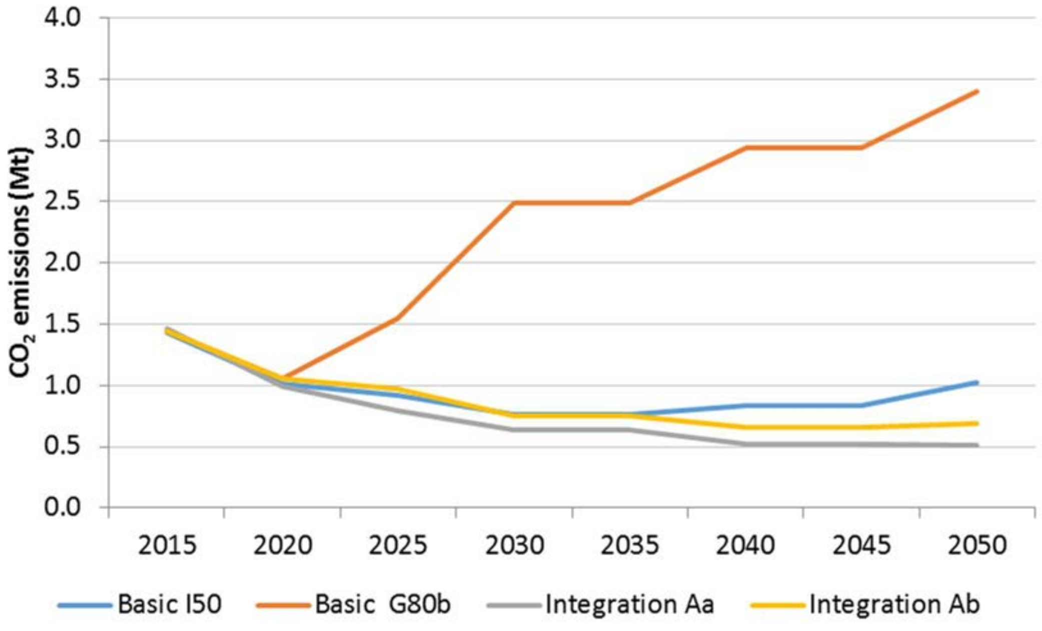

FIG. 15. CO_2 emissions from electricity and heat generation in four scenarios. Data source: Ref. [119]. Note: Mt — megatonne.

4.5.4. Conclusions and policy insights

The selection and implementation of emissions reductions measures needs to be carried out in accordance with the real conditions in the energy system. In this study, the Lithuanian emissions reductions strategy is considered in the context of the development of the energy sector operating under market conditions. This determines the cost effectiveness of various energy generation sources and the attractiveness of emissions reductions measures. Energy security requirements, reserve and balancing services, as well as country specific and EU energy policy requirements are taken into account.

Refurbishment of existing hydropower plants, construction of wind and solar power plants, combined heat and power plants fuelled by biomass, municipal waste, natural gas and biogas are the most attractive electricity generation options in Lithuania. The most economical balancing options include generation compensation obtained via interconnectors from available sources in neighbouring countries, electricity storage (e.g. hydropower plants with pumped storage), combined heat and power plants operated with gas turbines and internal combustion engines, and gas turbine power plants.

NPPs can be cost effective in Lithuania under circumstances in which some dimensions of energy security have priority — specifically, if a high share of domestically generated electricity is desired (in contrast, NPPs are not cost effective if sufficient domestic capacity is the principal energy security priority) — but the potential of large plants appears to be limited, including by reserve requirements to cover the outages of a single large unit. With the obligatory deployment of a large NPP (Aa scenarios) only a fraction of the nuclear generation capacity is used owing to reserve capacity requirements and other energy policy targets, in particular RES targets. While obligatory NPP deployment can achieve slightly lower GHG emissions, it results in a moderate increase in system cost. Higher electricity consumption due to rapid transport electrification or regional consideration does not bring NPPs into the set of cost efficient power plants for electricity generation and climate change mitigation strategy.

More people are likely to switch to electric vehicles for daily commuting as they become increasingly cheaper. A high penetration of electric vehicles in the transport sector will not only increase demand for electricity but it will affect the demand curve itself. For this reason, it is important to evaluate the effects of electric vehicles in planning possible paths of energy sector development in the future.

4.6. PAKISTAN

This section explores various development and energy scenarios to assess the effectiveness of domestic policies to invest in low carbon technologies, including nuclear power, with a view to their role in electricity supply and GHG emissions mitigation. It also estimates the water use impacts of the scenarios. The section is based on Refs [122, 123, 124].

4.6.1. Problem and situation assessment

Large amounts of energy and electricity will be needed in Pakistan to increase the pace of economic growth and meet the needs of growing population. There is a need to formulate strategies to meet the growing energy demand while dealing with the multifaceted challenges of climate change threatening water, food and energy security in the future.

Total proven fossil fuel reserves of Pakistan as of June 2018 are 3.856 billion tonnes of oil equivalent (toe) of which oil and natural gas resources are limited. Per capita primary commercial energy supply is 0.41 toe in 2018, supplied by oil, gas, coal, hydropower, nuclear and RESs. Around 46% of energy is imported.

During the fiscal year 2017–2018 (a fiscal year starts 1 July and ends 30 June of the next calendar year in Pakistan), grid supplied electricity was 131 TW·h provided by hydropower (21.3%), natural gas, including regasified LNG (37.4%), oil (22.5%), coal (8.3%), nuclear (7.5%) and RESs (3.0%) [125]. During the period 1994–2018, electricity consumption in Pakistan grew from 37 to 107 TW·h at an average growth rate of 4.5%/year. Total installed generation capacity increased to 33.55 GW by June 2018 comprising 21.3% hydropower, 61.5% oil and gas, 8.0% coal, 4.3% nuclear and 4.9% RESs [125]. This total installed capacity has increased to 38.72 GW by June 2020.

GHG emissions of Pakistan reached 405 Mt CO_2-eq in 2015. The energy and agriculture sectors were responsible for 89% of the total national GHG emissions. Pakistan’s current contribution to global GHG emissions is small but it may gradually increase with socioeconomic development, increasing access of people to commercial fuels and increasing food demand. GHG emissions of Pakistan are projected to reach 1.6 Gt CO_2-eq in 2030 [126], about 2–3% of the estimated total world emissions in that year (see Refs [1, 7]). The National Climate Change Policy [127] fosters a creative and sustainable energy policy framework that may help reducing GHG emissions by developing renewable energy resources and increasing the share of nuclear and hydropower.

The first NPP in Pakistan was connected to the grid in 1971. As of September 2020, five reactors are operating in the country [128]. Further extension of the nuclear reactor fleet is underway, with two reactor units under constructions. Nuclear energy is also recognized as inevitable in Pakistan’s INDCs [126].

4.6.2. Methodology and assumptions

Two projections of energy and electricity demand are quantified for Pakistan over the period 2018–2050 with the MAED (see Section 3) based on detailed socioeconomic information from Refs [129, 130]. The annual GDP growth rate in the base case is 5.5%, with total final commercial energy demand increasing from 750 TW·h in the base year (2018) to 2831 TW·h in year 2049–2050 at a growth rate of 4.2%/year. Electricity demand increases at an annual average growth rate of 5.3%, while demands for fossil fuels (coal, gas, residual oil) and motor fuels, also important for economic growth, increase at annual growth rates of 4.2% and 3.9%, respectively, between 2018 and 2050.

In the optimistic case, the assumed average annual economic growth rate is 6.5%, total final commercial energy requirement is projected to increase to 3698 TW·h in 2049–2050 at a growth rate of 5.1%/year. Electricity demand is estimated to increase at an average annual growth rate of 6.2%, while both fossil fuels and motor fuels demand grows at 5.0% in the 2018–2050 period. Non-commercial (e.g. traditional biomass) fuels for the residential and industrial sectors are also included in the MAED.

To assess options to satisfy the projected energy demand, an in-depth analysis of energy supply strategies, including options for GHG mitigation, is undertaken by using the detailed energy system model MESSAGE (see Section 3). The reference energy system represented in the model describes the flow of domestic energy resources and imported energy for Pakistan. Four energy and electricity supply scenarios are defined and analysed for the period 2018–2050, also considering national policy constraints, international climate mitigation guidelines and targets as well as technological evolution and replacement.

The baseline scenario assumes base case energy demand, potential hydropower capacity up to 35 GW, no limit on using local coal (lignite, Thar region), and an upper limit on nuclear capacity of 9 GW(e) by 2030 and around 30 GW(e) by 2050. Wind power may increase to 11 GW by 2050 and solar energy has no limit. Annual production of conventional oil and gas is expected to be maintained at base year level during the study period. There is no limit on oil, LNG and coal imports. In the optimistic scenario (OPTS), the optimistic case of energy demand and a nuclear capacity of up to 40 GW(e) by 2050 is considered. In two additional scenarios, baseline with GHG mitigation (RGMS) and optimistic with GHG mitigation (OPGM), GHG mitigation is considered and peaking of emissions from the energy system in 2045 is assumed, in contrast to the baseline and OPTS cases in which GHG emissions are not constrained.

The price of imported crude oil is assumed to increase from around 60 US $/barrel in the base year to 80 US $/barrel by 2030 and 108 US $/barrel by 2050 (see Ref. [130]). The price of LNG imports is linked to the price of crude oil, while the prices of local and imported coal are set at 46 US $/t and 80 US $/t, respectively, and are assumed to increase by 10% and 12%, respectively, during the study period.

The electricity load curve is divided into four seasons and five parts per day in each season (resulting in 20 load regions) on the basis of variations in electricity demand, water and availability of RESs. Load curves of hydropower plants and intermittence of wind and solar sources are also modelled.

Capital investment costs per kW capacity are assumed to be 1500–3000 $/kW for hydropower, 4000 $/kW for nuclear, 1200 $/kW for coal, 1900 $/kW for coal with CCS, 625 $/kW for

CCGTs using LNG, 1225 $/kW for wind and 750 $/kW for solar PV. Differences in the efficiency of fossil fired generation technologies and sources are also considered.

Direct GHG emissions (CO_2, methane and nitrous oxide) are modelled for combustion and fugitive emissions using IPCC guidelines [131]. Methane and nitrous oxide emissions of biomass combustions are also modelled and included in total emissions of the energy sector. Water consumption and land utilization are estimated by using the factors of land use per unit of installed capacity and water consumption per unit electricity generation.

4.6.3. Results

The MESSAGE is used to evaluate the four scenarios based on the assumptions described above. The results show that expansion of the energy and electricity systems in the 2018–2050 period requires the full exploitation of domestic energy resources to decrease energy import dependence. This also supports an increase in the share of low carbon resources in the primary energy supply, from 11.5% in 2018 to 21.0 % by 2050 (in the baseline) and up to 35–37% with GHG mitigation. In power generation, the share of clean technologies (hydropower, nuclear, RESs and coal with CCS) increases from 31.7% in 2018 to 44.0% in 2050 in the baseline scenario and to around 80% in both GHG mitigation scenarios, RGMS and OPGM. These scenarios require 21% and 33% additional generation capacity by 2050 compared to the baseline and OPTS scenarios, respectively. The nuclear capacity share increases from 4.3% in 2018 to 15% in the baseline scenario, 14% in the OPTS and around 20% in the GHG mitigation scenarios by 2050. Nuclear power accounts for about one third of generation in the mitigation scenarios in 2050 (see Fig. 16). The resulting GHG emissions are presented in Fig. 17.

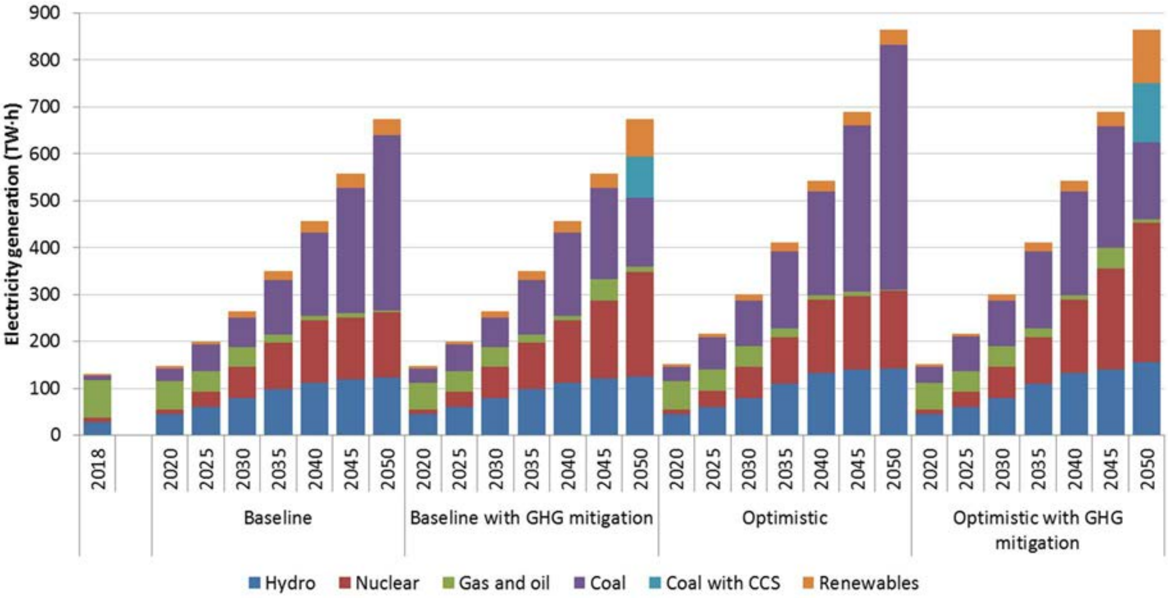

FIG. 16. Electricity generation by technologies and fuels in alternative scenarios. Data source: Ref. [124]. Note: TW·h — terawatt-hour, GHG — greenhouse gas, CCS — CO_2 capture and storage.

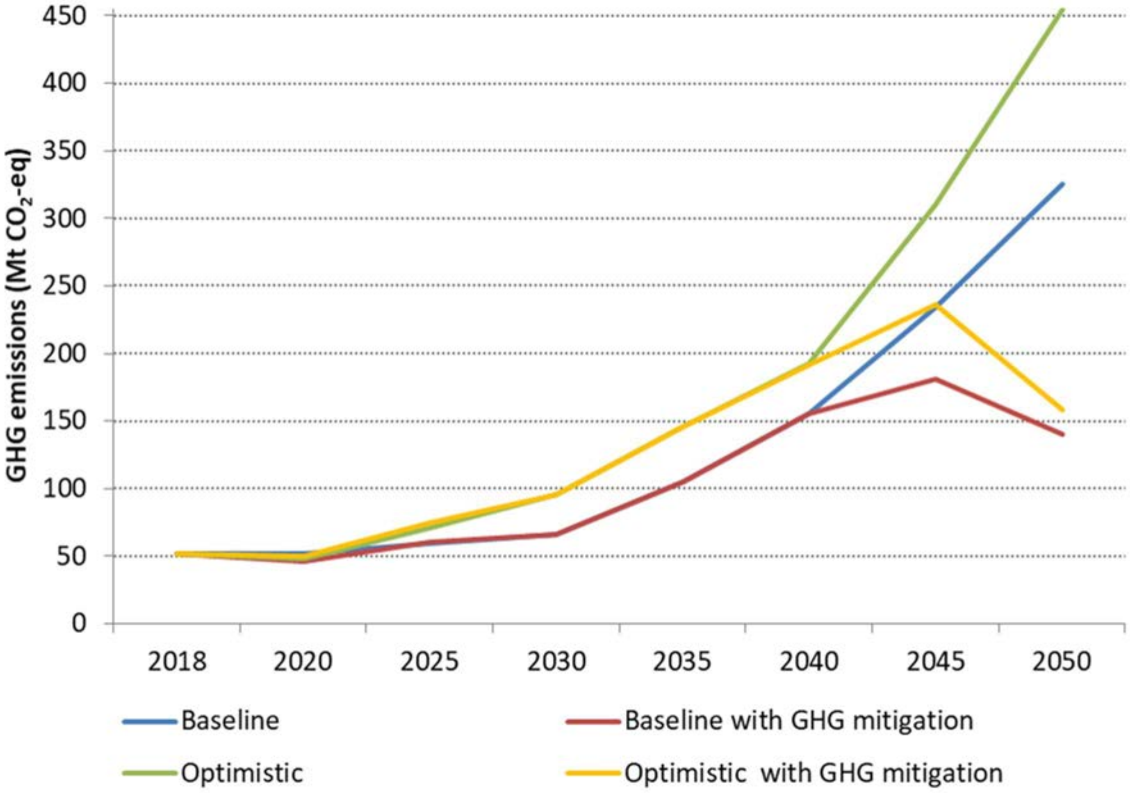

FIG. 17. GHG emissions from electricity generation in alternative scenarios. Data source: Ref. [124]. Note: GHG — greenhouse gas, Mt CO_2-eq — megatonne of carbon dioxide equivalent.

Since there are no GHG emissions constraints in the baseline and the OPTS scenarios, emissions from the power sector increase exponentially to reach 325.7 and 454.7 Mt CO_2-eq, respectively in 2050, despite substantial generation from nuclear, hydropower and other RESs. Emissions are constrained in the energy sector starting from 2045 in the RGMS and OPMG scenarios that results in emissions decline in absolute terms in the power sector after 2045. However, in order to achieve absolute GHG emissions reductions from the energy sector after 2045, mitigation would also be required in other subsectors such as manufacturing and transport.

Investments required for capacity additions in the 2018–2050 period amount to almost US $200 billion in the baseline and around 26% more in the OPTS scenario. The RGMS and OPGM scenarios involve 29% and 42% higher investments than their corresponding baseline scenarios, respectively. In these scenarios, the cost of GHG mitigation is about 36 US $/t CO_2-eq. Restricting nuclear capacity to the levels of the baseline and OPTS cases increases mitigation costs further by 1–2 US $/t CO_2.

Sensitivity analysis shows that if the discount rate is increased above 7% or the capacity factor of nuclear plants is reduced by 1 percentage point, nuclear power does not enter the optimal capacity mix in the baseline scenario and GHG emissions from the energy sector increase by 12% during the 2030–2050 period. If deployment of coal without CCS is restricted to a maximum of 20 GW during 2018–2050, for instance due to financing constraints on high carbon emitting technologies, the planned NPP capacity, hydropower projects, LNG fired plants and even some additional coal with CCS will be required after 2040. In this case, energy import dependence would increase by 4–5 percentage points due to LNG imports in the last decade of the study period.

The water use implications of the power sector enlargement have also been examined for the four scenarios, given the policy importance of water resource management in Pakistan. Figure 18 shows the evolution of annual consumptive water use, i.e. the amount of water that evaporates into the atmosphere from the power system, delineated into two categories: total (hydropower, thermal and solar PV generation) and thermal only. Thermal plants are reported separately to illustrate the potential of different cooling water system (once through versus closed cycle cooling). In this study, closed cycle cooling systems are assumed in future expansions of local coal and gas fired power plants, while nuclear and imported coal based plants are specified to use once-through cooling systems.

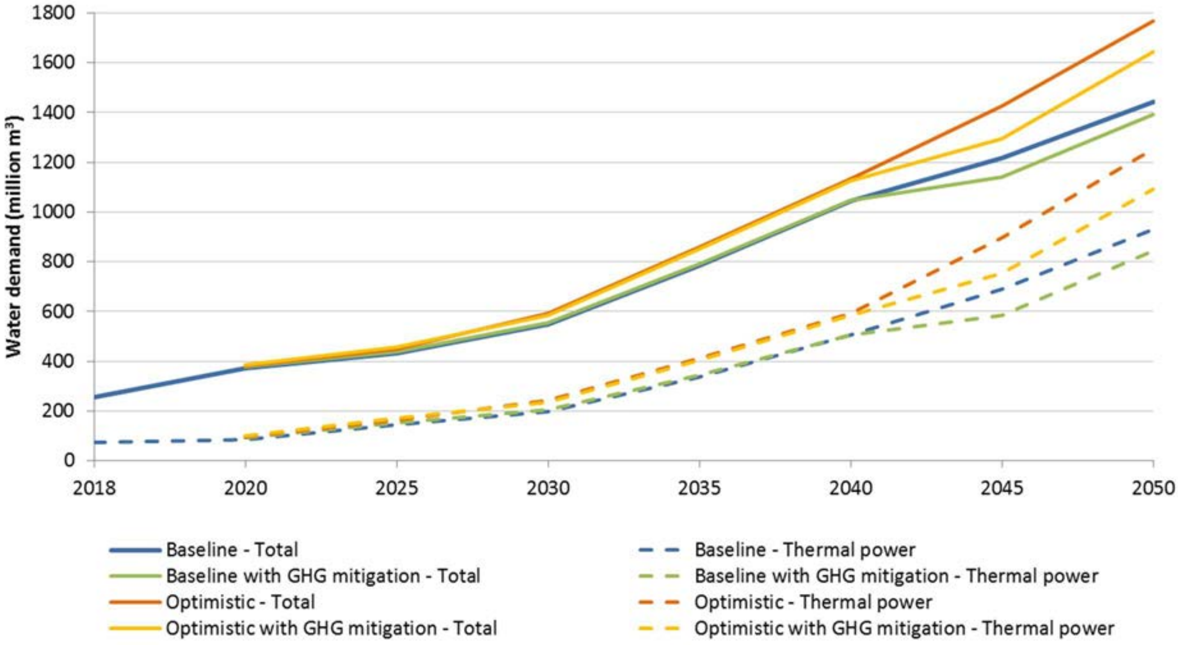

FIG. 18. Water demand for electricity generation in alternative scenarios. Data source: Ref. [124]. Note: GHG — greenhouse gas.

Water demand (consumptive use) of the overall power sector and thermal power generation keeps increasing in all four scenarios through 2050. Annual water demand of power generation is projected to increase from 255 million m^3 in 2018 to 1391–1768 million m^3 by 2050 (see Fig. 18). This is a significant amount, considering that the total amount of water resources available in the country is around 173 billion m^3, which needs to be included in the future water supply plans.

4.6.4. Conclusions and policy insights

To ensure continued rapid economic development to 2050 and to decrease energy import dependence, extensive exploitation of domestic energy resources will be required to support the expansion of the energy and electricity system. The share of low carbon energy sources in both primary supply and electricity generation is projected to increase; moderately in the absence of additional GHG mitigation measures, and strongly with efforts to cap emissions in 2045. In the mitigation scenarios presented here, the electric power sector plays a key role, with low carbon sources (hydropower, nuclear, coal with CCS and extensive installation of solar power) generating about 80% of the electricity by 2050. Shares of nuclear capacity are projected to increase significantly even without GHG mitigation considerations, from 4.3% in 2018 to 14–15% by 2050 and by even more (to 17–20%) with mitigation targets. The nuclear share in electricity generation increases to around one third in these mitigation cases.

Substantial investments in new electricity generation capacity are required in all scenarios, particularly in mitigation scenarios, which require 29–42% additional investments over the period 2018–2050. Further investments will also be required for GHG mitigation in other subsectors (e.g. manufacturing and transport) to achieve emissions reductions in absolute terms after 2045. The scenario analysis estimates the marginal cost of GHG mitigation at about 36 US \$/t CO_2 and somewhat higher if nuclear capacity is restricted in the GHG mitigation scenarios to the level of the capacity resulted in the non-GHG mitigation scenario, requiring larger generation by more expensive solar and coal with CCS capacities. In addition to climate change, the analysis also highlights potential challenges to sustainable water management. Water demand of total power generation is projected to increase six- to seven-fold between 2018 and 2050. Higher nuclear capacity shares in the mitigation scenarios decrease water demand because they replace coal fired plants. The explanation is that assumed future indigenous coal based capacity expansion will use closed cycle cooling.

This study shows that the importance of nuclear energy is expected to increase significantly in cost minimizing power generation portfolios, even in the absence of GHG mitigation efforts. As a developing country Party to the UNFCCC and signatory to the Paris Agreement, there is an expectation that Pakistan's GHG emissions will continue increasing in the short to medium term but it may need to reduce its GHG emissions in absolute terms before 2050. This would involve heavy investment and operational costs in nuclear, hydropower and coal with CCS capacities. Given the associated challenges, Pakistan needs international support in technology transfer, especially in nuclear power technologies, and financing to establish low carbon technologies.

4.7. POLAND

The Polish study in this CRP explores the extent to which the planned Polish nuclear power programme and the new energy policy adopted by the Polish government contribute to achieving the national targets of GHG emissions reductions. The study describes model and software development and the analysis of scenarios depicting energy policy, economic impacts and the decarbonization of the Polish economy. This section is based on Refs [132, 133, 134].

4.7.1. Problem and situation assessment

In the light of the Paris Agreement under the UNFCCC, a structural change in the Polish energy sector will be unavoidable. In electricity production, this includes reducing coal based generation and increasing the use of low carbon sources, despite the abundance of affordable domestic coal resources. Policy measures undertaken both at the global and the EU level to reduce GHG emissions will increase the costs of traditional electricity generation mix based on fossil fuels due to higher prices of emissions permits in the future under the EU emissions trading system. Switching to modern fossil generation equipped with CCS systems also remains costly.

These factors decrease the profitability of traditional energy sources based on fossil fuels compared to RESs and nuclear power. While RESs are thus expected to contribute to a significant reduction in CO_2 emissions, in many countries, including Poland, resistance to building NPPs is very high owing to historical reasons, political stereotypes, changes in consumer preferences and the lack of public awareness of nuclear energy and the consequences of GHG emissions.

Nevertheless, the inclusion of nuclear power in the Polish energy mix over the next two decades seems almost certain. Nuclear plants will provide baseload power and replace electricity from coal. The draft Energy Policy of Poland until 2040 (EPP2040) [135] and the recently released final policy [136, 137] envisage building 6–9 GW(e) of nuclear generation capacity, which will absorb a substantial share of the total investment outlays of the electricity sector over the next 20 years. This will affect the entire economy, not only CO_2 emissions.

4.7.2. Methodology and assumptions

The IAEA EMPOWER [76] (see Section 3.4.2) is extended and used to estimate the economic and environmental impacts of the EPP2040 programme and related scenarios. Model extensions in Empower.pl.cc (see Ref. [134]) include additional equations in the energy and emissions blocks to investigate GHG emissions. Another deviation from the original EMPOWER is the replacement of the Excel based software with Interdyme [138], a package designed for multi-sectoral macroeconomic models, which allows to run the Empower.pl faster and more efficiently.

The assumptions adopted in the simulations are based on the draft EPP2040. The objective is to assess the effects of structural changes in the power sector resulting from the EPP2040 provisions and from related considerations about climate change mitigation. For the purposes of this study, it is assumed that the annual rate of increase in total economic output in real terms is a conservative 2%, compared with about 4.1%/year in the 1990–2018 period. The wage reaction to the unemployment rate is assumed to be -0.7, i.e. in the middle of the range observed across EU countries. The income elasticity of demand is set at 0.8%, while an export price elasticity of -1% is assumed.

The EPP2040 identifies eight strategic directions: the optimal use of domestic energy resources, development of power generation capacity and transmission infrastructure, diversification and network infrastructure development of natural gas and oil supply, development of energy markets, introduction of nuclear energy, expansion of RESs, extension of heating and cogeneration, and improving energy efficiency. The policy anticipates a more ambitious nuclear programme than the plan in the 2014 Polish Nuclear Power Programme [139] but it postpones the commissioning of the first NPP until the 2030s. In the EPP2040, it is assumed that six reactor blocks will be built at two power plants, each with a capacity of 1–1.5 GW(e), resulting in a total capacity of 6–9 GW(e). It is also foreseen that the first block will be started in 2033 and subsequent ones will be added every two years thereafter, i.e. the entire programme will be completed by 2043. The government estimates the cost of the complete programme at PLN 100–135 billion. This means that the estimated construction costs per 1 GW(e) of installed capacity are PLN 16.7 billion for the lower total capacity (6 GW(e)) option and PLN 15 billion in the 9 GW(e) variant.

The EPP2040 also includes forecasts regarding the demand for electricity, installed capacity and electricity generation until 2040. According to the EPP2040 forecast, the annual rate of increase in electricity demand in the first decade of the forecast period is 1.9% and then it falls to 1.5%. This difference is due to the rapid increase of electromobility needs and heat pumps triggered by government programmes.

For the purposes of this study, the EPP2040 projection is extended for the 2040–2060 period assuming a continuation of economic growth of 2%/year and an increase in electricity demand of 1.5%/year (i.e. as in the final years of the EPP2040 forecast). These developments form the basis of the assumptions for four scenarios simulated with the Empower.pl.cc.

The baseline scenario assumes that no NPPs are built up to 2060, and instead installed capacity increases in line with demand, but its structure and capacity utilization factors are frozen at the level of 2033 in the EPP2040. The average unit costs of generating electricity in the Empower.pl.cc are based on the IEA estimates [105].

The three other scenarios assume that the larger total nuclear capacity delineated in the EPP2040 will be implemented in the 2023–2043 period at the total cost PLN 135 billion and six nuclear blocks, each with 1.5 GW(e) capacity, are built at two sites. The construction of the first reactor is assumed to be completed in 2032 and connected to the power grid in 2033. Subsequent blocks will be started every two years. Lignite and hard coal power plants will be phased out by 2044 and 2053, respectively.

Two of the scenarios also explore the potential of energy efficiency improvements in and beyond the electricity sector that significantly reduce CO_2 emissions from the energy sector. The resulting surplus electricity is assumed to be exported. The goal is to illustrate the capabilities of the Empower.pl.cc and show the role of the nuclear programme planned under the EPP2040 in the broader context of measures to reduce GHG emissions, i.e. how significant is the effect of building NPPs compared to other projects aimed at emissions reductions. The two scenarios differ in the rate of efficiency improvements in economic sectors: the AM1 scenario adopts an efficiency improvement at a rate of 1%/year from 2020 on, while the assumed efficiency improvement rate is 3%/year in the AM3 case, also starting in 2020.

4.7.3. Results

This section presents results of the following model runs: baseline (no NPP is built up to 2060) and scenarios based on the EPP2040 and beyond (up to 2060): basic (construction and operation of NPPs according to the schedule presented in the previous section), AM1 (basic + energy efficiency increase by 1%/year) and AM3 (basic + energy efficiency increase by 3%/year).

The Empower.pl.cc calculates results for the entire development programme presented above. The evolution of the power generation mix is presented in Fig. 19.

Macroeconomic impact assessments show that the implementation of the nuclear power programme increases GDP growth relative to the baseline path. Although financing the programme from public sources initially reduces GDP below the baseline path, the economy-wide benefits after 2036 (when the second reactor is also connected to the grid) outweigh the losses resulting from the higher taxes to finance the construction of additional blocks. The reason is that average electricity production costs decline as a result of the growing share of nuclear generation in the power mix. After the programme is completed, these benefits decrease because the shares of electricity generated from solar, wind and gas sources increase and their unit production costs are higher than that of nuclear power. Nevertheless, GDP in 2060 is above the baseline level by about 0.1%.

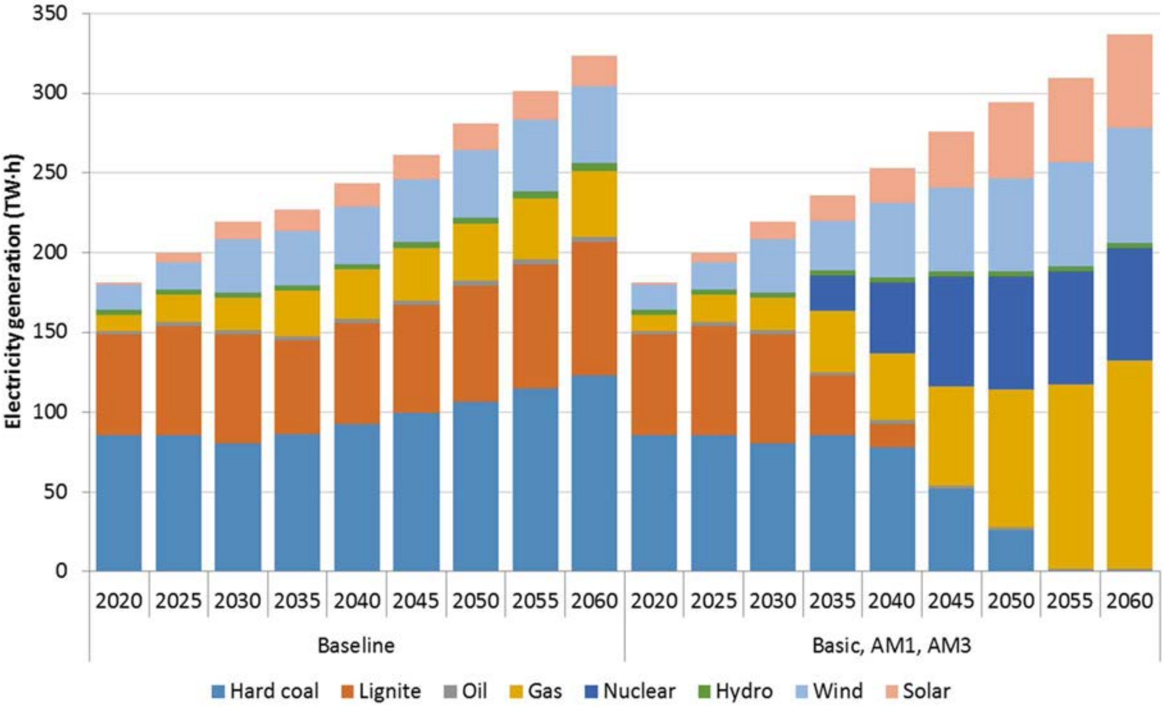

FIG. 19. Electricity generation in four scenarios. Data source: Ref. [134]. Note: TW·h — terawatt-hour.

The gradual decline of coal fired electricity generation reduces CO_2 emissions as the nuclear power programme envisaged in the EPP2040 is implemented. However, changing the power generation mix towards low or zero emission energy sources is just one of the two elements of the energy transformation. The second, equally important element, is the increase in energy efficiency that reduces energy consumption without limiting the utility of energy use in production or broadly understood consumption.

Emissions impacts of changes in energy efficiency in the entire economy and changes in energy consumption in 2060 compared to 2020 are calculated for the baseline, basic, AM1 and AM3 scenarios. In the first two scenarios, energy efficiency in the period under consideration increases only slightly, by about 5%. The effect of a systematic rise in energy efficiency in the other two cases is a 19% efficiency increase in the AM1 scenario and a 39% improvement in the AM3 scenario over the study period. These changes in efficiency result in energy savings. While energy consumption in the baseline and basic scenarios more than doubles (increases by about 110%), it is clearly lower in the other two cases: increasing by only 79% in the AM1 and by 47% in the AM3 scenario.

Figure 20 presents total CO_2 emissions from all energy sources in the four scenarios.

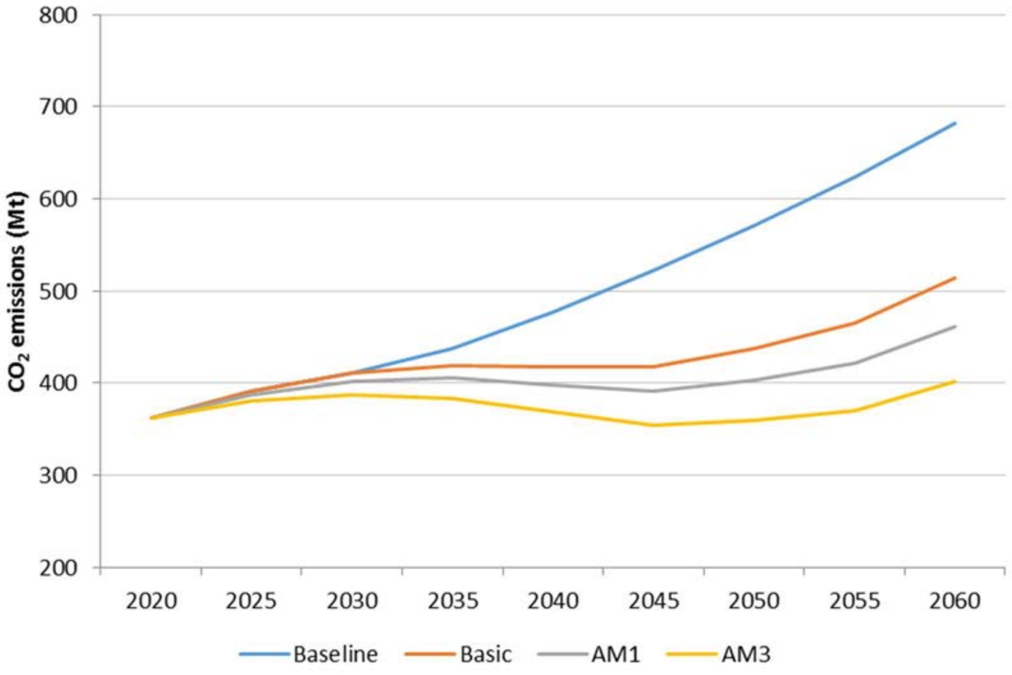

FIG. 20. Total CO_2 emissions in four selected scenarios. Data source: Ref. [134]. Note: Mt — megatonne.

A comparison of coal related emissions in the baseline and basic scenarios (not shown in Fig. 20) indicates that, as a result of launching subsequent nuclear reactor blocks, not only the marked increase in CO_2 emissions from coal combustion is prevented but even a 36% decrease is achieved: from 233 Mt in 2032 to 139 Mt in 2056. Considering total CO_2 emissions in Fig. 20, however, the evolution is less promising because — despite noticeable reductions relative to the baseline — total emissions keep rising in the basic scenario and the increase in the 2032–2056 period reaches 12%. This is due to the fact that in the basic scenario measures to reduce emissions affect the electric power sector only and do not consider other sectors of the economy (i.e. households and other economic sectors producing goods and services). The results show that CO_2 emissions from households in the baseline and basic scenarios overlap.

Changes in CO_2 emissions resulting from increasing energy efficiency under the AM1 and AM3 scenarios are also shown in Fig. 20. In the case of households (not shown in Fig. 20), a 1%/year improvement in energy efficiency helps reduce CO_2 emissions compared to the baseline but not in absolute terms as emissions increase by nearly 50% in the 2020–2060 period. If household energy efficiency increased at a rate of 3%/year, there would be an absolute reduction in household emissions from 56 to 36 Mt, i.e. by about 36% in the same time frame. As expected, total CO_2 emissions decrease and are lower in the basic, AM1 and AM3 scenarios compared to the baseline. In the basic scenario, the decline begins in 2033 when the first nuclear reactor is connected to the grid, and CO_2 emissions are 25% below the level in the baseline by 2060.

4.7.4. Conclusions and policy insights

Implementing plans to change the structure of electricity generation presents a big challenge for the energy sector and the Polish economy. The large scale investments in the electricity sector will affect the entire economy both in the construction and operational period of the

NPPs. The modelling results show that public financing causes a slowdown of GDP growth by less than 0.1% compared to baseline in the construction phase but the impacts of NPPs on the economy are positive, mainly due to lower electricity costs, in the operational phase. These effects diminish somewhat in the last decade of the study period when the share of nuclear energy in the power mix is decreasing but they are still positive. The overall conclusion is that the implementation of the nuclear power programme brings economic benefits in the form of GDP growth, higher employment and greater net public savings relative to the baseline path.

Achieving Poland’s GHG mitigation commitment under the Paris Agreement requires profound changes in the country’s economy and society. Resources, technologies and the ways energy is produced and used are considerably modified. The electric power sector is particularly affected as transformative changes involve phasing out coal based power generation and replacing it with low carbon sources.

Results of model based economic, energy and environmental assessments show that the power generation portfolio assumed in the EPP2040 falls short of achieving Poland's obligations. Policies and measures to foster GHG emissions reductions need to be much more radical because even an ambitious nuclear power programme in the restructured electricity generation mix combined with a systematic increase in energy efficiency at 3%/year over four decades between 2020 and 2060 is insufficient to decarbonize the energy sector. Therefore, a significant increase in the share of low carbon energy sources (nuclear power and RESs) in the power mix relative to the EPP2040 is necessary, likely combined with additional fuel switching in non-electric energy demands.

According to the adopted assumptions, CO_2 emissions reductions start already in 2021 in the AM1 and AM3 scenarios and are below the baseline in 2060 by 32% and 41%, respectively. These deep declines relative to the baseline, however, do not translate into absolute decreases if 2020 is taken as the base year for comparisons. CO_2 emissions increase by 11% relative to the 2020 baseline value even in the AM3 case. Taking 1996 as the base year for comparison, the total emissions in the AM3 variant are lower but only by 4%. NDCs for EU countries under the Paris Agreement require that GHG emissions be reduced by 55% by 2030 relative to 1990 levels. Even assuming that these obligations will be lower for Poland, the successful implementation of the AM3 scenario still seems to be insufficient to achieve the NDC goal.

A faster liquidation of coal based electricity and possibly even a limitation of the role of gas is needed to accelerate CO_2 emissions reductions. This may be supported to some extent with the planned entry into force in 2025 of a strict emissions limit of 550 g CO_2/kW·h in the capacity market, which has initially, and perversely, consolidated the strong position of coal in the Polish energy sector (see Ref. [140]).

Technological progress in the development of renewable energy is also a key factor in decarbonization. Costs of electricity from RESs are increasingly approaching market prices and are often already lower than the generation costs in coal fired power plants. This applies especially to wind energy (see Ref. [141]). Onshore wind farms can expand even without government support and contrary to the EPP2040 government scenario, which marginalizes them. If recent trends continue, the share of RESs in the power mix will increase without policy intervention above the level specified in the official documents. This contributes to fulfilling Poland's international commitments. Finally, unexpected innovations in and outside the energy sector may occur that might become game changers not only in industry but in the whole economy as well. However, estimating the probability of such phenomena is beyond the scope of the models used in this study.

4.8. SOUTH AFRICA

The overall objectives of the South African study in this CRP are to understand the policy and energy demand context in which decisions to invest in nuclear power are being made and to review the role nuclear power could play in South Africa to mitigate carbon emissions in the electricity sector under a range of scenarios. This section is based on Refs [142, 143, 144].

4.8.1. Problem and situation assessment

About 20 years ago, nuclear power was considered to be a low cost option for South Africa. Investment in nuclear power was perceived as an opportunity for building a nuclear industry that would contribute to economic growth. However, since the late 1990s, South Africa has scaled back considerably its nuclear power expansion plans from the ambition of adding 20 GW(e) stated in 2007 to adding 9.6 GW(e) stated in the 2010 Revision 2 Draft of the Integrated Resource Plan (IRP) [145], which is still used as the basis for procurement decisions.

In recent years, several reasons have been suggested for expanding nuclear generation capacity in South Africa, including the country's commitment to reduce GHG emissions, the predominant role of coal in electricity supply, the impending decommissioning of coal power plants in the medium term and the related capacity shortfall, the need to diversify the power mix and increase the security of supply and the positive experience with nuclear power in the country. Yet, there are also several counterarguments and new investment decisions have been delayed due to stagnant electricity demand — in contrast to the optimistic demand growth projected in the IRP 2010 [145] — and the realization that large scale investments into nuclear power plants (in addition to the two large coal plants (9.6 GW(e)) that are already under construction) may result in a large excess of generation capacity and stranded assets. Other concerns include the high cost of NPPs (especially upfront capital costs), and the availability of promising alternative energy sources (including more modular RESs and natural gas generators), as well as lack of transparency in the procurement process and potential for corruption, public perception, need for safe disposal of high level radioactive waste and high impacts of a possible nuclear accident.

4.8.2. Methodology and assumptions

The South African TIMES Model with the South African General Equilibrium Model (SAGE) (SATIM-GE, see Section 3) is used to compare least cost scenarios with alternative generation investments. The model combines the linear optimization model SATIM with the CGE model e-SAGE. The SATIM-GE was developed by the Energy Research Centre at the University of Cape Town [146].

The SATIM is a full sector energy system optimization model, similar to the MESSAGE (see Section 3), which accounts for economic costs, emissions and a range of sector specific technology characteristics and constraints in determining the least cost configuration of the energy system to meet an estimated future demand for energy services. Electricity demand profiles are denoted in eight time slices that represent seasonal day and night profiles for summer and winter.

The e-SAGE is a recursive dynamic CGE model. It includes 61 productive sectors and 49 commodities. The electricity sector is extended to allow investments in various types of electricity generation technologies. As in typical CGE models, industry and producers maximize profits whilst households maximize utility.

In the linked model, the SATIM is used to calculate electricity generation capacity requirements to meet the forecasted demand. This determines the expenditures required to implement the power capacity expansion plan and the resulting electricity price which is used as an input in e-SAGE. The SATIM results also inform the energy components of the sectoral production functions and household consumption functions in e-SAGE. The e-SAGE model generates profiles of GDP growth and household income that, in turn, determine the demand forecast for energy services for use by the SATIM. Energy demand in each sector is endogenously calculated in the SATIM, based on demand for energy services and the efficiency of technologies adopted to supply energy services. The SATIM and e-SAGE models run iteratively over the time horizon, swapping information after each model run.

Two economic growth paths underpin the energy scenarios between 2020 and 2050: a high growth path (H reference) with an average annual growth rate of 3.5% and a low growth path (L reference) with an average annual growth of 2.9%. Ten alternative cases for nuclear power expansion are explored, five in each of the high and low economic growth scenario groups. These alternatives consider three possible nuclear expansion plans: a ‘low’ case (in which 3 GW(e) capacity is added in 2035 and 2040), a ‘high’ case (with 5 GW(e) added in 2035 and 2040) and a ‘high spread’ case in which nuclear expansion is spread over a longer period (with 3 GW(e) added in 2035, 2040 and 2045). The remaining two cases consider the ‘high’ expansion plan in combination with reduced capital costs of NPPs (by 5% and 10%) compared to the costs in the reference cases, which assume a mid-range cost for nuclear capacity and other technologies based on the 2016 IRP [147].

The scenarios are estimated using a discount rate of 8.2% and assume a committed capacity (contracted for implementation) and high annual build constraints on RESs. The model inputs in SATIM are updated to reflect data released in the 2016 draft IRP [147] with some additional updates on renewable energy costs based on the latest rounds of the renewable energy independent power procurement programme, and cost projections obtained from other sources (e.g. International Renewable Energy Agency).

4.8.3. Results

Results of the electricity demand projections show that the reference case electricity consumption more than doubles in the high growth scenario over the study period, driven by increasing GDP that raises demand in all sectors. Electricity consumption in the low growth scenario less than doubles between 2020 and 2050.

Figure 21 shows the optimal (cost minimizing) power generation capacity mix in the reference scenarios defined above. In all other scenarios, deployment of nuclear power is forced by explicit constraints, since it does not otherwise enter the least cost generation mix. All other plants compete on a least cost basis. In Fig. 21, ‘L high’, ‘L low’ and ‘L high spread’ refer to the low, high and high spread nuclear expansion plans with low growth scenario assumptions, and equivalent labels are used to denote the respective high growth scenarios. The reduced cost cases with low growth are labelled ‘L C5%’ and ‘L C10%’, and ‘H C5%’ and ‘H C10%’ with high growth assumptions. As mentioned, the reduced cost cases include the ‘high’ nuclear expansion plans.

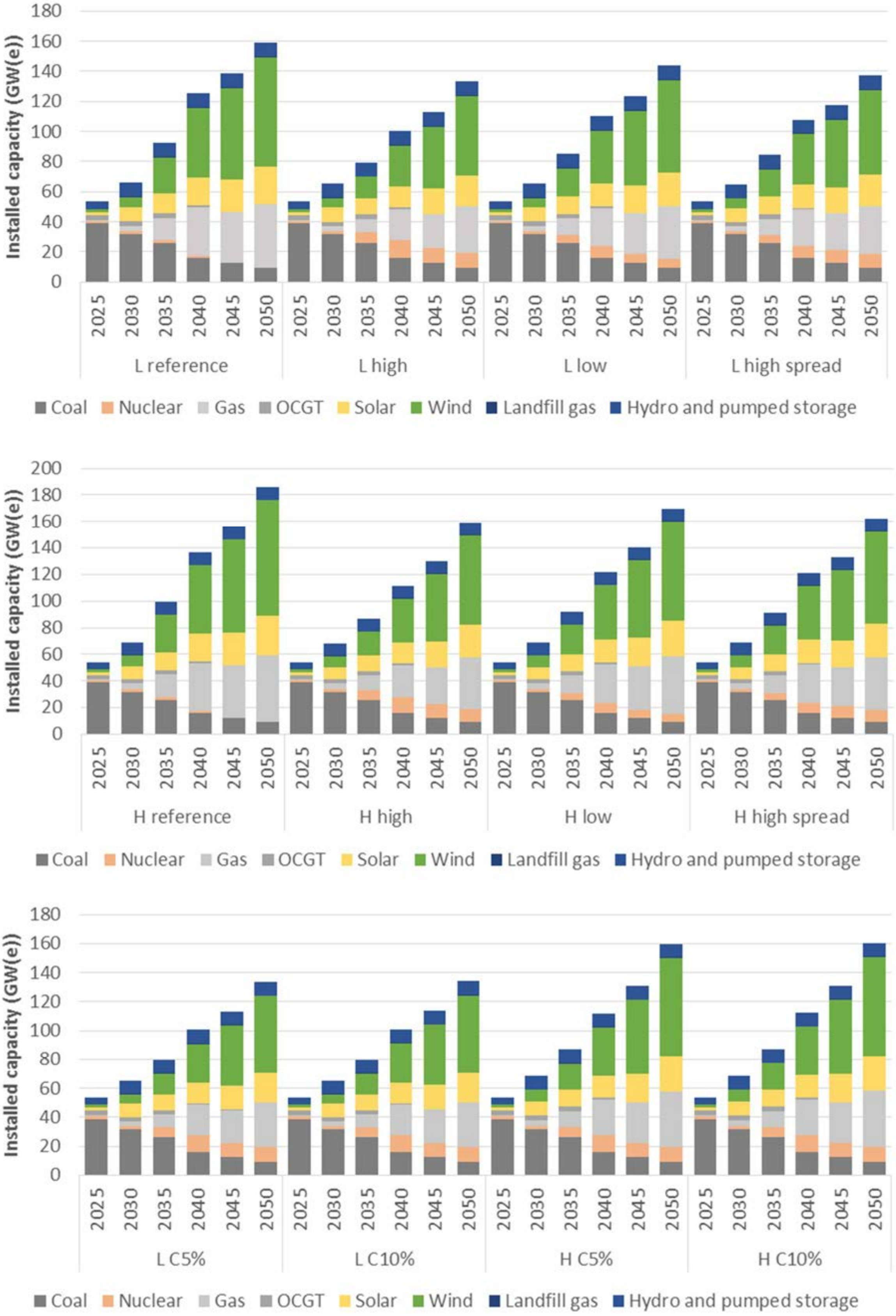

FIG. 21. Installed generation capacity in nuclear energy scenarios. Data source: Ref. [144]. Note: GW(e) — gigawatt electrical, OCGT — open cycle gas turbine.

In both reference scenarios (L reference and H reference), only 9.4 GW(e) of coal fired capacity remains by 2050 (compared to 38.8 GW(e) in the base year) due to the retirement of coal power plants. In the high growth case (H reference), an additional capacity of 131 GW(e) comes from wind, solar, gas and hydropower, while in the low growth case (L reference) 105 GW(e) is added in a similar mix. The hydro and pumped storage capacity remains the same in all scenarios. In all calculated cases (including those in which reduced nuclear investment costs are assumed), nuclear power is more expensive than many other technologies and does not appear in the least cost capacity expansion plans despite the large scale decommissioning of aging coal fired power plants that currently supply the bulk of South Africa's electricity. A reduction in capital cost of more than 30% would be needed for nuclear capacity to enter the least cost electricity generation portfolio. This is partly due to the quality of solar and wind resources in South Africa that makes these generation options highly competitive. However, the cost assumptions for gas and batteries are also important due to the intermittency of these renewable resources, hence an increase in their costs makes nuclear power more attractive.

In all cases where nuclear power is forced in, electricity prices increase while demand for electricity and GDP decrease relative to the reference case — for example, when 10 GW(e) of nuclear capacity is added by 2040, prices increase by around 6% compared to the reference case in both the high and low growth scenarios. The increase in prices is more pronounced in the low growth scenarios and far more modest when the cost of nuclear investment is reduced by 5 or 10%. The increase is also more pronounced in the years when investments are needed to expand generation capacities. These electricity price changes are reflected in a steady reduction in electricity demand over the period relative to the reference case, reaching close to 3% by the end of the period. A greater commitment to nuclear results in a larger reduction in electricity demand in both the low and high economic growth scenarios, while reducing the costs of nuclear plants leads to a marginally smaller demand decrease. Lower demand for electricity in all scenarios reduces the required installed capacity by around 20 GW(e) (over 10%) in 2050, with slightly larger reductions in the scenarios with the largest nuclear capacity (H high, L high). This is partly due to the ability of NPPs to operate at higher capacity factors than the intermittent renewable and new gas capacities they crowd out of the capacity portfolio. Reducing the cost of nuclear plants by 5 or 10% compared to the reference case has very little impact on the build plan.

Not surprisingly, higher electricity prices affect the performance of broader economic activity and result in higher product prices throughout the economy that, in turn, reduces demand and changes the consumption mix of households. The outcome is slightly lower GDP growth rates between the second half of the 2020s and the late 2030s in the nuclear scenarios. GDP growth is slower in all scenarios compared to the reference case. However, it is important to note that the model does not include the development of an industrial supply chain, one of the reasons cited to promote the investment in the large nuclear build plan. As anticipated, the forced deployment of a larger nuclear capacity (whether over 10 or 15 years) results in a larger impact on GDP. However, lower capital costs can reduce these losses: a 10% reduction of capital costs in the high growth scenario reduces economic losses over the 2030–2050 period by about 0.4 percentage points, from 2.90% to about 2.48% and 2.46% in the high and low nuclear expansion scenarios, respectively.

One of the main reasons to invest in nuclear energy is to reduce CO_2 emissions in the power sector. Figure 22 shows the CO_2 emissions paths in all scenarios. The 12 emissions trajectories are barely distinguishable. Emissions decrease in all cases, including the reference cases, as generation by coal fired power plants declines. The high and low growth scenarios have similar

CO_2 emissions due to the continued use of the residual coal capacity at the same level in both scenarios.

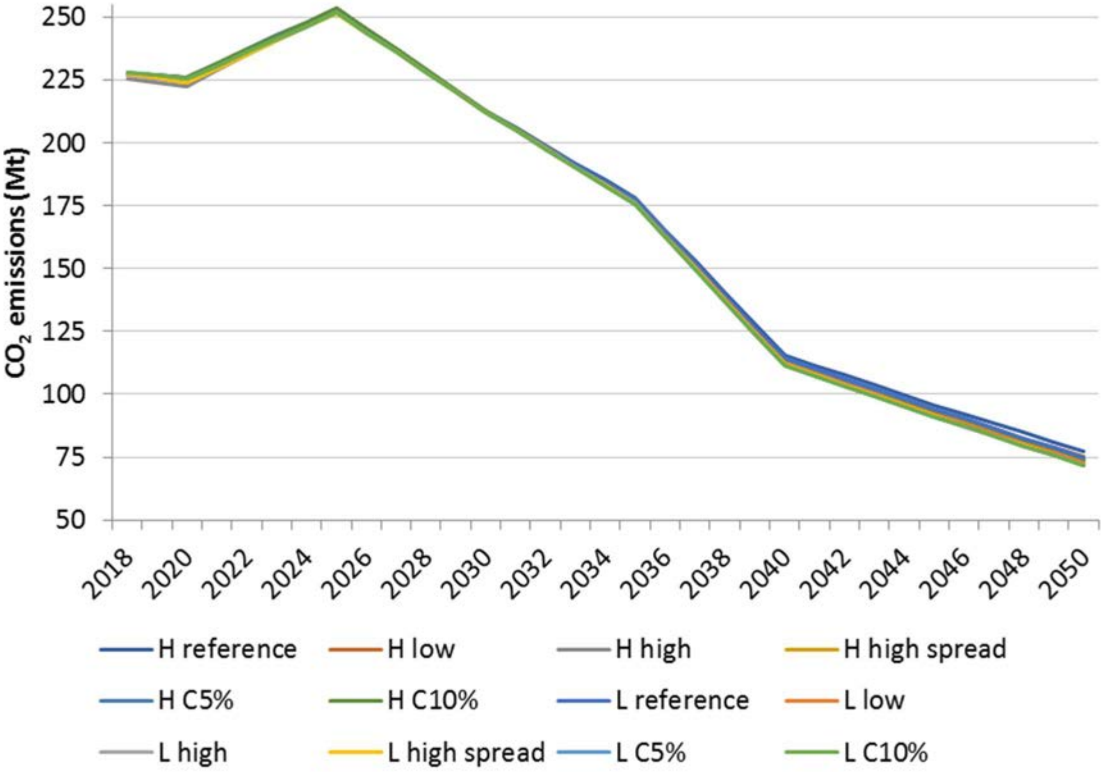

FIG. 22. CO_2 emissions the power sector in all energy scenarios. Data source: Ref. [144]. Note: Mt — megatonne.

The prescribed addition of NPPs reduces the combined gas, solar and wind capacity in all cases. This reduces CO_2 emissions by an annual average of 2–3% from 2030 onwards compared to the reference case due to the displacement of gas capacity. Although the annual average reduction is small, cumulatively it is large. Notably, emissions in the two nuclear scenarios are virtually identical because the forced addition of more nuclear capacity in the high nuclear case mostly replaces low carbon renewable generation capacities.

Results also indicate that much more ambitious levels of mitigation than currently considered in the IRP can be achieved without significant economic impacts due to the availability of cheap wind and solar resources in South Africa.

4.8.4. Conclusions and policy insights

The forced deployment of nuclear power in the generation mix increases the price of electricity and reduces electricity demand and economic activity across the scenarios analysed in this study. Nuclear power displaces large investments in both RESs and CCGT plants in all scenarios; the system relies on gas to accommodate high additions of intermittent renewable capacities, which are highly cost competitive in South Africa. The price of gas will therefore have an influence on the price of electricity (and the competitiveness of nuclear power) in all cases. Since South Africa has very limited domestic gas resources, it must import gas to supply the CCGT plants and compete in foreign markets for gas.

CO_2 emissions decrease when nuclear capacity is added because it replaces gas fired plants used along with RESs. Although the reduction in CO_2 emissions is modest, it could be as large as 4% by 2050 compared to the reference case. There is therefore a benefit to have additional nuclear power generation from a climate change mitigation perspective. However, if batteries or other carbon neutral storage technologies can replace gas, these benefits are reduced. Further research is needed to evaluate the impact of more stringent mitigation policies, including high carbon emission charges (taxes or quota prices) on the cost competitiveness of nuclear power in the generation portfolio.

Nuclear energy has the potential to play a role in climate change mitigation in South Africa but cost remains an important consideration along with public perception and acceptability. If the cost reductions anticipated in the IRP 2016 for wind and solar technologies are realized, it will be extremely difficult to motivate and finance large scale investments required for NPPs. There are clear advantages to nuclear power that are not considered in this study such as spatial diversity of supply, electricity transmission and water–energy interactions. Recently, the Department of Energy has again expressed interest in nuclear power and therefore work on exploring the implications of nuclear power in South Africa's electricity generation mix will continue.

4.9. TURKEY

This study explores the potential role of nuclear energy in the climate change mitigation strategy of Turkey by adopting a model to analyse energy transition pathways over the long term. The assessment builds on global socioeconomic scenarios and energy system costs. This section draws on Refs [148, 149, 150, 151].

4.9.1. Problem and situation assessment

The energy economy of Turkey is dominated by fossil fuels. The total primary energy supply in 2015 amounted to 129.3 Mtoe, with coal (26.9%), natural gas (30.7%) and oil (30.4%) having the largest shares. Electricity generation was 261.8 TW·h, mostly produced from natural gas (37.9%), coal (29.1%) and hydropower (25.6%). Total primary energy supply per capita was 1.6 toe and power generation per capita was 3.3 MW·h, compared to the average of 4.5 toe and 9.9 MW·h of IEA member countries. The main objectives of the current energy policy include increasing domestic resources, decreasing energy imports, diversifying supply sources, implementing oil and gas pipeline projects, increasing energy efficiency and renewable energy usage, decreasing fossil fuel consumption, improving competitiveness in electricity and natural gas markets, implementing natural gas storage projects and introducing nuclear energy.

The final energy demand in Turkey is increasing together with growing domestic production, leading to increasing CO_2 emissions from the energy sector. Although Turkey is highly vulnerable to climate change, there is little ambition in the INDCs to divert from the BAU emissions path unless access to international climate financing mechanisms increases. Nuclear energy is mentioned in the INDCs as a mitigation option together with focus areas such as RESs, energy efficiency and market mechanisms. However, the potential role of these options in energy transition pathways is not defined in the INDCs.

Several factors motivate this study. Turkey is a potential nuclear newcomer country among IAEA Member States, and nuclear energy is considered an important tool for economic development, while there are also increasing concerns about energy security and environmental protection. In addition, many recent studies have tended to focus on renewable and local energy resources, with limited analysis of the nuclear energy. The objective here is to provide a deeper scientific basis for considering the role of nuclear energy in climate change mitigation strategies in Turkey.

4.9.2. Methodology and assumptions

The backdrop for modelling energy and electricity demand and supply in Turkey are the shared socioeconomic pathways (SSPs) (see Ref. [152]). Three of the five SSPs are used in this study: SSP1 that involves low energy demand due to a major paradigm change and characterizes the low baseline; SSP2 represents the BAU case, i.e. development along historical patterns; and SSP3 with high energy demand represents the high baseline. The socioeconomic projections for Turkey are taken from OECD data hosted by IIASA for SSPs [153] and the techno-economic results of integrated assessment modelling studies evaluating the costs of carbon emissions reductions represented by the so-called representative concentration pathways (RCPs) describing GHG emission trajectories consistent with specific atmospheric GHG concentrations and levels of radiative forcing (see Ref. [154] for more information on the assumptions). Final energy demand is calculated with the Kaya identity using population and GDP projections from the SSP database [153] and energy intensity of production for SSPs from Ref. [155].

The MESSAGE (see Section 3) is used to analyse the development of the energy supply from 2015 to 2050 with reference year 2014 based on the socioeconomic and techno-economic assumptions for the SSP baselines and the associated mitigation scenarios to achieve climate change targets as defined by RCPs. The model minimizes total energy system costs under user defined constraints. Mitigation scenarios are quantified by applying carbon prices to achieve global RCPs. The carbon prices are obtained from integrated assessment modelling of SSPs using the MESSAGE-GLOBIOM by IIASA and used until 2050 [153]. The technology options include energy conversion technologies from resources to primary energy (resource extraction and imports), secondary energy (electricity and oil products) and final energy such as electricity, heat and non-energy demand. Seasonal and daily patterns are represented in electricity demand.

All costs occurring in the future are discounted by the social discount rate of 5.04% for long term capital investments in Turkey [156]. Capital and operation and maintenance costs are obtained from the public database of the Global Energy Assessment study of IIASA [157]. Operational costs include fixed costs of energy assets and variable costs of operation. Resource costs are the extraction costs of energy resources. Other costs are related to externalities of the energy system such as environmental and health costs. Variable costs of coal power plants include the marginal costs of flue gas desulphurization for SO_2 with 90% abatement and catalytic reduction for nitrogen oxide pollutants with 50% abatement [158].

The availability of fossil fuel technologies is calculated from energy balance tables for Turkey [159]. Market penetration of electricity generation capacities are calculated from generation licence applications until 2020 [160]. Nuclear power capacity is added in discrete steps of 1000 MW(e) unit capacity (see Ref. [69] for information about modelling nuclear energy systems in the MESSAGE).

The availability of renewable energy depends on environmental conditions in suitable regions. Renewable energy load regions are selected as follows: Konya for solar energy, Izmir for wind power and Erzincan for hydropower. The availability of total installed capacity to supply peak load demand in final electricity is taken from Sullivan et al. (Ref. [161]) and considering the intermittency of some RESs. Emission factors for final energy sources such as coal, natural gas and oil are from the IPCC database used for the Global Energy Assessment Study of IIASA [131].

4.9.3. Results

The results presented in this section illustrate possible trajectories for the second commitment period of the Paris Agreement until 2050. Primary energy demand for fossil energy resources increases for both domestic and imported coal and imported natural gas and crude oil. Primary demand is projected to increases to 1361 TW·h in the baseline scenario SSP1, to 1445 TW·h in SSP2 and to 1733 TW·h in SSP3 in 2050. Demand for primary RESs such as hydropower, biomass and geothermal also increases. Hydropower is also used to provide flexibility in the electricity transmission grid to supply peak load electricity. Biomass and geothermal sources are used for both electricity and heat generation. Primary renewable energy demand is estimated to reach 368.2 TW·h in SSP1, 206.0 TW·h in SSP2 and 178.8 TW·h in SSP3 in 2050. Lastly, final electricity demand is projected to increase from 207.8 TW·h in 2014 to 352.4 TW·h in the SSP1, to 352.5 TW·h in the SSP2 and to 393.6 TW·h in the SSP3 scenario in 2050. These projections of final demand for energy and electricity serve as exogenous inputs to the MESSAGE. Figure 23 shows the amount and composition of electricity generation in the three baseline and the related mitigation scenarios.

Imports of energy are constrained by infrastructure capacity (pipelines for natural gas and transport terminals for coal and oil) and socioeconomic requirements (existing labour used for domestic upstream activities). The results are highly sensitive to upper limits for imported coal as the model seeks to use this low cost energy source in all scenarios. Imported coal is the lowest cost energy source (and lower in SSP1 and SSP2 due to lower global demand) and also contributes to grid flexibility together with large penetration of RESs.

As the low baseline case (SSP1) assumes a major paradigm shift towards sustainable development in which consumption is oriented toward low material, resource and energy intensity, it leads to stabilizing final energy demand and favours an intensive penetration of wind and solar energy, albeit with concerns over grid stability and flexibility. In this scenario, the role of nuclear power is highly sensitive to the potential decrease in capital costs after 2030 when more CO_2 emissions reductions are required and when CO_2 prices are higher. (The objective is to reduce emissions by controlling CO_2 prices and floating the resulting emissions based on multiple criteria in the optimization model. Controlling the emissions and floating the prices would be incomplete for representation in a national model as it would neglect global prices.) The decreasing capital costs of wind and solar power together with great improvements in energy efficiency obviate the need for nuclear electricity generation in this scenario for all mitigation targets. However, results of electricity generation in Fig. 23 show that nuclear power, together with renewable energy, has a potential role in climate change mitigation in the medium (SSP2) and high (SSP3) baseline scenarios. Turkey has high potential for renewable energy technologies that can be balanced by a large installed capacity of hydropower exceeding 18 GW in 2014.

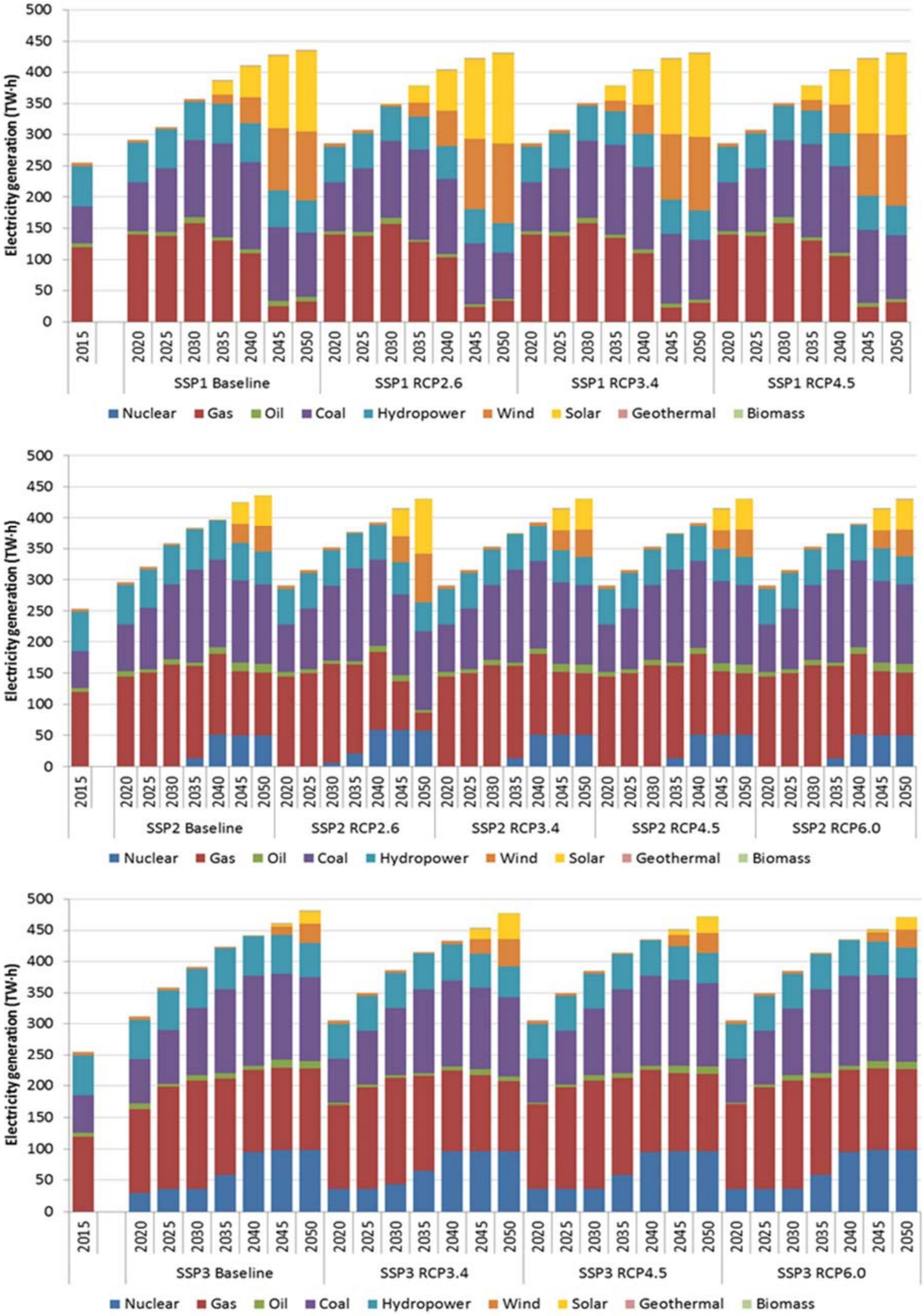

FIG. 23. Electricity generation in various scenarios. Data source: Ref. [150]. Note: TW·h — terawatt-hour, SSP — shared socioeconomic pathway, RCP — representative concentration pathway.

Annual investment requirements in the electric power sector vary considerably across scenarios. Shares of technologies targeted by the investments also differ depending on the baseline pathway and the stringency of the climate change target. In SSP1, the total capital investment in renewable electricity is US $143.5 billion and in fossil power US $32 billion during the modelling period. Investment patterns are rather different in SSP2. Here the total installed capacity of nuclear power grows to 7000 MW(e) and requires US $35.7 billion capital investment, complementing investment in RESs of US $85.9 billion and US $39.5 billion in fossil power during the modelling period. Nuclear power plays an even more important role in SSP3, with total installed capacity starting at 4000 MW(e) in 2020 and increasing to 14 000 MW(e) in 2045, requiring US $71.4 billion capital investment. The total capital investment in renewable electricity is US $70.1 billion and in fossil power US $35.3 billion.

Figure 24 shows CO_2 emissions from electricity generation over the entire time horizon in different scenarios.

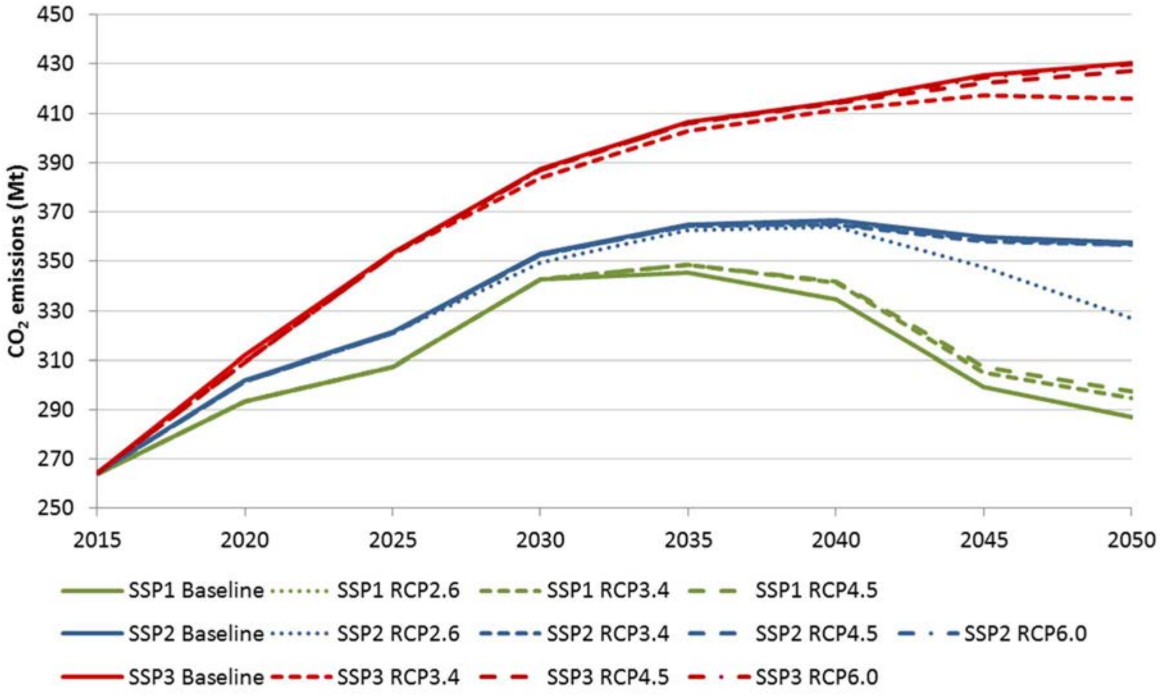

FIG. 24. CO_2 emissions from electricity generation in various scenarios. Data source: Ref. [150]. Note: Mt — megatonne, SSP — shared socioeconomic pathway, RCP — representative concentration pathway.

CO_2 emissions from electric power generation follow distinctively different paths in the three SSP baselines. Mitigation paths towards different climate change targets in the SSPs often overlap, hence some of them are not visible in Fig. 24. The targets are applied by taking CO_2 prices from the marker scenarios for SSPs based on MESSAGE–GLOBIOM modelling by IIASA for RCPs taken as climate targets [152]. The more stringent the climate target, the larger the mitigation need and thus the lower the CO_2 emissions within the SSPs, except SSP1 in which the baseline emissions pathway itself achieves the required climate target. Note that RCP2.6 is not even an option in SSP3 in which baseline emissions make the required magnitude of emissions reductions practically impossible with the model assumptions. The model does not install more wind and solar energy and less coal and gas based capacities in this scenario because the large penetration of nuclear power competes with wind and solar energy for low carbon electricity generation. Therefore, this is also driven by intertemporal optimization of the energy system.

Peak emissions of CO_2 from the entire energy sector, i.e. electricity and final energy sources (whereas Fig. 24 shows emissions only from electricity generation) could be achieved by the end of the commitment period of the Paris Agreement in all SSP1 baseline and mitigation scenarios. Entire energy sector emissions in SSP2 peak only by applying carbon costs in RCP2.6, while CO_2 emissions in SSP3 keep increasing although at a decreasing rate as population and GDP growth level off.

4.9.4. Conclusions and policy insights

Turkey has high potentials for hydropower and other RESs, and these resources are exploited due to their cost effectiveness in all SSPs. Nuclear energy contributes to reducing the carbon intensity of the economy together with renewable energy in both the SSP2 and SSP3 scenarios. In the SSP3 scenarios, nuclear energy is deployed already in 2020 and provides a larger contribution to supply baseload electricity to satisfy the increasing energy demand driven by increasing population and production and slower improvement in energy intensity compared to the SSP2 scenarios. Realizing this potential of nuclear power across the scenarios naturally depends on the availability of front-end nuclear fuel services and measures to address back-end liabilities by the utilities and the government.

This study also demonstrates that the potential role of nuclear energy in climate change mitigation in the Turkish energy sector is sensitive to decreasing costs of renewable energy and increasing costs of NPPs. The intermittency of solar and wind power leads to their convergence to their upper limits in electricity generation by the end of the modelling period because the minimum requirement for grid flexibility puts constraints to generation from these sources in order to preserve capacity reserves for grid stability.

Increasing costs of CO_2 emissions also lead to nuclear power investments early in the study period in both SSP2 and SSP3. Total CO_2 emissions from the entire energy sector (as opposed to emissions from only power generation presented in Fig. 24) peak in 2040 in the SSP2 scenarios and in 2035 in the SSP1 scenario but total emissions from energy sector keep increasing in the SSP3 scenario for all RCPs despite increasing emissions costs.

As of mid 2021, Turkey is one of the few countries worldwide and the only member in the Group of Twenty (G20) that has not ratified the Paris Agreement of the UNFCCC or submitted an NDC, despite earlier signing the Agreement and submitting an INDC. Nonetheless, Turkey continues investing in low carbon energy technologies using both domestic and international financing mechanisms. The MESSAGE calculates that annual revenues collected from atmospheric emissions penalties keep increasing and in 2050 exceed US $5 billion in the SSP1 and US $12 billion in the SSP2 to achieve the RCP2.6 climate target. Investing these revenues in low carbon energy sources could reduce emissions of CO_2 and other air pollutants from the energy sector.

Introducing nuclear energy in Turkey can be a policy option in climate change mitigation but possible negative economic and social consequences of building and operating NPPs go beyond emissions mitigation strategies. It is important to balance social, economic and environmental priorities in national mitigation strategies. Therefore, NDCs and energy supply security dimensions also need to be analysed in future studies.

4.10. VIET NAM

Viet Nam had been considering the introduction of nuclear energy over a number of years but in 2016 the National Assembly voted to suspend the nuclear power programme given the large investment requirements and increasing government debt. This allows time for Viet Nam to accumulate additional technological experience and investment capital. In this context and to support current national energy policy and planning, this study focuses on other low carbon energy sources. This section is based on Refs [162, 163, 164].

4.10.1. Problem and situation assessment

Viet Nam's economy grew steadily at about 6%/year between 2005 and 2015. The growth was particularly strong in the industrial sector that achieved 9.6%/year, followed by the service sector at 7.5%/year and agriculture at 4.5%/year. As a result of increasing demand for goods and services by growing and rapidly urbanizing population and fast expanding economic activities, demand for energy and electricity is growing strongly. Adequate and reliable energy resources are needed for supplying this demand.

The electric power sector has an important role in supporting future economic development. The current national Power Development Master Plan VII for the period up to 2020 with long term vision up to 2030 was prepared in 2011, revised in 2014 and approved by the prime minister in 2016. The revised plan projects a rapid increase in electricity consumption with total installed capacity expected to reach 57.4 GW in 2020 and 115.1 GW in 2030 (compared to 38.5 GW in 2015). Coal fired capacity is projected to grow at 11.2%/year and account for 49% of the total generation capacity in 2030.

The revised plan also projects that the first NPP will come on line in 2028 and nuclear power will account for 3.9% of the total generation capacity by 2030, with the objectives to contribute to diversifying the energy sources, reduce dependence on fossil fuels and decrease GHG emissions. However, the National Assembly indefinitely suspended the nuclear energy programme in 2016. Therefore, nuclear power is not considered in the analysis presented in this section.

4.10.2. Methodology and assumptions

The LEAP model (see Section 3) is adopted to evaluate the potential role of different low carbon energy supply options in long term GHG mitigation strategies. Two scenarios are developed with LEAP based on local potentials and market requirements. The baseline scenario outlines BAU energy demand for the period of 2015–2035 based on GDP and population projections, changes in technology and existing policies with reference to the LEAP files from existing studies by the Economic Research Institute for ASEAN and East Asia (see Ref. [165]). The alternative policy scenario (APS) is based on accessible potentials of all types of RESs, assuming that additional action plans or policies for their utilization are developed and implemented. The difference between the BAU (baseline) and the APS scenarios thus illustrates the additional renewable energy production and potential fossil energy savings as well as potential GHG emissions reductions. The estimates of primary energy requirements stem from an accounting model in which the future selection of technologies and fuels is based on country programmes and the most likely available supply in the future. Emissions factors for each technology and fuel type (available in LEAP) are taken from the IPCC document Ref. [131].

The LEAP modelling is informed by an assessment and selection of renewable energy technologies based on an MCA covering monetary and non-monetary social, economic and environmental aspects needed for the RES development strategy and action plans. The MCA technique is used for evaluating technology and resource options to examine trade-offs across multiple objectives of policy such as economic growth, social inclusion and the environment. Nuclear energy is not included in the MCA (see above).

The scenarios assume that the population of Viet Nam grows from 91.58 million in 2015 to 105.39 million in 2035, with rapid urbanization from 33.6% in 2015 to 48.2% in 2035 (see Ref. [166]). The assumed annual GDP growth rate is 7.0% from 2016 to 2020, 6.5% in the 2020s and 5.5% between 2031 and 2035. In the baseline scenario, electricity demand increases from 150 TW·h in 2015 to about 650 TW·h in 2035.

4.10.3. Results

Figure 25 shows the projected amount and mix of electricity generation capacity in the two scenarios.

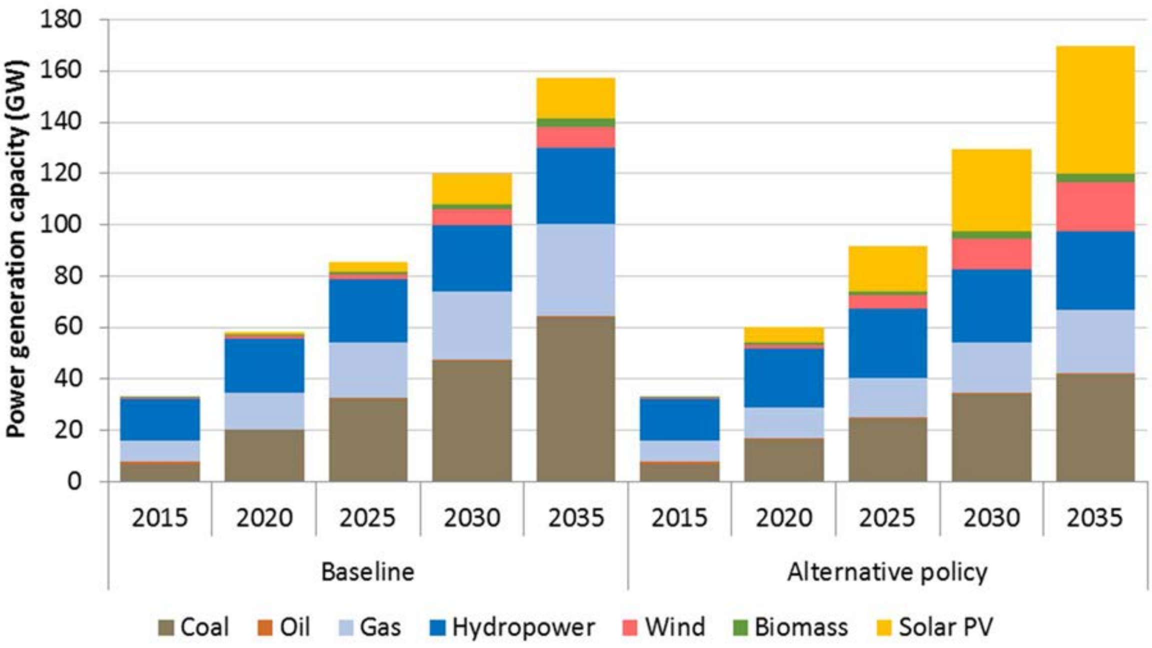

FIG. 25. Electricity generation capacity in two scenarios. Data source: Ref. [163]. Note: GW — gigawatt, PV — photovoltaic.

The share of renewable generation capacities in the baseline scenario reaches 36% by 2035 and increases to over 61% in the APS. Hydropower capacities grow gradually at the same rate in both scenarios but solar and wind capacities increase much more vigorously in the APS, which incorporates additional RES action plans and policies.

These developments have a major impact on GHG emissions. Trends in CO_2 emissions from electricity generation are presented in Fig. 26.

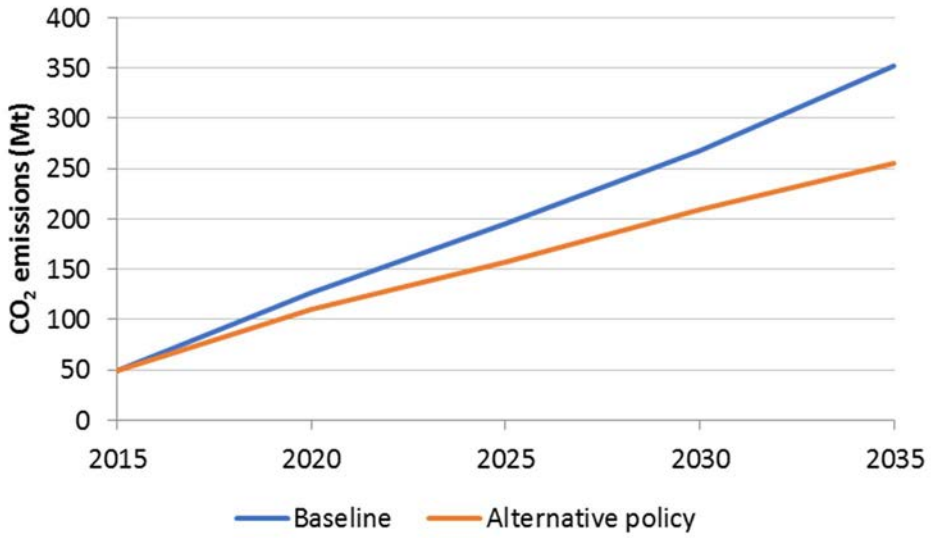

FIG. 26. CO$_2$ emissions from electricity generation in two scenarios. Data source: Ref. [163]. Note: Mt — megatonne.

Figure 26 shows that CO$_2$ emissions in the APS are about 100 Gt CO$_2$ lower in 2035 relative to the BAU scenario (a 29.0% reduction), indicating that the promotion of renewable energy development is very effective in reducing GHG emissions in Viet Nam.

Results of the MCA show that wind power achieves the highest score (3.98 points), followed by solar PV (3.8 points) owing to the performance of these technologies against criteria for environmental benefits and the country's development priorities. Biomass and small hydropower are ranked third and fourth with 3.68 and 3.48 points, respectively, mainly due to high scores for their GHG emissions reductions potentials.

4.10.4. Conclusions and policy insights

Viet Nam can achieve a high renewable energy target in total power generation in 2035 to support economic, social and environmental objectives. Among the various renewable technology options, wind and solar energy have a large potential and perform strongly in terms of Viet Nam's development and environmental goals. The main barriers for achieving high levels of renewable energy development are related to finance, policy and local capacity. RES projects face challenges accessing capital and their attractiveness to financiers is limited by indirect subsidies to power production from natural gas and coal. At the same time, cumbersome requirements are imposed for establishing plans for RES development and there are only limited and unattractive feed-in tariffs for RES power generation. At the local level, there is also a limited understanding of renewable energy technologies, as well as weakly developed supply chains and a lack of capacity to service the operation and maintenance of renewable energy equipment. Overcoming these barriers will be critical for climate change mitigation in Viet Nam.

The assessment of renewable energy technologies proposed for power generation also shows that there are several options with low or negative abatement costs such as biomass, small hydropower and biogas that could be pure win–win solutions, i.e. delivering economic benefits while reducing GHG emissions. These options save money in general and — if implemented carefully — many segments of the society could obtain various kinds of benefits, including reduced local and regional air pollution, job creation and other benefits.

While Viet Nam is not currently considering nuclear power, it is notable that even with the rapid expansion of RESs in the optimistic alternative policy scenario, the installed capacity of coal fired power plants is projected to increase from less than 10 GW in 2015 to over 40 GW by 2035, contributing to a fivefold increase in CO_2 emissions from electricity generation. Given the long lifetime of coal power plants, combined with the need to decarbonize power generation globally around 2050 to meet the Paris Agreement objectives, consideration of other low carbon technologies (including nuclear power) in place of coal capacity may help to avoid stranded investments and enable Viet Nam to contribute further to global mitigation.

5. CONCLUSIONS AND OUTLOOK

The national studies conducted in this CRP and summarized in the previous section provide valuable complements to recent scientific literature on the potential contribution of nuclear energy to reducing GHG emissions reviewed in Section 2. The first section below briefly summarizes the main results of the national studies presented in Section 4 and highlights some key factors contributing to the range of conclusions. This is followed by a concise appraisal of the analytical frameworks and methods (see also Section 3) adopted by the study teams against the broader context of tools and models used by similar studies as reported in Section 2. Finally, the last two sections list areas for future work on the topic of the CRP identified by the national teams and potential opportunities for the IAEA to Member States address these further research needs.

5.1. THE ROLE OF NUCLEAR ENERGY IN CLIMATE CHANGE MITIGATION

The low carbon nature of nuclear energy has long been demonstrated by numerous studies over the past four decades since global climate change emerged and became increasingly prominent in scientific and political agendas. Sweeping changes have occurred in this period with essential implications for using nuclear energy to reduce GHG emissions. Foremost, rapid global economic growth — which has been fuelled by, and has also driven, increasing energy and electricity production and use based on abundant resources of cheap fossil fuels — has led to a dramatic increase in emissions of GHGs, especially CO_2, and changes in the Earth’s climate clearly attributable to these anthropogenic emissions.

Over the same period, nuclear energy technologies have also evolved and an increasing number of countries have decided to include nuclear power in their national electricity supply portfolios, often independent of climate change concerns. These decisions have been motivated by a wide variety of factors ranging from scarce or expensive domestic fossil fuel resources to concerns about extensive dependence on imported energy and energy supply security, among others. Nonetheless, alongside technological development, public concerns have remained about nuclear energy regarding possible severe accidents and the disposal of high level radioactive waste.

Another principal development influencing responses to climate change has been the emergence and fast development of renewable energy technologies since the 1990s. Thanks to massive financial support for research and development initially followed by enormous economic subsidies in various forms to promote deployment, these technologies are now a major player in the global energy supply.

In the context of these transformations, the possible contribution of nuclear energy to climate protection has been increasingly debated. The issue is still intensively researched and results supporting and opposing the role of nuclear power are published regularly (see Section 2). Results of the studies conducted in this CRP represent a valuable addition to this global applied science landscape. They properly frame the energy systems using different types of analytical tools (see next subsection), consider the most important constraints and challenges for nuclear energy and formulate policy relevant questions about its role in climate change mitigation strategies in their national contexts.

Table 5 presents an overview of the most important results of the national reports.

TABLE 5. NUCLEAR ENERGY IN CLIMATE CHANGE MITIGATION AND RELATED FACTORS IN MSs PARTICIPATING IN THE CRP

Country	Nuclear status	Nuclear power economics	Other objectives and concerns	Broader context	Role in future mitigation and supporting conditions
Armenia	Operating	Not competitive but present value of thermal and nuclear mitigation scenarios are similar	Supply security	RESs[a] limited	Key
Chile	Planning	Not competitive at or above overnight cost of 5000 US $/kW	Supply security and quality	Ample cheap RESs[a]	At 3000 US $/kW overnight cost
Croatia	Operating	Not competitive	Supply security, quality	Ample cheap RESs[a]	None but open as option
Ghana	Planning	Not competitive at 5000 US $/kW overnight cost, 12% discount rate	Fast growing demand for electricity, power shortage	Limited solar and wind potential, risk of largest hydropower plant	At low (e.g. 6%) discount rate or with 15% CO_2 cut (NDC[b])
Lithuania	Operated (permanent shutdown)	Not competitive with other available technology options	Supply security, grid reserves and flexibility	Available RESs[a], interconnection	If high share domestic generation is required
Pakistan	Operating	Competitive if discount rate is below 7%	Fast growing electricity demand, import dependence, water use	Full exploitation of domestic energy sources	Increasingly important over time
Poland	Planning	Competitive due to increasing carbon tax	Energy transformation, public opposition	Declining costs of RESs[a]	Significant
South Africa	Operating	Competitive at 30% below capital cost of 6300 US $/kW	Gas imports	Ample cheap wind and solar potential	Small, likely to replace RESs[a]
Turkey	Under construction	Competitive due to carbon taxes imposed to reach climate targets	Supply diversification, import reduction	Solar and wind power approach upper limit to preserve grid stability	Increases with larger energy demand and mitigation need
Viet Nam	Postponed	n.a.[c]	Government debt	Ample cheap RESs[a]	None

[a] RESs: renewable energy sources.

[b] NDC: nationally determined contribution.

[c] n.a.: not applicable.

Table 5 shows the current status of nuclear energy in participating countries, the economic performance of nuclear power as calculated by the analytical modelling studies and other important energy objectives and/or concerns relevant for nuclear energy discussed by the national studies, including various aspects of the broader geographical and natural resource characteristics of the given country. The final column summarizes key findings concerning the role of nuclear energy in national GHG emissions mitigation: overall, several of the studies identify a significant potential for nuclear power in national climate change mitigation (e.g. in Armenia, Pakistan, Poland and Turkey). If cost and financing barriers can be addressed then nuclear power becomes increasingly attractive for mitigation also in other countries (e.g. Chile, Ghana and South Africa). Further details in Table 5 are elaborated below.

Nuclear power is already used in four of the ten participating countries while another (Lithuania) operated reactors until the 2000s. Four of the other participating countries are either in the process of building their first reactor (Turkey) or planning to introduce nuclear energy and are participating in the IAEA's nuclear newcomers programme (see e.g. Ref. [167]). Only Viet Nam has recently made a decision to postpone the decision about introducing nuclear power indefinitely, mostly due to cost and financing issues.

The economic performance of nuclear power, especially its costs in absolute terms and relative to those of available low carbon alternatives, is a key factor in the decision concerning its role in climate change mitigation. Baseline calculations without GHG emissions restrictions show that nuclear power is often not competitive — i.e. it is not included in cost minimizing supply portfolios analysed in the CRP and other studies — due to its high overnight construction costs or the high discount rates applicable in some of the countries. According to the modelling studies, overnight costs would need to be more than 50% below the initially estimated value of 7000 US $/kW (in Chile) or at least 30% below the assumed mid-level cost of 6300 US $/kW (converted at 2015 exchange rates) (South Africa). The sensitivity to the applied discount rate is similar: nuclear power becomes competitive if the discount rate is reduced from 12% to 6% in Ghana or if it is below 7% in Pakistan.

There are two main ways to reflect national climate change mitigation targets in energy system models used in the CRP, like the IAEA's MESSAGE. The first is to include an equation that directly caps aggregate GHG emissions arising from all emitting activities. The second is to impose a charge on emissions thereby accounting for the assumed social costs of emitting activities. The latter approach is also applied in macroeconomic models in the CRP (see Poland and South Africa). Both approaches have the effect of making the outputs of emitting activities more expensive in absolute terms and more expensive in relative terms compared to the outputs of activities that emit less or no GHGs.

As a low carbon technology, nuclear power benefits from constraints or charges on emissions relative to more GHG intensive technologies. The magnitude of the benefit and whether it is large enough for nuclear energy to become competitive in the electricity supply portfolio depends primarily on the availability and costs of other low carbon technologies, predominantly new RESs such as wind and solar power. Table 5 shows that in countries where ample cheap RESs are available, the role of nuclear power in GHG emissions reductions can be limited (e.g. Chile, Croatia, South Africa) whereas in countries where the potential or availability of such sources is estimated to be low, or nearing the limit beyond which more intermittent supply would jeopardize grid stability, nuclear power is assessed to have a significant or even key role in climate change mitigation (e.g. Armenia, Ghana, Pakistan, Turkey). Given the influence of these factors, the studies highlight the value of methodological approaches able to represent in detail features of the electricity grid and RES potentials.

In addition to the availability of other low carbon energy sources competing with nuclear energy in the mitigation portfolio, other objectives in national energy policies also influence the prospects for nuclear power. Fast economic growth driving rapidly increasing demand for electricity in Ghana and Pakistan are mentioned by the national studies as important factors. The same is true for Viet Nam where nuclear power has been seriously considered for some time until a recent political resolution to postpone the decision about its introduction, partly in light of the increasing availability of ample cheap RESs. In addition, most of the CRP studies identify energy supply security and reducing import dependence to be among the most important policy objectives, other than climate change mitigation, supporting the use of nuclear energy despite its costs and other drawbacks. Avoiding power shortages when hydropower plants are constrained by low water flows, enhancing grid flexibility and reserves or, more generally, diversifying electricity supply are additional related issues considered when studies look beyond the direct costs and low emissions merits of nuclear energy.

In summary, while not a panacea for all energy and climate related challenges, the studies in this CRP confirm that nuclear energy can be an important part of the solution depending on specific national circumstances and priorities, fostering not only GHG emissions reduction but also other aspects of sustainable energy development (some which were not analysed in detail in this project).

5.2. FRAMEWORKS AND METHODOLOGIES

The analytical frameworks adopted by researchers around the world to investigate the potential role of nuclear energy in climate change mitigation range from single issue and comparative life cycle analyses to different kinds of techno-economic assessments through technology rich energy system models all the way to highly complex integrated assessment models covering the global economy and energy use together with GHG emissions and the resulting climate change. Even studies focusing on the practical aspects of whether and, if so, how and to what extent nuclear energy could support national and regional efforts to mitigate emissions apply a rather diverse range of models and analytical frameworks (see Section 2).

The models and tools used by the study teams in this CRP represent only part of this full methodological spectrum but nevertheless cover a diverse set of approaches. Some models developed and applied by the research teams originate in the IAEA while others are based on international or domestic sources. As presented in Section 3, energy system models are the most frequently used tools such as the IAEA’s MESSAGE, the LEAP system developed and distributed by the Stockholm Environment Institute and the modelling platform TIMES developed by the IEA. Research teams interested in broader macroeconomic implications of whether and how nuclear power can help GHG emission reduction efforts use extended IOMs such as IAEA’s EMPOWER or CGE models. These tools are supplemented by other analytical frameworks such as MCA and cost–benefit analysis.

Similarly to the observation from the broader literature review in Section 2, the findings of the national studies of this CRP indicate that, if applied properly, the choice of analytical tool does not determine per se the results of the analysis. The same type of model properly reflecting the economy and the energy system of different countries produces very diverse results concerning the importance of nuclear energy in climate change mitigation, ranging from key to negligible. Many such differences in results emerge because the models reflect the most important and relevant characteristics of the systems they denote, hence differences in results are driven by differences in the underlying systems and by the assumptions specified in the form of scenarios and model parameters.

The general observation is that all research teams have the required expertise and experience to set up, calibrate and run the applied models and interpret the calculated results. Based on the properly explained scenario specifications, the results of all model runs presented in the national reports are plausible and insightful. They provide useful contributions to the national scientific and policy discussions about energy development, climate change mitigation and the potential role of nuclear energy in future plans and strategies.

5.3. AVENUES FOR FUTURE NATIONAL RESEARCH

The Paris Agreement will be the global political framework for GHG emissions reductions for the foreseeable future. There are many ongoing activities to transform and decarbonize the energy sector at the national (e.g. China, USA) and international (e.g. EU) levels. Therefore, the research teams in the CRP have plans to continue work on these types of analyses in order to identify the best pathways to a zero carbon economy. The potential role of nuclear energy in addressing climate change is acknowledged and the importance of having all the technical information required for evaluating the nuclear alternative is highlighted by all national studies. Irrespective of the status of nuclear power in a country and the status of political decisions about its future role, the studies illustrate the value of regularly (re-)evaluating the introduction or extension of nuclear energy in national energy mixes given rapid energy technology and market developments, along with increasing recognition of the need for urgent climate action. The studies also illustrate potential areas for additional analysis to specify and assess different scenarios to support medium and long term national energy planning and climate change strategy formulation.

All participating countries in this CRP are aware of their vulnerabilities to global climate change. The project was relevant to (and in some cases overlapping with) the energy planning activities of all national research teams because they were already engaged in energy–climate change studies and modelling activities when this CRP was initiated. Most of them had already years of experience in working with the IAEA’s models as well, while others had track records in working with their own tools originating from national or international sources. This has made their work on the research questions and objectives of this CRP particularly productive. Yet several teams reported that the project contributed to the technical capacity development of the professionals involved and reinforced the role of the participating institutes in the national assessments and debate on climate change and clean energy.

As an immediate follow-up to this CRP, some teams intend to perform further sensitivity analyses concentrating on key model parameters (e.g. economic growth rate, income and price elasticities of demand). Other teams plan to organize workshops and seminar series to disseminate their findings as well as briefings to elicit feedback from policy makers and other experts or to synthesize the findings of this project to serve as input to developing policies and strategies for public information to improve acceptance of nuclear energy.

Most research teams indicate in their final CRP reports that the project has fostered their work on energy planning and the development of analytical frameworks to assess the role of nuclear energy in climate change mitigation. Most if not all teams continue working on the subjects of the CRP, building on the results achieved and experience gained. Planned forthcoming activities include analysing future plans for national energy system development and operation, and assessing implications of proposed and future laws and regulations, including decarbonization plans such as government policies to achieve quantified targets for the penetration of RESs and nuclear energy, the deep decarbonisation of the entire economy and other policies under consideration.

Research teams list many ideas about how their analytical frameworks and models could be extended to provide more realistic and reliable information about climate change and nuclear energy. Possible model extensions include the integration of non-electric applications of nuclear energy such as desalination and district heating, and enhancing the representation of the electricity grid (including expansions) and the broader energy sector, such as by integrating demand side management options (e.g. changing incandescent lamps to CFL and LEDs, replacing fridges with more efficient refrigeration technologies). Other potential extensions include modelling foreign trade implications of energy strategies (exports and imports), disaggregating the assessments produced in this project into five year plans while still capturing the long term details, and assessing the role of nuclear energy in water scarcity scenarios (reduced hydropower generation in periods of low inflow, water resource use of different energy technologies in regions with limited water resources). There is also interest to evaluate the role of RESs and nuclear energy in further detail, particularly in least cost decarbonization of the power, heat and transport sectors for small countries by integrating detailed sectoral models able to account for the potential role of flexible electric vehicle charging to balance electricity generation fluctuations from variable renewable sources (potentially resulting in higher penetration of RESs and lower GHG emissions). The teams are also seeking to develop further the underlying methodological bases of their analytical frameworks by improving model dynamics, endogenizing demand and capacity forecasts, exploring alternative approaches to changing input–output coefficients based on international comparisons and linking macroeconomic models with technology rich engineering type energy models like the MESSAGE, and modelling energy system integration at broader sectoral or regional scales.

In addition to improving and extending the modelling tools, teams emphasize the need to look beyond the direct linkages between climate change and nuclear energy and analyse other factors that may help or hamper using nuclear energy in GHG emissions mitigation efforts. For example, future activities could look at the broader impacts of nuclear energy by quantifying and assessing the IAEA's Energy Indicators for Sustainable Development [168] and by widening the assessment framework to integrate climate, land, energy and water aspects by using the IAEA's CLEW approach (see Refs [169, 170, 171]) or the evaluation of fundamental socioeconomic impacts of nuclear energy. Analysing the impact of the energy transition on energy justice with a special focus on gender issues and the impact of nuclear energy on well-being of women in rural regions (especially in developing countries) is another suggested topic.

Even wider but possibly important research directions proposed by some of the teams include the impacts of nuclear energy on a broader range of airborne pollutants, assessing the effects of implementing climate change mitigation strategies on adaptation requirements as well as the issues of nuclear liability for both countries hosting nuclear energy programmes and neighbouring countries.

5.4. OUTLOOK FOR RESEARCH COLLABORATION

The research teams in the CRP expressed a strong interest in future cooperative research and capacity building activities on similar topics, including many of the follow-up activities listed in the previous section. Some of the possible areas suggested by the research teams that would benefit particularly from a cooperative cross-country approach are outlined below.

As a related aside, it is notable that the IAEA is already responding to some of the needs identified by Member States. For instance, the work of the CRP and consultations with participants informed the design of the Agency's Technical Cooperation Project on "Assessing the Role of Low Carbon Energy Technologies for Climate Change Mitigation" (RER/2/017), supporting countries in Europe and Central Asia. This ongoing TC project, launched in 2020, responds to some of the energy planning issues identified in Section 5.3 while providing potential opportunities to disseminate the CRP outputs to experts in the region.

The CRP has shown that nuclear power provides a way of reducing emissions in the electricity sector but it is not the only technology that could be deployed. It is therefore important to understand which of the available technologies will be viable and optimal for each country — including, for example, by evaluating in more detail the impacts and costs of integrating RESs in the electricity system, beyond the traditional LCOE approach, to determine the optimal generation mix. Addressing in more detail interactions with the broader energy system, such as the role and costs of ambitious efficiency improvements in the manufacturing and residential sectors, battery storage and enhanced e-mobility, also represent areas of common interest across several countries.

Exploring such questions is of high relevance for Member States seeking to increase the level of ambition in their NDCs and quantify the potential contribution of nuclear energy. This may be particularly valuable for nuclear newcomers developing strategies for a low carbon transition. Joint work using the same set of tools and methods across countries — including both energy system models and other approaches used in the CRP such as MCA, life cycle assessment and spatial analysis — and/or a common set of indicators of GHG mitigation, could provide additional cross-country insights into the potential of different mitigation options.

More broadly, to understand some of the social barriers to an increased contribution from nuclear energy in climate change mitigation, additional research into the public perceptions can complement the technology oriented perspective of the CRP. This can feed into broader analysis exploring the need to balance social, economic and environmental priorities in national mitigation strategies, including whether and how countries can make an equitable and differentiated contribution to the long term 1.5°C global climate change target.

The IAEA is uniquely placed to support Member States build capacity in energy planning to assess a wide range of challenges, including the needs identified by CRP participants. This represents one of several ways in which the Agency is responding to the increasing priority and urgency among Member States, and the international community at large, to address the challenges of climate change while realizing broader development objectives.

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LIST OF ABBREVIATIONS

AEG	accelerated economic growth
BAU	business as usual
CCGT	combined cycle gas turbine
CCS	carbon dioxide capture and storage
CDM	clean development mechanism
CGE	computable general equilibrium
CO_2	carbon dioxide
COP	Conference of the Parties
CRP	coordinated research project
e-SAGE	Energy extension to the South African General Equilibrium
EMPOWER	Extended Input–Output Model for Sustainable Power Generation
EPP2040	Energy Policy of Poland until 2040
EU	European Union
GDP	gross domestic product
GHG	greenhouse gas
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
INDC	intended nationally determined contribution
IO-E	econometric input–output model
IOM	input–output model
IPCC	Intergovernmental Panel on Climate Change
IRP	Integrated Resource Plan
LEAP	Long-range Energy Alternatives Planning
LCOE	levelized cost of electricity
LNG	liquefied natural gas
MAED	Model for Analysis of Energy Demand
MCA	multi-criteria analysis
MESSAGE	Model of Energy Supply Strategy Alternatives and their General Environmental Impacts
NDC	nationally determined contribution
NPP	nuclear power plant
PELP	Long Term Energy Plan
PV	photovoltaic
RCP	representative concentration pathway
RES	renewable energy source
SATIM	South African The Integrated MARKAL-EFOM System
SMR	small modular reactor
SSP	shared socioeconomic pathway
TIMES	The Integrated MARKAL-EFOM System
toe	tonnes of oil equivalent
UNFCCC	United Nations Framework Convention on Climate Change

CONTRIBUTORS TO DRAFTING AND REVIEW

Ahmad, I.	Pakistan Atomic Energy Commission, Pakistan
Debrah, S.K.	Nuclear Power Institute, Ghana
Eid, N.	International Atomic Energy Agency
Fisher, M.N.	International Atomic Energy Agency
Galinis, A.	Lithuanian Energy Institute, Lithuania
González Cáceres, P.	Chilean Nuclear Energy Commission, Chile
Güngör, G.	Middle East Technical University, Turkey
Hoang T. Dung	Ministry of Industry and Trade, Viet Nam
Hughes, A.	University of Cape Town, South Africa
Imtiaz, M.	Pakistan Atomic Energy Commission, Pakistan
Jamal, N.	Pakistan Atomic Energy Commission, Pakistan
Konpielko, L.	Lazarski University, Poland
Konstantinavičiūtė, I.	Lithuanian Energy Institute, Lithuania
Kovachev, M.	International Atomic Energy Agency
Krstanović, L.	Energy Institute Hrvoje Požar, Croatia
Lekavičius, V.	Lithuanian Energy Institute, Lithuania
Monti, S.	International Atomic Energy Agency
Muradyan, R.	Scientific Research Institute of Energy, Armenia
Nagel Araya, B.	Chilean Nuclear Energy Commission, Chile
Neniškis, E.	Lithuanian Energy Institute, Lithuania
Nguyen A. Tuan	Institute of Energy, Ministry of Industry and Trade, Viet Nam
Norvaiša, E.	Lithuanian Energy Institute, Lithuania
Nyasapoh, M.A.	Nuclear Power Institute, Atomic Energy Commission, Ghana
Petrosyan, A.	Scientific Research Institute of Energy, Armenia
Plich, M.	University of Lodz, Poland
Saleemullah, M.	Pakistan Atomic Energy Commission, Pakistan
Sargsyan, V.	Scientific Research Institute of Energy, Armenia
Sari, R.	Middle East Technical University, Turkey
Turton, H.	International Atomic Energy Agency
Vincze, P.	International Atomic Energy Agency
Zeljko, M.	Energy Institute Hrvoje Požar, Croatia

RESEARCH COORDINATION MEETINGS

1st RCM: Vienna, Austria, 14–17 March 2017

2nd RCM: Vienna, Austria, 12–14 June 2018

3rd RCM: Vienna, Austria, 24–27 September 2019

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