NGFS Occasional Paper

Running the NGFS Scenarios in G-Cubed: A Tale of Two Modelling Frameworks

17 June 2022

About the NGFS

The Network for Greening the Financial System (NGFS), launched at the Paris One Planet Summit on 12 December 2017, is a group of central banks and financial supervisors, which on a voluntary basis are willing to share best practices and contribute to the development of environment and climate risk management in the financial sector, and to mobilise mainstream finance to support the transition towards a sustainable economy. The NGFS brings together over 100 central banks, financial supervisors and observers. Together, they represent around 85 per cent of global greenhouse gas emissions, and are responsible for the supervision of all of the global systemically important banks and two thirds of global systemically important insurers. The NGFS is chaired by Ravi Menon, Managing Director of the Monetary Authority of Singapore. The Secretariat is provided by Banque de France.

About this report

The NGFS Workstream on “Macrofinancial” commissioned a pilot project in 2021 to explore the feasibility of integrating the G-Cubed general equilibrium model into the NGFS suite of models. At the time this project was completed, the workstream on macrofinancial was chaired by Sarah Breeden, Executive Director for Financial Stability, Strategy and Risk at the Bank of England.

This project was conducted in partnership with Australian National University (ANU) and a consortium of academics representing the models used within the existing NGFS scenarios: Potsdam Institute for Climate Impact Research (PIK); International Institute for Applied Systems Analysis (IIASA); University of Maryland (UMD); Pacific-Northwest National Laboratory (PNNL); and the National Institute of Economic and Social Research (NIESR).

This report documenting the findings of the G-Cubed pilot project was prepared by the pilot project working group, with special thanks given to the lead coordinating authors: Christoph Bertram (PIK); Antoine Boirard (Banque de France); Jae Edmonds (UMD); Roshen Fernando (Australian National University); David Gayle (Bank of England); Ian Hurst (NIESR); Larry Weifeng Liu (Australian National University); Warwick McKibbin (Australian National University); Clément Payerols (Banque de France); Oliver Richters (PIK) and Edo Schets (Bank of England).

Disclaimer

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Foreword from Sarah Breeden

Understanding the economic and financial impacts of climate change is a complicated process, and the prudent management of these risks calls for a forward-looking approach which is able to account for future uncertainties. Against this backdrop, scenario analysis emerges as the primary tool for sizing the potential risks arising from climate change. In projecting a range of possible future pathways, scenario analysis is crucial for enhancing our management of climate-related risks, and has an integral part to play in supporting an orderly transition to net-zero.

It is in this vein that the NGFS developed a harmonised set of climate pathways to further enable central banks and supervisors to conduct scenario analysis. The NGFS released its first iteration of freely available scenario pathways in 2020, with a further update released in 2021. The NGFS scenarios provided the first set of climate scenarios to include consistent assumptions across physical and transition risks as well as the associated macroeconomic pathways, filling an important gap in the tools available.

The NGFS is constantly exploring new ways to enhance the scenarios and deepen the technical capabilities on which they are based. Increasing the sectoral coverage and detail within the scenario pathways was of major interest to NGFS members, in order to boost their usability "off the shelf", but also to increase the applicability of the scenarios for a variety of other users and use-cases.

The G-Cubed pilot project was commissioned in 2021 to serve this very purpose. The project's objective was to understand whether the G-Cubed general equilibrium model could be used to expand the sectoral coverage of the existing NGFS scenario pathways. Such sectoral pathways would enrich the analytical depth of the NGFS scenarios, enabling users to explore how the physical and transition risk narratives could unfold within particular areas of the real economy and within an increased number of world regions.

While divergences in the results generated by the G-Cubed model and the existing NGFS models mean that we cannot incorporate the sectoral breakdown into our NGFS scenarios at this stage, the G-Cubed model undoubtedly provides a rich set of insights. We have therefore made the scenarios and data generated by this exercise available for download on the NGFS website as a standalone resource for central banks and others to use.

Indeed, beyond exploring whether and how the detailed sectoral information reflected in the G-Cubed model could be incorporated within the existing suite of NGFS models, the pilot project allowed for a rich and fruitful dialogue to take place between the different model providers as well as with the central banks involved. Over the course of the project, model providers representing different modelling philosophies collaborated to understand better their differences in approach and so how sensitive the NGFS scenarios are to different modelling approaches. This open dialogue has produced an abundance of learnings for all modelling teams involved as well as the NGFS community.

The value of this project, therefore, has been significant, and the learnings stretch beyond the realm of technical detail. It is the intention of this Occasional Paper to make these learnings as accessible as possible for the wider community, and I am hugely excited to be able to share our findings with you.

Sarah Breeden

Chair of the workstream on "Macrofinancial", April 2018 – April 2022

Executive Director, Financial Stability, Strategy and Risk, Bank of England

Executive Summary

The NGFS workstream on macrofinancial ran a pilot project from October to December 2021 to understand how the G-Cubed general equilibrium model could be utilised to increase the sectoral granularity of the NGFS scenarios. G-Cubed is a multi-country, multi-sectoral model with detailed representation of the macroeconomy, and was selected for this pilot project following a review process in which several other models were considered (see Chapter 2). The G-Cubed pilot project posed a unique opportunity to compare and contrast the approach of this model with the models included in the existing package of NGFS scenarios.

This project builds on two previous iterations of NGFS scenarios. The first set of scenarios, Phase I, was released in 2020 and included six scenario narratives covering a broad range of physical and transition-related risks. The scenarios were modelled within three highly established integrated-assessment models (IAMs): GCAM, MESSAGEix-GLOBIOM and REMIND-MAgPIE.[1] In 2021, the six scenario narratives were expanded on in a second phase of the package (Phase II), when a set of macroeconomic variables were added (via the global macroeconomic model NiGEM). An interactive online portal was also established as part of Phase II, through which users could explore the physical and transition risk pathways included in the package.

The main purpose of the pilot project was to explore whether the detailed sectoral modelling within G-Cubed could be incorporated into the existing suite of models to provide more sectoral granularity. In order to assess the feasibility of this, three of the Phase II transition risk scenarios were run within G-Cubed: Net Zero 2050; Delayed Transition; and Current Policies. The results from the G-Cubed model runs were compared with those of the three IAMs from Phase II to understand the potential alignment between the two modelling frameworks, and whether the G-Cubed model could be integrated into a further phase of the NGFS scenarios. While this project focuses primarily on comparing the modelling of transition risks, some consideration is also given to how physical risks are modelled.

The rationale for this Occasional Paper is to **make the learnings from the G-Cubed pilot project freely available, recognising that they will be of value to a wider community of stakeholders, and that they comprise a public good.** These learnings will serve those seeking practical insights around the expansion of climate scenarios, and those with a general interest in the different approaches to the modelling of climate-related risks.

Overall, as is clear from the results of this exercise, the benefits of integrating the G-Cubed model into the NGFS scenarios package are material, and present a valuable means to understand how the scenarios will play out within specific sectors of the economy or at the regional level (in a way that is not currently possible with the scenarios available in Phase II). While there are a number of areas where these models are able to coherently interact, the prevalence of fundamental differences in modelling approach drives differences in the technical results. The persistent differences in results currently limit the potential for the G-Cubed model to be fully integrated within the NGFS scenarios

[1] For a breakdown of the full NGFS model specification (i.e., including models representing physical risks), see: NGFS Climate Scenario Database: Technical Documentation V2.2 (2021), and the NGFS Scenario Explorer: https://data.ene.iiasa.ac.at/ngfs/#/login?redirect=%2Fworkspaces.

at this stage, but this valuable pilot project has helped us identify where further exploration might be continued in future.

The key technical findings on the modelling of transition risk-related outputs in G-Cubed and the NGFS IAMs are as follows:

- Within the NGFS Net Zero 2050 and Delayed Transition scenarios, G-Cubed assumes a lower degree of substitutability between electricity-generating technologies than in the IAMs, and models the adjustment costs associated with rapid large-scale deployment of new technologies. Both the lower substitutability between electricity-generating technologies and the modelling of adjustment costs for new technologies limit the potential for largescale future renewable energy deployment in G-Cubed, and lead to a slowdown in aggregate economic activity in the long-run. In contrast, the three NGFS IAMs rely heavily on the penetration of wind and solar technologies to reach net-zero, and model steady growth in energy consumption.
- GDP outcomes vary substantively between the two approaches because of different philosophies in how the energy system is modelled. G-Cubed uses a top-down macroeconomic approach, while the three IAMs take a bottom-up engineering approach.
- G-Cubed is able to sufficiently model a net-zero transition despite assuming a materially lower carbon price than in the NGFS IAMs. While the transition in the NGFS IAMs is driven by a substitution between energy sources prompted by a price differential (the carbon price), G-Cubed achieves the transition via reducing overall energy production, and reduces the carbon intensity of non-electricity sectors via greater substitution between activity in these areas. The extent to which the pronounced economic slowdown would hold in G-Cubed if greater penetration of renewable energy technologies were enabled is a crucial open question arising from this pilot project.

On the modelling of physical risks, the key difference is that:

- In G-Cubed, economic shocks from extreme weather events are applied at the sector level (to sector and labour productivity). In contrast, the IAMs do not explicitly incorporate the economic shocks associated with physical risks as these are applied within the macroeconomic model NiGEM. However, as the global temperature differences between G-Cubed and the IAMs for each transition scenario examined are moderate, this difference in approach is of minor consequence relative to the differences associated with modelling transition risks.

The final and comprehensive modelling results are available on a dedicated dashboard.

The G-Cubed pilot project has demonstrated the value of collaboration and conducting comparison exercises to understand how to model climate policy pathways. A specific objective of the NGFS workstream on macrofinancial has been to extract as much two-way learning as possible, meaning that findings should be insightful for each of the represented modelling communities in equal measure, as well as the NGFS itself. As a result of this pilot project, each of the represented groups have increased their own understanding and appreciation of alternate approaches to modelling climate policy pathways, and this has led to the refinement of some models where alterations could be made.

Model intercomparison exercises such as the G-Cubed pilot project are relatively unique within the field, and the richness of the conclusions presented here reflects the value of open academic discourse between those with differing perspectives. Given the need to upskill and develop tools in this space at pace, similar exercises would usefully be undertaken in the future.

1. Introduction

The collaboration between central banks, supervisors and academic experts in the context of modelling climate-related impacts on the macroeconomy is a nascent field which continues to develop. Specifically, central banks and supervisors are only just beginning to employ the use of models (whether taking an integrated assessment structure or otherwise) in relation to their work on safeguarding financial stability. As this field and work becomes more mature, it will be necessary to understand further how models from differing frameworks relate to one another, and how models can continue to serve the work of central banks and supervisors in a way that is coherent and enhances policymaking from a practical perspective.

1.1 Contribution to the literature

The learnings from this pilot project contribute to filling a general gap in the academic literature regarding not merely the comparison of models used to understand future physical or transition risk pathways (notwithstanding e.g. Nikas et al., 2019), but the comparison of the results of differing types of model for a consistent set of scenarios. In comparing the results from these models for the same three scenarios, this project aimed to better understand whether results from models with a detailed representation of the energy system can be emulated by models which take a general equilibrium approach. Similarly, we aimed to understand how the macroeconomy and trade dynamics could be better represented in energy system models, at least in a stylised form. It is to this academic discourse that the G-Cubed pilot project, and this resulting Occasional Paper, aim to contribute.

1.2 Requirement for a sectoral model within the NGFS scenarios

Phase II of the NGFS scenarios offers granular estimates of energy-related variables on a sectoral level, including emissions, carbon-intensity of production, and energy demand. However, the number of sectors represented is limited, and the package does not include estimates of the economic impacts across sectors.[2] Such sectoral pathways covering the entire economy are important because they shed light on the distribution of climate-related risks across the economy. Economic sectors will be impacted in various ways by both transition risks (positively or negatively), and physical risks (mostly negatively, but to varying degrees), so the ability to model the potential impacts is often essential in climate scenario analysis.

Both the requirement for sectoral representation, and the lack of sectoral economic impacts within the current NGFS model package underlines the importance of including an additional sectoral model as key for understanding how physical and transition-related climate risks could materialise within different sectors. Such a model could equip the NGFS scenarios with additional functionality and increase their potential application to understand the impact of future policy pathways. A sectoral model could also enrich the discussion on the interaction between the energy system and monetary

[2] Sectors currently represented in the NGFS scenarios are agriculture, forestry and other land use (AFOLU), buildings, electricity, transport, and industry (with subsectors steel, cement and chemicals).

and fiscal policy. It is in this thematic and conceptual context that the NGFS conducted a pilot project to explore whether G-Cubed could be integrated within the existing suite of models.

Aside from a priori knowledge concerning the different approaches taken by integrated assessment models and computable general equilibrium models (see Chapter 2), which had some influence on the expected results, no explicit rubric determining the integration of the G-Cubed model was set out. This pilot project has therefore been conducted with a predominantly exploratory lens, with a view to maximising the potential learnings beyond the immediate purpose of improving the sectoral coverage of the NGFS package.

We discuss the rationale for choosing G-Cubed over an alternative sectoral model in Chapter 2 of this paper.

2. Review of Sectoral Models

This Chapter details the considerations made by the NGFS when selecting an additional model for increasing the sectoral resolution of the NGFS scenarios. It first provides an overview of the selection criteria and the types of models examined, before setting out the advantages of using the G-Cubed model for increasing sectoral representation in the model package.

The NGFS had 5 considerations when reviewing additional models in order to narrow the search and focus attention on the most salient aspects of the requirement:

1. **Rich sectoral outputs.** The provision of outputs for a large number of sectors additional to those currently reflected in the package, with coverage for a broad set of regions around the world. The provision of additional sectoral variables (e.g. sectoral gross value added and sectoral unemployment) was similarly important to the outputs of sectors themselves.
2. **Feasibility of integration with the existing scenarios.** The potential time and effort needed from the existing consortium of modellers and NGFS members to integrate the selected model into the NGFS suite of models, in light of project time constraints.
3. **Nature of the model provider.** Whether the model provider's interests are primarily academic or commercial. The intention of this consideration was to retain the transparency and open accessibility that has characterised the NGFS scenarios since their inception.
4. **Funding implications and model provider availability.** The costs associated with piloting the model, and whether model providers were able to commit to the time constraints of the project.
5. **Usability.** Whether the model could be run by central banks (should they need to develop the scenarios further), or whether a high-degree of additional expertise would be required to run the model.

With these 5 considerations in mind, several types of models were considered, each using a different approach with relative strengths and weaknesses.

The key features of these types of model are summarised in brief below:

- **Process-based Integrated Assessment Models (IAMs),** such as those used to produce the NGFS scenarios (see Chapter 3 for details), include relatively simple long-term macroeconomic growth models, and link these to energy system models, including production, transformation, trade and end-use applications, as well as models of the biosphere, hydrosphere, atmosphere and climate.[3] Process-based IAMs tend to focus, in particular, on creating a sophisticated replication of the energy system, the land-use system and resulting emissions. Some of these models (e.g., REMIND-MAgPIE and MESSAGEix-GLOBIOM) then determine the optimal economic allocation of capital to maximise intertemporal welfare given

[3] The counterpart to process-based IAMs are aggregated IAMs, such as the DICE model (Nordhaus 1994). Aggregated IAMs are similarly composed of a rather simple, long-term economic growth model, and use aggregated mitigation and damage cost curves. They hence do not have the level of detail that is included in process-based IAMs, and typically do not include any sectoral disaggregation. For an overview of types of IAMs, see Bosetti (2021) and Weyant (2017), and for a framework for the evaluation of IAMs see Schwanitz (2013).

some constraints. In contrast, GCAM, another process-based IAM, is a dynamic-recursive model which assumes that economic agents follow their own interests, but do not know about the future. While these models can disaggregate at the sectoral level for variables such as emissions and energy demand, economic variables such as sector-specific output prices and quantities are generally not available. Process-based IAMs also assume long-term system equilibrium and use real prices (not nominal prices), hence they do not explicitly represent unemployment, inflation, or other short-term macroeconomic issues

- **Computable General Equilibrium (CGE)** models have been designed to explore the sectoral distribution of the economic impacts of different policies. They are typically linked to input-output tables or social accounting matrices and as such are calibrated to economic data. This approach contrasts with the IAMs, which calibrate to physical data. Notably, some CGEs do have a detailed representation of the energy system, similar to process-based IAMs. Like IAMs, CGEs generally assume long-term system equilibrium and use real prices, although G-Cubed is an exception to this generalisation as it explicitly considers market disequilibrium
- **Dynamic Stochastic General Equilibrium (DSGE)** models incorporate more forward-looking behaviour and capture monetary and business cycle dynamics. DSGE models are typically rich in economic variables, though do not usually reflect many sectors of the economy, and they tend to abstract from real-world data. DSGE models have been employed substantially by monetary and fiscal policy authorities, and are not typically associated with a highly granular representation of the energy system
- **Climate-Macroeconometric** models capture the impact of (mostly transition and policy-related) climate risks on macroeconomic variables such as GDP or labour productivity. These models are calibrated based on historical relationships, although they are increasingly being modified to capture forward-looking behaviour (e.g., in Mercure et. al., 2018, the E3ME model by Cambridge Econometrics[4] is augmented with a technology diffusion model to capture forward-looking technological growth)
- **Stock-Flow Consistent (SFC)** models are a flow-of-funds representation of an economy, i.e. balance sheet positions and flows between economic sectors. Consistent with post-Keynesian theories, SFC models ensure that every monetary flow is recorded as a payment for one sector and a receipt for another, and that every financial stock is recorded as an asset for one sector and a liability for another. These features are particularly helpful for modelling the financial sector, and also allow for natural resource and energy stocks and flows to be readily integrated (though these are often integrations of exogenous climate-related variables and aren't explicitly produced by the model).

The NGFS examined a range of models that could have been considered, across a diversity of types. **In light of available capacity, three specific models were shortlisted as contenders for increasing the sectoral granularity of the NGFS Scenarios: MIT-EPPA, EIRIN and G-Cubed:**[5]

1. **MIT Emissions Prediction and Policy Analysis Model (MIT-EPPA)** is a CGE model which includes input-output linkages across sectors, but also accounts for trade, government and investment. It incorporates standard economic specifications, such as capital, labour and resource inputs and gross sectoral outputs, in addition to some physical aspects of the economy (e.g. emissions, land

[4] See: https://www.e3me.com

[5] The working groups also considered another five models which were discounted on the basis that they were less aligned with the five considerations mentioned on p10, namely: E3ME, GEM-E3, IMACLIM, AIM and GTAP.

use, energy). The physical representation of the economy allows for a link between economic accounts and emissions, the use of natural resources and land availability. As well as being used to understand the effects of hypothetical policy pathways (e.g., Palstev et al., 2021), MIT-EPPA has also been linked to macro projection models for central bank scenario analysis (e.g., Bank of Canada OSFI, 2022).

2. **EIRIN** was developed relatively recently (appearing first in Monasterolo and Raberto, 2017) and is the only non-general equilibrium model considered. EIRIN is a SFC model rooted in a balance sheet approach with agent based macro-dynamics. It adopts a Leontief production function[6] with production factors for labour, capital, and raw materials. Its sectors are endowed with adaptive behaviours and expectations, and interact with the other sectors and the foreign sector through a set of markets. Notably, EIRIN has been used to study the role of the financial sector in the low-carbon transition (e.g., Monasterolo and Raberto, 2017, and Gourdel et al., 2021). EIRIN did however need to be calibrated for each separate country and sector included in the analysis which was considered impractical given the time constraints involved in this project.
3. **G-Cubed** is a hybrid DSGE and CGE model that integrates emissions and energy data with a sectoral model of the economy, developed by Warwick McKibbin and Peter Wilcoxen. It incorporates real and nominal rigidities, fiscal and monetary policies, international trade, capital flows, financial assets and valuations. A variety of climate policies can be introduced in the model which impact sectoral outputs, unemployment and inflation until energy substitution occurs. It has been used to study the macroeconomic implications of climate change (Fernando et al., 2021), transition pathways (Jaumotte et al. 2021; Liu et al., 2020) as well as a broad range of other questions (McKibbin and Stoeckel, 2018).[7]

The choice to run the pilot project with the G-Cubed model was motivated by several factors. While each of the considered models presented their own unique set of features and strengths, and while a more protracted pilot could have examined all three, the G-Cubed model was best suited to the specific requirements set out by the NGFS. In summary, the reasons for selecting G-Cubed for this pilot are as follows:

- G-Cubed is the most well-reflected model in the academic literature (McKibbin & Vines, 2000), and presents a set of variables and features that are highly useful for central banks and supervisors (the primary target group of the NGFS scenarios package). These are variables such as: inflation, interest rates, exchange rates, unemployment, financial valuation, and several options for monetary and fiscal policy responses.
- G-Cubed is further complemented with a detailed regional and sectoral breakdown (the representation of which was most detailed out of each of the three models reviewed), and has the ability to model a broad array of climate policies.

[6] I.e., in which all production factors are used in fixed proportions, with constant returns to scale.
[7] E.g., including infectious diseases (Fernando & McKibbin 2021) and population ageing (Liu & McKibbin 2021), although these policy issues were investigated using versions of the G-Cubed model with fewer energy-related sectors than the version used in this pilot project.

3. Specification of Models

3.1 Overview of the G-Cubed model

The G-Cubed model is a multi-country, multi-sector, intertemporal general equilibrium model developed by McKibbin and Wilcoxen (1999, 2013). G-Cubed is designed to bridge the gaps between econometric general-equilibrium modelling, international trade theory, and modern macroeconomics. There are ten regions and twenty sectors in the model (version GGG20v164) used in this paper. The model regions are presented in Table 5. The sectors in the model are set out in Table 6.[8]

The G-Cubed sectors 1-12 are aggregated from 65 sectors of the Global Trade and Analysis Project (GTAP) 10 database.[9] The electricity sector is then disaggregated into the electricity delivery sector (sector 1 in Table 6) and eight electricity generation sectors (sectors 13-20 in Table 6). There are many macroeconomic, financial and sectoral variables in the model covering all countries and regions in Table 6. These variables are set out in Tables 7 through 9.

Model structure and features

The structure of the model is set out in McKibbin and Wilcoxen (2009; 2013), and the latest version with the electricity sector disaggregation is summarised in Liu et al. (2020). An illustration of the production structure is contained in Figure 1. CO_2 emissions are measured through the burning of fossil fuels in energy generation. In particular, emission coefficients are calculated for emissions from coal, natural gas and gas utilities and burning of petroleum. In earlier versions of the model, emission coefficients for oil extraction were used. However, a better alignment with emissions accounting is to assign emissions to the burning of refined petroleum (given the extent of international trade in petroleum).

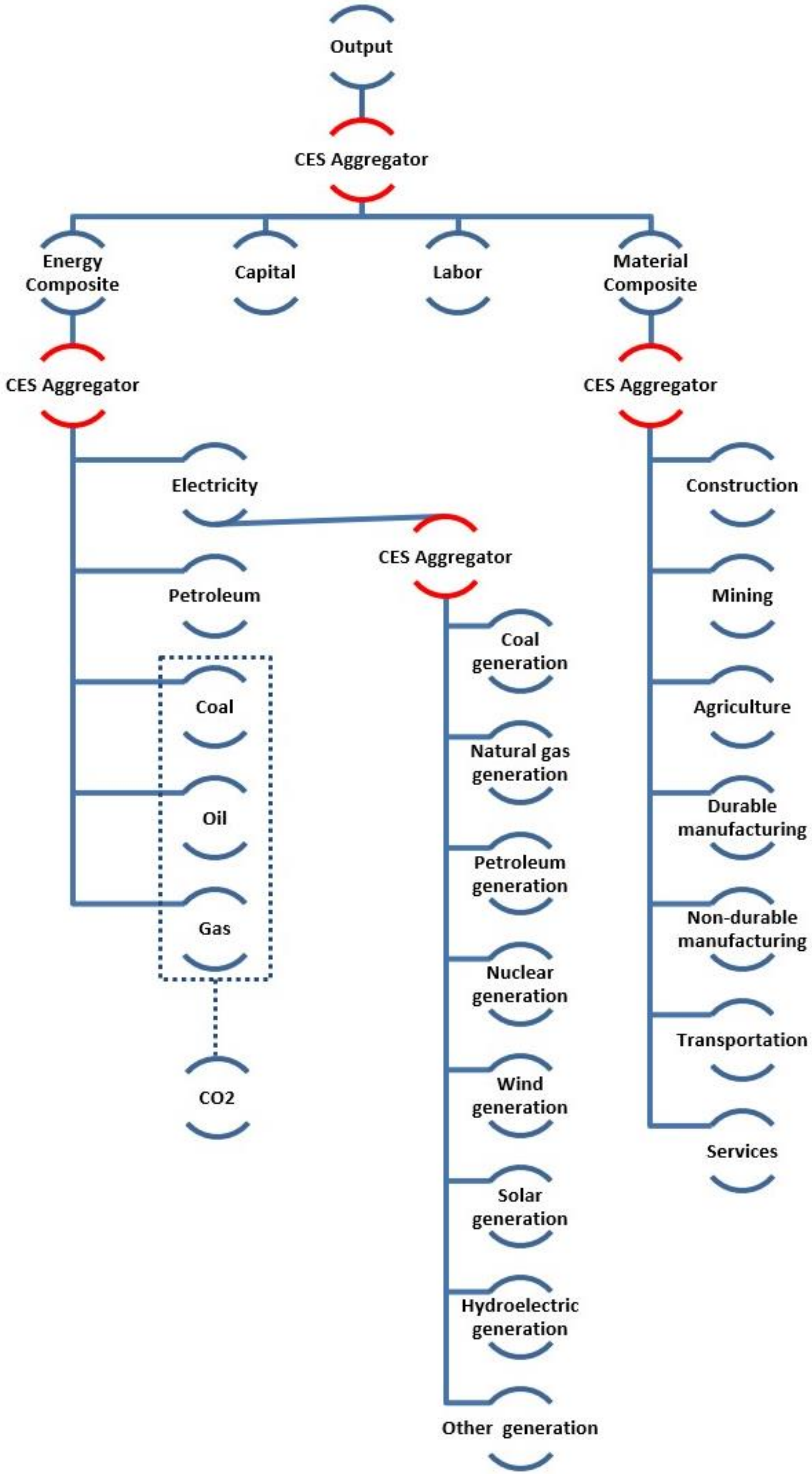
G-Cubed consistently accounts for stocks and flows of physical and financial assets. The model imposes an intertemporal budget constraint on all households, firms, governments, and countries. For example, budget deficits accumulate into government debt, and current account deficits accumulate into foreign debt. Thus, a long-run stock equilibrium is obtained by adjusting asset prices, such as the interest rate for government fiscal positions or real exchange rates for the balance of payments. However, adjusting to each economy's long-run equilibrium can be slow, occurring over much of a century.

Rigidities prevent the economy from moving quickly from one equilibrium to another. Rigidities include nominal stickiness caused by wage stickiness, lack of complete foresight in the formation of expectations, cost of adjustment in investment by firms with physical capital being sector-specific in the short run, and monetary and fiscal authorities following particular monetary and fiscal rules. Short-term adjustment to economic shocks can differ from the long-run equilibrium outcomes. The focus on

[8] Tables 5 through 9 appear in the Technical Annex to this paper.
[9] See: https://www.gtap.agecon.purdue.edu/databases/default.asp.

short-run rigidities is essential for assessing the impact over the initial decades of climate policy.

Figure 1: Production Structure of Sectors 2 to 12 in the G-Cubed Model[10]



[10] Figure 1 adapted from: Fernando R., Liu W. and W. McKibbin (2021). See Table 6 for a full list of the 20 sectors in the G-Cubed model. CES stands for Constant Elasticities of Substitution.

3.2 Summary of NGFS suite of models

The transition pathways for the NGFS scenarios have been generated with a 'suite' of models, comprising three well-established IAMs: GCAM, MESSAGEix-GLOBIOM and REMIND-MAgPIE. The pathways generated by this suite of IAMs are then used as inputs to NiGEM, a leading macroeconomic model used by institutions across the world for high-level policy formation including forecasting, scenario building and stress testing.

The combination of models used within the current NGFS scenario vintage allows users to explore transition risk, physical risk, and the economic implications of both for a range of variables and variables projections. Through its choice of IAMs, the NGFS scenarios are grounded in mitigation scenarios that inform the reports of the IPCC.[11] In addition, each of these models have been well-documented and cited extensively in academic literature. These features bolster the credibility of the overall package within the global community of climate modellers and further afield.

Given the focus on the Net Zero 2050 and Delayed Transition scenarios in the pilot project, this paper mainly focuses on the transition risk pathways generated by the models. However, the model suite additionally contains climate and earth system models to capture the full global mean temperature uncertainty (MAGICC6),[12] changes in biophysical systems and extreme events (via ISIMIP),[13] and the direct damage from extreme events (CLIMADA).[14]

The model suite is depicted visually in the schematic diagram (Figure 2) appearing below:

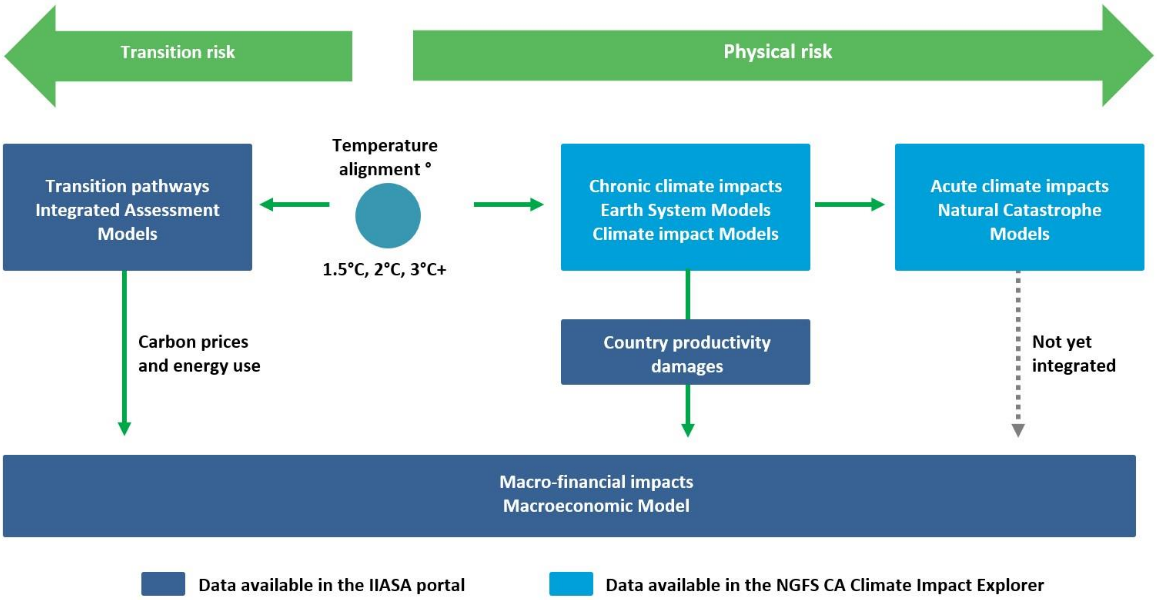


Figure 2: Schematic overview of models appearing in the second vintage of the NGFS scenarios.

[11] See: IPCC, Working Group III Report, Summary for Policymakers (2022).
[12] Model for the Assessment of Greenhouse Gas Induced Climate Change. See: http://www.magicc.org/.
[13] The Inter-Sectoral Impact Model Intercomparison Project. See: https://www.isimip.org/.
[14] Climate Adapt. See: https://climate-adapt.eea.europa.eu/metadata/tools/climada.

3.3 Comparison of key model features

In the following sections (3.3.1-4), we compare the most salient features of the NGFS IAMs and the NiGEM macroeconomic model with G-Cubed, elucidating some of the key differences in approach taken by the models. This comparison also provides additional context to the results of the project explored in detail in Chapter 4.

3.3.1 Fossil fuels

All models representing the energy sector necessarily abstract from a highly complex combination of fossil fuels, where a myriad of different forms of coal (anthracite, bituminous, subbituminous, lignite), crude oil (varying viscosity, sulphur content, etc.) and natural gas (conventional, shale, etc.) exist. In G-Cubed, MESSAGEix-GLOBIOM and REMIND-MAgPIE, there is only one generic form of each of these three fossil fuels, but the details of extraction costs (i.e., as a function of region, time and cumulative extraction) differ across models. In GCAM, both conventional and unconventional sources of fossil fuels are tracked.

The detail of representation of different transformation steps for these fuels also varies. In G-Cubed, petrol (as the generic product of oil refineries), natural gas and coal can be either used directly by the model's demand sectors, or for transformation into electricity. In the NGFS IAMs, coal can also be transformed into gaseous or liquid fuels, and all fuels can be transformed to hydrogen. Various alternative technologies exist for each transformation route within the NGFS IAMs, differentiated by efficiency, the availability of carbon capture and storage (CCS), and with the option of heat co-production. For a more detailed breakdown of the actual technologies reflected in the NGFS IAMs, see section 3.3.4 of this paper.

Finally, the NGFS IAMs track the release of CO_2 via the combustion of fossil fuels, as well as the CH_4 (methane) emissions that are emitted during extraction, and additional air pollutants occurring during combustion. By comparison, G-Cubed currently only tracks the CO_2 content of the fuels being used. To ensure alignment between the fossil fuel trajectories of G-Cubed and the NGFS scenarios, G-Cubed reduces CO_2 emissions by 80% within the scenarios that were run (with the remaining emission reduction to be from carbon removal technologies).

3.3.2 Carbon prices

Two of the IAMs used by the NGFS (MESSAGEix-GLOBIOM and GCAM) endogenously generate a carbon price trajectory based on the emission constraints applied in each scenario. By contrast, the REMIND-MAgPIE model takes the carbon price trajectory as an exogenous assumption to each iteration of the model optimisation, calibrated by an iterative adjustment algorithm in a way that ensures consistency with the assumed reduction in CO_2 emissions. The G-Cubed model can either project the emissions associated with a carbon price (or other policy), or it can calculate the carbon price trajectory that meets certain requirements. For the purposes of this pilot project, G-Cubed solves for the carbon price trajectory in each region that both follows Hotelling's rule, wherein the carbon price increases at an exogenous and constant real rate over time, and also achieves a specified cumulative emissions target for the years 2020 to 2050. Thus, carbon prices in G-Cubed can be endogenous, as has been the case in this pilot project, or the user can specify the carbon prices and the model will project the resulting emissions.

Within G-Cubed, carbon prices apply fully to the CO_2 released by fossil fuels, whereas in the three NGFS IAMs, carbon prices only apply to the fraction of CO_2 released into the atmosphere (which is less than one for technologies with CCS), as well as non-CO_2 greenhouse gases. The NGFS IAMs use 100-year global warming potentials to convert emissions of other greenhouse gases into their CO_2-equivalent value. The G-Cubed model does not explicitly account for CCS technology or non-CO_2 greenhouse gases and enables 20% reduction to achieve the emission trajectory in each scenario as arising from the deployment of carbon removal technologies (including CCS).

Carbon prices drive substitutions between energy technologies within the NGFS IAMs. Such substitutions can be a change of fuel, as well as shifting from technologies without CCS to those with. The modelling of decarbonisation is highly nuanced in the IAMs, with the actual process parameters explicitly modelled, accounting for constraints and other dynamics in the ramp-up process (such as equipment costs, efficiencies etc.). The link between carbon prices and substitutions is strong because all three IAMs explicitly consider linear aggregation in the electricity sector, treating all electricity delivered to the grid as equivalent and independent of the technology employed to deliver that power (that is, there are no differences between electrons). This equivalence in electrons independent of source does not change the fact that where and when electrons are delivered will differ seasonally and diurnally (i.e., impacting certain technologies such as solar or wind). Linear aggregation also ensures that full decarbonisation of the power generation sector can be achieved (Pietzcker et al. 2017), and contributes to broader decarbonisation of the energy demand sectors via electrification.

In G-Cubed, the substitution of electricity sources is comparatively more restricted due to use of Constant Elasticity of Substitution (CES) production functions with an elasticity of substitution of 3 (cf. Section 3.3.4). In contrast to the IAMs, the G-Cubed model includes an alternative channel for reducing input of fossil fuels, namely by shrinking fossil fuel intensive sectors. Similarly, in G-Cubed, lower carbon prices are sufficiently strong to shift investments from carbon-intensive to low-carbon sectors, as there is greater substitutability in other areas of the economy which allow for decarbonisation outside of electricity generating technologies. G-Cubed allows for substitution throughout the economy, so it is not only substitution in electricity generation but the change in behavior across all sectors and consumers which leads to greater structural shifts in the economy over time.

3.3.3 Technological assumptions

The three NGFS IAMs represent technology in broadly similar ways, drawing heavily on an engineering style of model. G-Cubed also represents technology, but using a less detailed approach more familiar to CGE economic modelling.

As noted in section 3.3.2, the NGFS IAMs represent technologies in fixed relationships, and as such they emphasise the preservation of physical flows. For example, the production from a wind turbine may be mapped to a specific wind resource (i.e., wind of a specific grade and geographical availability) along with capital, operating and maintenance costs, and backup technology (e.g., battery storage or natural gas turbine) that enables the technology to operate at a specific reliability. Iron and steel production may include a variety of technology options using alternative fuels and/or electricity.

Frequently, technologies are characterised in mathematical form as fixed input-output coefficients (i.e., Leontief production functions) for a broad range of technology options that can be chosen. The NGFS IAMs also use various cost-based methods to determine the distribution of technology choice.

The NGFS IAMs model a wide range of technologies that trace the pathways of energy, from resources (which are potentially utilisable), to reserves (which are deployed), to transformations (e.g., gas to liquids, wind to power, biomass to biofuels to hydrogen), to end-use fuels and to energy end use technologies. Notably, energy end use technologies transform final energy products into energy services such as: passenger transport, heating, cooking, or process heat of different temperatures and grades.

Moreover, the NGFS IAMs are calibrated to accurately reproduce energy aggregates and disposition. Emissions of CO_2, other greenhouse gases, aerosols, and short-lived species such as carbon monoxide or non-methane hydrocarbons are associated with specific processes and fuels. CO_2 capture technologies are represented as specifically more costly options, with prescribed capture rates to be used in production, for example natural gas turbines with CCS. Negative emission technologies, primarily the use of bioenergy with CCS, afforestation, and/or direct air capture, are also explicitly modelled and/or deployed in the IAMs as economic and policy circumstances warrant (although not all technologies are fully used in the NGFS scenarios to maintain conservatism).

The coupling of technology to the aggregate economy tends to be indirect within the NGFS IAMs. That is, the feedback between technology and the aggregate economy tends to be through aggregate end-use energy. Within both REMIND-MAgPIE and MESSAGEix-GLOBIOM, GDP is modelled as a function of aggregate capital, labour, and end-use energy, whereas in GCAM, the GDP pathway is prescribed exogenously.

By comparison, the focus of G-Cubed is on modelling economic sector interactions and capturing the consequences of those interactions for the allocation of resources across the full economy. Thus, key macroeconomic variables such as GDP, value added by sector, wages, returns to capital and international capital flows emerge directly from G-Cubed as the model features are designed to explore those aspects and their changes in response to external shocks. It is for this reason that G-Cubed has made a unique contribution in modelling financial transactions in and across domestic and international markets.

In G-Cubed, each representation of a sector is a technology characterisation. Each of the 20 sectors in G-Cubed (except the electricity dispatching sector) is represented as being produced using a combination of four inputs, Capital (K), Labour (L), Energy (E), and Materials (M), referred to in combination as a "KLEM" production function. G-Cubed models Materials (M) as an aggregation of sectors 6-12 using a CES production function to calculate the aggregate materials from these sectors. A similar approach is used to create a Power Sector aggregate from the outputs of sectors 13-20.[15]

[15] The Constant Elasticity of Substitution (CES) function takes the form,

$$Q^{\rho} = \sum_{i=1}^{N} a_i X_i^{\rho}$$

The Power Sector aggregate is in turn aggregated together with sectors 2-5 to create the Energy aggregate.

In the NGFS IAMs, technology is assumed to improve over time, with regards to both the reduction of unit costs and an increase in overall efficiency. In G-Cubed, improvements affect the labour input only, with the rate differing by sector and country. G-Cubed uses a catch-up model to generate these labour productivity growth rates, assuming that the United States is the world frontier in productivity in each sector. The exception is for the renewable sectors, which are assumed to grow more quickly at an additional rate of 5 per cent (6.4 per cent in total). For all other economies, the sectoral productivity projections follow the Barro approach, estimating that the average catch-up rate of individual countries to the worldwide productivity frontier is 2% per year. Some of these regions in G-Cubed are expected to catch up more quickly due to economic reforms (or more slowly to the frontier due to institutional rigidities), but the calibration of the catch-up rate attempts to replicate recent growth experiences of each country and region in the model.

While the approaches taken by the NGFS IAMS and G-Cubed to represent technologies have important differences, both still emphasise the role of competition and markets in determining technology choice.

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where Q is the aggregate output (for example Materials), X_i are inputs such as Labour or Capital, the a_i are constant terms, and ρ is a term that sets the elasticity of substitution between the inputs (X_i's) and can take on any value between 1 and $-\infty$. Larger values for ρ reflect easier substitutability across inputs, while smaller values reflect lesser substitutability.

3.3.3.1 Renewable energy technologies

The NGFS IAMs model a range of renewable energy technology options to a significant degree of detail, with wind and solar power production reflected the most prominently. For example, distinctions are made by between solar power generated from PV arrays, heliostats, and distributed rooftop power as well as access to and need for backup energy generation capacity in a variety of forms (e.g., gas turbines and/or batteries). The cost and performance metrics for renewable technologies in the IAMs also include a graded resource representation that considers location characteristics to capture seasonal cycles of availability and quality of the resource.

Representations for other renewable categories such as geothermal, and hydroelectric power are also included within the NGFS IAMs. While not classified as a renewable energy technology, nuclear power is included as a technology option with no direct CO_2 emission.

The NGFS IAMs treat bioenergy as an explicit technology option. Growing bioenergy crops is a land use that must compete with other land uses. It directly interacts with other dynamics including afforestation, deforestation, food, and fibre production. The IAMs consider a variety of bioenergy sources including the harvest of crop residues, landfills, traditional bioenergy, and purpose grown bioenergy with regionally specific crop yields for a variety of alternative cultivars. Once produced, bioenergy can be transformed to liquids and/or gas or used directly as a solid. Bioenergy can be utilised to produce fuels for transport, used directly to produce power, or used as a feedstock for long-lived products such as plastics, or to produce hydrogen. Large point-source conversion facilities can employ CCS to capture the CO_2 released in the conversion process, specifically fuel refining, power generation, hydrogen production, or use in large industrial facilities such as steel manufacture. The combination of bioenergy with CCS creates energy and net negative CO_2 emissions (BECCS). Negative CO_2 emissions are a result of the fact that during their growth, plants obtain their carbon from the atmosphere. If that carbon is not returned to the atmosphere, but captured and stored in permanent reservoirs, the net effect is negative emissions.

G-Cubed includes renewable or low-carbon power sources which are represented as a KLEM production function with the CES property, so the substitution between renewable and non-renewable technologies is comparatively more restricted than in the IAMs.

3.3.3.2 Negative emissions technologies

The NGFS IAMs include representations of negative emissions technologies, sometimes referred to as carbon dioxide removal technologies (CDR). A potentially large number of CDR technologies exist, (Table 1 below), but these have widely different costs and deployment potential (Figure **3**3). While the NGFS IAMs differ regarding the specific technologies represented, in general, all include a representation of BECCS, forest restoration (afforestation), and direct air capture. These three technology clusters are chosen because they are considered to have costs and potentials that could lead to deployment at scale before mid-century. Other options in Figure 3 have either relatively small deployment potential and/or very high-cost estimates. None of the IAMs include all potential CDR technology options.

The NGFS IAMs represent CDR technology deployment interactively with other emissions mitigation options, such as low-carbon forms of energy generation. While the IAMs deploy technology as a market-driven phenomenon, technology deployment could also reflect the regulatory regime.

G-Cubed does not include CCS or CDR technologies explicitly within its modelling structure. G-Cubed does however make allowance for deployment of some combination of CCS and CDR technologies, by calculating a potential contribution of selected technologies exogenously (which is assumed to be fixed over time). The selected technologies include:

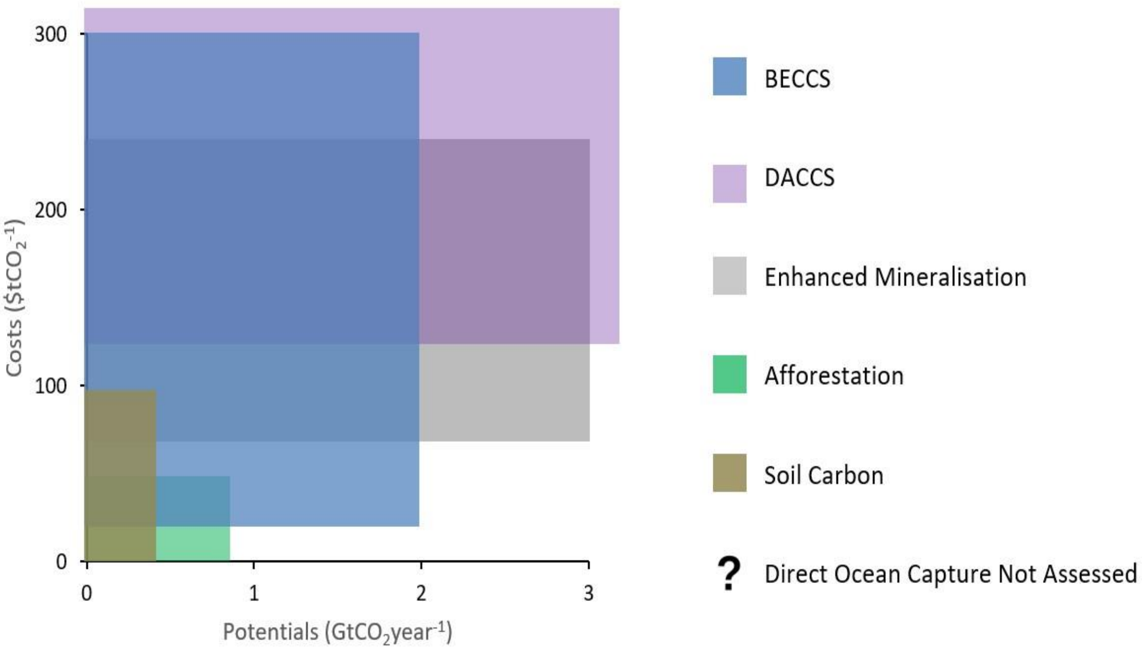
- Carbon capture and storage
- Afforestation and reforestation
- Bio Energy with Carbon Capture and Storage
- Biochar
- Enhanced weathering
- Direct Air Capture and Storage
- Soil carbon sequestration

The calculated potential of these technologies is used to set the net zero emissions target for fossil fuel CO_2 emissions. CO_2 emissions are assumed to be net zero when G-Cubed emissions, which are positive, decline to the calculated CDR contribution. This means that G-Cubed emissions need to decline by roughly 80% rather than 100% in the Net Zero 2050 scenario.

Table 1: Carbon Dioxide Removal Technology Options

Technology Category	Technology Variants
Direct Air Capture and Sequestration (DAC)	• Solvent (high-temp. heat) • Sorbent (low-temp. heat)
Enhanced Carbon Mineralization	• Carbonating alkaline waste products • Agriculture soil amendments
Bioenergy with Carbon Capture and Sequestration (BECCS)	• Bioliquids • Bioelectricity
Afforestation and Forest Restoration	• Expanding forested land area • Enhancing carbon stocks in existing forests
Soil Carbon Management	• Biochar • Low & no-till agriculture
Direct Ocean Capture	• Electrochemical separation of CO2 from ocean water

Figure 3: Potential cost and Deployment Potential of CDR Technologies in the United States



3.3.4 Monetary and fiscal policy assumptions

Policy rules for interest rates and the government sector are essential for the operation of a coherent model of the economy. Given the sophistication of the monetary and fiscal policy assumptions represented in G-Cubed, it is of value to compare the approach taken by G-Cubed with that of the macroeconomic model NiGEM.

Monetary policy

Within the macroeconomic model in the NGFS package, NiGEM, the monetary policy authority operates predominantly through the setting of the short-term nominal interest rate. This is done with reference to simple policy feedback rules that depend on targets such as inflation, the output gap, the price level, and nominal output. The interest rate reaction function responds to "gaps" between observed and targeted values of inflation, the output gap, etc. The target values (nominal GDP - NOMT, inflation - INFTS, price level - CEDT) are set to the baseline values of the relevant variable, so that a shock that delivers a deviation in GDP, inflation or the price level from baseline values will initiate an endogenous reaction in interest rates, depending on the rule selected.

G-Cubed also includes an endogenous monetary response function for each region, with the monetary authority for represented regions assuming the adjustment of short-term nominal interest rates following a Henderson-McKibbin-Taylor rule (Henderson and McKibbin, 1993; Taylor, 1993). Rules for key macroeconomic indicators such as interest rates, output growth and changes in the exchange rate evolve as functions of real rates relative to central bank targets for each individual region.

Two-pillar rule

The default rule for floating economies in NiGEM (those countries who set their own interest rate and exchange rates, not pegged to other currencies) follows a 'two-pillar' strategy, targeting a combination of inflation and a nominal aggregate. An effective lower bound is applied which restricts the scope for monetary policy easing when interest rates reach this lower boundary (normally this is a zero lower bound).

The two-pillar strategy sets the short-term interest rate as a function of the ratio of the nominal GDP target to nominal GDP and the difference between inflation expectations and the inflation target. This policy brings current nominal GDP back to its target level:

$$INT_t = \gamma * INT_{t-1} + (1-\gamma) * \left[\alpha * ln\left(\frac{NOMT_t}{NOM_t}\right) + \beta * (INFL_{t+i} - INFTS_{t+i})\right]$$

INT: Central bank Intervention rate (policy interest rate)
NOM: nominal GDP, defined with the GDP deflator (PY) by default[16]
NOMT: nominal GDP target
INFL: expected inflation, defined with the consumer expenditure deflator (CED)
INFTS: inflation target

[16] Model users can also choose to define nominal GDP with reference to the consumer expenditure deflator (CED).

Interest rates with fixed exchange rates

In the absence of capital controls, uncovered interest parity means that monetary authorities within NiGEM can control either an interest rate or an exchange rate, but not both. Countries with fixed exchange rates (including all members of the Euro Area), or that follow an exchange rate regime that "shadows" another currency, therefore have a fixed interest rate or follow the interest rate path of another central bank. For example:

$$INT_t = ELINT_t$$

INT: Central bank Intervention rate (policy interest rate)
ELINT: nominal short-rate for the Euro Area, as set by the ECB

Exchange rates

Bilateral exchange rates against the US$ (RX) are modeled for all countries and regional blocks within NiGEM, and each country can be assigned a floating or fixed exchange rate regime. Floating exchange rates are driven by interest rate differentials relative to the US. For global consistency in financial markets, all countries and regional blocks follow the same exchange rate solution path. Within G-Cubed, the monetary rule assigned to each country determines how interest rates are adjusted to trade off policy targets, including exchange rates.

Within NiGEM, the exchange rate option used in the NGFS transition scenarios assumes rational expectations in currency markets. This means that exchange rates are forward looking, 'jump' when there is news, and then follow an arbitrage path to reach their new equilibrium (Dornbusch, 1976). The size of the jump depends on the expected future path of interest rates in the domestic economy and in the US, solving an uncovered interest parity condition. The expected change in the exchange rate is given by the difference in the interest earned on assets held in local and foreign currencies. Agents look one period forward along the arbitrage path, with expected exchange rates next period being solved for in the same way to produce a forward recursion:

$$ln(RX_t) = ln(RX_{t+1}) - 0.25 * ln\left(\frac{100+INT}{100+USINT}\right)_t$$

RX: nominal exchange rate (domestic currency units per US$)
INT: Central bank Intervention rate (policy interest rate)
USINT: US Federal Reserve Intervention rate (policy interest rate)

A shock to the exchange rate risk premium, which introduces a wedge between the interest rate differential and the exchange rate path, can be introduced as an endogenous shock to the exchange.

The G-Cubed model assumes uncovered interest rate parity where the real interest rate in each country is equal to the US real interest rate plus the rationally expected change in the real exchange rate relative to the US over the period of the interest return plus a country risk premium. This equation is inverted and used to solve for the current exchange rate as the sum of all rationally expected future interest rate differentials plus country risk premia plus the long run equilibrium exchange rate which is endogenous to the model. The nominal exchange rate is the real exchange rate adjusted by the country price level relative to the US price level.

Fiscal policy and solvency rules

NiGEM includes a well-specified government sector in which fiscal deficit flows onto the stock of government debt.[17] The fiscal solvency rule in NiGEM is introduced through income tax, so that a deviation of the deficit or debt stock from their specified targets initiates an endogenous shift in the tax rate. This pulls the deficit and debt stock back towards targeted sustainable levels. By default, the solvency rule in NiGEM operates through the deficit target, but this can also be "switched off" temporarily (or permanently) for specific scenario studies.

Within G-Cubed, fiscal rules vary and can also be adapted according to the specifications of the scenario. In the version of G-Cubed used for this pilot project, governments are assumed to levy lump-sum taxes on households adjusted to ensure fiscal sustainability. In the long run, the changes in interest servicing costs from any changes in revenue or expenditure exogenously imposed are offset through a lump sum tax on households. Thus, the government debt level can permanently change in the long run with the change in debt to GDP equal to the long-run fiscal deficit ratio to the economy's long-run real growth rate.

Macroeconomic policy options for the NGFS scenarios

Within NiGEM, the NGFS scenarios are modelled as a stacked series of shocks, in which successive shocks are layered. This set of shocks broadly consists of: transition shocks (driven by NGFS IAM data to assume carbon pricing, fuel consumption levels etc.), policy shocks and physical risk impacts (based on a damage function). [18] The first set of policy shocks comprise options for carbon tax recycling, whereas a second layer of shocks relate to the response of businesses to carbon taxation.

The recycling of carbon tax revenues is a particularly important aspect of the macroeconomic modelling, and there are a number of potential options available:

- The adjustment of income tax (either boosting or reducing private consumption)
- Paying down debt where the fiscal balance is allowed to rise permanently
- Channelling revenue via government investment in infrastructure (raising potential output in the long run)
- Cutting corporate tax, stimulating private investment and offsetting the effects of any carbon taxes

For the orderly NGFS scenarios, NiGEM recycles carbon tax revenue by increasing government investment and reducing debt (with the fiscal solvency rule switched off). For the disorderly scenarios, the default solvency rule was used, which meant carbon tax revenues lead to a cut in income tax. In addition, a temporary negative shock to business confidence was implemented.

[17] Barrell and Sefton (1997) demonstrate that the existence of an equilibrium in a forward-looking model requires that debt stocks do not explode. This requires a fiscal solvency rule, to ensure that the deficit and debt stock return to sustainable levels.
[18] A damage function being a simplified expression of economic damages, as a function of climate impacts (Neumann et al, 2020).

Given that NiGEM models the second layer of shocks (fiscal or business) as part of a stacked series of shocks meant to represent a domestic economic (policy) response to carbon taxation, care must be taken to prevent double counting. This means that the energy sector is “turned off” and exchange rates were fixed to reduce trade spillovers. Within the orderly transition scenario, interest rates were also held fixed to prevent monetary policy counteracting the effects of the fiscal stimulus.

In a similar vein, within G-Cubed:

- For the Net Zero 2050 scenario, carbon tax revenue is rebated partially towards infrastructure investment and partially towards reducing government debt
- For the Delayed Transition scenario, carbon tax revenues are a lump sum which is rebated to households. G-Cubed did not incorporate an additional shock to business confidence at this stage

4. Results: Running the Selected Scenarios with G-Cubed

4.1 Creation of the model baseline within G-Cubed

The baseline scenario in G-Cubed does not assume that Paris commitments are necessarily implemented as, judging by current policies, these are unlikely to be met in many countries. Instead, the G-Cubed baseline relies on population projections, sectoral productivity growth rates by sector and country/region, and projections of energy efficiency improvements based on historical experience. The key inputs into the baseline are the initial dynamics from 2018 to 2019 (the evolution of each economy from 2018 to 2019) and subsequent projections from 2019 onwards for sectoral productivity growth rates by sector and country. Sectoral output growth from 2019 onwards is driven by labour force growth and labour productivity growth. The model is solved from 2019, adjusting various constants in the model so that the model solution for 2019 replicates the database for 2019 (the latest data available at the time of this project).

For the labour force, G-Cubed uses the working-age population projections (medium variant) from the UN Population Prospects 2019 to calculate the economy-wide labour growth rates for each region; these population data align broadly with the IPCC Shared Socioeconomic Pathway 2. For a more detailed description on sectoral productivity growth, see 3.3.4 above.

In addition, G-Cubed assumes that autonomous energy efficiency in every sector increases at a constant rate of 1 per cent every year for all economies except China and India. In the case of these two countries, there is an additional rate of 2 per cent (3 per cent in total), assuming the two largest developing economies gain energy efficiency faster due to technological catch-up.

The baseline scenario abstracts from the 2020 pandemic-related fall in output and emissions, assuming that the subsequent rebound brings output and emissions levels in 2021 close to their 2019 level—the latest year for which the model has been calibrated. The baseline assumes (somewhat above) trend increases in energy efficiency in line with this. While this assumption on energy efficiency simplifies, it is expected to be of minor significance for the results, especially in the medium and long run. For example, Black and Parry (2020) find that the expected emission reductions for meeting temperature stabilisation goals are unchanged by the current economic crisis. Nonetheless, the Covid-19 turmoil could lead to long-term behavioural changes that would raise or lower emissions (such as reduced use of public transportation and greater reliance on individual vehicles or greater use of digital communication, leading to reduced commuting and less travel).

Figure 39 (see Annex 3) shows the growth rates on real GDP for all regions in the baseline. These are consistent with the economic growth rates in the NGFS IAMs.

The baseline projects global carbon emissions to continue rising at an average annual pace of 1.7 per cent and reach 57.5 gigatons by 2050 (Figure 40, see Annex 3). Within G-Cubed, Improvements in energy efficiency and some penetration of renewables, reflecting an implicit assumption of the continuation of current policies and some autonomous increases (for example, reflecting consumer preferences), cannot offset the forces of population and economic growth driving emissions. Economic growth projections over the next 30 years determine the expected growth of future emissions, and therefore the scale of effort needed to keep temperature increases to 1.5–2°C. Global growth progressively declines from 3.7 per cent in 2021 to 2.1 per cent in 2050, reflecting a tapering off of growth in emerging market economies as they catch up toward the income levels of advanced economies. Whereas advanced economies have historically contributed the majority of emissions, China and India, as large and fast-growing emerging market economies, are significant emitters and are expected to account for growing shares of carbon emissions. However, the per capita emissions for India remain relatively small compared with advanced economies.

While projections are inherently uncertain, the baseline considered here is broadly consistent with those from the IPCC (IPCC 2014, 2018a), most of which indicate that, under unchanged policies, carbon emissions will continue growing strongly.

Notably, the emissions results from G-Cubed are materially higher than the emission profiles generated by the IAMs, and this difference is driven by assumptions relating to the cost of renewable energy technologies. Where G-Cubed extrapolates the improvements in energy efficiency and the growth in renewable energy technologies observed today (and historically), the decisive driving force for technologies in the NGFS IAMs is economic competition. The representation of economic competition in the IAMs leads to the rapidly decreasing price of renewables, and their increased share of future capacity additions.

4.2 Overview of results from the model runs

When simulating the NGFS scenarios within G-Cubed, the implications of chronic physical risks (on sector and labour productivity) and transition risks (arising from carbon pricing) are calculated. Formulating the economic shocks due to chronic physical risks follows the approach in Fernando et al. (2021) and is detailed in Annex 2. When formulating transition risks, different carbon prices in each country and region are solved to achieve a particular emissions outcome by 2050. Following Jaumotte et al. (2021), this is implemented by calculating a Hotelling carbon price path with an initial jump in carbon prices in the year of the policy announcement and then increasing this price by 7% per year in all countries and regions. The rate of change of carbon prices is constrained to be the same in all countries and regions, but the initial price increase will differ across countries and scenarios.

Three NGFS scenarios are explored: Current Policies (CP), Net Zero 2050 Orderly Transition (NZ2050), and Delayed Transition (DT). The emission projections for CP are first obtained after imposing the economic shocks due to chronic physical risks. Thereafter, the Hotelling carbon price for each country/region is obtained so that each region matches the GCAM emission projections for 2050 under CP.

NZ2050 is then explored, in which countries begin implementing climate policies in 2021 and achieve net zero emissions by 2050. As G-Cubed only incorporates carbon dioxide emissions from burning fossil fuels, the approach in Jaumotte et al. (2021) is followed, and it is assumed that emissions reductions of other gases and carbon outside the energy system and technologies for sequestering emissions within the energy system (such as CCS) will achieve 20% of the reduction towards net-zero by 2050. The remaining decrease of 80% is assumed to be from burning fossil fuels.

Countries are not expected to implement policies in DT scenario prior to 2030. In 2030, policies are announced ‘surprisingly’ and aim to reduce emissions in 2050 by the same amount as in NZ2050. The emissions target for DT in 2050 is again based on the results of the GCAM model. Still, cumulative emissions between 2021 and 2050 differ under the NZ2050 and DT scenarios because of the delay in emission reductions under DT.

The NGFS scenarios are also replicated with regards to differing fiscal policy responses in the NZ2050 and DT scenarios. Under NZ2050, 50% of the revenue from the carbon tax in each country is invested in government infrastructure spending, and 50% is used to reduce the budget deficit. In the DT scenario, all revenue is rebated as a lump sum to households. Different fiscal rules make a direct comparison across the two scenarios more complicated but comparable with the scenario storyline already appearing in the NGFS scenarios (cf. Section 3.3.3).

In comparing key differences across countries for a given variable, results are presented for GDP, investment, trade balance and the real effective exchange rate in Tables 2 through 4. A snapshot of real GDP is shown at two points in time (2030 and 2050) for the three scenarios relative to the baseline. Results for each country/region for the various variables are shown in Annex 6.

The results for the level of real GDP expressed as a per cent deviation from the baseline is contained in Table 2. The results for the CP scenarios imply that the growth rates of real GDP shown are not much affected by adjusting the carbon taxes to replicate the carbon emissions under the CP scenario from the IAMs. For all countries, DT has worse GDP outcomes by 2050 than NZ2050 and CP. In contrast, in 2030, NZ2050 has lower GDP than DT because policies have already been in place for nine years under the NZ2050 policies. As shown in the dynamic results in Appendix A, there is a cross over in GDP losses around 2035 for most countries. The most significant GDP losses are experienced by the countries with large endowments of fossil fuels, particularly Russia and the OPEC countries. All fossil fuels are traded in G-Cubed, and for some regions, there are large income transfers from importing countries to countries that export coal, oil, gas and refined petroleum (these are explicitly modelled in G-Cubed).

Table 2: Real GDP (% Deviation from Baseline)

Model Region	Current Policy		Delayed Transition		Orderly Transition	
	2030	2050	2030	2050	2030	2050
United States	-0.29	-0.67	0.20	-1.87	-0.72	-1.60
Japan	-0.92	-2.21	0.92	-3.32	-1.40	-2.75
Australia	-0.48	-0.60	-0.49	-3.19	-1.97	-2.97
Europe	-0.92	-1.24	0.02	-2.69	-1.54	-2.18
ROECD	-0.90	-2.29	-0.44	-6.01	-2.36	-5.38
China	-1.28	-2.16	-1.33	-4.19	-2.25	-3.89
India	-1.62	-0.93	-1.01	-5.77	-4.38	-5.55
ROW	-2.08	-2.37	-0.65	-8.96	-6.67	-8.50
Russia	-1.03	-2.48	-0.73	-15.66	-6.98	-15.37
OPC	-1.84	-2.76	-0.24	-11.54	-5.62	-11.29

Table 2b: Real GDP in the REMIND model (% Deviation from Current Policies as Baseline)

Model Region	Current Policy		Delayed Transition		Orderly Transition	
	2030	2050	2030	2050	2030	2050
World	–	–	0.00	-5.13	-2.20	-4.55

Table 3 contains the equivalent results for real private investment in each country and region for each scenario in 2030 and 2050. Under the assumptions in the scenarios, the fall in investment in the fossil fuel-intensive sectors is significant compared to the increase in investment in the renewables sectors. Thus, total investment falls in all economies in the short and long run. Note that the decline in private investment is front-loaded because forward-looking firms know the future carbon prices and cut investment immediately in fossil fuel-intensive sectors. The fall in private investment reduces aggregate demand in each economy which lowers economic activity and private investment in other sectors. The climate policies also lead to a re-evaluation of the value of assets in fossil fuel-intensive industries. The decline in asset valuations reduces the private financial wealth of the shareholders of these firms, however, the overall impact on consumption is offset by lower real interest rates, which increases the value of human wealth.

Table 3: Investment (% Deviation from Baseline)

Model Region	Current Policy		Delayed Transition		Orderly Transition	
	2030	2050	2030	2050	2030	2050
United States	-1.94	-3.01	-0.43	-7.84	-5.95	-7.64
Japan	-4.84	-7.89	3.93	-8.75	-9.14	-8.11
Australia	-2.58	-2.02	-10.52	-8.84	-10.80	-8.80
Europe	-3.53	-3.58	-4.23	-6.92	-7.34	-6.41
ROECD	-5.44	-8.86	-13.65	-23.86	-15.40	-22.41
China	-2.59	-3.65	-6.40	-6.31	-5.00	-6.05
India	-2.15	-0.99	-8.50	-9.59	-8.80	-9.24
ROW	-5.66	-3.96	-14.73	-17.45	-22.78	-17.52
Russia	-6.65	-9.76	-27.51	-53.77	-35.76	-56.62
OPC	-4.54	-4.54	-13.27	-23.32	-19.01	-23.00

The changes in trade flows are shown in Table 4. The current account in G-Cubed is the difference between national savings and investment. The trade balance is the current account adjusted by net factor payments. If investment falls by more than national savings, the current account will move into surplus. The mechanism by which this happens is that financial capital will flow from sectors with declining rates of return into other sectors and other countries where the rate of return to capital are less impacted. As capital flows overseas, the real exchange rate will depreciate, making imports more expensive and exports less expensive. This change in relative prices will improve the current account and the trade balance. Thus countries that lose capital for a given level of national savings will experience an improvement in the trade balance. Countries that receive foreign investment will experience a deterioration in the trade balance. This pattern is clear from Table 4: financial capital flows into the US, Japan and Europe, and disproportionately flows out of the fossil fuel-intensive economies.

Table 4: Trade Balance (% GDP Deviation from Baseline)

Model Region	Current Policy		Delayed Transition		Orderly Transition	
	2030	2050	2030	2050	2030	2050
United States	-0.06	0.14	-1.65	-0.12	-0.50	0.02
Japan	-0.22	0.18	-4.23	-0.88	-1.39	-0.47
Australia	0.23	-0.09	2.66	-0.54	0.66	-0.64
Europe	-0.06	-0.08	-1.17	-0.37	-0.47	-0.20
ROECD	0.41	0.45	2.61	1.20	0.90	0.87
China	0.32	0.27	1.30	0.31	0.35	0.20
India	-0.11	-0.04	2.48	1.38	1.29	1.08
ROW	-0.03	-0.20	1.59	0.16	0.74	0.02
Russia	0.18	0.08	2.99	1.07	1.40	0.82
OPC	0.18	0.09	3.31	1.71	1.67	1.49

The adjustment in real exchange rates that accommodate these financial flows is shown in Table 10 (see Annex 5). Countries with financial capital outflows experience a real depreciation (negative) of the real exchange rate, and countries receiving financial capital experience a real appreciation.

4.3 Comparison with the NGFS IAMs

This section explicitly compares and contrasts the results of the G-Cubed model runs with Phase II of the NGFS scenarios. The most significant difference in the outcomes from the G-Cubed model and the IAMs is that the carbon prices required in the G-Cubed model to achieve a comparable quantity of emissions reductions under each scenario, are much lower than in the NGFS scenarios. In NZ2050, for example, the G-Cubed model achieves reductions at an average price of $US100 per ton while the NGFS IAMs have prices between $US600 and $US800 per ton. There is also a more substantial front-loaded fall in GDP globally and across countries in the G-Cubed model compared to the IAMs. These two outcomes are interrelated.

First, the carbon price in the G-Cubed model changes the behaviour of all economic actors in all sectors in all countries. Specifically, the rise in the price of carbon causes substitution in the energy sectors away from carbon-intensive energy inputs, and substitution in all production processes across the entire economy. Substitution is the largest away from carbon primary energy inputs and away from carbon-intensive goods and services because of the increase in the relative price of these goods and services. There is substitution away from fossil fuels in energy use throughout the economy in production and consumption decisions.

Investment in fossil fuel energy sectors and fossil fuel-intensive goods falls substantially because firms are forward-looking and understand that capital stock in carbon-intensive industries is less viable. This fall in the expected return of additional investment in these sectors causes a collapse in investment in these sectors. There is an expansion in investment in non-fossil fuel energy inputs. Still, the investment growth in the initially small renewables sectors is less than the contraction of investment in the fossil fuel and fossil-fuel intensive sectors because of quadratic adjustment costs. As shown in Jaumotte et al. (2021), the inability of renewable energy sectors to expand quickly can be offset by substantial government infrastructure investment to provide productivity improvement to increase the demand for renewable energy. Thus aggregate investment falls, and it is front-loaded because of anticipation of future carbon prices.

Investment goods are produced mainly by the durable manufacturing sectors, so the linkages from the decline in the demand for investment goods further reduce investment in durable goods. Given the co-existence of forward-looking firms and rule of thumb firms, a Keynesian Accelerator impact (McKibbin and Vines, 2000) reduces investment across the global economy. In addition to the decline in global demand due to the investment slump, there is a decline in the value of existing assets in fossil fuel extraction and energy generation sectors and fossil fuel-intensive manufacturing industries.

The difference in GDP outcomes across the models is also due to how the models are structured. G-Cubed takes a top-down macroeconomic approach to the modelling of the energy sector, while the IAMs take a bottom-up engineering approach. With regards to the economy, G-Cubed disaggregates each economy into multiple sectors based on input-output tables and has new Keynesian features with many frictions. In contrast, the macroeconomic module in both REMIND-MAgPIE and MESSAGEix-GLOBIOM follow a less-detailed Ramsey-type model of the aggregate economy, and the GDP loss between two scenarios can be calculated by subtracting the GDP in one scenario from the other.[19]

It is also worth noting that there is a difference in replicating the physical risks in the models. In G-Cubed the economic shocks to sector and labour productivity are applied at the sector level for all sectors in all regions for each scenario. In comparison, the IAMs do not explicitly incorporate physical risks and NiGEM applies physical damages post-hoc (i.e., without feedback to the transition pathway)

[19] As GCAM does not employ an energy-GDP feedback mechanism, GDP in the policy scenarios is replaced with a modified GDP that uses the scenario carbon price and the relationship between the carbon price and GDP change from the MESSAGEix-GLOBIOM model to create a GDP path consistent with the MESSAGEix-GLOBIOM model response to emissions mitigation.

at the aggregate country level. However, as the global temperature differences in the transition scenarios is moderate, this difference in approach is of minor consequence relative to the differences discussed above.

Thus, the explicit differences in the design, calibration and overall conceptual mechanisms of these models drives measurable divergences in the results of the model runs.

4.3.1 Current policies scenario (CP)

Figure 4 contains results for the level of GDP over time in the G-Cubed model compared to the three IAMS. Although the level results show a gradual increase in the gap between the level of GDP in the models, the difference in growth rates between G-Cubed and the IAMs is relatively small.

Figure 5 contains the results for CO_2 emissions in CP. These emissions outcomes were generated by adjusting carbon taxes in the model to move the emissions projections in the G-Cubed baseline closer to the IAM emissions projections for the CP. As shown in Figure 5, the G-Cubed emissions in CP are the average of the emissions in the IAMs.

Primary energy follows a similar path in G-Cubed relative to the IAMs, starting at a higher initial level and staying above the IAMs to 2050 (Figure 6). More electricity is generated in the G-Cubed model than in the IAMs, although G-Cubed is similar to GCAM (Figure 7). Looking at individual energy sources, it can be observed that electricity from coal is similar between G-Cubed and the IAMs (Figure 8), while G-Cubed has substantially less gas in electricity generation (Figure 9). There is more electricity from nuclear (Figure 10) and hydro (Figure 11) in G-Cubed than in the IAMs, but the difference is small. Electricity from solar (Figure 12) in G-Cubed is within the range of the IAMs. Electricity from wind (Figure 13) and biomass and geothermal (Figure 14) are higher in G-Cubed.

Figure 4: GDP

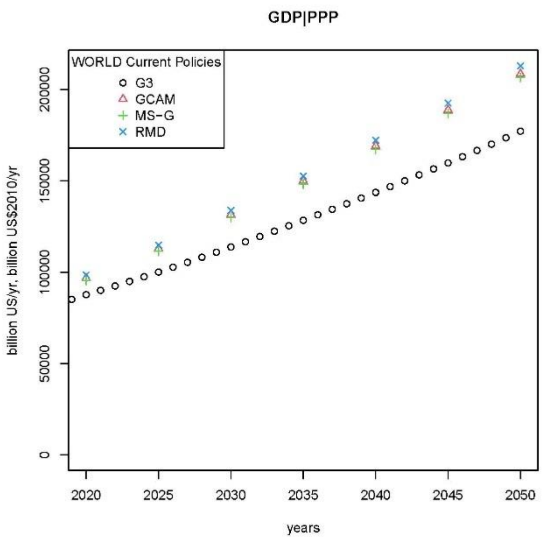


Figure 5: CO2 Emissions

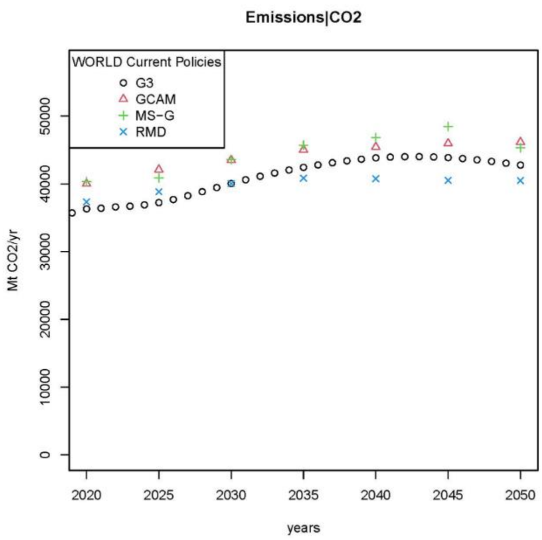


Figure 6: Primary Energy

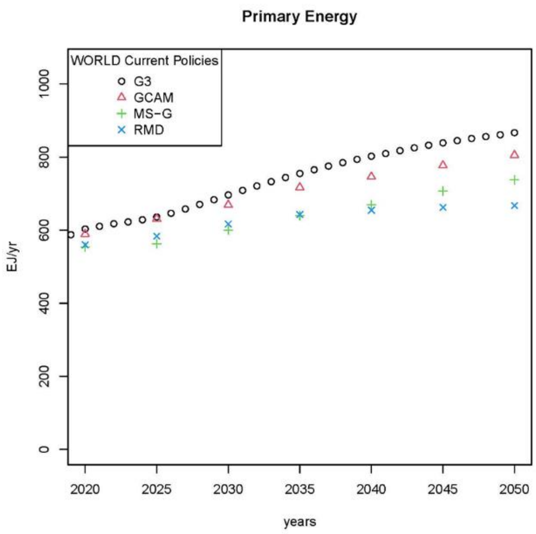


Figure 7: Electricity

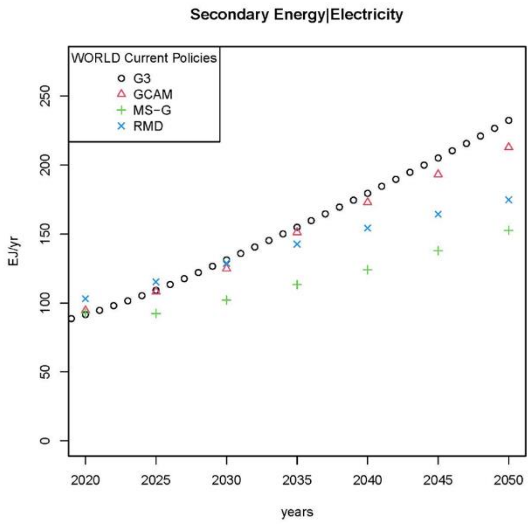


Figure 8: Electricity from Coal

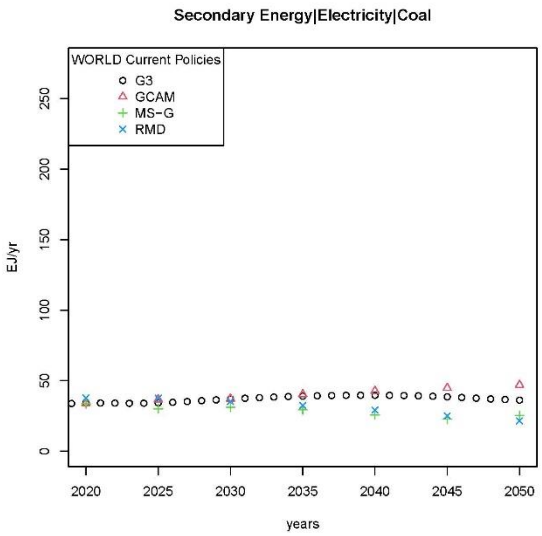


Figure 9: Electricity from Gas

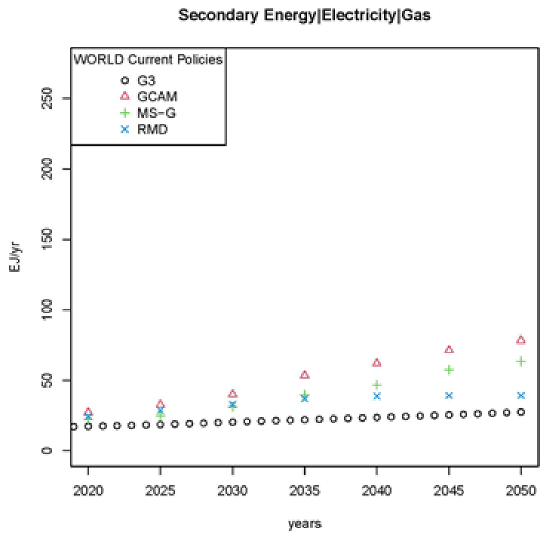


Figure 10: Electricity from Nuclear

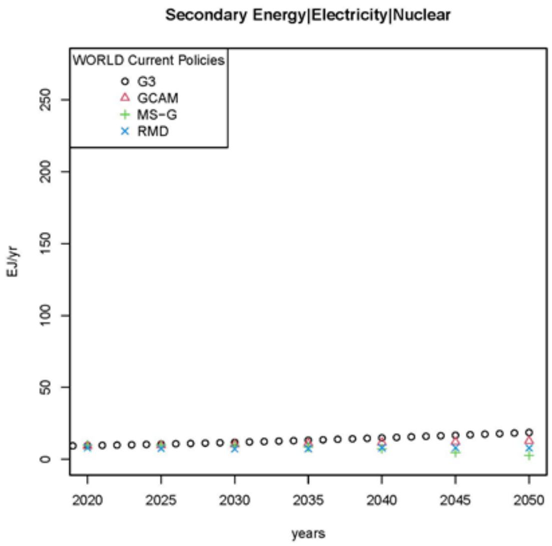


Figure 11: Electricity from Hydro

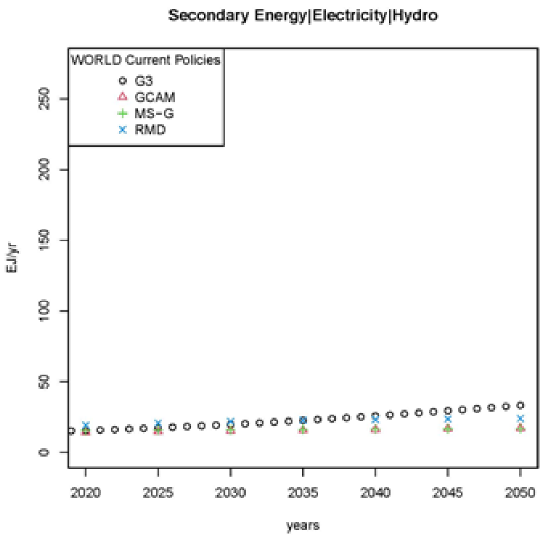


Figure 12: Electricity from Solar

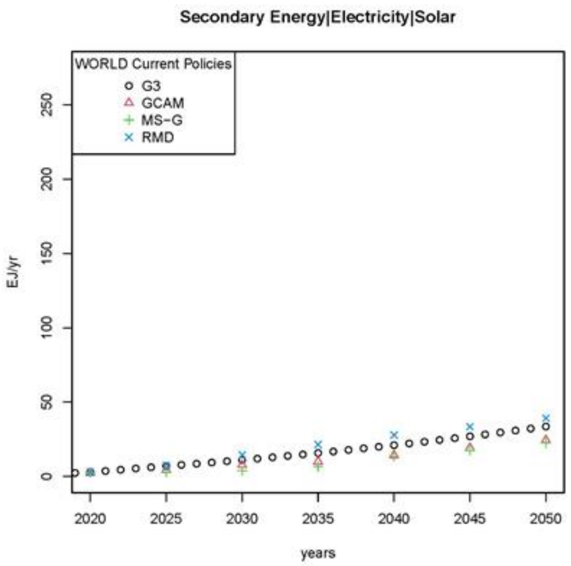


Figure 13: Electricity from Wind

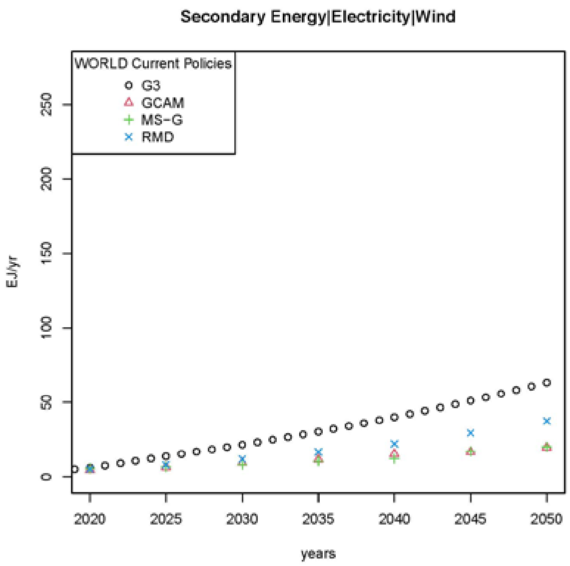
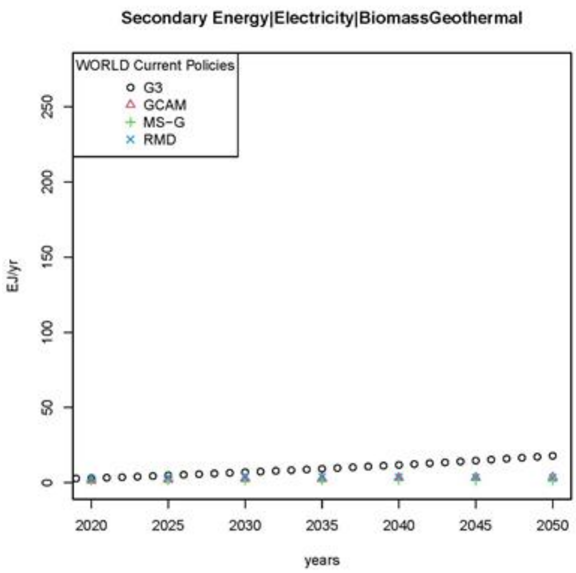


Figure 14: Electricity from Biomass, Geothermal



4.3.2 Orderly transition: Net Zero 2050 scenario (NZ2050)

Starting from CP, we calculate carbon taxes in each country to achieve net-zero emissions in each economy by 2050. As discussed above, this implies an 80% reduction in CO_2 emissions from the energy system.

The levels of GDP over time within NZ2050 are shown in Figure 15. The percentage falls in global GDP are larger in G-Cubed (see Table 2) than in the NGFS IAMs. Although the visual difference appears small when comparing GDP levels in Figure 15 to those for CP (Figure 4), Table 2b helps to clarify the delta by indicating the deviation from CP (the baseline for the IAMs) in the REMIND model for NZ2050 and DT. The change in GDP in the G-Cubed model is calculated by adding up the change in value-added for all sectors in each economy. Adding up GDP from sectoral outcomes (including the temporary loss in employment in some sectors that reduce GDP) is very different from the IAMs where aggregate GDP is calculated using marginal abatement costs assumptions and applying these to the IAM baselines. The G-Cubed model has a full accounting of economic activities at the sectoral level with different marginal abatement costs in each sector. Intermediate inputs such as labour, materials and energy can move across the sectors in each economy. However, unemployment can emerge if the total labour supply in an economy in a year exceeds the sum of labour demand from all sectors. The physical capital stock is sector-specific and can only be moved through investment and divestment decisions over time. This rigidity of physical capital at the sectoral level, modelled through quadratic adjustment costs, is a crucial reason for the fall in GDP in G-Cubed in response to the significant restructuring of the global economy. If physical capital could move freely across sectors and countries, the GDP losses would be substantially reduced.

Figure 16 contains results for the emissions of CO_2 from the energy system. It takes longer to reduce emissions for two reasons. Firstly, the way we implement the carbon tax is as a Hotelling tax that increases at 7% per year from 2021 to 2050. The initial value of the tax is calculated in 2021 to hit an emissions target broadly equivalent to the NGFS IAMs in 2050. Cumulative emissions are higher in G-Cubed by 2050 even though the level of emissions achieves the target. Secondly, it takes time to restructure the global economy, which implies changes in private investment in the energy sectors and across the economy in response to the carbon policy. The G-Cubed model suggests that it is costly to restructure the global economy over 30 years when only using carbon prices to achieve the adjustment. Using the same model under a different set of policy assumptions, Jaumotte et al. (2021) show that a combination of public infrastructure in targeted sectors can significantly reduce GDP losses and increase the penetration of renewables in the energy system.

An essential difference between G-Cubed and the NGFS IAMs is the role of electricity generation in NZ2050. The IAMs increase electricity generation driven by a significant increase in solar and a moderate rise in wind generation. On the other hand, G-Cubed shows a slight fall in electricity generation in NZ2050 relative to CP because the fall in fossil fuel-generated electricity is larger than the increase in non-fossil fuel generation of electricity. The absence of an overall rise in electricity generation is partly driven by the more significant fall in GDP under NZ25050 in G-Cubed relative to the IAMs. Lower GDP reduces the demand for energy, including electricity. The difficulty of switching generation from fossil fuels to renewables within electricity generation also drives the lack of overall electricity generation response. It is difficult to scale up generation via renewables within G-Cubed while simultaneously reducing fossil fuel generation because of the adjustment costs in ramping up renewable energy in the electricity sector and stranded assets in the fossil fuel generation sector. Additional policy responses such as government direction of technological innovation in electricity use across the economy (particularly in transportation) or significant infrastructure investment to encourage renewables could reverse this dynamic. Still, in G-Cubed, the carbon tax-driven relative price adjustment alone does not generate the response of technology that is apparent in the NGFS IAMs.

It is clear from Figure 17 that despite the more significant GDP losses during the transition, the adjustment is achieved at much lower carbon prices than in the IAMs. Figure 17 shows the average world price of carbon is around $US100 per ton of CO2 by 2050 in G-Cubed compared to between $US500-$US700 per ton in the IAMs. The distribution across countries in Figure 43 of Annex 4 is between $US33 and $US140 per ton CO_2. The efficacy of lower carbon prices in G-Cubed is explored more completely in 4.3 above (i.e., lower carbon prices are sufficient to slow down overall economic activity and reduce carbon emissions as a result).

Figure 15: GDP

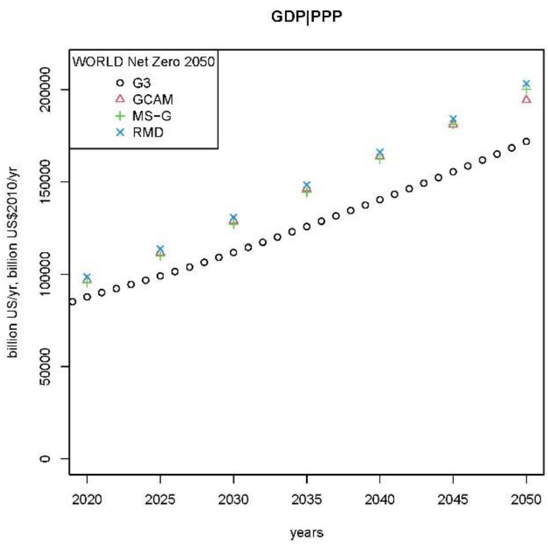


Figure 16: CO2 Emissions

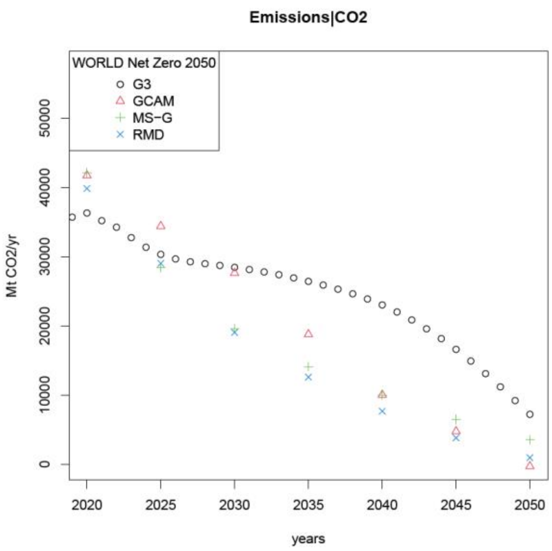


Figure 17: Carbon Prices

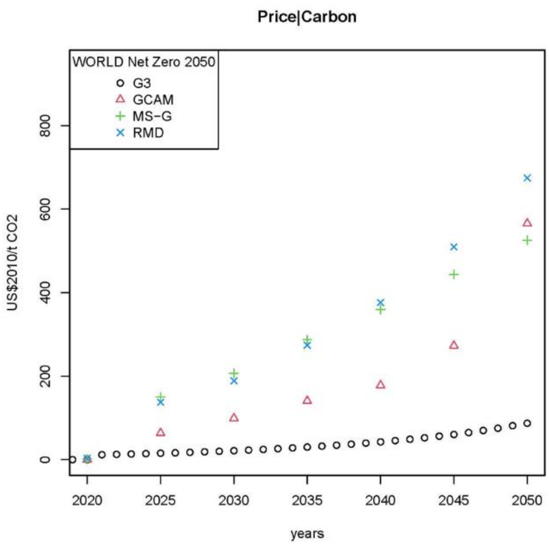


Figure 18: Primary Energy

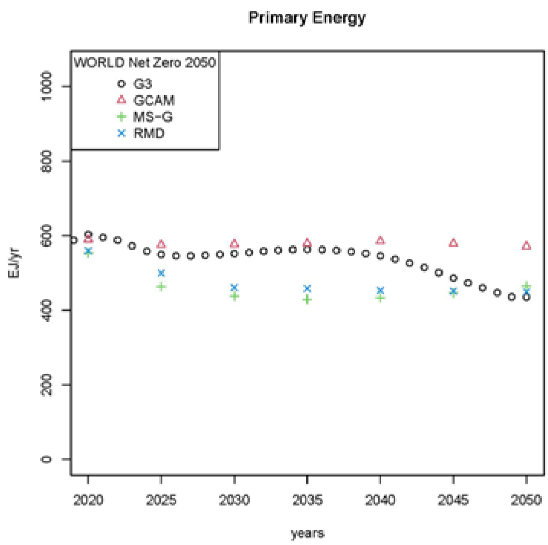


Figure 19: Electricity

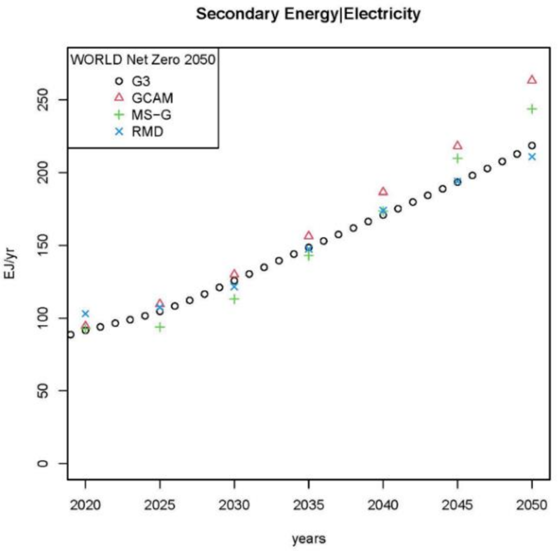


Figure 20: Electricity from Coal

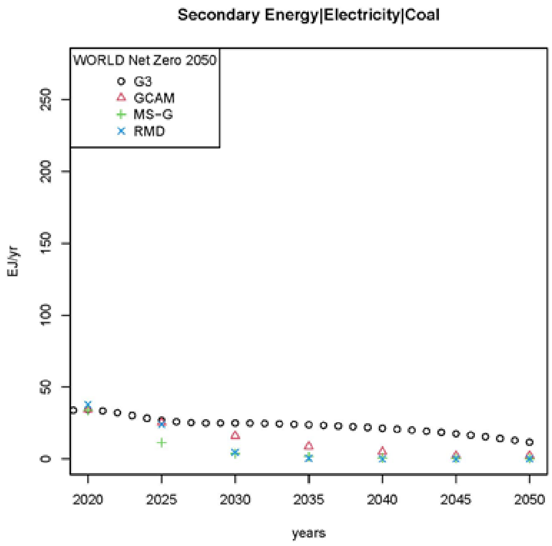


Figure 21 Electricity from gas

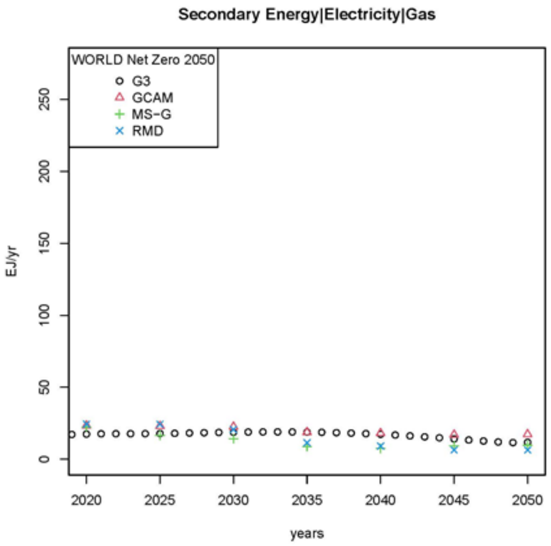


Figure 22: Electricity from Nuclear

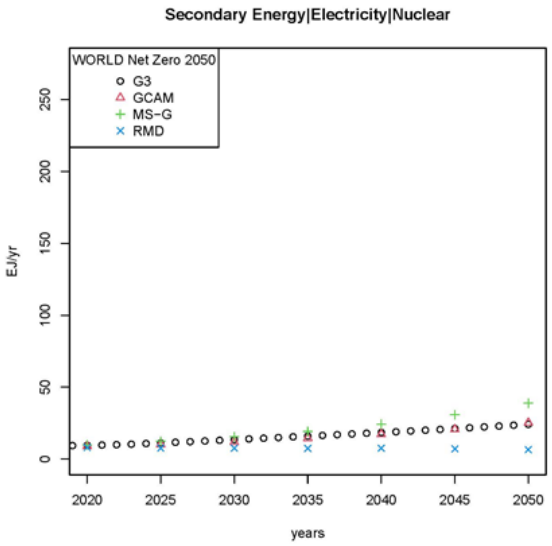


Figure 23: Electricity from Hydro

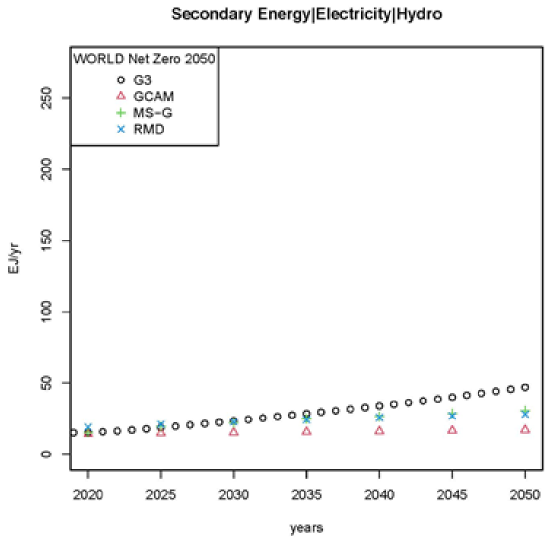


Figure 24: Electricity from Solar

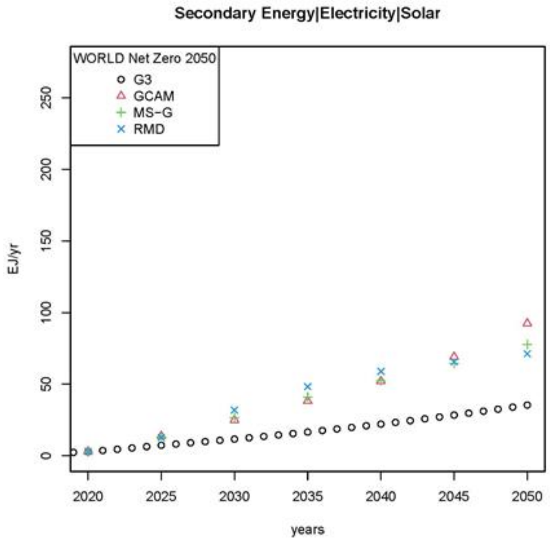


Figure 25: Electricity from Wind

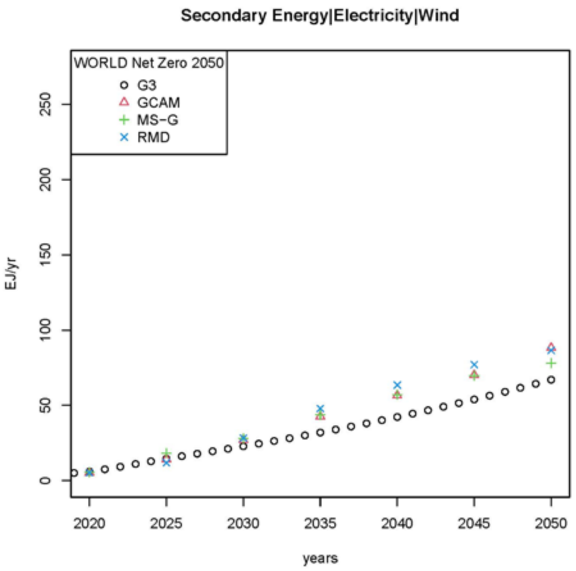
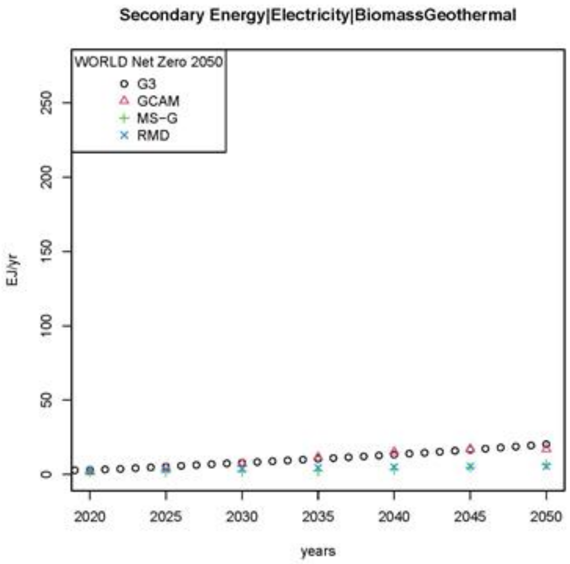


Figure 26: Electricity from Biomass, Geothermal



4.3.3 Disorderly transition: Delayed transition scenario (DT)

The DT scenario is considered in figures 27-38. The GDP path is the same as CP until 2030. In 2030 the carbon taxes required to hit the target for emissions in 2050 (assumed to be the same at NZ2050) are uniformly higher than the carbon taxes in G-Cubed from 2021. However, the carbon taxes (figure 29) are significantly lower than the prices from the IAMs. The path for primary energy in G-Cubed is similar to the IAMs.

Figure 27: GDP

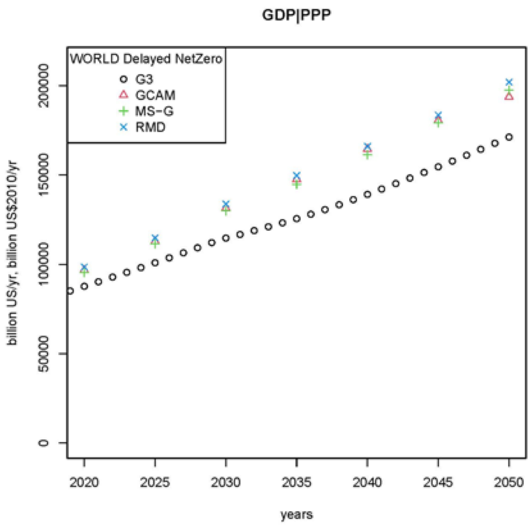


Figure 28: CO2 Emissions

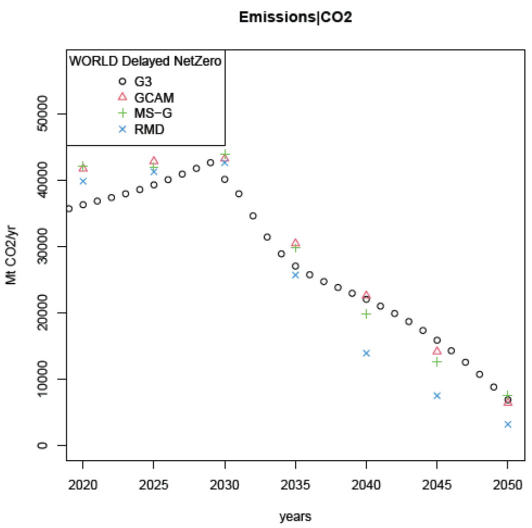


Figure 29: Carbon Prices

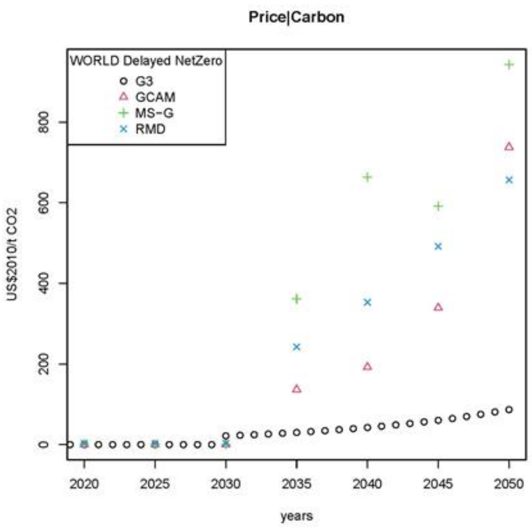


Figure 30: Primary Energy

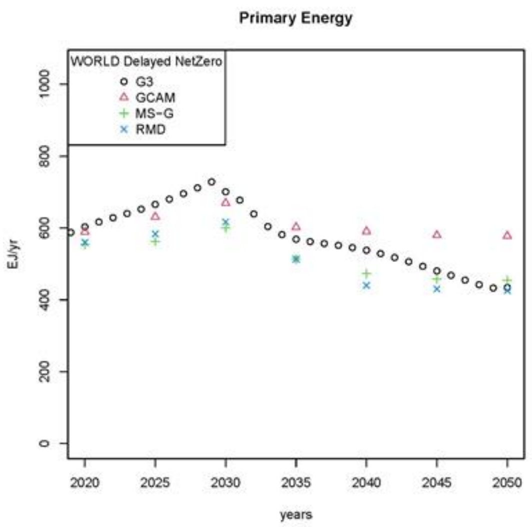


Figure 31: Electricity

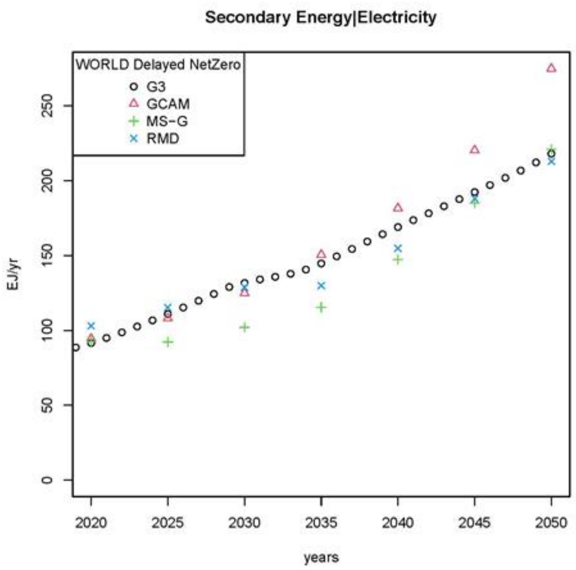


Figure 32: Electricity from Coal

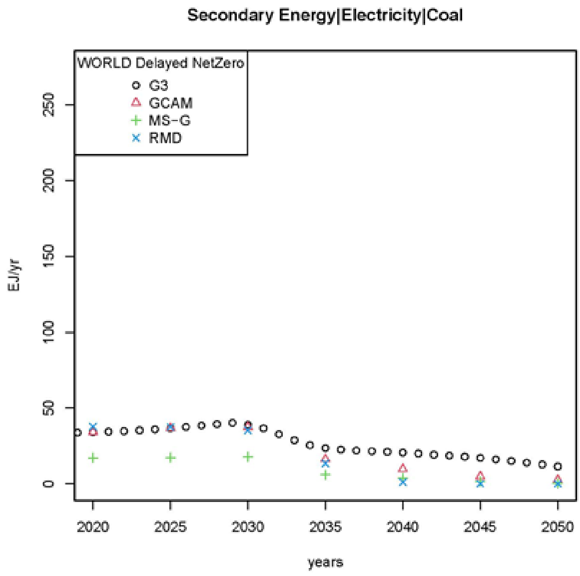


Figure 33: Electricity from gas

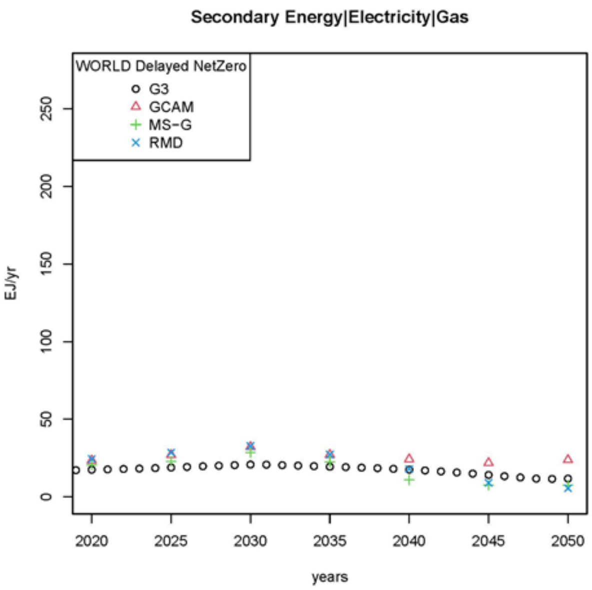


Figure 34: Electricity from nuclear

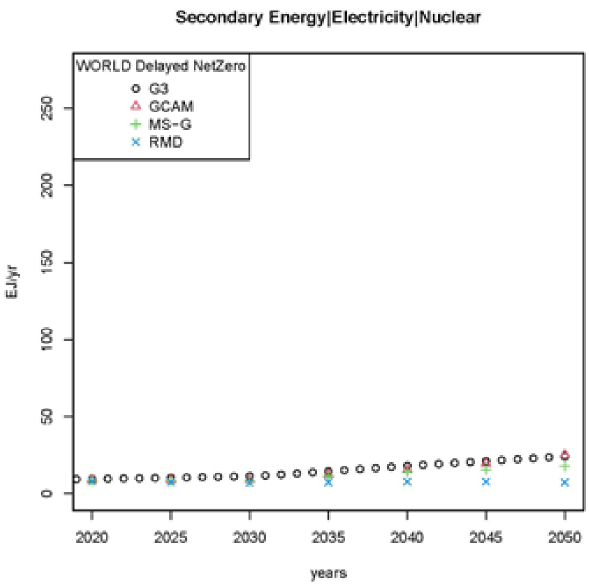


Figure 35: Electricity from Hydro

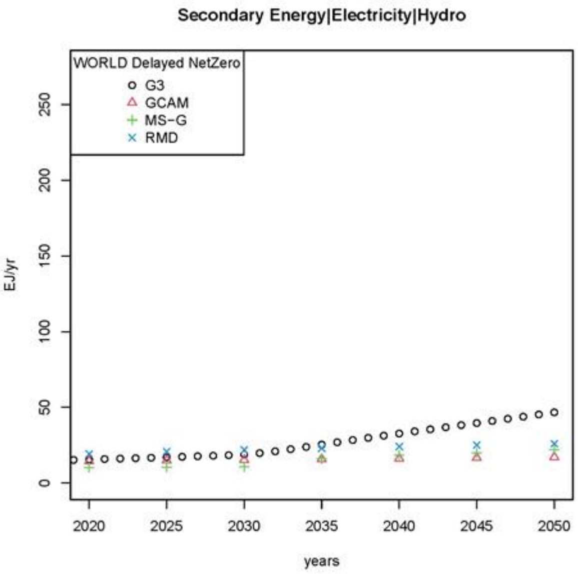


Figure 36: Electricity from Solar

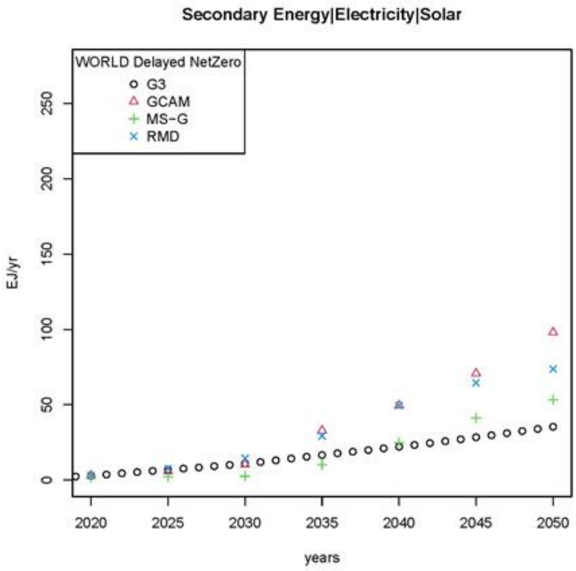


Figure 37: Electricity from Wind

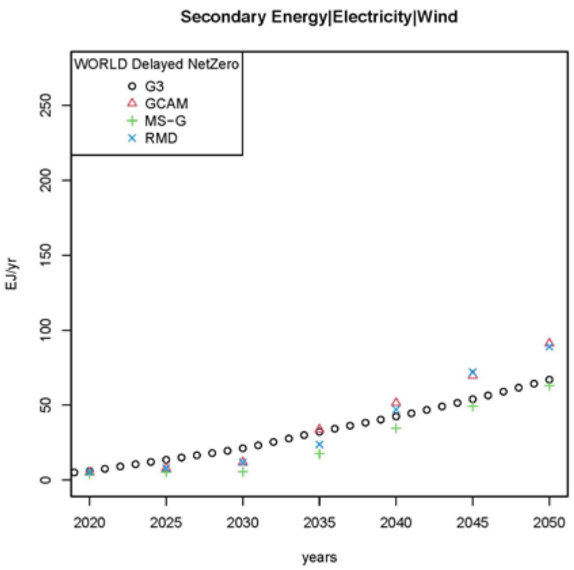
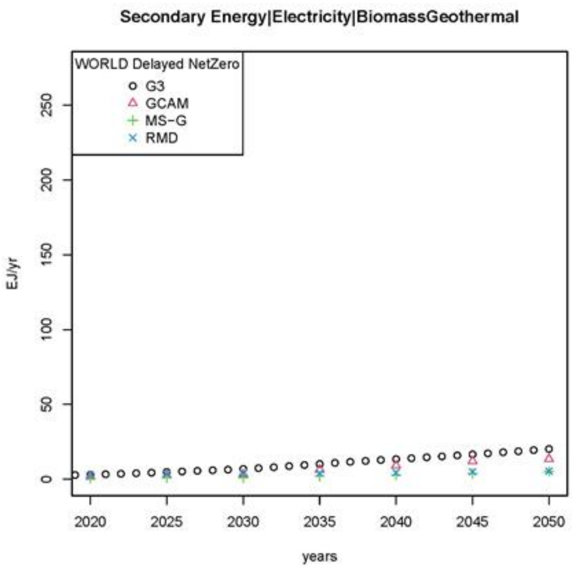


Figure 38: Electricity from Biomass, Geothermal



4.4 Commentary on adjustments made

In attempting to generate results more similar to the NGFS IAMs, several modifications were made to the G-Cubed model arising from fruitful academic dialogue between the teams of modellers involved in this project. In brief, two fundamental changes that will remain a part of the G-Cubed model were made:

1. **Carbon pricing was changed to be levied on refined petroleum rather than oil extraction.** Changing the source of emissions changes the carbon accounting since emissions are counted

when petroleum is burnt (mostly in transportation) rather than when petroleum is refined. Since there is a large trade in refined petroleum, this better captures transportation sector emissions. This modification had the effect of roughly doubling the carbon price in advanced economies (especially Japan and Europe) since emissions from oil were counted within the national borders of petroleum importers rather than in the countries extracting oil. It reduced the price in emerging economies so that the average global carbon price was roughly unchanged.

2. **The elasticities of substitution in electricity generation were lowered to reduce the substitutability of primary energy inputs in the KLEM production function.** The original calibration of the electricity sector (this part of the model was not estimated initially) allowed for a significant increase in electricity generation from non-primary energy inputs inconsistent with the IAMs. This approach is a more plausible way to model the technologies in the Electricity sector, but the changes did not significantly change the carbon prices or GDP outcomes.

Separately, many tests were implemented to attempt to change the estimated elasticities of substitution in different sectors and international trade in various goods and services. Although having some impact on the model results, these changes were not sufficient to substantially increase the carbon prices at the global level nor to significantly change the GDP outcomes.

5. Conclusion and Next Steps

In collaboration with G-Cubed, the NGFS workstream on macrofinancial undertook a pilot exercise to understand whether and how the G-Cubed general equilibrium model could be integrated within the current suite of models underlying the NGFS scenarios, to increase their sectoral outputs. This exercise included the running of three of the NGFS Phase II scenarios within the G-Cubed model, and has resulted in substantial learnings for each of the model providers involved, as well as the NGFS more broadly.

These technical learnings are summarised as follows:

- G-Cubed assumes a lower level of substitutability between energy-generating technologies, and explicitly models the adjustment costs of rapidly expanding small scale technologies for widespread use, limiting the potential for largescale renewable energy deployment in the future and leading to a slowdown in aggregate economic activity in the long-run. This represents an alternative approach to that taken by the IAMs, which respond to climate policies to limit CO2 emissions by increasing the efficiency of energy generation via the substantial deployment of solar and wind technologies.
- It may be possible to replicate the more substantial deployment of renewable energy technologies in the IAMs with the G-Cubed model, but this is dependent on other aspects of the model calibration being altered first. Within G-Cubed, the inability of renewable energy sectors to expand quickly (due to adjustment costs) can be offset by substantial government infrastructure investment to provide productivity improvement and increase the demand for renewable energy. This adjustment to government infrastructure investment could be explored in future iterations of a similar exercise involving the NGFS scenarios.
- While the NGFS IAMs tend to generate higher carbon prices throughout the low-carbon transition, G-Cubed achieves a net-zero economy with materially lower carbon prices. The low carbon price dynamic in G-Cubed is driven by greater substitutability across high-carbon to low-carbon sectors of the economy in response to a given emissions target.
- Notably, this work has focused on the aggregate GDP implications of the assumptions taken by this set of models under the given scenarios. Further work could explore these impacts using more direct measures of social welfare, given the close relationship between GDP and welfare outcomes.

The divergences in outcomes for the three NGFS scenarios across G-Cubed and the IAMs is not merely due to the different structures of the models, but the underlying model philosophies that drive assumptions about the future of the energy system and macroeconomy. As is reflected in the results set out in this paper, there are clear differences in approach taken by the NGFS IAMs as compared with G-Cubed, and these differences occur at the deeper theoretical level rather than emerging simply as a result of model structure. This reflection has generated an exciting set of learnings, shedding further light on the importance of comparing different approaches to a consistent set of climate scenarios. Future exercises could continue to explore the extent of the alignment between the G-Cubed model and the NGFS IAMs.

Following the completion of this project, there are several potential next steps concerning the future of this work:

- Further work to explore the potential inclusion of G-Cubed within the scenarios package could take a number of forms, focusing on the sectoral outputs or alignment more broadly.

- As has been reflected in the results of the pilot project, the integration of models of differing conceptual approach within a single scenario package remains a complicated process. The highly complex nature of this exploratory work may present challenges to the full integration of the G-Cubed model, or lower the potential for coherence among these models in a future package. These sensitivities are of course subject to the future requirements of the scenario users, and how these requirements may continue to evolve.

While the initial intention of this pilot project has been to explore the feasibility of integrating the G-Cubed model within the NGFS suite of models for the purposes of enriching their sectoral output, the outcomes and resultant learnings are clearly far broader, encompassing a variety of conclusions that contribute significantly to the future of this work and the academic literature.

Glossary of Key Terms

Acronym	Term	Definition
CCS	Carbon Capture and Storage	Innovations designed for capturing the carbon dioxide produced by human activities, transporting it and then committing it to permanent storage (often in geological formations)
CGE	Computable General Equilibrium (Model)	Computable General Equilibrium (CGE) provide a standard set of long-run economic variables (employment, interest rates, GDP and exchange rates) to reflect how the economy might respond to hypothetical policy scenarios.
GCAM	Global Change Analysis Model	GCAM is an integrated tool for exploring the dynamics of the coupled human-Earth system and the response of this system to global changes. It includes detailed energy, agriculture, land-use, water, economy and atmosphere-climate modules. https://jgcri.github.io/gcam-doc/
G-Cubed	Global General Equilibrium Growth Model	G-Cubed is a hybrid of CGE and Dynamic Stochastic General Equilibrium models http://www.msgpl.com.au/software/g_cubed.html
IAM	Integrated Assessment Model	Integrated assessment models (IAMs) integrate knowledge from two or more domains into a single framework. They are one of the main tools for undertaking integrated assessments. One class of IAM used in respect of climate change mitigation may include representations of: multiple sectors of the economy, such as energy, land use and land-use change; interactions between sectors; the economy as a whole; associated GHG emissions and sinks; and reduced representations of the climate system. This class of model is used to assess linkages between economic, social and technological development and the evolution of the climate system. Another class of IAM additionally includes representations of the costs associated with climate change impacts, but includes less detailed representations of economic systems. These can be used to assess impacts and mitigation in a cost–benefit 70 framework and have been used to estimate the social cost of carbon.
MAgPIE	Model of Agricultural Production and its	Land use system component of PIK's IAM framework REMIND-MAgPIE: https://www.pik-potsdam.de/research/projects/activities/land-use-

	Impacts on the Environment	modelling/magpie/magpie-2013-model-of-agricultural-production-and-its-impact-on-the-environment
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact	Energy system module of IIASA's IAM framework MESSAGEix-GLOBIOM, used here as short form to refer to the whole model: https://message.iiasa.ac.at/projects/global/en/latest
NiGEM	National Institute Global Econometric Model	The leading global macroeconomic model, developed and maintained by the National Institute of Economic and Social Research (NIESR): https://www.niesr.ac.uk/national-institute-global-econometric-model-nigem
REMIND	Regional Model of Investments and Development	Energy system component of PIK's IAM framework REMIND-MAgPIE: https://www.pik-potsdam.de/research/transformation-pathways/models/remind

Bibliography

- Barrell, R., Sefton, J. (1997). *Fiscal Policy and the Masstricht Solvency Criteria*. The Manchester School of Economics and Social Studies, 65(3), 259-279.
- Barro, RJ., Xavier, S. (1991). *Convergence across States and Regions*, Center Discussion Paper, No. 629, Yale University, Economic Growth Center, New Haven, CT.
- Black, S., Parry, I. (2020). *Implications of the Global Economic Crisis for Carbon Pricing: A Quantitative Assessment for Coalition Member Countries.* Informal Note for Members of the Coalition of Finance Ministers for Climate Action. IMF.
- Ens, E., Johnston, C. (2020). *Scenario Analysis and the Economic and Financial Risks from Climate Change*. Bank of Canada, Staff Discussion Paper 2020-3. Available at: https://www.bankofcanada.ca/wp-content/uploads/2020/05/sdp2020-3.pdf.
- Bosetti, V. (2021). Integrated Assessment Models for Climate Change. *Oxford Research Encyclopedia of Economics and Finance*.
- Dornbusch, R. (1976). *Expectations and Exchange Rate Dynamics*. Journal of Political Economy, 84(6), 1161–1176.
- Fernando R., Liu, W., McKibbin, W. (2021). *Global Economic Impacts of Climate Shocks, Climate Policy and Changes in Climate Risk Assessment*. Brookings Climate and Energy Economics Discussion Paper, March 31, 2021 (CAMA Working Paper 37/2021).
- Fernando, R., McKibbin, W. (2020). *The Global Macroeconomic Impacts of COVID-19: Seven Scenarios.* CAMA Working Paper 19/2020.
- Gourdel, R., Monasterolo, I., Dunz, N., Mazzocchetti A., Parisi, L. (2021). *The double materiality of climate physical and transition risks in the euro area*. Available at: https://ssrn.com/abstract=3939895.
- Hotelling, H. (1931). *The economics of exhaustible resources*, Journal of Political Economy, 39, pp. 137-75.
- Jaumotte, F., Liu, W. & McKibbin, W. J. (2021). *Mitigating Climate Change: Growth-friendly Policies to Achieve Net Zero Emissions by 2050*. Australian National University.
- Liu, W., McKibbin, W., Morris, A., Wilcoxen., P.J. (2020). *Global economic and environmental outcomes of the Paris Agreement*. Energy Economics, Vol. 90.
- Liu, W., McKibbin, W. (2021). *Global macroeconomic impacts of demographic change.* The World Economy, 45(3), 914-42.
- McKibbin, W. and Fernando, R. (2021). *The global macroeconomic impacts of COVID-19: seven scenarios.* Asian Economic Papers, 19(4), pp. 1-26.
- McKibbin W., Stoeckel, A. (2018). *Modeling a Complex World: Improving Macro Models.* Oxford Review of Economic Policy vol. 34 nos. 1-2, 2018, pp 329-347.
- McKibbin, W., Vines, D. (2000). *The need for both inter-temporal optimization and stickiness in models for policy-making.* Oxford Review of Economic Policy, 16, 4, 106-37
- Nikas A., Doukas H., Papandreou A. (2019). *A Detailed Overview and Consistent Classification of Climate-Economy Models*. In: Doukas H., Flamos A., Lieu J. (eds) Understanding Risks and Uncertainties in Energy and Climate Policy. Springer, Cham.
- Mendelsohn, R., Schlesinger, M. & Williams, L. (2000). *Comparing impacts across climate models.* Integrated Assessment 1, 37–48.

- Mercure, J.F., Pollitt, H., Edwards, N.E., Holden, P.B., Chewpreecha, U., Salas, P., Lam, A., Knobloch, F., Viñuales, J.E. (2018). *Environmental impact assessment for climate change policy with the simulation-based integrated assessment model E3ME-FTT-GENIE.* Energy Strategy Reviews, Volume 20, 195-208.
- Mercure, JF., Pollitt, H., Viñuales, J.E. et al. (2018). *Macroeconomic impact of stranded fossil fuel assets.* Nature Climate Change 8, 588–593.
- McKibbin, W., Wilcoxen, P.J. (1999). *The theoretical and empirical structure of the G-Cubed model.* Economic Modelling, 123-148.
- McKibbin, W., Wilcoxen, P.J. (2013). *A Global Approach to Energy and the Environment: The G-Cubed Model.* Handbook of Computable General Equilibrium Modelling, vol. 1, 995-1068.
- Monasterolo, I., Raberto, M. (2017) *The EIRIN Flow-of-funds Behavioural Model of Green Fiscal Policies and Green Sovereign Bonds*, Ecological Economics, 144, 228-243.
- Neumann et al. (2020) *Climate Damage Functions for Estimating the Economic Impacts of Climate Change in the United States*. Review of Environmental Economics and Policy, Vol. 14, No.1.
- Nordhaus, W.D. (1994). Managing the global commons: the economics of climate change. *MIT Press.*
- Palstev, S., Ghandi, A., Morris, J., Chen, H. (2022) *Global Electrification of Light-duty Vehicles: Impacts of Economics and Climate Policy*. Economics of Energy & Environmental Policy, Vol. 11, No. 1.
- Pietzcker, R.C., et al. (2017). *System integration of wind and solar power in integrated assessment models: A cross-model evaluation of new approaches*, Energy Economics, Volume 64, Pages 583-599.
- Roson, R. & Sartori, M. (2016) Estimation of climate change damage functions for 140 regions in the GTAP9 database. Policy Research Working Paper. Washington D. C.: World Bank Group.
- Schwanitz, V.J. (2013) *Evaluating integrated assessment models of global climate change*, Environmental Modelling & Software, Volume 50, 120-131.
- Weyant, J. (2017). Some Contributions of Integrated Assessment Models of Global Climate Change. *Review of Environmental Economics and Policy*, Vol.11-1.

Technical Annexes: Tables and Charts

ANNEX 1: Regions, sectors and variables of the G-Cubed model

Table 5: Regions in the G-Cubed Model

Region Code	Region Description
AUS	Australia
CHN	China
EUW	Europe
IND	India
JPN	Japan
OPC	Oil-Exporting developing countries
OEC	Rest of the OECD
ROW	Rest of the World
RUS	Russian Federation
USA	United States

Source: G-Cubed Model (version GGG20v164).

Table 6: The 20 sectors in the G-Cubed model

Number	Sector Name	Notes
1	Electricity delivery	Energy Sectors Other than Generation
2	Gas extraction and utilities	
3	Petroleum refining	
4	Coal mining	
5	Crude oil extraction	
6	Construction	Goods and Services
7	Other mining	
8	Agriculture and forestry	
9	Durable goods	
10	Non-durable goods	
11	Transportation	
12	Services	
13	Coal generation	Electricity Generation Sectors
14	Natural gas generation	
15	Petroleum generation	
16	Nuclear generation	
17	Wind generation	
18	Solar generation	
19	Hydroelectric generation	
20	Other generation	

Source: G-Cubed Model (version GGG20v164).

Table 7: Macro variables by country

Macro variables by country
Real and nominal GDP
Real GNP
Real private consumption – aggregate and by sector
Real private investment – aggregate and by sector
Private Employment – aggregate and by sector
Government spending on goods and services
Government spending on labour
Real Imports – aggregate and by sector by country of origin
Real Exports – aggregate and by sector
Trade balance
Current Account balance
Housing Stock (proxied by household durable capital stock)
Households stock of human capital
The stock of government debt

Table 8: Financial Variables by country

Financial Variables by country
Policy interest rate (nominal and real)
Bond rates 2, 5 ,10 year (nominal), 10 year (real)
Nominal and real effective exchange rates
Nominal and real exchange rate relative to $US
Equity prices by sector
Money Supply

Table 9: Price Variables by country or region

Price Variables by Country
Aggregate price index
Consumer price index
Consumer price inflation (actual and expected)
Produce price inflation (actual and expected)
Producer price by sector
Commodity prices where the sector is a commodity
Consumer price by sector
Energy price
Materials price
Nominal wage
Housing price (proxied by the price of household's purchases of durable goods)

ANNEX 2: Formulation of economic shocks from chronic climate risks

Chronic climate risks

There is a broad range of long-term effects of climate change and an extensive body of literature discussing these effects. However, the availability of damage functions, which map the physical impacts of climate change onto economic variables, is minimal. Roson and Sartori (2016) review the literature on the damage functions and compile six damage functions for economic modelling assessments. These chronic risks include rising sea levels, variation in crop yields, heat-induced impacts on labour productivity, changes in the occurrence of diseases, changes in tourism, and changes in household energy demand. Out of these, following Fernando et al. (2021), we focus on the first four chronic risks.

Roson and Sartori (2016) express the damage functions related to the chronic risks using climate variables' changes compared to a benchmark level. The damage functions then use the relative changes in the climate variables compared to the benchmark to derive the economic shocks. The benchmark variable primarily used in the damage functions is the average value of the climate variables from 1985 to 2005.

The damage functions we consider in this paper primarily use temperature as the climate variable, and we use the projections for temperature under the NGFS climate scenarios from the GCAM model from 2019 to 2100 to derive the temperature benchmark and the variations of the future temperature from the benchmark. Using these variations, we use the damage functions to develop various economic shocks.

From the four chronic climate risks focused on in this paper, which are rising sea levels, variation in crop yields, heat-induced effects on labour productivity, and changes in the occurrence of diseases, the first two risks affect various economic sectors' productivity while the last two risks affect labour supply.

Shocks to labour supply

Roson and Sartori (2016) present parameters to compute the heat-induced impacts on labour productivity in the three main production sectors of agriculture, manufacturing, and services. We map these parameters to the model sectors: those for agriculture to coal mining, coal extraction, construction, mining, and agriculture; those for manufacturing for electric utilities, gas utilities, petroleum refining, durable manufacturing, non-durable manufacturing, and electricity generation sectors; and those for services for transportation and other services. Depending on the mean temperature variation in each country each year compared to the benchmark temperature for that country, we calculate the heat-induced reductions in the labour productivity in the model sectors under each climate scenario.

Similar to the heat-induced impacts on the labour supply, we estimate the labour productivity changes due to the climate-induced variations in the incidence of diseases. However, in contrast to the heat-induced impacts, we assume equal levels of exposure to the diseases across a given economy and apply the shock to the whole country. The diseases considered when deriving Roson and Sartori's damage function (2016) include malaria, dengue, and diarrhoea.

Shocks to productivity

Roson and Sartori (2016) derive damage functions to demonstrate the loss of land due to rising sea levels under various temperature increments from the benchmark. We use these estimates to calculate the percentage of land lost in each country each year under the climate scenarios. We then translate the loss of land into a productivity shock using the percentage reliance of each sector in each country on land compared to other inputs.

We also use the damage function parameters estimated by Roson and Sartori (2016) to estimate the changes in crop yields for maize, rice, and wheat for temperature variations from the benchmark. We then compute the yield changes for each of the crops under the climate scenarios for each country in each year. We map the estimates for maize, rice, and wheat on eight of the fourteen agriculture sub-sectors in the GTAP 10 version. The excluded sub-sectors account for livestock, forestry, and fisheries. We assume similar impacts to rice on vegetables and fruits, sugar cane and sugar beet, and plant-based fibres. We also assume a similar impact on wheat on oilseeds and other crops. We derive the total impact on agriculture productivity from the chronic risks of climate change with these assumptions. We also calculate the productivity impacts on other production sectors due to the reliance on inputs from the agriculture sector.

ANNEX 3: Pathways for Real GDP and emissions in the G-Cubed baseline

Figure 39: Real GDP growth rates in the G-Cubed baseline

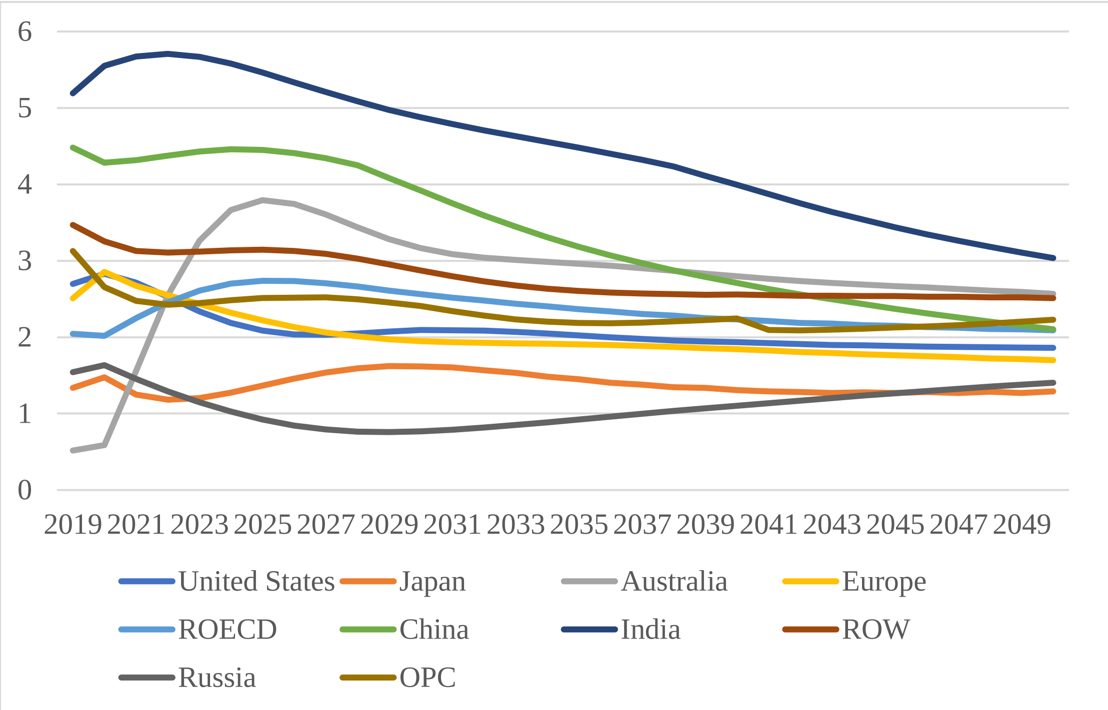
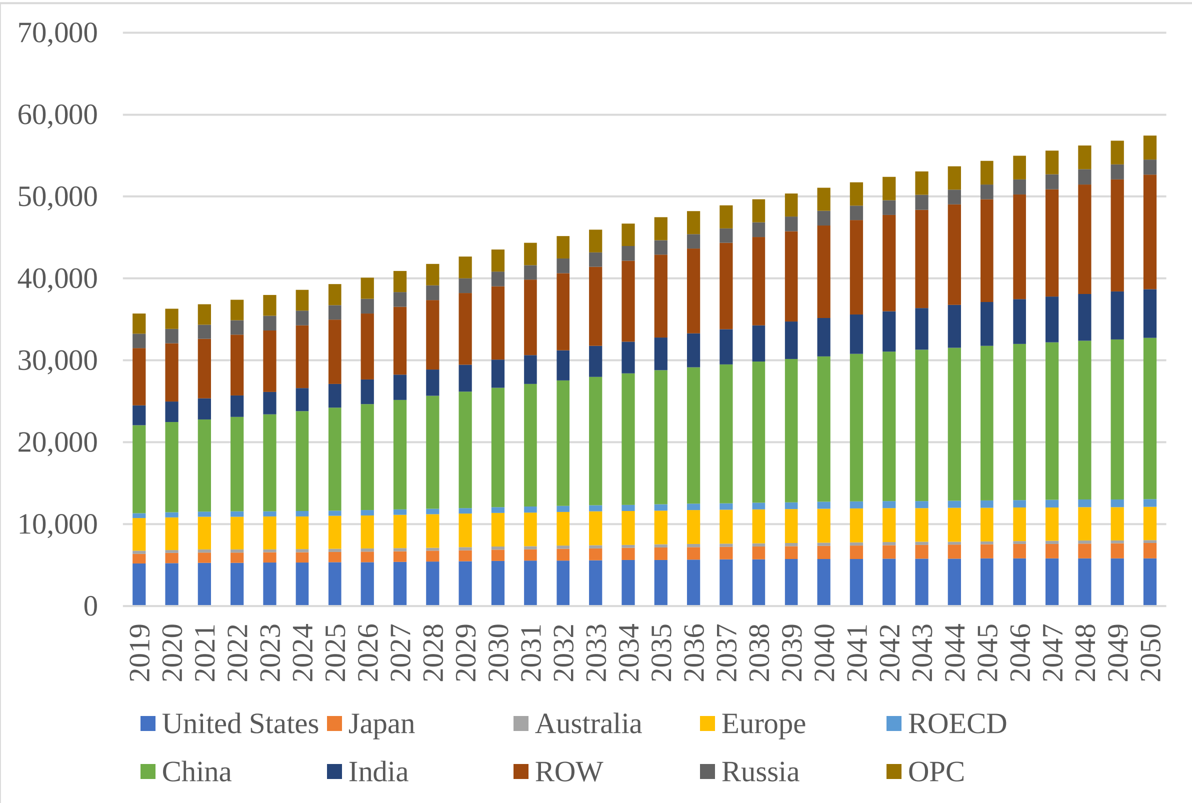


Figure 40: Emissions in the G-Cubed baseline (Million Metric Tonnes)



ANNEX 4: Carbon prices for each modelled scenario in G-Cubed

Global carbon prices across the two transition scenarios in G-Cubed vs. NGFS IAMs (i.e., the price per ton of carbon – to calculate per ton of CO_2, multiply by 12/44).

Figure 41: Carbon Prices in the Delayed Transition Scenario ($US per ton of CO_2-eq)

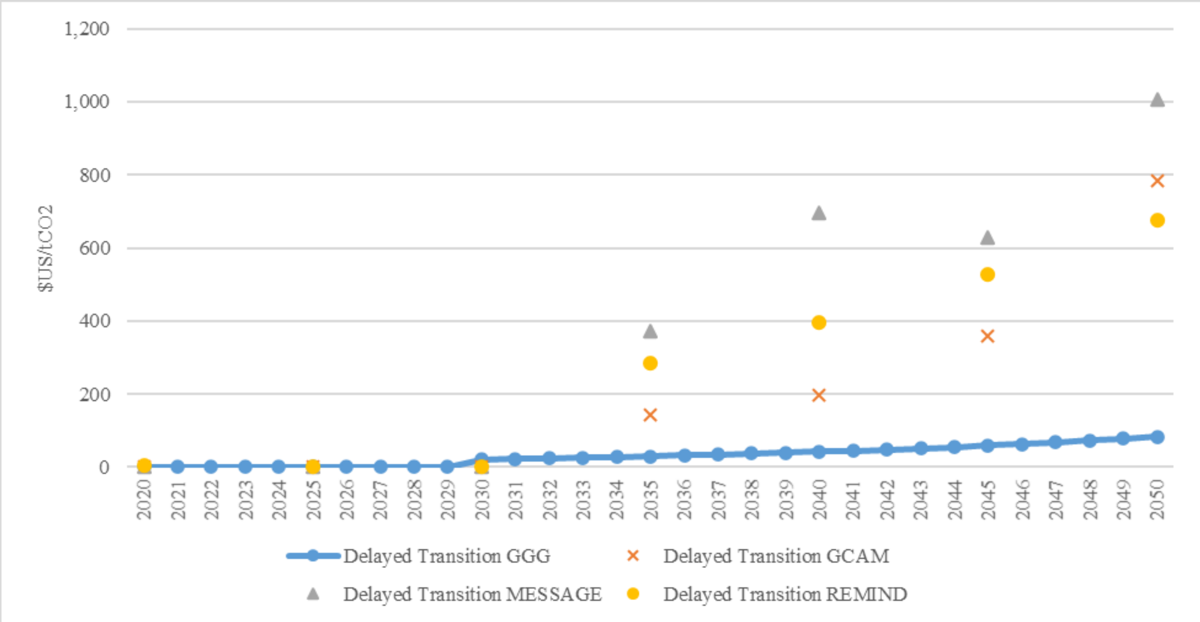
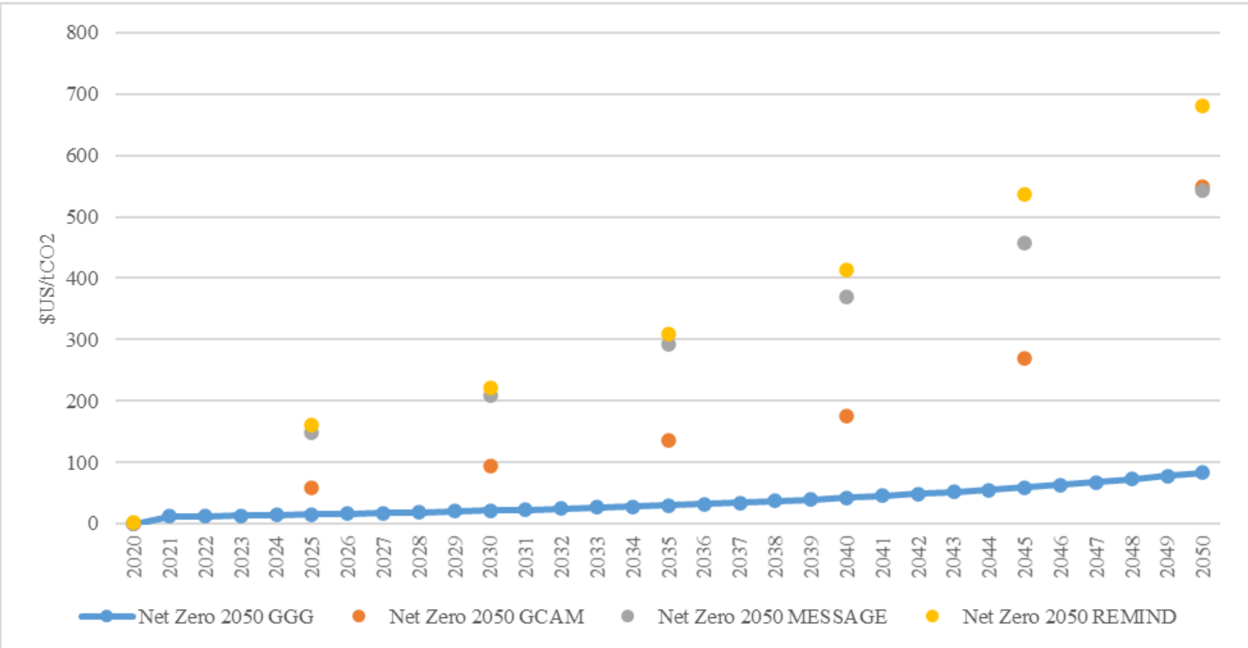


Figure 42: Carbon Prices in the G-Cubed Net Zero 2050 Scenario ($US per ton of CO_2-eq)



ANNEX 5: Real exchange rate changes within G-Cubed, all scenarios/countries

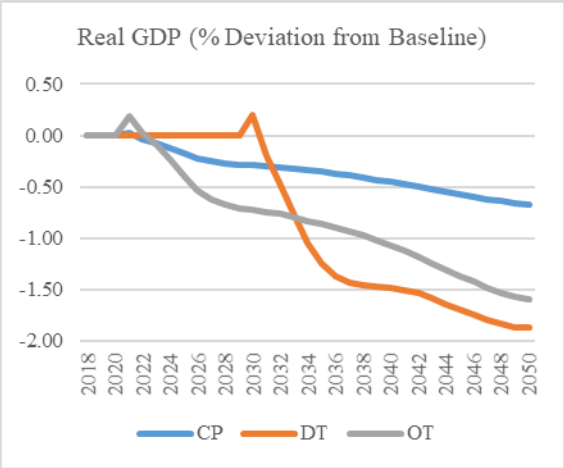
Table 10: Trade-weighted Real Exchange Rate (% Deviation from Baseline)

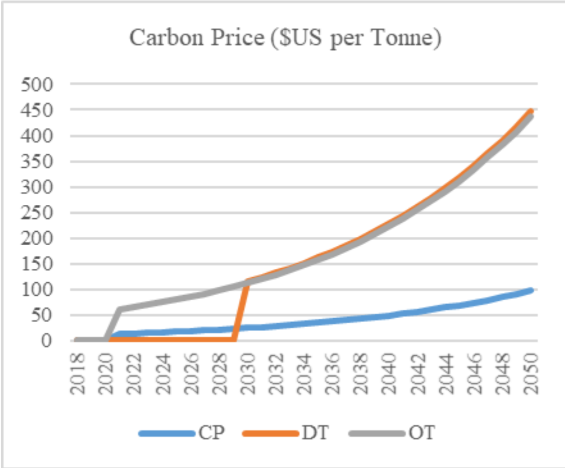
Model Region	Current Policy		Delayed Transition		Orderly Transition	
	2030	2050	2030	2050	2030	2050
United States	0.29	0.06	6.65	2.57	2.32	1.88
Japan	0.59	1.68	7.45	1.84	1.62	0.90
Australia	-1.87	-4.04	-8.05	-6.16	-5.61	-5.57
Europe	-0.06	-0.10	3.72	0.26	0.61	-0.36
ROECD	-0.46	-0.26	-5.25	-5.99	-2.48	-5.33
China	-0.17	2.22	-3.03	1.80	-1.33	2.08
India	1.80	1.02	-6.59	11.33	1.51	13.22
ROW	0.21	0.03	-1.55	3.99	1.30	4.42
Russia	-1.17	-3.31	-5.97	-12.40	-4.38	-12.09
OPC	-0.61	-2.80	-8.36	-16.62	-4.88	-16.15

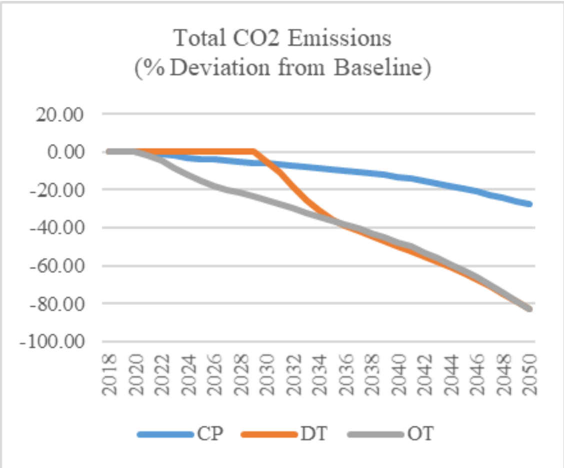
Appendix: G-Cubed Modelling Results of NGFS Climate Scenarios

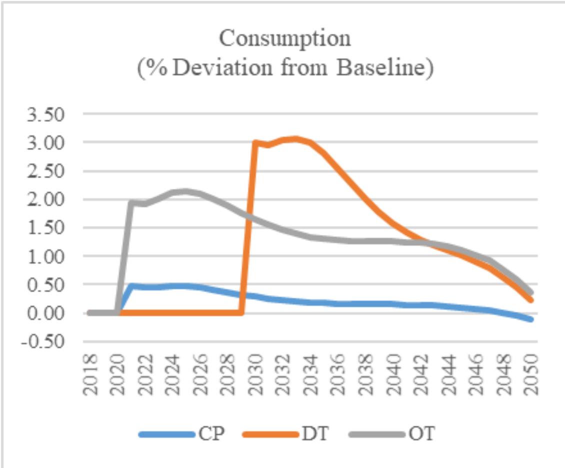
The final and comprehensive modelling results are available on a dedicated dashboard, including the following graphs.

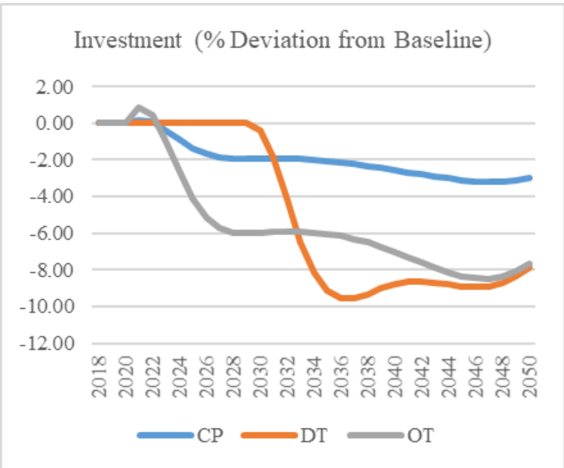
Dynamic Results: United States

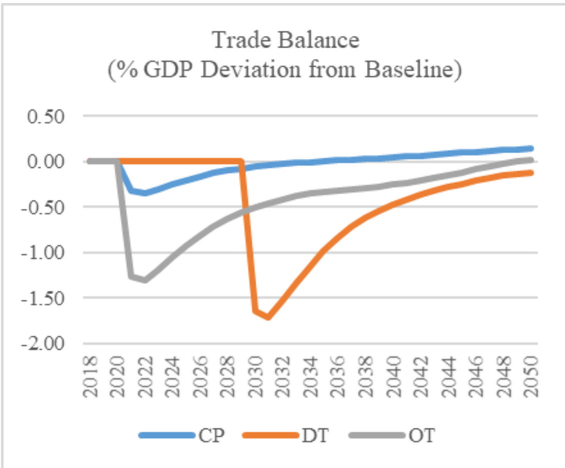




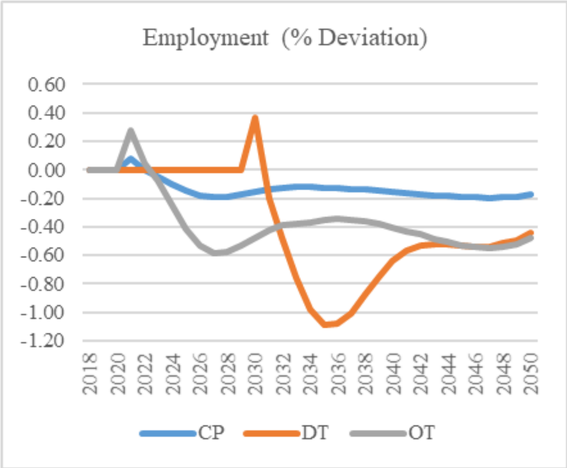


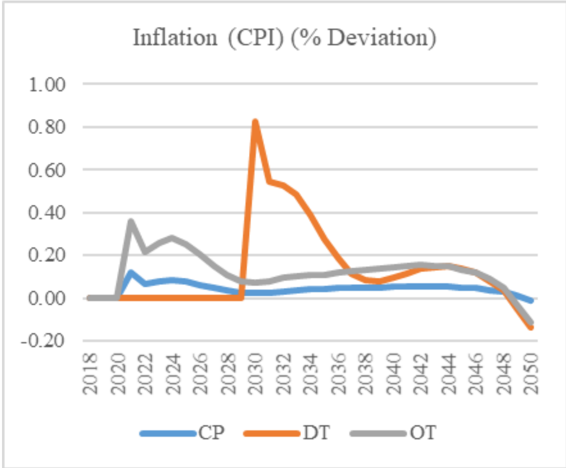


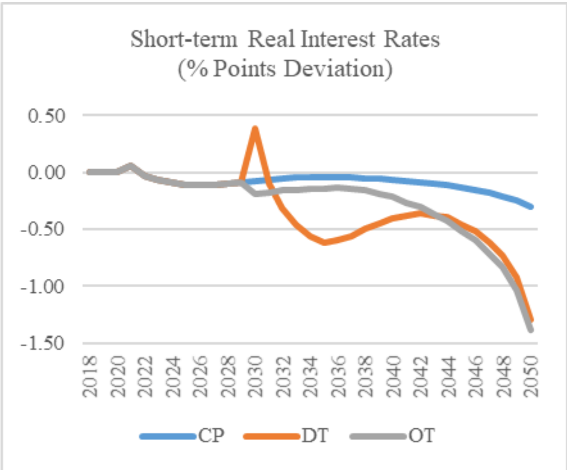


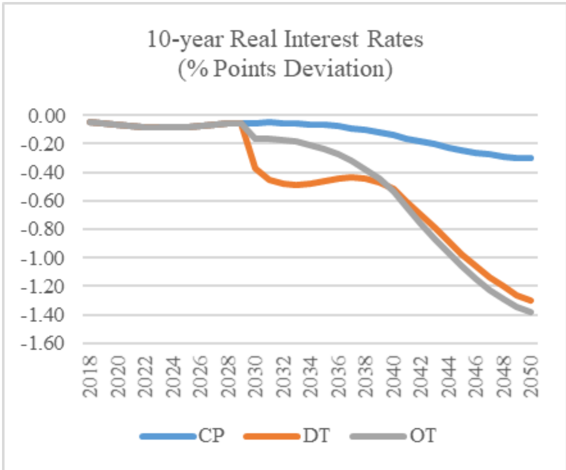


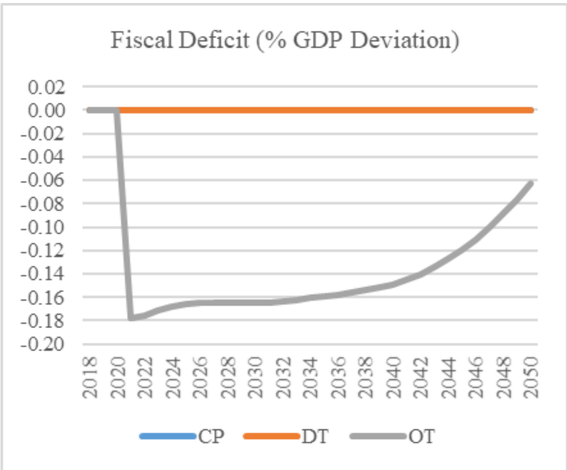
Dynamic Results: United States (Contd.)

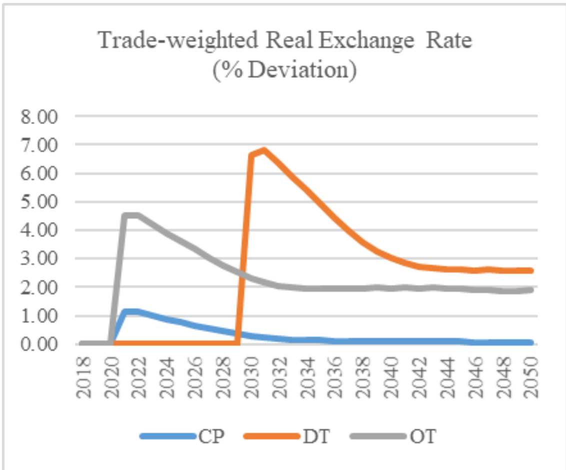




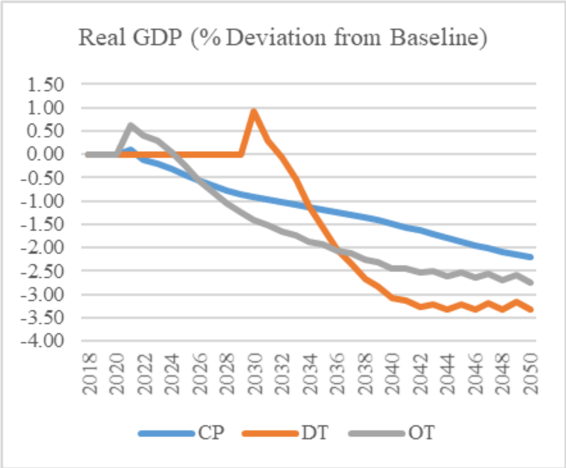


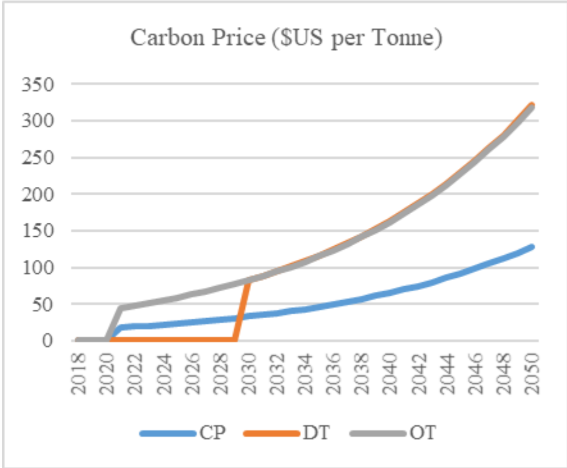


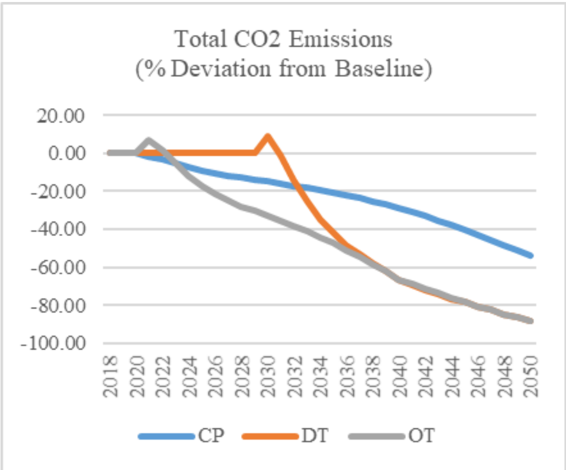


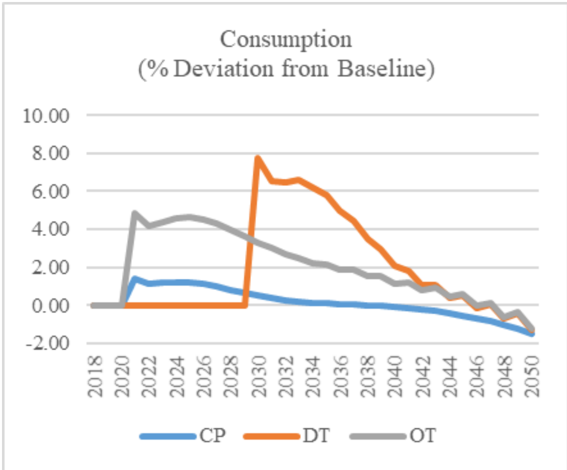


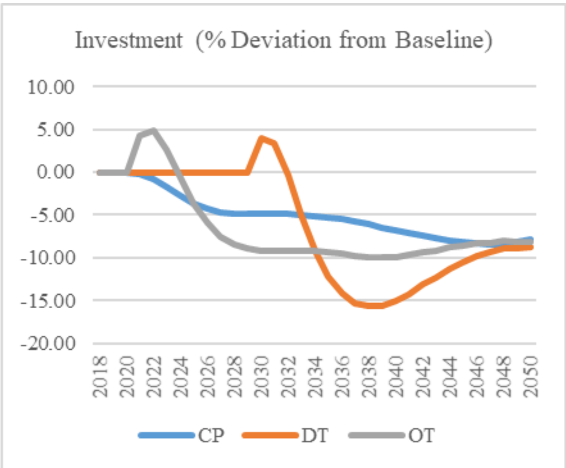
Dynamic Results: Japan

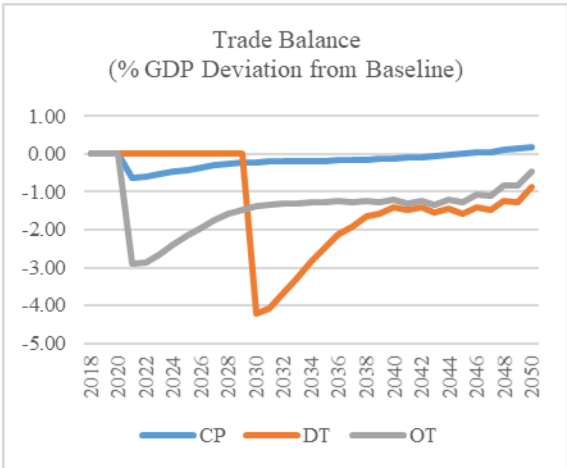




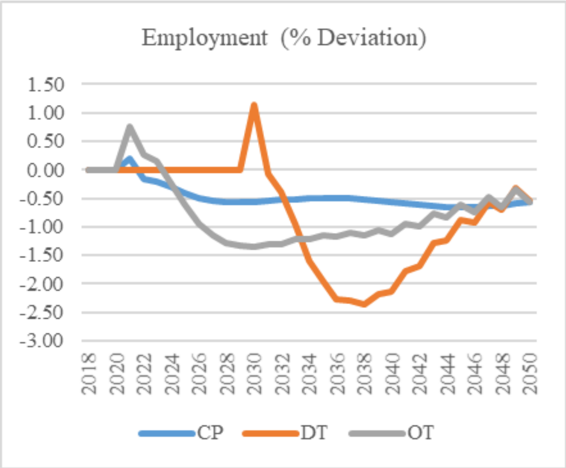


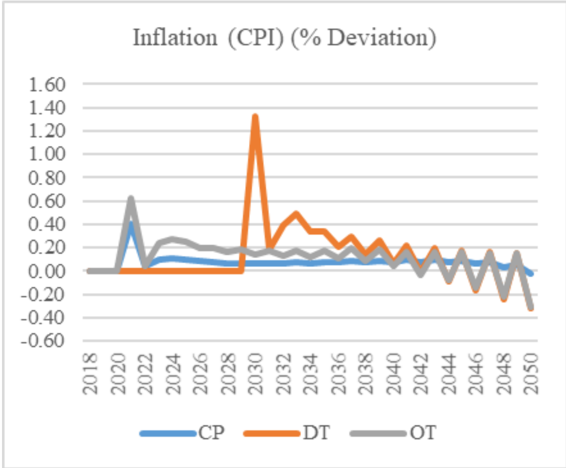


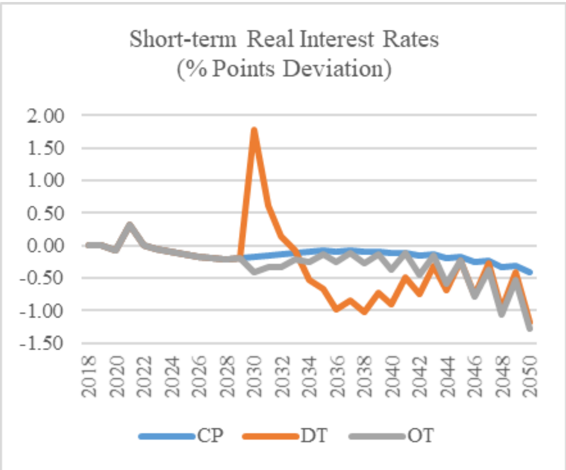


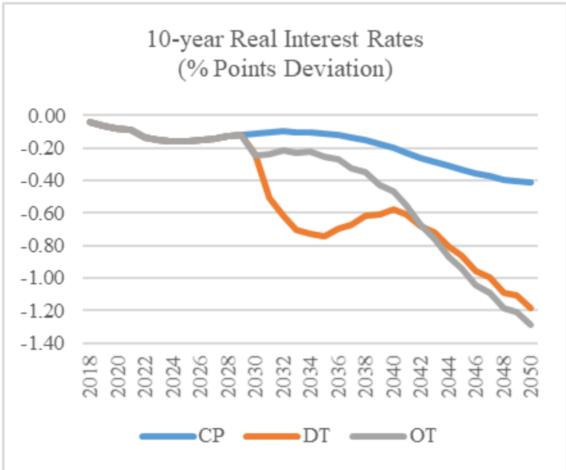


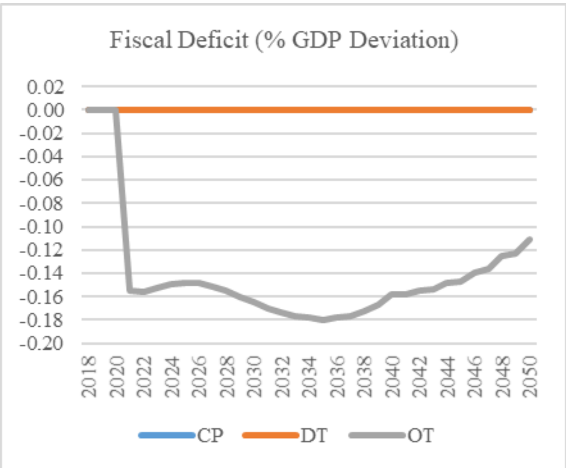
Dynamic Results: Japan (Contd.)

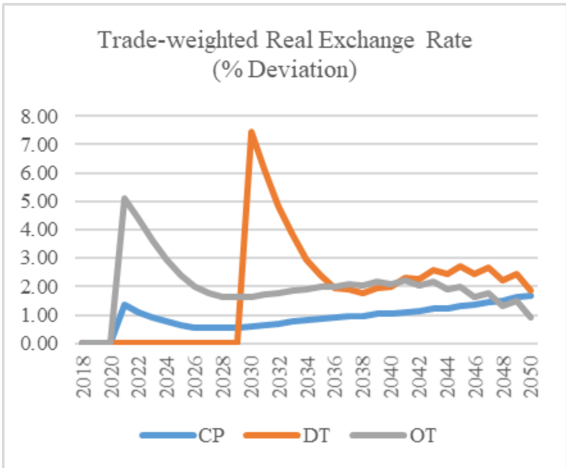




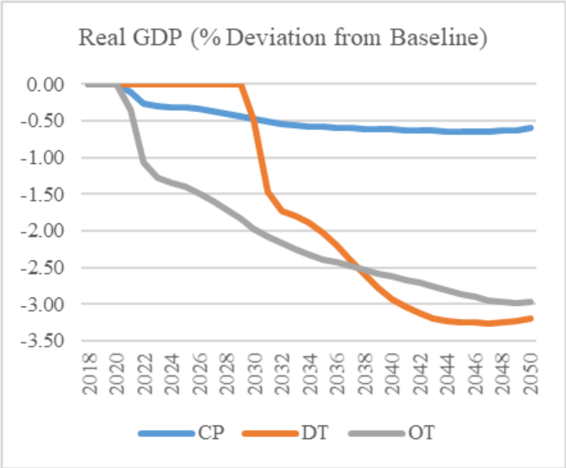


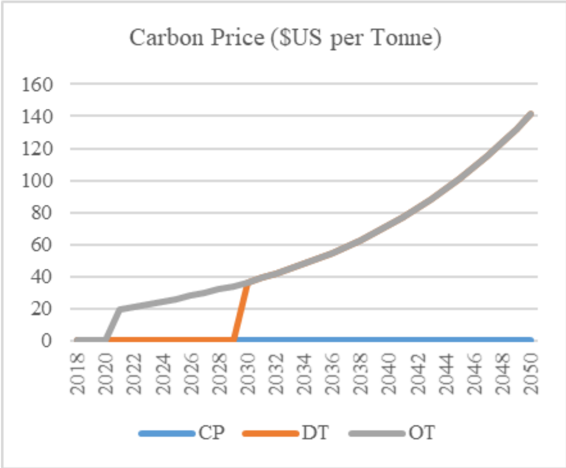


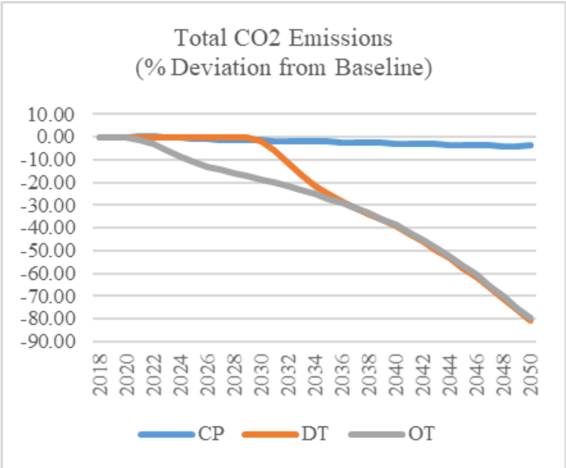


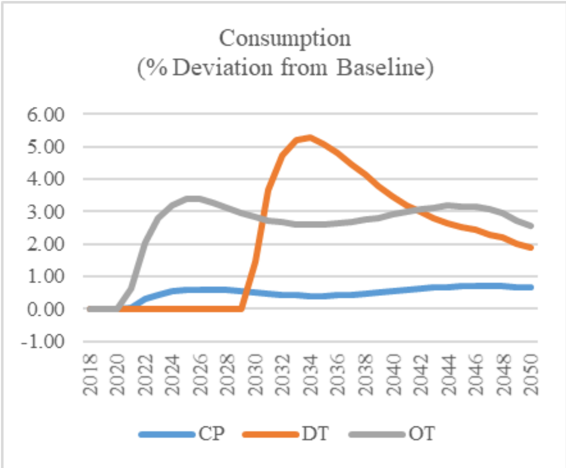


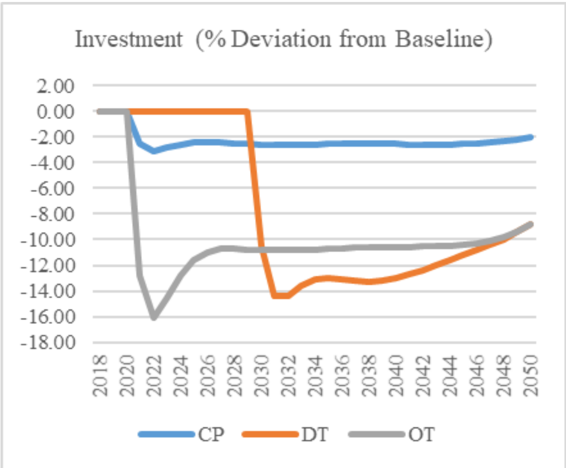
Dynamic Results: Australia

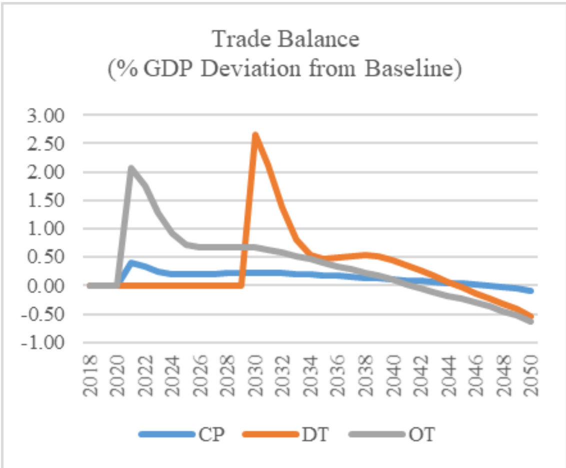




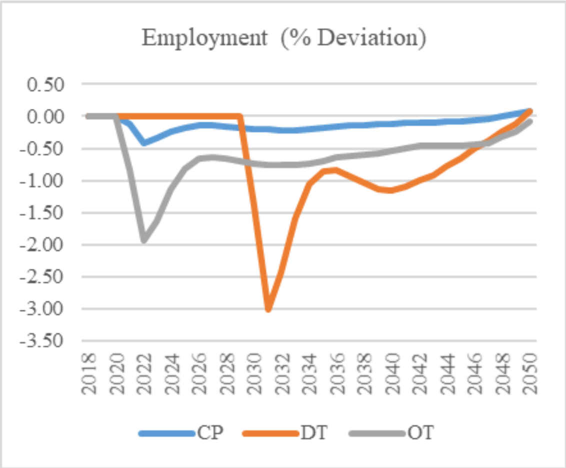


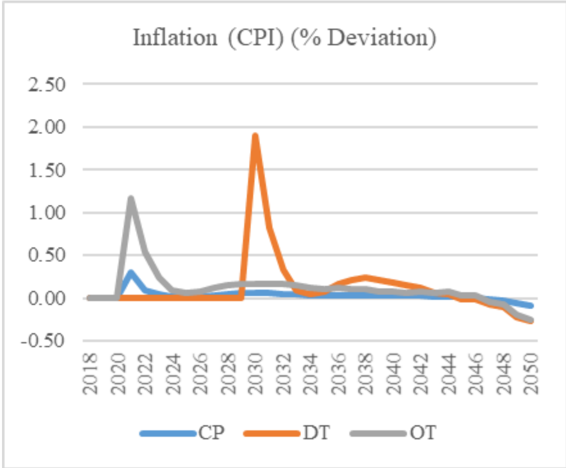


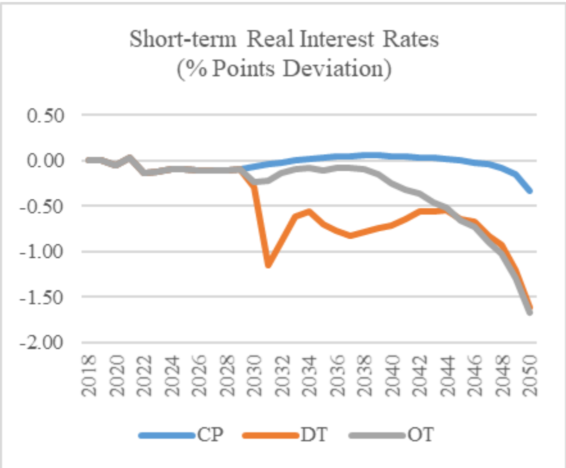


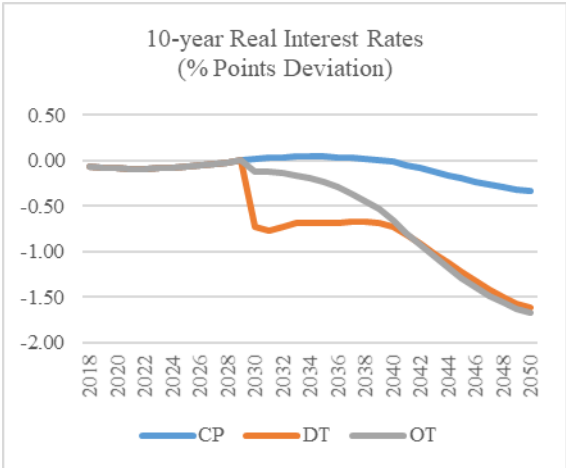


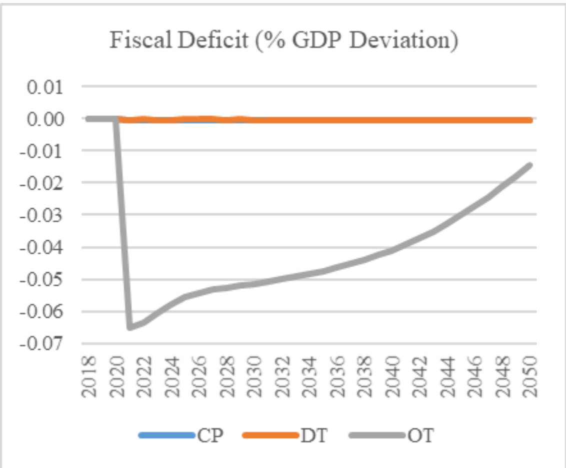
Dynamic Results: Australia (Contd.)

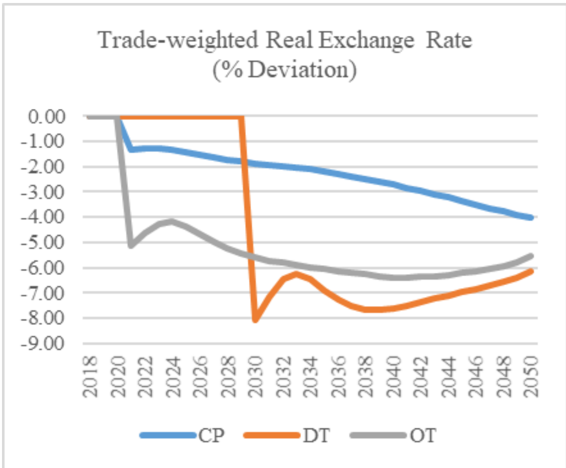




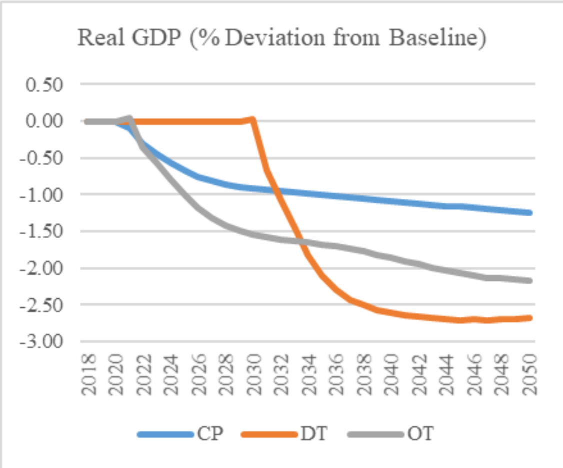


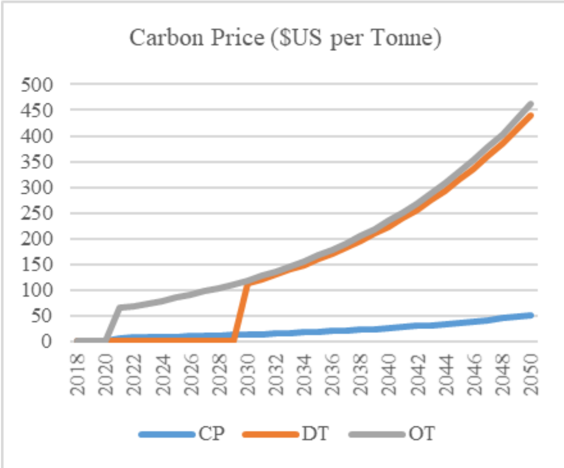


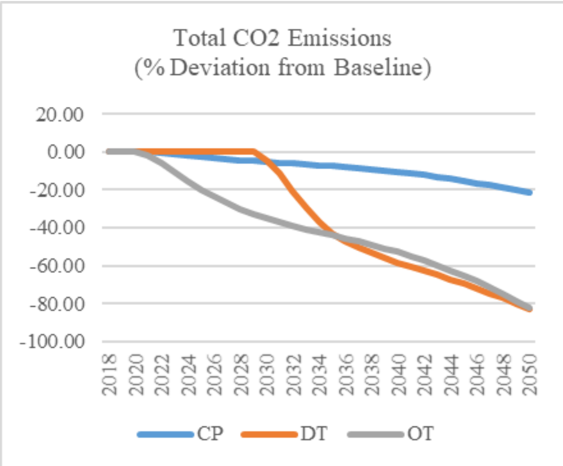


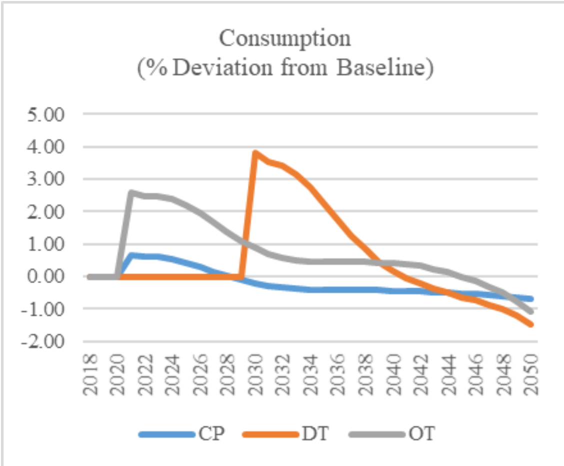


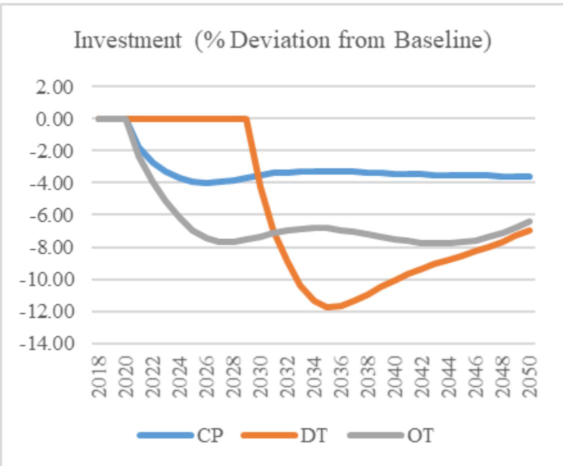
Dynamic Results: Europe

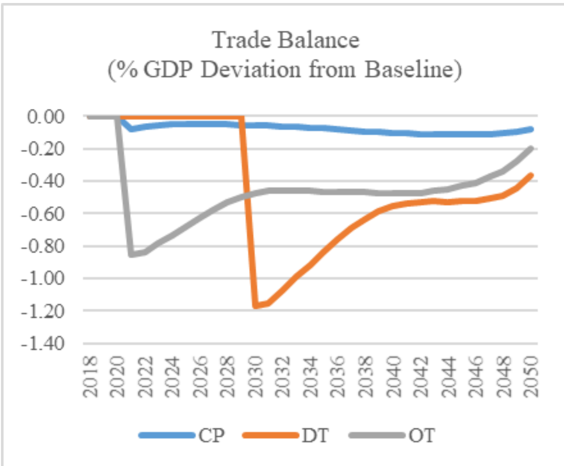




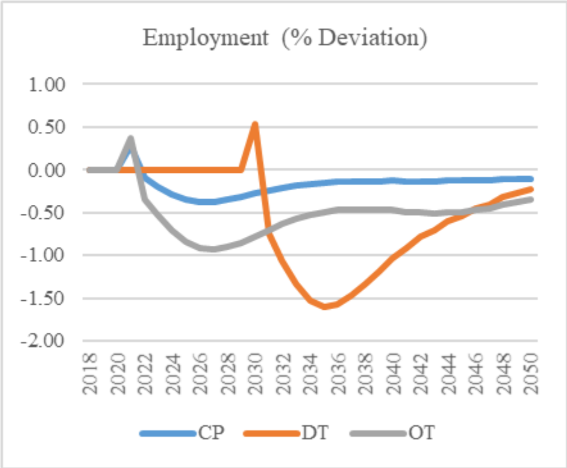


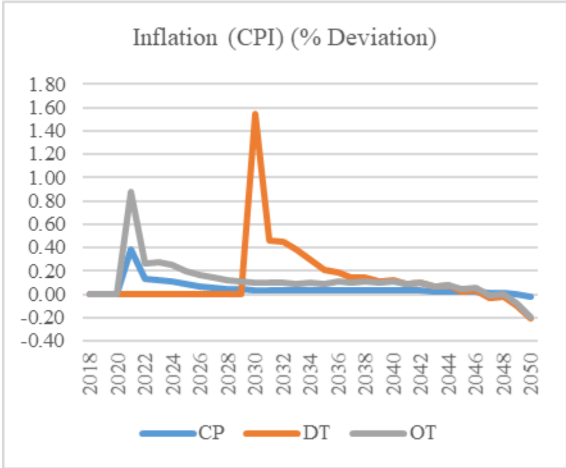


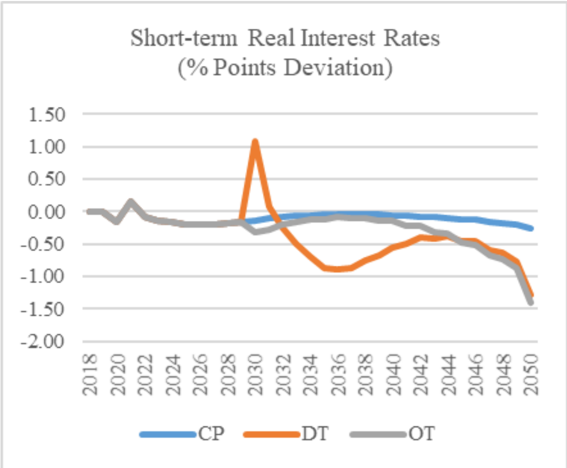


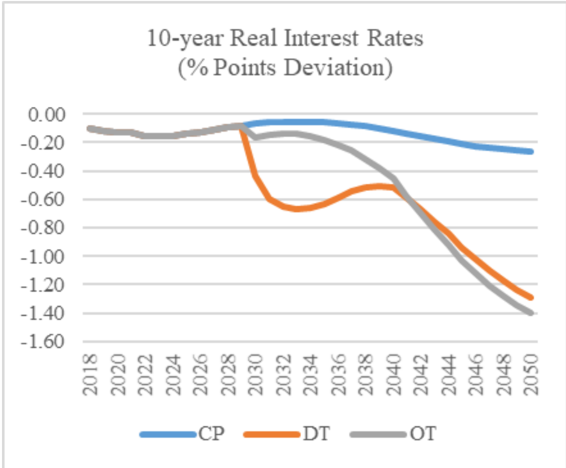


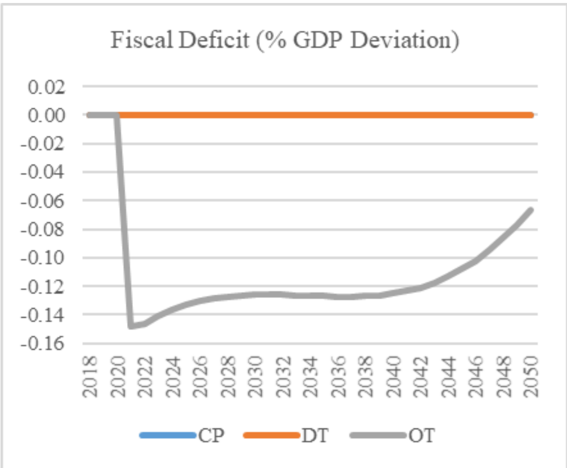
Dynamic Results: Europe (Contd.)

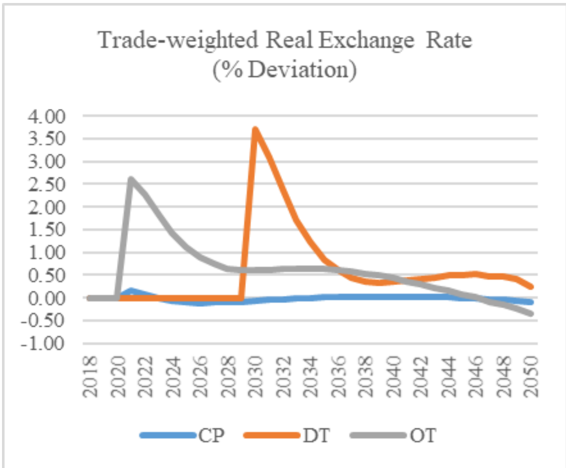




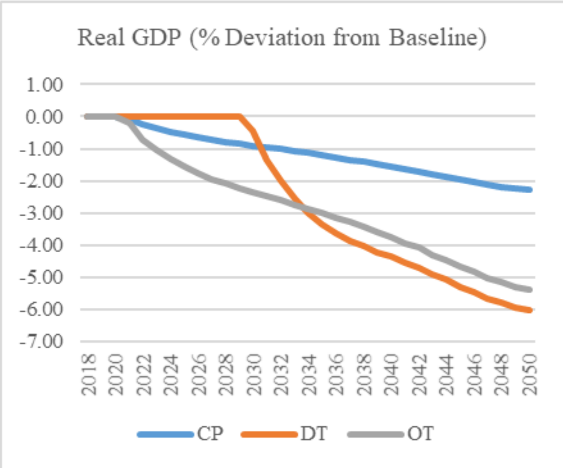


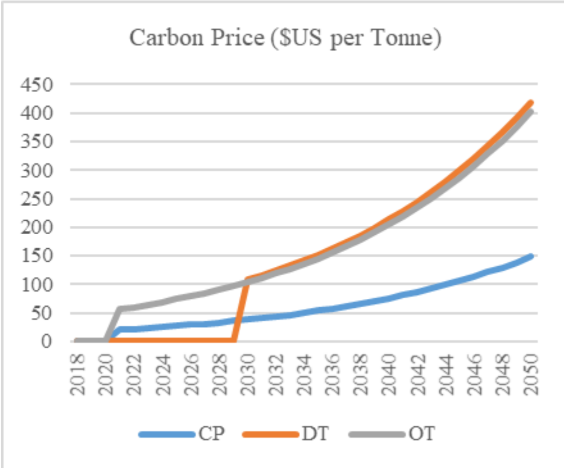


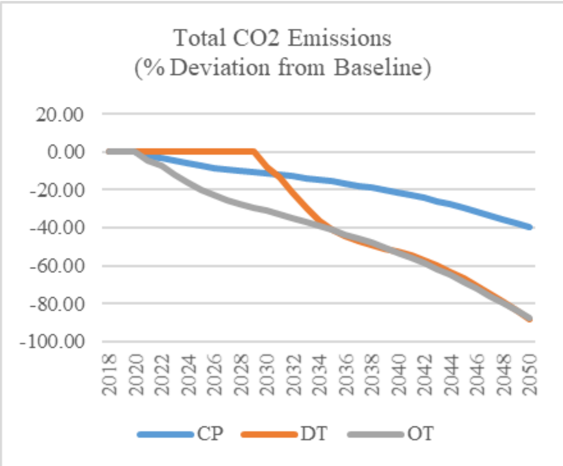


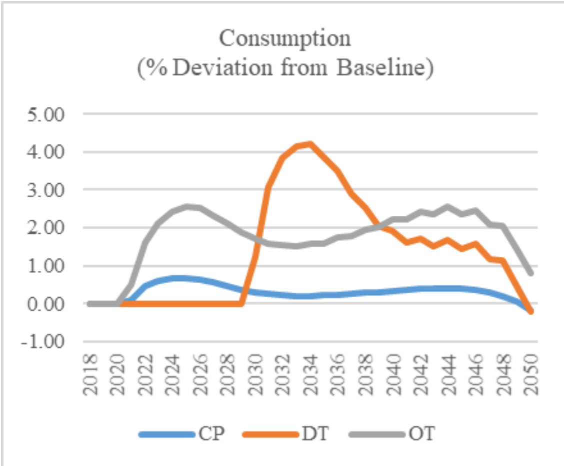


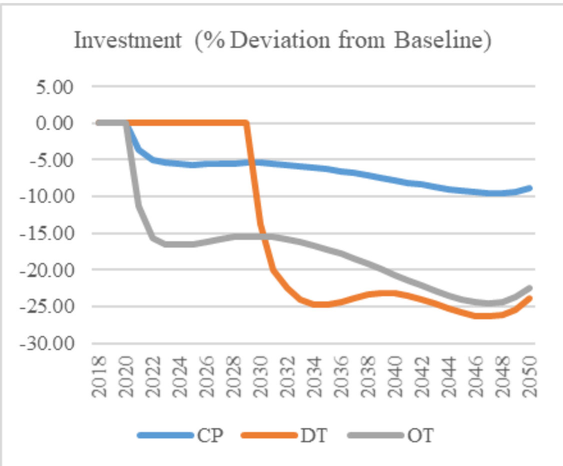
Dynamic Results: Rest of OECD

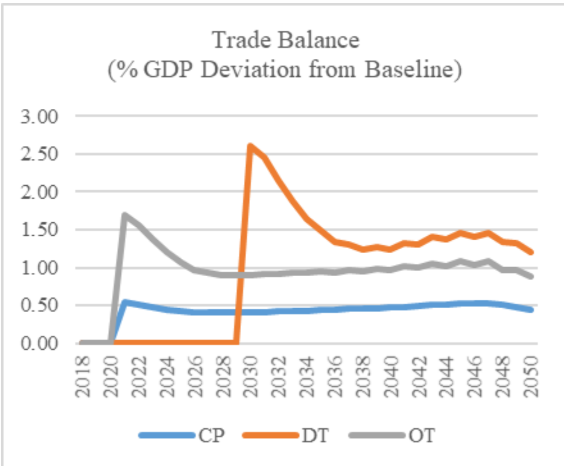




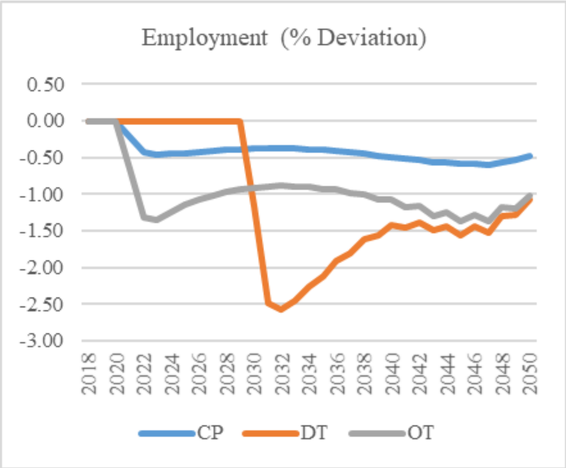


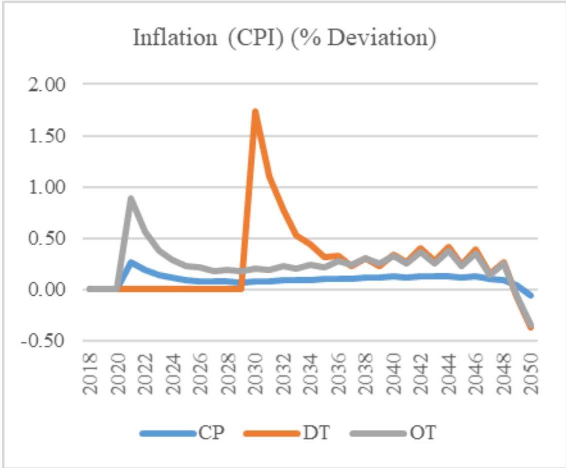


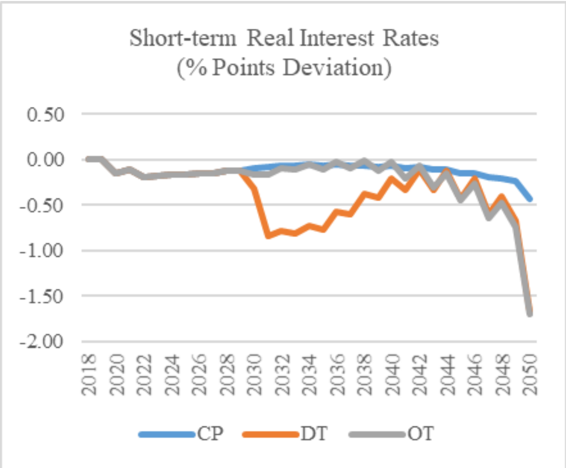


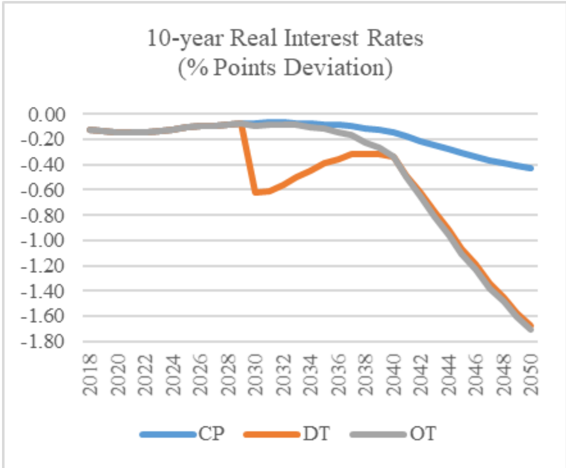


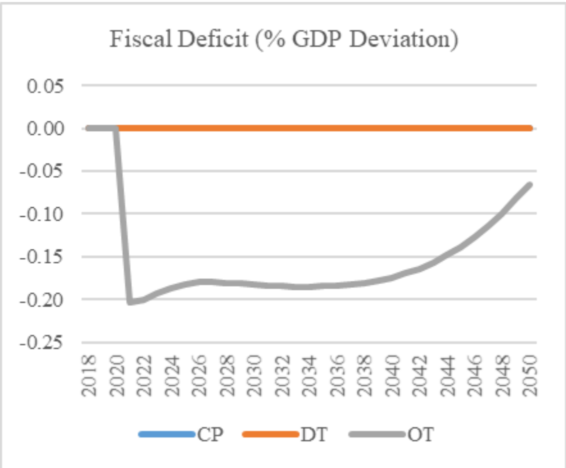
Dynamic Results: Rest of OECD (Contd.)

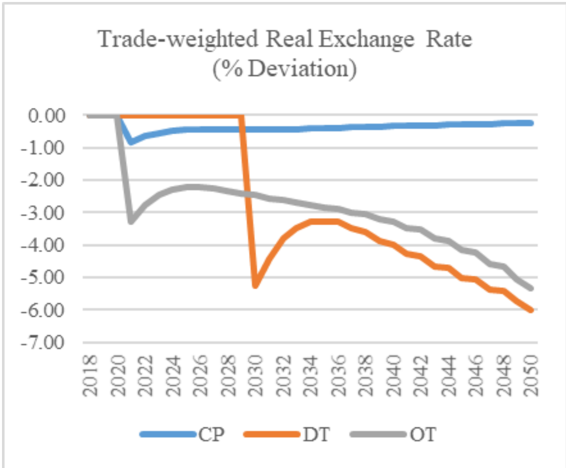




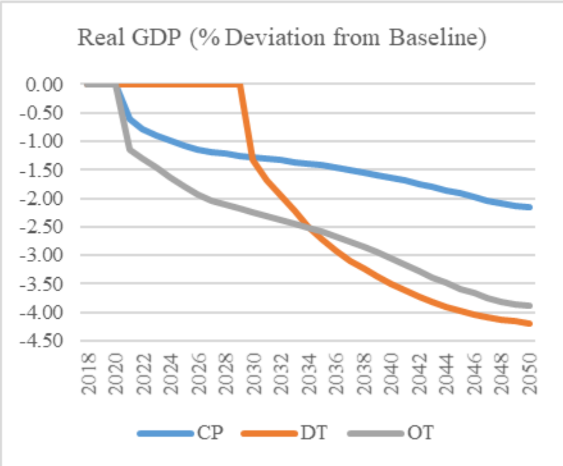


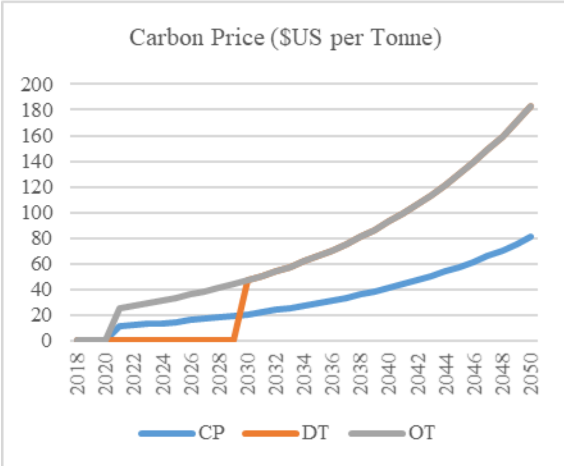


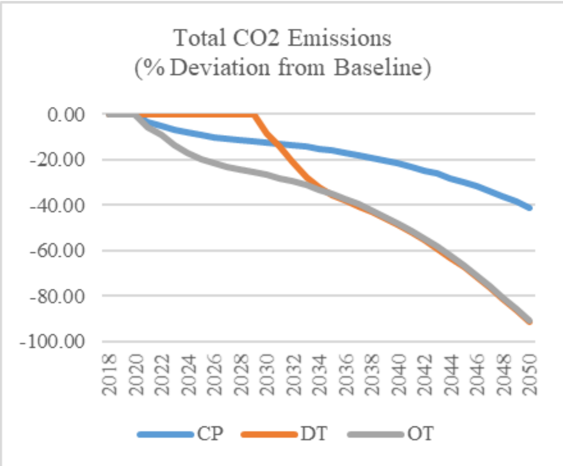


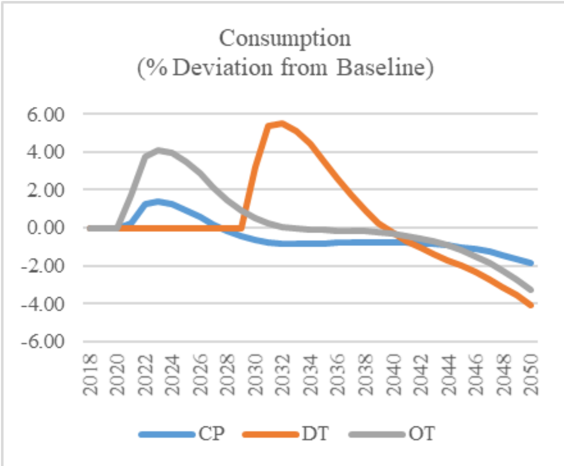


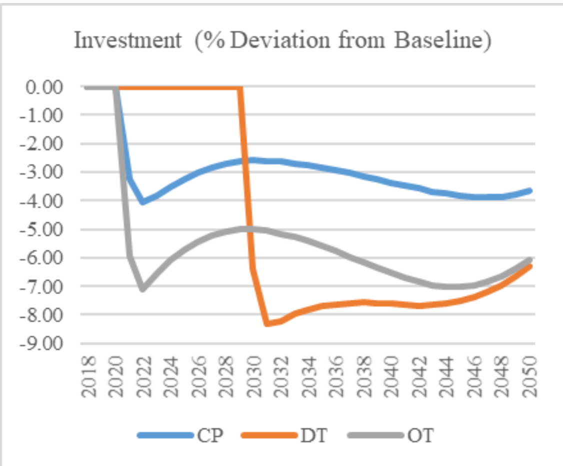
Dynamic Results: China

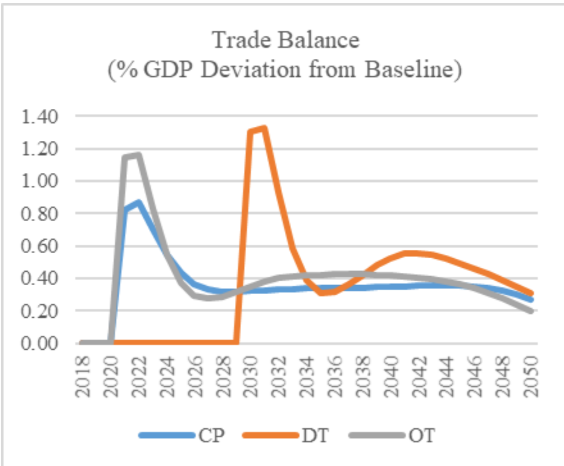




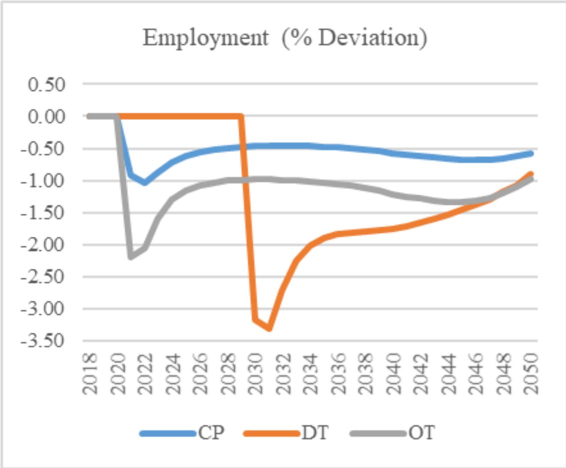


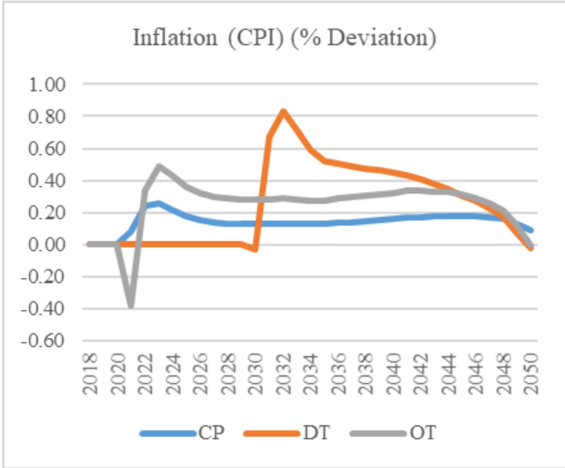


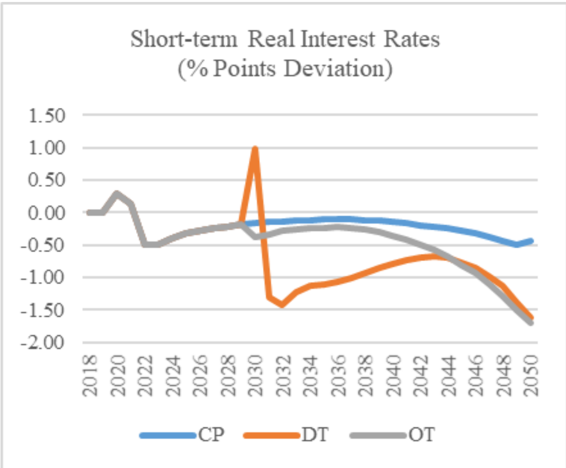


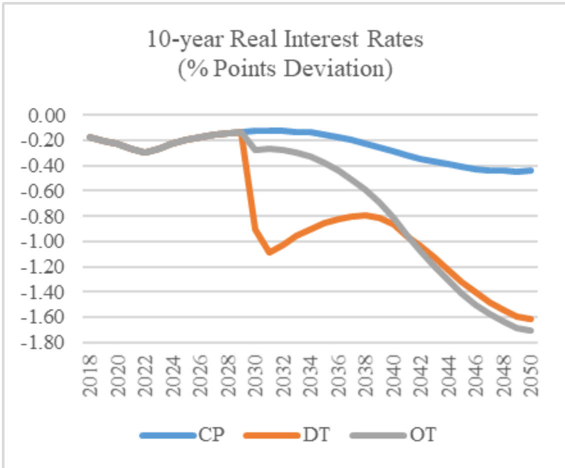


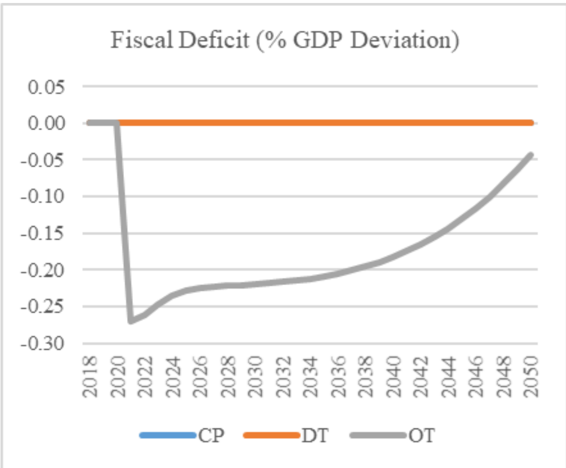
Dynamic Results: China (Contd.)

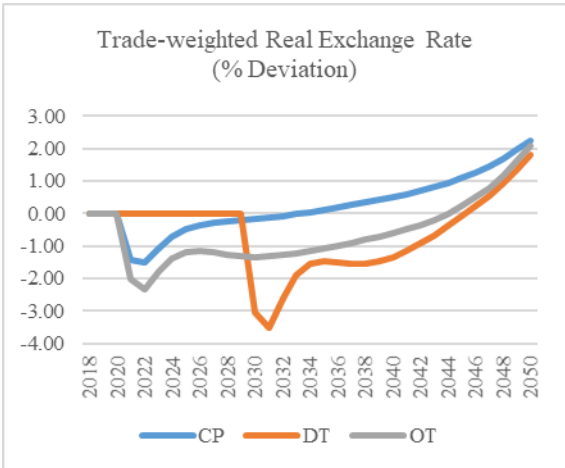




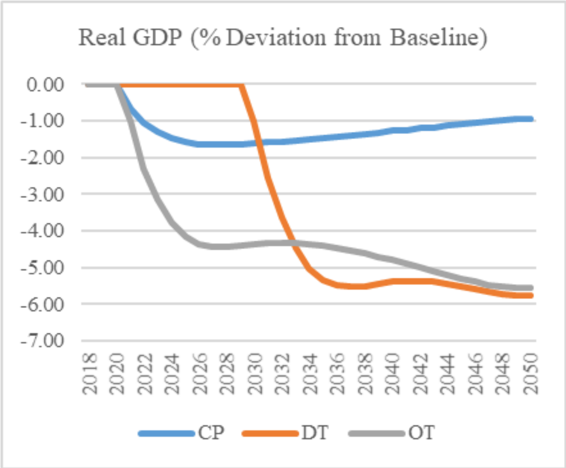


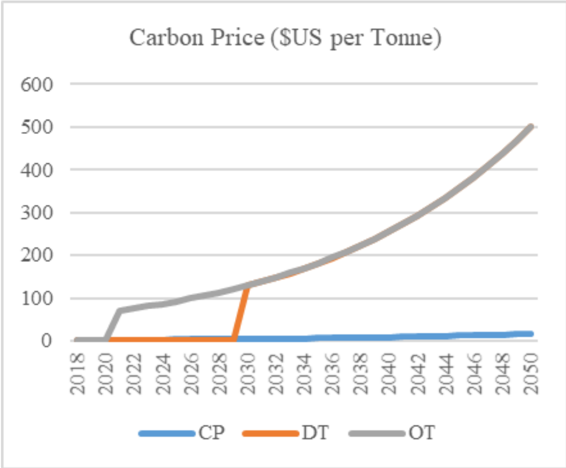


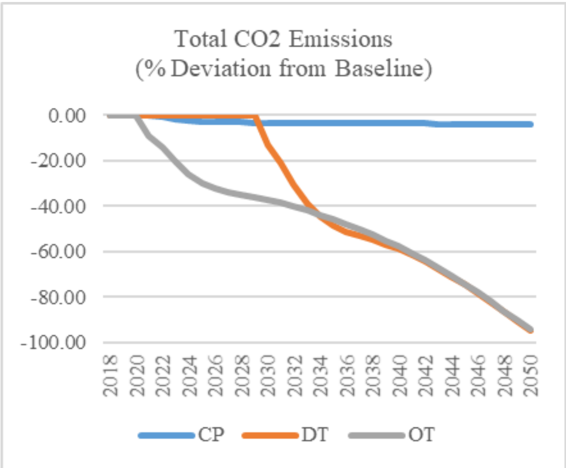


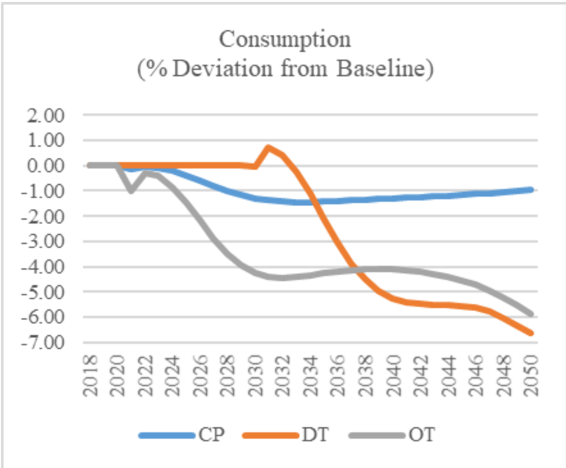


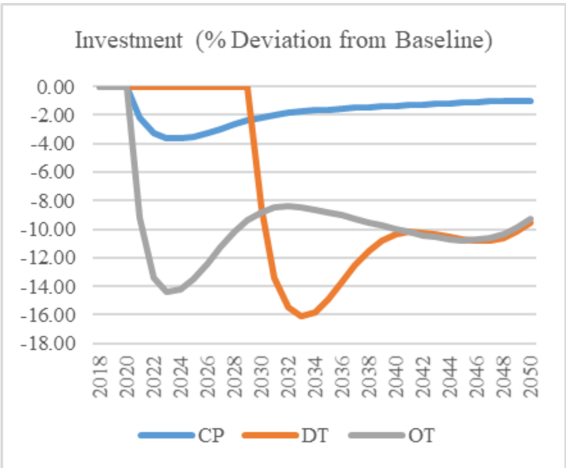
Dynamic Results: India

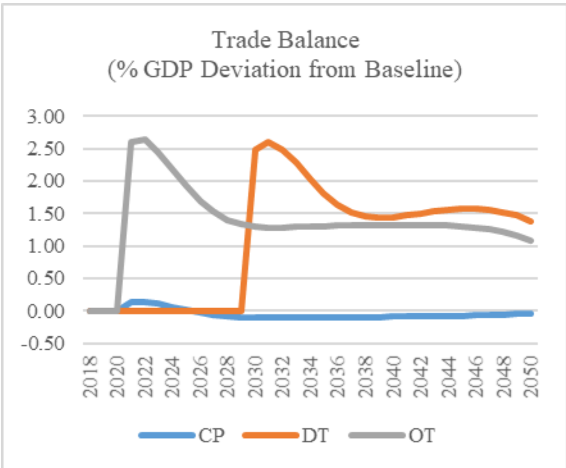




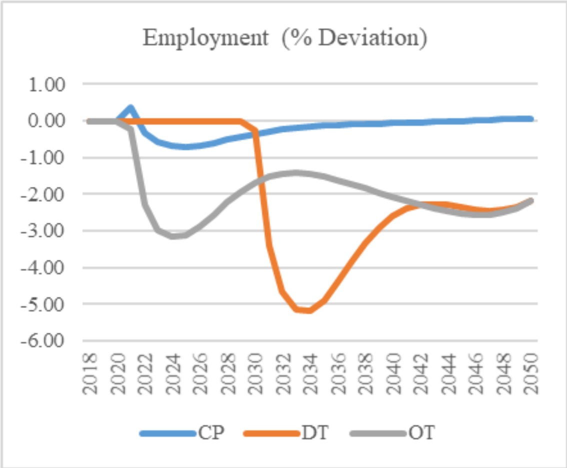


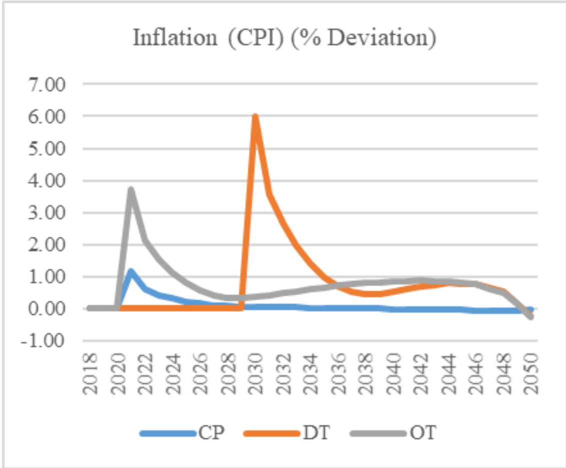


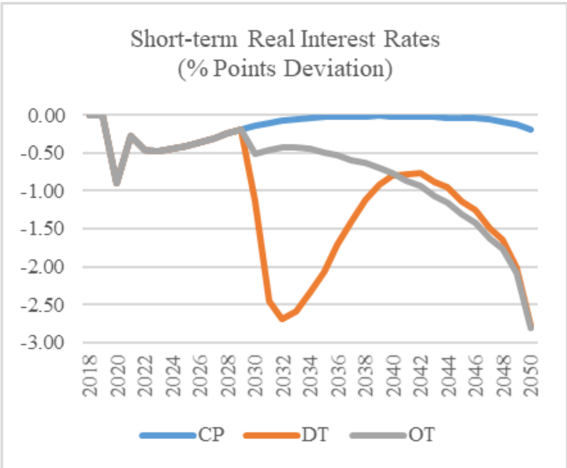


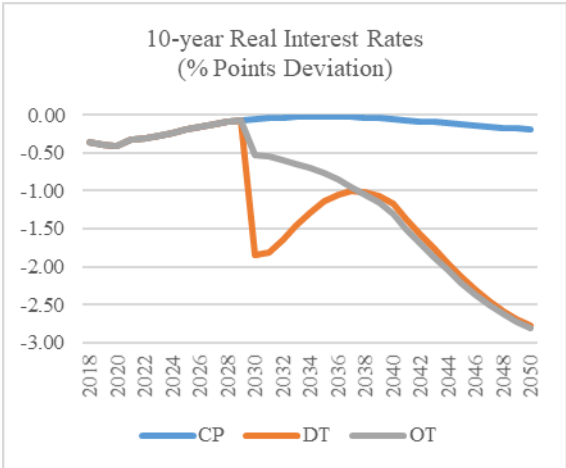


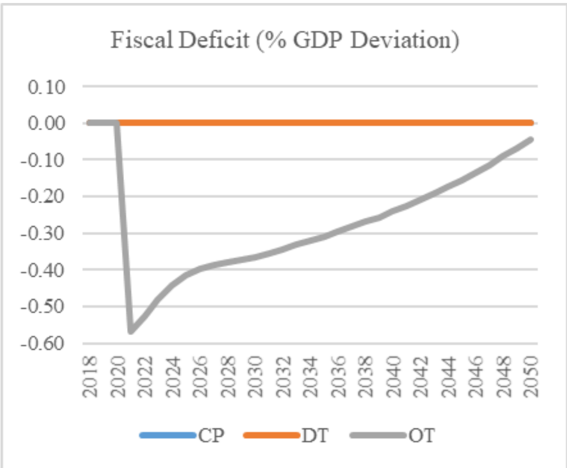
Dynamic Results: India (Contd.)

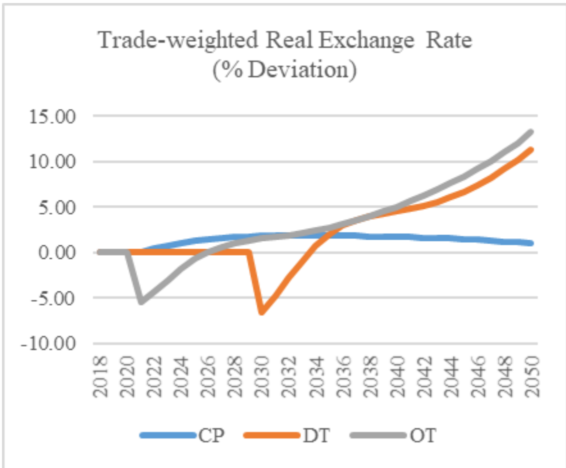




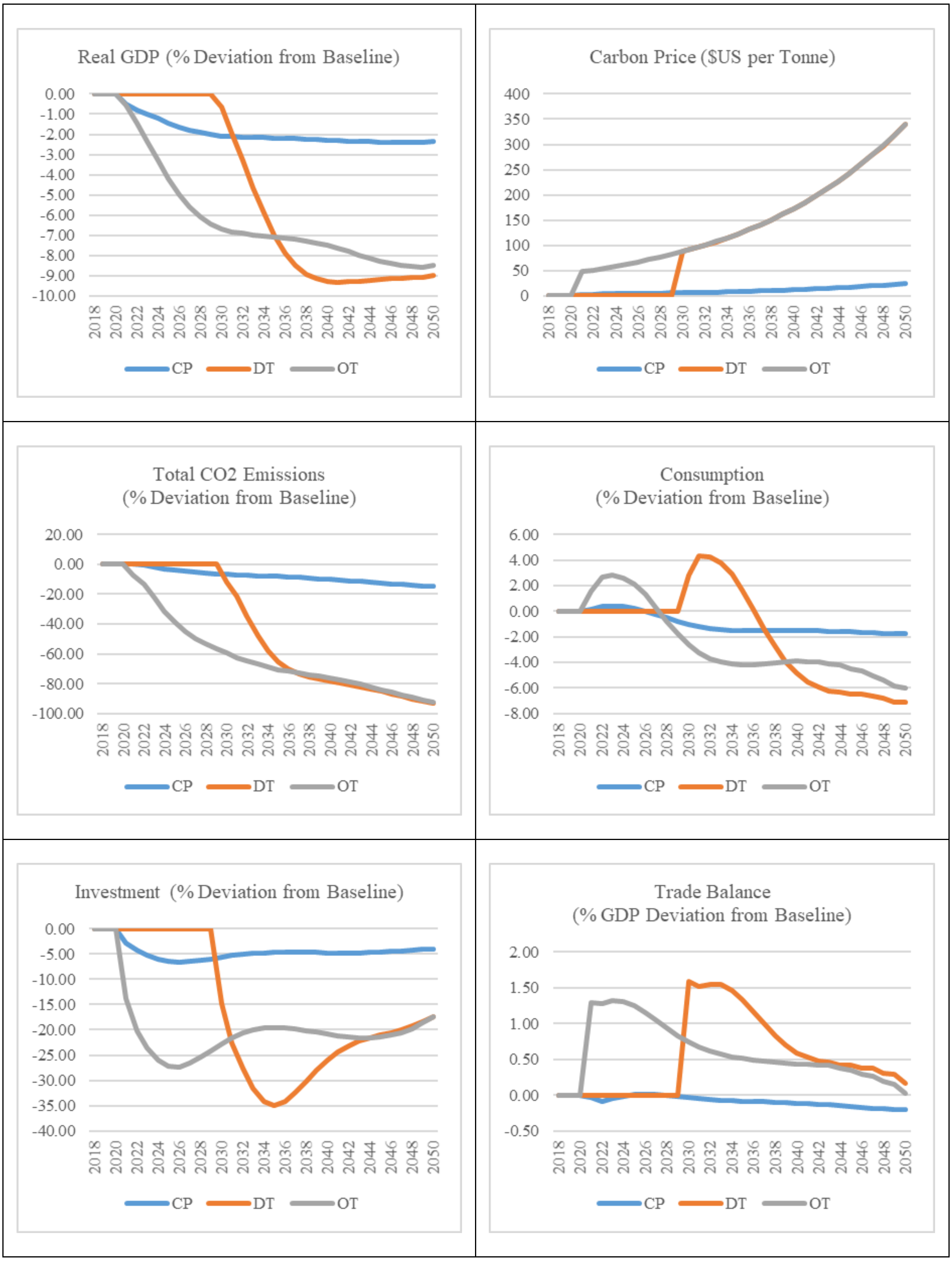




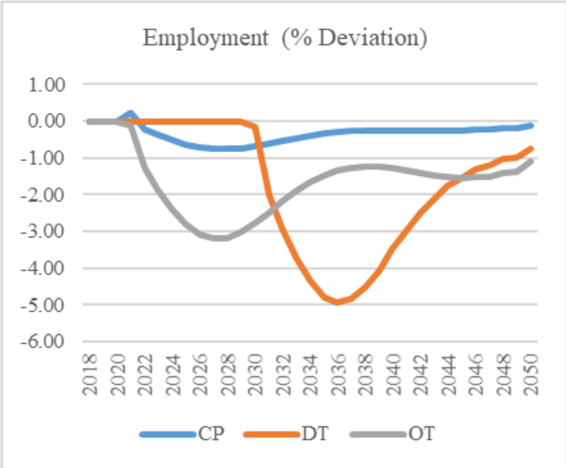


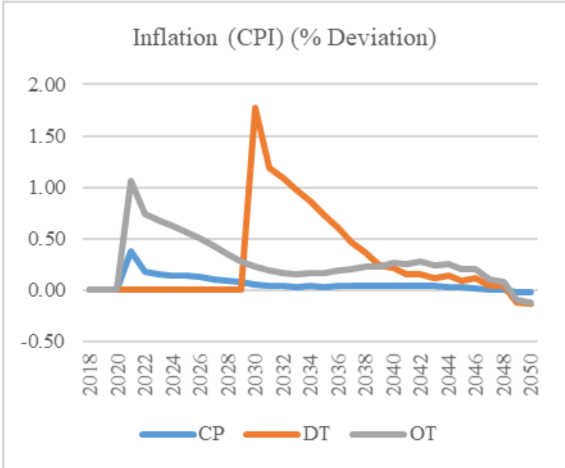


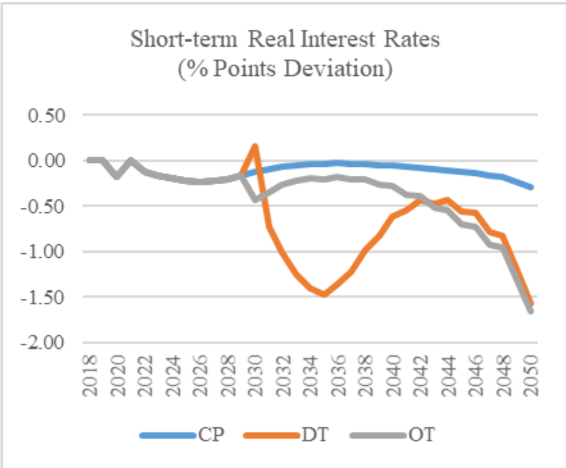
Dynamic Results: Rest of the World

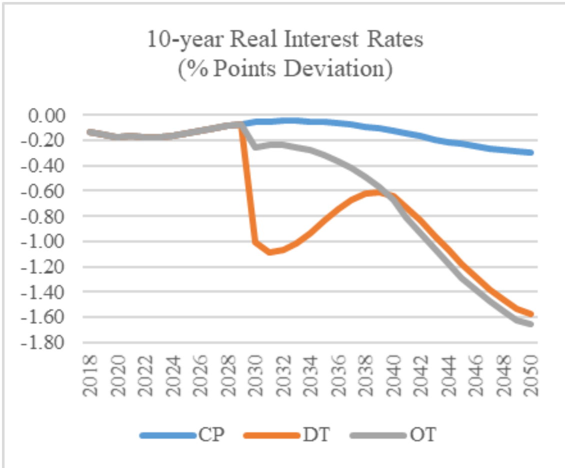


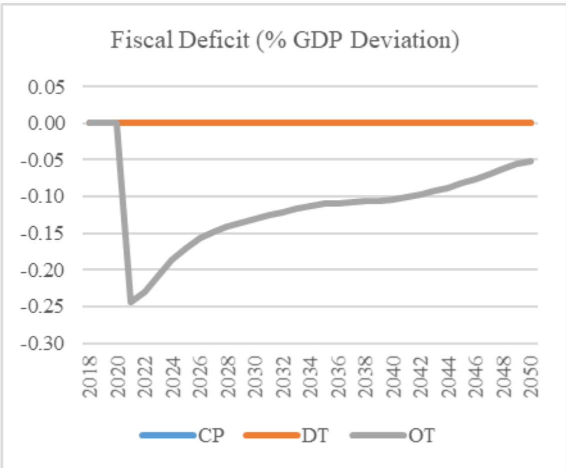
Dynamic Results: Rest of the World (Contd.)

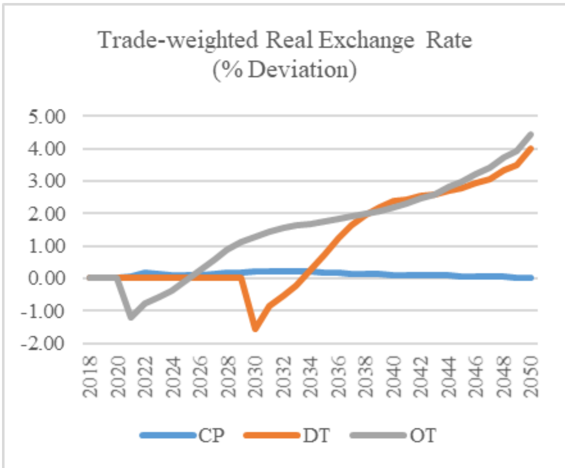




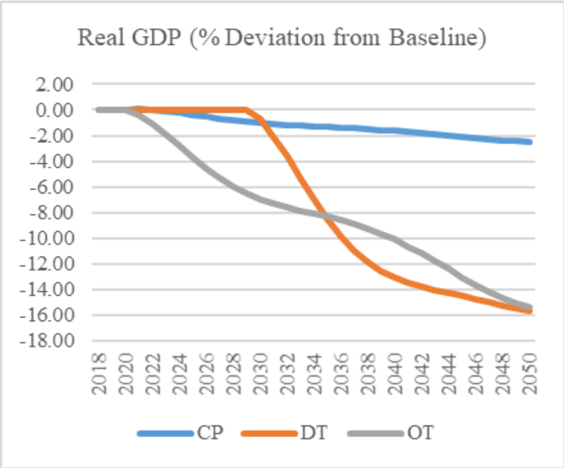


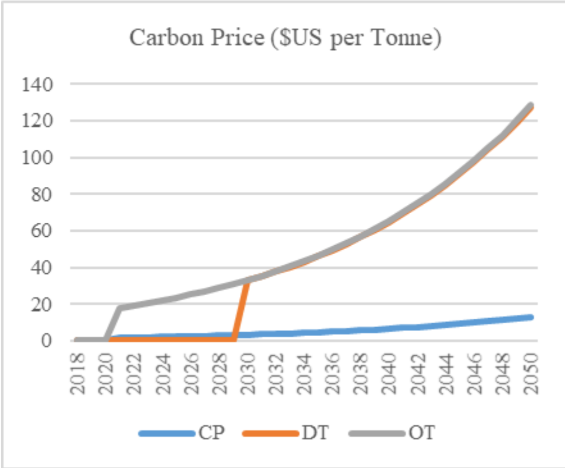


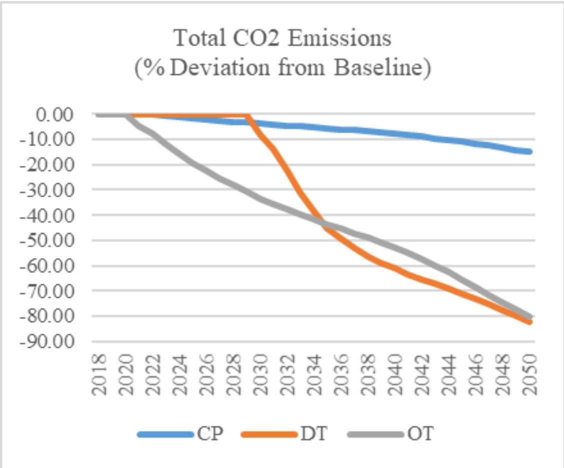


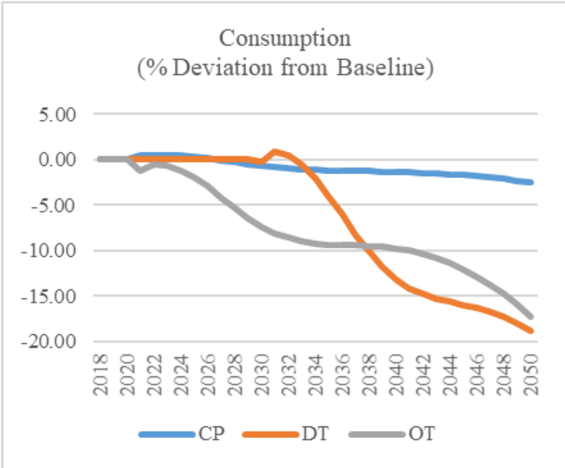


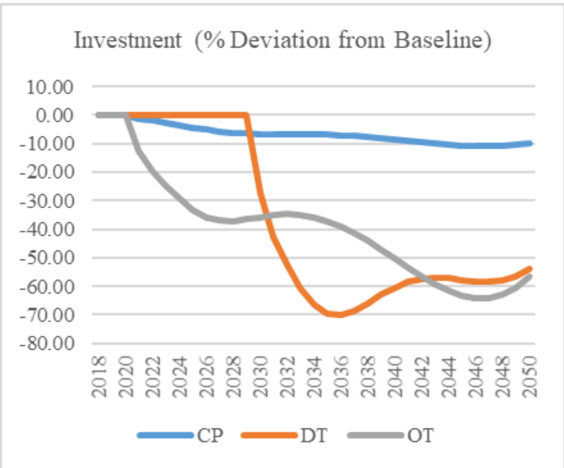
Dynamic Results: Russia

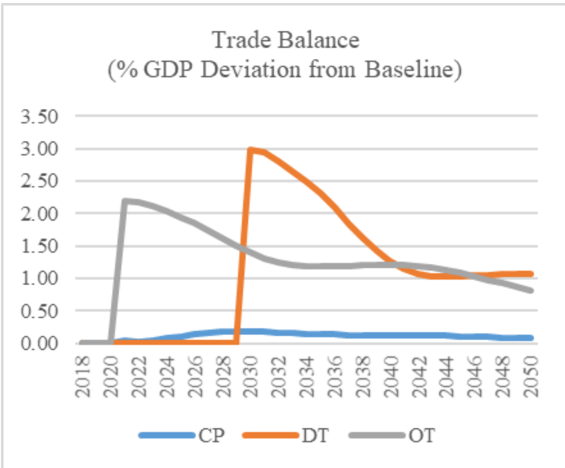




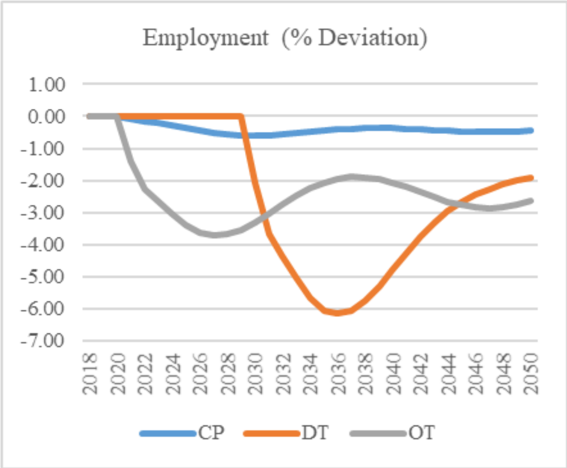


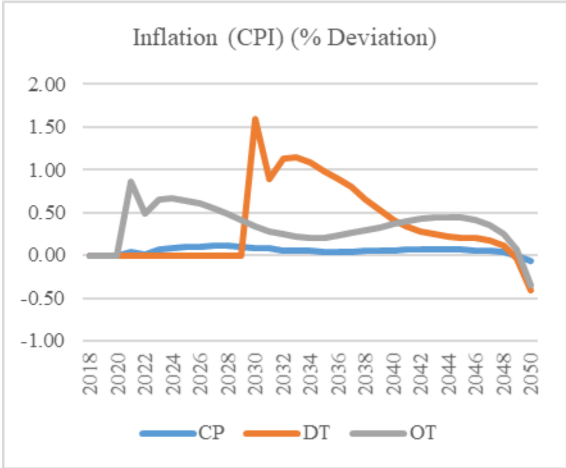


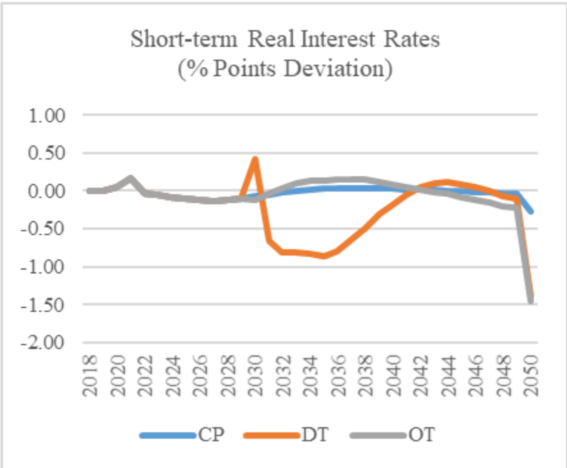


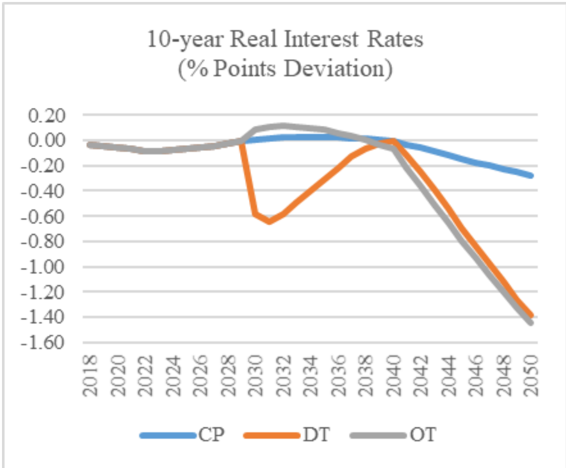


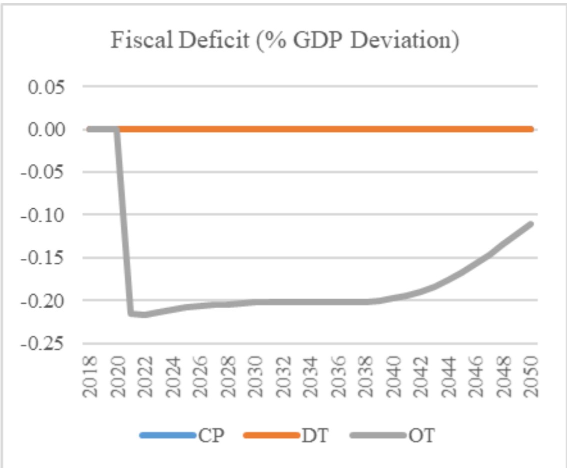
Dynamic Results: Russia (Contd.)

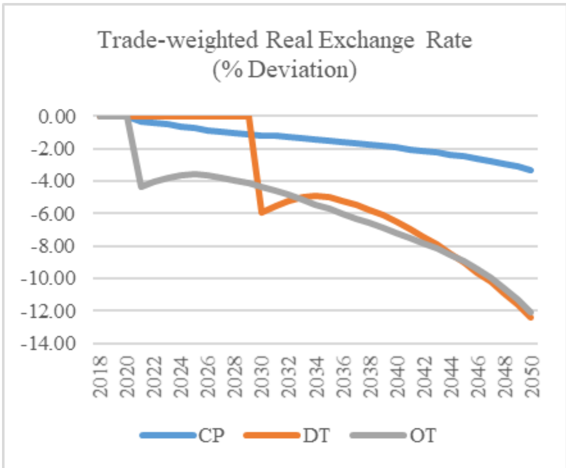




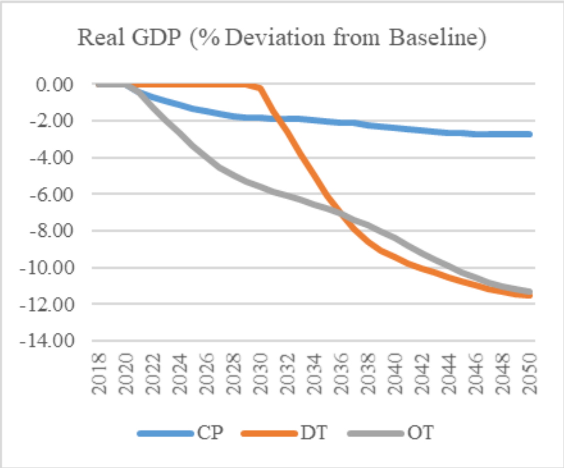


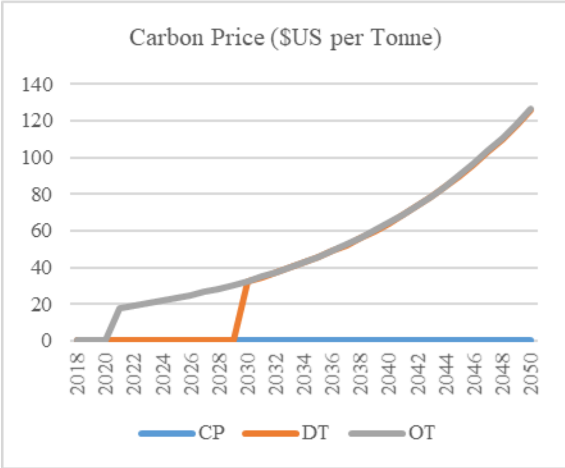


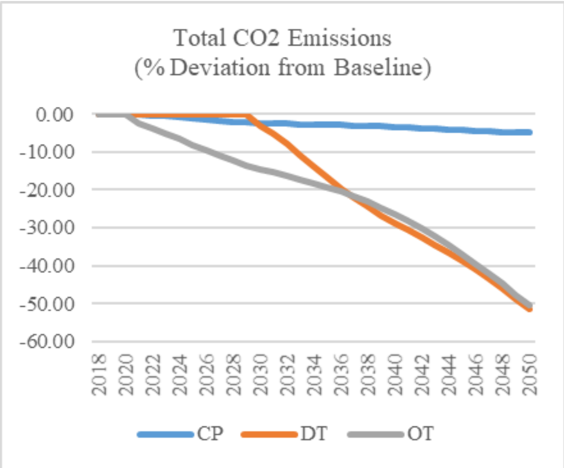


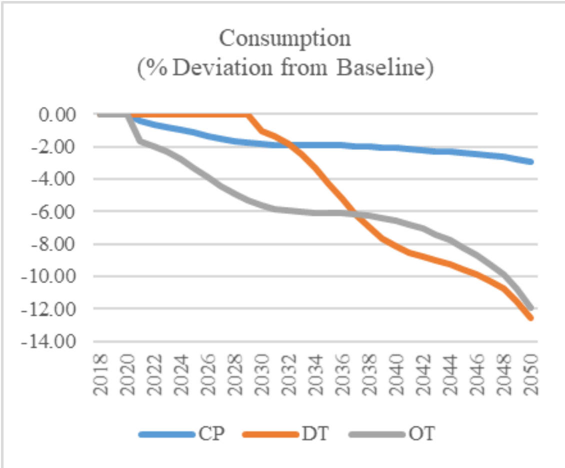


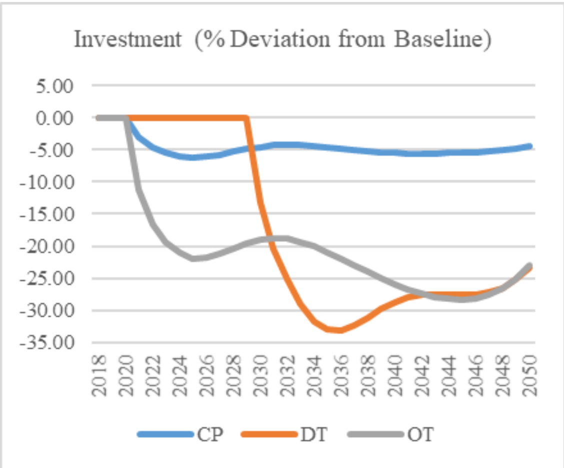
Dynamic Results: Oil Producing Developing Countries

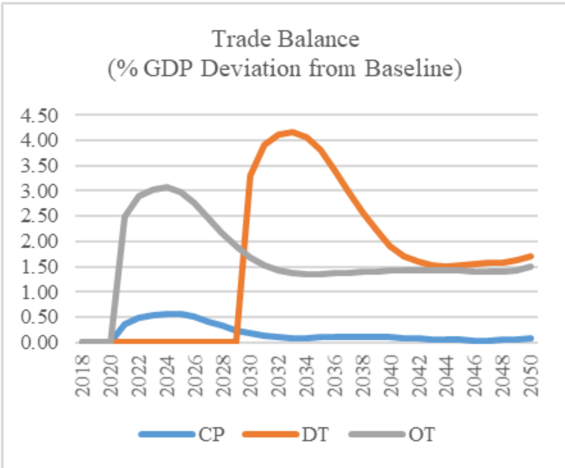




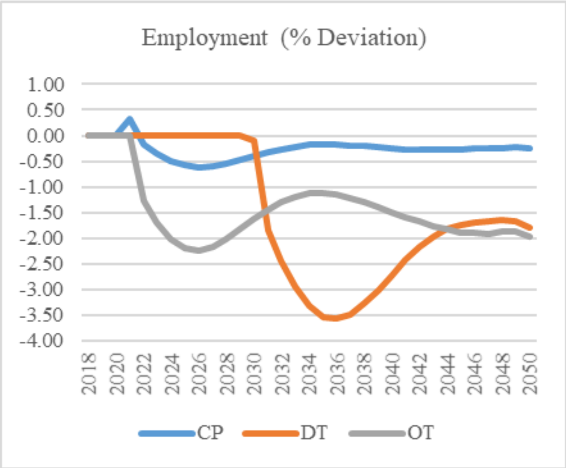


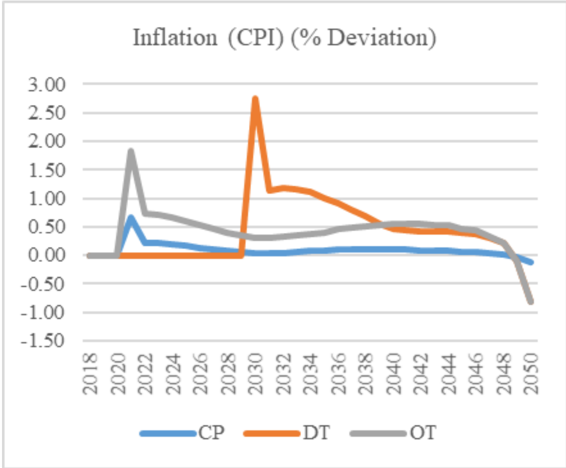


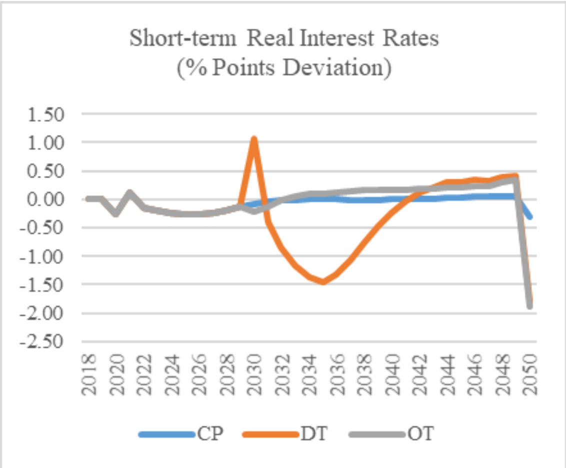


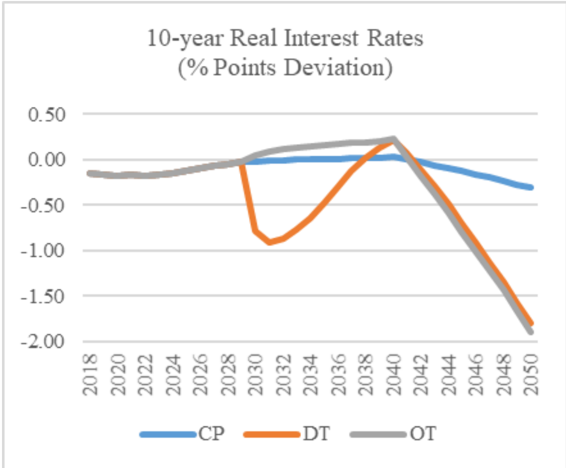


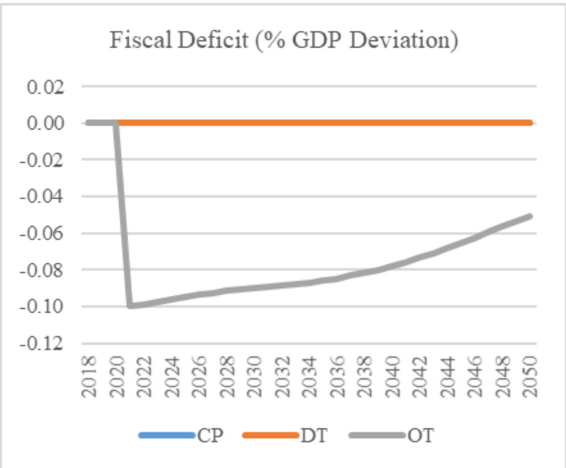
Dynamic Results: Oil Producing Developing Countries (Contd.)

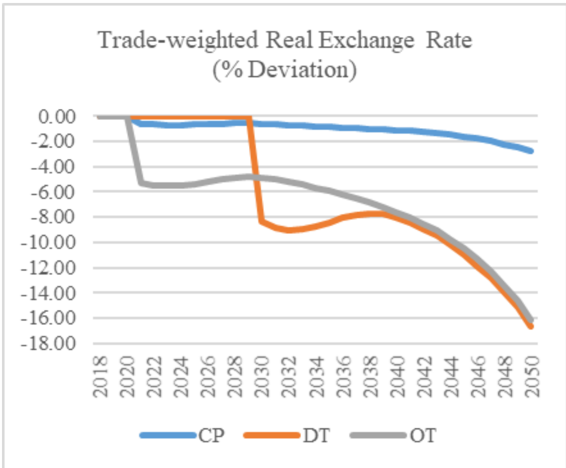




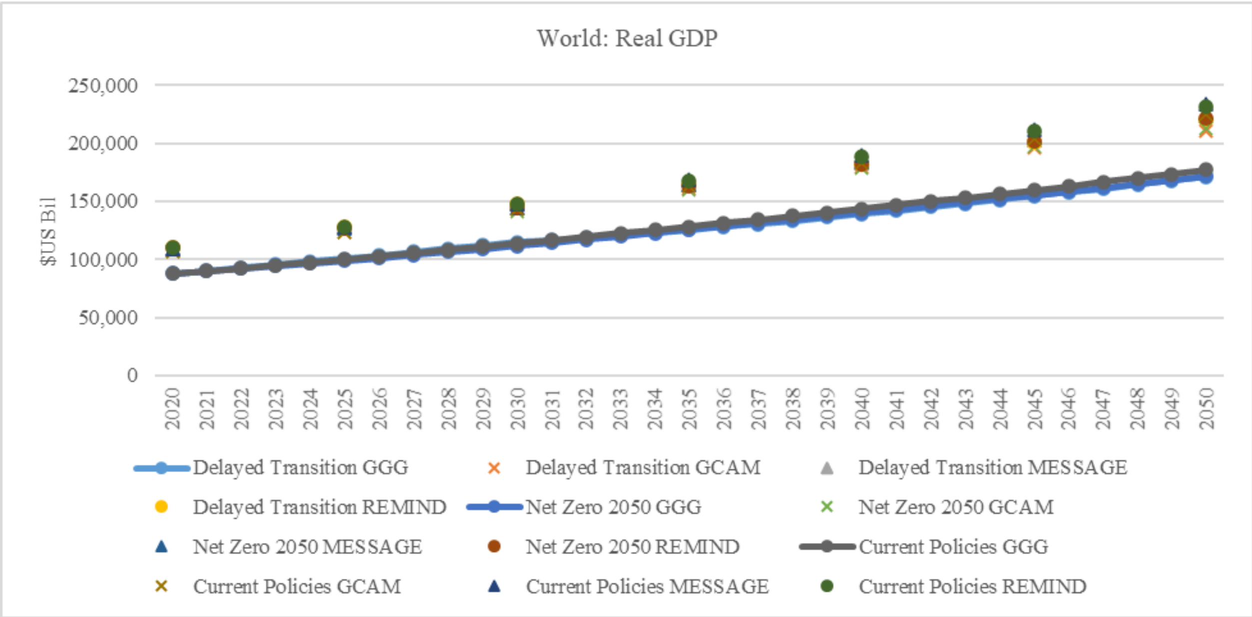


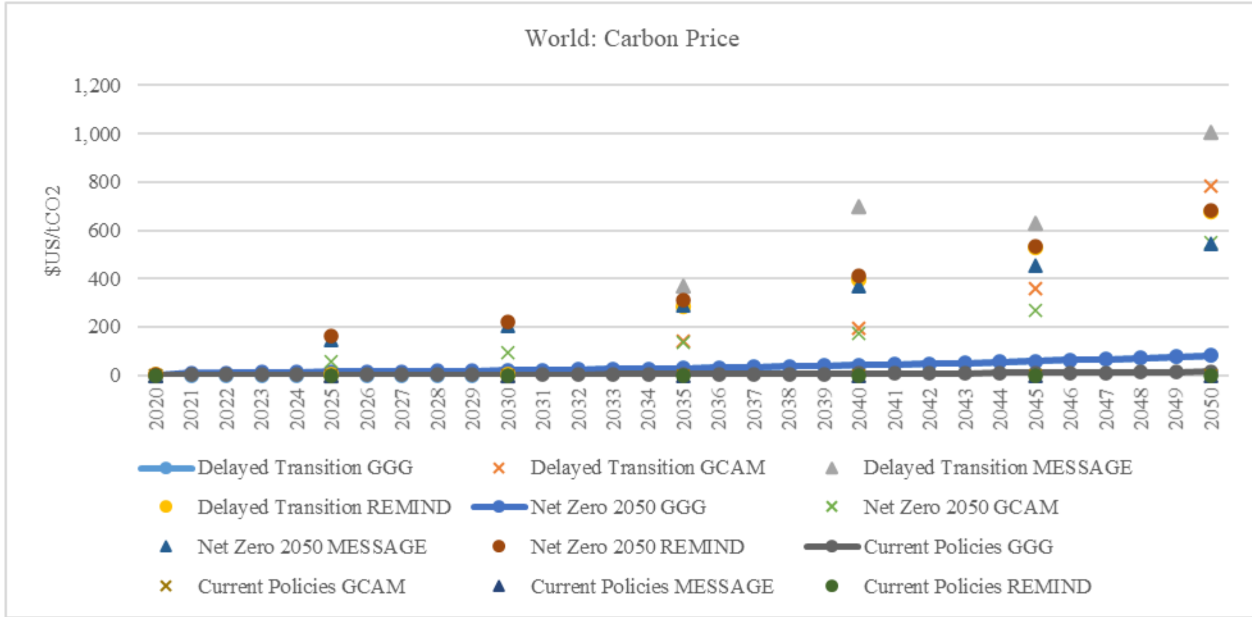


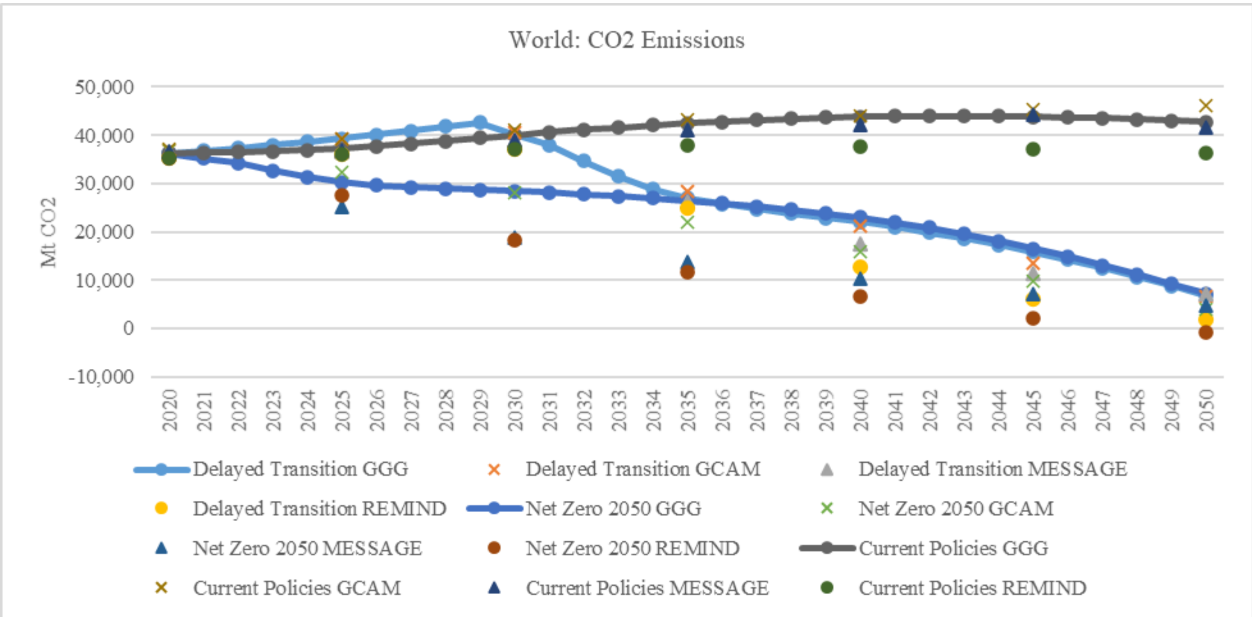


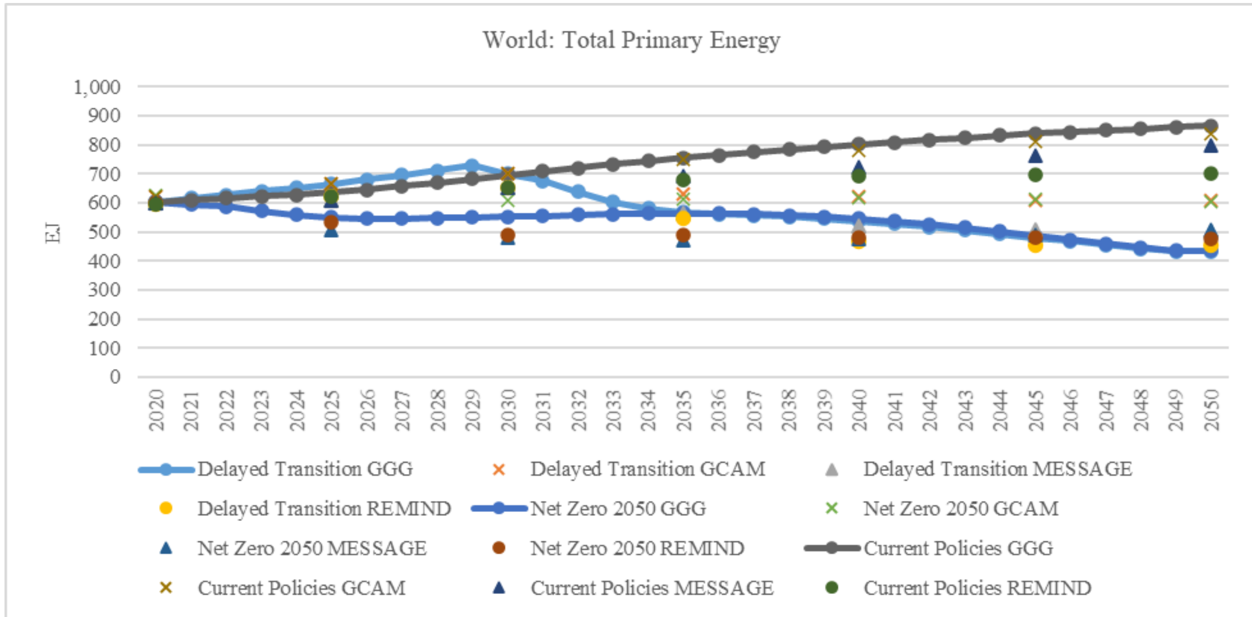


Comparison of Scenario Results among G-Cubed and NGFS IAMs: World

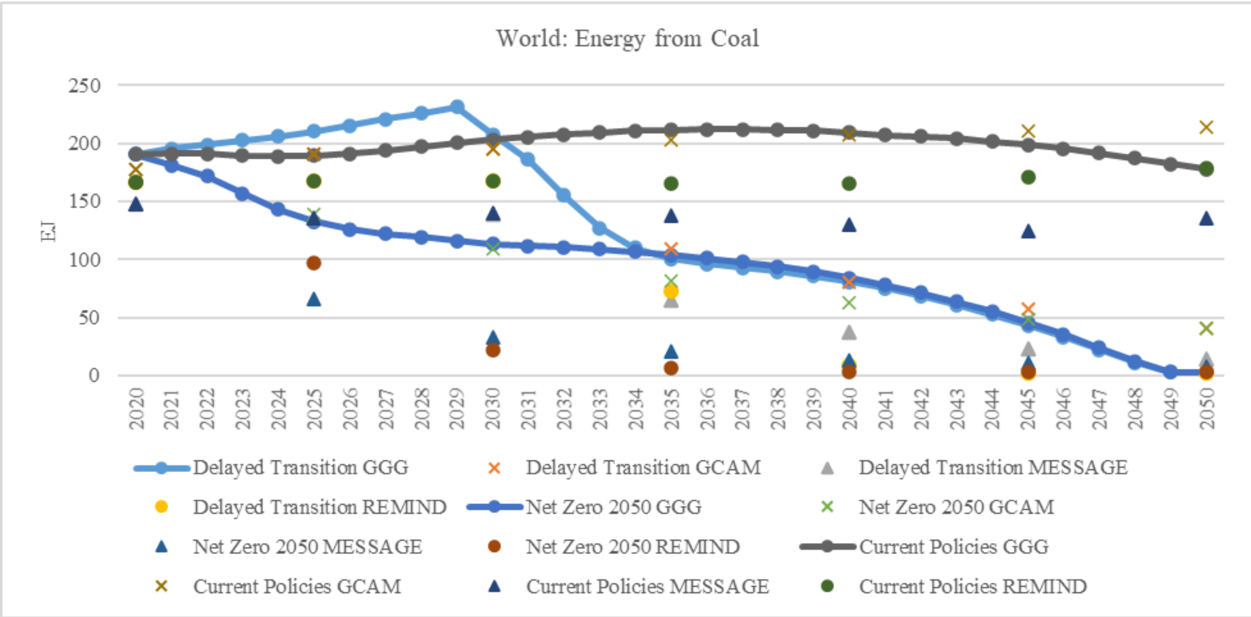


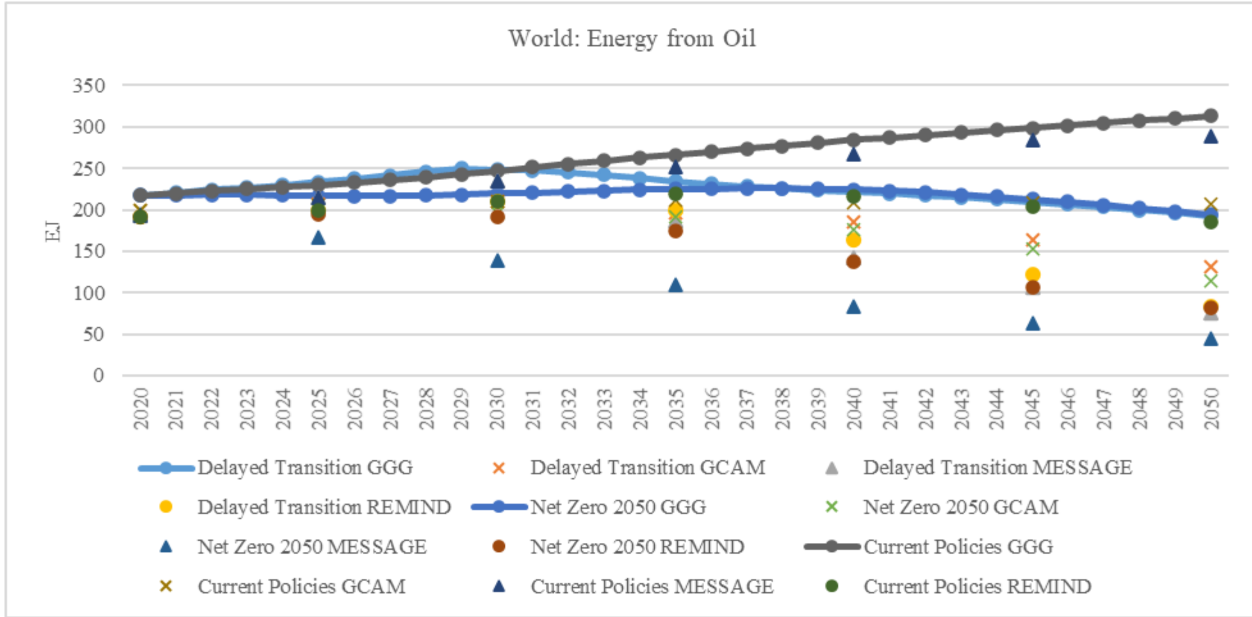


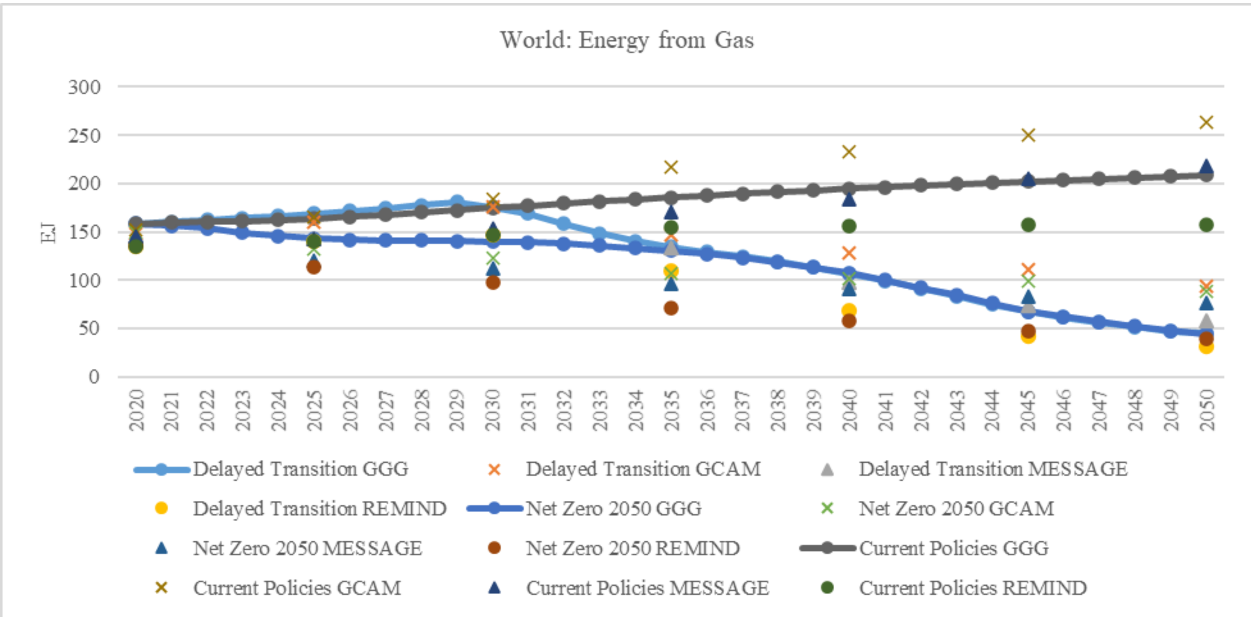


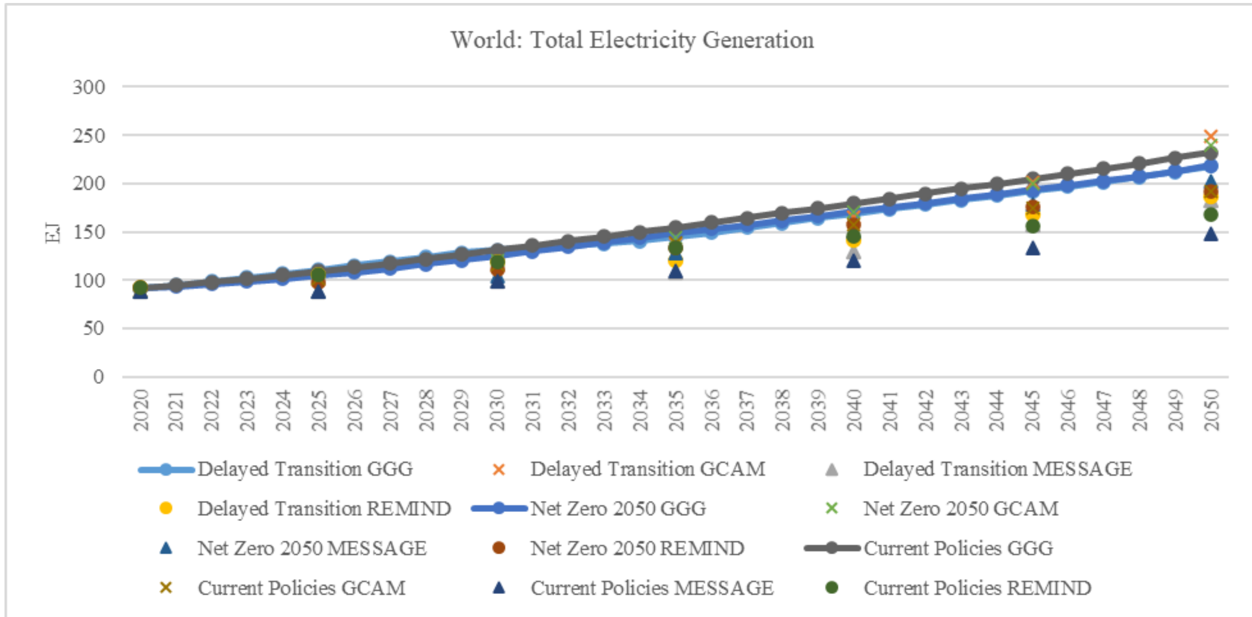


Comparison of Scenario Results among G-Cubed and NGFS IAMs: World (Contd.)

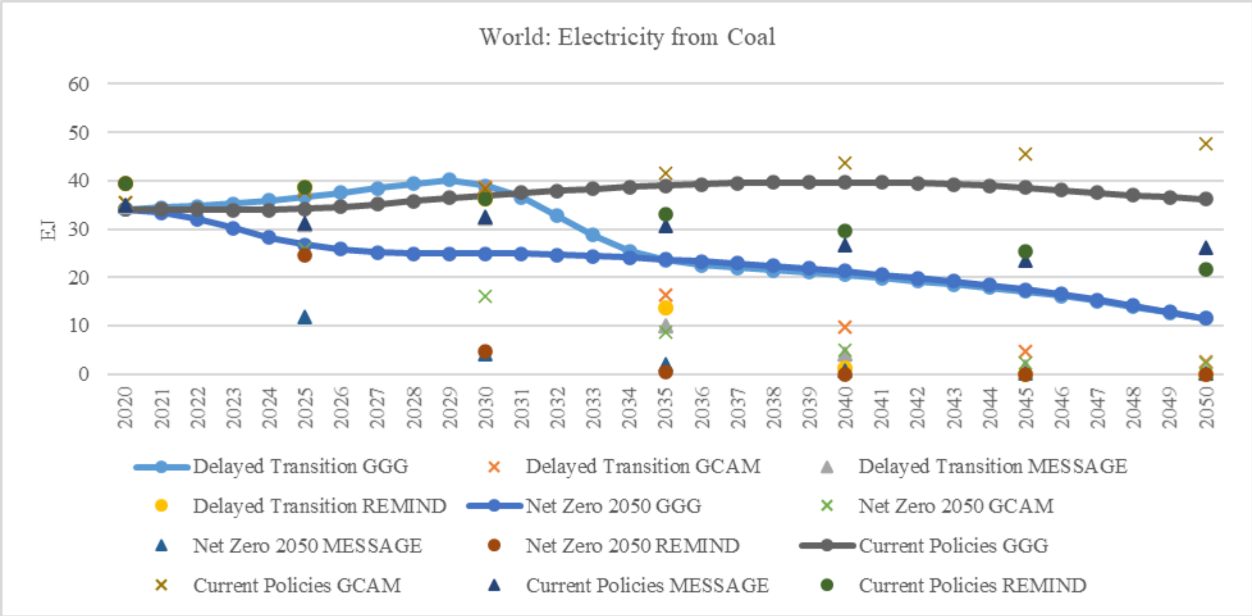


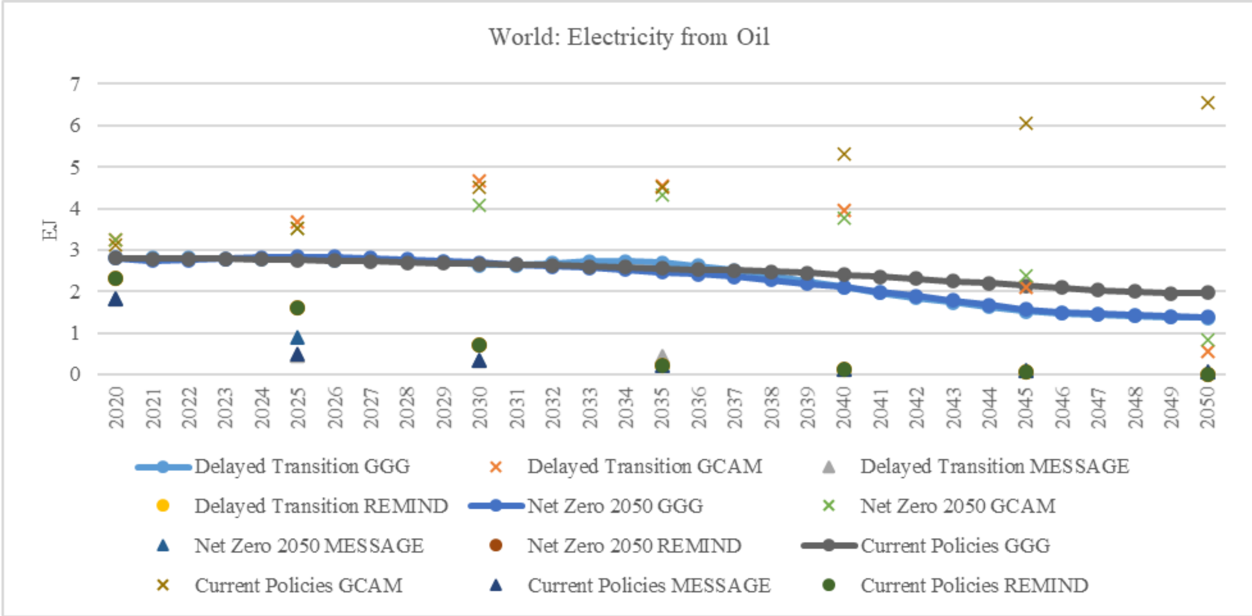


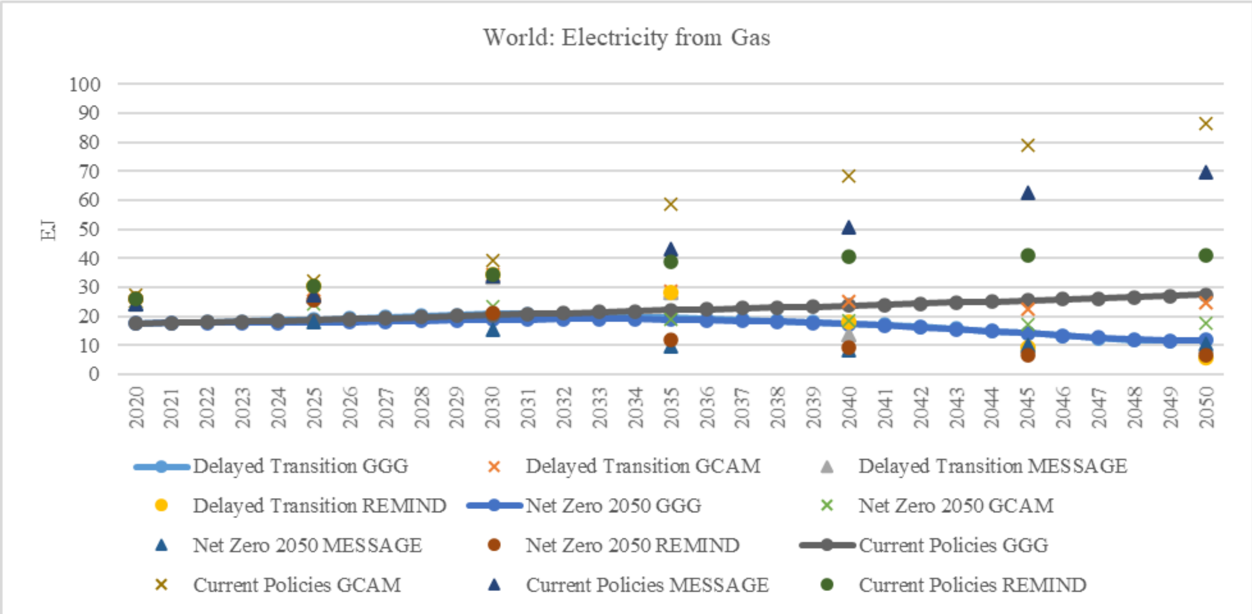


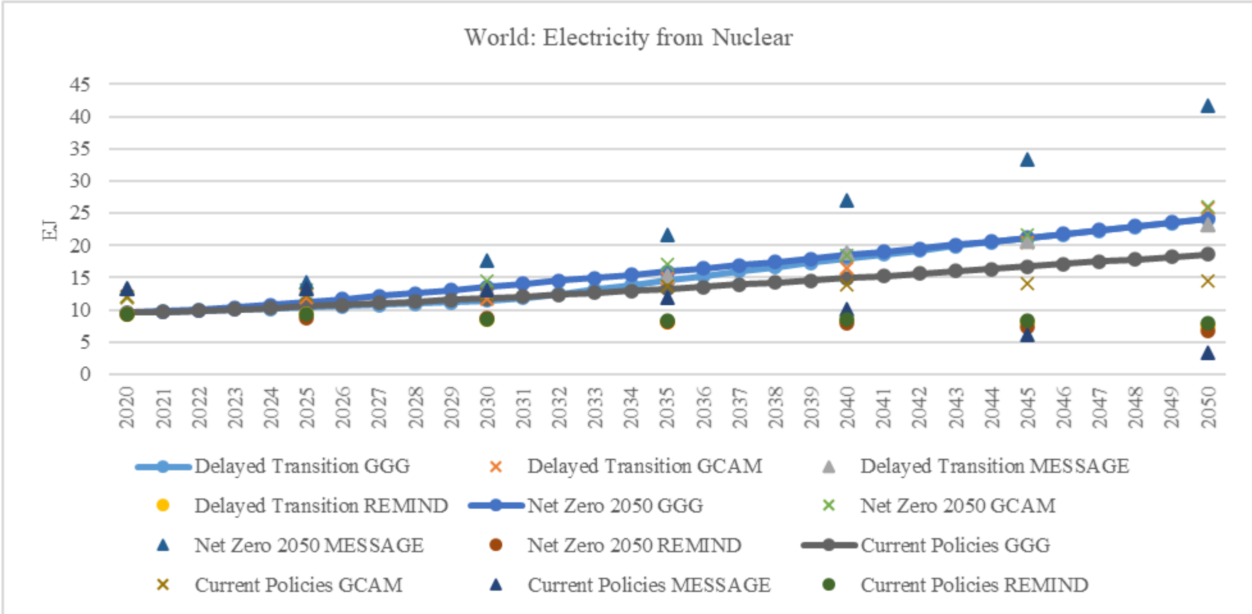


Comparison of Scenario Results among G-Cubed and NGFS IAMs: World (Contd.)

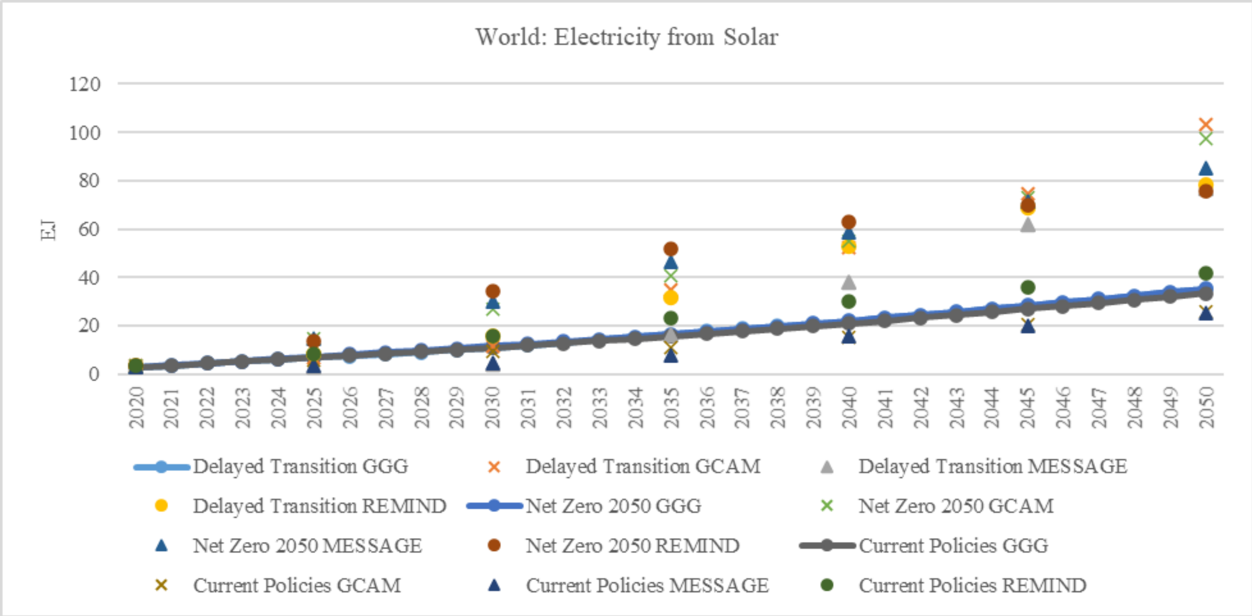


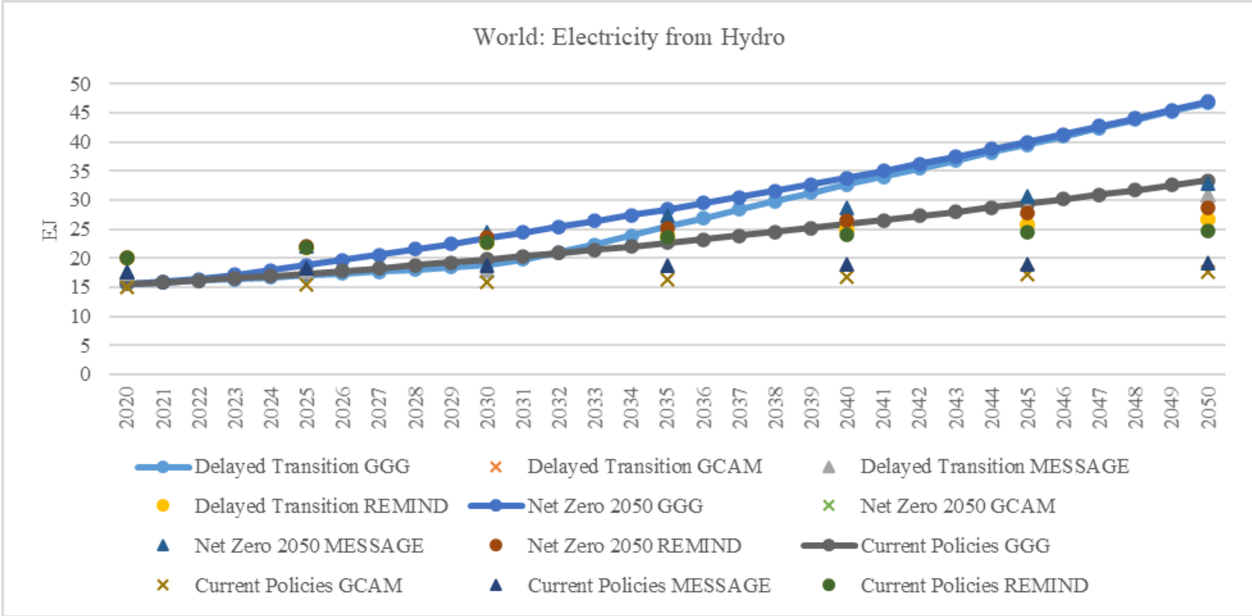


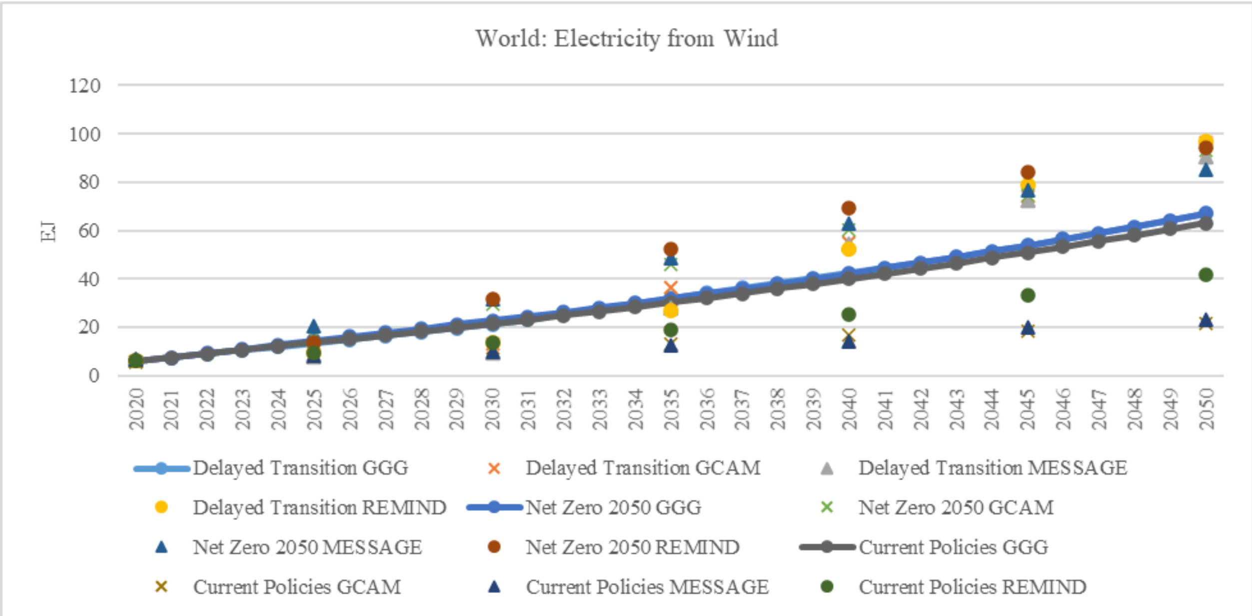


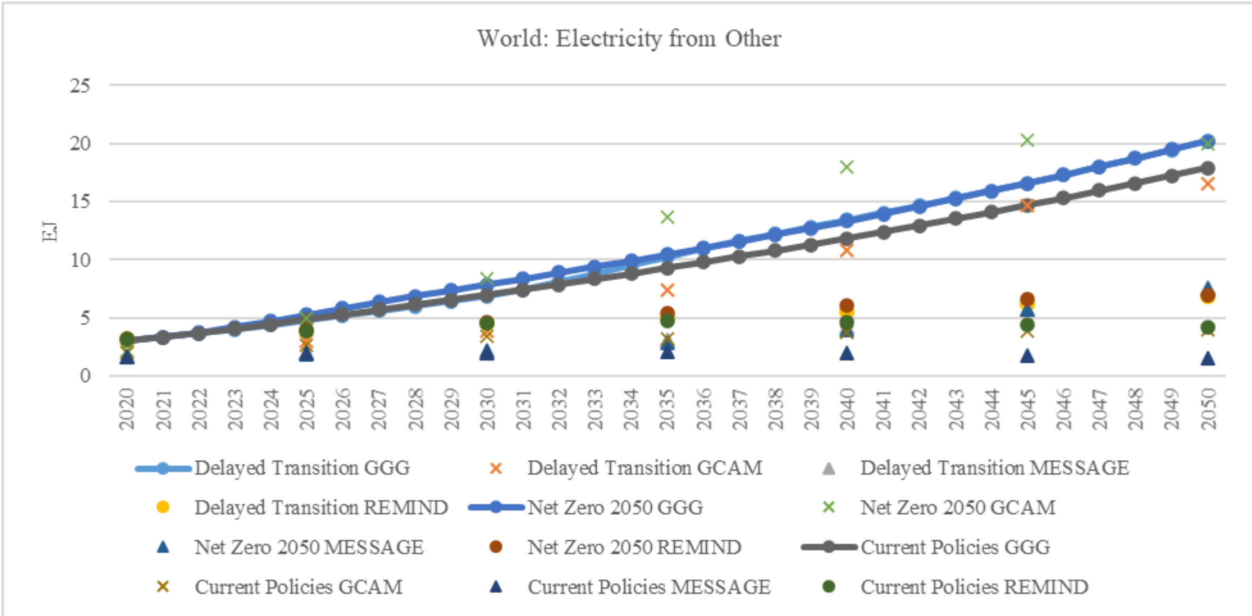


Comparison of Scenario Results among G-Cubed and NGFS IAMs: World (Contd.)

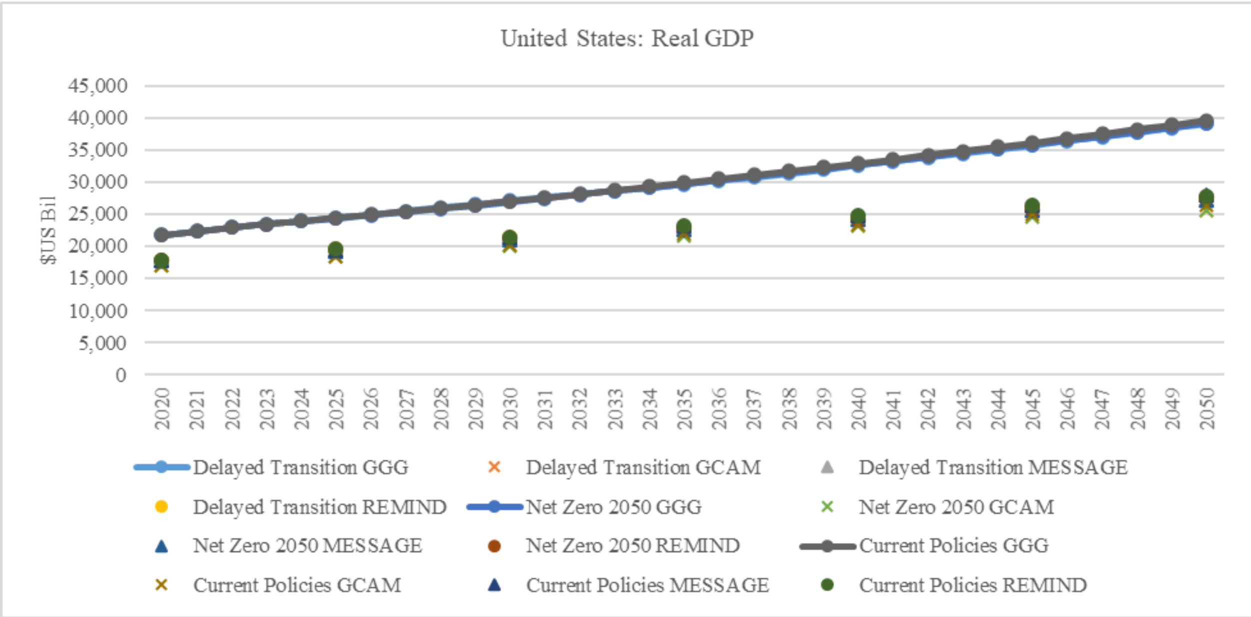


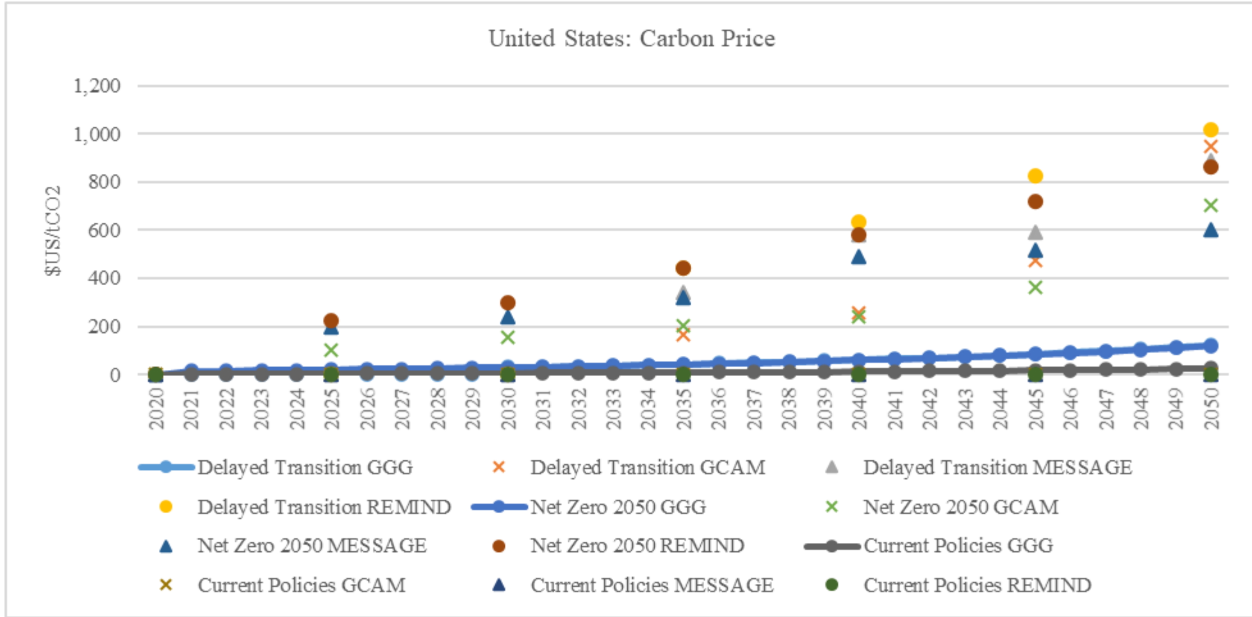


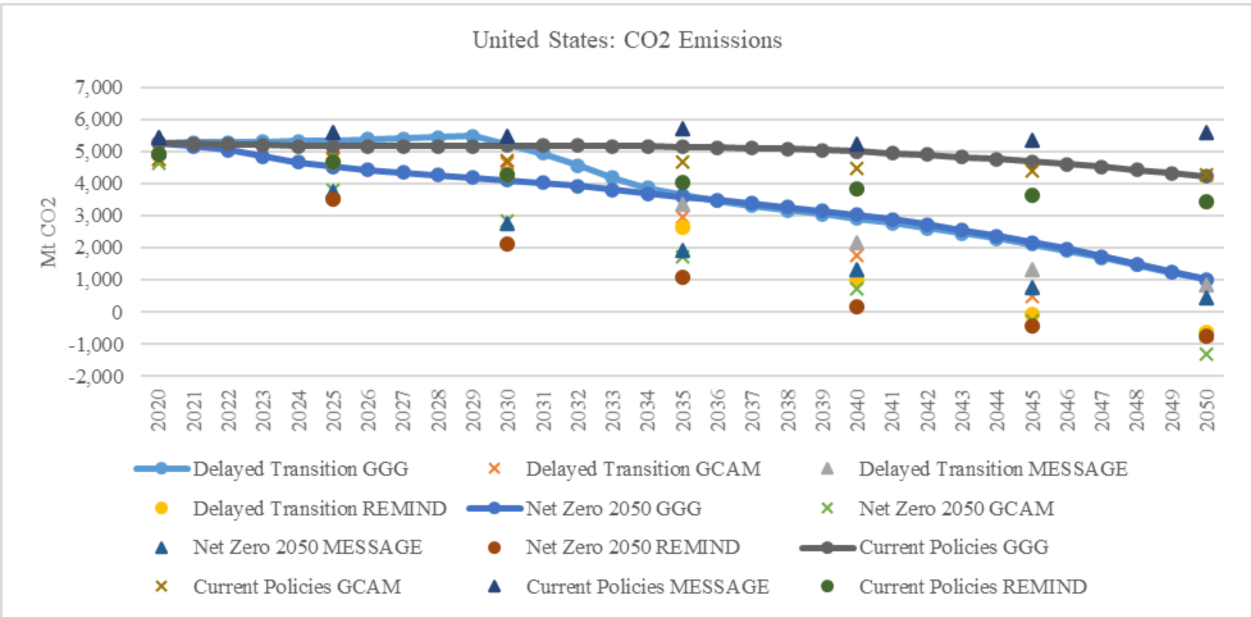


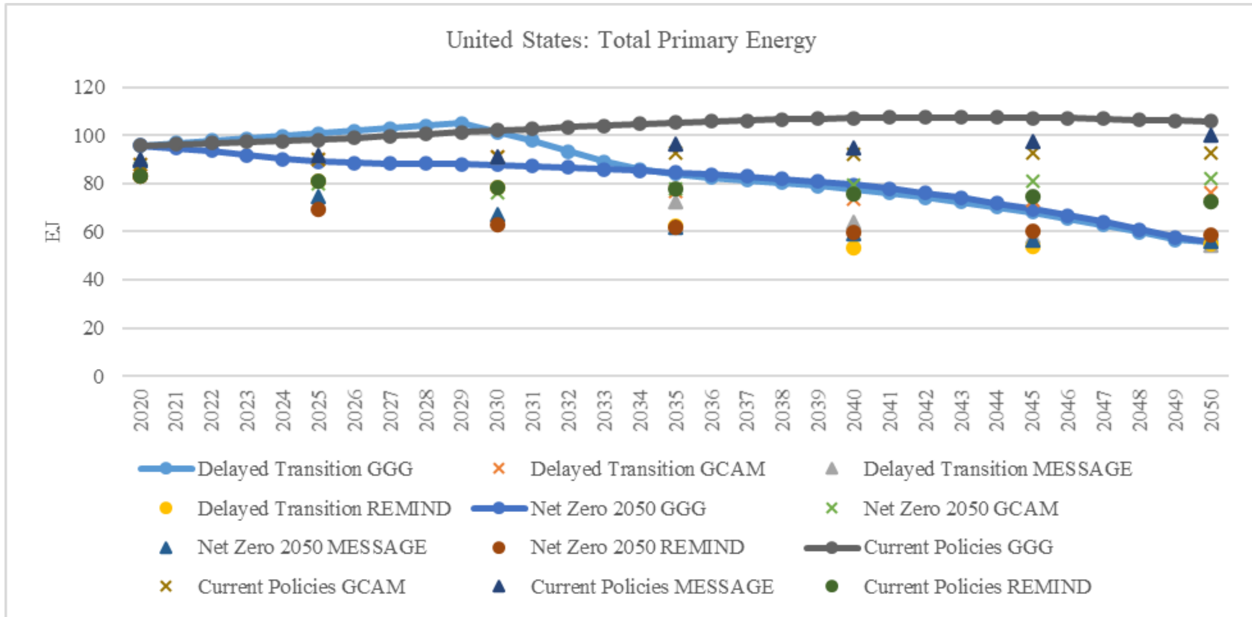


Comparison of Scenario Results among G-Cubed and NGFS IAMs: United States

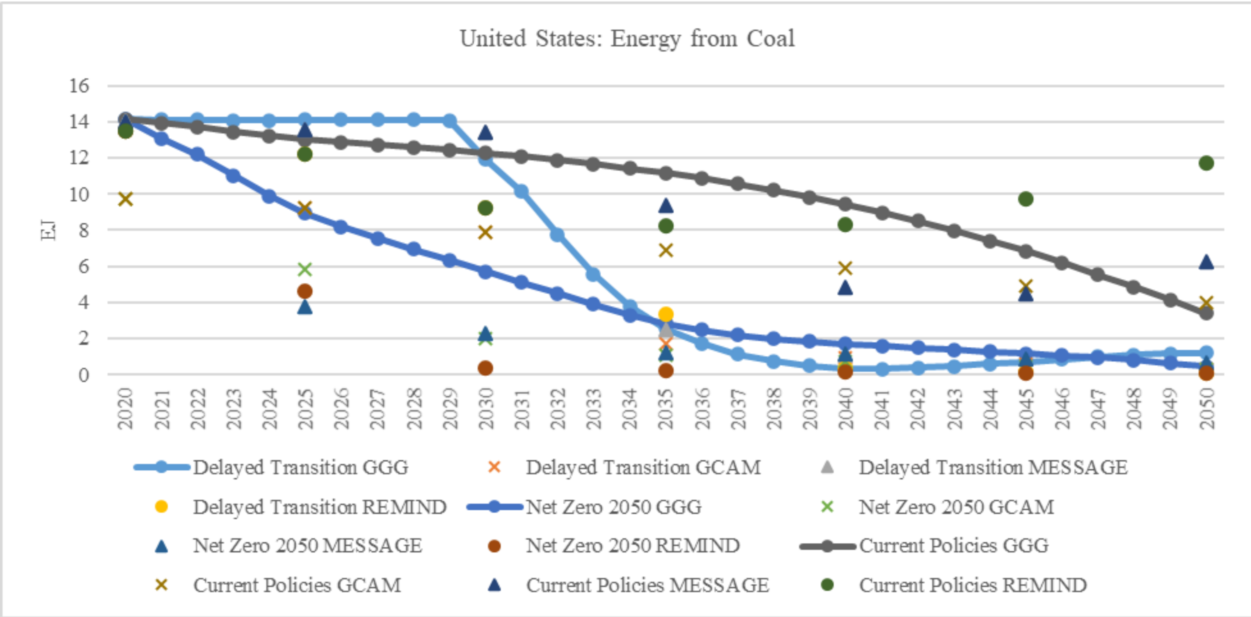


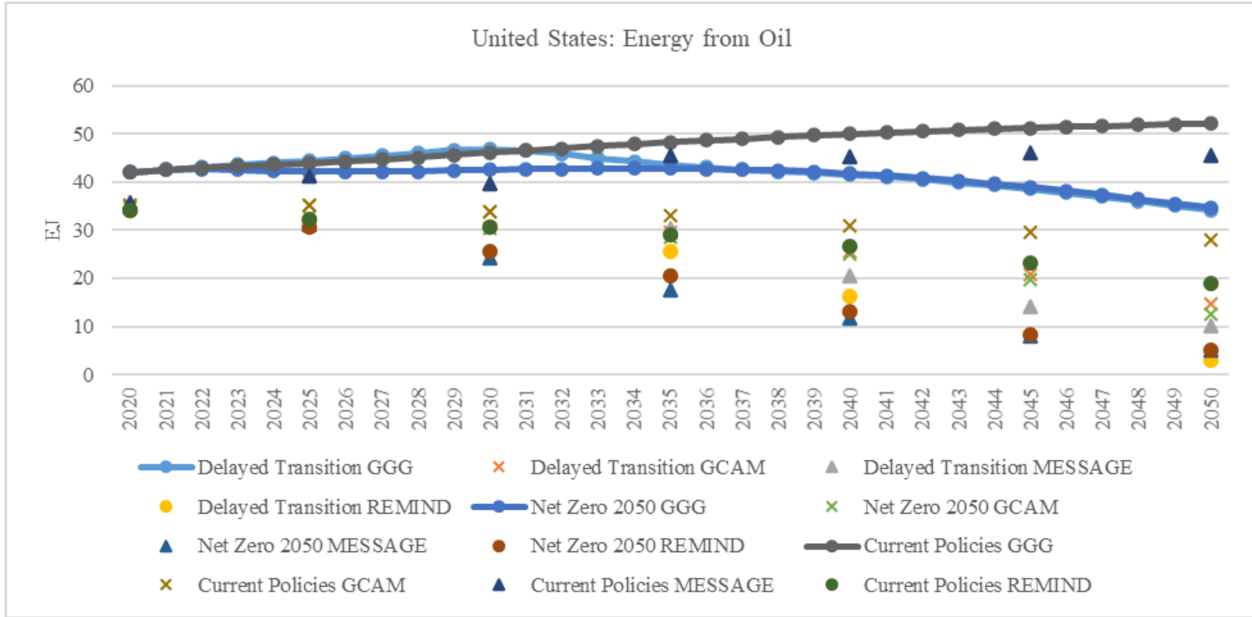


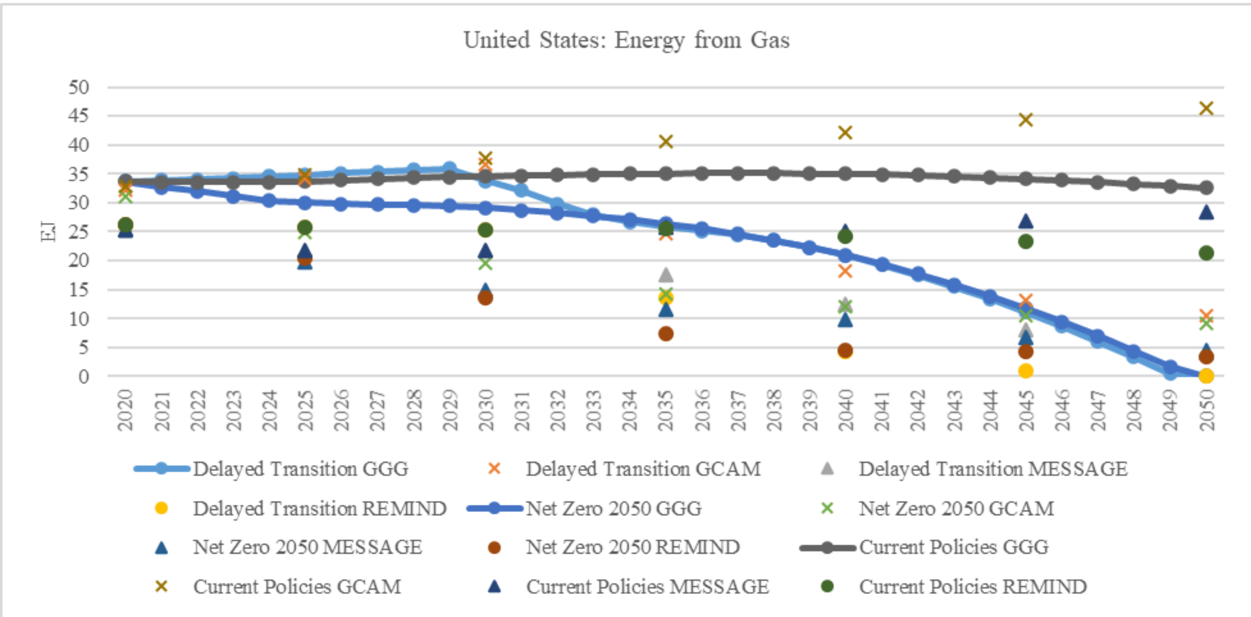


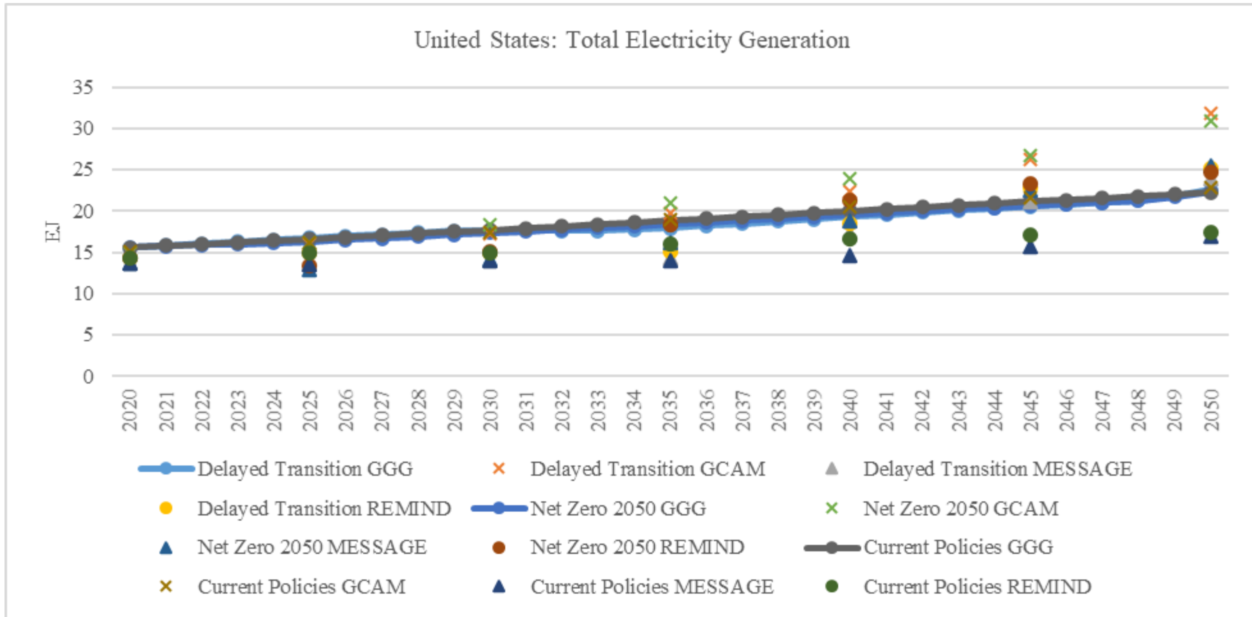


Comparison of Scenario Results among G-Cubed and NGFS IAMs: United States (Contd.)

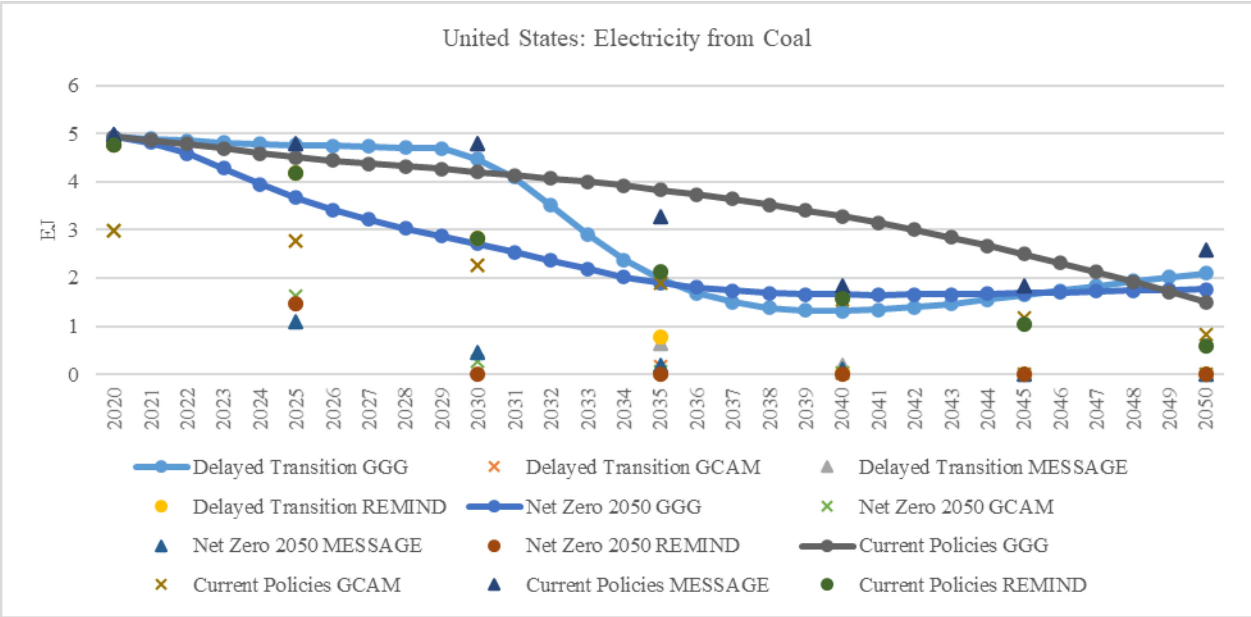


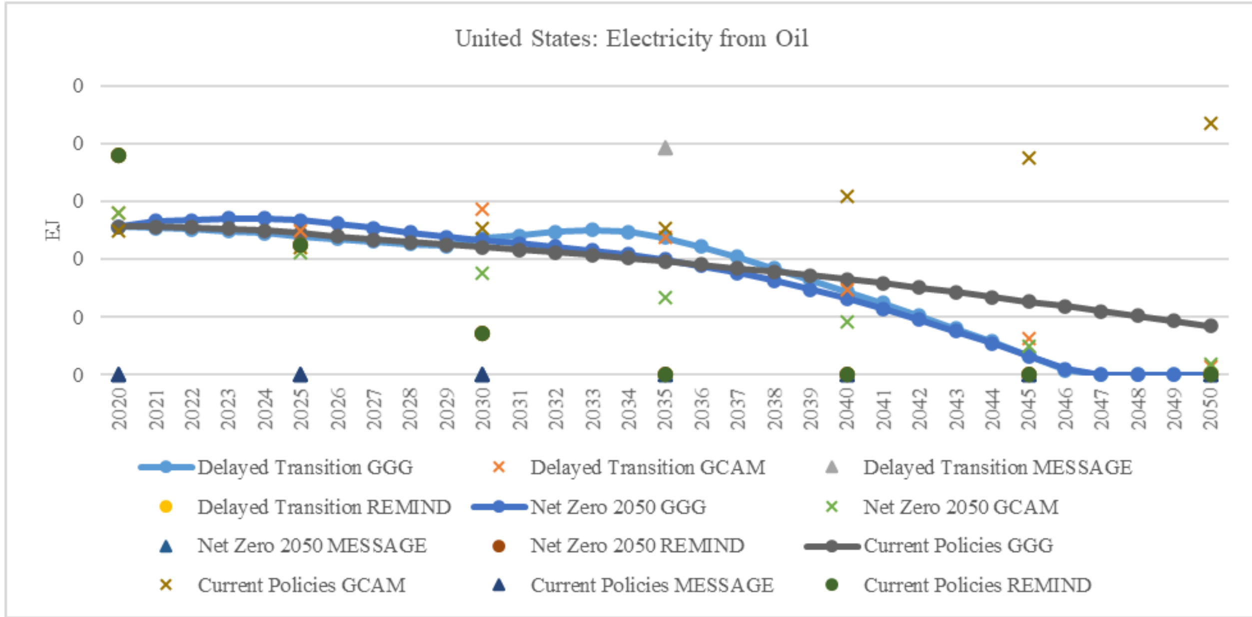


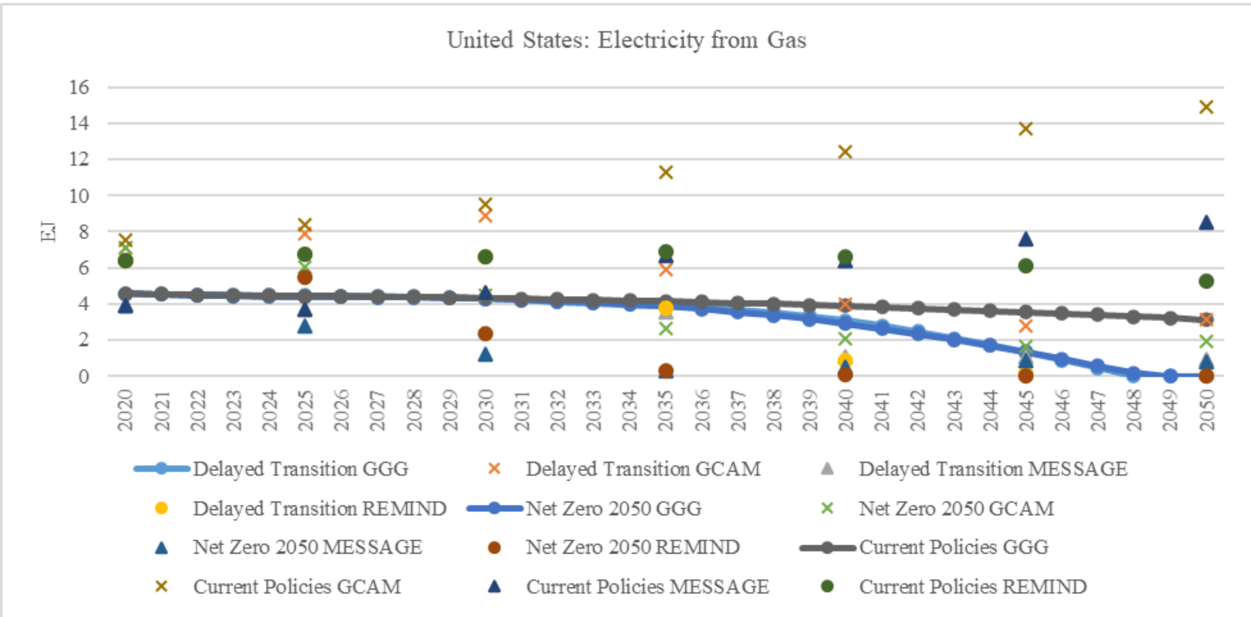


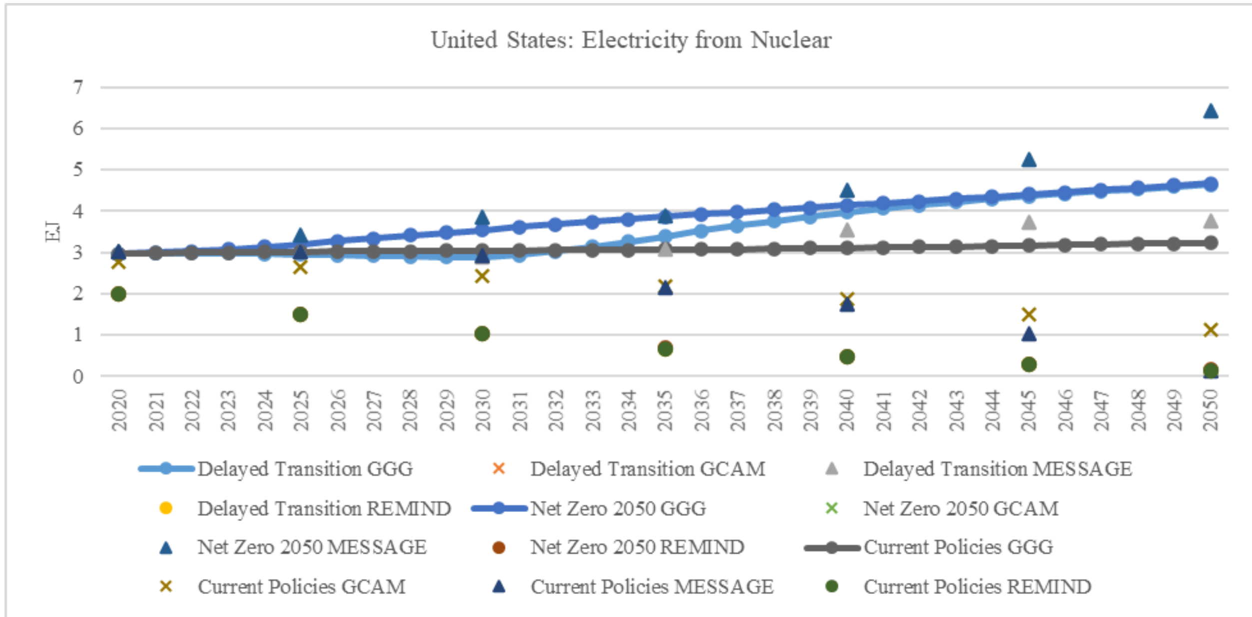


Comparison of Scenario Results among G-Cubed and NGFS IAMs: United States (Contd.)

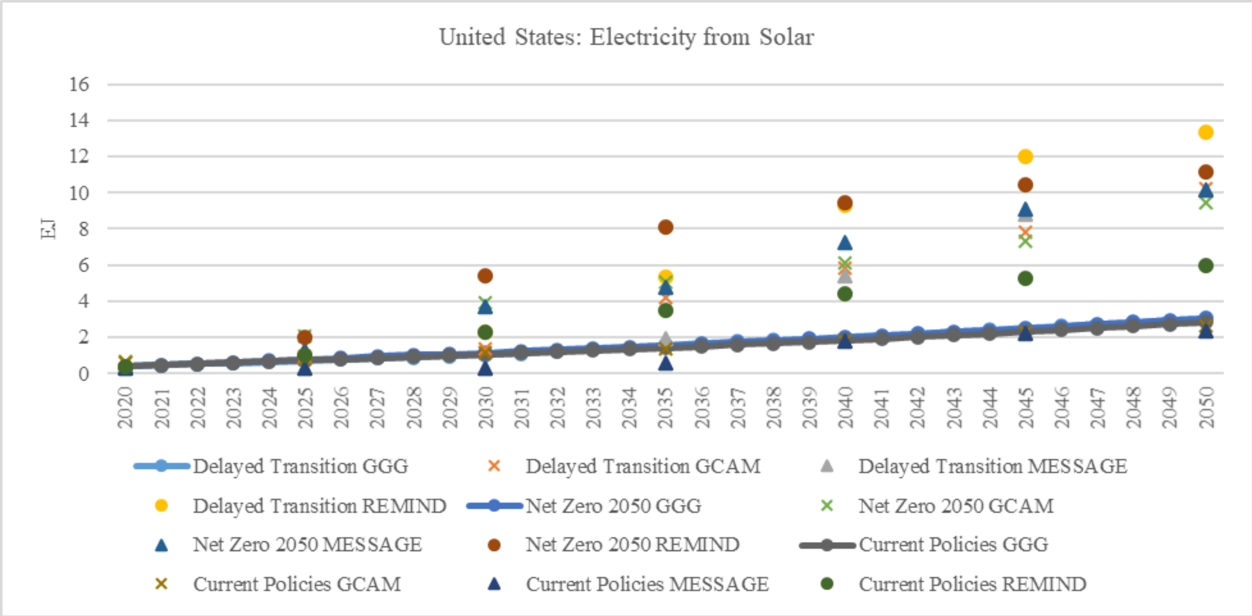


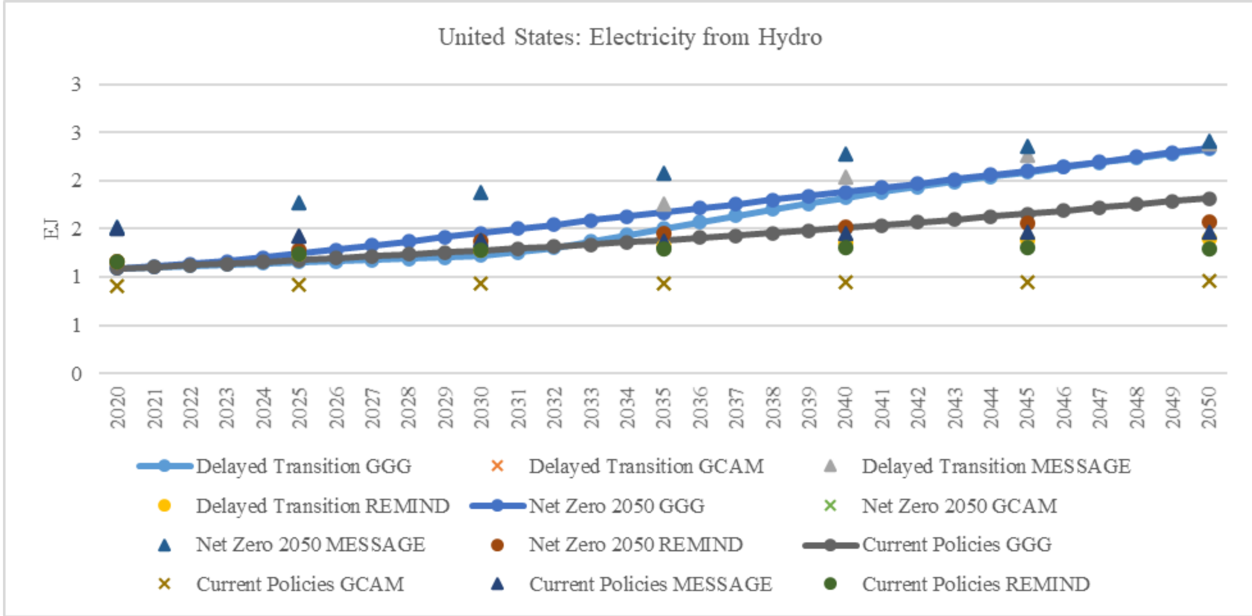


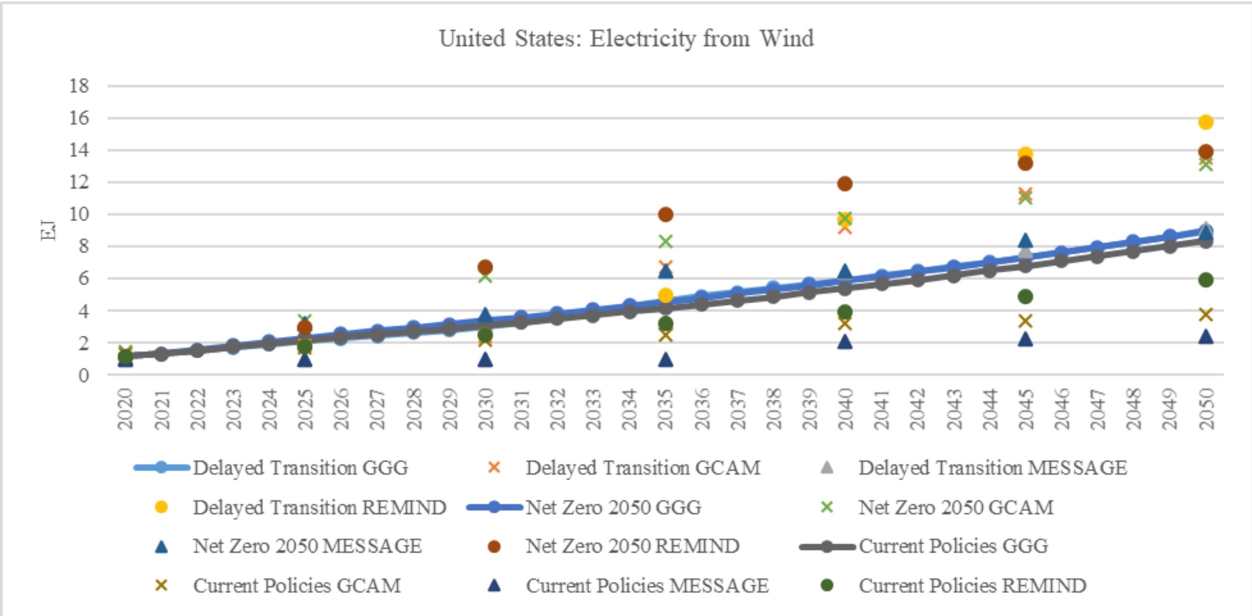


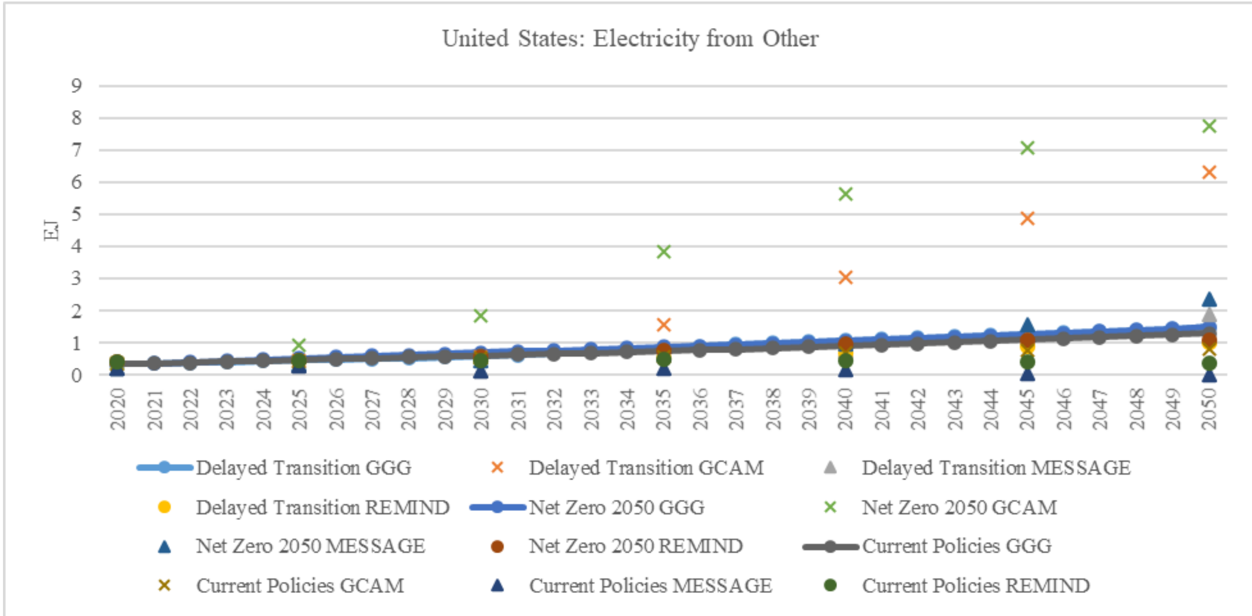


Comparison of Scenario Results among G-Cubed and NGFS IAMs: United States (Contd.)

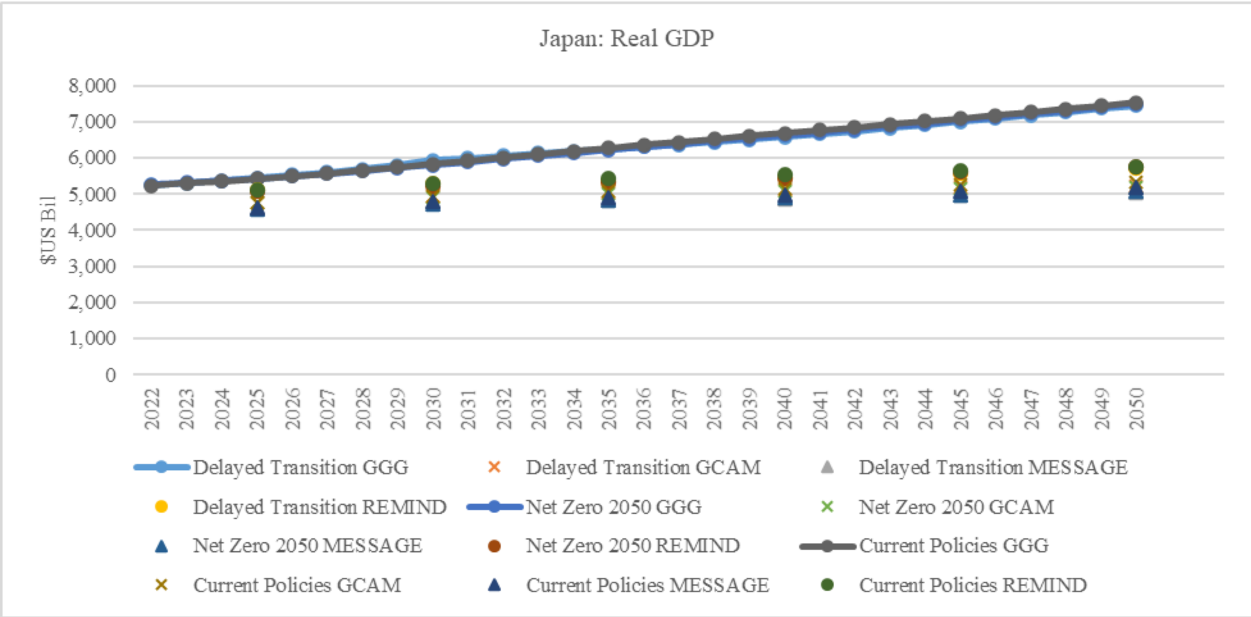


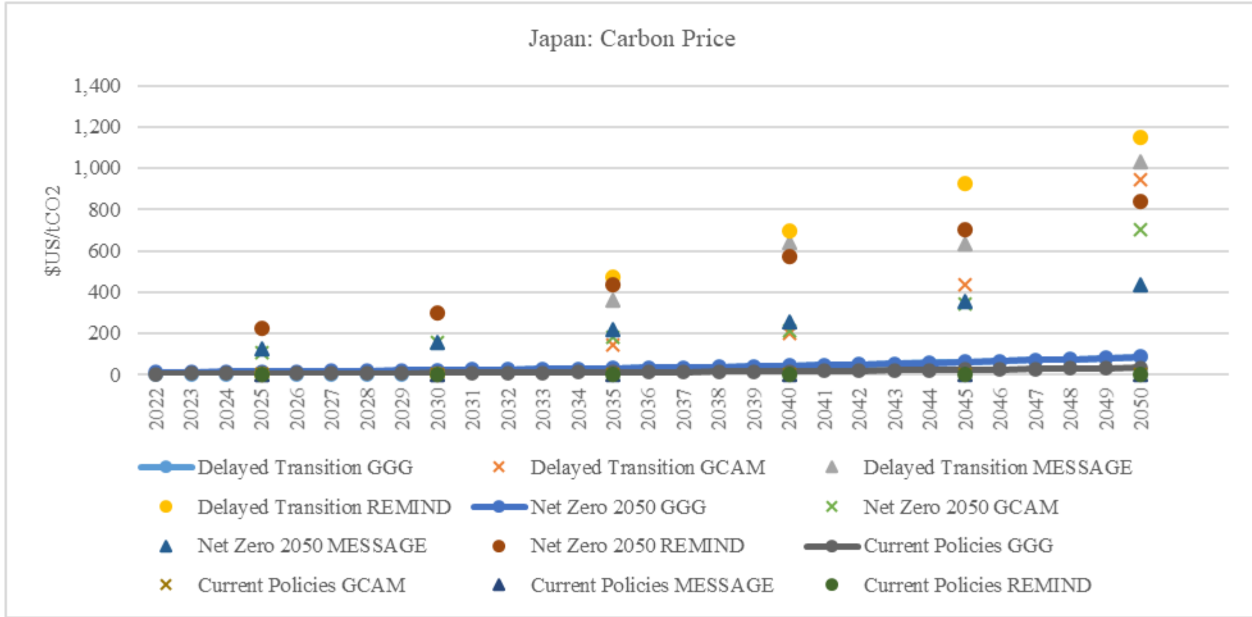


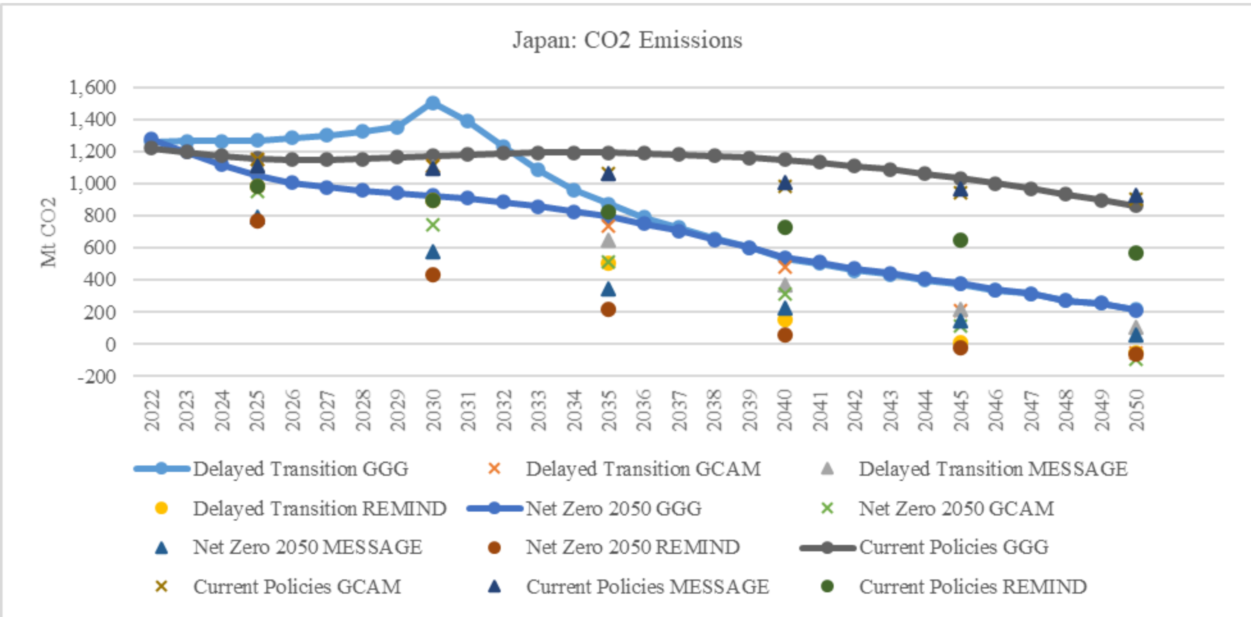


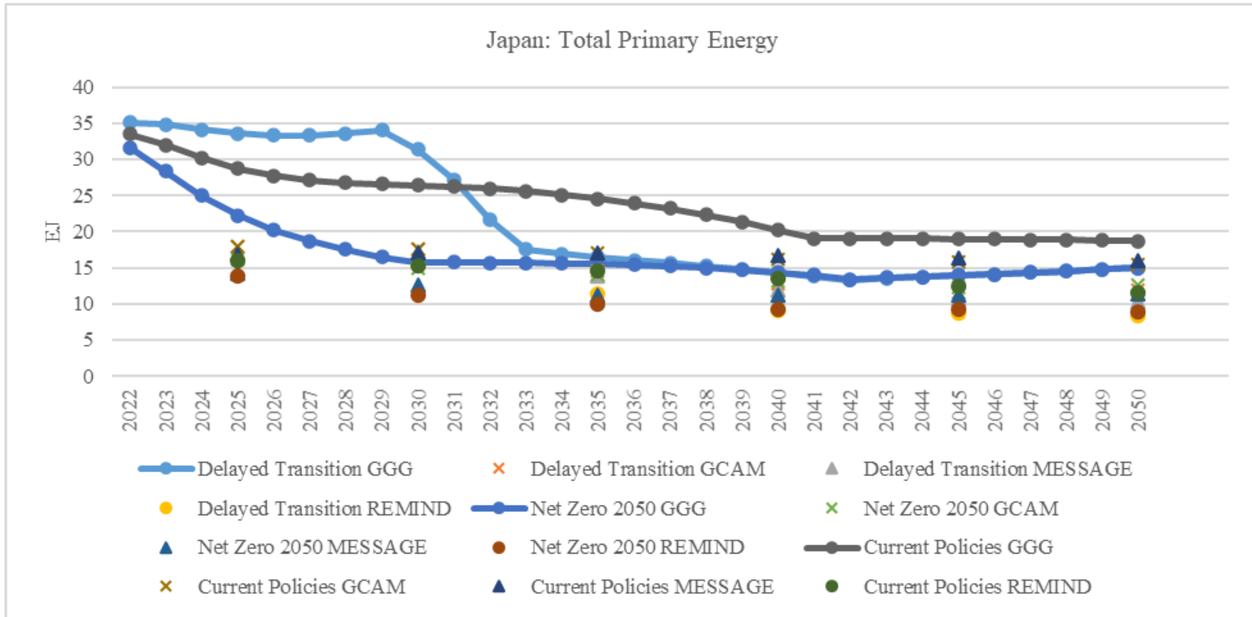


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Japan

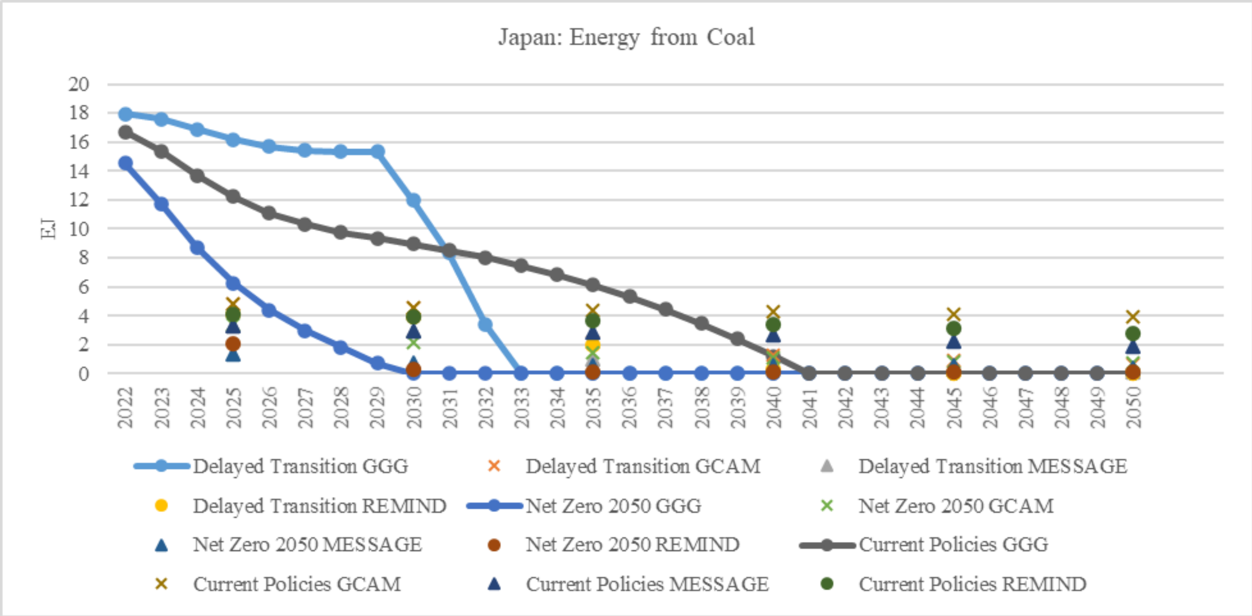


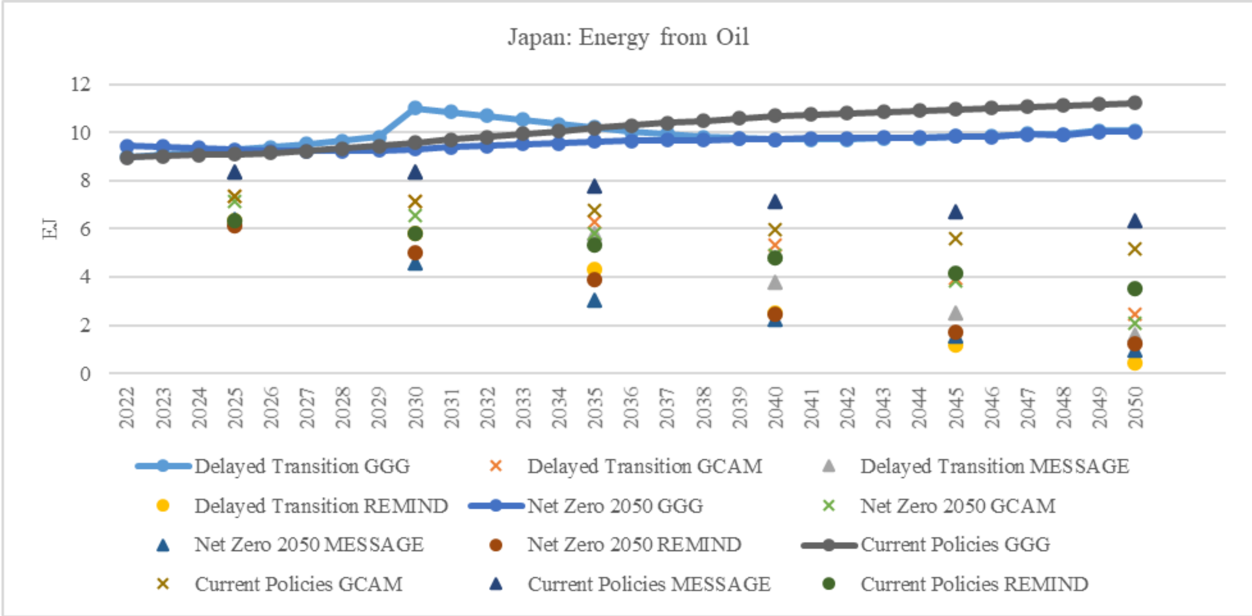


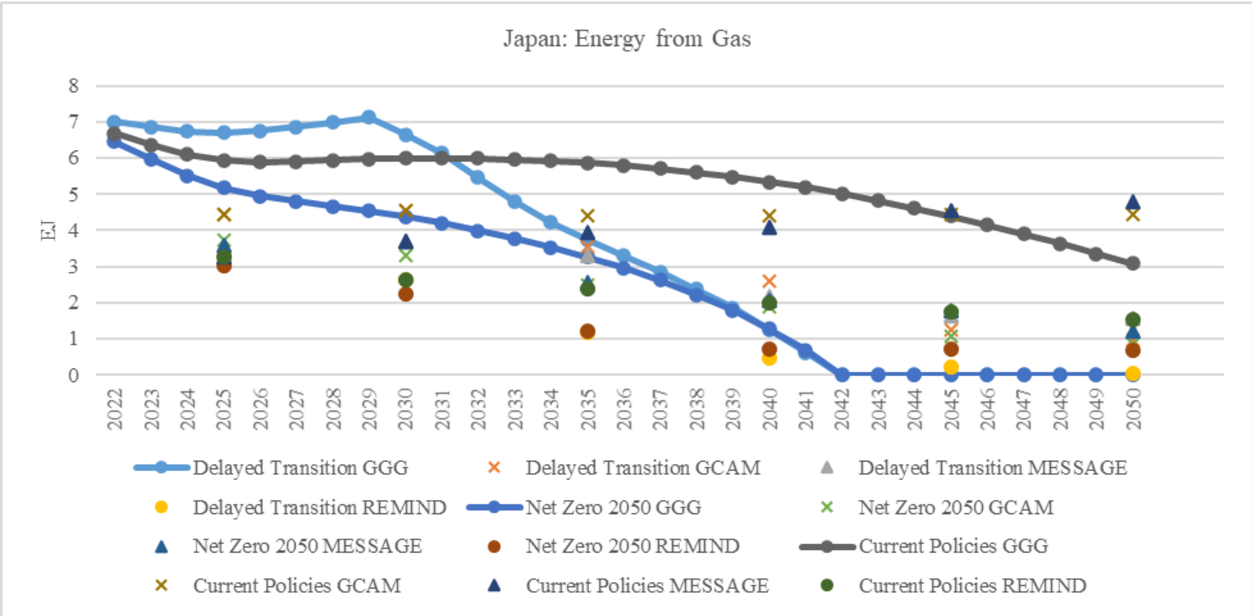


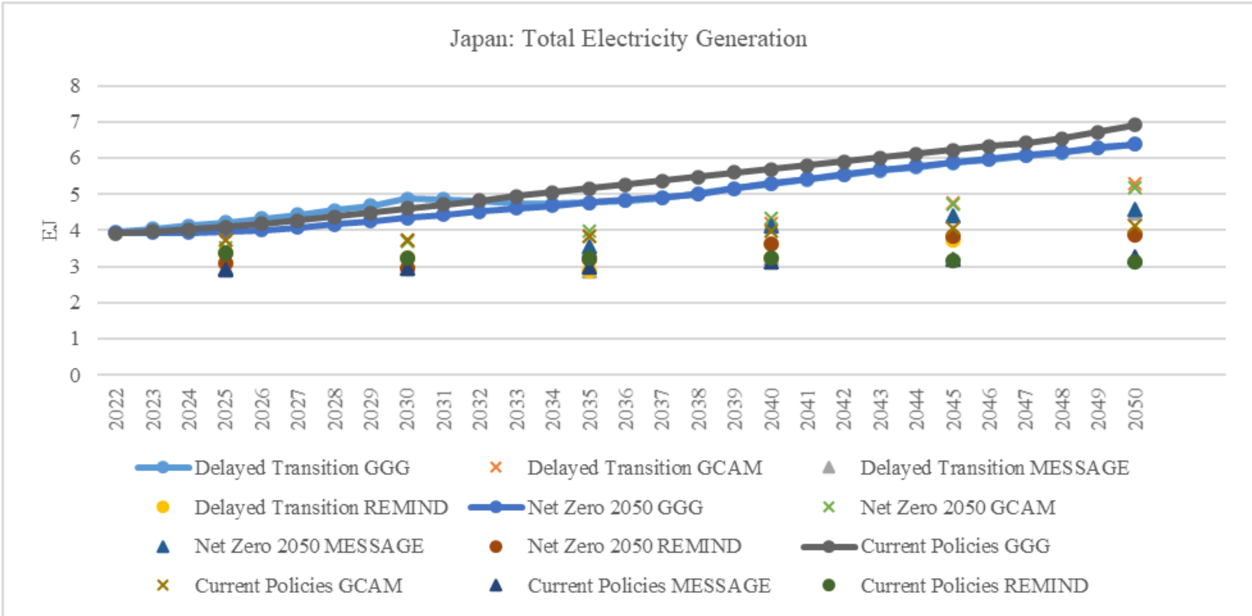


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Japan (Contd.)

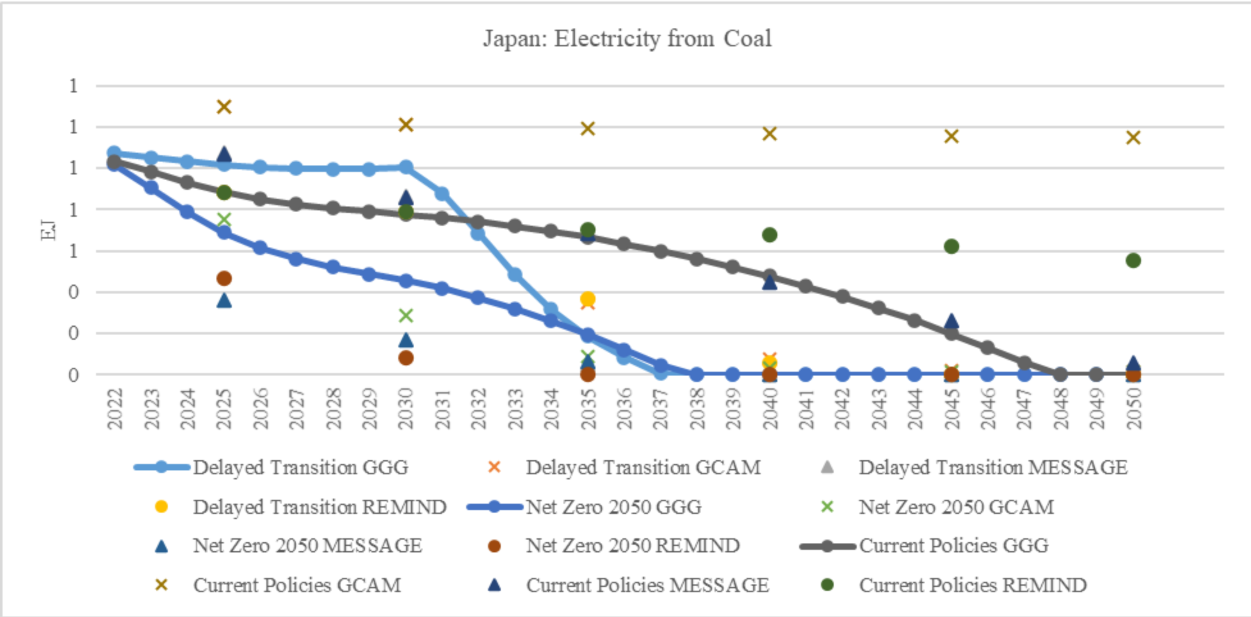


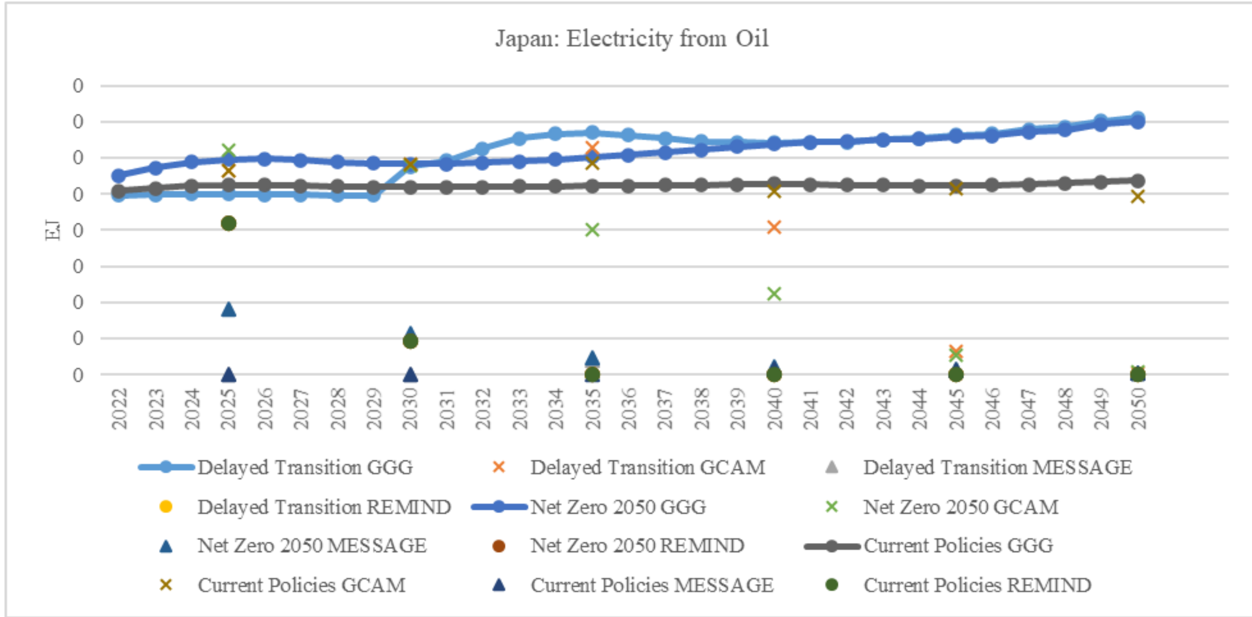


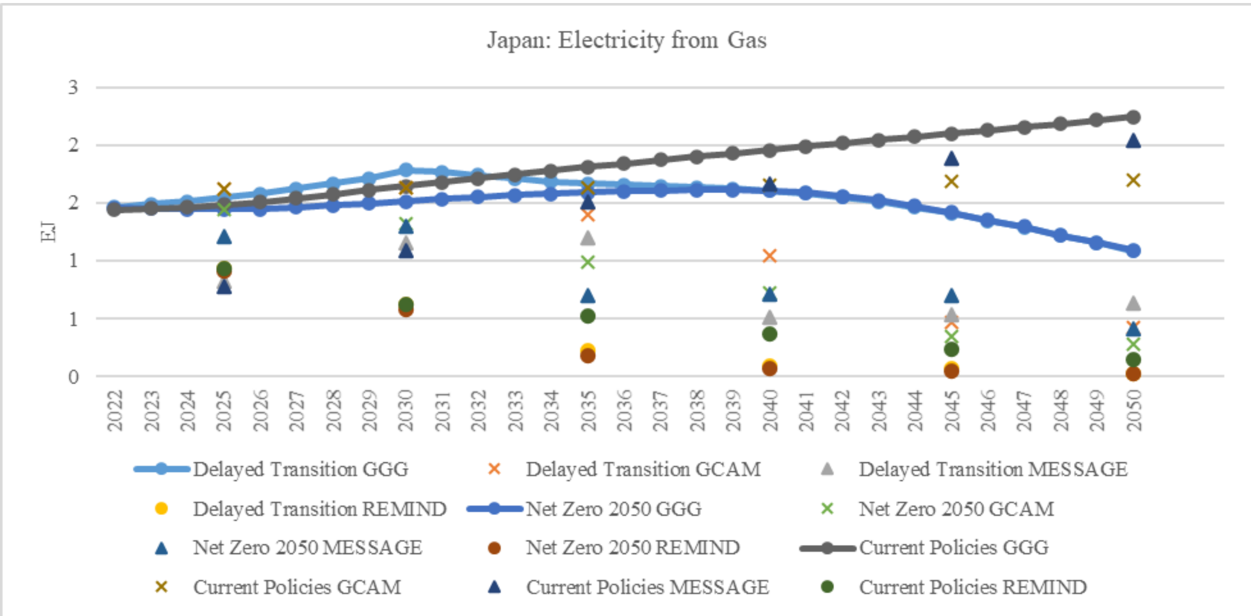


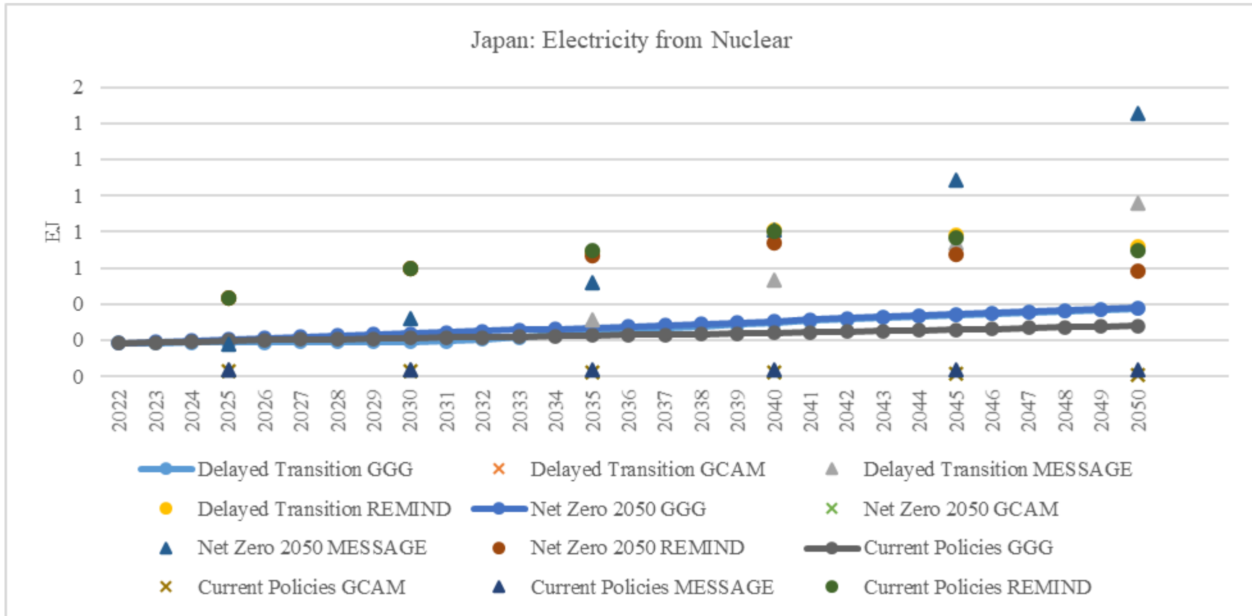


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Japan (Contd.)

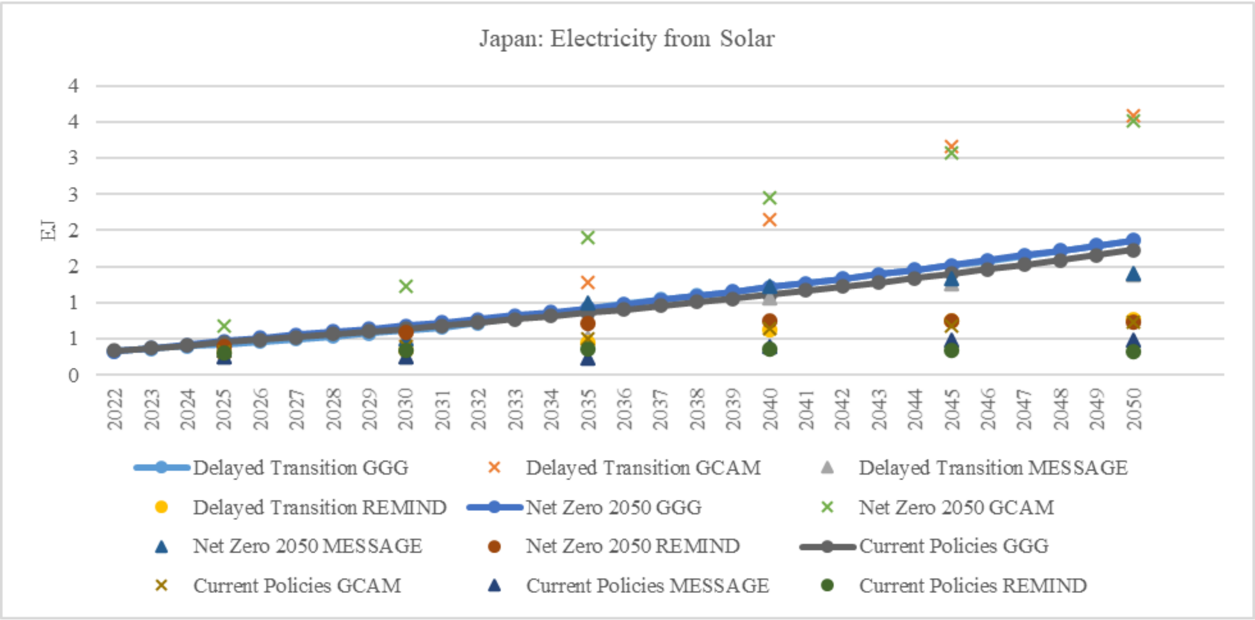


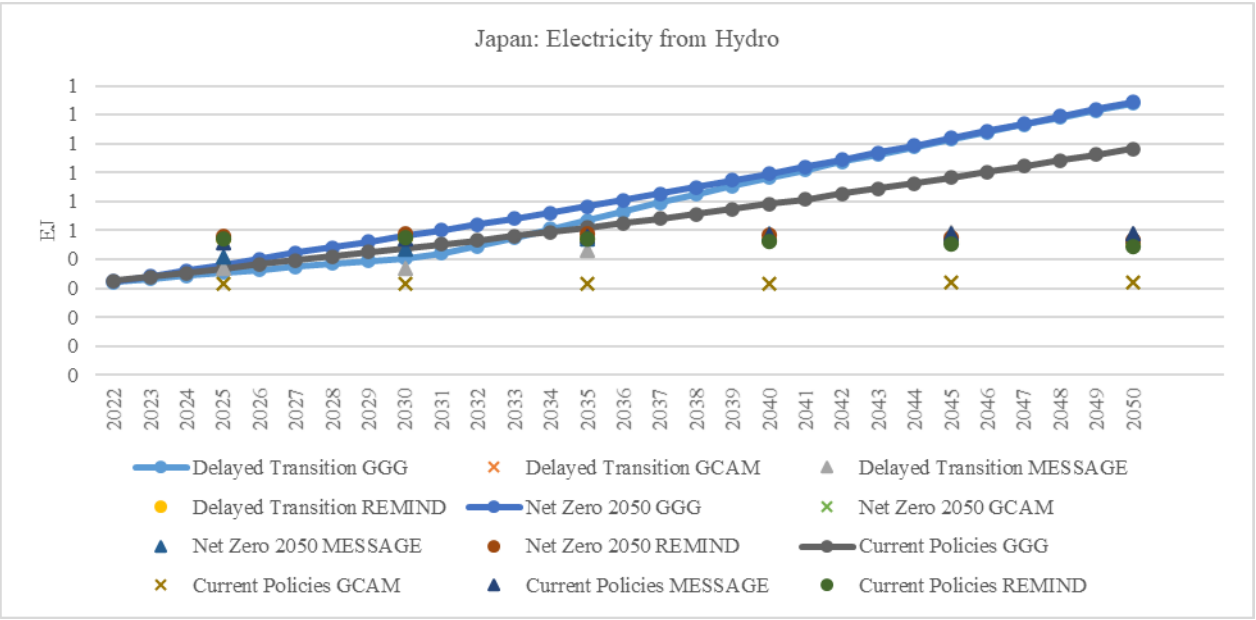


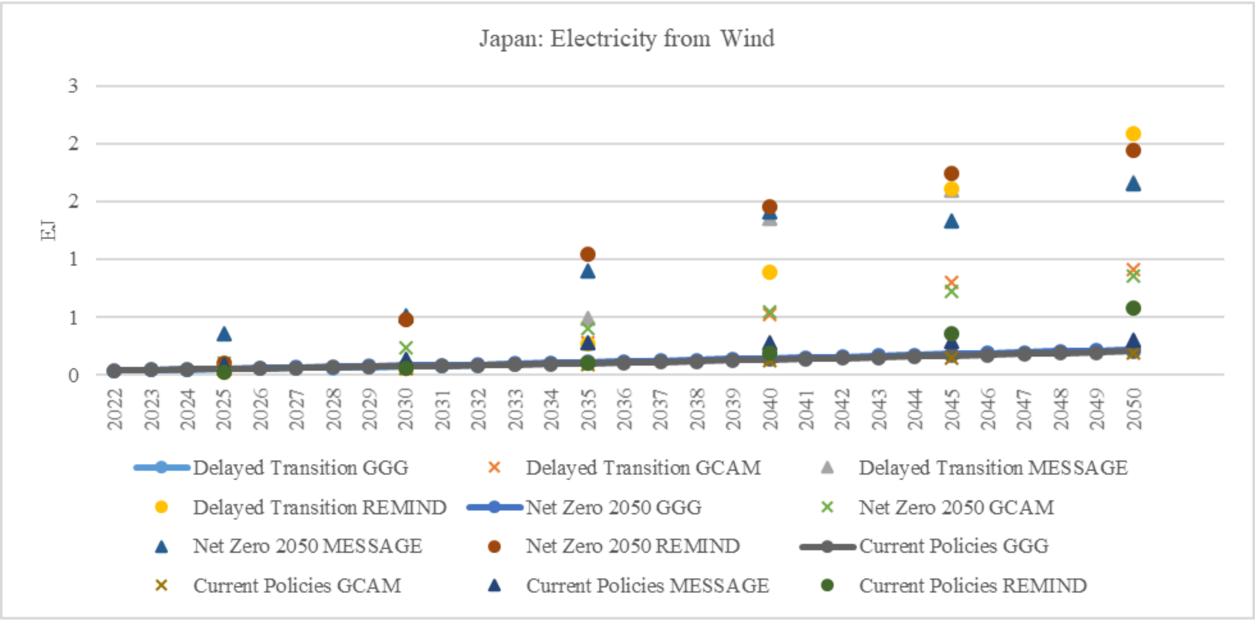


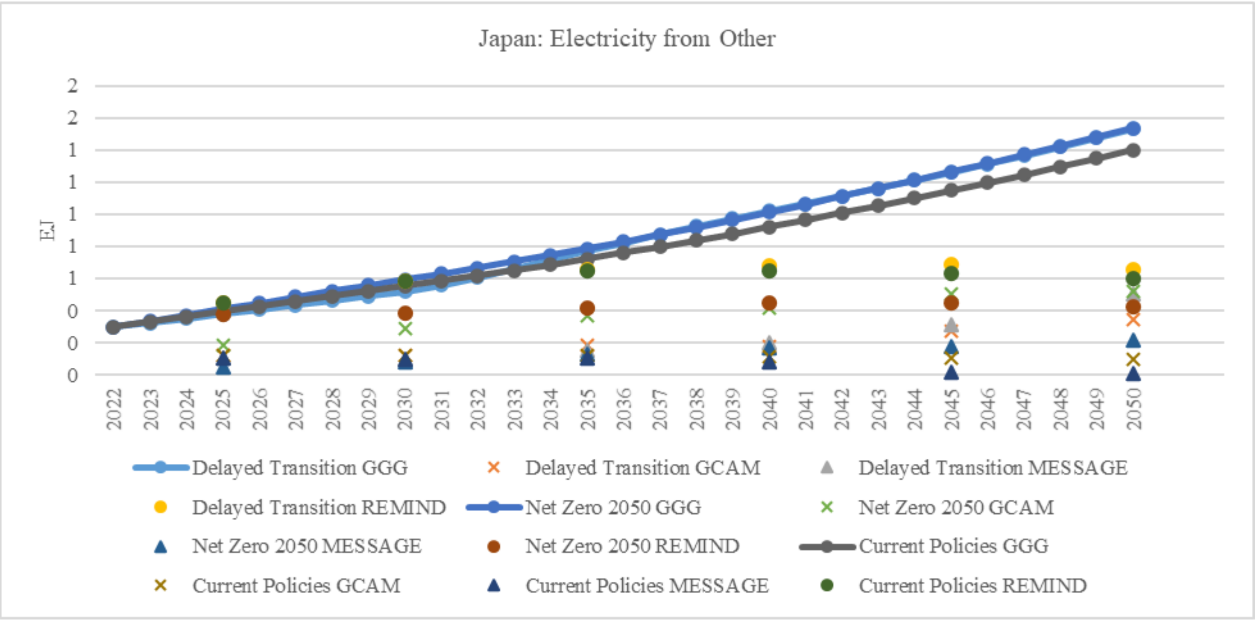


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Japan (Contd.)

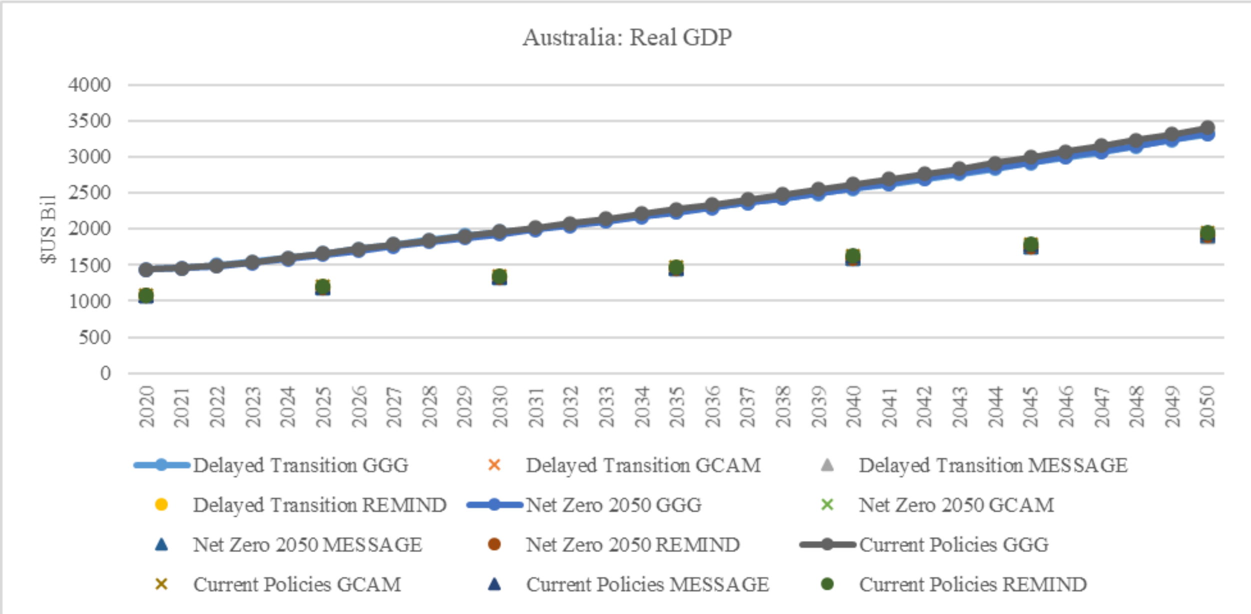


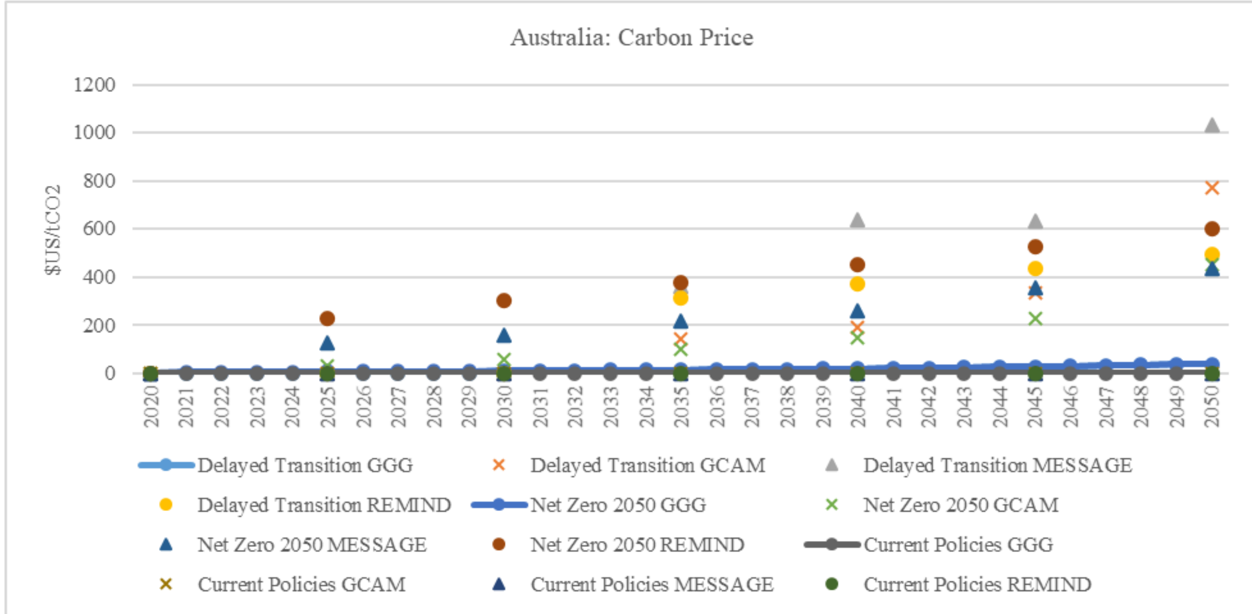


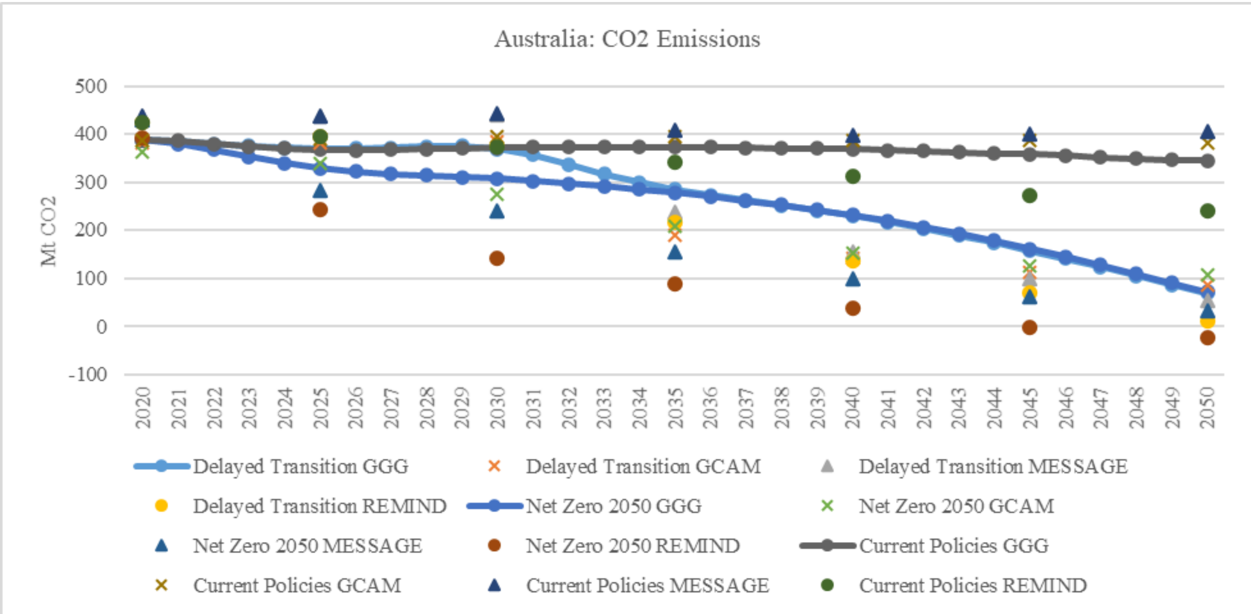


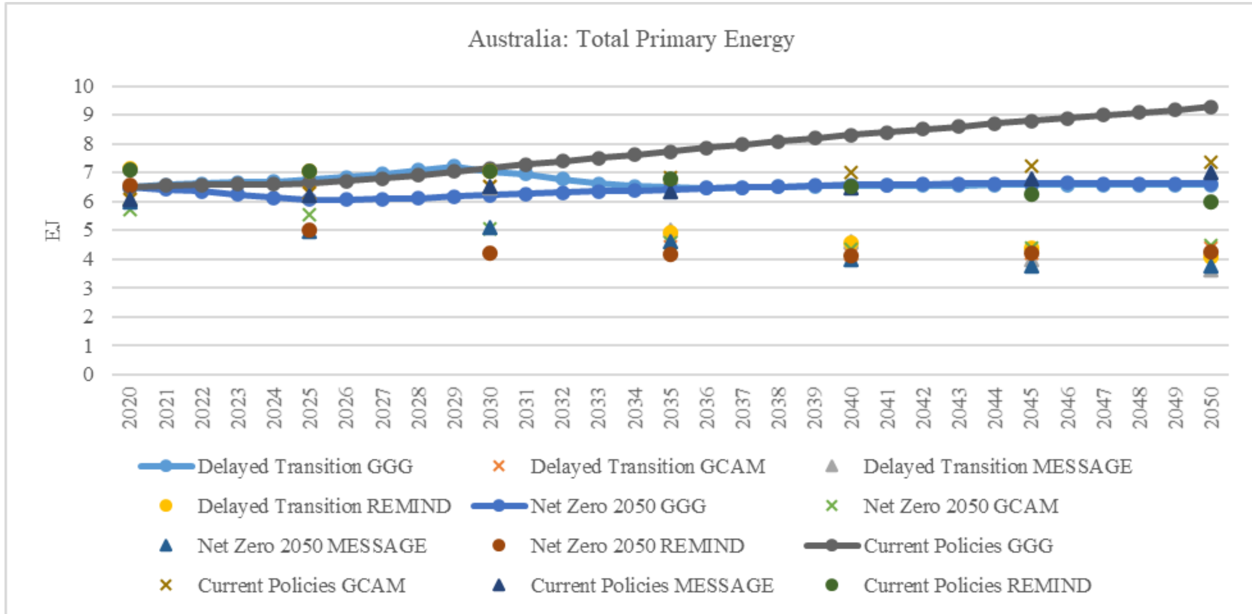


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Australia

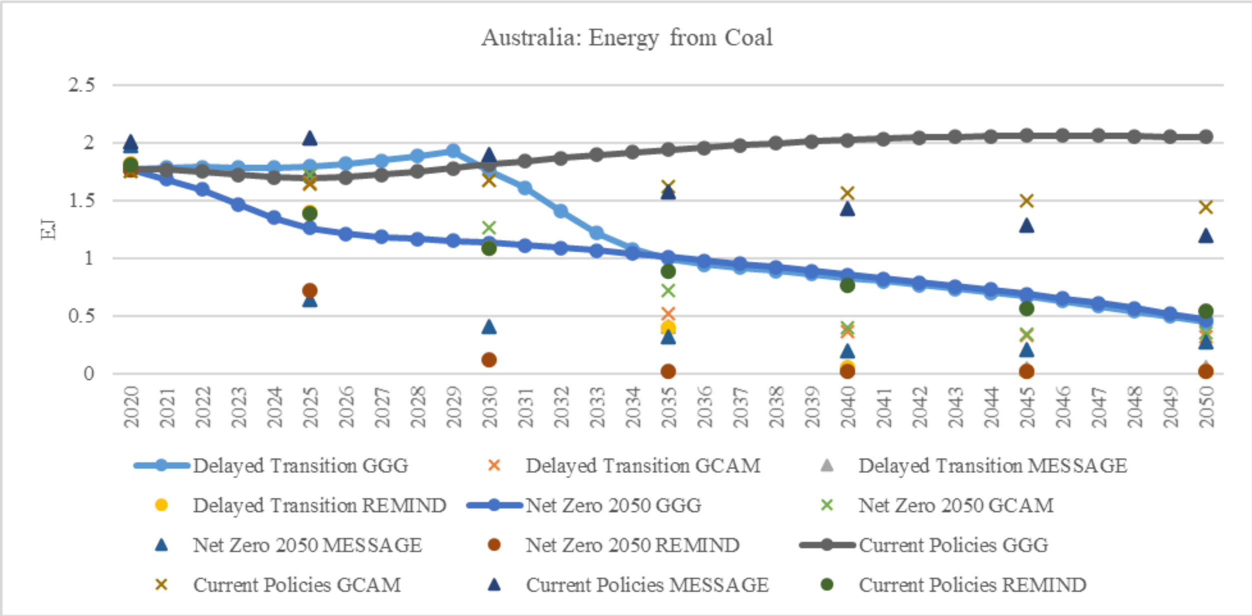


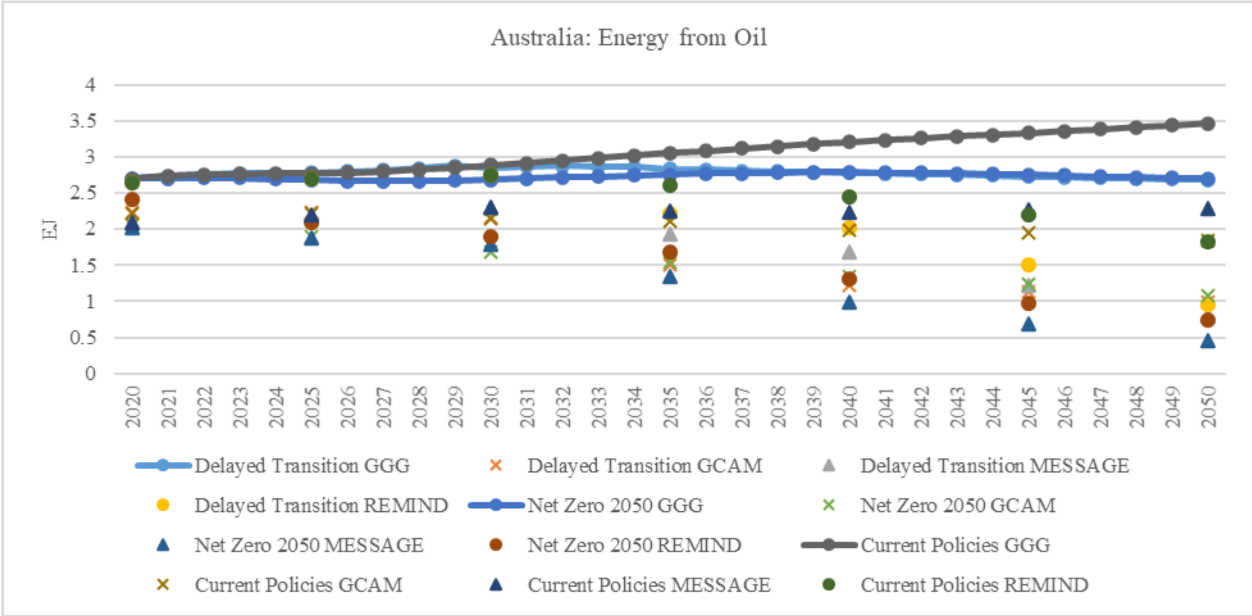


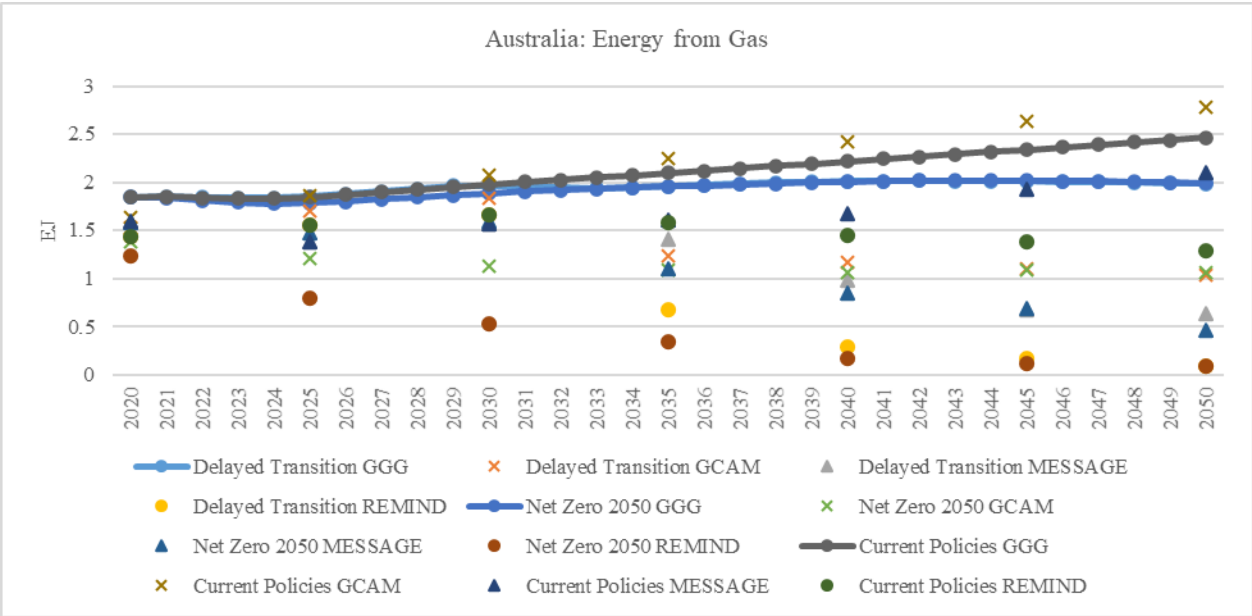


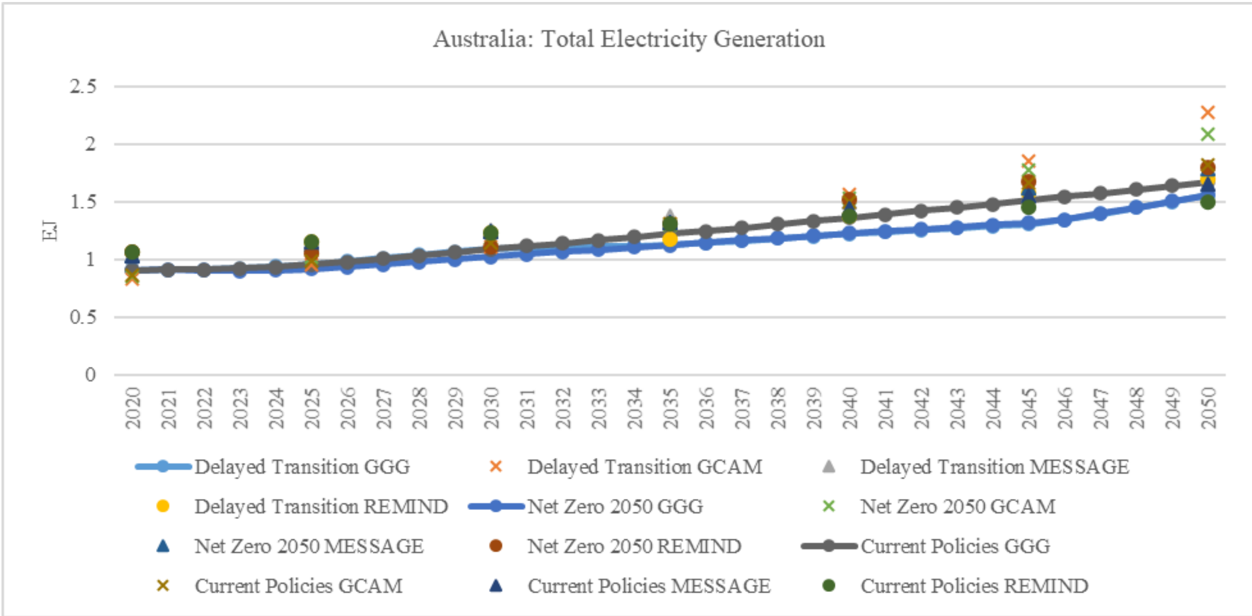


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Australia (Contd.)

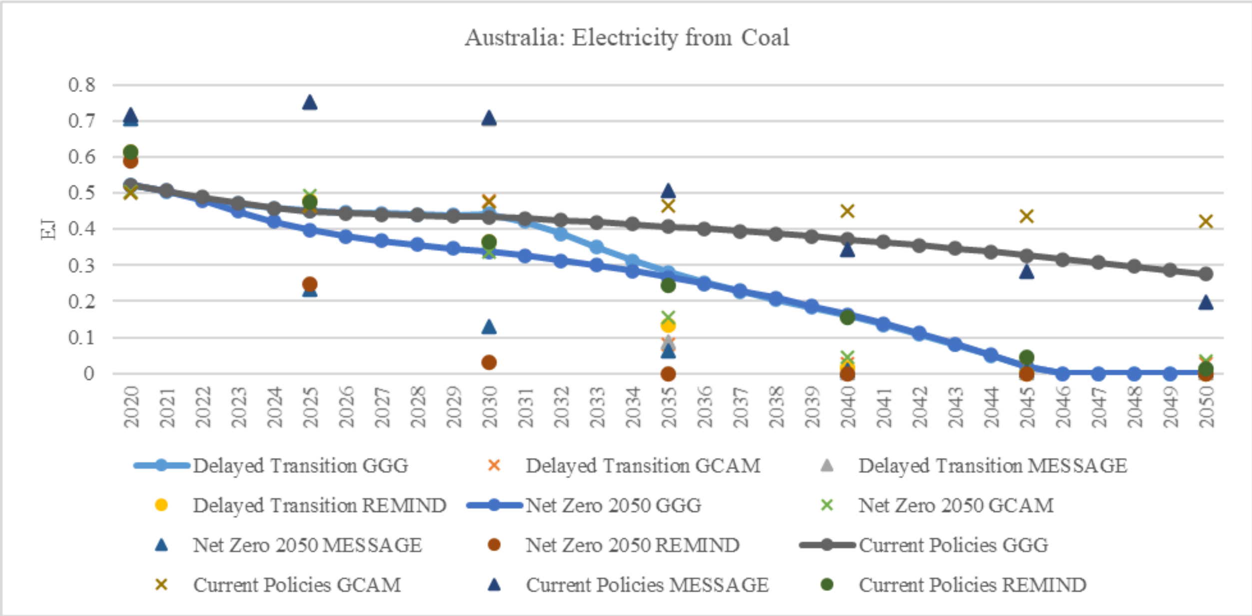


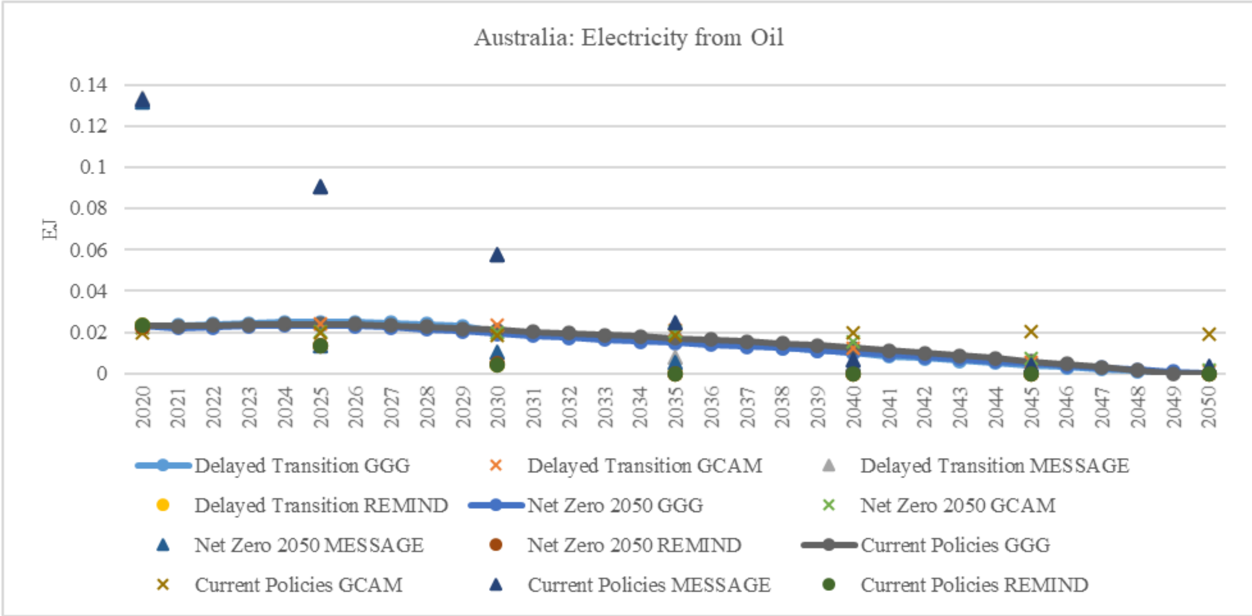


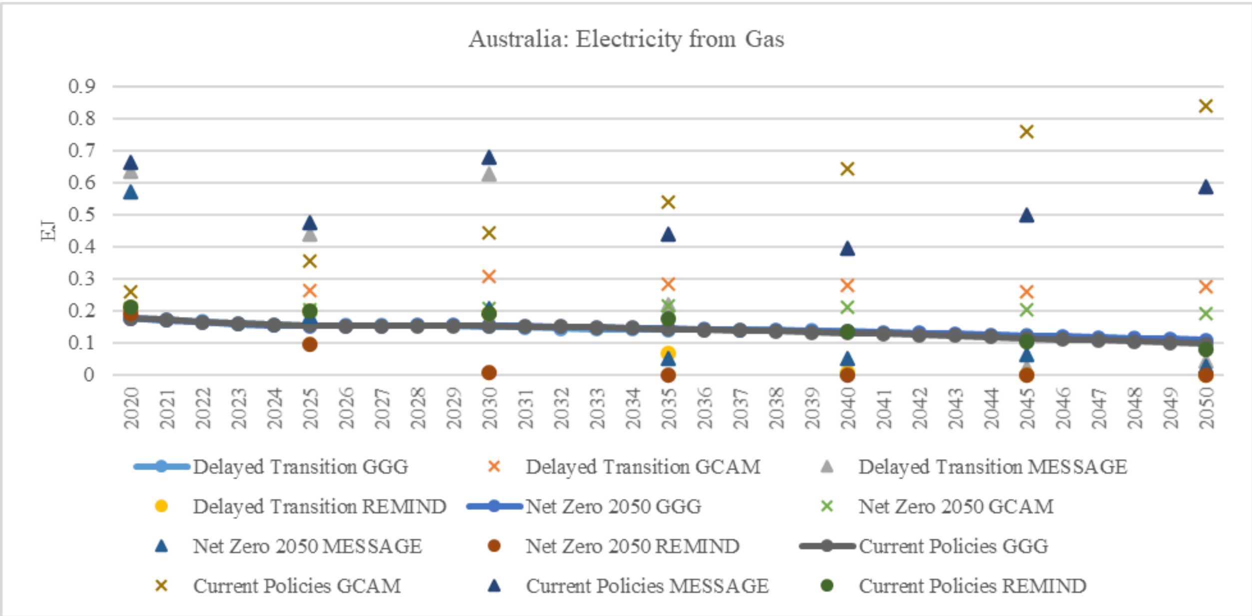


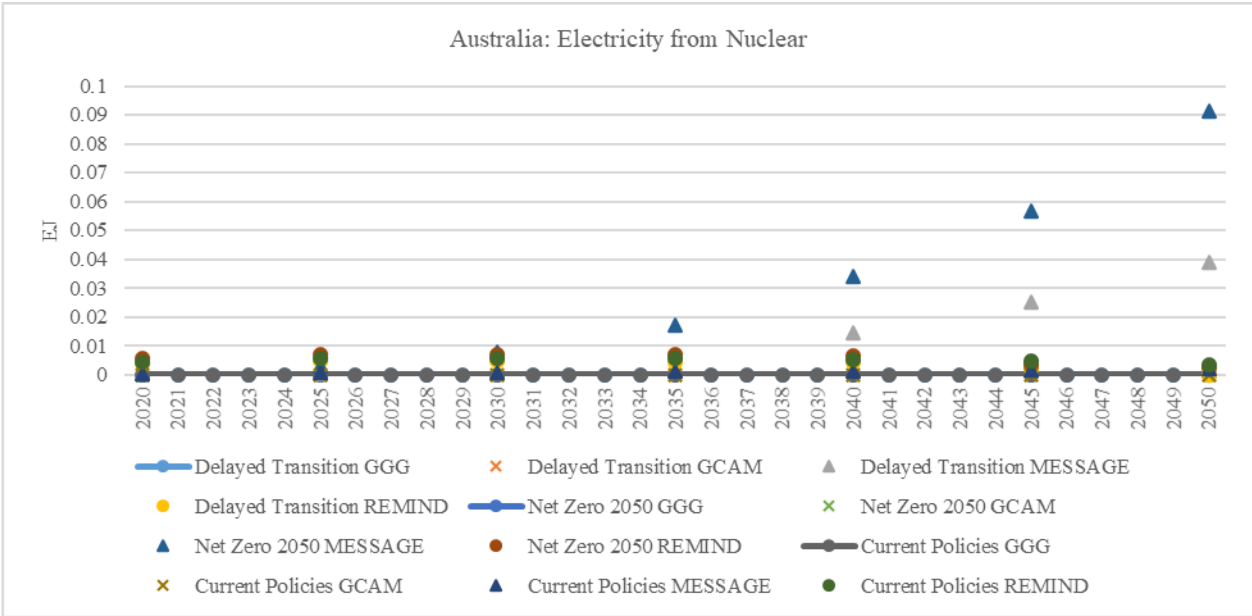


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Australia (Contd.)

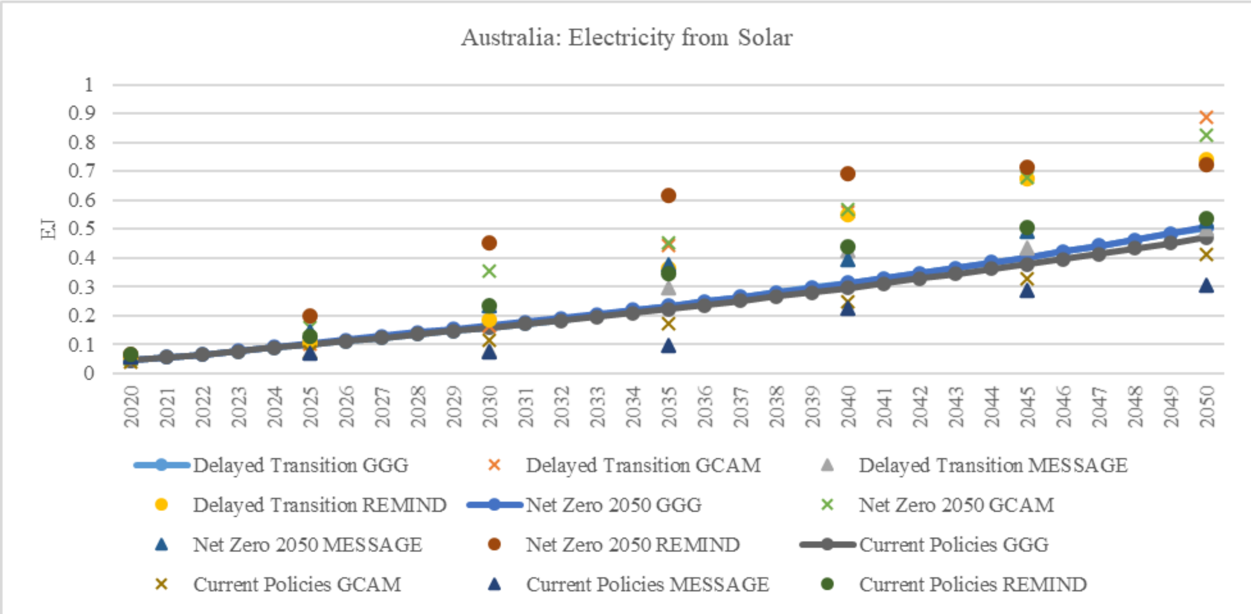


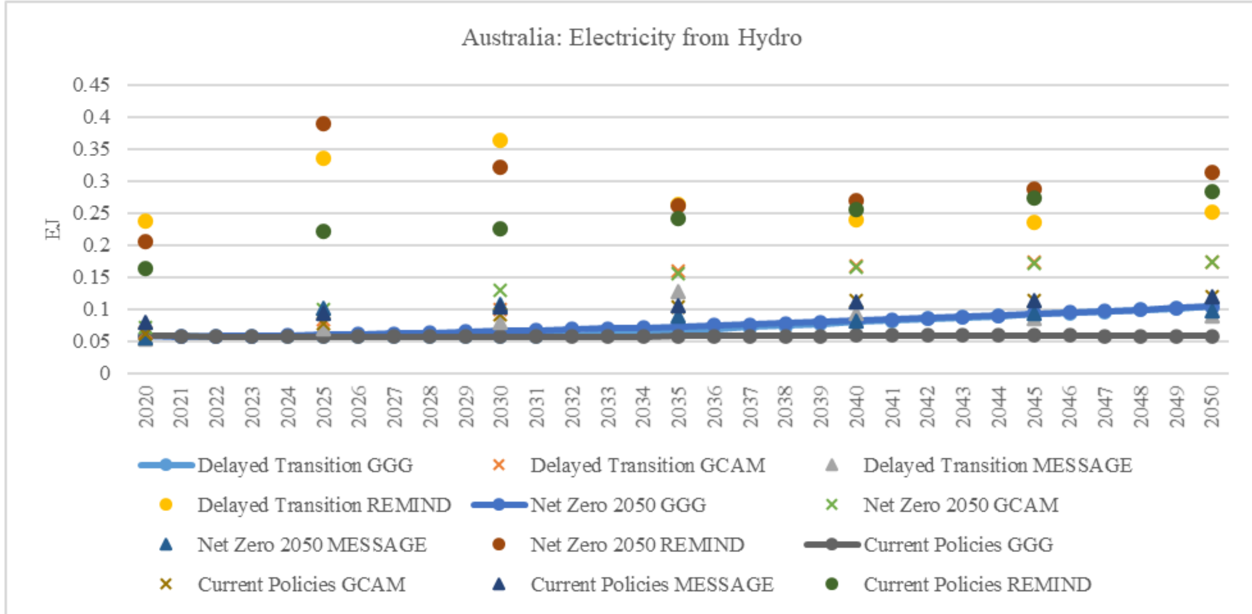


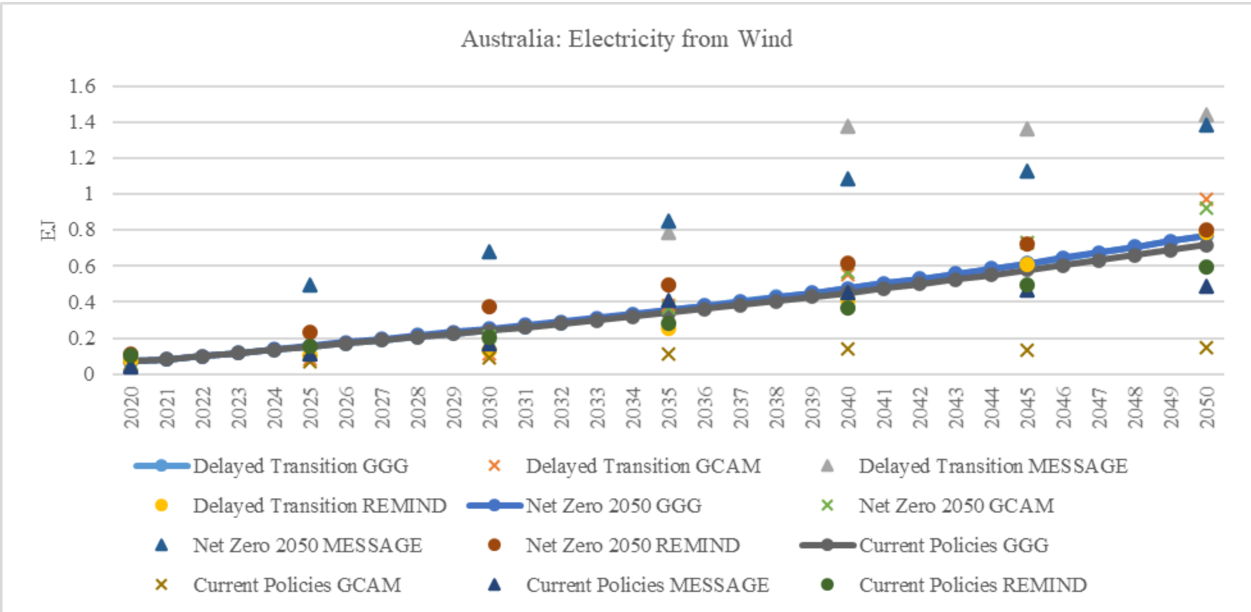


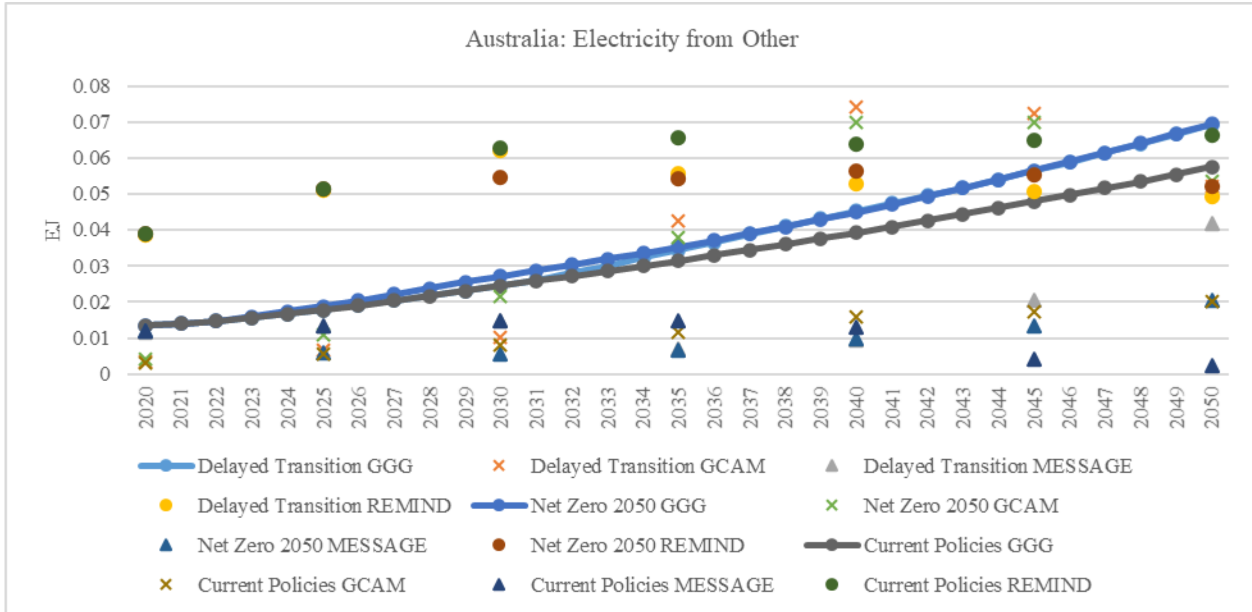


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Australia (Contd.)

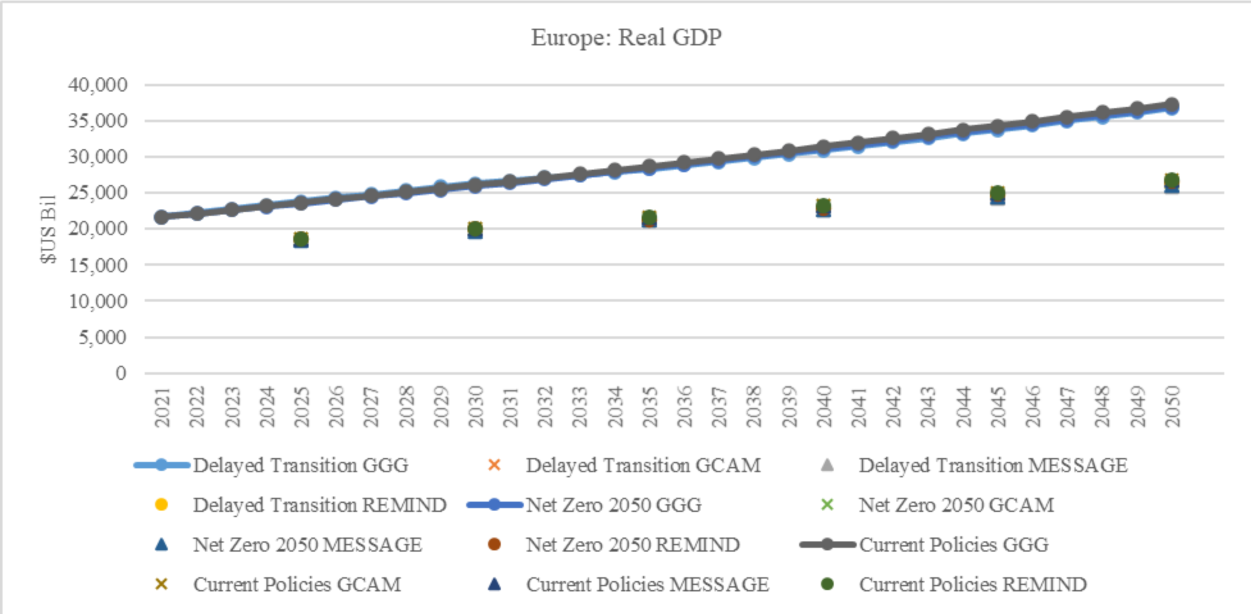


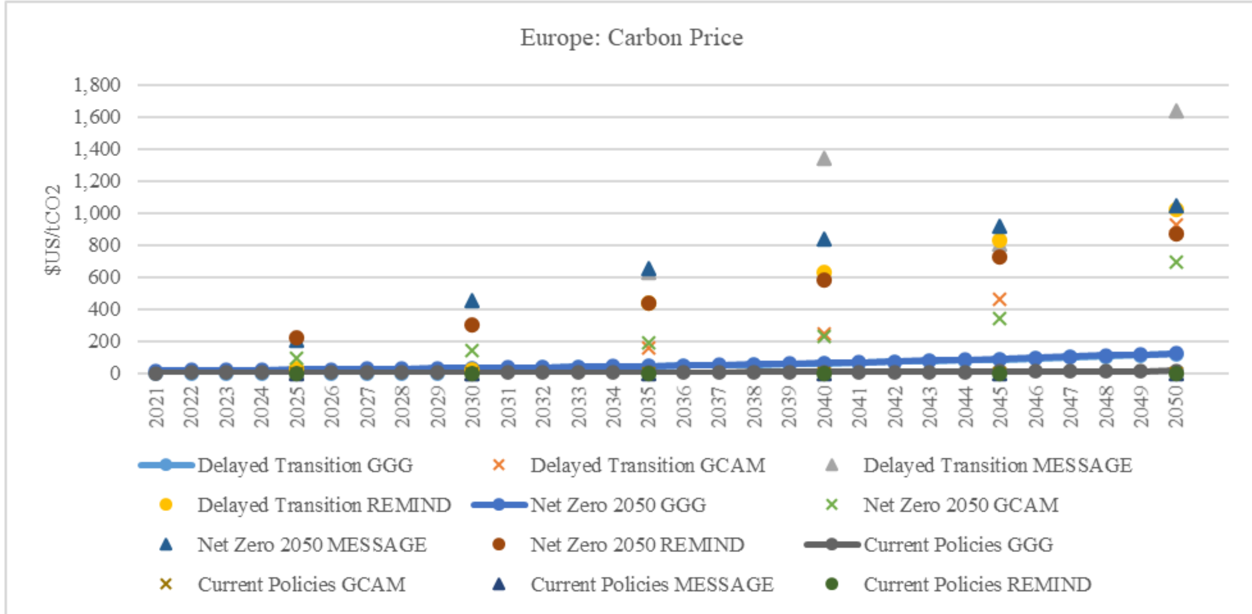


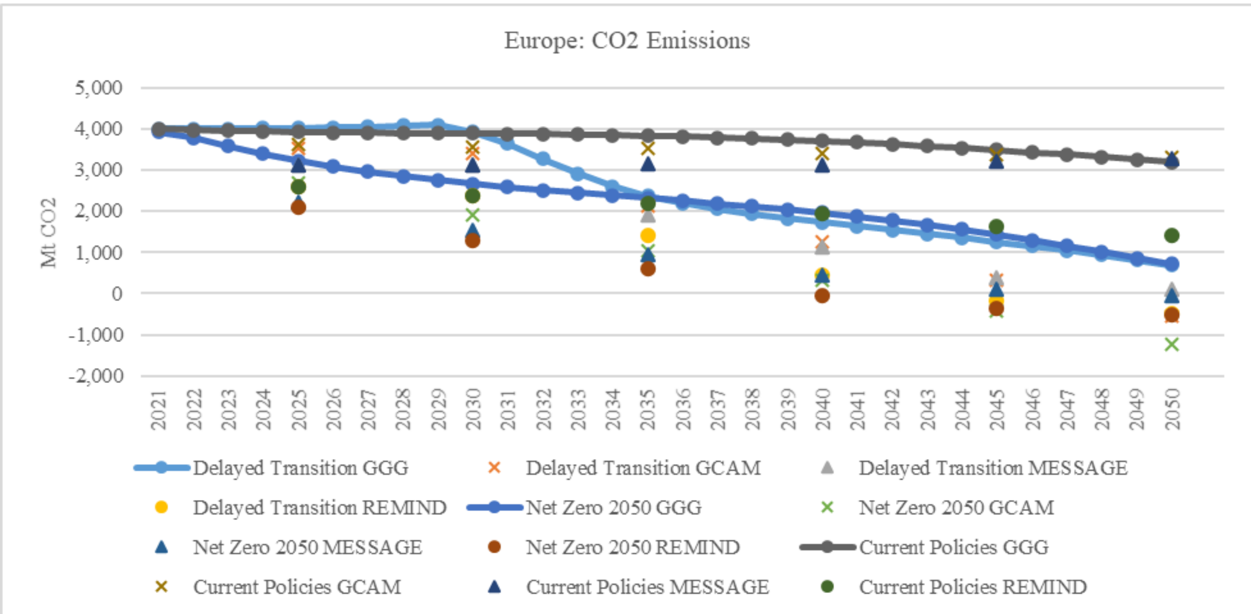


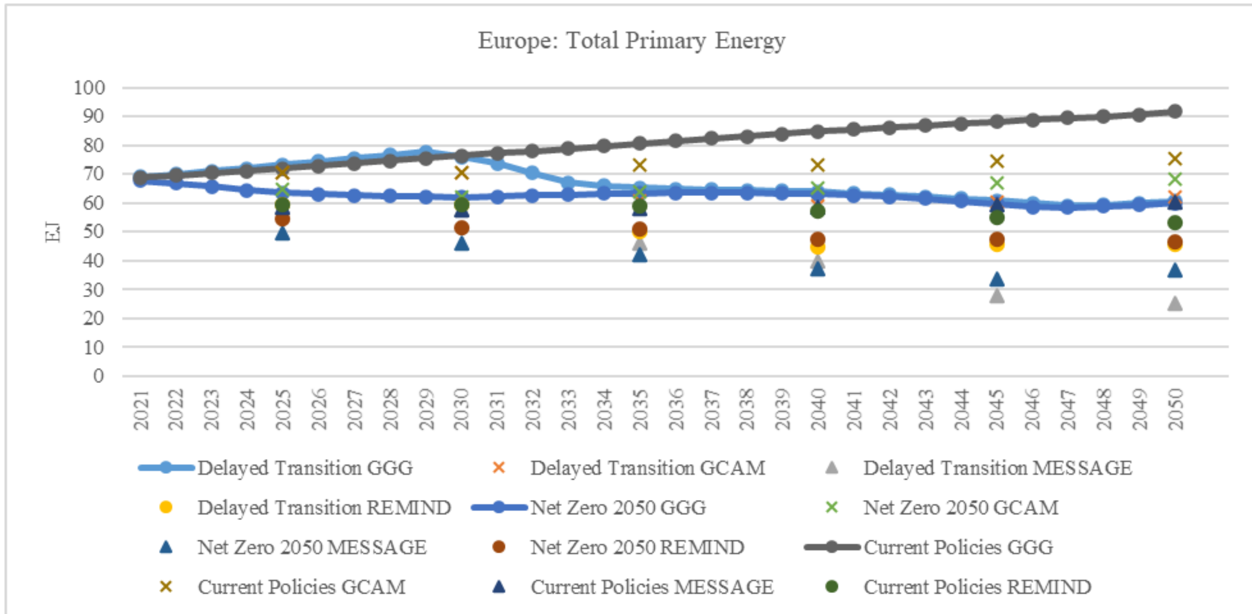


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Europe

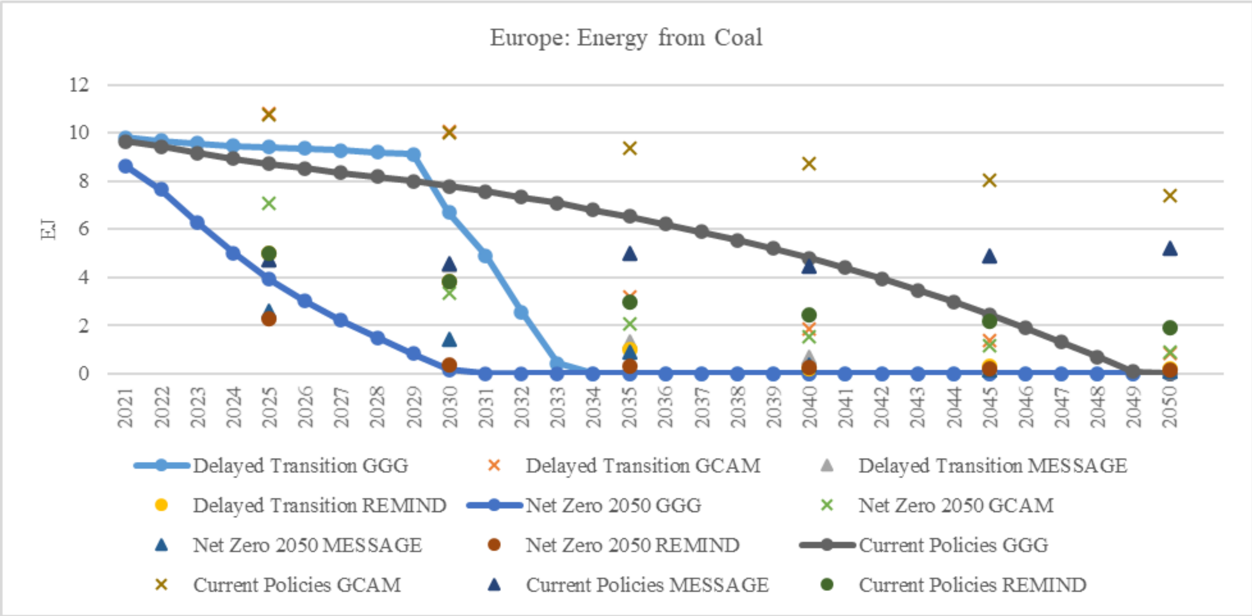


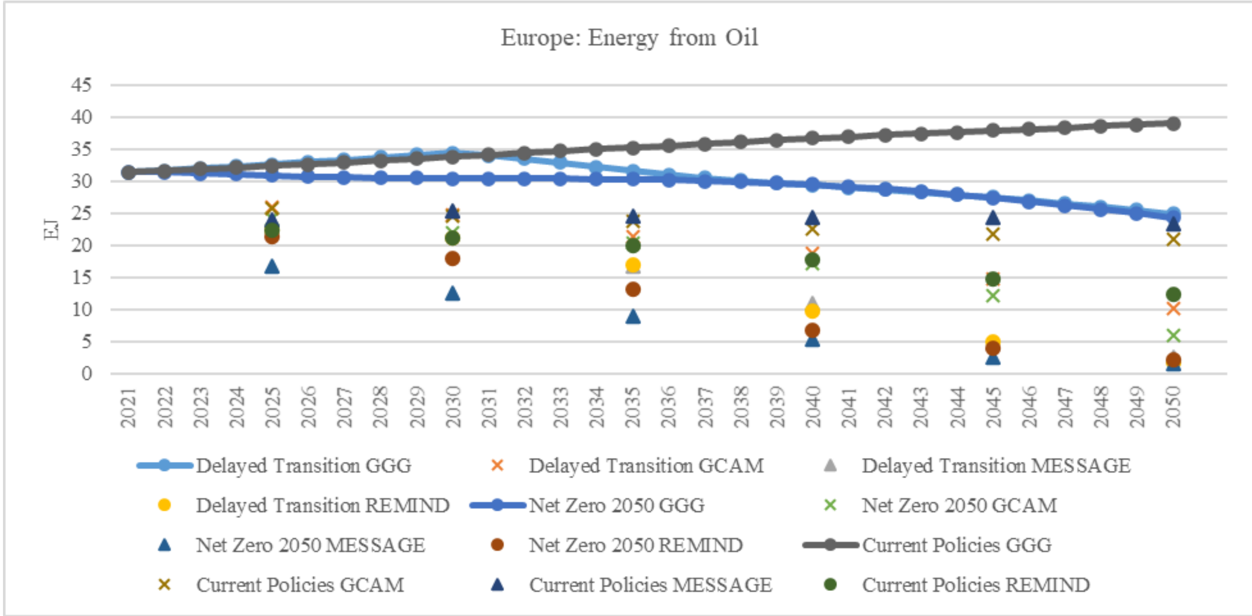


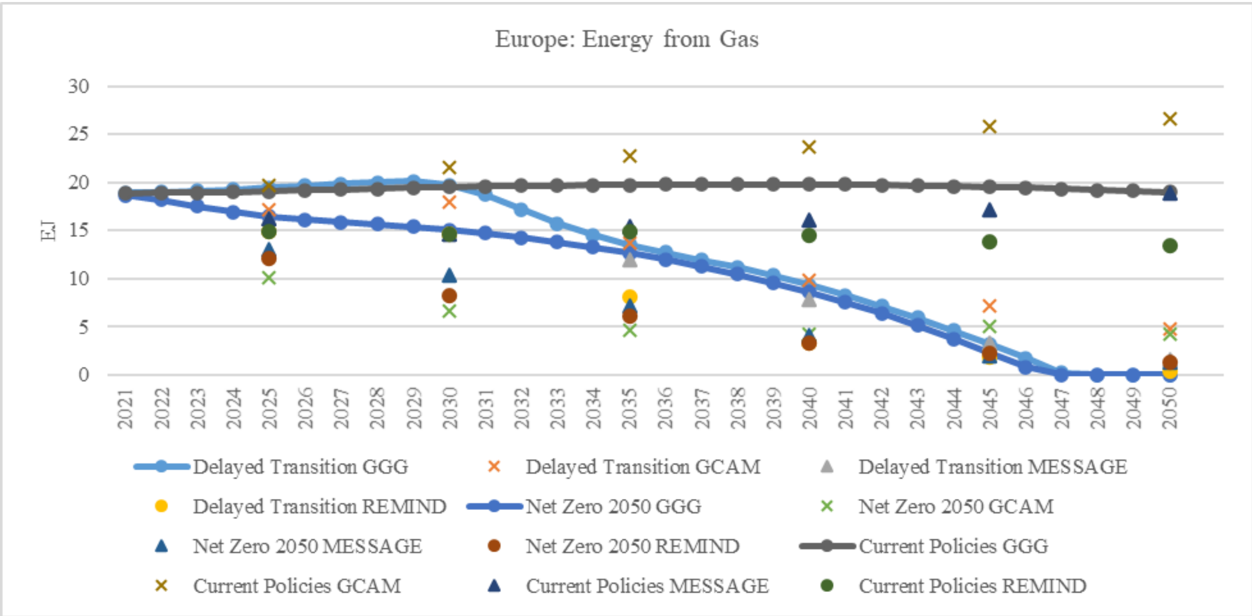


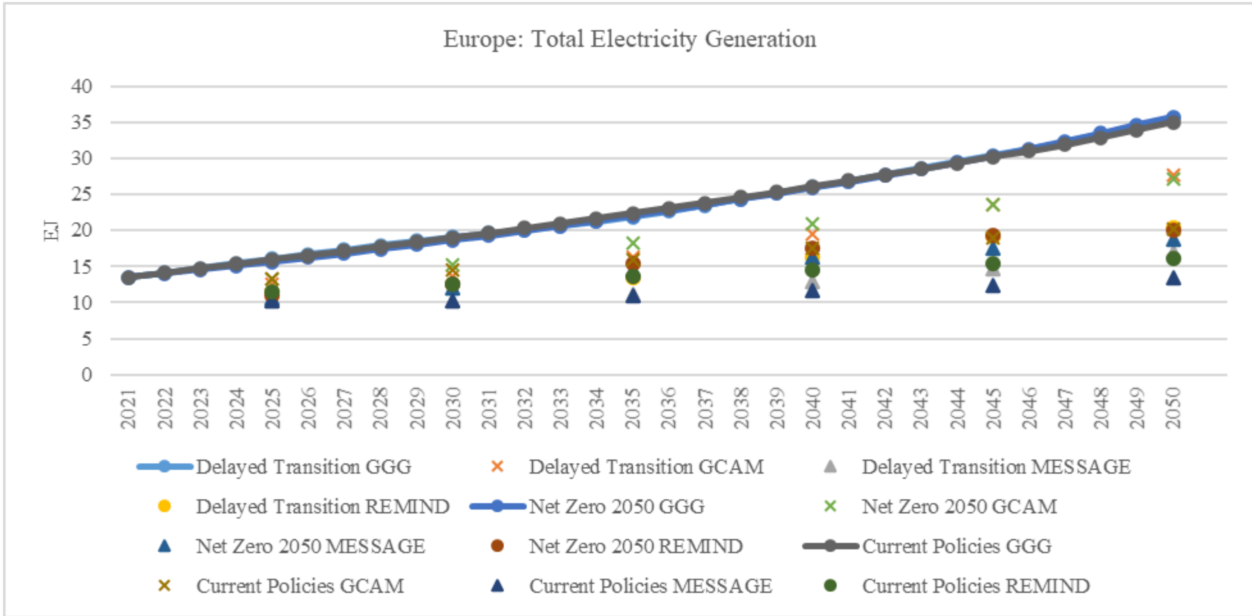


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Europe (Contd.)

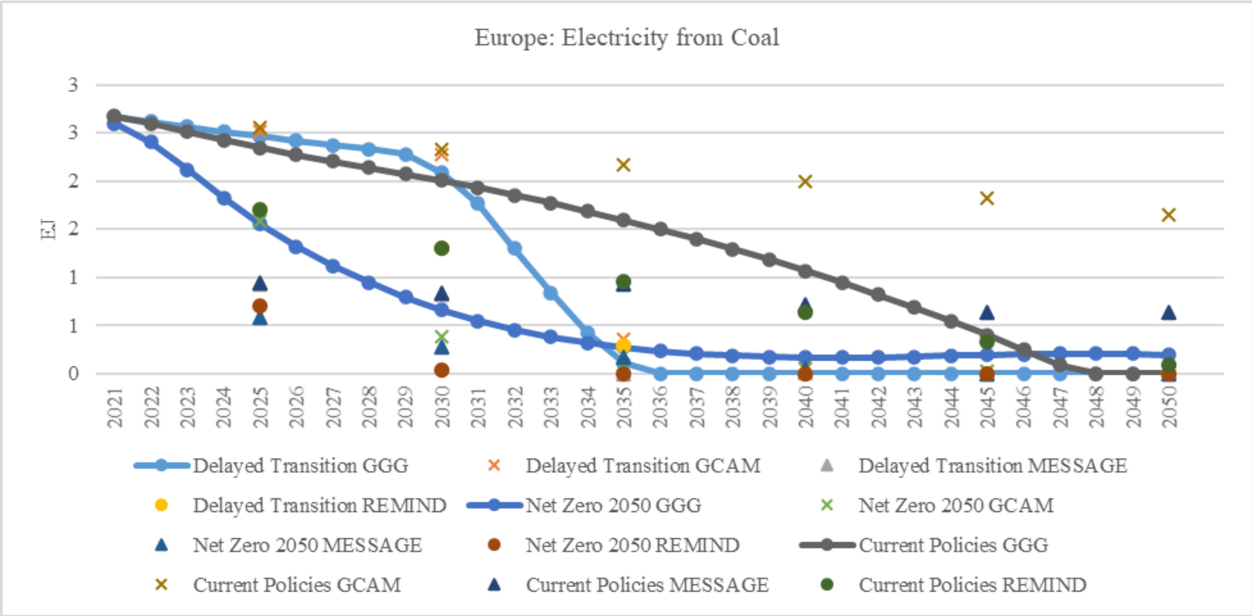


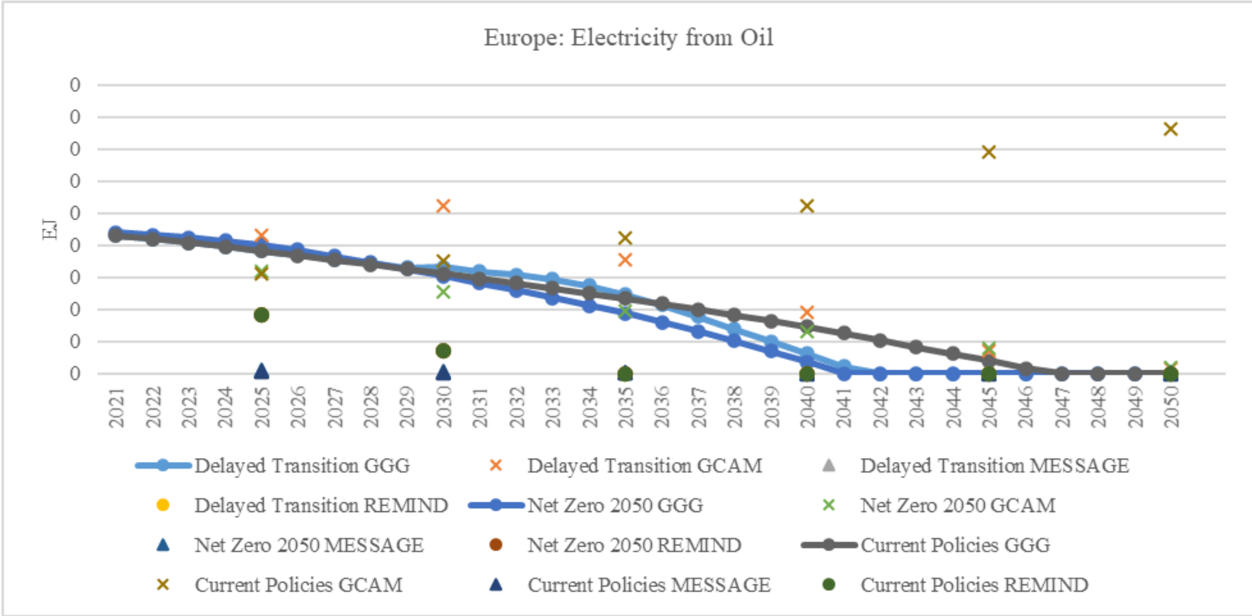


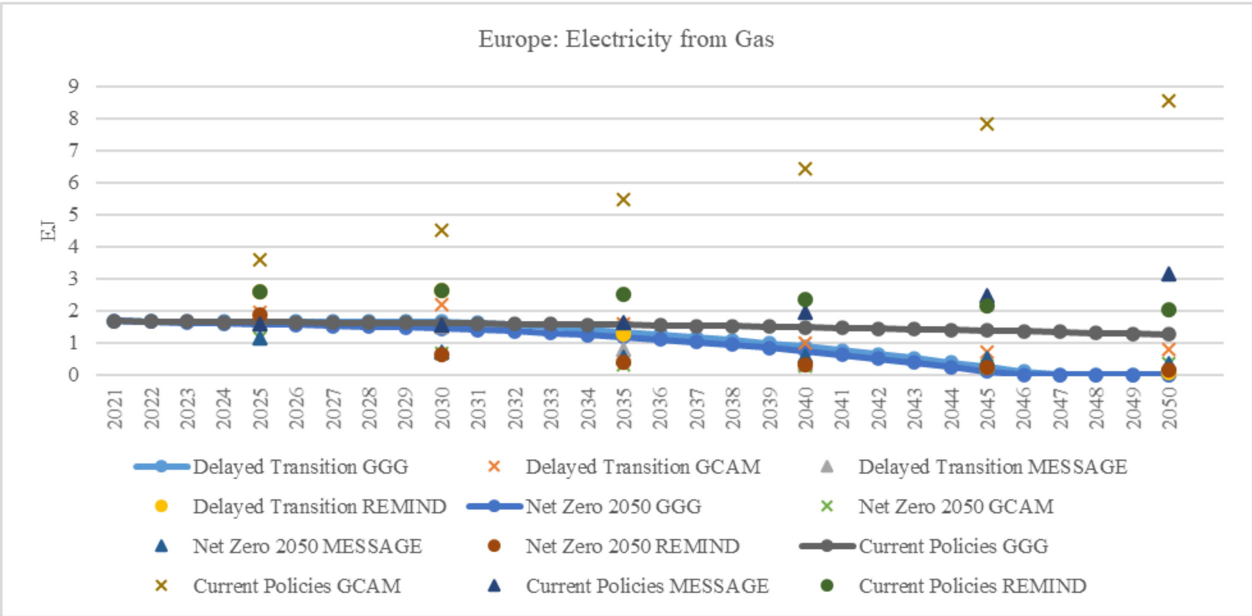


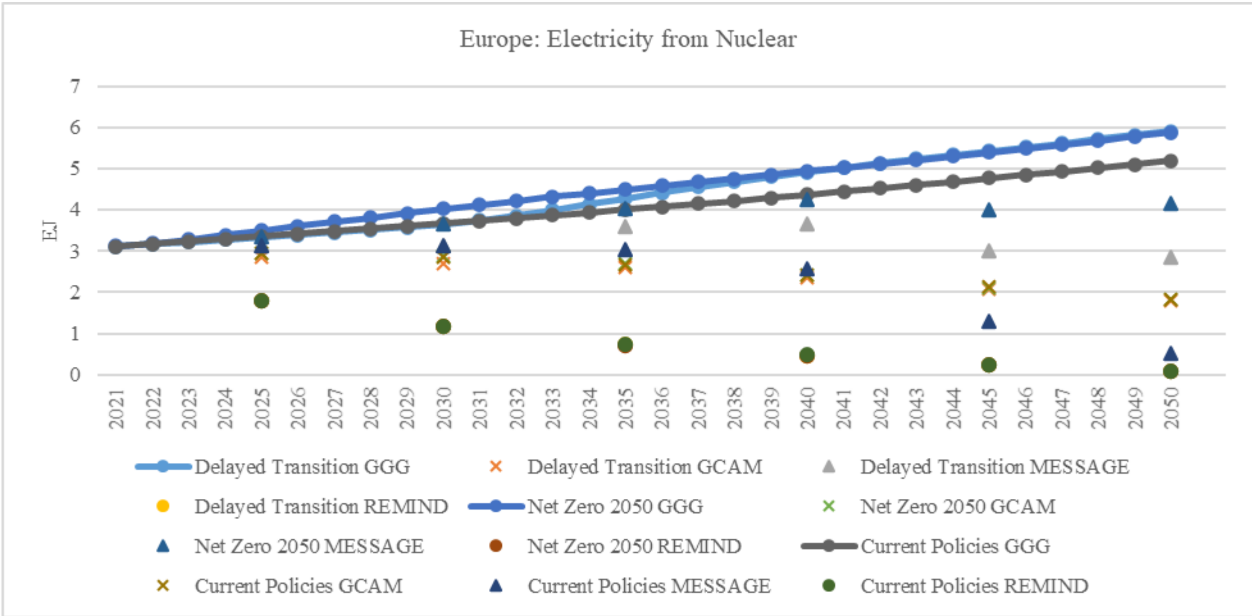


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Europe (Contd.)

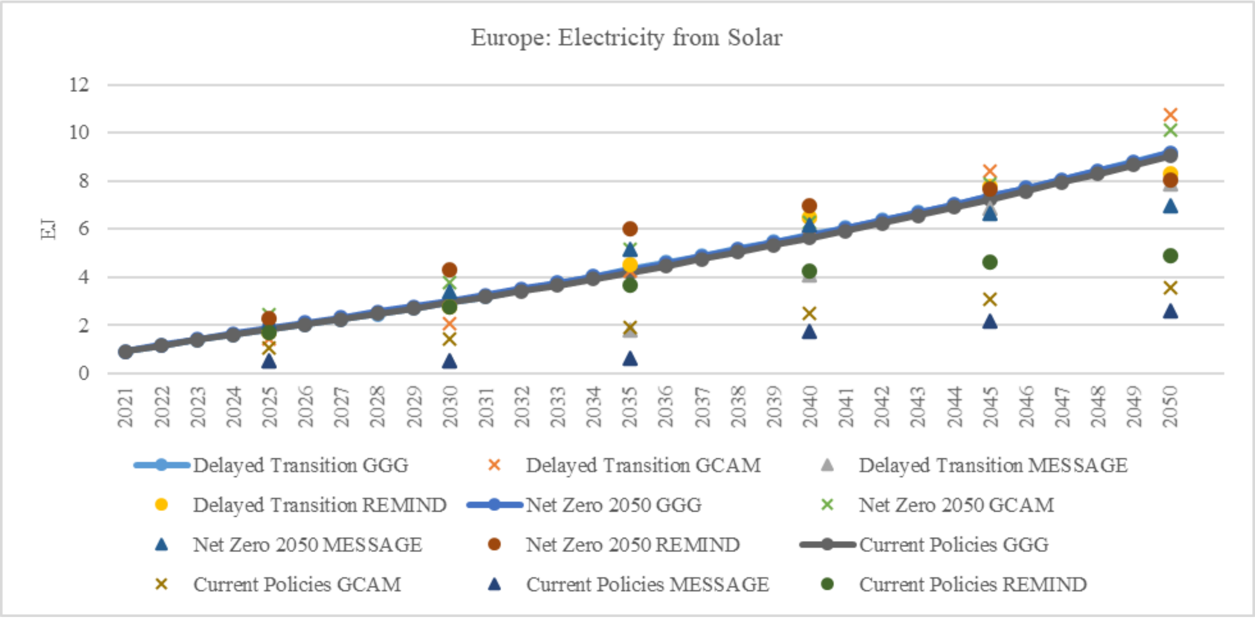


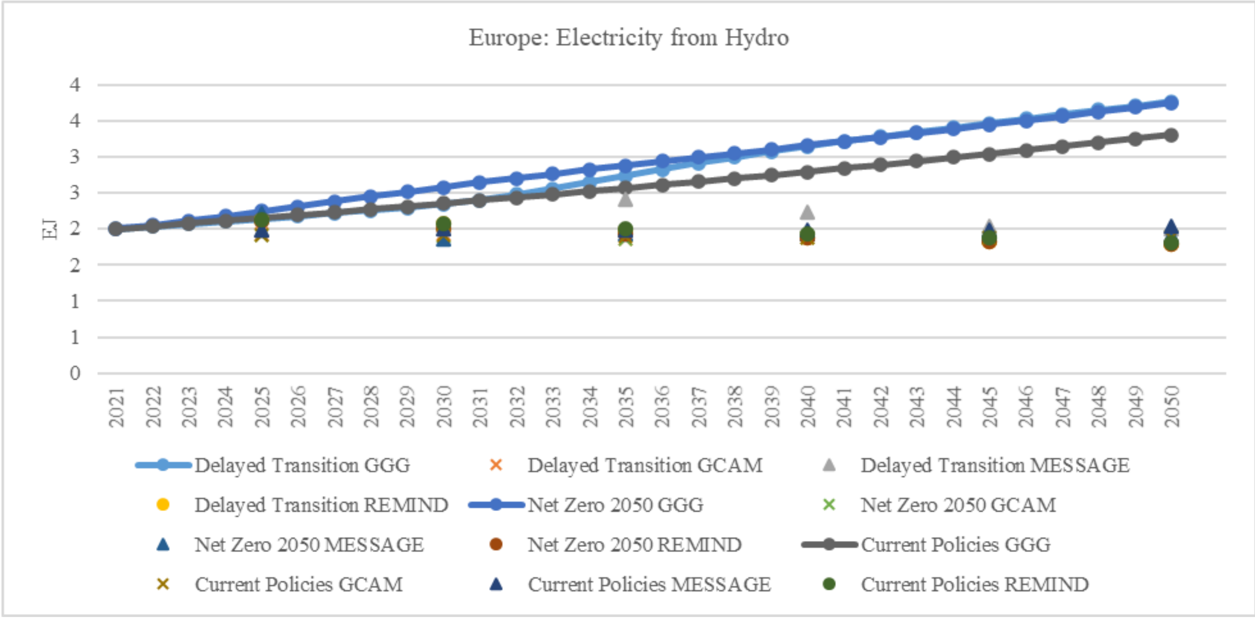


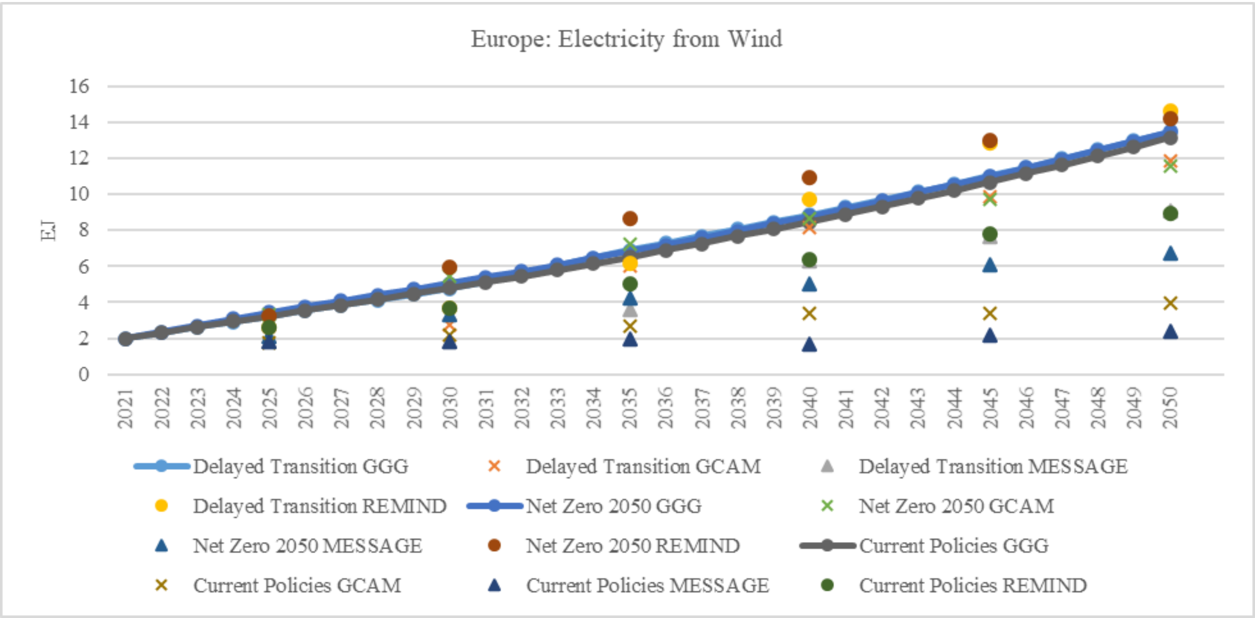


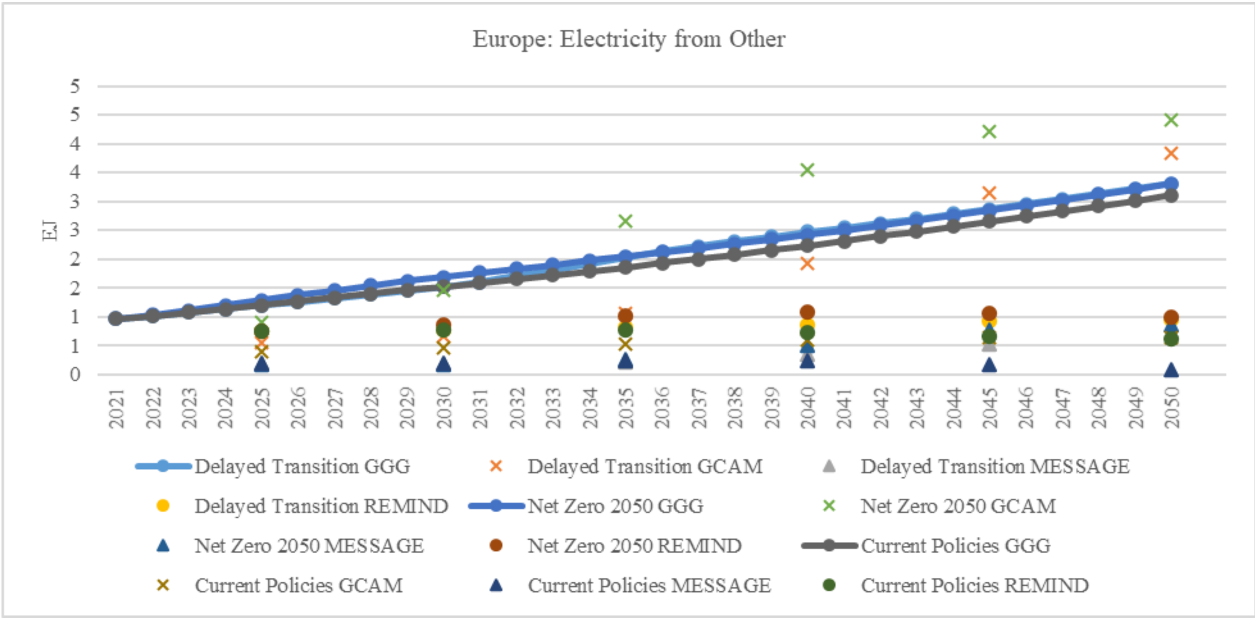


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Europe (Contd.)

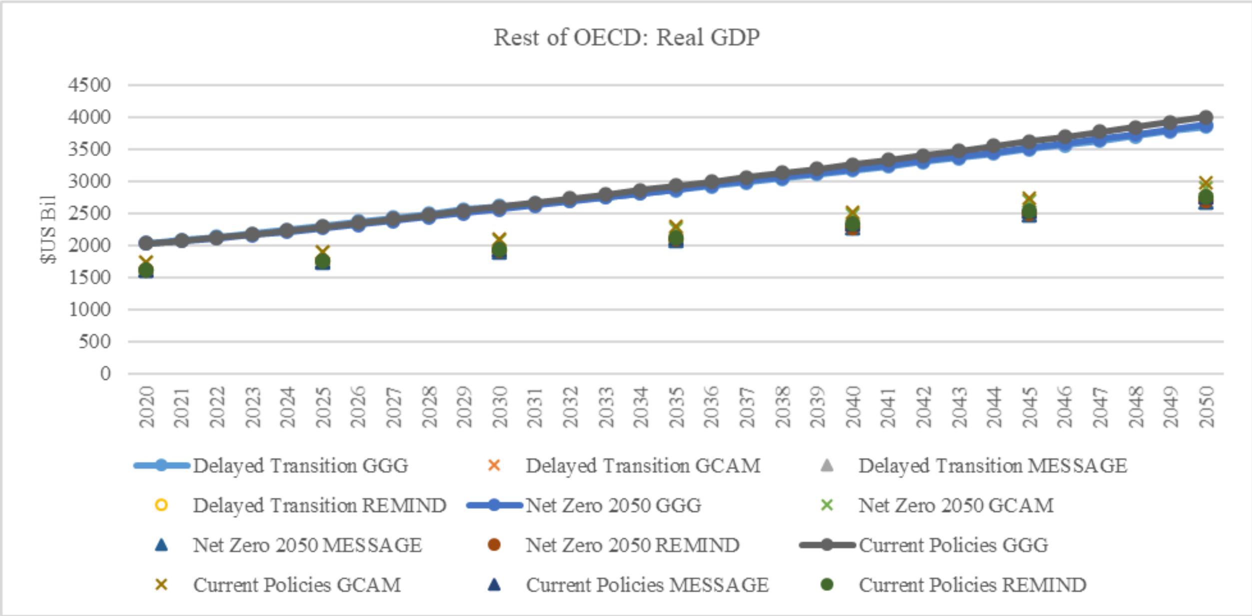


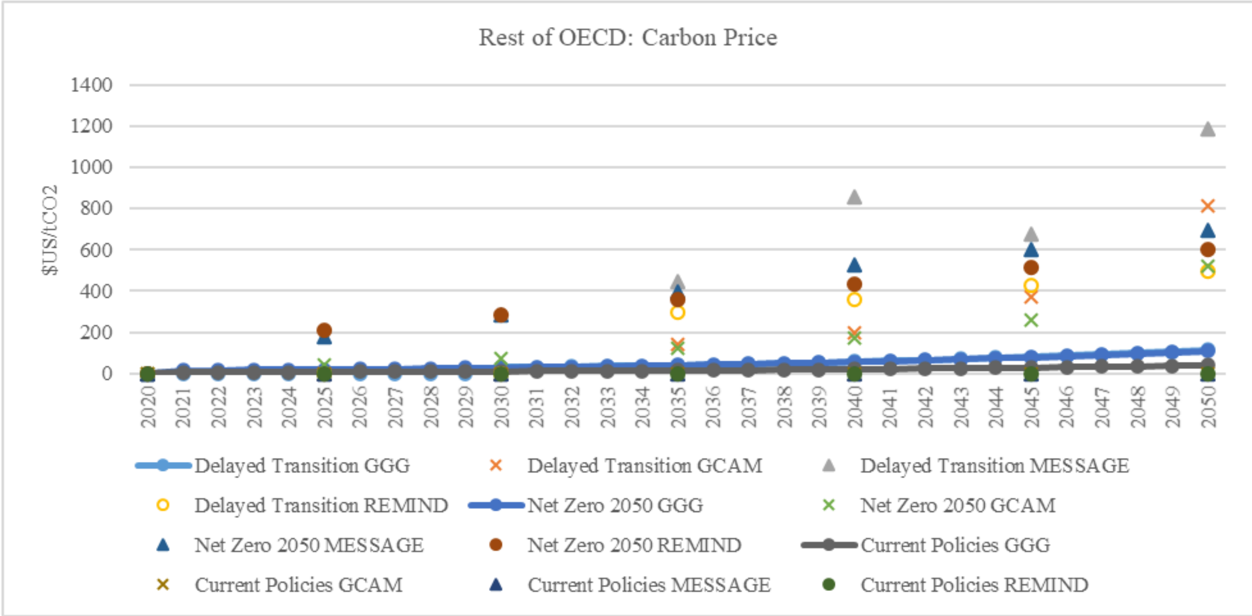


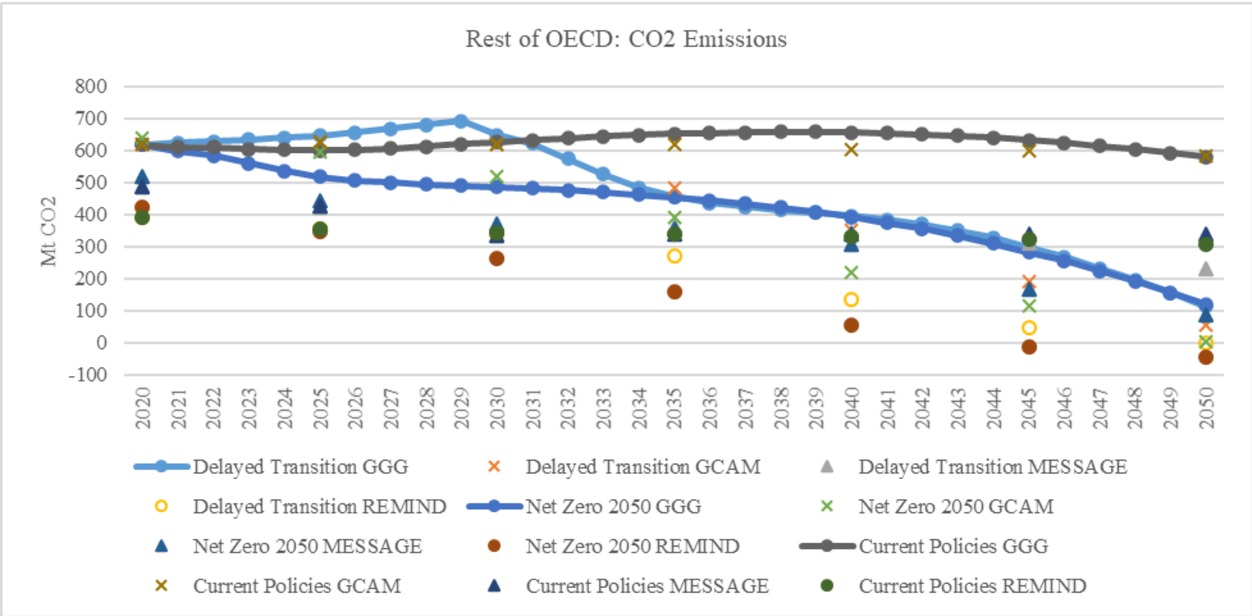


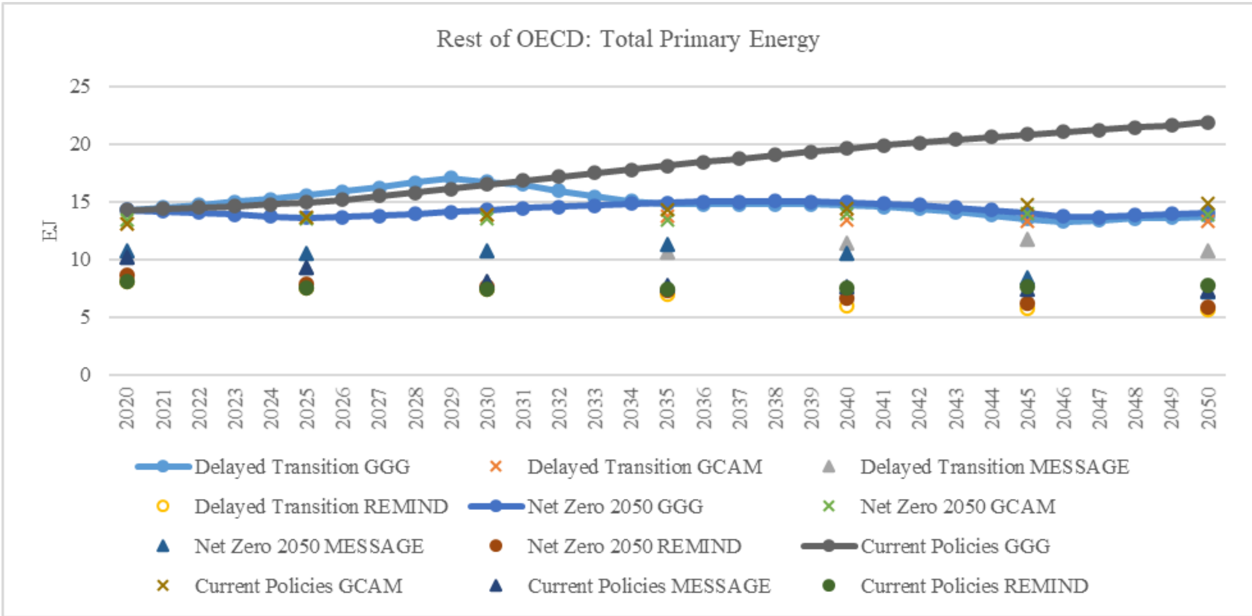


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Rest of OECD

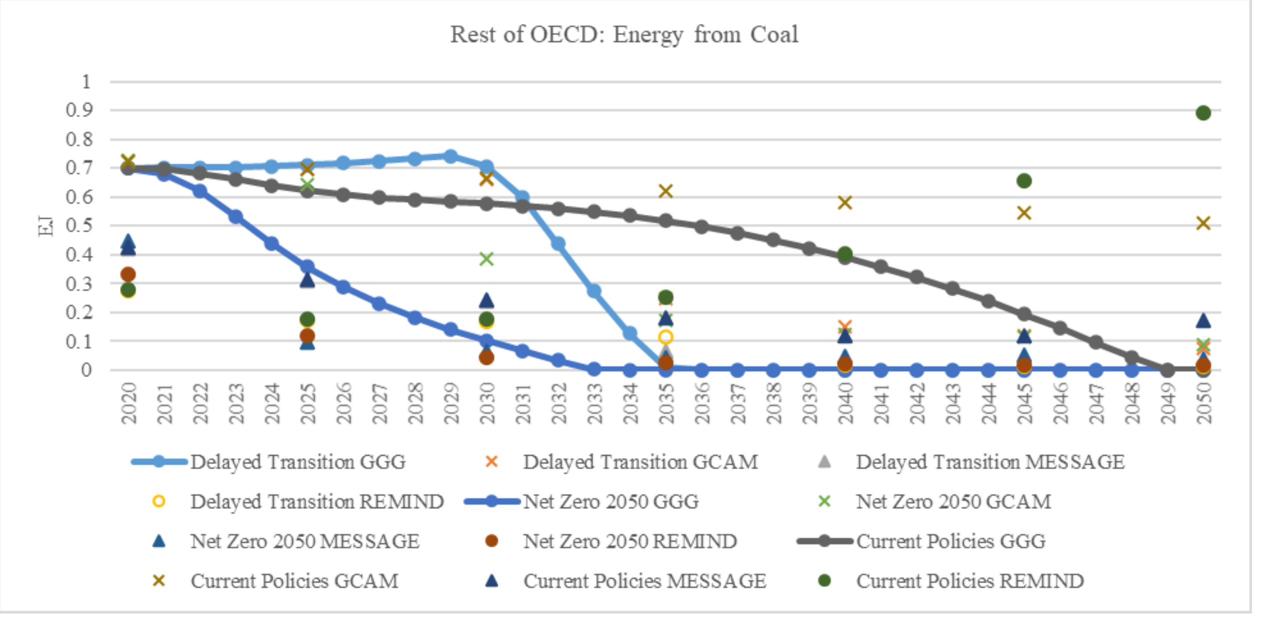


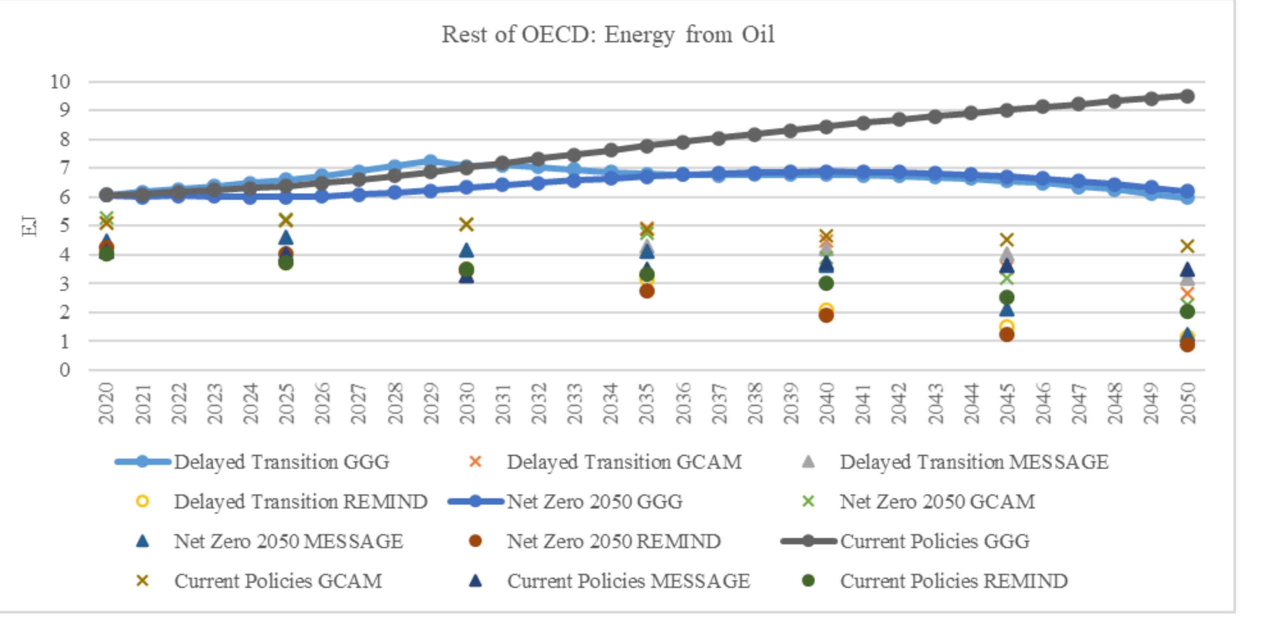


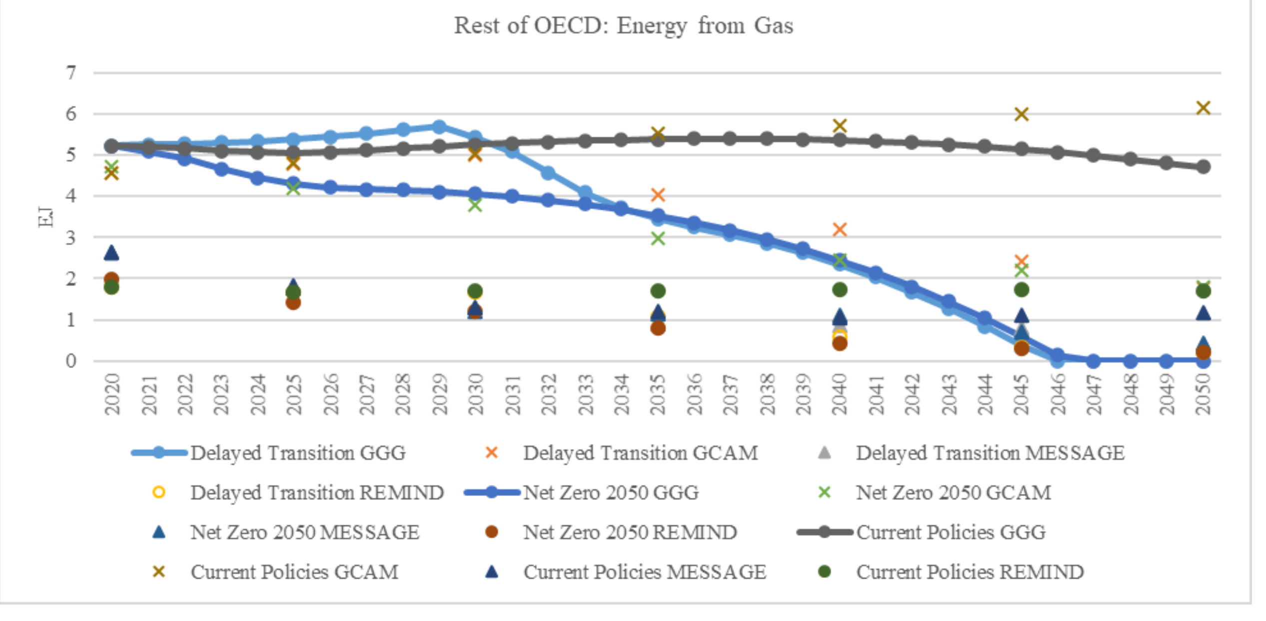


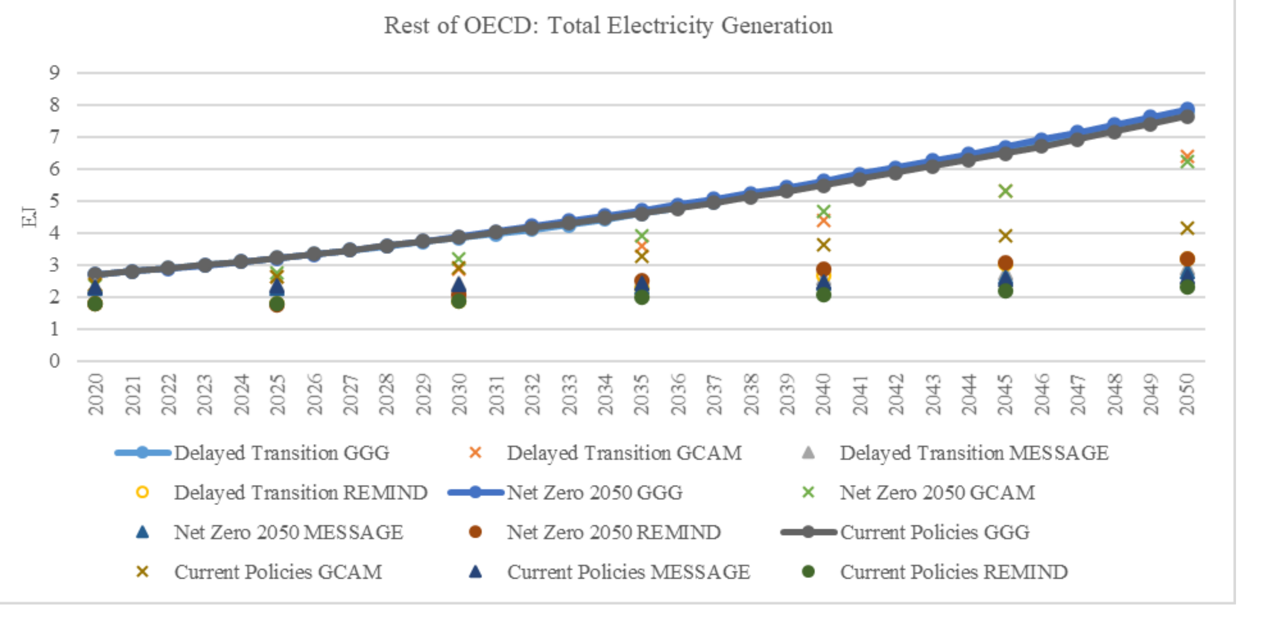


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Rest of OECD (Contd.)

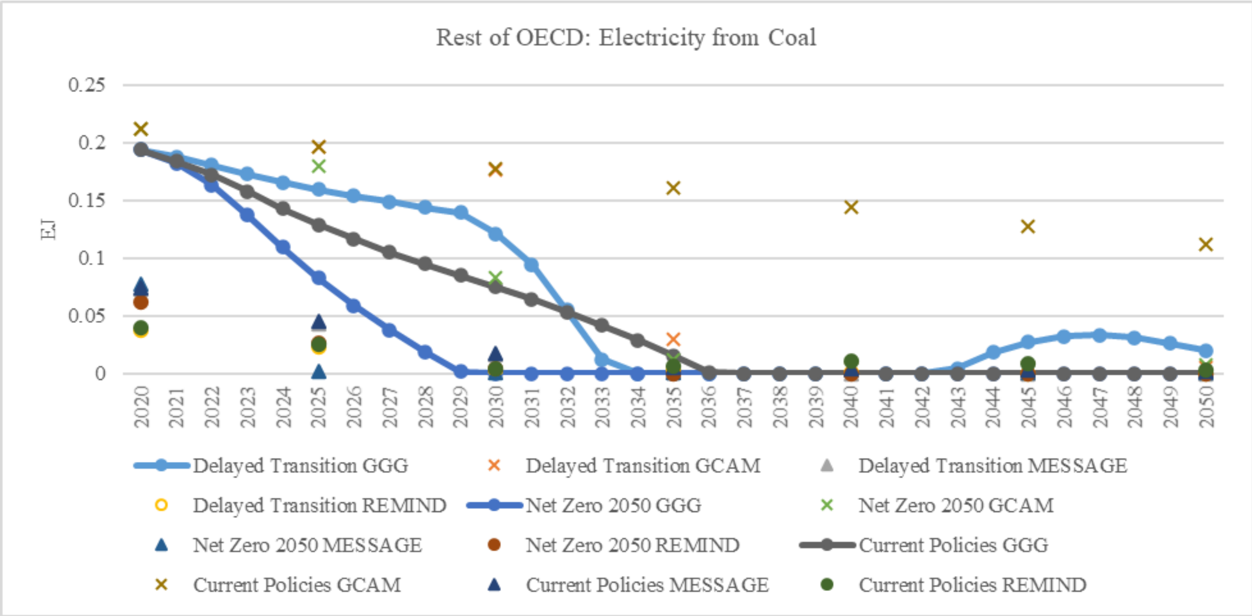


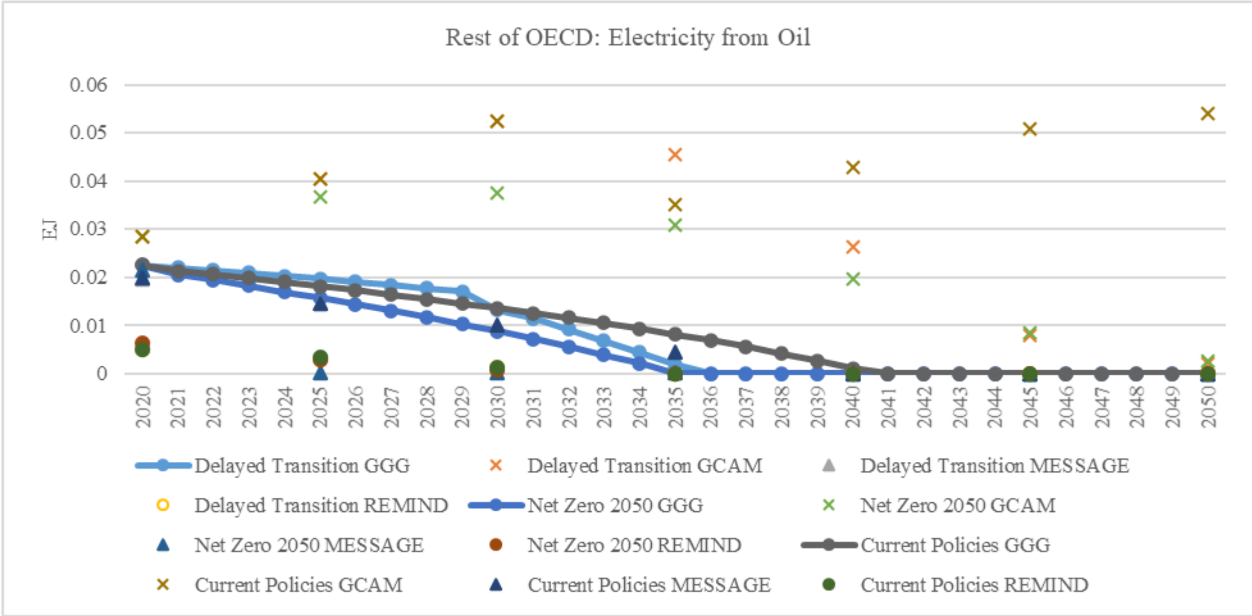


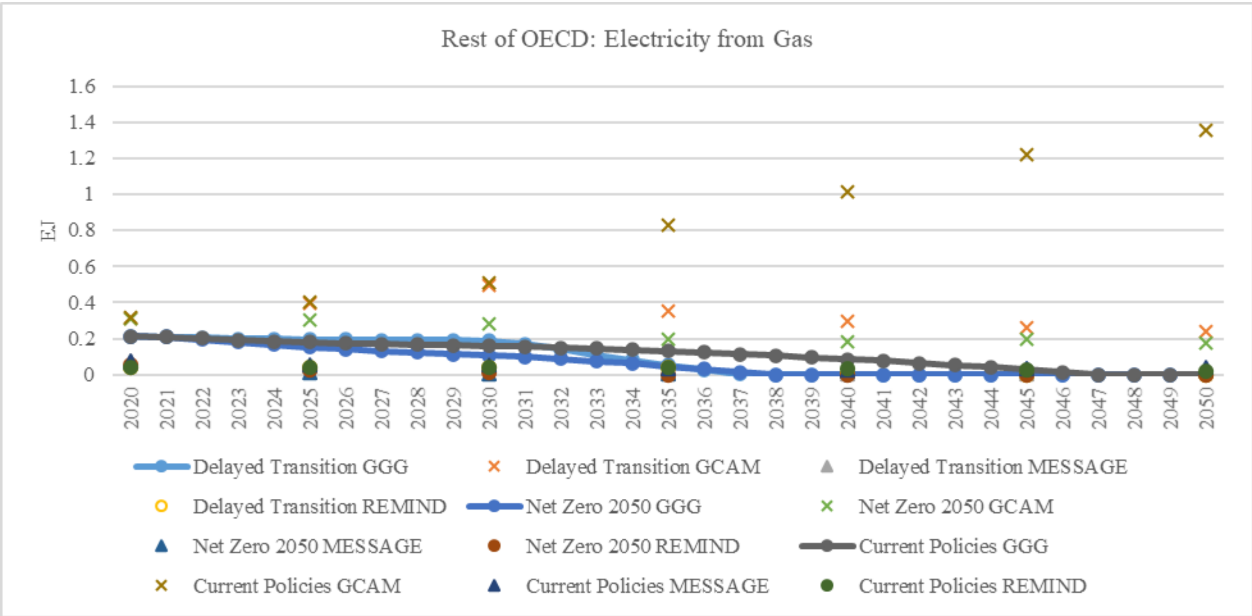


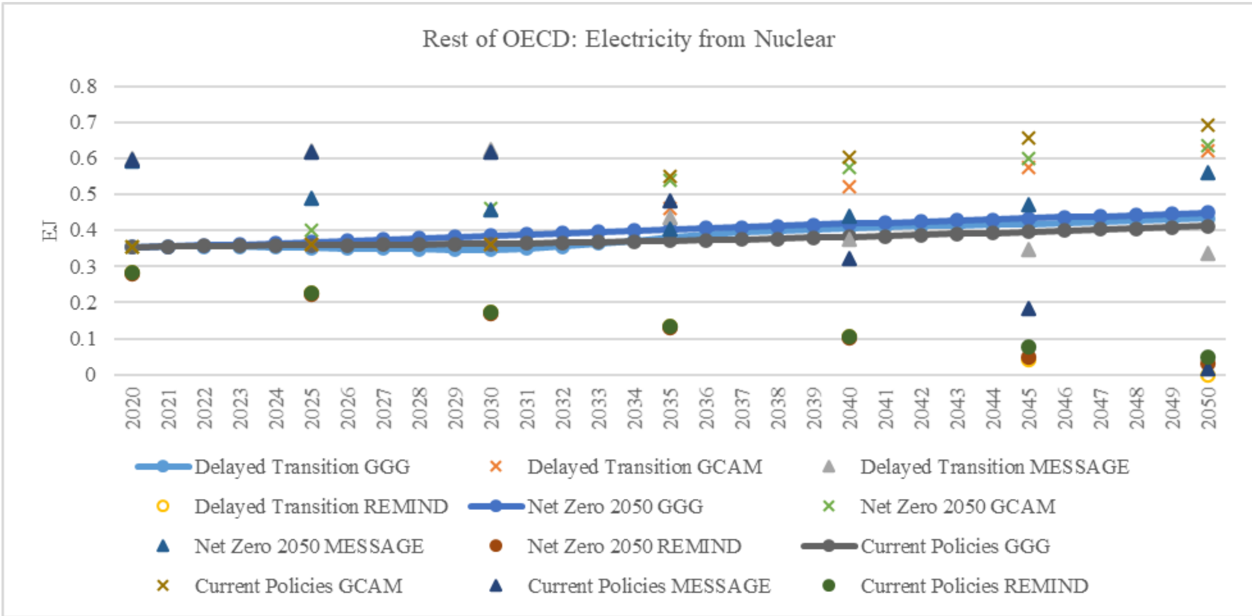


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Rest of OECD (Contd.)

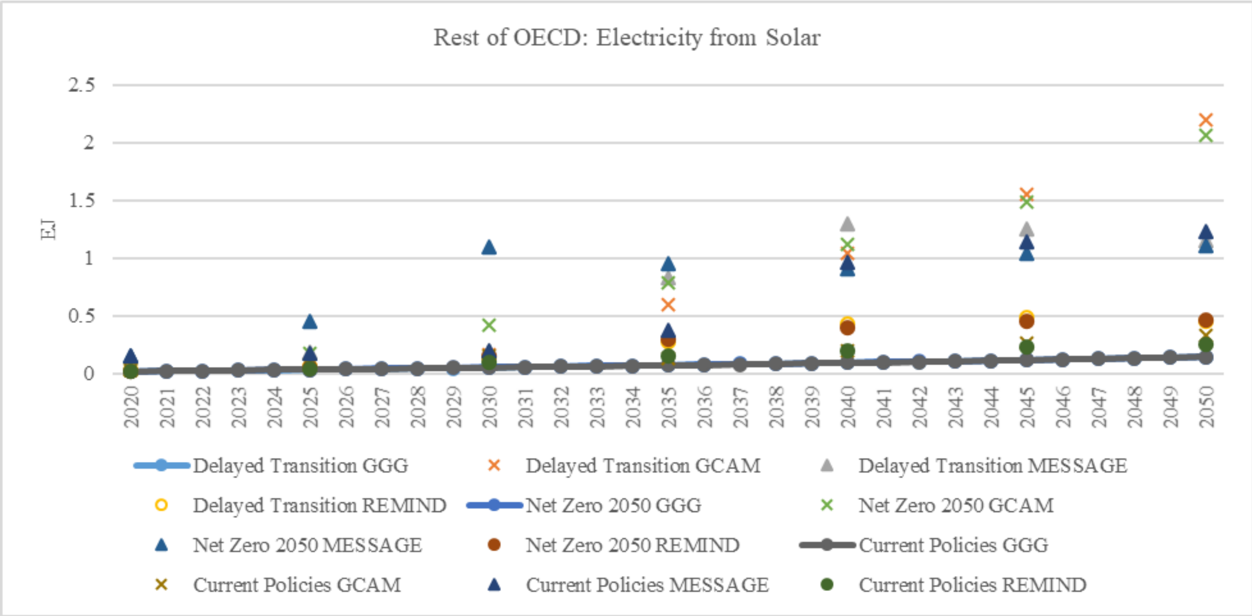


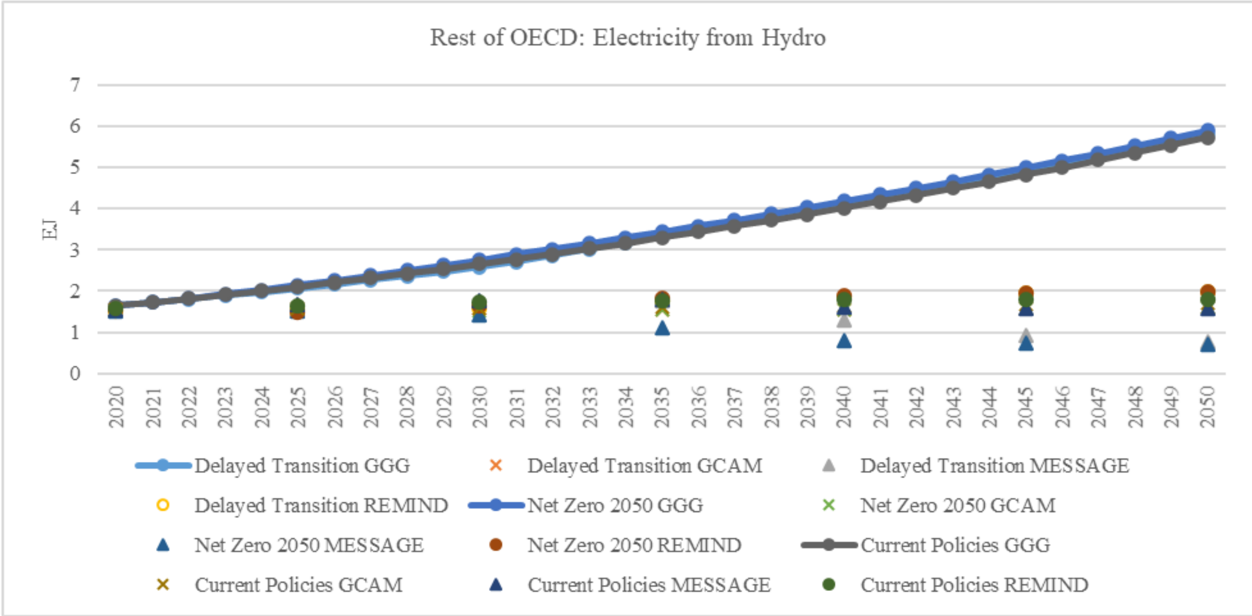


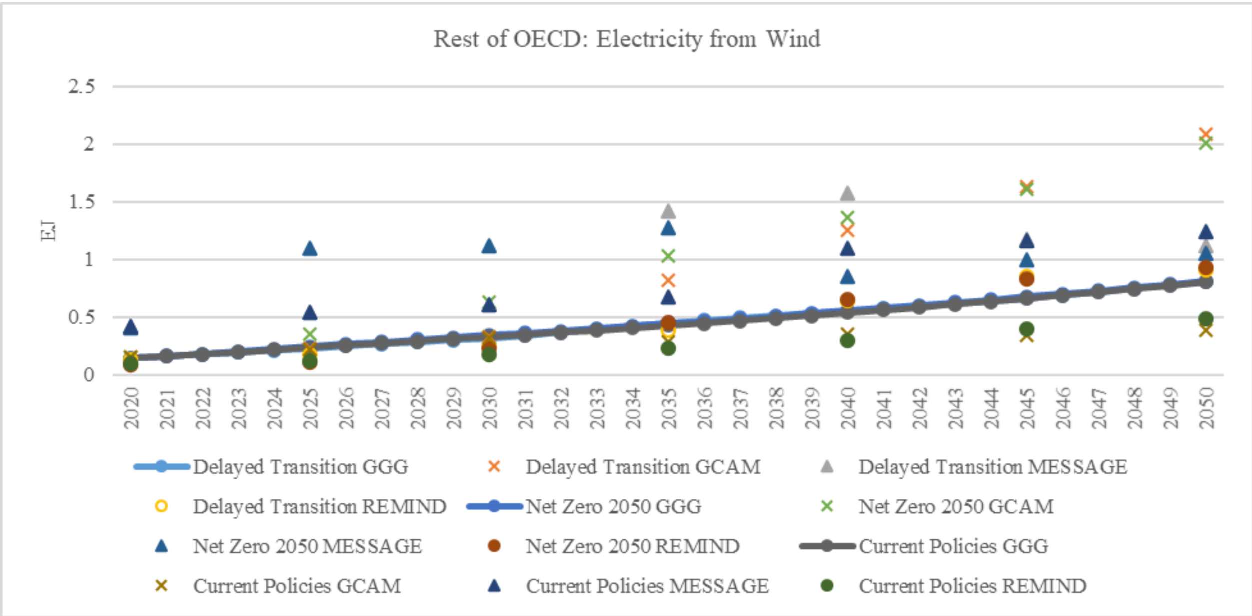


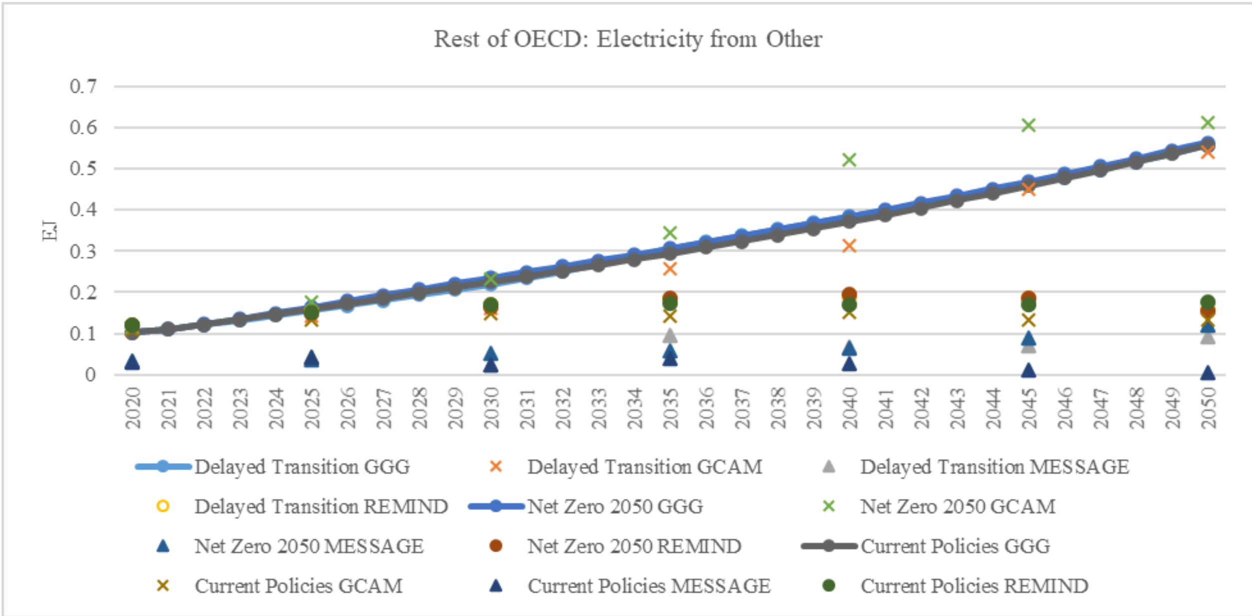


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Rest of OECD (Contd.)

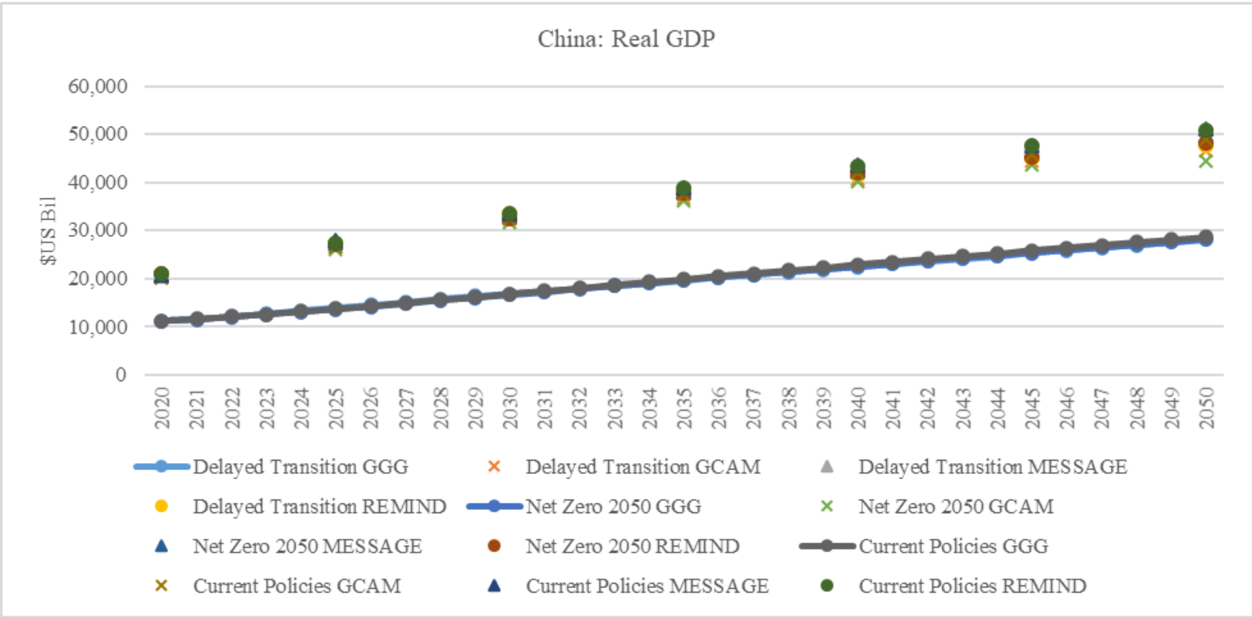


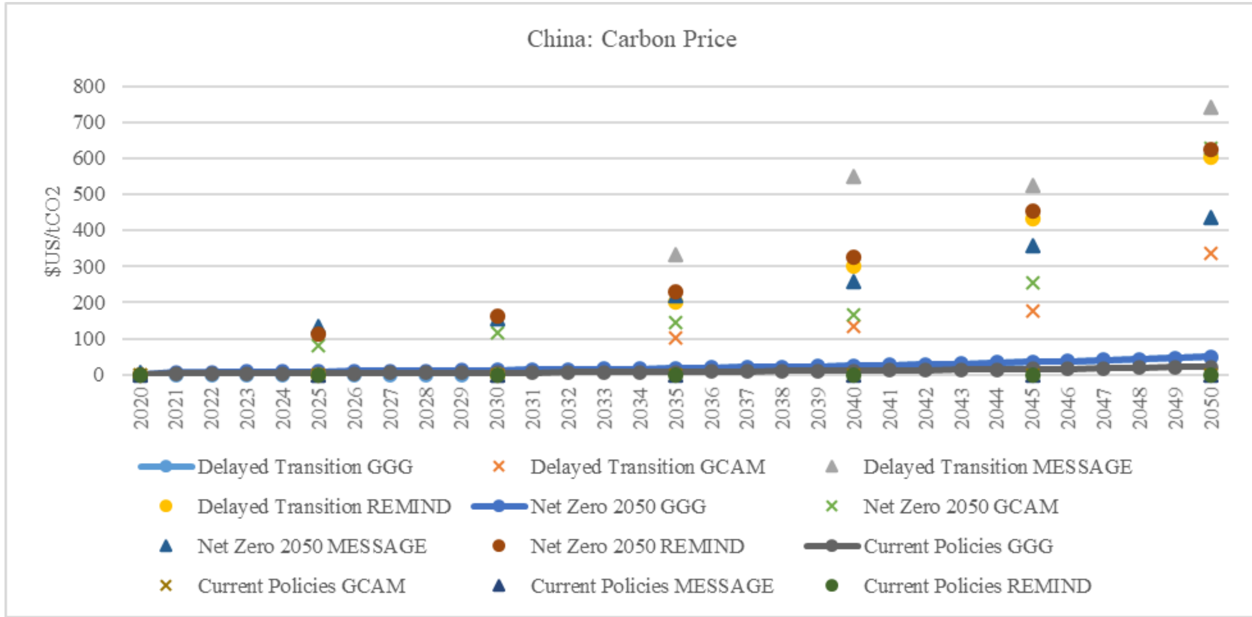


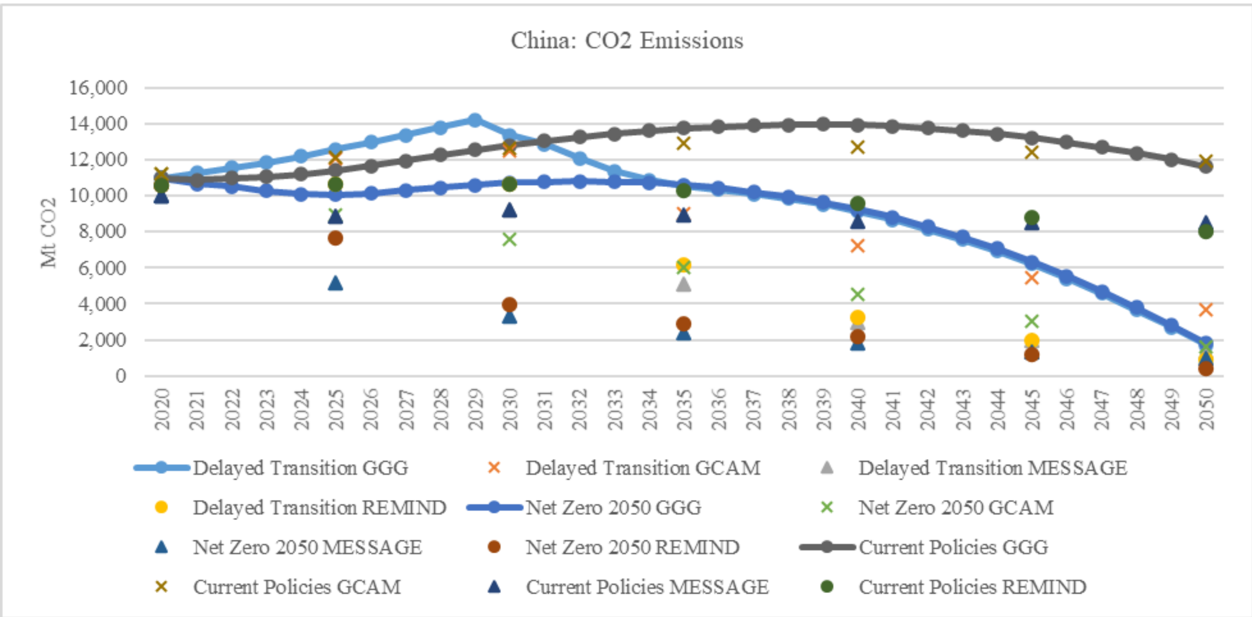


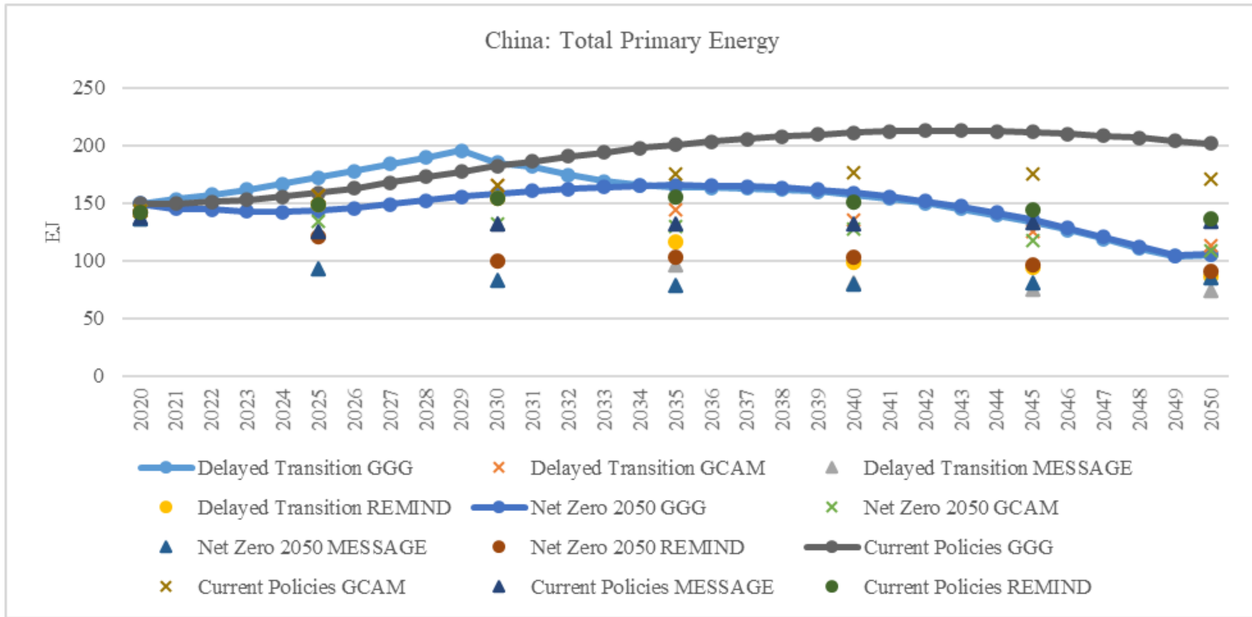


Comparison of Scenario Results among G-Cubed and NGFS IAMs: China

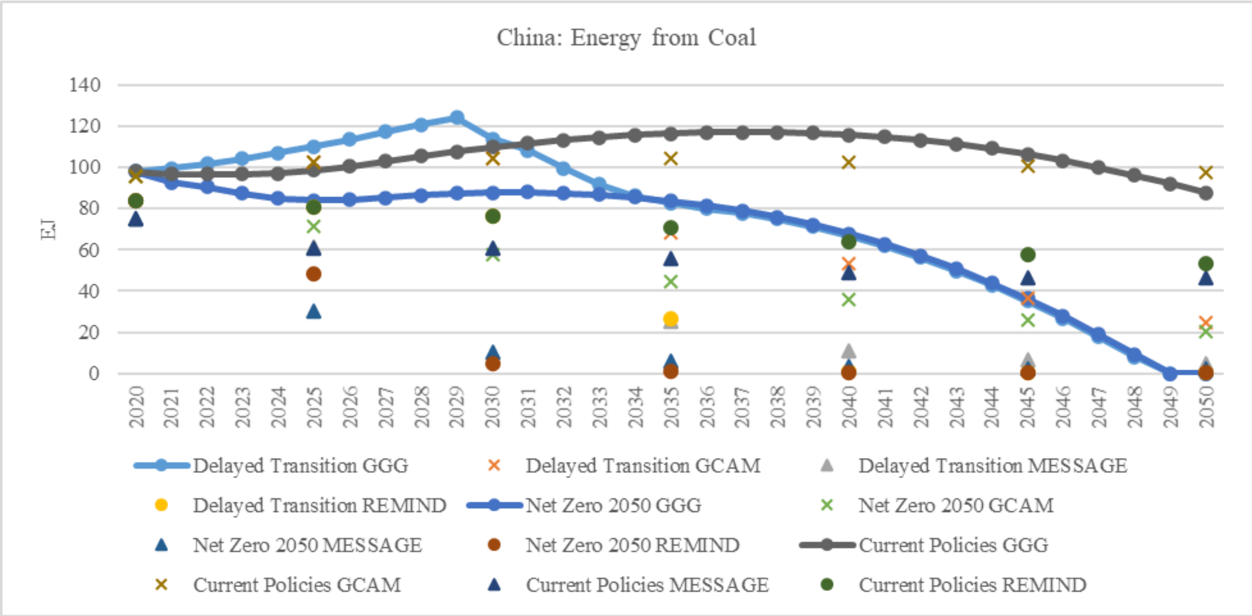


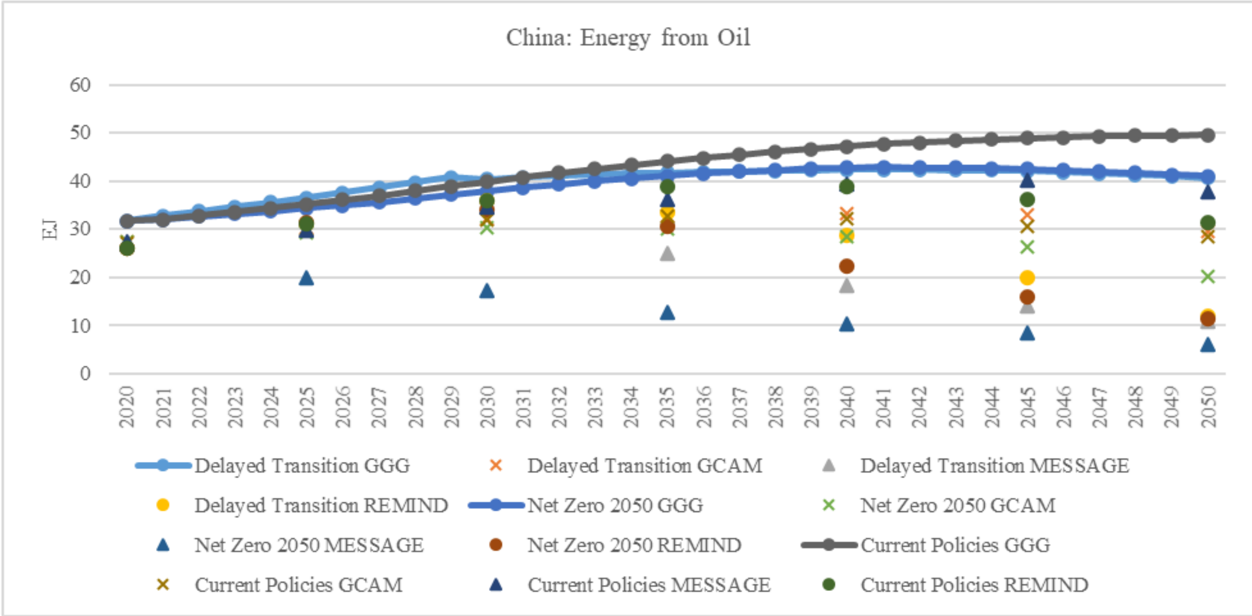


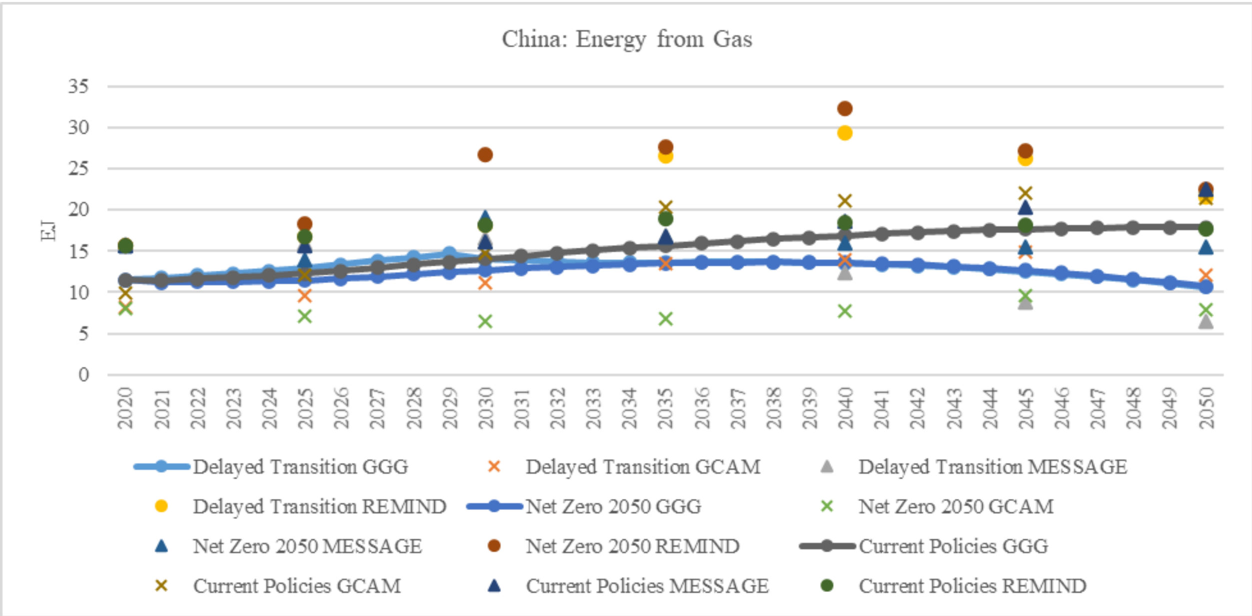


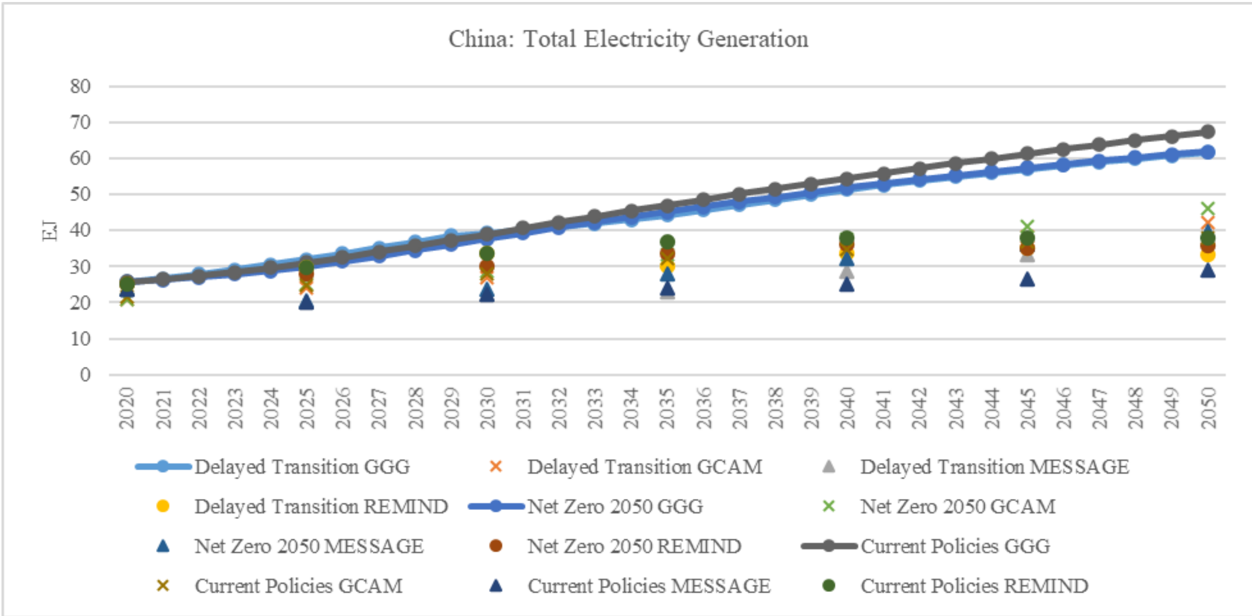


Comparison of Scenario Results among G-Cubed and NGFS IAMs: China (Contd.)

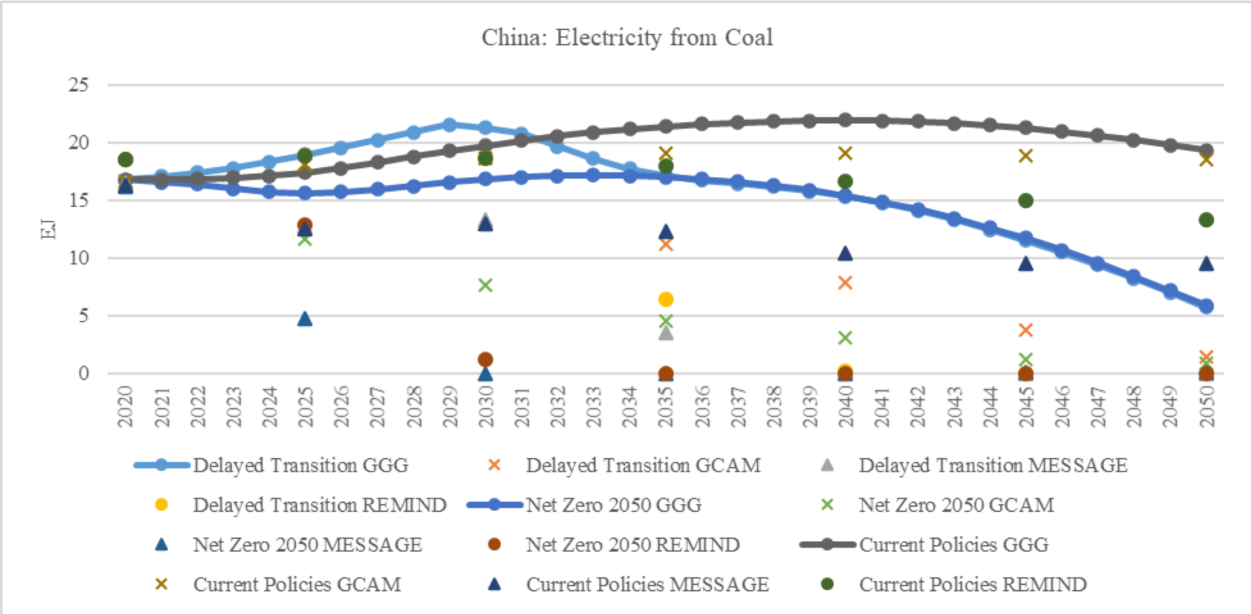


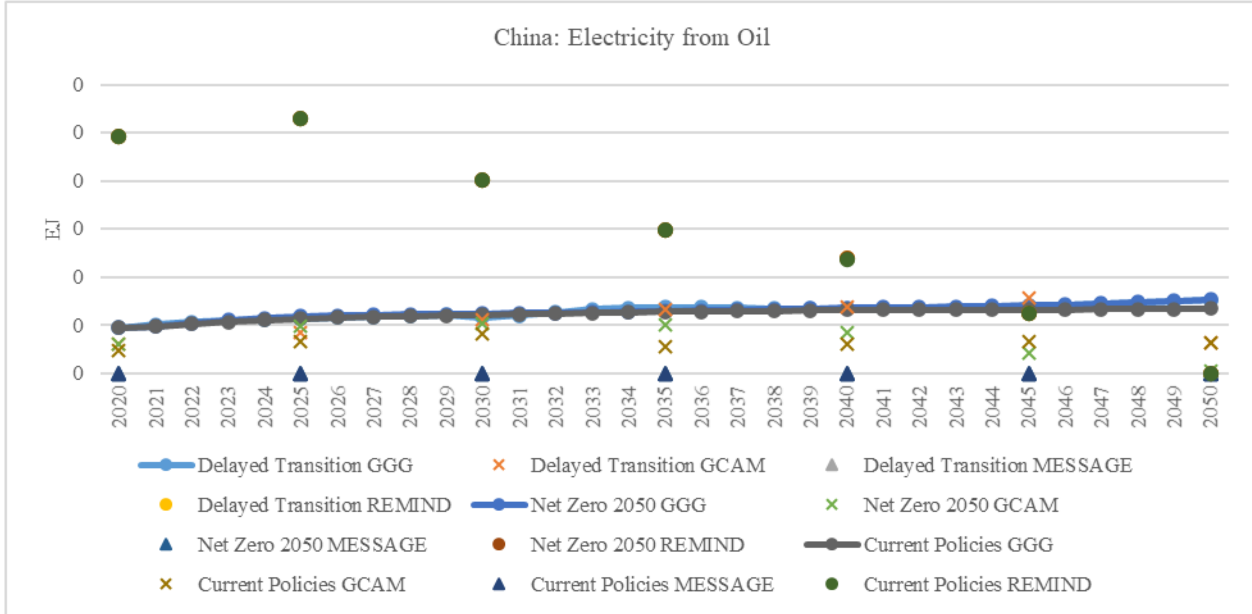


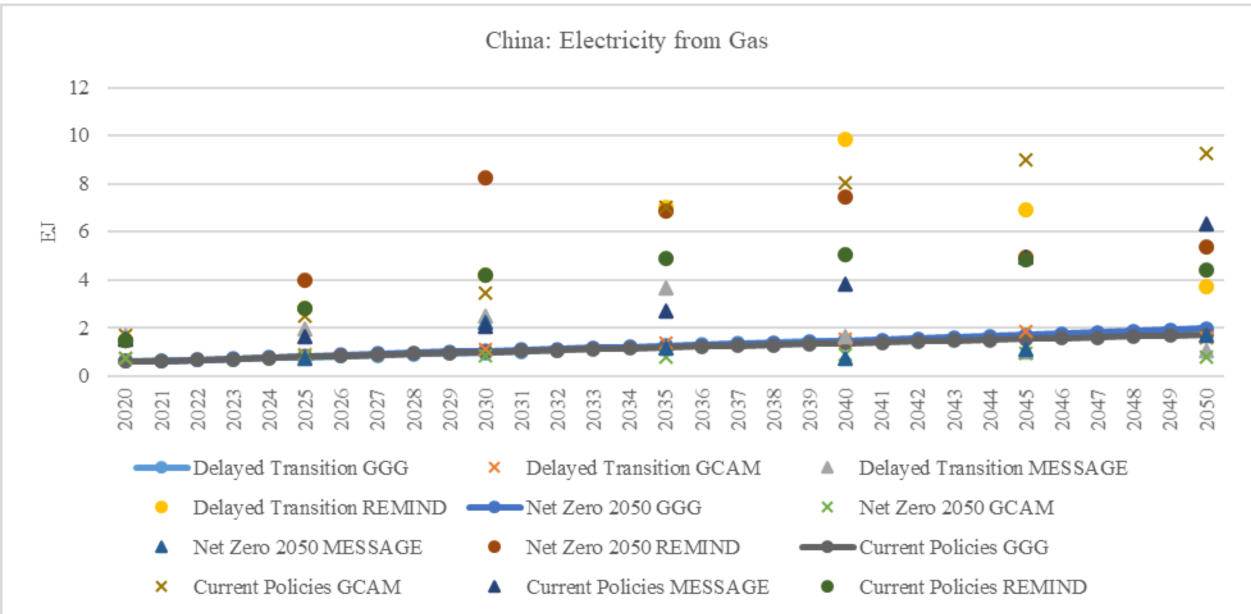


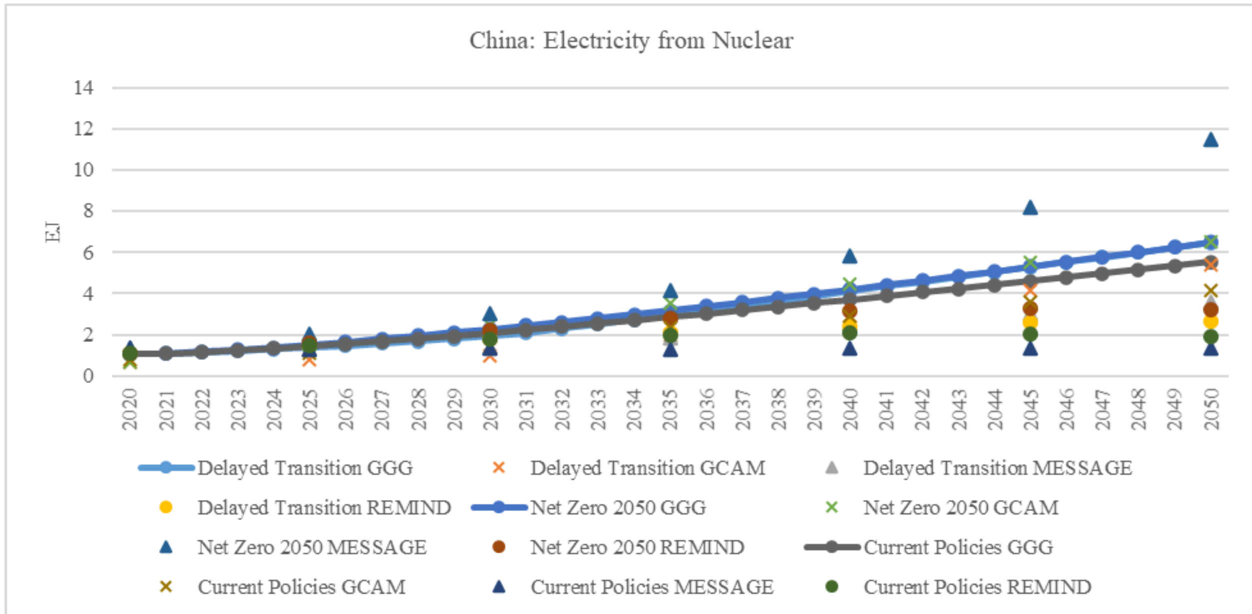


Comparison of Scenario Results among G-Cubed and NGFS IAMs: China (Contd.)

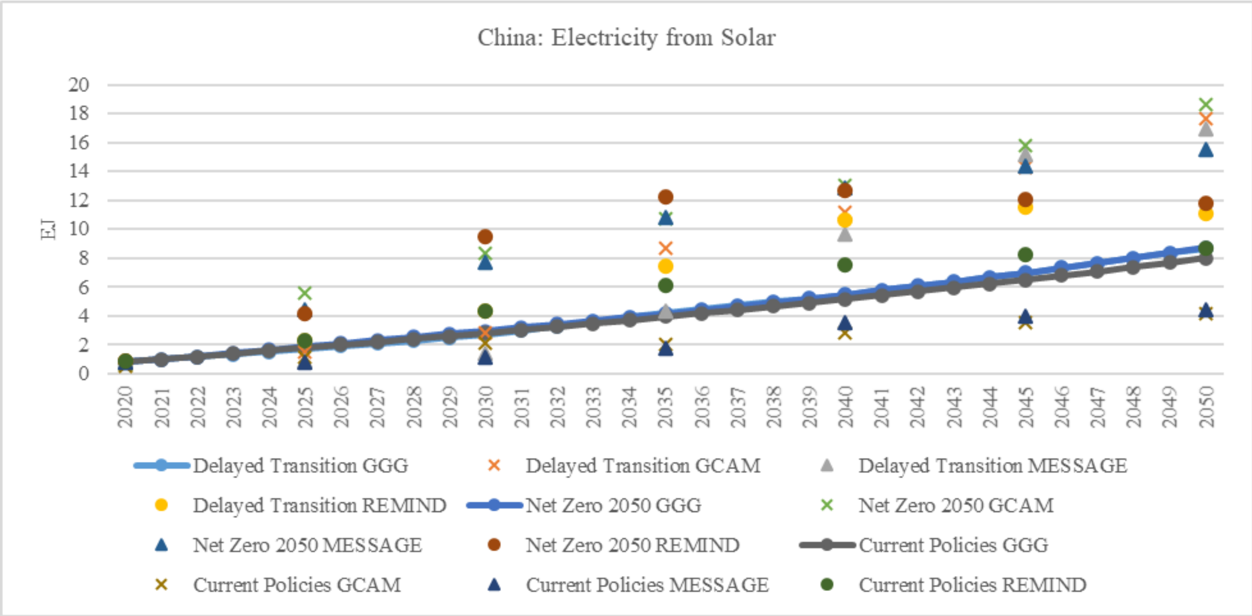


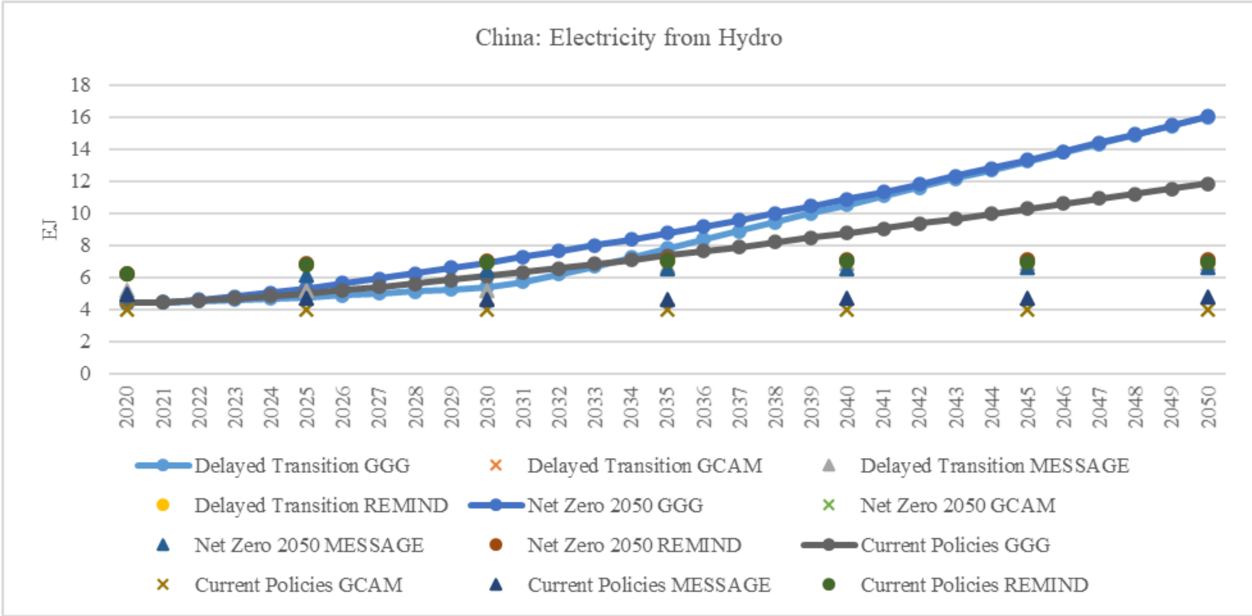


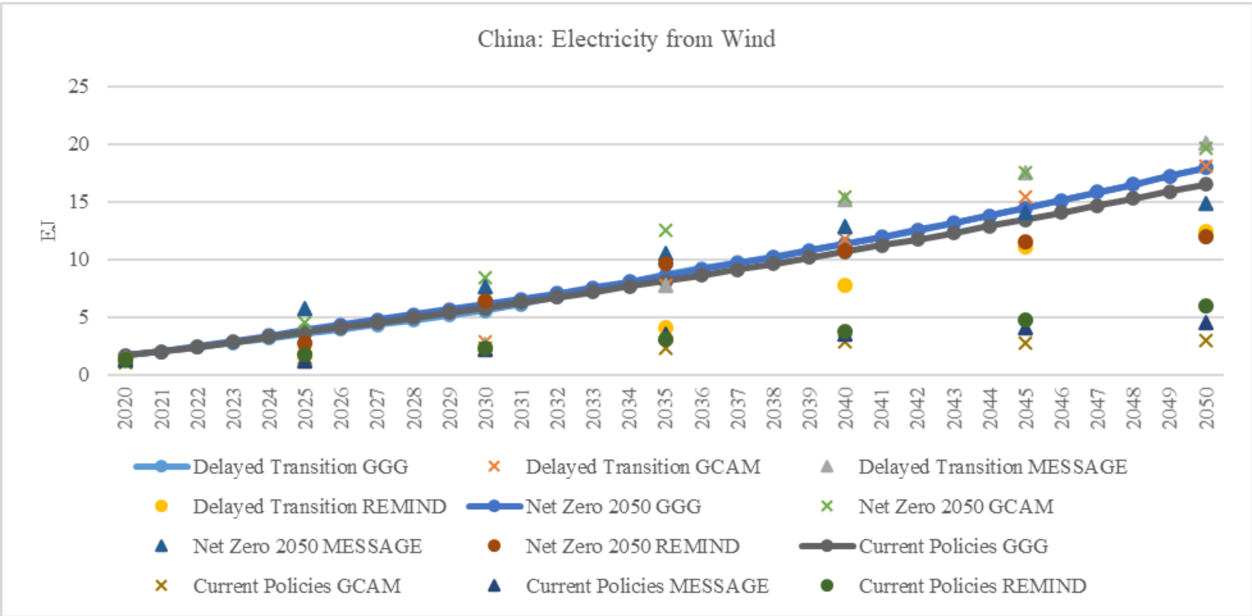


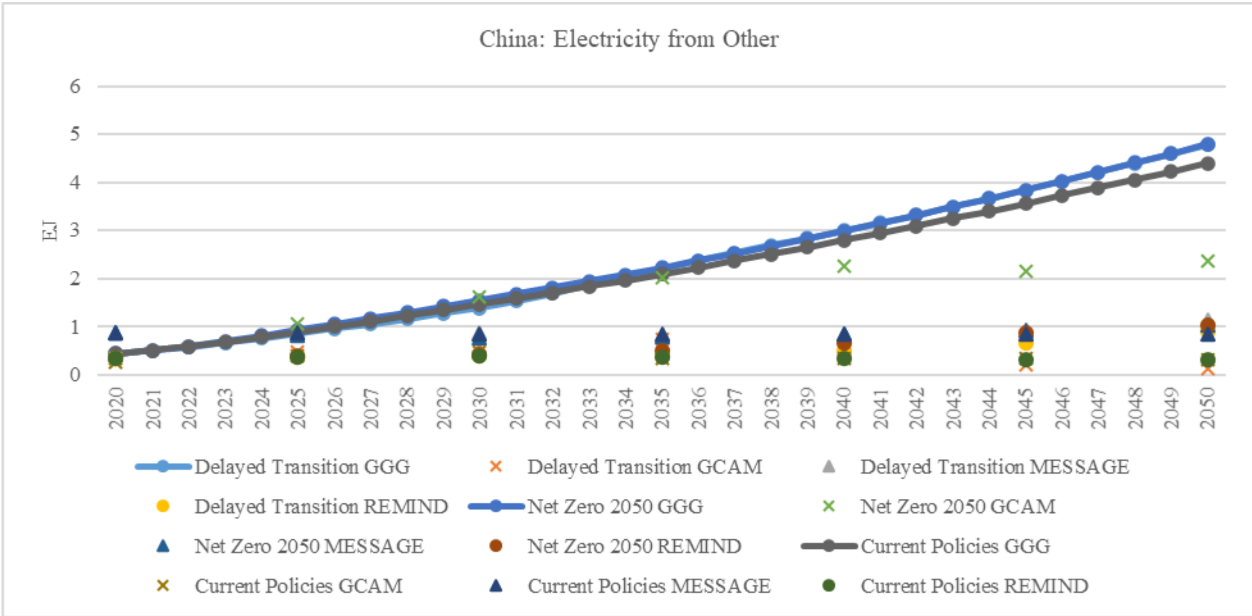


Comparison of Scenario Results among G-Cubed and NGFS IAMs: China (Contd.)

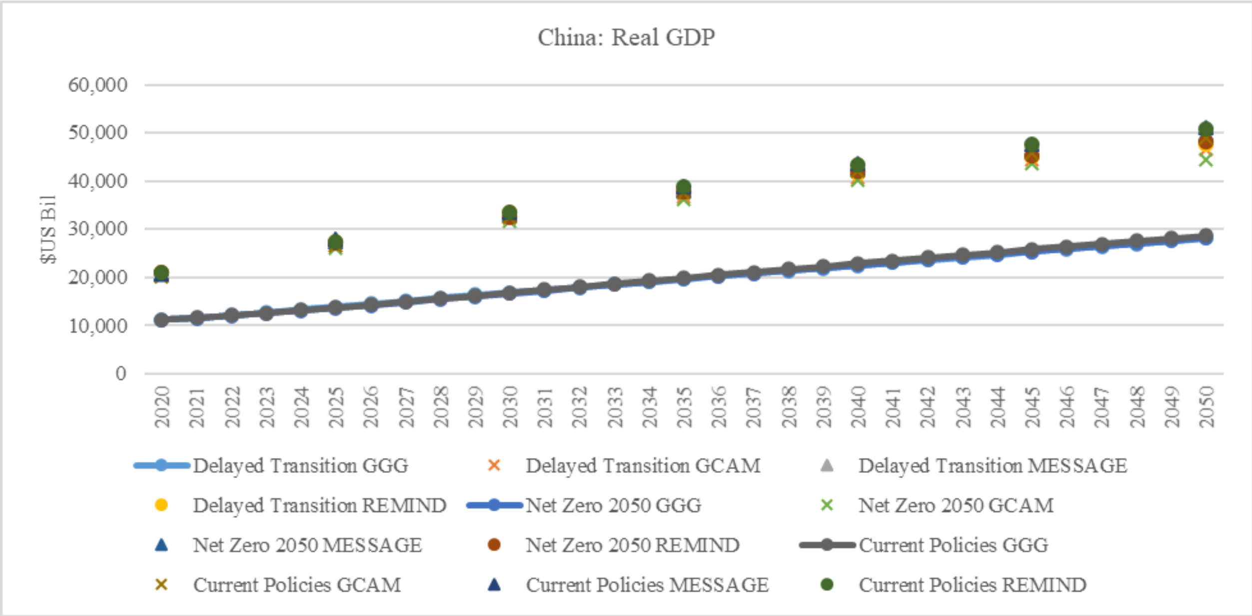


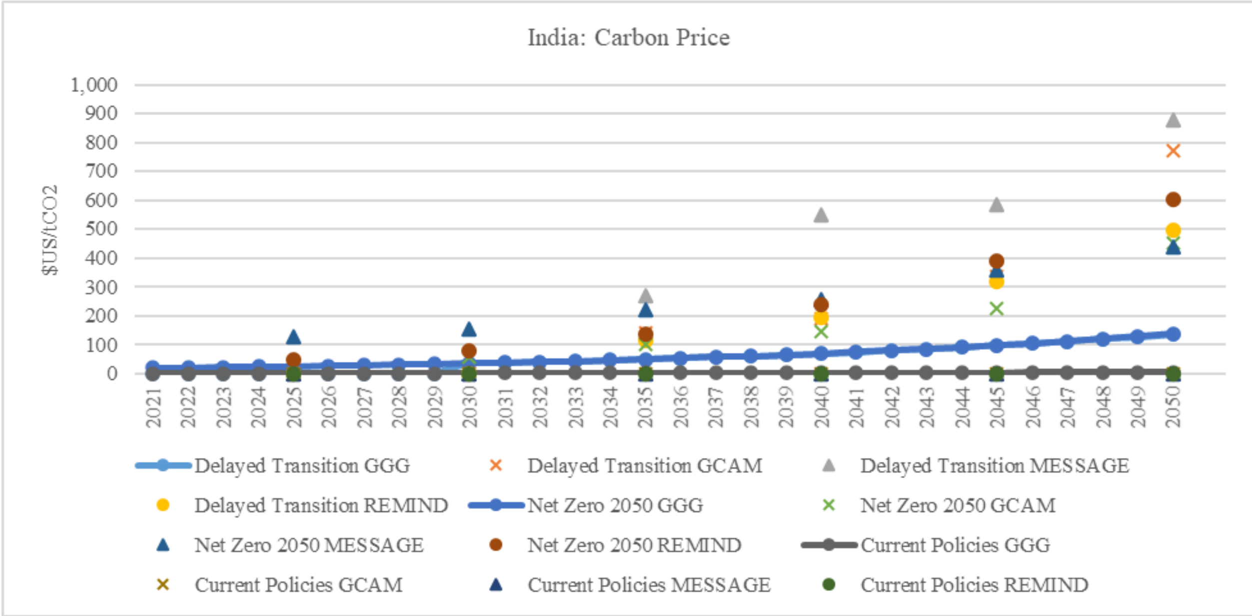


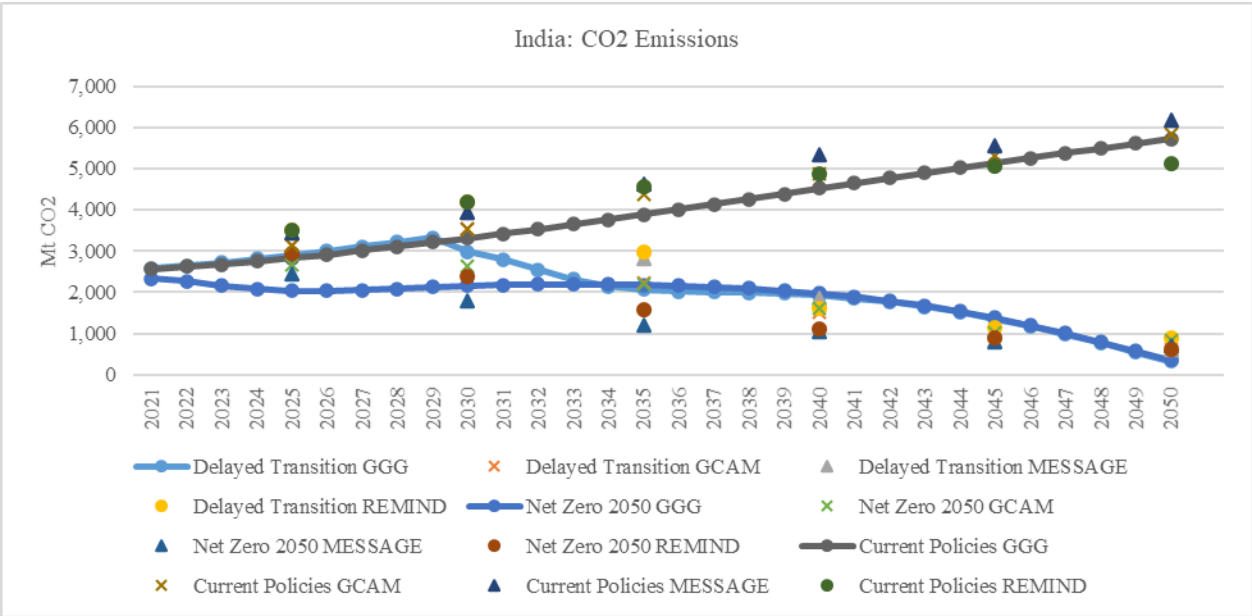


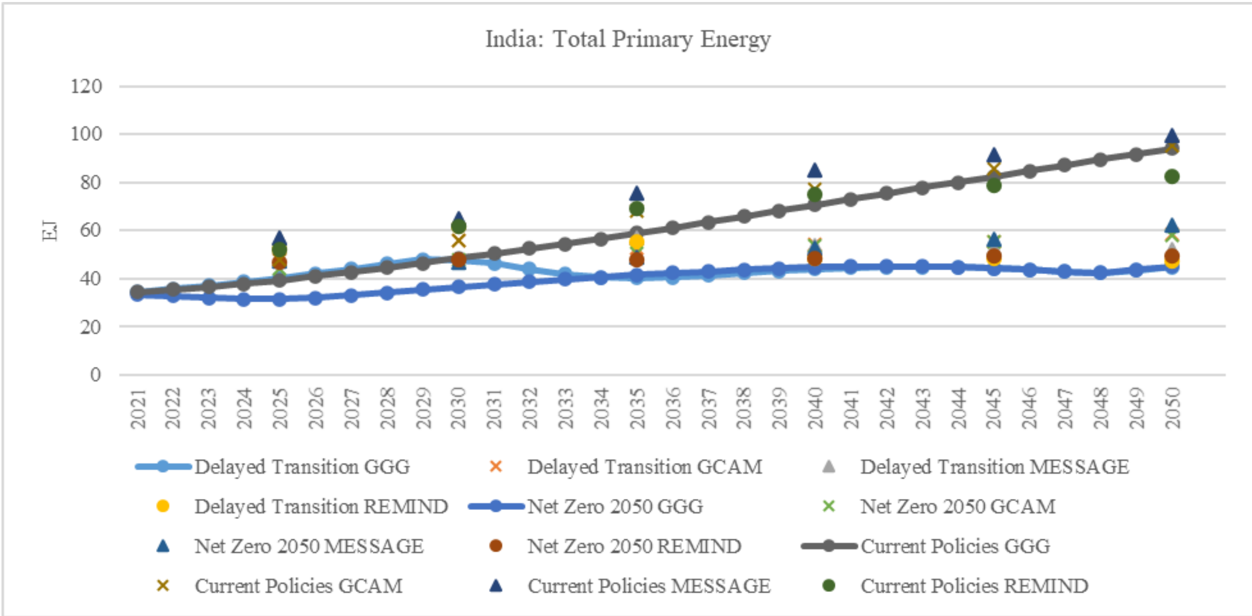


Comparison of Scenario Results among G-Cubed and NGFS IAMs: India

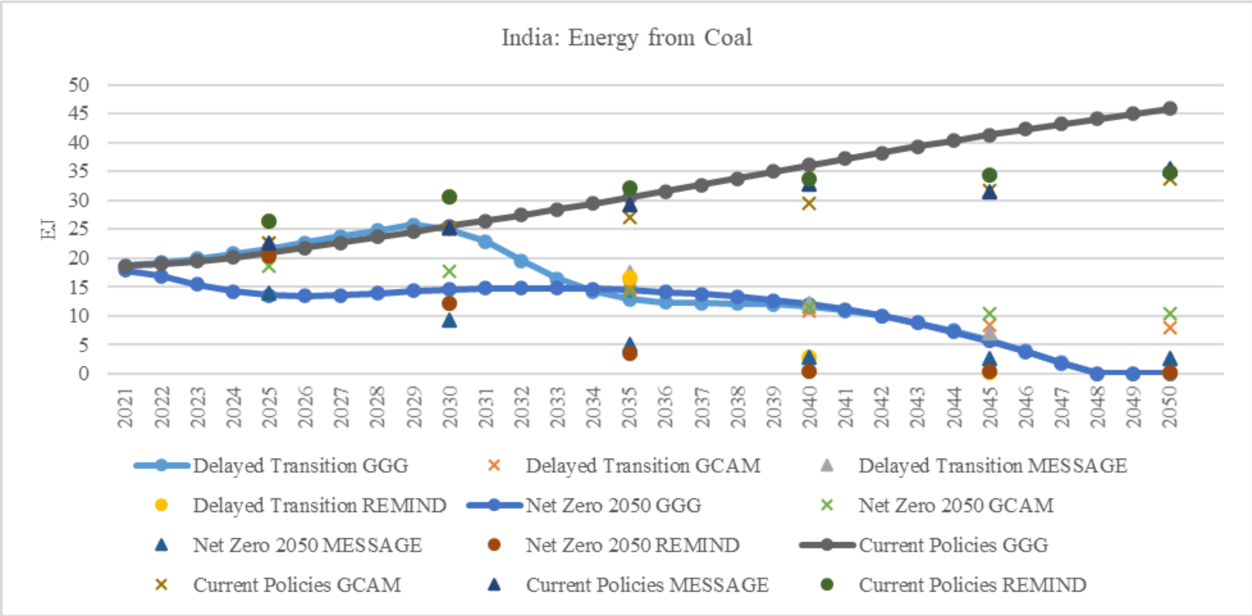


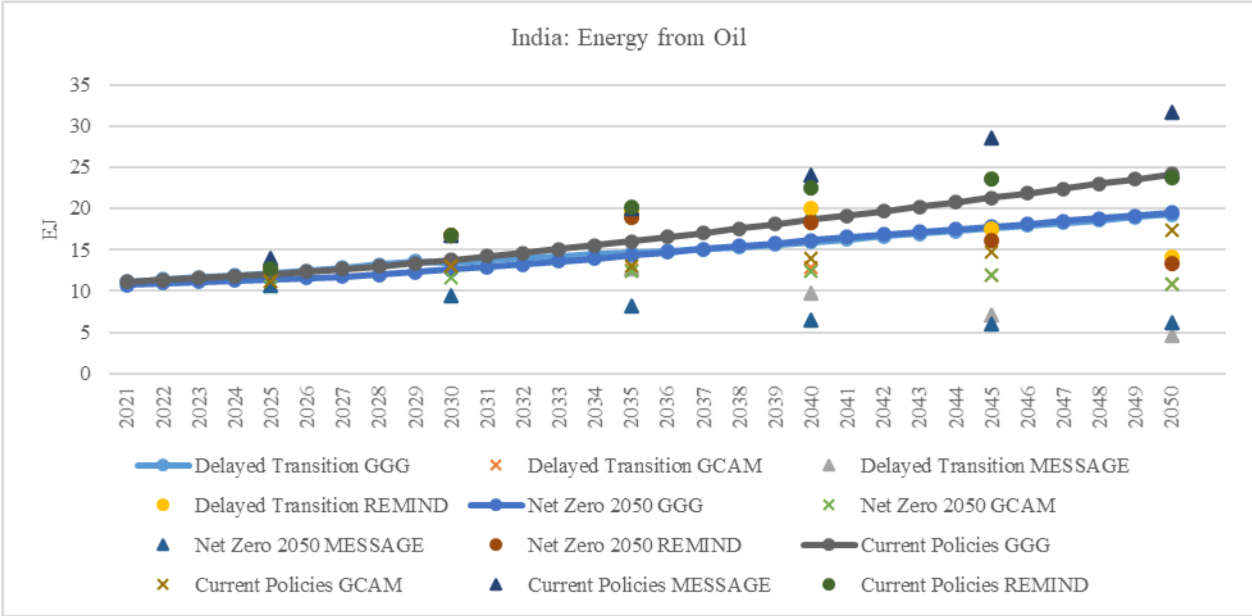


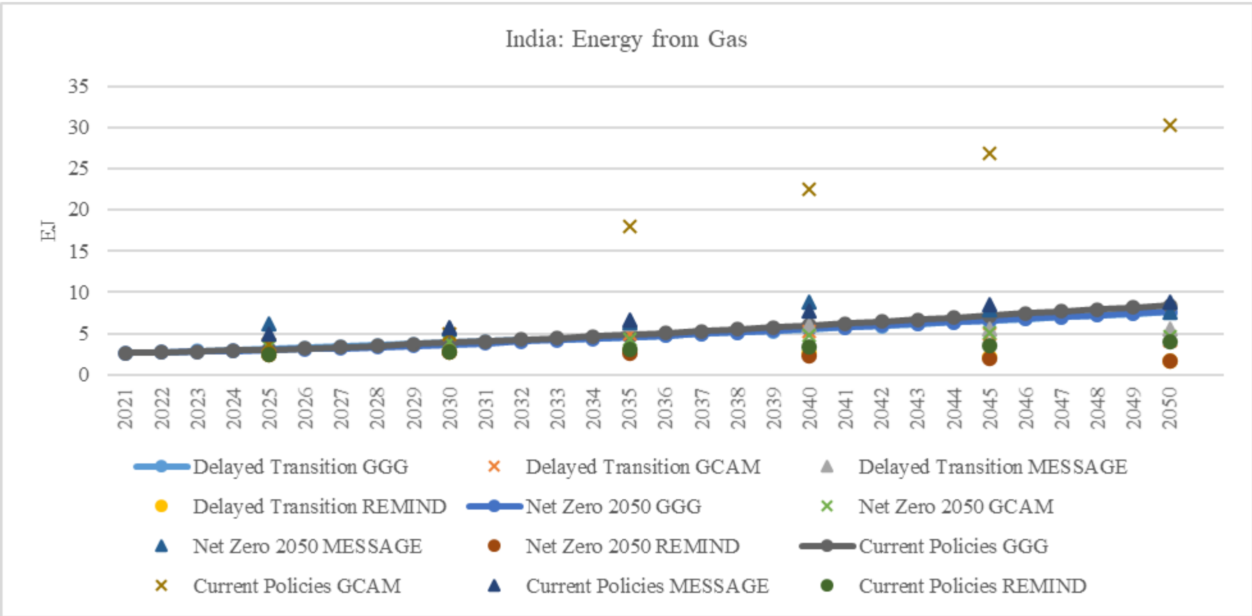


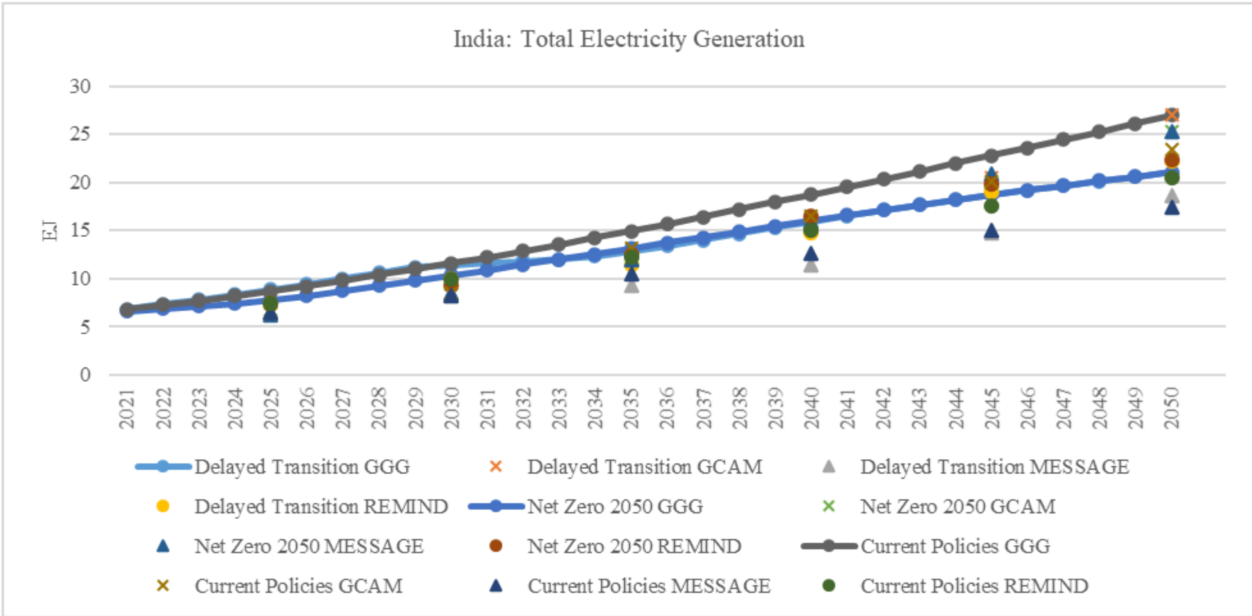


Comparison of Scenario Results among G-Cubed and NGFS IAMs: India (Contd.)

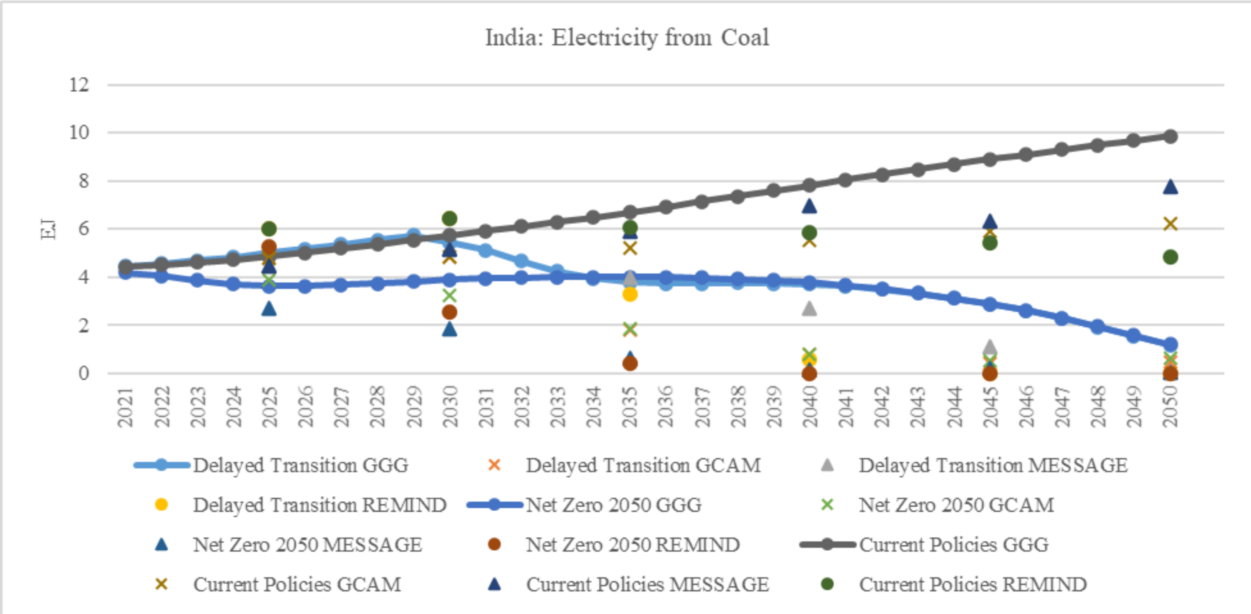


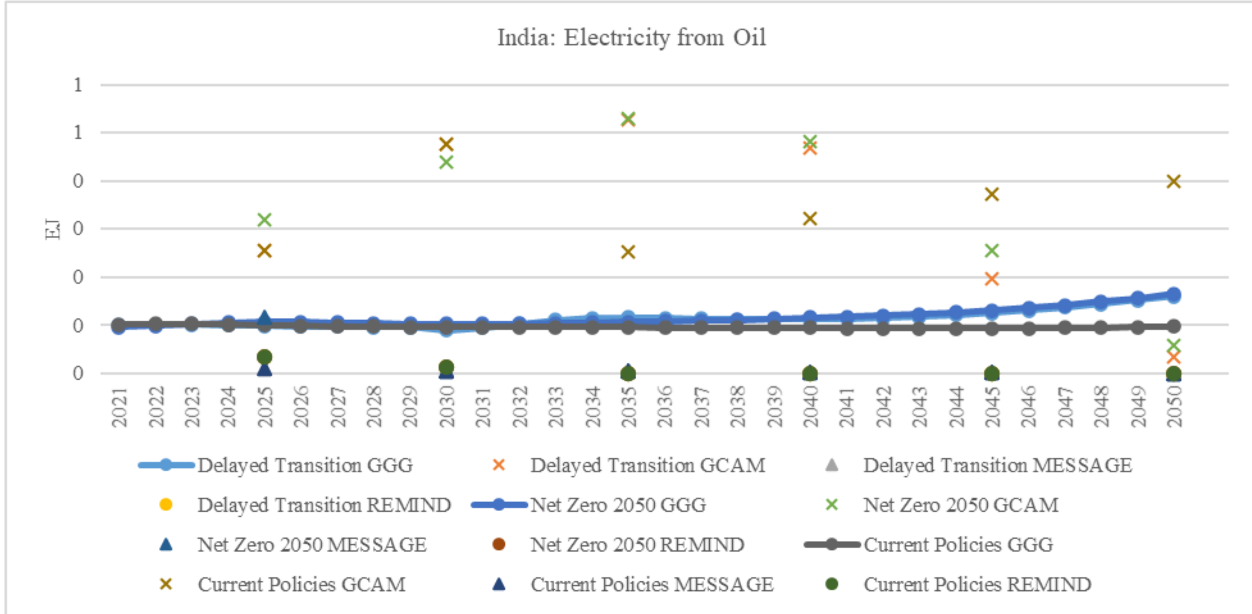


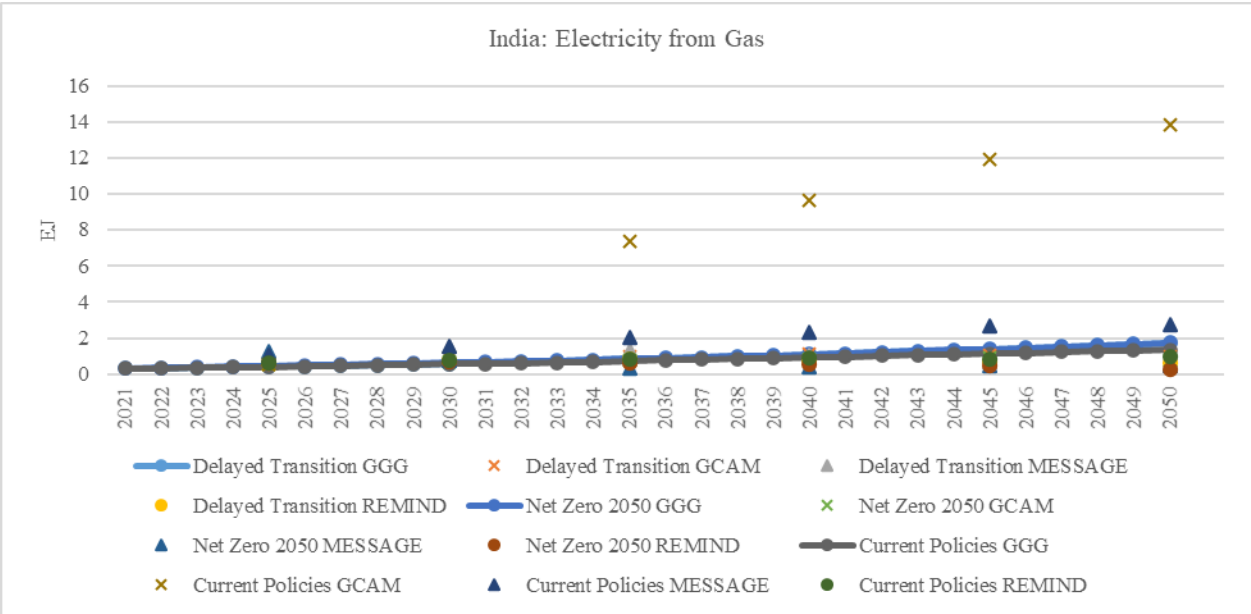


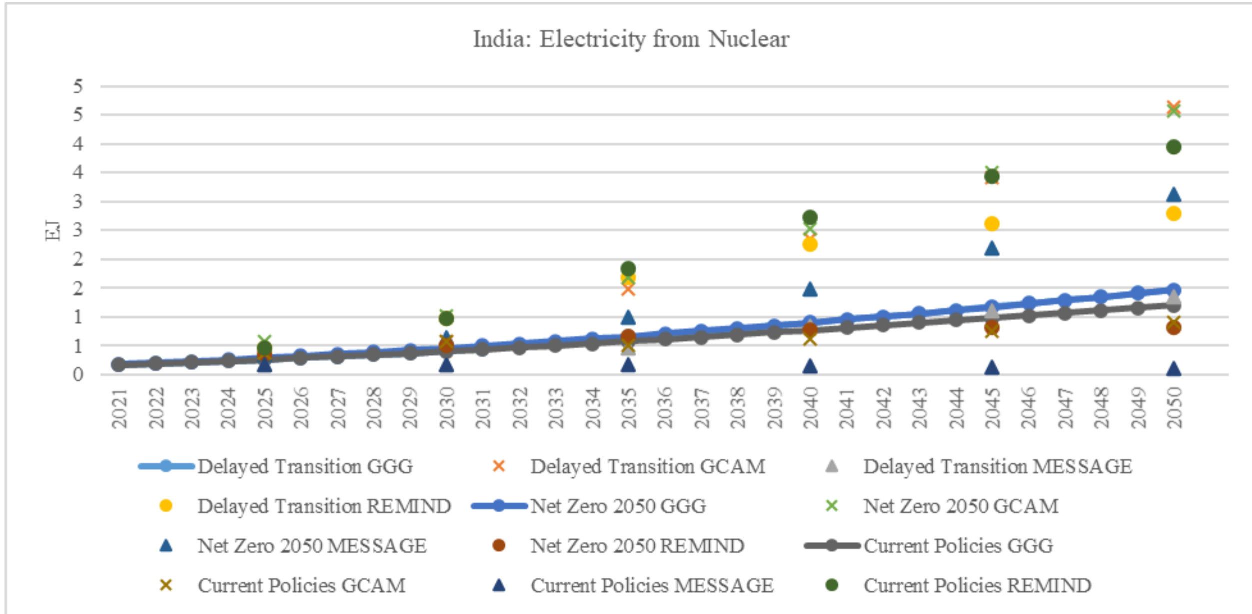


Comparison of Scenario Results among G-Cubed and NGFS IAMs: India (Contd.)

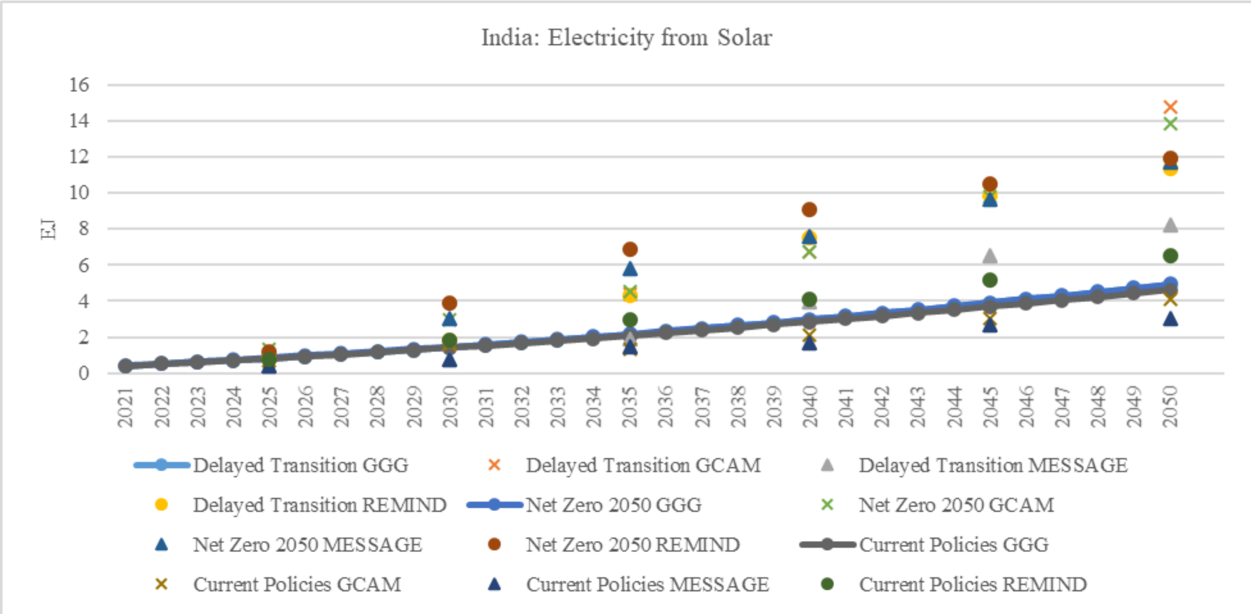


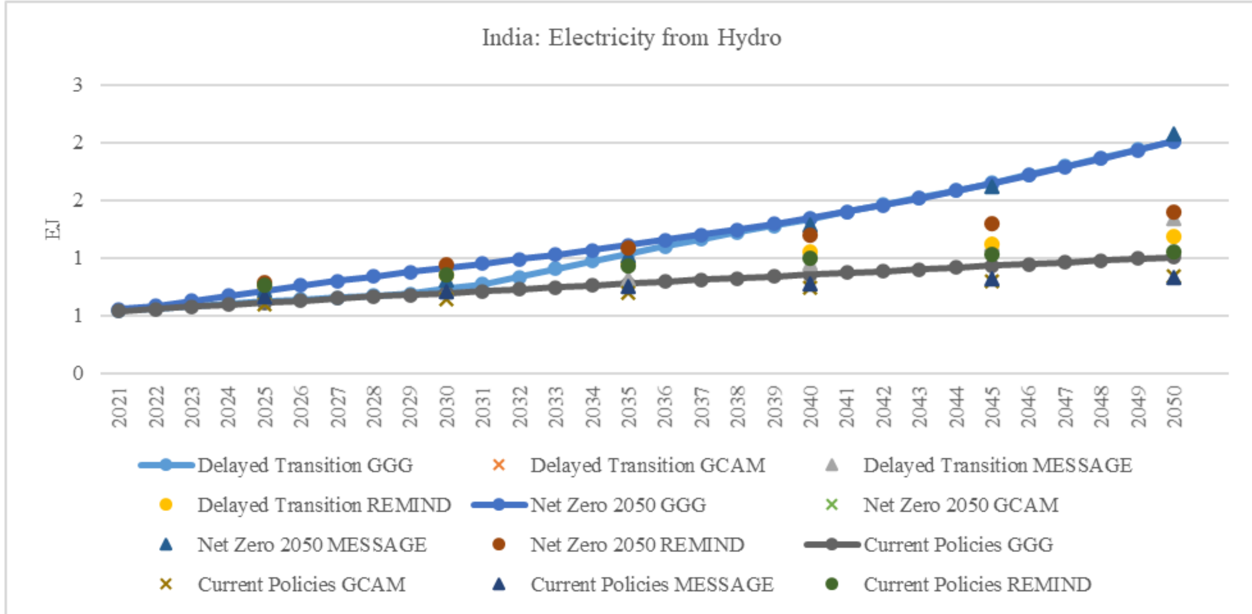


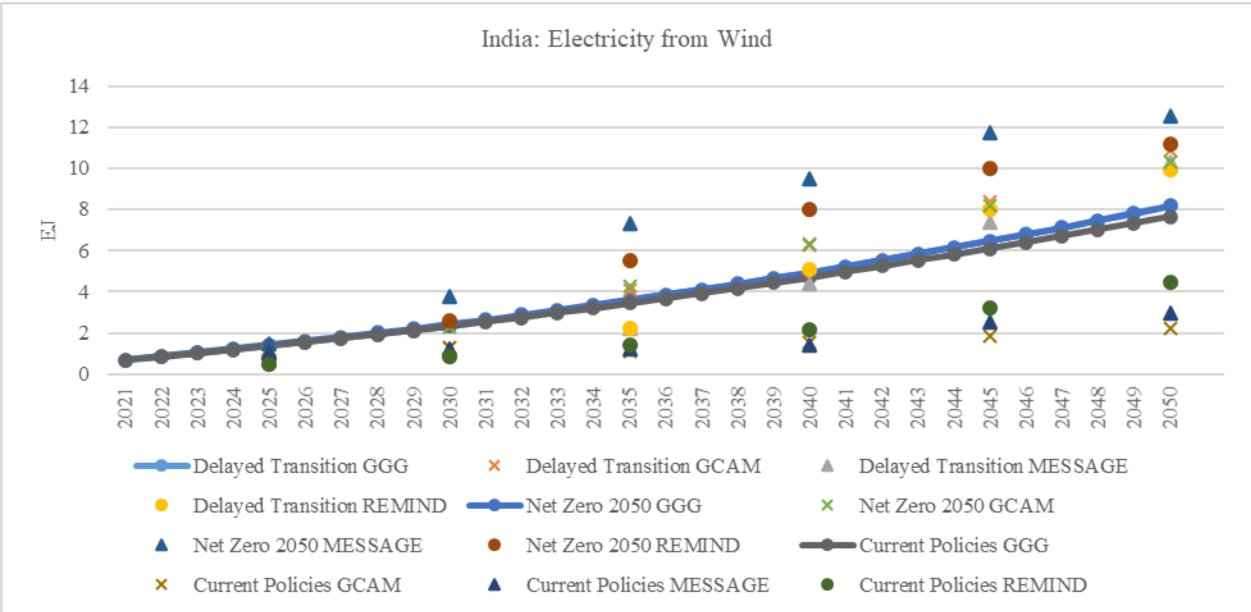


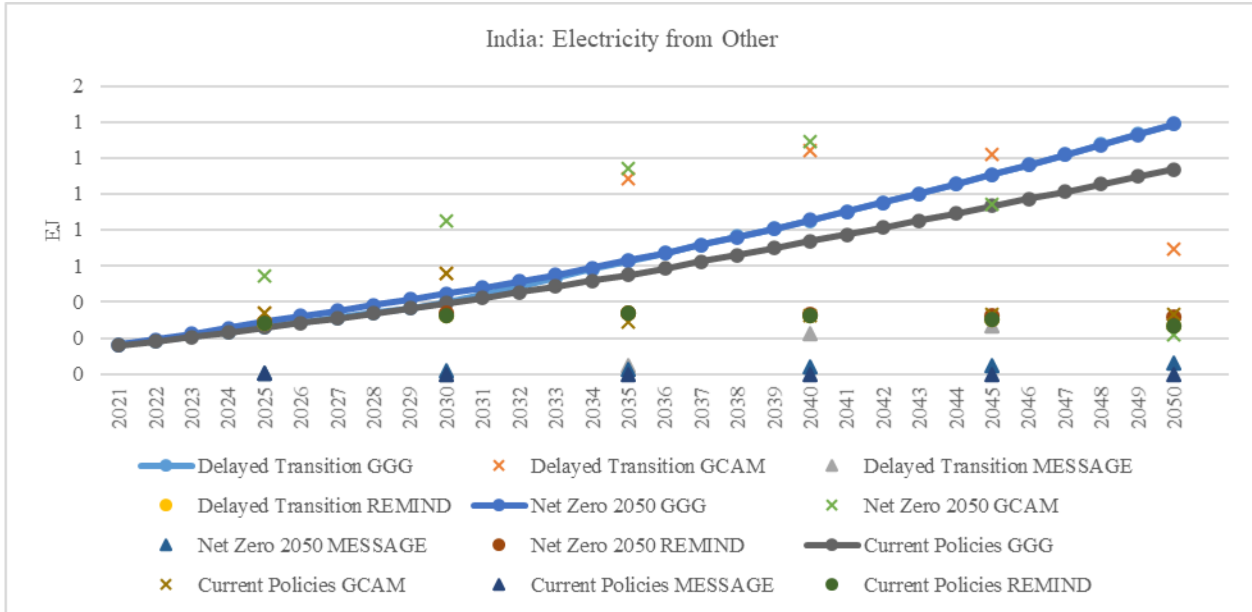


Comparison of Scenario Results among G-Cubed and NGFS IAMs: India (Contd.)

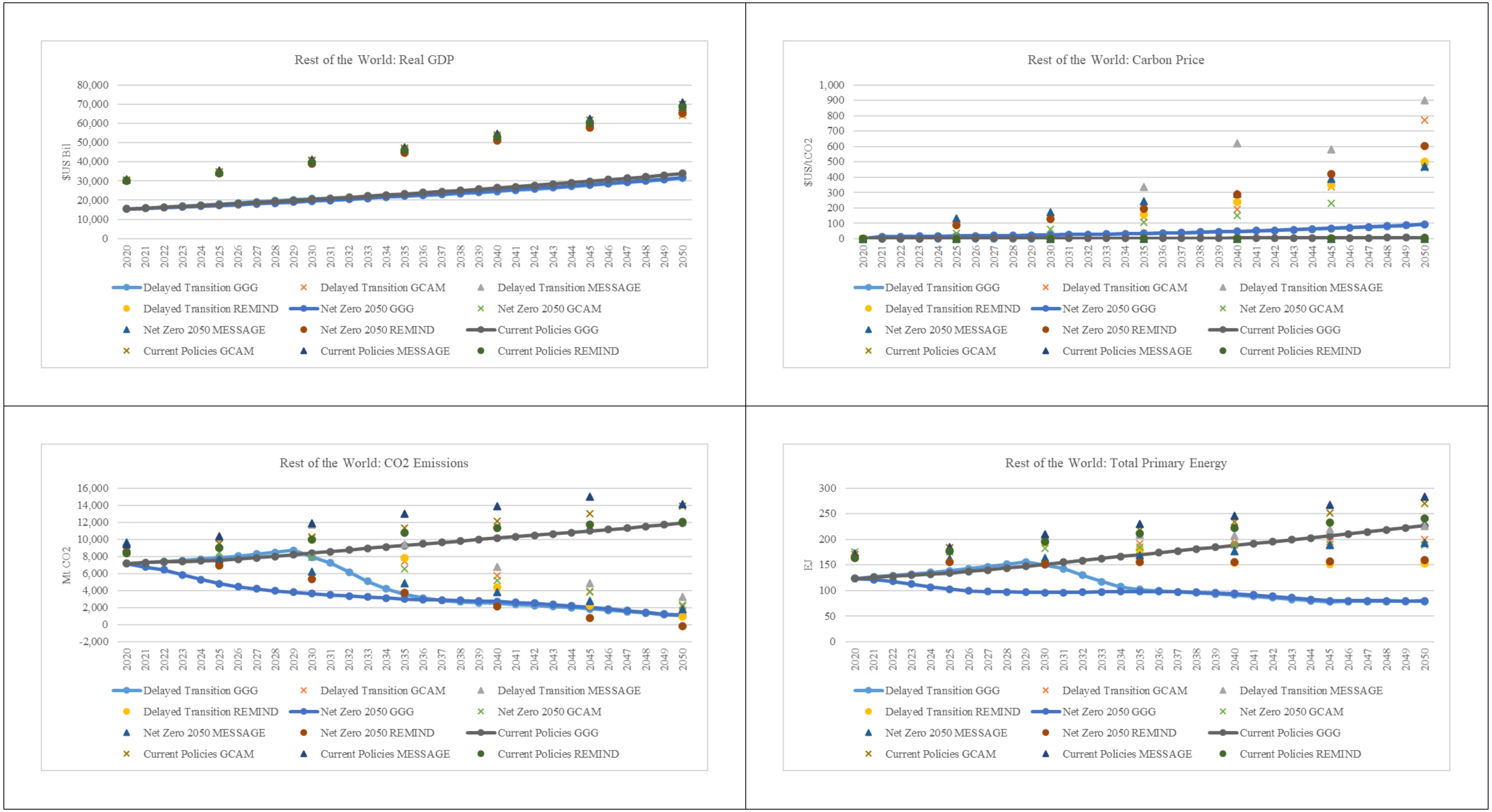




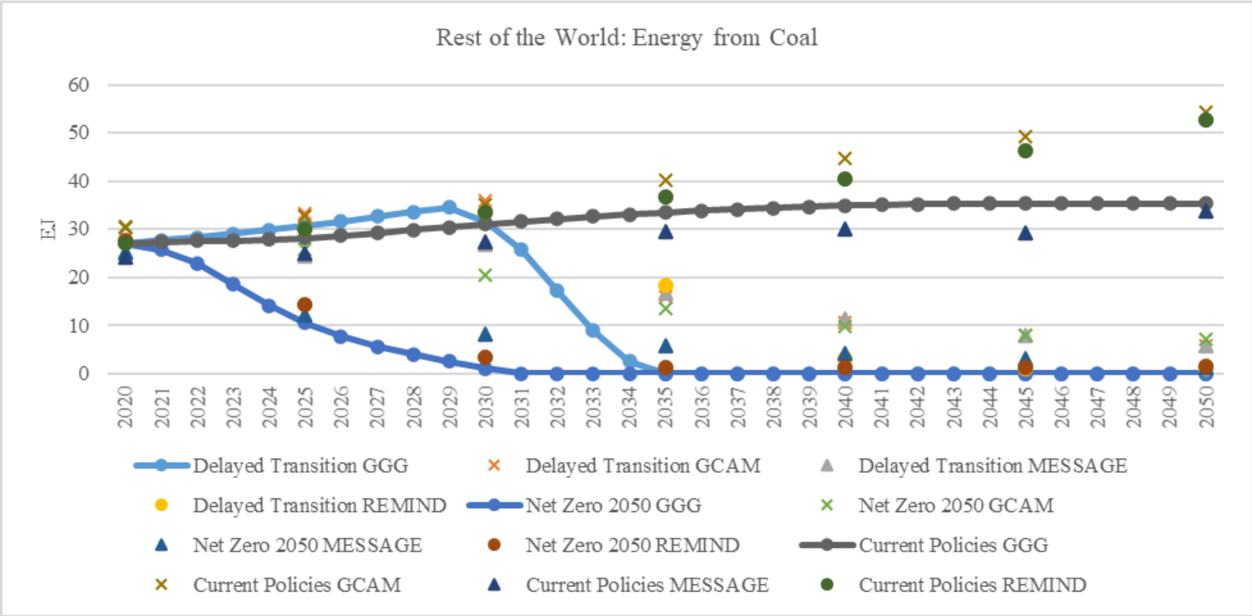


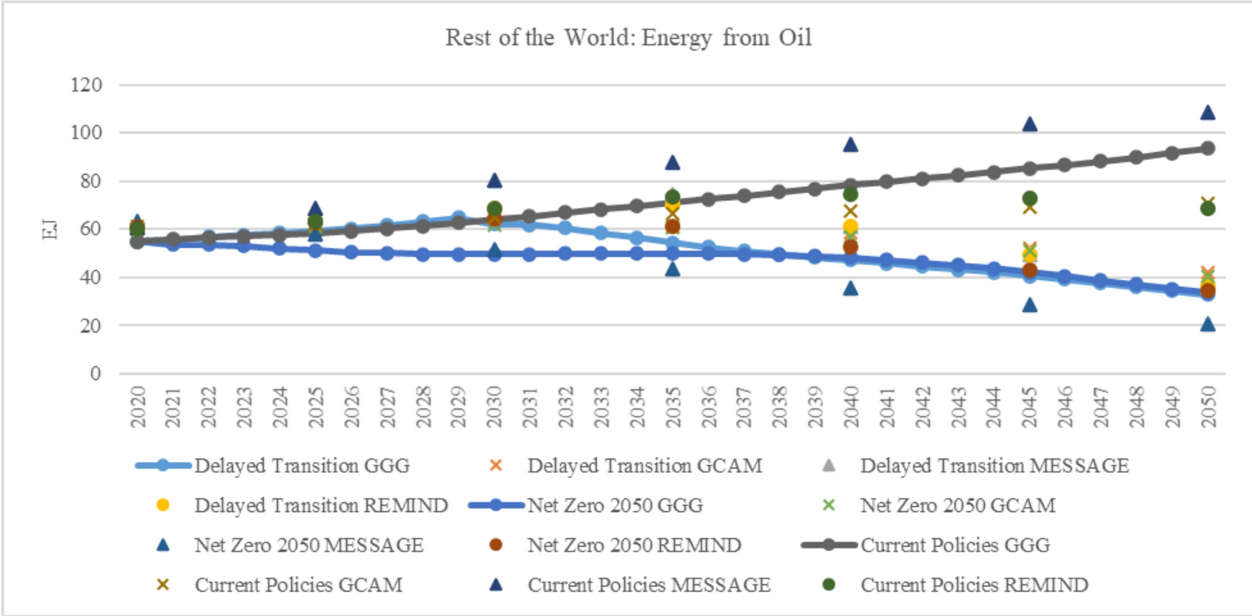


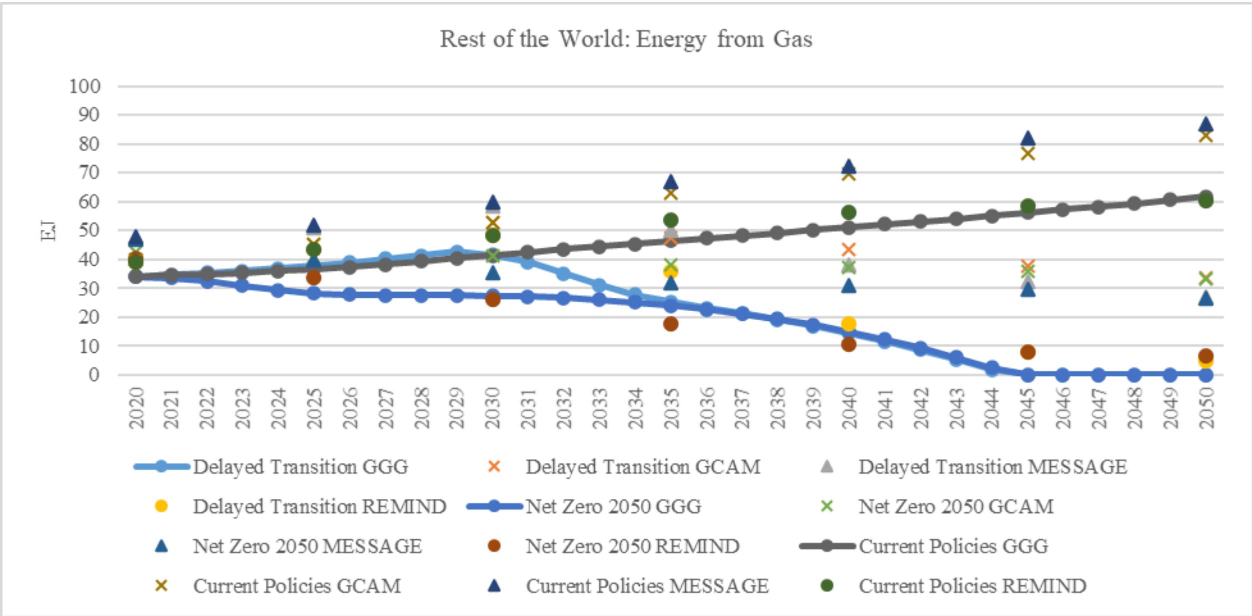
Comparison of Scenario Results among G-Cubed and NGFS IAMs: Rest of the World

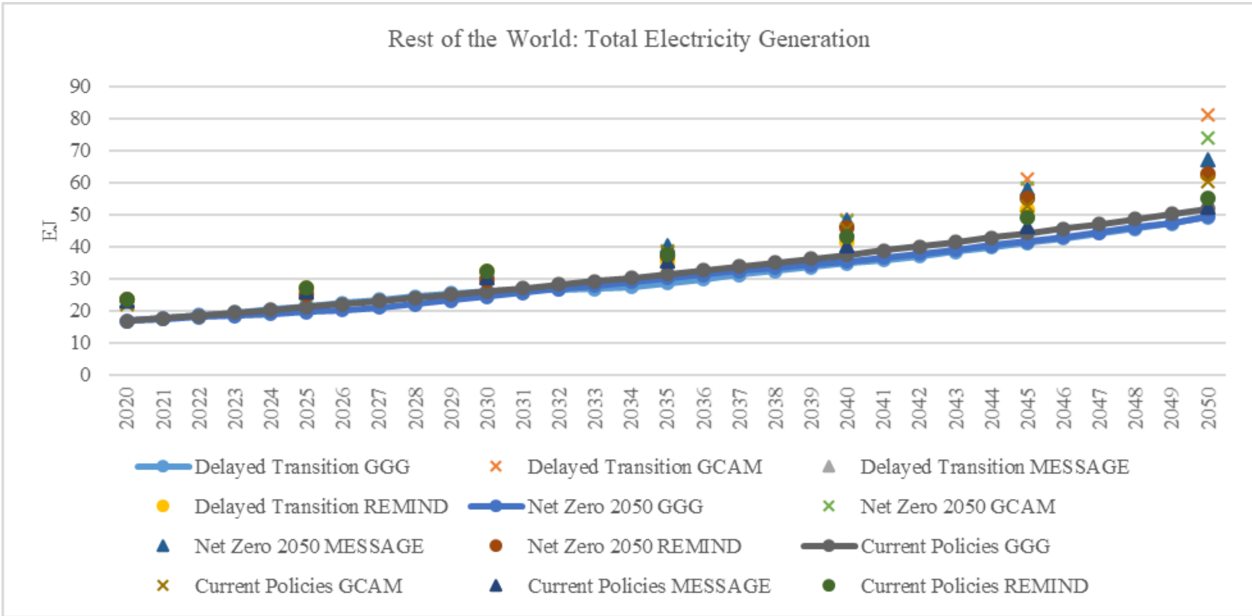


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Rest of the World (Contd.)

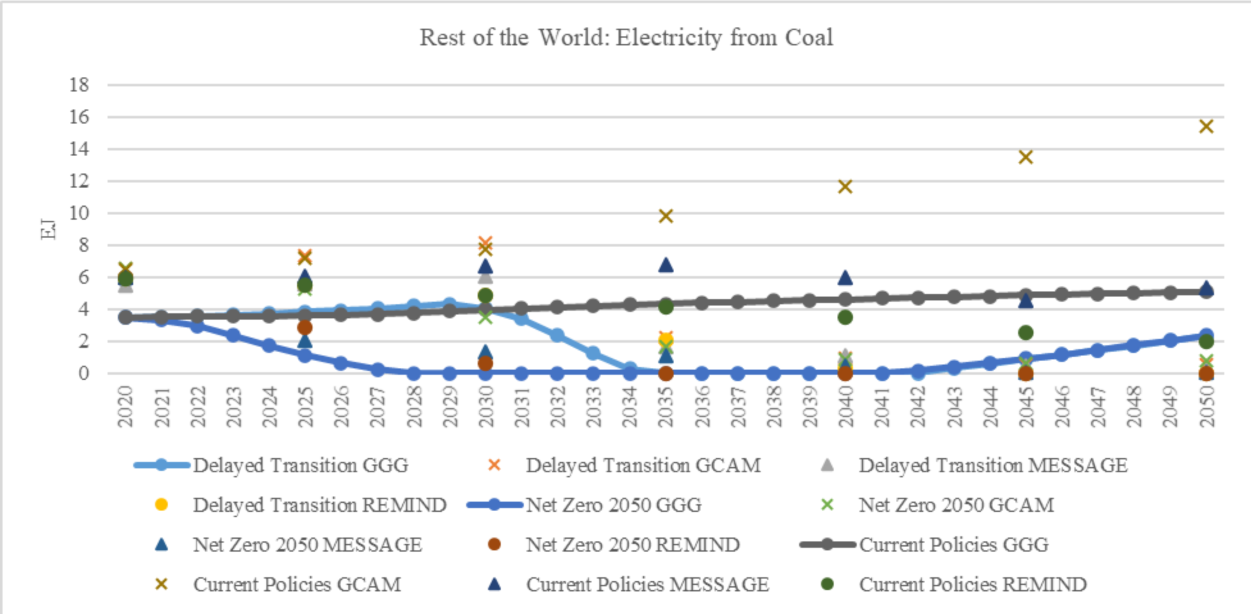


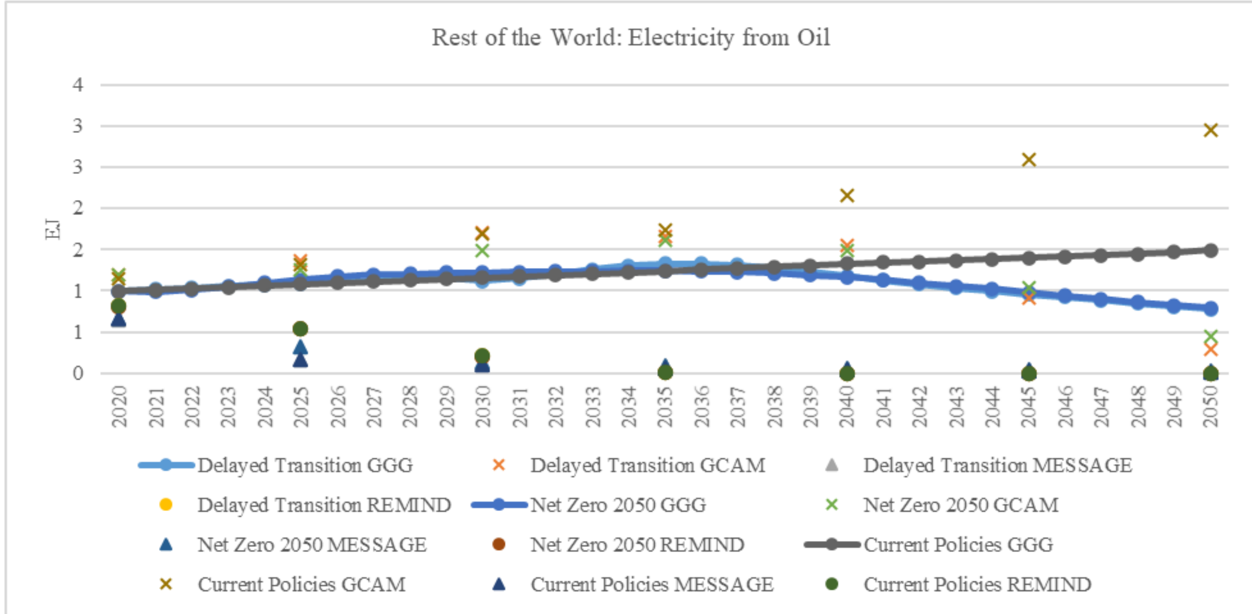


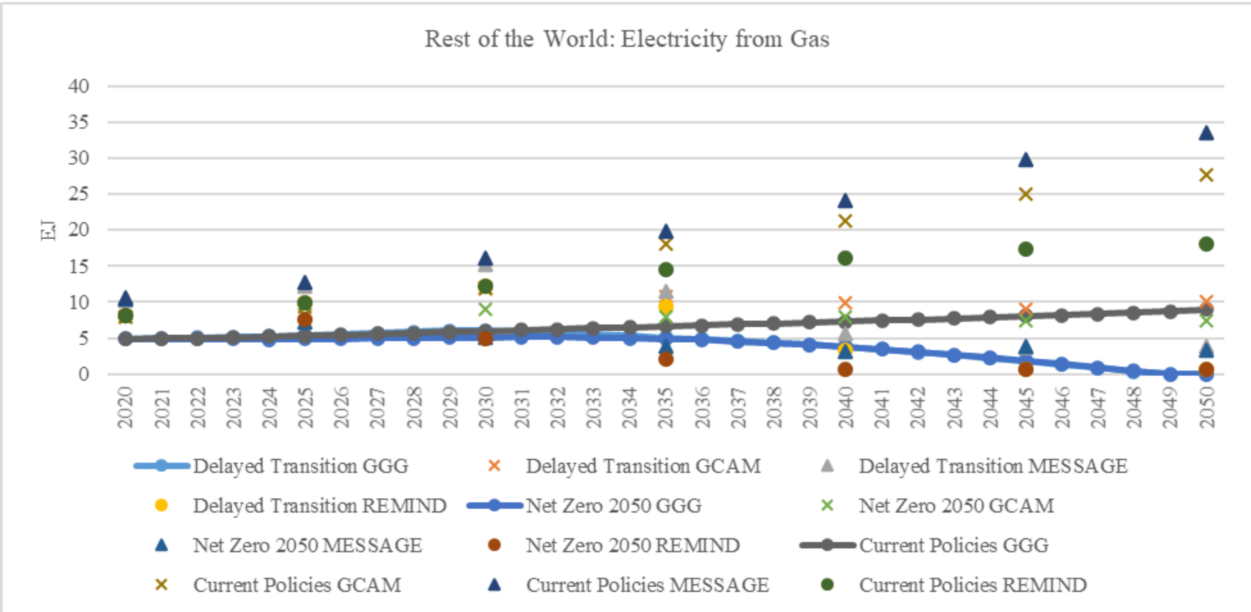


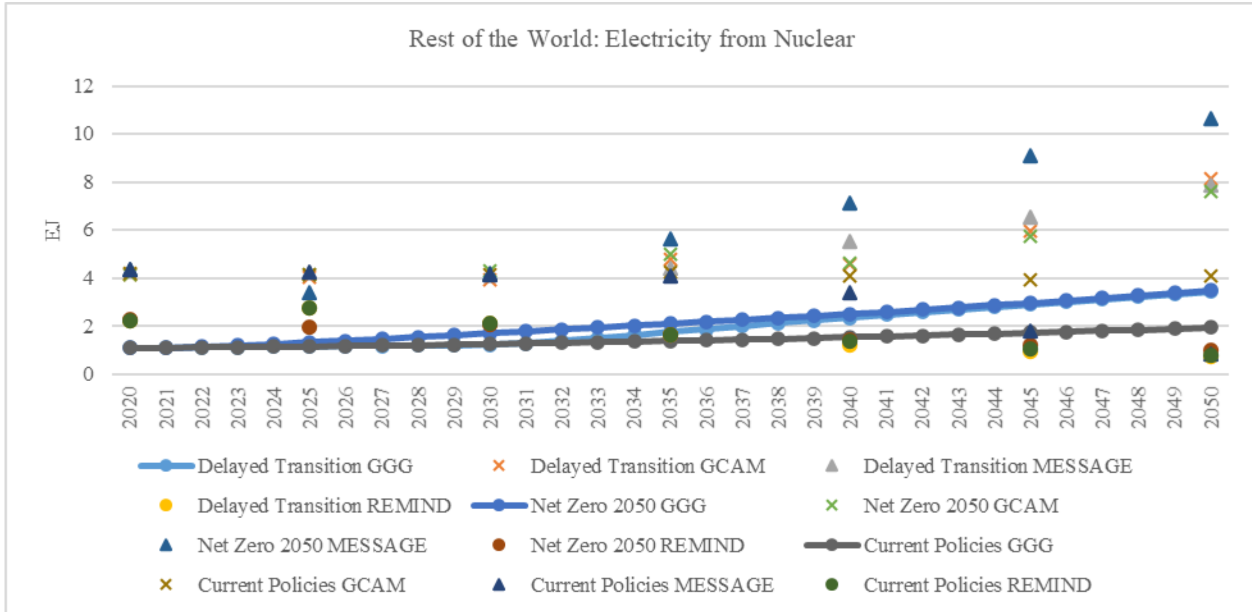


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Rest of the World (Contd.)

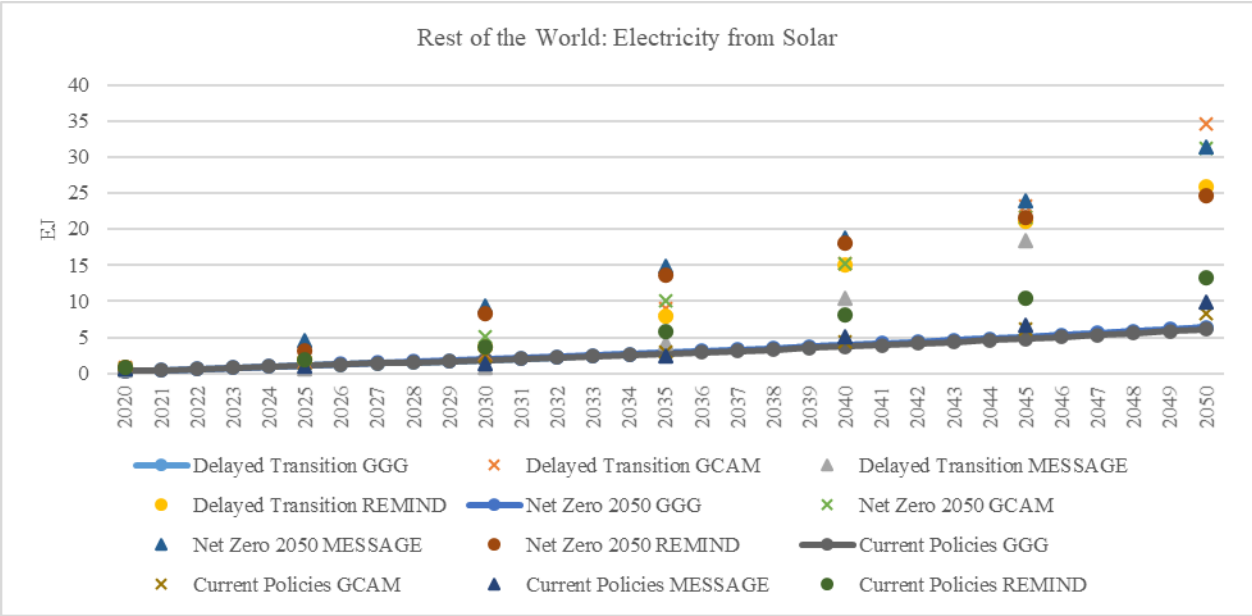


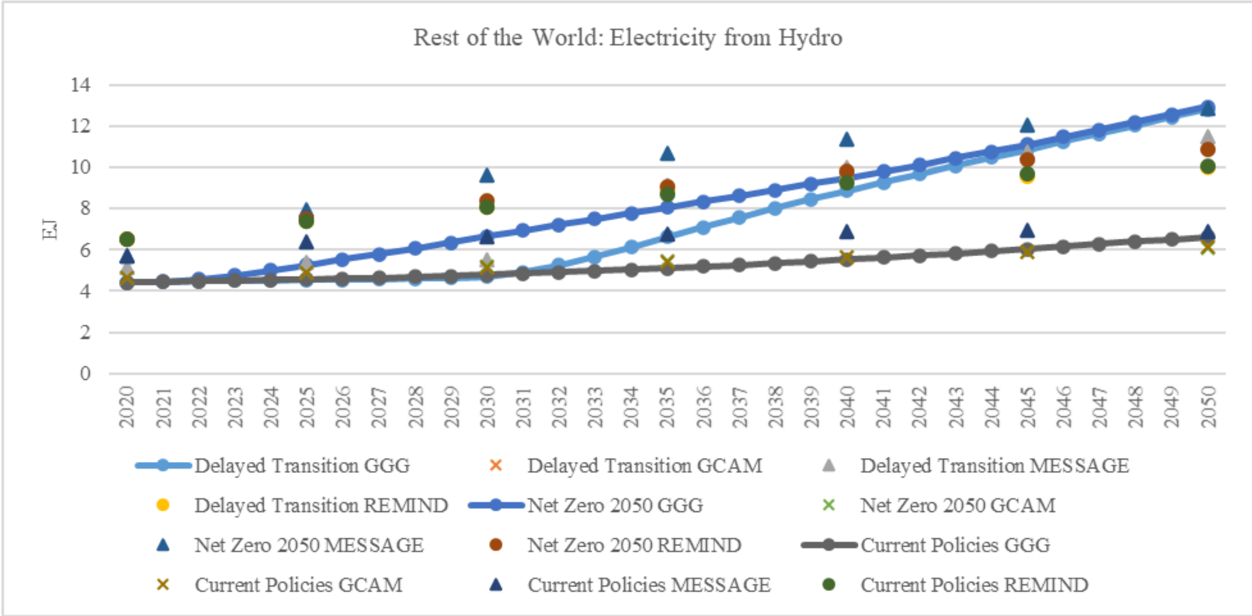


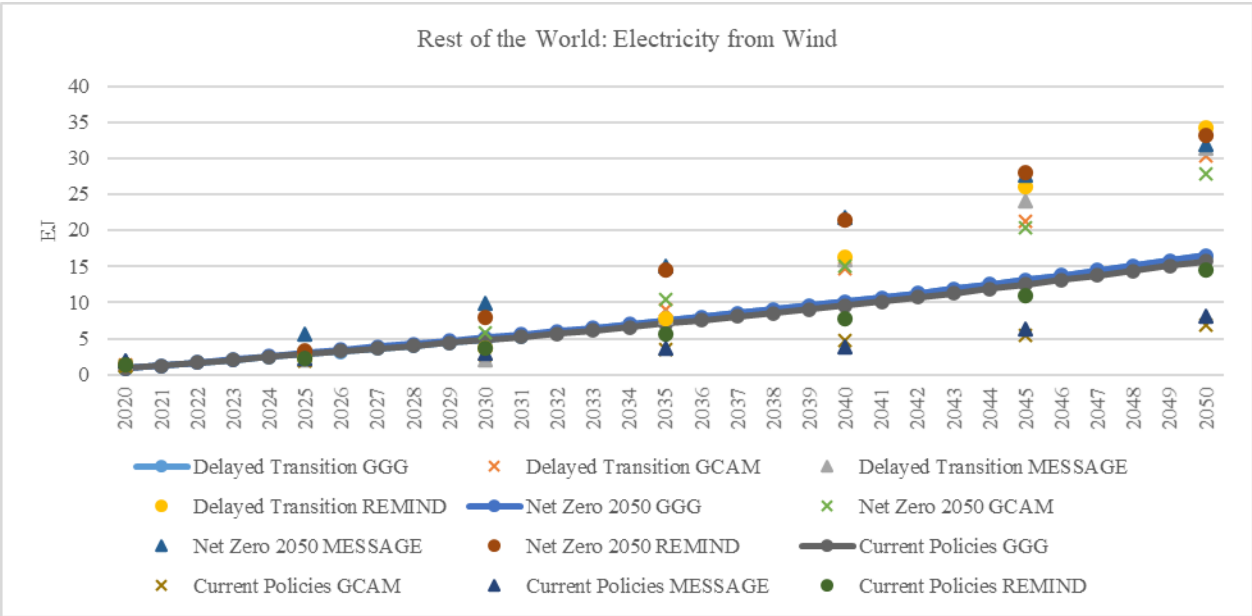


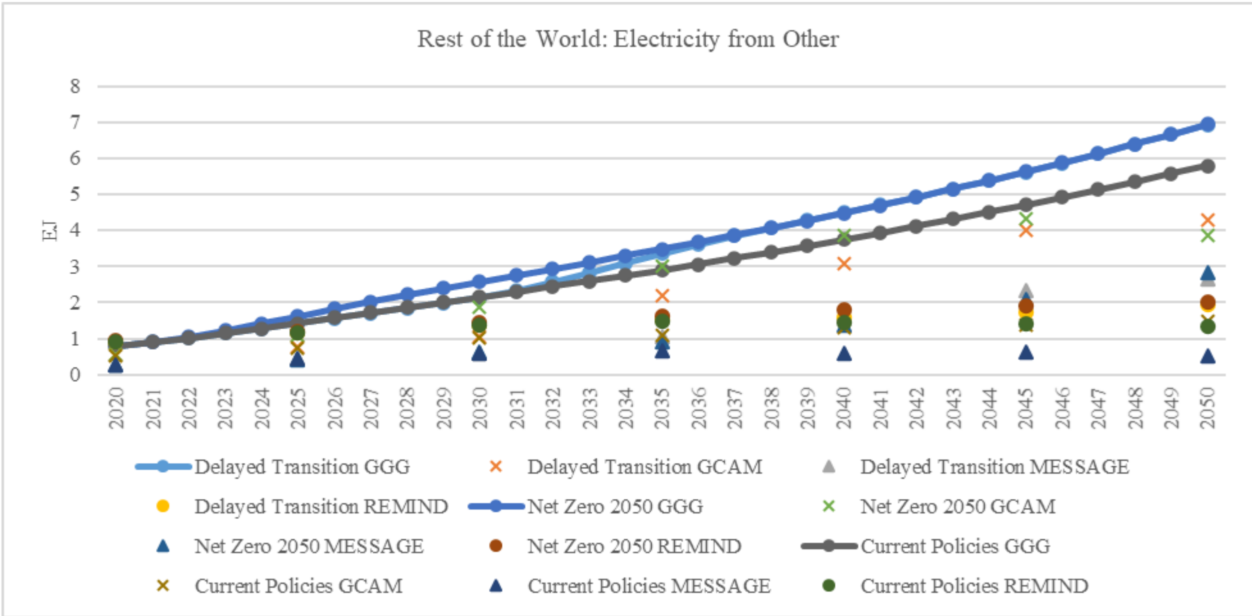


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Rest of the World (Contd.)

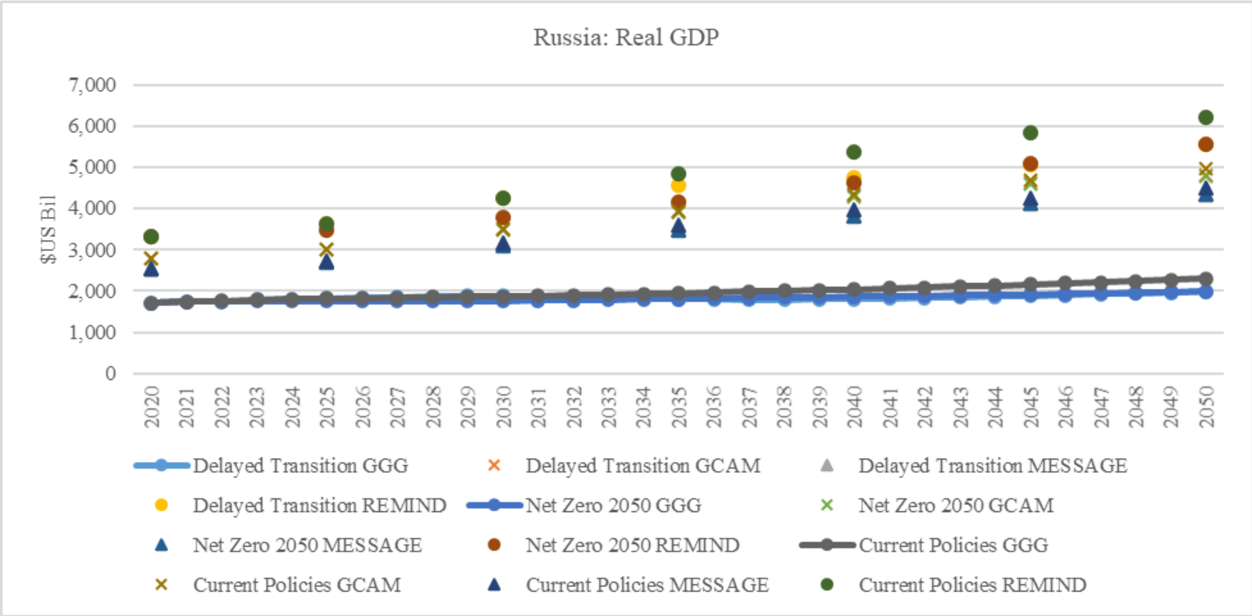


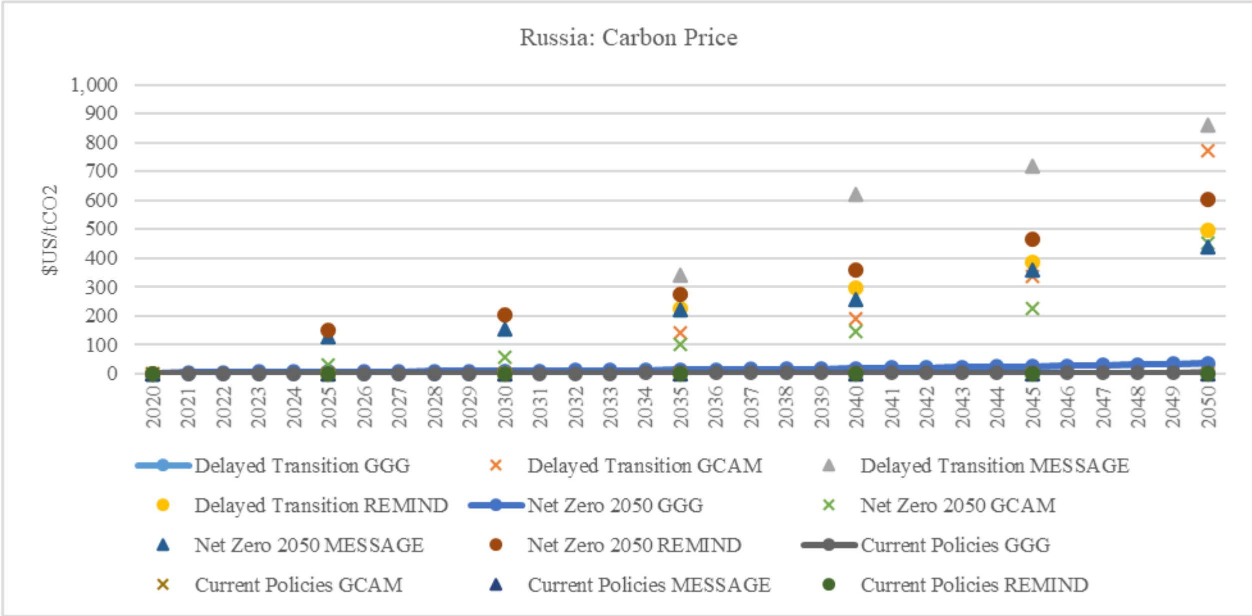


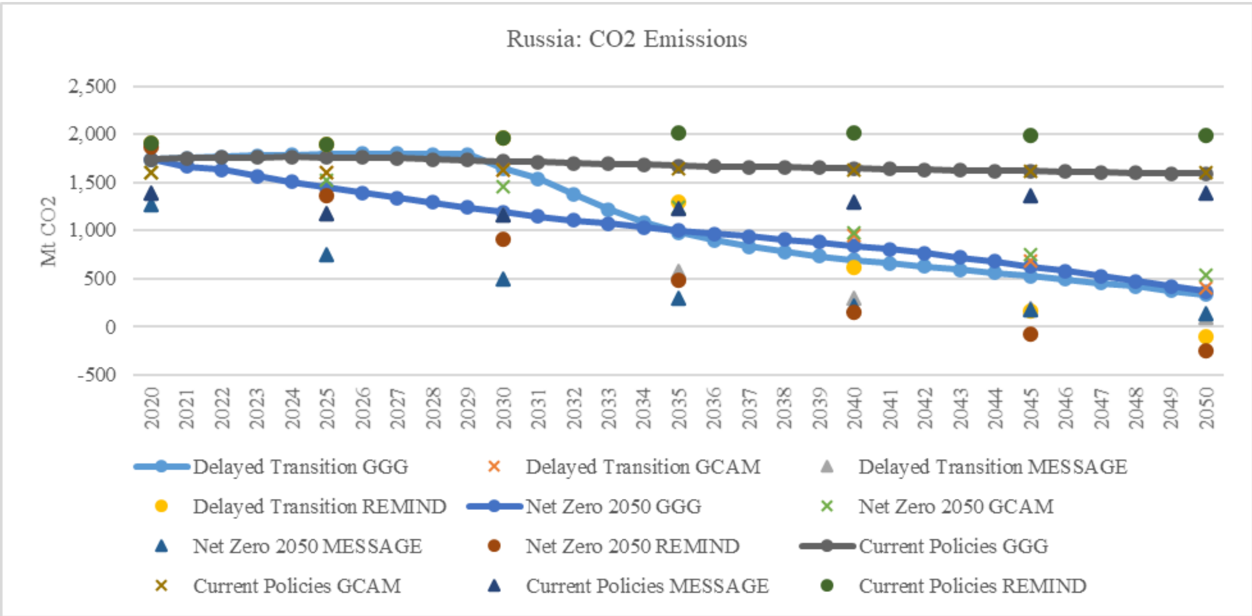


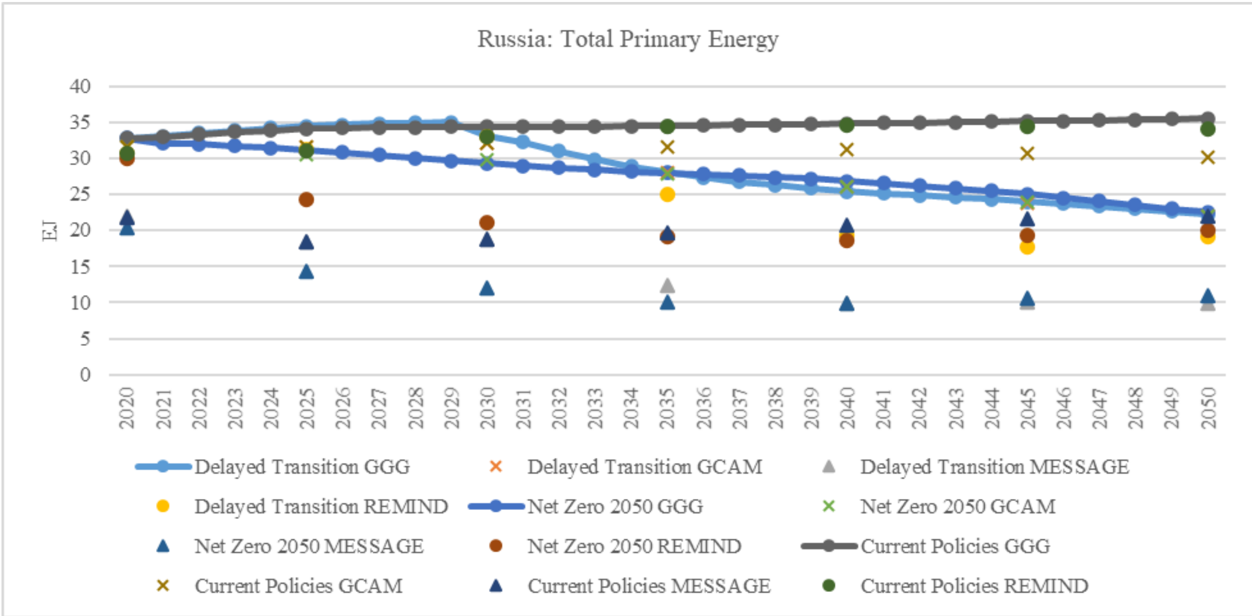


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Russia

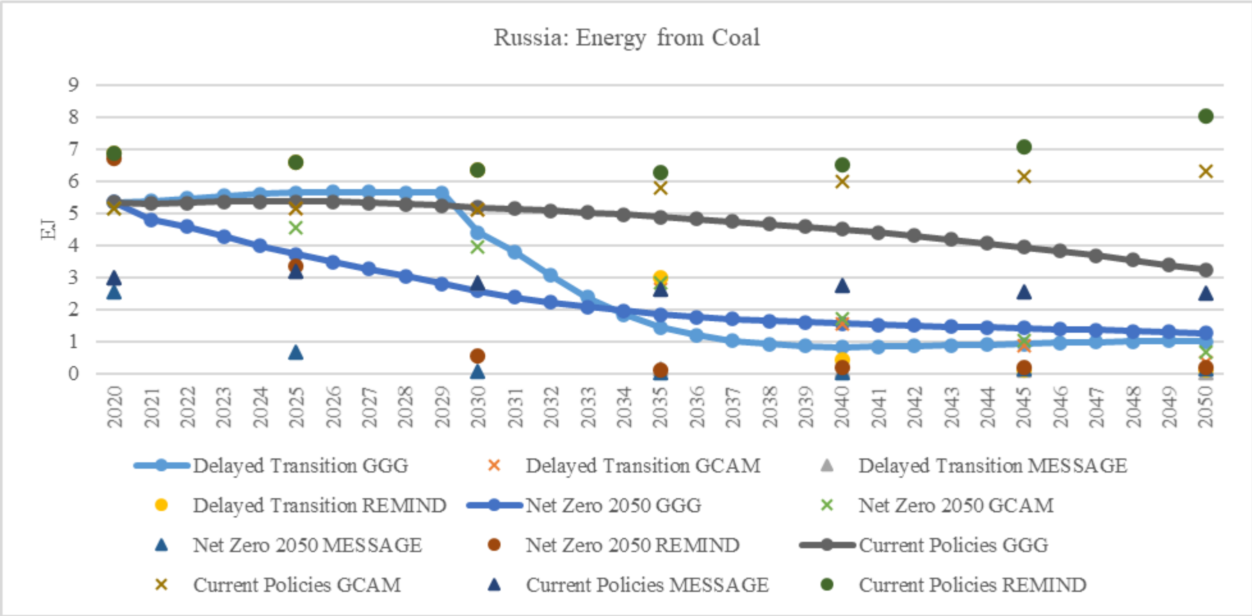


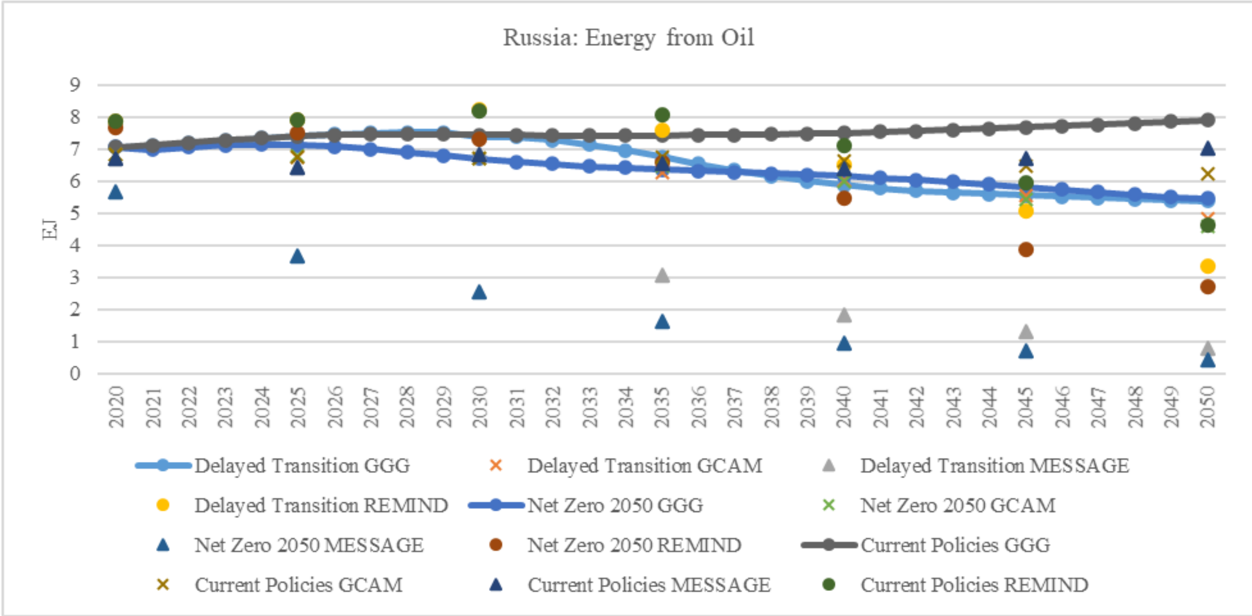


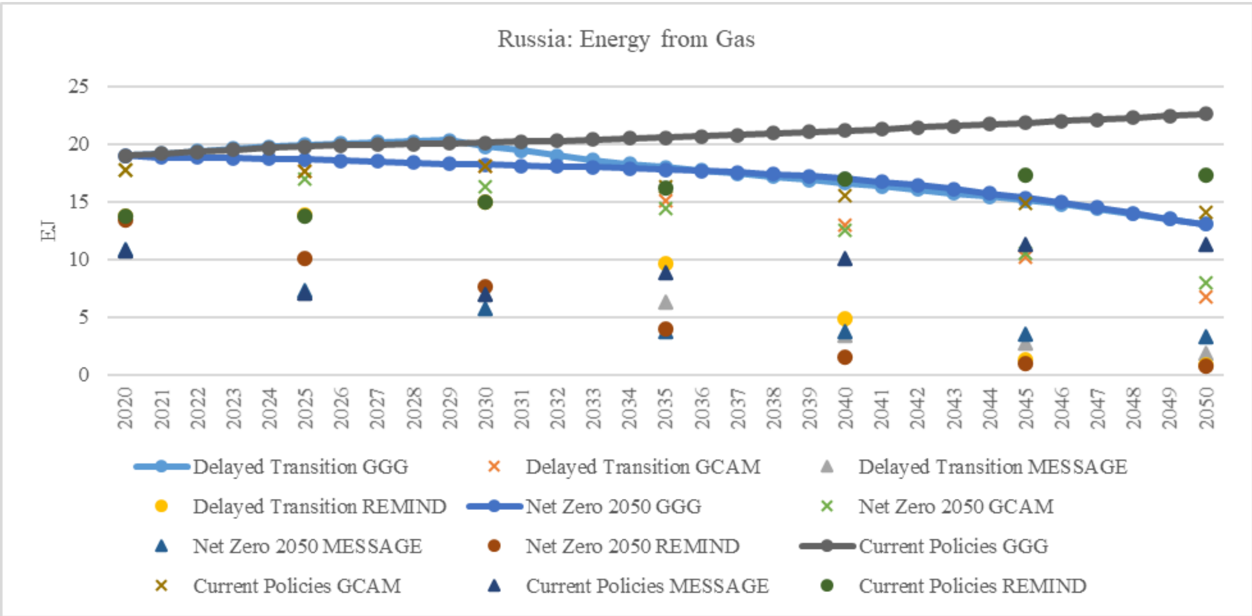


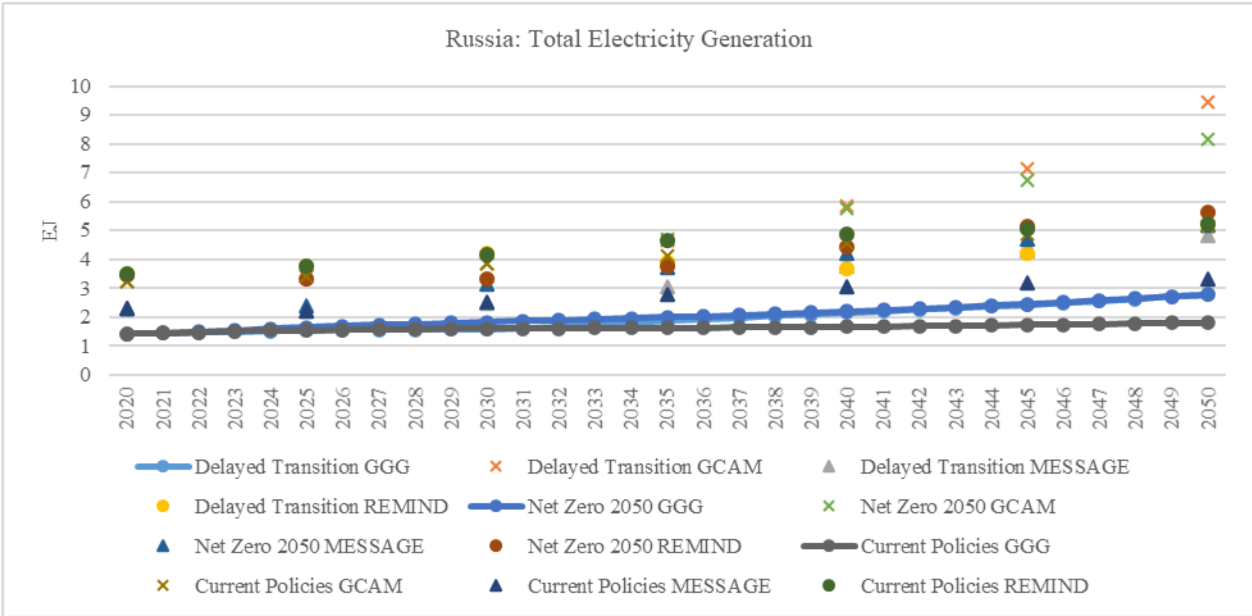


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Russia (Contd.)

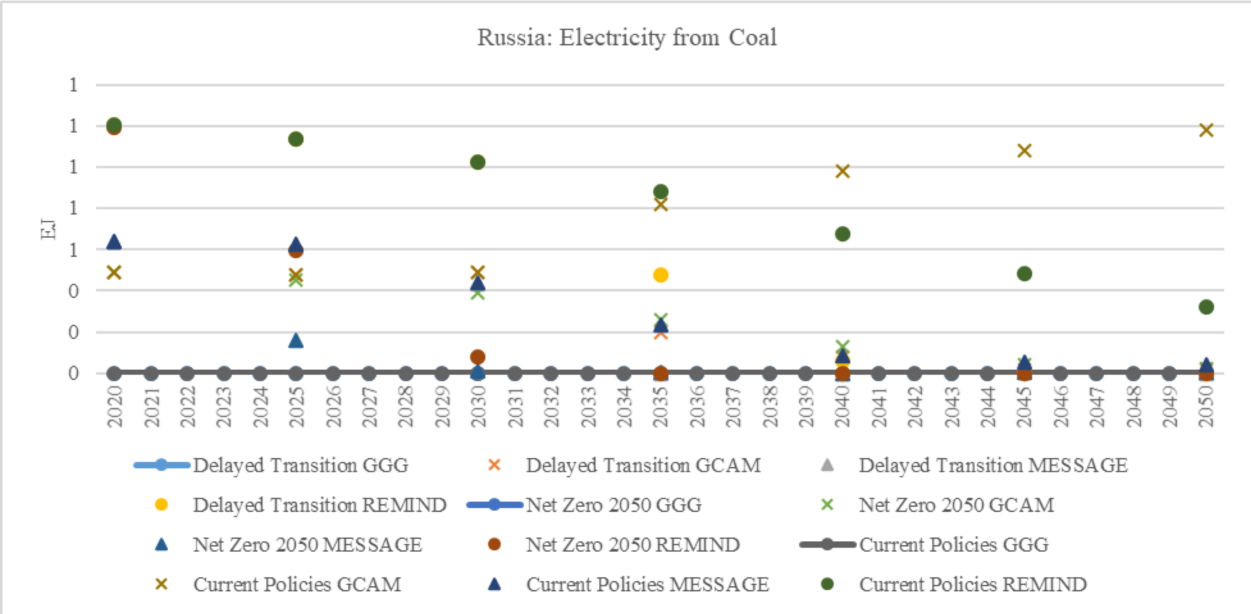


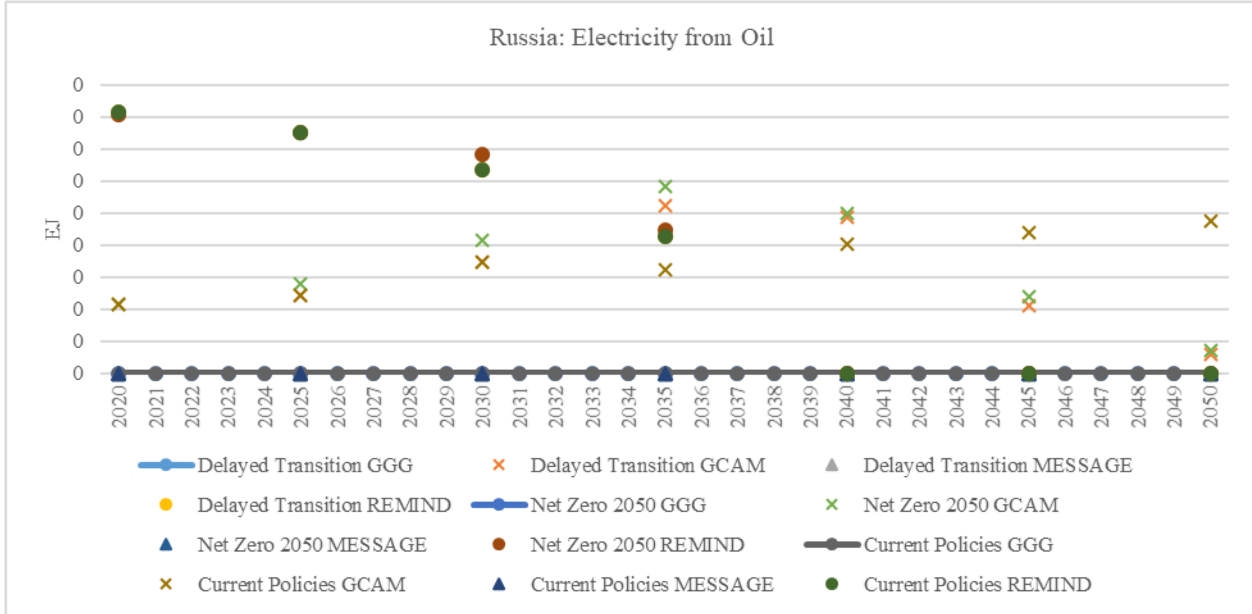


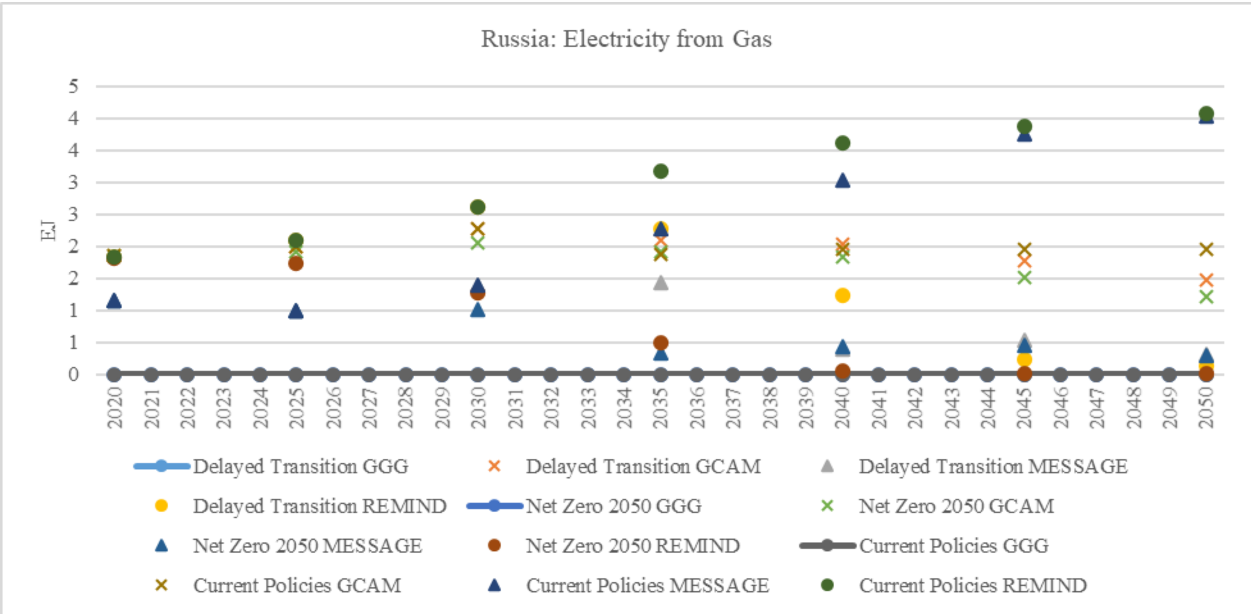


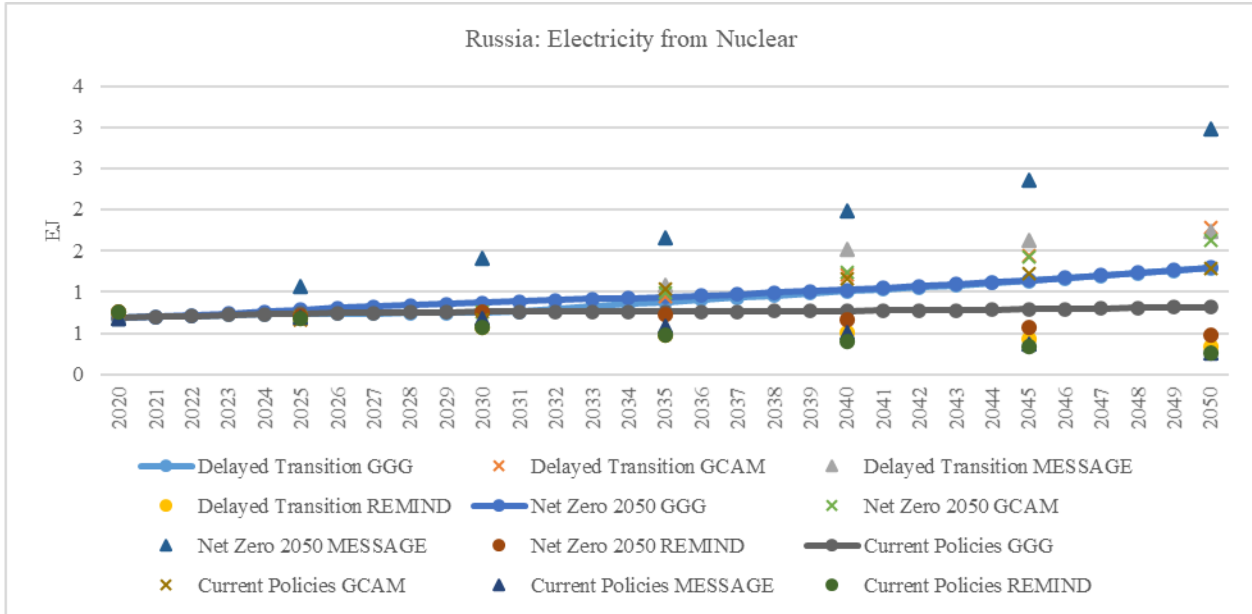


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Russia (Contd.)

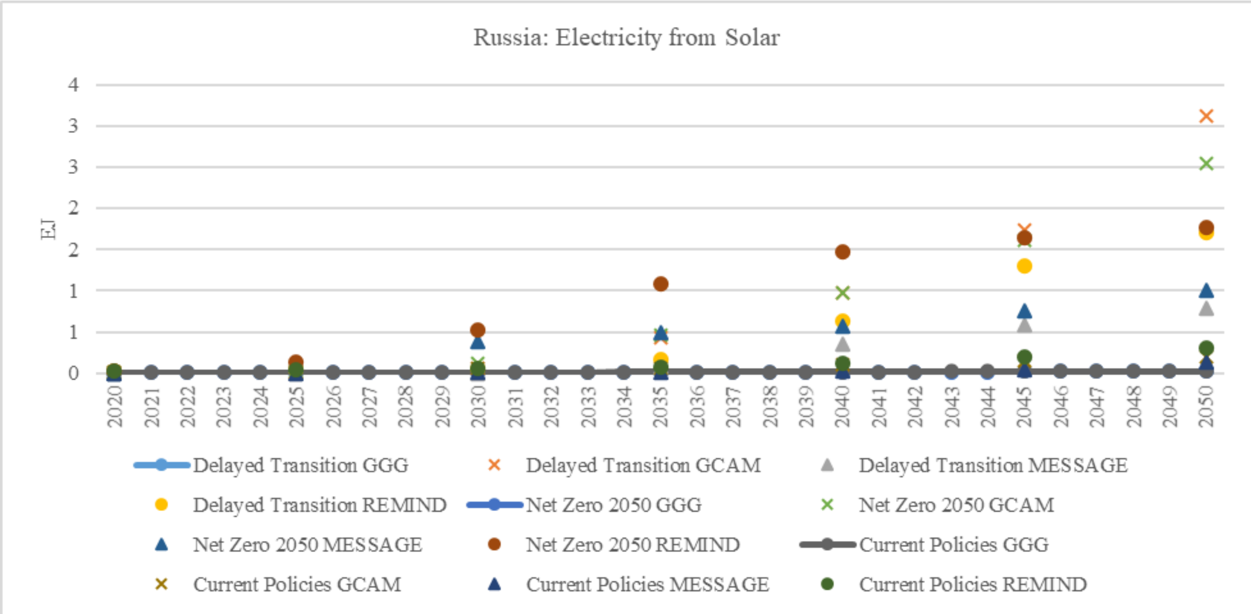


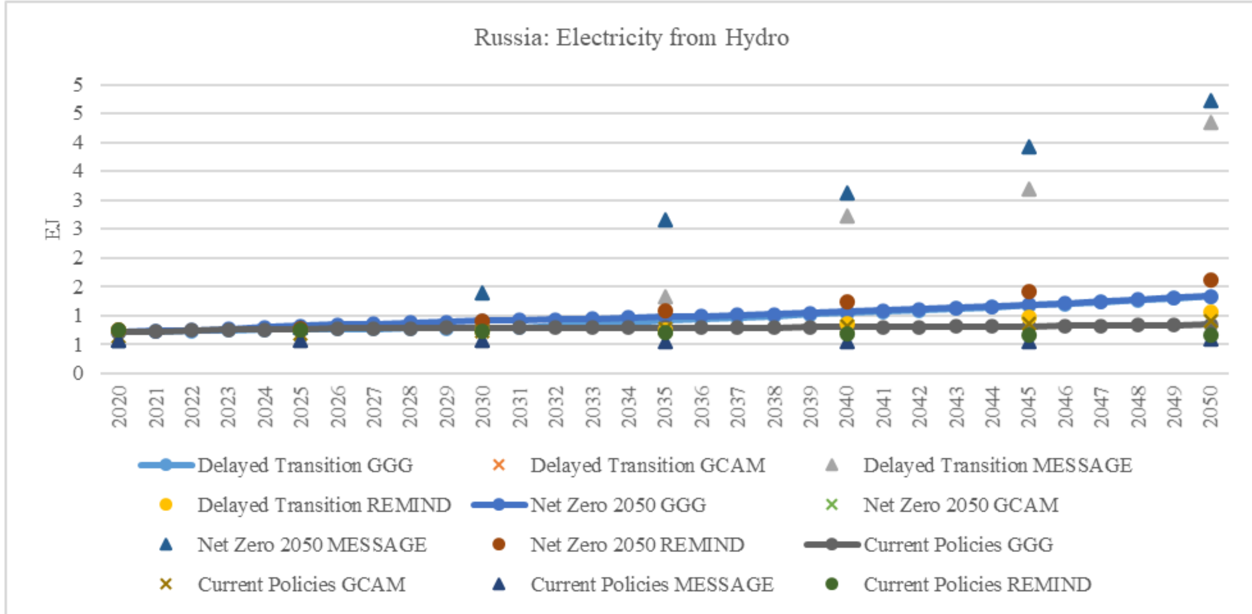


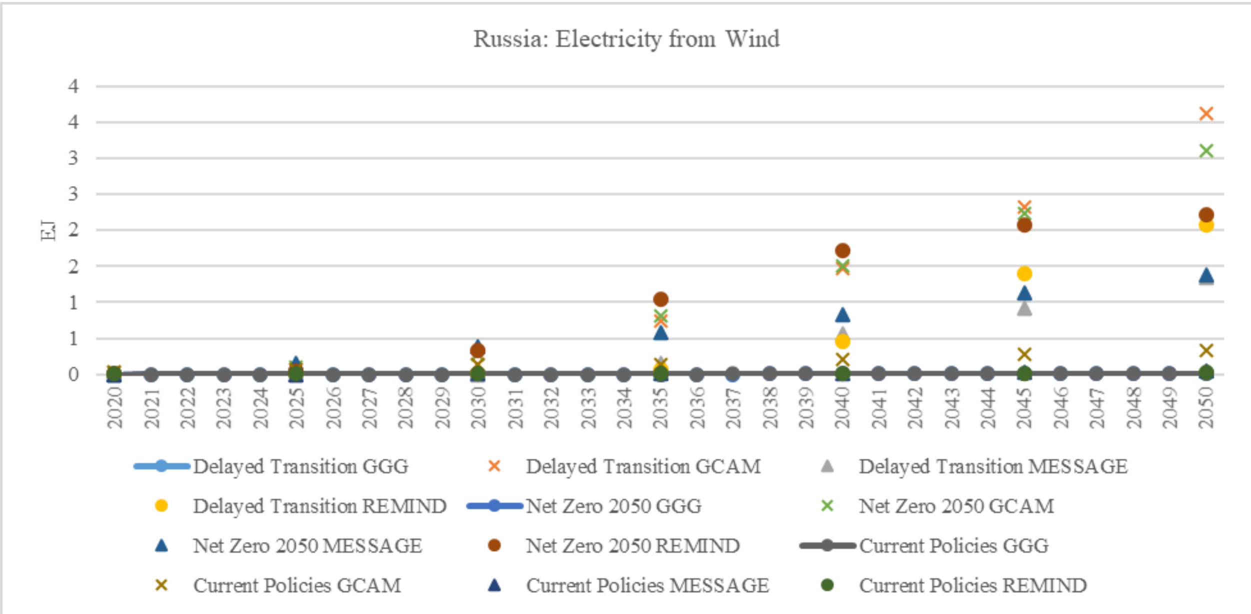


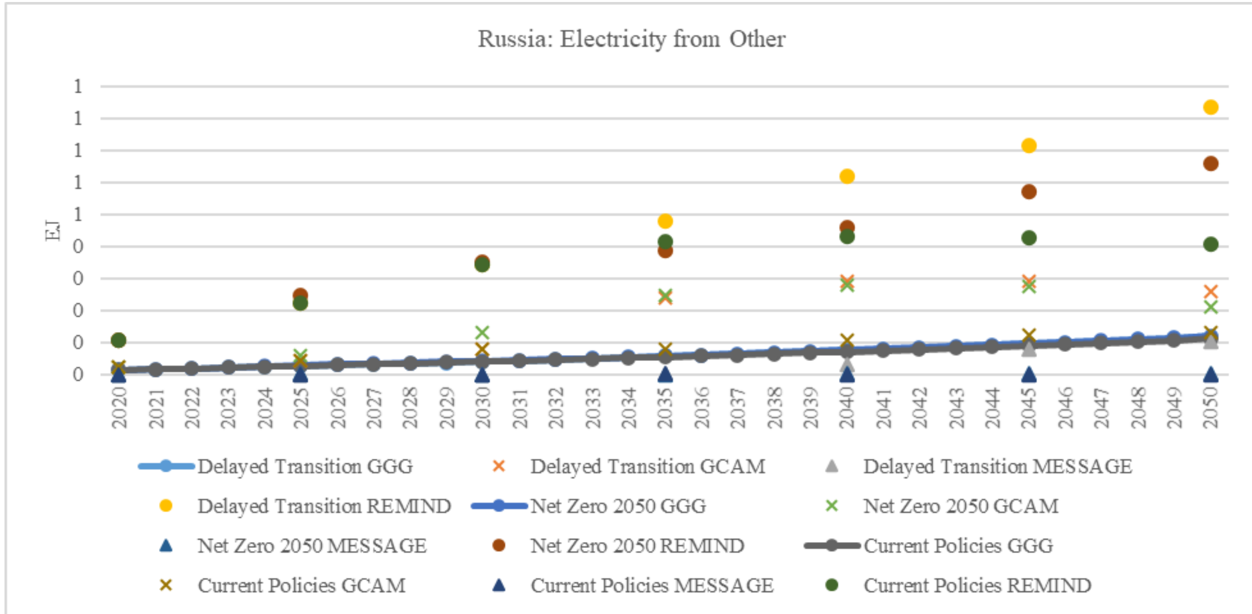


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Russia (Contd.)

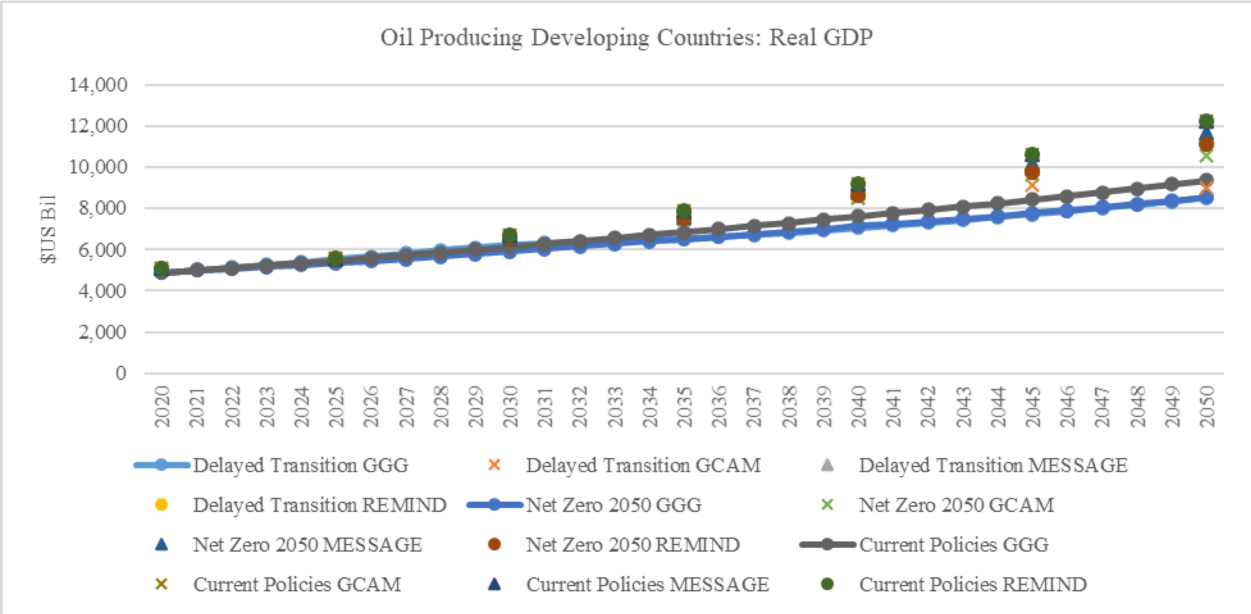


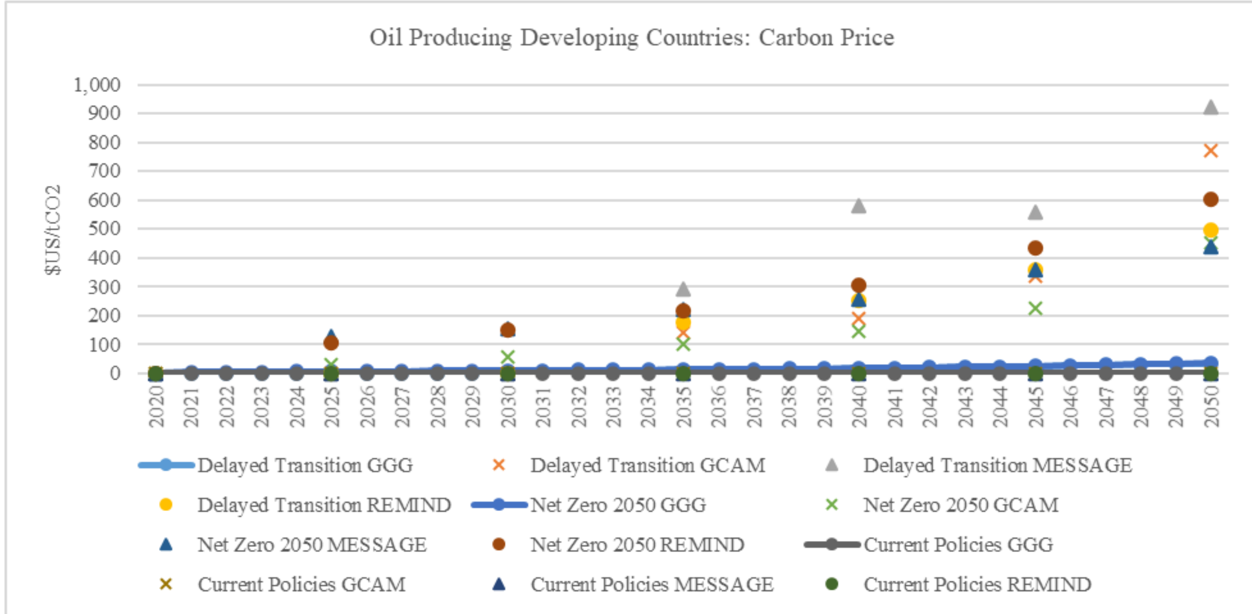


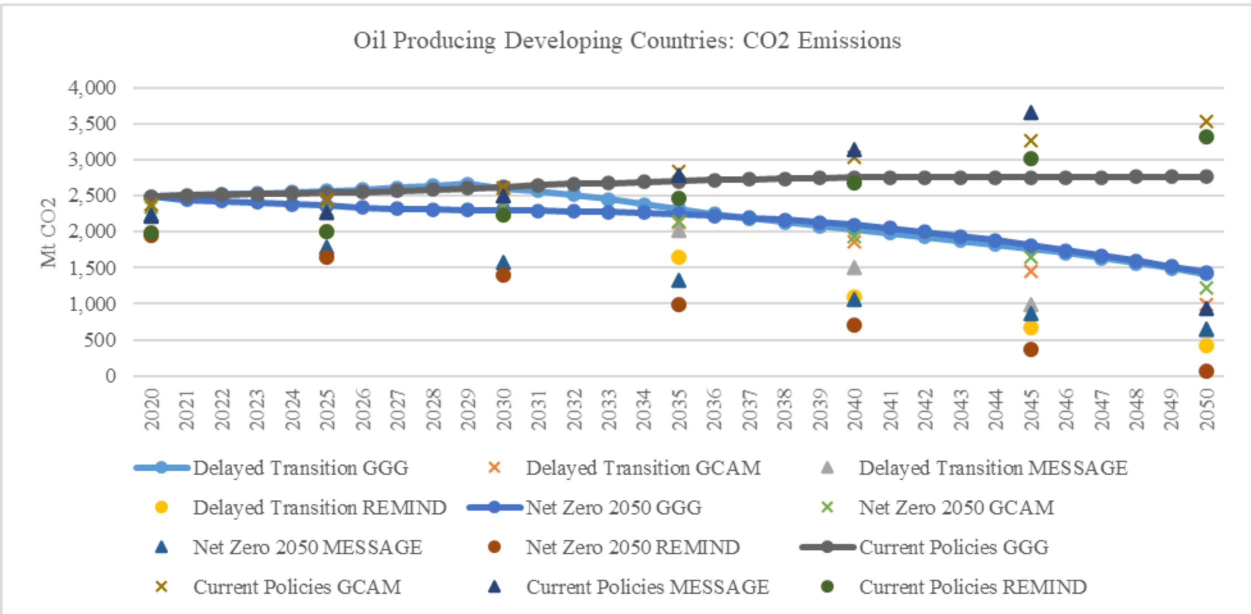


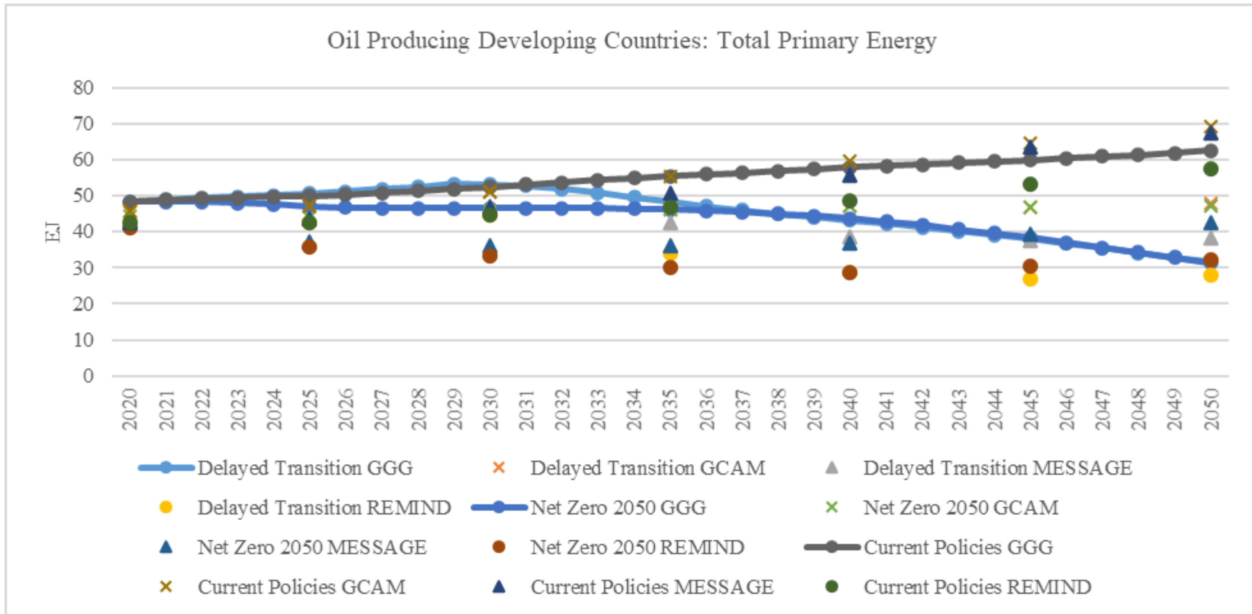


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Oil Producing Developing Countries

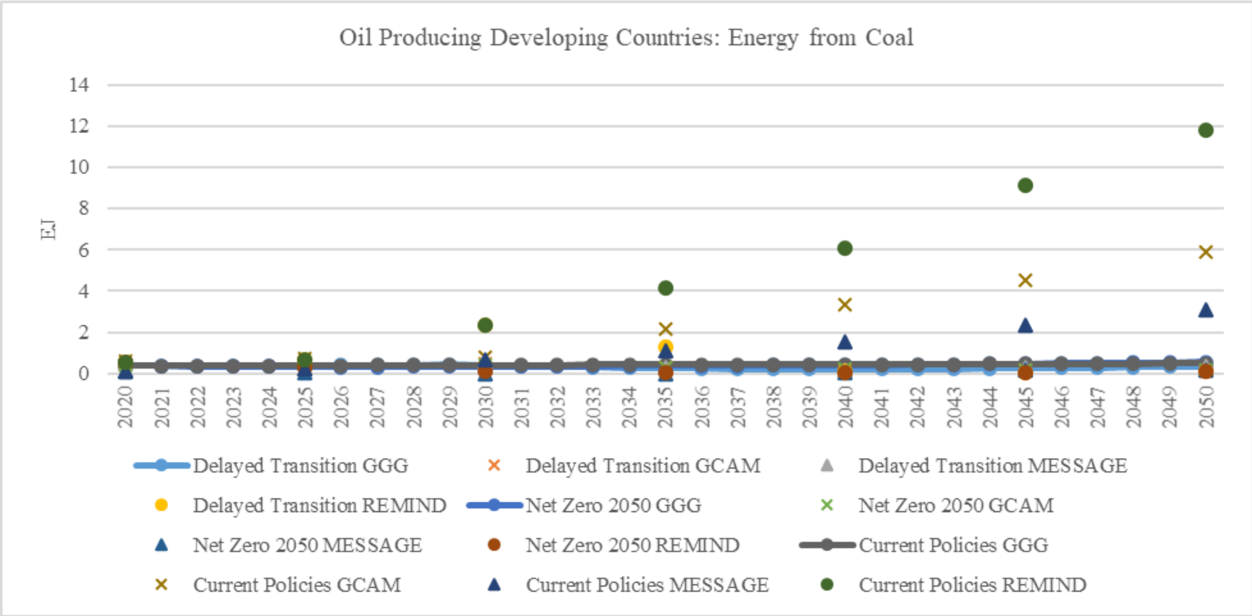


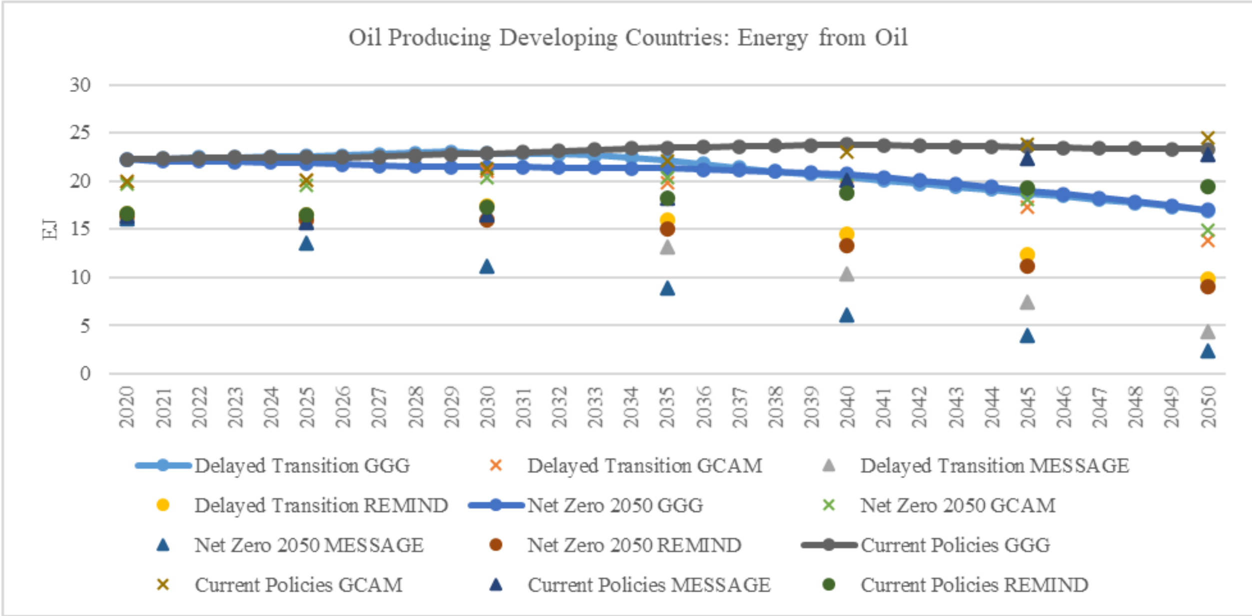


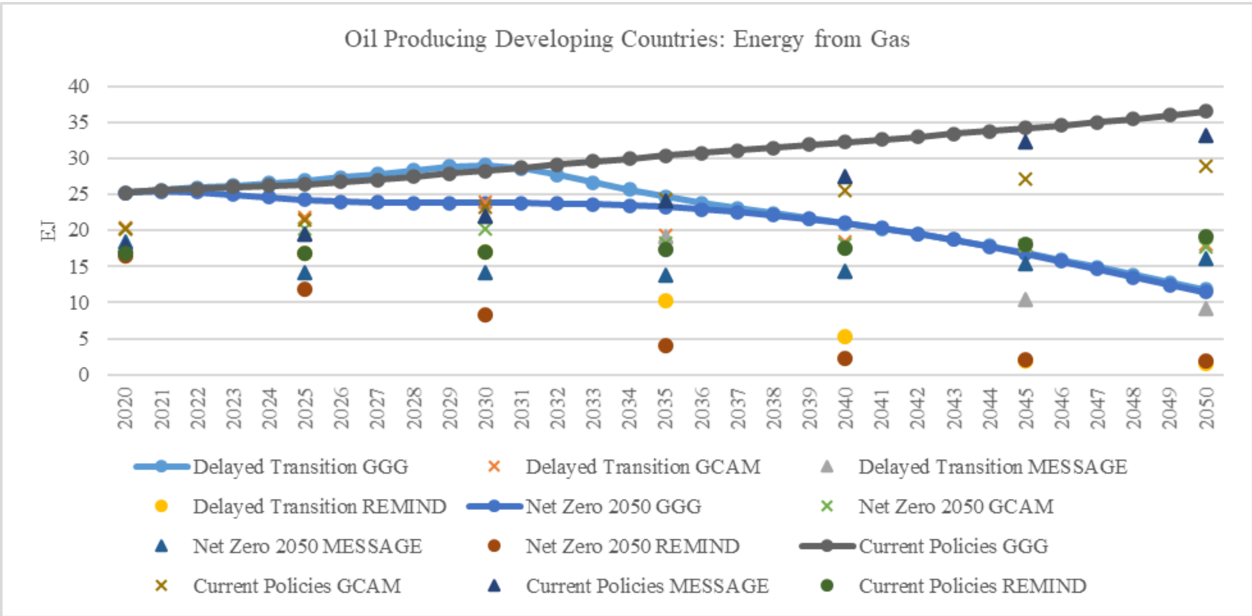


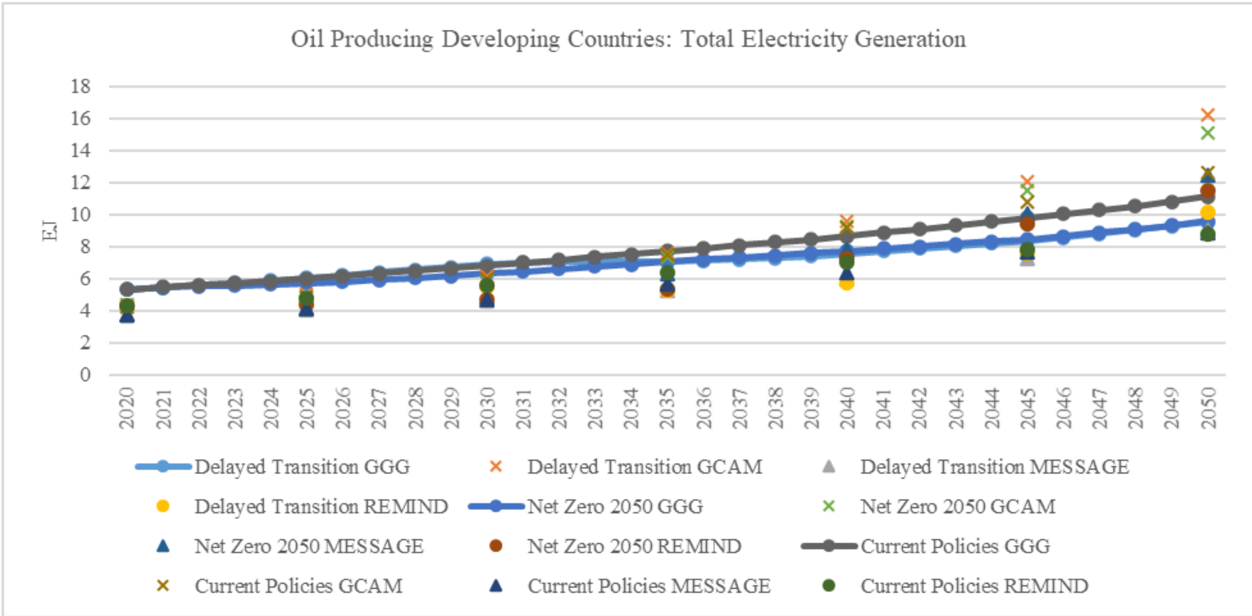


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Oil Producing Developing Countries (Contd.)

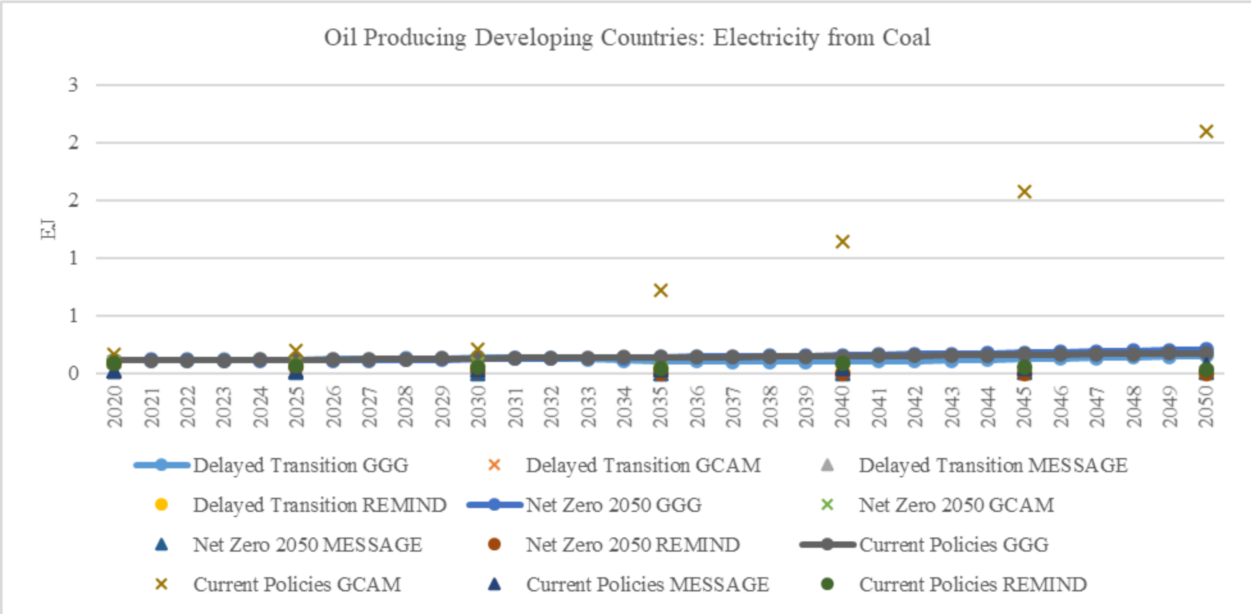


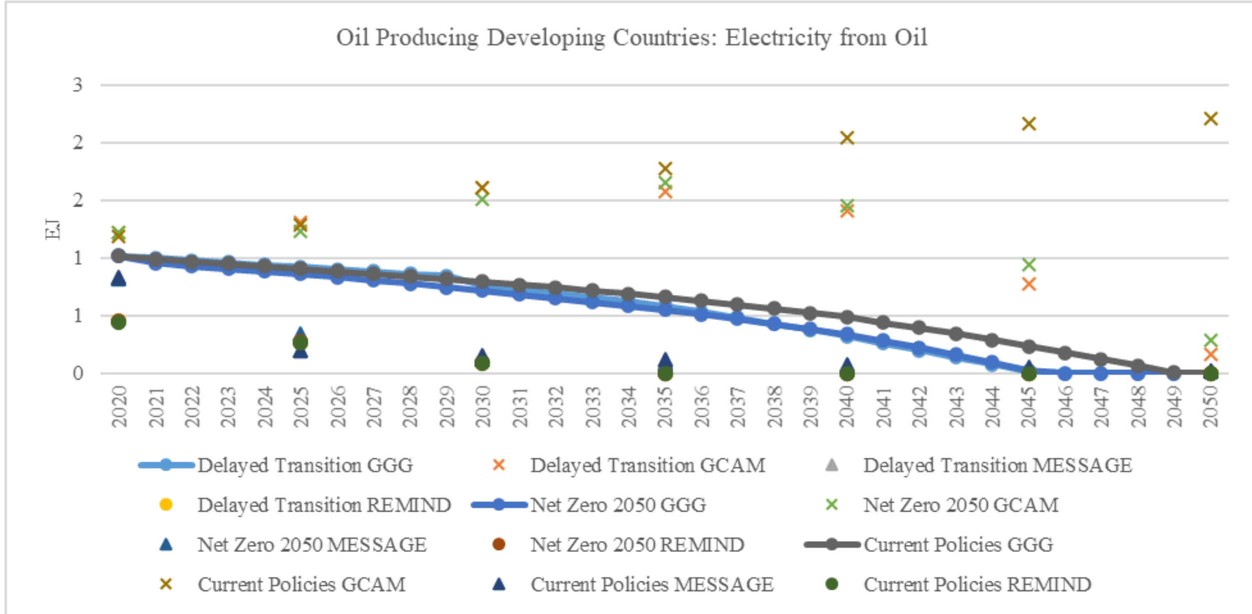


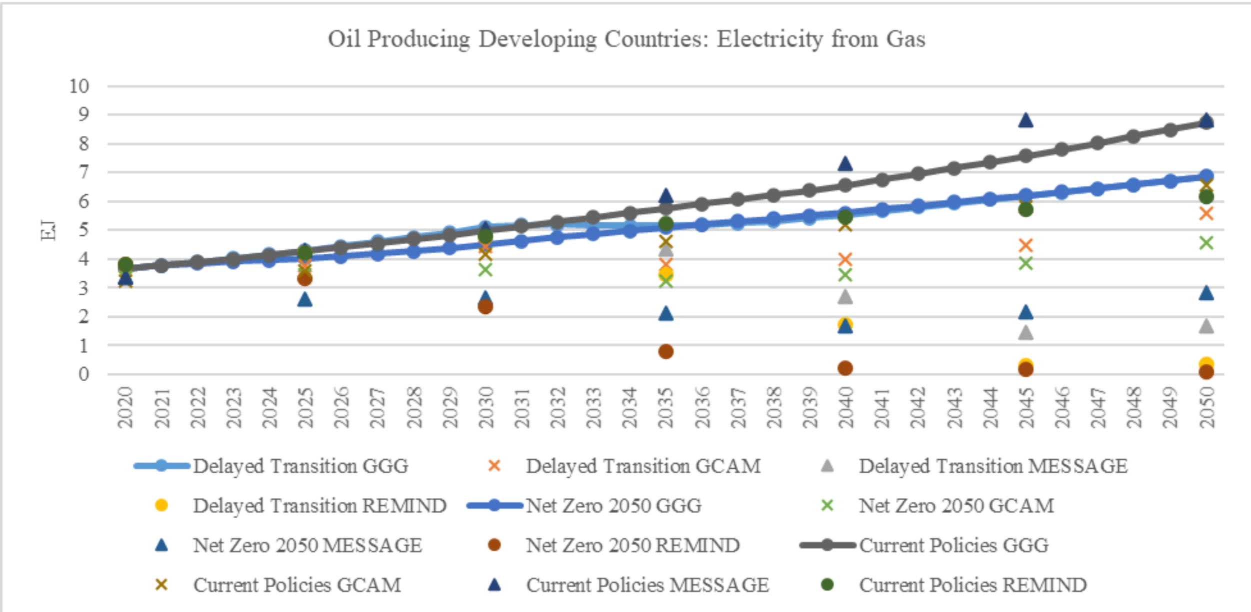


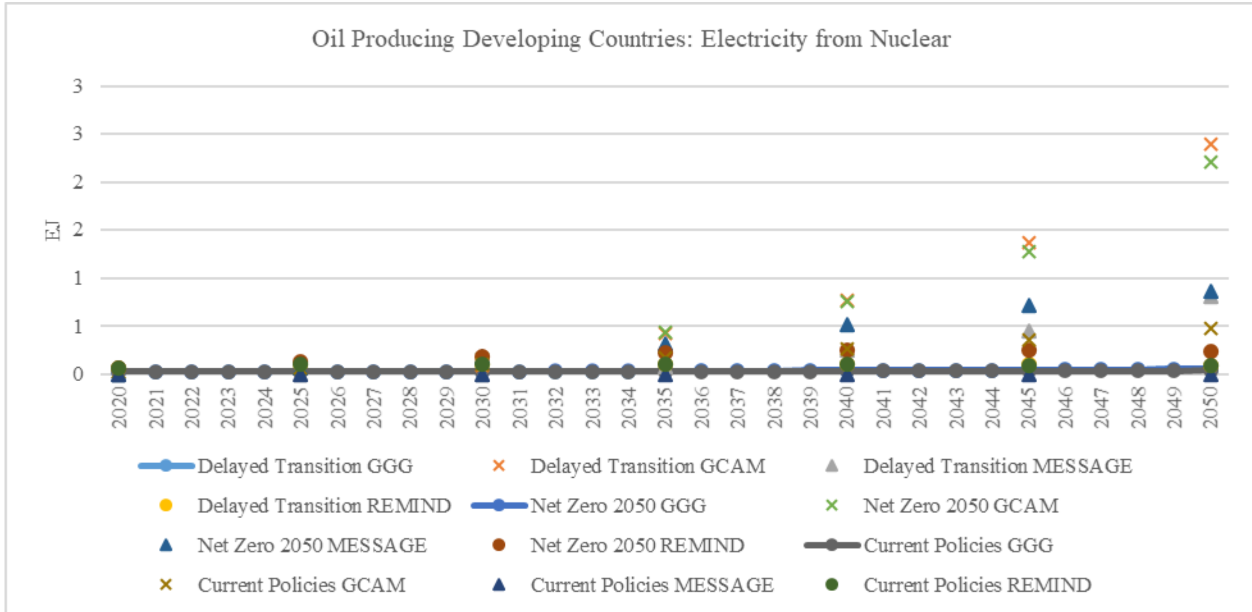


Comparison of Scenario Results among G-Cubed and NGFS IAMs: Oil Producing Developing Countries (Contd.)









Comparison of Scenario Results among G-Cubed and NGFS IAMs: Oil Producing Developing Countries (Contd.)