Economic Implications of Global Energy Interconnection

CoPS Working Paper No. G-307, September 2020

Feng Shenghao
University of International Business and Economics

Philip Adams
Centre of Policy Studies, Victoria University

Zhang Keyu
Beijing Wuzi University

Xiujian Peng
Centre of Policy Studies, Victoria University
and
Yang Jun
University of International Business and Economics

ISSN 1 921654 02 3 ISBN 978-1-921654-15-2

The Centre of Policy Studies (CoPS), incorporating the IMPACT project, is a research centre at Victoria University devoted to quantitative analysis of issues relevant to economic policy.
Address: Centre of Policy Studies, Victoria University, PO Box 14428, Melbourne, Victoria, 8001
home page: www.vu.edu.au/CoPS/ email: copsinfo@vu.edu.au Telephone +61 3 9919 1877

Economic Implications of Global Energy Interconnection

Feng Shenghao[1], Philip Adams[2], Zhang Keyu[3], Peng Xiujian[2], Yang Jun[4]

Abstract

This study uses a Computable General Equilibrium (CGE) model to quantify the economic implications of the proposed Global Electricity Interconnection (GEI) electricity system.

Enhancements to the model for this study include:

- a detailed and up-to-date electricity database;
- a new fuel-factor nesting structure;
- re-estimated values for the constant elasticity of substitution (CES) parameters between fossil fuel power generation and non-fossil fuel power generation;
- a base-case (for years between 2011-2050) consistent with the New Policy Scenario outlined in the World Energy Outlook 2018; and
- the stylized characteristics of the operation of the GEI network.

Modelling results suggest that, by 2050, compared to the base-case:

1. the GEI network will increase world GDP by 0.33 per cent;
2. all regions will benefit from GEI development;
3. world output of coal, oil and gas will fall by 1.4, 0.2 and 0.9 per cent, respectively;
4. the shares of renewable energy in total electricity and total primary energy will increase by 4.3 and 2.9 percentage points; and
5. global CO2 emissions will fall by 0.72 per cent.

Keywords: GEI (global energy interconnection), CGE (computable general equilibrium), nesting structure, CES (constant elasticity of substitution), Economic impacts

JEL: C68, F17, Q43

---

[1] Corresponding author, University of International Business and Economics (UIBE), fengshenghao@uibe.edu.cn

[2] Centre of Policy Studies (CoPS), Victoria University

[3] Beijing Wuzi University

[4] University of International Business and Economics (UIBE)

Table of Contents

Abstract 1

1 Introduction 5

2 Literature review 6

3 Model, database, developments and base-case 8

3.1 Model and database 8

3.2 Nesting structure, parameter calibration and econometrics estimation 9

3.3 Dynamics 10

Investment and capital 11

Lagged adjustment process in the national labour market 11

3.4 A base-case scenario 11

4 The GEI scenario 12

5 Simulation results 16

6 Conclusion and policy implications 26

List of tables

Table 1: Summary of main results of existing quantitative analyses on GEI 7

Table 2: Power sectors in GTAP-power database, mapping to new sectors, and abbreviations 8

Table 3: econometrically estimated σGEN for different regions 10

Table 4: base-case development summary 12

Table 5: Interregional transmission through backbone network, projection in 2050, Hydropower (TWh) 14

Table 6: Interregional transmission through backbone network, projection in 2050, Wind power (TWh) 14

Table 7: Interregional transmission through backbone network, projection in 2050, Solar power (TWh) 15

Table 8: Renewable energy production by region and technology, New Policy Scenario (NPS) and GEI scenario, 2050 15

Table 9: GEI's impact on non-energy sectors at the regional level (% deviation in output from base-case, 2050) 21

Table 10: GEI's impact on fuel mix 25

List of Figures

Figure 1: New, expanded production nesting structure…… 9

Figure 2: projected transmission capacity (10000kW) of the backbone network…… 13

Figure 3: GEI's impact on real GDP…… 17

Figure 4: GEI participation and importance of fossil fuel in different regions…… 17

Figure 5: A decomposition of real GDP from the income side, 2050…… 18

Figure 6: GEI's impact on labour and capital, 2050…… 19

Figure 7: Capital-labour cost ratios for renewable energy production…… 19

Figure 8: A decomposition of real GDP from the expenditure side, 2050…… 20

Figure 9: GEI's impact on non-energy sectors at the global level…… 21

Figure 10: GEI's impact on hydropower importing prices…… 22

Figure 11: GEI's impact on wind power importing prices……22

Figure 12: GEI's impact on solar power importing prices…… 23

Figure 13: GEI's impact on hydropower domestic market prices……23

Figure 14: GEI's impact on wind power domestic market prices…… 24

Figure 15: GEI's impact on solar power domestic market prices…… 24

Figure 16: energy sector outputs, world total, by year…… 25

Figure 17: world CO2 emissions, GDP, and emissions intensity of GDP…… 26

1 Introduction

The world has huge untapped renewable energy potential [1] but is behind schedule in its efforts to raise the renewable energy share[5][2]. Renewable technologies are becoming more cost-competitive than coal-fired power plants in many parts of the world, including China, the United States and the European Union[6][2]. Advancements in ultra-high voltage (UHV) technology can reduce efficiency loss in power transmission significantly [3]. Some parts of the world already have interconnected power systems, UHV lines and smart grid systems [4]. The lack of transmission capacity, though, have led to renewable curtailment[7] [5] and poor electricity access. Low electrification rate, often caused by poor grid infrastructure, is a major obstacle for industrialization and urbanization in the less-developed world. Relatedly, the use of traditional biomass fuels poses major health concerns in these regions. In the more developed European Union, meanwhile, a more interconnected grid infrastructure with higher trade volume and converging prices has been a key for ensuring reliability of the regional power system (ibid, p.76). Hence, economic, environmental as well as moral considerations all underpin the importance of a more integrated power system with higher renewable energy penetration.

GEI aims to optimize global renewable power development by developing renewable generation capacities in areas with the richest renewable resources – which are often located in severe conditions such as seas and deserts. It will send the power generated in those areas onto large-scale electricity networks, and through which, to the load centers of the world. Such networks will rely on new technologies, especially UHV power transmission and smart grid systems to satisfy demand peaks. Renewable energy output will shift across time zones and climate zones. In doing so, it will also increase the complementarity of different types of renewable energy and enhance grid stability. Intergovernmental negotiations have led to the Paris Agreement and its Nationally Determined Commitments (NDCs) but these commitments are neither guaranteed to be accomplished [6] nor sufficient to meet our mitigation needs [7]. GEI, however, has a top-down perspective that promotes better global collaborations with tangible, industry-level, project-based plans.

GEI could have profound social-economic implications. New production associated with cleaner technologies may generate new job opportunities. Production and consumption activities could benefit from lower power costs. Cleaner assets would displace their dirtier counterparts and reduce investment risks. Former desolated land, such as deserts and valleys, can be used to set up solar farms, wind mills, and electricity networks connecting them, thus increasing capital productivity or creating new capital. A cleaner energy mix would also mitigate pollution and climate stress. GEI will also have different social-economic implications to different regions. Regions with the greatest renewable potentials may gain the most. Load centers that are close to abundant renewable resources can benefit from getting access to cheaper electricity. Regions that can tap into more renewable sources from different altitudes, latitudes, and longitudes can have more flexible power systems. The complementarity of various renewable sources can help to sustain larger shares of renewables in the power system. Regions' energy profiles will change. The current pattern of global fossil fuel production, consumption and trade will be reshaped. Will this reduce growth in regions that have strong reliance on traditional fossil fuels? What are the implications to labors and different sectors in different regions?

Such changes could be profound, but most of our current understanding has been qualitative. Only a small number of studies have quantitatively assessed GEI's implications to GDP, employment, energy structure, sector output, or carbon emissions – at the global or even at the regional levels. This study uses a Computable General Equilibrium (CGE) model to quantify the

---

[5] The World Energy Outlook 2018 suggests that the world share of renewable energy (including hydropower, bioenergy and other renewables) will be 20% of total primary energy use in 2040 (it was 14% in 2017), under the New Policy Scenario. Under the Sustainable Development Scenario, however, that share needs to be 31%.

[6] The World Energy Outlook 2018 suggests that, under the new policy scenario, the value-adjusted levelized cost of electricity (VALCOE, $/MWh) for coal-fired power will be 75, 120 and 65 in the United States, the EU and China, respectively; for solar PV will be 55, 105, 65, respectively, and for onshore wind will be 60, 105 and 70, respectively.

[7] In areas of China and the U.S., among others, renewable curtailment rates have been more than 10%, and the lack of sufficient transmission capacity was found to be a main problem.

economic implications of the proposed Global Electricity Interconnection (GEI) electricity system. The study is based on simulations of a model of the global economy with an enhanced specification of electricity supply and demand. Called GTAP-E global, the model has at its core a CGE system of supply and demand across for twelve economic regions.

The remainder of this paper is organized as follows. Section 2 reviews the literature. The model and database are described in Section 3. Details of the simulation and simulation design are outlined in Section 4. Section 5 shows and discusses the simulation results, while concluding remarks are given in Section 6.

2 Literature review

It has been widely acknowledged that GEI has many economic opportunities. Liu 2015 outlined some of these potential benefits, including the promotion of globalization, reduction in social costs, improvement of economic structure, carbon dioxide mitigation [9]. Other qualitative analyses, including [10] and [11], echoed these potentials. Brinkerink et al [12] provided a comprehensive review on the benefits of GEI and concludes that while the opportunities are clearly qualified, quantitative analysis is at a very early stage.

The few quantitative studies of GEI generally agree that GEI promotes GDP growth and reduces CO_2 emissions (see Table 1). Zong [13] estimated that GEI will reduce CO_2 emissions by 775 million tons and increase employment by 9.8 million in China. Bompard et al [14] compared various energy and emissions indices[8] between a GEI scenario[9] and many other established scenarios[10] and show that GEI can lead to better readings for all these indices. Jin et al [15] estimated that, under GEI development, by 2050, non-fossil fuel energy will account for more than 70% of total electricity in the world, Africa's GDP will be 0.44% higher than the base-case in 2030, and 0.26% higher in 2050[11]. Wang et al [16] expected GEI to help world CO_2 emissions to peak in 2025 at more than 30 billion tons, and fall rapidly to just over 10 billion tons in 2050[12]. Jiang et al [17] suggested that Southeast Asia will receive a benefit of 600 billion in GDP, 1 billion tons in CO_2 emissions saving, and an additional employment of 2.5 million[13]. Feng et al [18] estimated that China's participation in GEI will expand its GDP by 0.2% and reduce its emissions by 1%. Although the results are generally positive, few of them are directly comparable, as they rely on various base-case and policy-case assumptions and show results for various regions and indicators. This could lead to misunderstanding of the magnitude of simulation results.

We identify six areas for improvement in the existing literature. First, the existing analyses ignore much of the cross-border aspects of GEI. Most studies only show results for the world as a whole or a single region of the world, with the only exception being Jin et al [15]. Second, the existing analyses assume highly aggregated renewable power generation types. Since the newly proposed GEI has explicit plans for hydropower, wind power and solar power, it is desirable to account explicitly for those different renewable energy types across regions. Third, the existing analyses generally have base-cases that are not carefully defined. In a forward-looking analysis, it is critical to formulate a realistic base-case to which policy changes (GEI development

---

[8] including energy intensity (energy use per unit of GDP), per capita energy consumption, CO2 emissions per unit of energy and the ratio of gross inland consumption from renewable to primary energy

[9] As the one outlined in Liu 2015

[10] Including those of IEA's, EIA's, WEC's, and some others'. (IEA is International Energy Agency, EIA is Energy Information Administration of the U.S., and WEC is World Energy Council)

[11] They divided the world into six large regions. Africa gains the most, in terms of GDP, under the GEI scenario in 2030.

[12] We read these numbers from Figure 2, p.471. Note that Wang et al 2018 has not provided a formal justification to these numbers. They have, instead, cited an original study (Global Energy Interconnection Development Organization, 2018, The Action Plan of the Global Energy Internet promotes the implementation of the Paris Agreement) – which has not been included in their end-of-the-article reference list. We have not been able to find this original study either.

[13] These are the benefits in clean development scenario comparting with high-fossil fired power scenario, by 2050.

in this case is the policy change) are compared.

Table 1: Summary of main results of existing quantitative analyses on GEI

Study	Method	Base-case	GEI scenario	Year	Region	GDP	Employment	CO_2
Zong 2017 [13]	PSR(1) model	n.a.	Smart grid plan, China	2020	China	n.a.	9.8 million more	776 million tons less
Bompard et al 2018 [14]	Scenario comparison	Various (from literature)	Liu 2015 [9]	2050	World	n.a. (2)	n.a. (2)	n.a. (2)
Jin et al 2018 [15]	GTAP	Self-defined	Electricity planning model	2050	Six world regions	0.07%-0.29% more (3)	12 million more	n.a.
Wang et al 2018 [16]	n.a.	n.a.	The literature	2050	World	n.a.	n.a.	At 11.8 billion tons(4)
Jiang et al 2019 [17]	System dynamics	Nine scenarios (three GDP, three fuel mix)		2050	South-east Asia	USD$600 billion(5) more	2.5 million more(5)	1 billion tons less(5)
Feng et al 2019 [18]	GTAP-E	IEA 2018 [2]	GEIDCO 2018 [19]	2050	China	0.2% more	0.14% more	1% less

Notes: (1) Pressure-State-Response model (2) GEI results are for year 2050, all other results are for year 2040, thus we cannot deduce difference between GEI and other scenarios. (3) The deviation from base-case (in 2050) in Asia, Oceania, Europe, North America, South America and Africa are 0.24, 0.29, 0.07, 0.12, 0.28 and 0.26 per cent, respectively. (4) The original article does not provide a number, we read this result (for 2050) from Fig.9, p.6. (5) in high GDP growth scenario, the difference between high clean energy and high thermo-power.

Fourth, the GEI scenarios investigated are often poorly specified. Most existing studies have not explicitly illustrated their GEI scenarios – it is unclear, for example, how much of solar power have been transmitted from one region to another via the GEI networks. That said, there do exist a recent, detailed plan in the literature that provides such information, namely the Global Backbone network[14] (GBN) plan. Feng et al [18] is the only study to have used such information, but theirs is only an analysis on China's participation in GEI.

Fifth, most of the studies are based either on *ad hoc* scenario analysis or on partial equilibrium frameworks. Four of the six existing quantitative studies use modelling techniques, the other two only compare scenarios. Computable general equilibrium (CGE) modelling has a clear advantage because it represents input-output relationships. Indeed, CGE models have been widely used to study energy and environmental issues and their social economic implications (e.g., [21] ,[22], [23],[24], [25], [26]). The GTAP model, thanks to its global input-output database and theoretical framework, has become the go-to model to analyze global effects, it is also the basic model framework used in Jin et al [15] and Feng et al [18]. This study follows this tradition.

Sixth, existing studies that use CGE modelling techniques use out-of-date parameter estimates and inappropriate nesting

---

[14] Although not the entirety of GEI, it can be considered as the major infrastructure network of GEI. Section 4 will discuss the GBN plan in more detail.

structures. It has long been argued that econometrically estimated elasticity parameters shall be used in CGE models (e.g., [27],[28]), but few has done so in a robust manner. A more comprehensive econometrics study that covers all regions of the world would recognize the potential heterogeneities and enhance model's credibility.

The analysis in this paper overcomes some of these gaps in the literature by having: 1) properly disaggregated regions and renewable energy sectors, 2) clearly defined base-case and GEI scenarios, and 3) a suitable fuel-factor nesting structure. For the modelling reported in this paper we identify 12 regions and 3 regional energy sectors. We use a base-case and GEI assumptions, consistent with the relevant literature. Finally, following the nesting structure of Feng et al [18], we employ econometrically estimated values for key substitution (CES) parameters across regions.

3 Model, database, developments and base-case

The core model and its database are described in Subsection 3.1. The remaining subsections discuss model developments. In Subsection 3.2 we illustrate the nesting structure and the calibration of parameters, including the econometric estimation of the constant elasticity of substitution (CES) parameter between fossil fuel power generation and non-fossil fuel power generation. Subsection 3.3 is about the dynamic mechanisms, and Subsection 3.4 presents the base-case.

3.1 Model and database

Our base model is the standard GTAP-E model. GTAP-E is an energy-environmental version of the GTAP model [29]. GTAP-E has an emissions account. This allows us to assess the implications of CO_2 emissions. GTAP-E has a multi-level fuel-factor nest. This allows substitutions between different energy sources – for example, that between electricity and non-electricity energy. Finally, GTAP-E has an emissions trading module. This allows investigations over the combined effects of GEI development and international emissions trading[15]. However, GTAP-E only has one electricity sector, so it does not allow substitution between fossil fuel and non-fossil fuel. This would leave out important environmental and economic benefits brought about by GEI development through higher shares of renewable energy.

Table 2: Power sectors in GTAP-power database, mapping to new sectors, and abbreviations

Sector names in GTAP-power	Mapping to new sectors	New sector abbreviations
Nuclear power generation - baseload	Other power generation	OtherP
Coal-fired power generation - baseload	Fossil fuel power generation	FFP
Gas-fired power generation - baseload	Fossil fuel power generation	FFP
Wind power generation – baseload	Wind power generation	WindP
Hydropower generation – baseload	Hydropower generation	HydroP
Oil-fired power generation – baseload	Fossil fuel power generation	FFP
Other power generation – baseload	Other power generation	OtherP
Gas-fired power generation – peak load	Fossil fuel power generation	FFP
Hydropower generation – peak load	Hydropower generation	HydroP
Oil-fired power generation – peak load	Fossil fuel power generation	FFP
Solar power generation – peak load	Solar power generation	SolarP
Power transmission and distribution	Power transmission and distribution	tnd

Source: GTAP-power database, authors' compilation

To overcome this limitation, and following Feng et al [18], we use the GTAP-power database. The GTAP-power database disaggregates the electricity sector into 12 individual sectors, including 11 power generation sectors by technology and 1 power transmission and distribution sector (see Table 2). The current study, however, does not require such detailed sector classification. In order to reduce model complexity, we map the 11 power generation sectors to five, namely Fossil fuel power, Hydropower,

---

[15] Due to the limitation of the scope, the current study does not have this scenario. Nevertheless, it is a valuable feature to have in future studies.

Wind power, Solar power, and Other power. The mapping from the original GTAP-power sectors to the new sectors is also shown in Table 2.

We aggregate the original GTAP-power database into 12 regions and 21 sectors. The 12 regions are aggregated from the 140 regions in the original GTAP-power database. The mapping for regions is shown in Appendix 1. We choose these 12 aggregated regions for two main reasons. First, this level of regional detail can be afforded in the construction of the base-case, which will be discussed in more detail in Subsection 3.4. Second, this is an appropriate level of detail to model GEI development, which will be discussed in Section 4. The 21 sectors[16] are aggregated from the 68 sectors in the original GTAP-power database. The mapping for sectors is shown in Appendix 2.

3.2 Nesting structure, parameter calibration and econometrics estimation

Fitting the GTAP-power database into the GTAP-E model requires changing the existing fuel-factor production nesting structure in GTAP-E. This is because the existing structure does not differentiate power generation technologies. We thus need to expand the original structure. Figure 1 shows the new, expanded structure. The existing structure of GTAP-E contains the parts outside the 'dome', while the added parts are inside it. The parts inside form a four-level nest for electricity, or the 'electricity nest'.

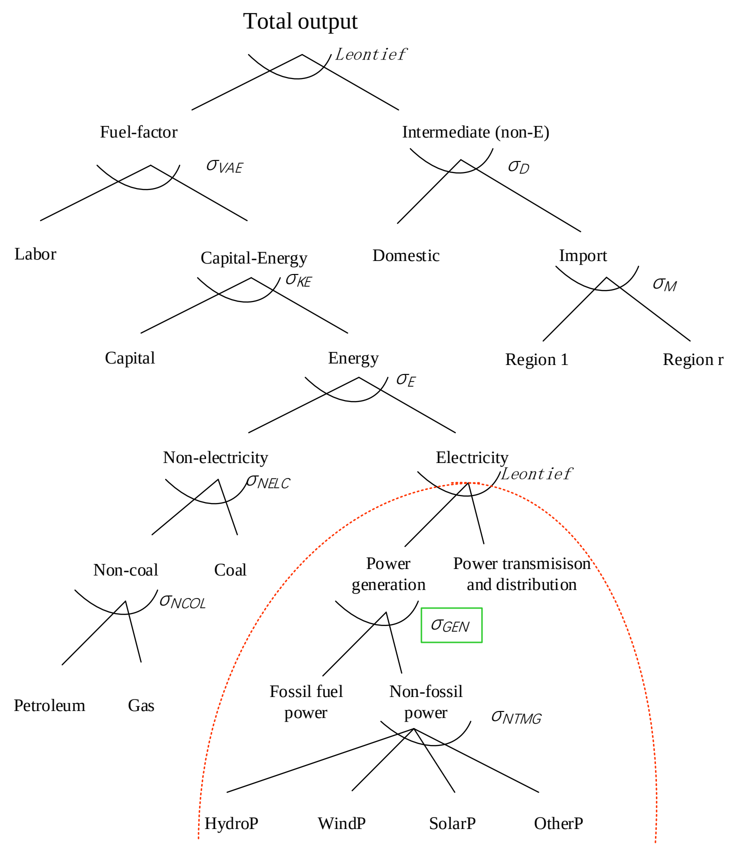

Figure 1:New, expanded production nesting structure

---

[16] Apart from having 6 electricity sectors, there is no definite rule for how to aggregate sectors, although more sectors could almost always show more results. That said, more sectors would also result in longer solution times. We find that, in a year-by-year simulation up to year 2050, 21 is about the largest number of sectors we could afford timewise.

The nesting strategy of the electricity nest is as the following. The top level is a fixed proportion (Leontief) combination between an electricity generation bundle and the power generation and distribution sector (tnd). We choose a Leontief combination on the top to reflect the fact that there exist little opportunities for substitution between electricity and power transmission and distribution facilities even if their relative prices change. In the second level, the power generation bundle is a constant elasticity of substitution (CES) bundle between a non-fossil fuel power generation bundle and the fossil fuel power generation sector (FFP). We choose this particular form in order to use econometrics techniques to estimate the CES parameter – we will discuss why σ_{GEN} is chosen to be estimated later in this subsection. In the third level, the non-fossil fuel power generation bundle is a CES bundle of HyrdoP, WindP, SolarP and OtherP – these four sectors form the fourth and the bottom level[17].

Next, we calibrate the elasticity of substitution parameters to our new nesting structure. The values of these parameters are taken from the GTAP-E model. We show these values in Appendix 3. However, not all values of the elasticity of substitution parameters are available in GTAP-E. Two key CES parameters are missing, namely σ_{GEN} and σ_{NTMG}. We choose to use econometrics techniques to estimate σ_{GEN}. This particular parameter is chosen for three main reasons. First, a key aspect in modelling GEI's development is to model the substitution away from fossil fuel power generation and towards non-fossil fuel power generation. This parameter determines the extent to which an improvement in non-fossil power generation would reduce demand for fossil power generation. Second, we wish to estimate this parameter for different regions of the world. This is can help to show GEI's social-economic implications to different countries. The literature offers little guidance regarding this parameter in different regions. Third, the power generation bundle is the right structure (having only two inputs) for deploying econometrics techniques. This means the parameters estimated using the same production function as the one used in the CGE model. We show our estimation methods in Appendix 4 and results in Table 3. These results conform with the general finding that inter-fuel substitution values are typically between zero and two ([32]).

Table 3: econometrically estimated σ_{GEN} for different regions

The 12 regions in the model	Mapping to the regions estimated	Estimated σ_{GEN} values
North America (NAmr)	North America	1.51
Central-south America (CSAmr)	Central-south America	1.26
North Europe (NEur)	Europe	1.69
Continental Europe (CEur)	Europe	1.69
North Africa (NAfr)	Africa	1.56
Sub-Saharan Africa (SSAfr)	Africa	1.56
West Asia (WAsia)	Asia and Pacific	1.37
Eurasia	Eurasia	1.53
South Asia (SAsia)	Asia and Pacific	1.37
China	Asia and Pacific	1.37
North-east Asia (NEAsia)	Asia and Pacific	1.37
South-east Asia and Pacific (SEAsPc)	Asia and Pacific	1.37

Source: Authors' estimation results using data from IEA

3.3 Dynamics

GEI is a multi-year project and therefore we need to add dynamisms to the static GTAP-E model. We choose to include two relatively simple mechanisms. The first relates to capital and investment. The second relates to the behavior of each region's

---

[17] Ideally, we should have only two inputs, or bundles, in each level, and use econometrics techniques to estimate all CES parameters. This is because a CES function with more than two factors would generally imply that a constant elasticity of substitution does not exist among all factors [30]. However, we do not have convincing reasons for how to form a bundle. That is, we do not have strong reasons to combine, for example, WindP and SolarP as a bundle instead of WindP and HydroP. Due to the scope of the study, we do not attempt to identify a more appropriate nesting structure for the four non-fossil fuel power generation technologies. Therefore, for simplicity and reasons stated above, we put all four non-fossil fuel power generation sectors in a single paralleled bundle.

labour market.

Investment and capital

In the model used for this study, it is assumed that in region r investment undertaken in year t will become operational at the start of year t+1. Given a starting value for capital in t=0, and with a mechanism for explaining investment, the capital accumulation equations trace out the time paths of regional capital stocks.

Investment in year t in each region is explained as an increasing function of the ratio of a region's expected rate of return to its required rate of return. In standard closures of the model, the required rate of return is an exogenous variable which can be moved to achieve a given growth rate in capital

It will generally be assumed that investors take account only of current rentals and asset prices when forming expectations about rates of return (static expectations).

Lagged adjustment process in the national labour market

Simulations with the proposed model will be year-to-year recursive-dynamic simulations, in which it is assumed that deviations in the national real wage rate from its base-case level increase through time in inverse proportion to deviations in the national unemployment rate. That is, in response to a shock-induced increase (decrease) in the unemployment rate, the real wage rate declines (increases), stimulating (reducing) employment growth. The coefficient of adjustment will be chosen so that effects of a shock on the unemployment rate are largely eliminated after about ten years. This is consistent with macroeconomic modelling in which the nation's unemployment rate is determined by demographic factors that are largely unaffected by energy and environmental issues.

3.4 A base-case scenario

A dynamic CGE model needs a base-case scenario, or a 'business-as-usual' scenario, to which policy scenarios are compared. Our base-case has two phases – the historical phase and the projection phase. The historical base-case is between 2011, the base-data year, and 2017, the year for which the latest data are available. Table 4 summarizes the controlled variables, their data sources, and the endogenized variables. In the historical base-case, we control GDP, population and employment levels and endogenize total factor productivity[18] (TFP) for the 12 regions. We also control private consumption and investment levels for the 12 regions by endogenizing marginal propensity to consume (mpc) and expected rate of return (eror), respectively. We take data from the world development indicator (WDI) [33] for all regions but China, for which we use data from China National Bureau of Statistics (CNBS) for more accuracy.

In the projection base-case we control both macroeconomic and energy variables. When constructing a projection base-case, a common practice in the literature is to only control a set of macroeconomic variables, such as GDP, employment and total factor productivity (TFP). A more suitable base-case for the current study, however, should present a case for not only macroeconomic variables but also energy, and especially renewable energy variables. For macroeconomics variables we use CEPII's forecast for GDP, population and employment, while endogenizing TFP. We choose CEPII's projections for its comprehensiveness, a documentation can be found in [36]. Other main macroeconomic forecast suffer from either too short time span (e.g., the IMF World Economic Outlook) or too few economies (e.g., the OECD long-term economic outlook [37]). We use energy projections from the World Energy Outlook 2018's New Policy Scenario to formulate projections for coal, oil, gas and total electricity use, as well as projections for fossil-fuel power, hydropower, wind power, solar power and other power, for the 12 regions. Sectoral production technologies are endogenized to facilitate development in the energy sector. All base-case projection strategies can also be found in Table 4.

---

[18] Population and employment are naturally endogenous variables and hence do not require swaps in the closure.

Table 4: base-case development summary

Controlled variables	Data sources	Endogenized variables to facilitate closure swaps
Historical phase (2011-2017)		
GDP	WDI[34], CNBS[35]	TFP
Population	WDI[34], CNBS[35]	none
Employment	WDI[34], CNBS[35]	none
Private consumption	WDI[34], CNBS[35]	mpc
Investment	WDI[34], CNBS[35]	eror
Projection phase（2018-2050）		
Controlled variables	Data sources	Endogenized variables to facilitate closure swaps
GDP	CEPII	TFP
Population	CEPII	n.e.
Employment	CEPII	n.e.
Domestic use（coal、oil、gas and total electricity）	WEO[2]	Sector productivity
Domestic production（fossil fuel power, hydropower, wind power, solar power and other power）	WEO[2]	Sector productivity

4 The GEI scenario

We formulate the GEI scenario by considering the inter-regional trade of renewable energy that is made possible by the backbone network. In particular, we need the quantities of hydropower, wind power and solar power that are transferred among regions via this new electricity transmission infrastructure. Such information can be found in two recent studies, namely Li et al [38] and GEIDCO [19]. Li et al [38] used power generation potential, historical power supply, existing power generation capacity, and power system operation requirements as constraints to minimize global power supply costs. They proposed an optimal allocation of power generation capacity on the aforementioned three forms of renewable power generation. Following Li et al [38], and considering different power resources' complementarity, as well as the ability to use long-distance power systems, GEIDCO [19] proposed the first, and to our knowledge the only, inter-regional power transmission network. Figure 2 shows the projected power transmission capacity[19] of the backbone network in 2050.

---

[19] Power flow here refers to the hourly power transmission capacity on the network.

Figure 2: projected transmission capacity (10000kW) of the backbone network

Source: GEIDCO [19].

We deduce two important results from Figure 2.

1. We deduce the total hydropower, wind power and solar power traded among regions by assuming that the effective power generation hour for all renewable technologies are 5000 hours in 2050. This was the same assumption made in Liu [20].
2. We deduce the additional hydropower, wind power and solar power generated in each region due to the development of the backbone network. Here we assume that a region's power generation output is higher than its base-case level by the same amount as its total export via the backbone network.

Table 5, 6 and 7 show the trade of hydropower, wind power and solar power, respectively, among the 12 regions, in 2050. The first column of each table shows the exporting regions and the first row shows the importing regions. The last column shows each region's total export, which is equivalent to the additional output generated for the backbone network[20].

Table 5: Interregional transmission through backbone network, projection in 2050, Hydropower (TWh)

	NAmr	CSAmr	NEur	CEur	NAfr	SSAfr	WAsia	Eurasia	SAsia	China	NEAsia	SEAsPc	Total
NAmr	90												90
CSAmr	50	100											150
NEur			50	162.5									212.5
CEur													0
NAfr													0
SSAfr					90	250	40						380
WAsia													0
Eurasia										130			130
SAsia													0
China									50			135	185
NEAsia													0
SEAsPc									60	135			195

Source: GEIDCO [19], authors' compilation.

Table 6: Interregional transmission through backbone network, projection in 2050, Wind power (TWh)

	NAmr	CSAmr	NEur	CEur	NAfr	SSAfr	WAsia	Eurasia	SAsia	China	NEAsia	SEAsPc	Total
NAmr	420												420
CSAmr		75											75
NEur			40	48									88
CEur													0
NAfr													0
SSAfr													0
WAsia													0
Eurasia				55						100	120		275
SAsia													0
China									25		100		125
NEAsia													0
SEAsPc													0

Source: GEIDCO [19], authors' compilation.

---

[20] Notice that there are more regions in the figures than in the tables. This is mainly to save computing time as more regions would greatly add to the complexity of the modelling work. Future studies might want to add further regional details. That said, the current study is already a significant improvement from the existing studies, which only modelled GEI development for six regions (e.g., Jin et al. 2018)

Table 7: Interregional transmission through backbone network, projection in 2050, Solar power (TWh)

	NAmr	CSAmr	NEur	CEur	NAfr	SSAfr	WAsia	Eurasia	SAsia	China	NEAsia	SEAsPc	Total
NAmr	150	50											200
CSAmr		75											75
NEur													0
CEur													0
NAfr				295									295
SSAfr													0
WAsia				150	55	40			225				470
Eurasia				100				150		195			445
SAsia													0
China									25				25
NEAsia													0
SEAsPc													0

Source: GEIDCO [19], authors' compilation.

As Table 5-7 show, the backbone network, which will start operation in 2031, will, in 2050, transfer 3835 TWh of renewable power across regions of the world. Hydropower, wind power and solar power will supply 1343 TWh, 983 TWh, and 1510 TWh to this new network, respectively. Sub-Saharan Africa (SSAfr) and Northern Europe (NEur) will supply the most hydropower – 380 TWh and 213 TWh, respectively. North America (NAmr) will supply the most wind power – 420 TWh. West Asia and Eurasia will supply the most solar power – 470 TWh and 445 TWh, respectively. Adding all renewable power, Eurasia and NAmr will supply the most to the network – 850 TWh and 710 TWh, respectively. Continental Europe (CEur) will be the largest importer with 810 TWh. CEur will also be the biggest net-importer on the network, importing 810 TWh and not exporting any at all. Eurasia will be the biggest net-exporter with 700 TWh.

Table 8: Renewable energy production by region and technology, New Policy Scenario (NPS) and GEI scenario, 2050

2050 (TWh)	NPS			GEI		
	Hydro	Wind	Solar	Hydro	Wind	Solar
NAmr	872	1001	780	962	1421	980
CSAmr	1395	277	204	1545	352	279
NEur	322	360	0	534	447	0
CEur	484	1121	436	484	1121	436
NAfr	84	193	766	84	193	1061
SSAfr	509	0	0	889	0	0
WAsia	46	319	601	46	319	1071
Eurasia	353	149	8	483	424	453
SAsia	448	804	1789	448	804	1789
China	1716	2057	2160	1901	2182	2185
NEAsia	111	48	104	111	48	104
SEAsPc	784	413	545	979	413	545
World	7127	6741	7392	8469	7723	8902
Cumulative deviation NPS to GEI in 2050:				18.8%	14.6%	20.4%

Source: IEA [2] , GEIDCO [19], authors' compilation.

In the GEI scenario, we increase (relative to base case) the interregional trade as well as exporting regions' production of these three power sources according to Table 5-7. The amount of additional power generated and transmitted are the same, and will increase gradually by an equal amount between 2030 and 2050, until they reach their 2050 levels. Table 8 shows the level of production in 2050 for hydropower, wind power solar power by regions, under both the base-case (the New Policy Scenario) and the policy case (the GEI scenario). In order to facilitate these increases, we allow power generation and power transmission technologies to change endogenously. Essentially, by endogenizing these technological variables, we ask the model to infer the required technological improvement, in both renewable power generation and long-distance power transmission, for developing the backbone network. Such technological improvements imply the combined effects of all possible efforts and mechanisms, such as adding previously desolate lands in the deserts into the capital stock of solar production, or establishing new ultra-high voltage power transmission lines that are more efficient than the more traditional lines. These technological improvements would therefore, through inter-fuel substitution, help us to understand the extent to which the GEI would stimulate economic and energy market transformation[21].

5 Simulation results

We show results for real GDP (All results, unless otherwise stated, are shown as cumulative percentage deviations from base-case levels[22]) in Figure 3. Global GDP in the GEI scenario is always higher than it is in the base-case - by 2050, it is 0.33 per cent higher. All regions benefit from connecting to the backbone network. These results show that GEI development is not only for the global economy as a whole but it also has long-run positive effects on all regions.

Regions, however, benefit from their participation into the backbone network to different extents. In 2050, North Africa benefits the most (0.92 per cent), followed by North Europe (0.80 per cent) and Continental Europe (0.65 per cent). West Asia (0.09 per cent), South Asia (0.13 per cent) and China (0.18 per cent) are the three regions that gain the least. North Africa benefits the most because, relative to its income, it has the largest volumes of trade using the backbone network. Figure 4 shows (on the left-hand side) the level of involvement of regions' participation to the backbone network relative to the sizes of their economies. Adding export to and import from the backbone network, as Figure 4 shows, North Africa's renewable energy trade is the largest compare to the size of its economy.

Not all regions with deep GEI involvement, however, benefit as much as North Africa does. Eurasia, for example, has the second largest renewable trade volumes through the backbone network relative to the size of its economy (see Figure 4, LHS), but its GDP is only 0.25 per cent (the 7th largest increase) higher than it is in the base-case in 2050. This is mainly because Eurasia also has a large fossil fuel industry and one that will be negatively affected by the development in the renewable sector. West Asia benefits the least from its participation to the backbone network – its GDP will only be 0.09 per cent higher than its base-case level in 2050. This is because, first, the extent of its participation is relatively low –10 per cent lower than the world average (see LHS of Figure 4), and second, the share of fossil fuel energy is large, in fact, it is the largest, at 4.3 times of the world average (see RHS of Figure 4).

The mechanisms of GDP improvement are different among the regions. A decomposition on the income side of GDP (Figure 5) shows that technological improvement contributes the most to GDP improvement. For regions that mainly exports to the backbone network, such as North Europe, technological improvements can be seen as a result of gains in domestic production. For regions that mainly imports from the backbone network, such improvements can be seen as a result of gains in long-distance power transmission. For hubs such as North Africa, the improvements can be seen as a result of gains in both domestic production and import.

---

[21] It is worth noting, however, that we do not explicitly model the GEI-related investment and financing activities. We do not model these for four main reasons. First, they do not necessarily affect GDP as the effect of investment and financing on GDP tend to offset each other. Second, investment in the model does not have a sector dimension. Third, the model lacks mechanisms linking sectoral investment to sectoral productivity. Fourth, we do not have information for how financing is divided among regions.

[22] A ten per cent difference in 2050, for example, implies a ten per cent difference between the level in base-case and the level in policy case in year 2050.

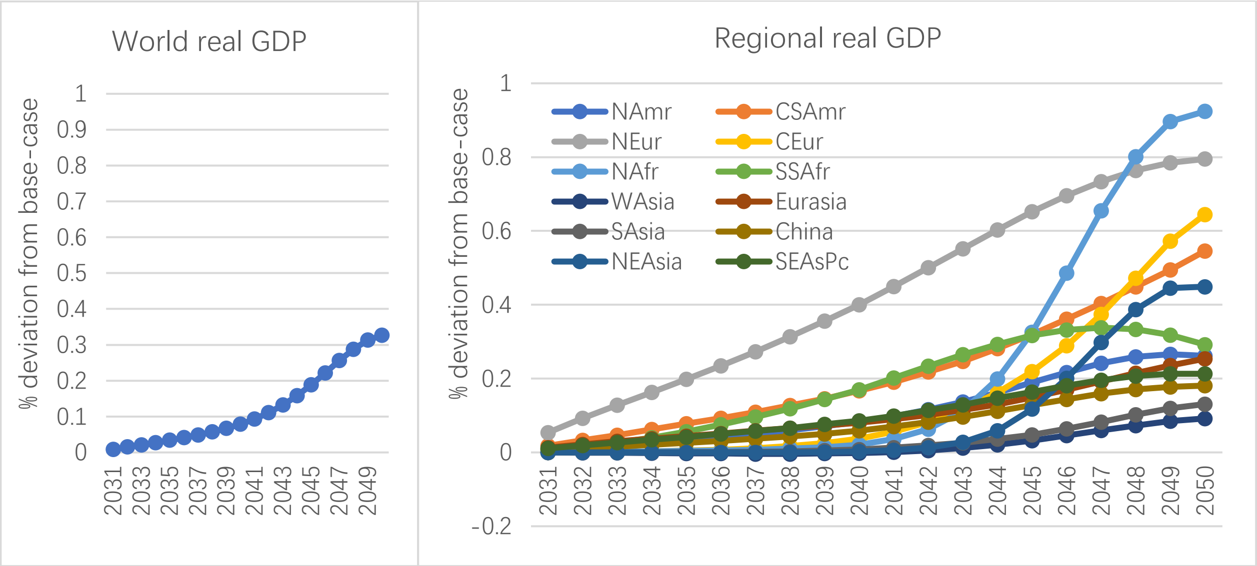

Figure 3: GEI's impact on real GDP

Source: authors' modelling results.

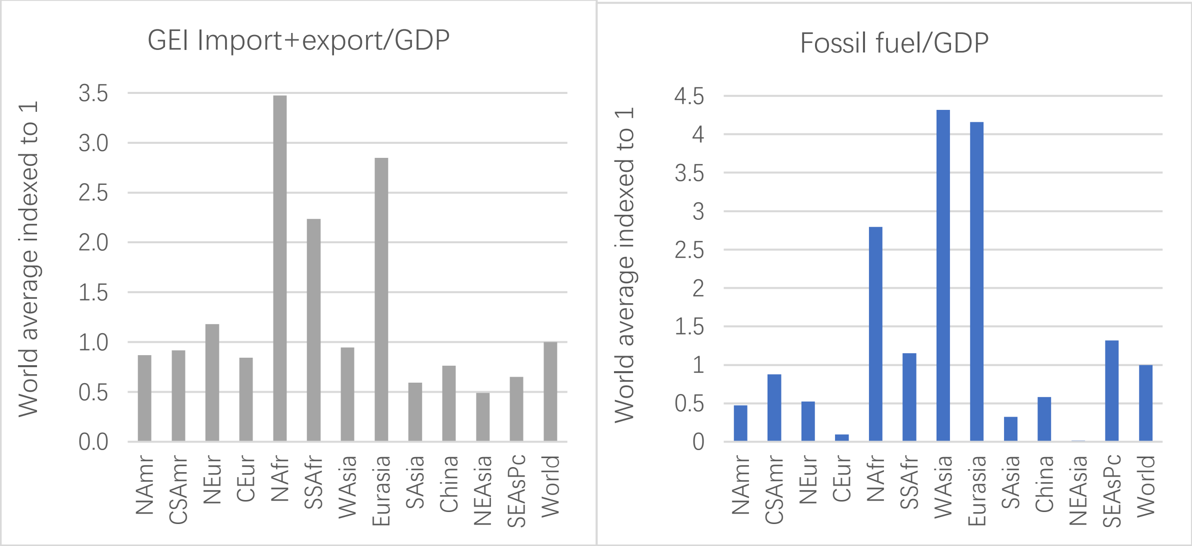

Figure 4: GEI participation and importance of fossil fuel in different regions

Source: authors' calculation using results from the base-case.

Note: For the figure on the LHS, we first calculate the physical sum of a region's renewable export to and import from the backbone network and divide the sum by the sum of the region's GDP between 2030 and 2050 (in the base-case), we then normalize these ratios by setting the ratio for the world as 1. Similarly, for the figure on the RHS, we divide regions' total fossil fuel value by their respective GDP (for years between 2030 and 2050, using numbers in our base-case), and normalize the ratios by setting the world average as 1.

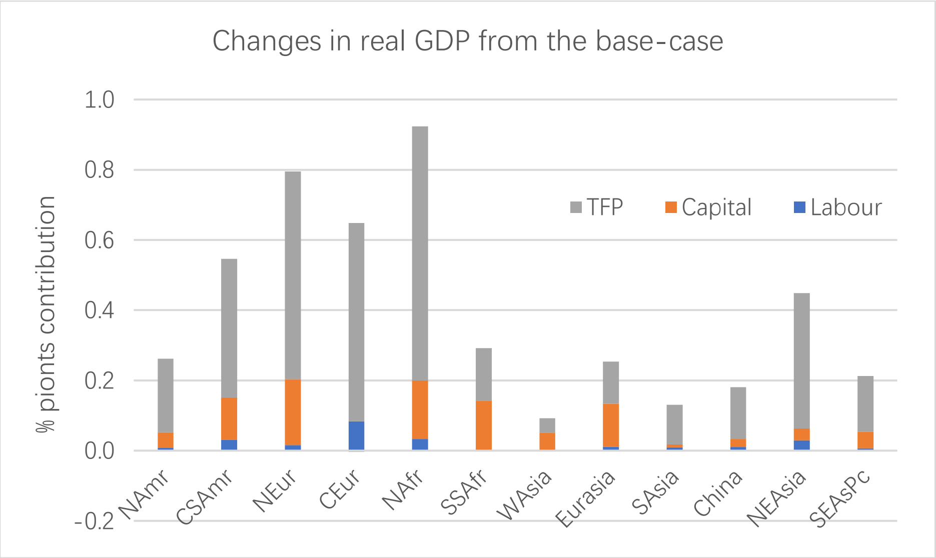

Figure 5: A decomposition of real GDP from the income side, 2050

Source: authors' modelling results.

Between capital and labour, the former tends to benefit more in GEI development. We show employment and capital changes in Figure 6. By 2050, capital increases are generally larger than employment increases. This is mainly because renewable energy production is capital-intensive across all regions (see Figure 7). Therefore, the development in renewable power will have a larger positive effect on capital than on labour. Capital does not increase in Continental Europe as much, this is because the region does not export to the backbone network but does import a lot from the network. Importing cheaper electricity from abroad could reduce local prices and stimulates local economy. In the case of Continental Europe where the economy is very labor-intensive, the gains accrue mostly to labour.

A region's exporting or importing status in the backbone network can therefore affect its capital-labour compositions. Exporting regions are more likely to see stronger increase in capital employment as a result of expanding domestic renewable production. For example, GDP improvements in North Europe and Continental Europe are similar (0.80 per cent and 0.65 per cent, respectively) capital and labour improvements in the former are 0.42 per cent and 0.03 per cent, respectively, and -0.01 per cent and 0.15 per cent, respectively. Thus, capital-labour ratio in North Europe increases by 0.41 per cent but decreases by 0.16 per cent in Continental Europe. This implies that the relative costs of labour and capital also move in opposite directions in these two regions, with real cost of capital decreases in the former region and real costs of labour decreases in the latter one.

Moreover, the composition of a region's renewable profile also matters to the relative development between labour and capital. Across the regions, solar power tends to be more capital-intensive than hydropower, and in turn, than wind power. Thus, regions that emphasis on solar production in the backbone network could see more growth in capital than regions that emphasis on wind production. For example, North Africa's GDP increases more than North Europe does, but the former's capital grows slower than the latter does, this is because the former's renewable exports comprise a mix of hydropower and wind power but the latter's mainly of solar power.

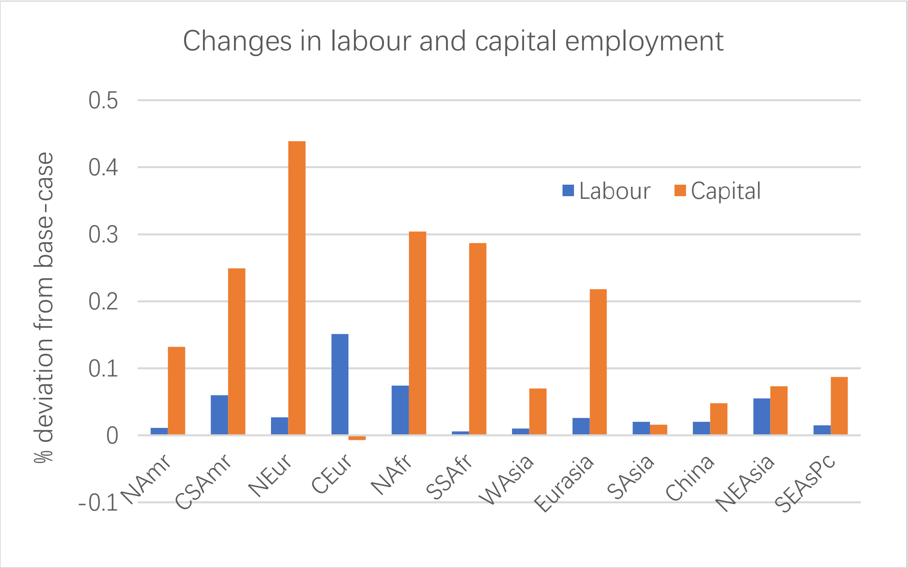

Figure 6: GEI's impact on labour and capital, 2050

Source: authors' modelling results.

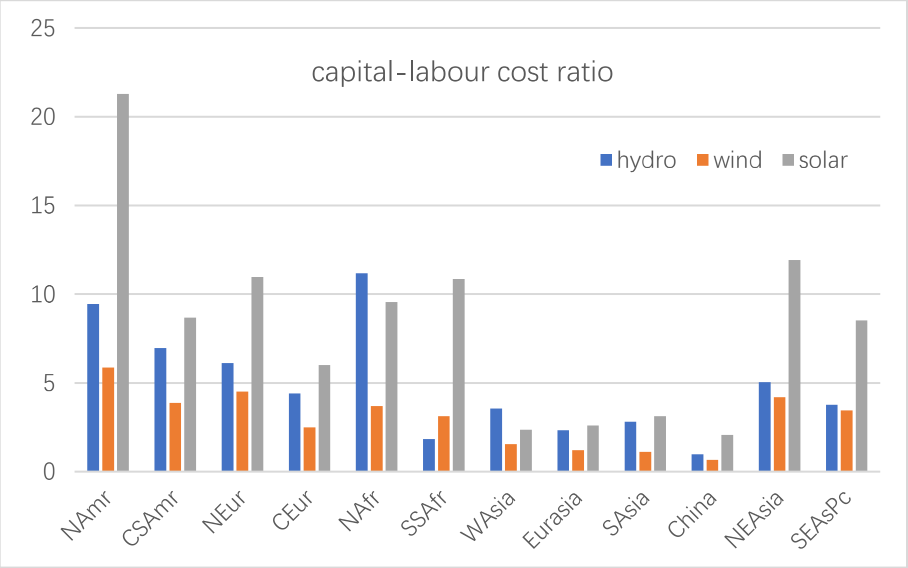

Figure 7: Capital-labour cost ratios for renewable energy production

Source: authors' calculation, sum of total costs between 2030 and 2050 (base-case).

The growth in real GDP, driven by technological improvement on the income side, has a general and positive effect on all components of the expenditure side. We show a demand side decomposition of real GDP increase in Figure 8. Consumption in general contribute the most to GDP improvement as it accounts for the largest share of GDP. Countries that specialize in supplying to the backbone network, such as North Africa and North Europe, also have large contributions from investment – this can be expected as these regions also see significant growth in capital (see Figure 6). Both export and import make significant contribution to GDP, too, but their effects tend to offset each other and so the balance of trade contributions are generally small.

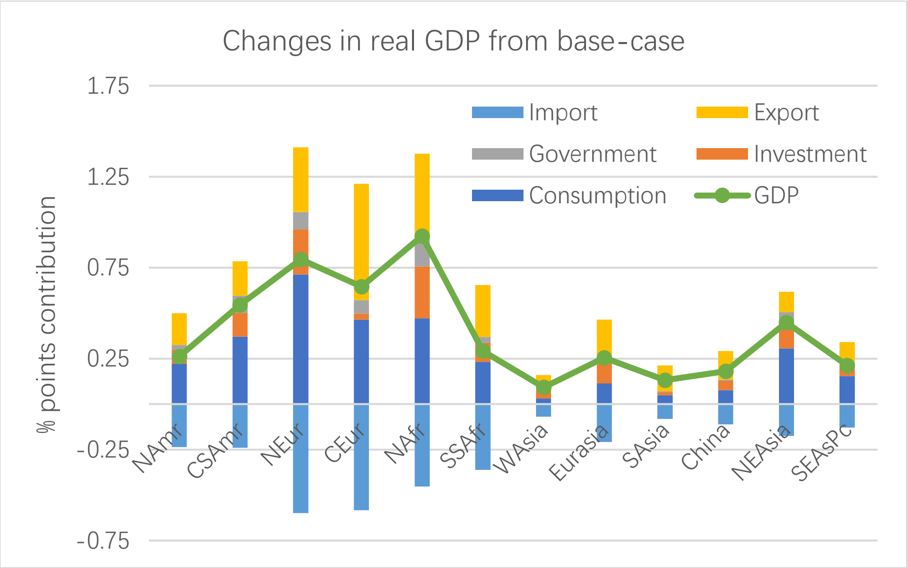

Figure 8: A decomposition of real GDP from the expenditure side, 2050

Source: authors' modelling results.

GEI participation mainly affects energy sectors. Therefore, we show results for energy sectors and non-energy sectors separately. We begin with showing the global non-energy sector output changes (Figure 9). All non-energy sectors will expand under the GEI scenario. The variations in the size of expansions are small – between 0.17 per cent for the agriculture sector (agri) and 0.28 per cent for the metal products sector (mtp). The increase is the smallest in the agriculture sector – one that does not sell much to the renewable energy sector as an intermediate input, nor it requires much electricity in their total costs of intermediate inputs. Hence the agriculture sector cannot not receive a huge demand boost from the downstream or a significant cost reduction from the upstream. Nevertheless, the agriculture sector still expands thanks to the general increase in demand. The transportation sector's gain (0.18 per cent) is the second smallest among all non-energy sectors. A significant portion of the transportation sector is devoted to transferring fossil fuel energy. The development of renewable energy in the GEI scenario reduces this part of demand and therefore constrained the growth of the transportation sector. Nonetheless, like the agriculture sector, the transportation sector expanded as other parts of the economy grow. The metal products sector benefits the most as it is relatively electivity-intensive and capital-intensive in its production and it also sells a relatively large proportion to the renewable energy sector. 9 out of the 11 non-energy sectors' output grow more than 0.2 per cent. These sectors benefit from cheaper electricity from both production linkages and final demand expansions. Clearly, renewable energy development has a general and positive effect on all non-energy sectors.

Results for non-energy sectors at the regional level, however, are not uniformly positive. We show these in Table 9. Across the regions, 6 (North America, Central South America, Central Europe, North Africa, China and North-east Asia) out of the 12 regions do not have a single non-energy sector that is worse off in the GBN scenario. These are generally regions with high GBN participations and low fossil fuel concentrations. Across the sectors, 3 (Construction, Trade and Services) out of the 11 sectors see positive effects in all regions. These are generally non-tradables that are less likely to have negative import-substitution effects. Three sectors' results show most variations among regions, namely Iron and Steel, Metal products, and Chemical and Rubber products. These three sectors see strong expansions in Central Europe and North Africa but some moderate contractions in Sub-Saharan Africa, West Asia and Eurasia. This is caused by the trade connections around the Mediterranean and its neighbouring regions. As electricity prices fall in the North Africa and Continental Europe – the two regions that benefit the most from GBN participation – production costs fall significantly in these three aforementioned electricity-intensive sectors, so their exporting prices also fall. This leads to negative import substitution effects in their nearby trade partners (Sub-Saharan Africa, West Asia and Eurasia) and cause output contractions in their domestic production.

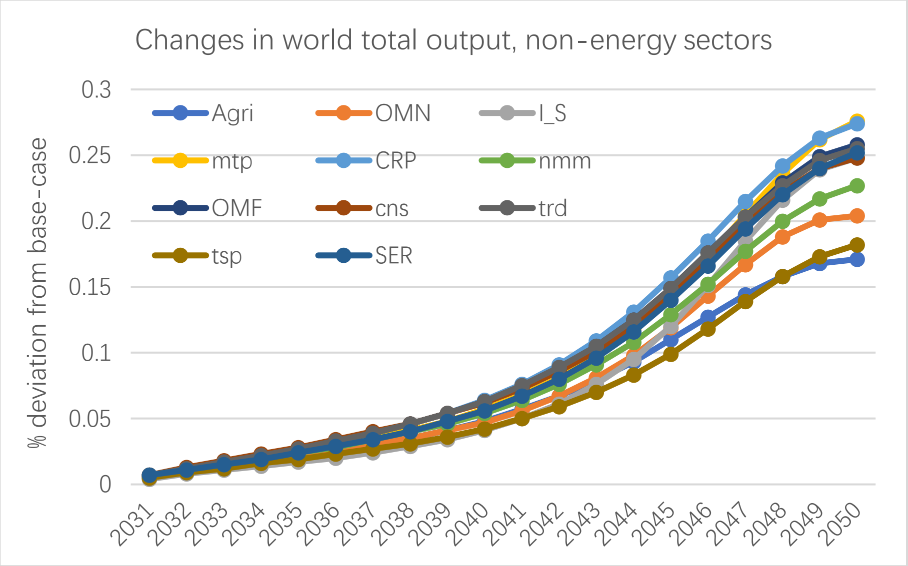

Figure 9: GEI's impact on non-energy sectors at the global level

Source: authors' modelling results.

Table 9: GEI's impact on non-energy sectors at the regional level (% deviation in output from base-case, 2050)

	1 NAmr	2 CSAmr	3 NEur	4 CEur	5 NAfr	6 SSAfr	7 WAsia	8 Eurasia	9 SAsia	10 China	11 NEAsia	12 SEAsPc
Agri	0.19	0.19	-0.30	1.31	0.26	-0.02	-0.02	0.01	0.16	0.14	0.40	0.10
OMN	0.46	0.29	0.35	1.11	1.03	0.01	-0.12	-0.15	0.33	0.07	0.65	-0.07
I_S	0.03	0.75	0.44	3.58	1.51	-0.45	-0.52	-0.68	-0.03	0.04	1.25	-0.02
mtp	0.19	0.70	1.51	1.89	1.75	-0.30	-0.36	-0.49	0.25	0.10	0.85	0.04
CRP	0.04	0.28	-1.13	2.33	1.24	-0.17	-0.35	-0.07	0.34	0.11	0.63	-0.17
nmm	0.17	0.52	0.22	1.06	1.60	0.22	-0.04	0.21	0.08	0.08	0.81	0.05
OMF	0.06	0.28	-0.34	1.38	0.45	-0.14	-0.10	-0.12	0.22	0.13	0.54	0.07
cns	0.31	0.60	0.89	0.27	1.10	0.40	0.16	0.47	0.07	0.10	0.42	0.15
trd	0.22	0.45	0.34	0.72	0.49	0.19	0.03	0.02	0.08	0.20	0.50	0.12
tsp	0.16	0.30	-0.07	0.71	0.23	0.00	0.09	-0.02	0.03	0.13	0.35	0.09
SER	0.17	0.56	0.12	0.58	0.48	0.19	0.06	0.01	0.11	0.15	0.42	0.10

Source: authors' modelling results.

Results for energy sectors vary much more than those for non-energy sectors do. First, we show results for the renewable power sectors. The trade and output increases are exogenous shocks and have been shown in Table 5-8. Here we present the modelling results. The backbone network largely increases renewable energy output and makes inter-regional renewable energy transmission possible. In terms of modelling results, these are shown as substantial falls in both importing and market prices for renewable energies. Figure 10-12 show the changes in average import prices for the three renewable energy types. For some regions (e.g., Hydropower import price in North Africa, wind power import price in North-east Asia and solar power import price in South Asia), renewable energy importing prices fall almost 100 per cent. This shows that the opening of backbone networks eliminates the previously prohibitive levels of renewable energy costs and makes inter-regional trade possible. As a result of both falling domestic production costs and importing costs, the market prices for renewable energies fall in all regions. Figure 13-15 show changes in market prices of renewable energies in different regions over the years. Hydropower prices will fall the most (23 per cent) in North Europe due to output expansion. Wind power and Solar power prices fall the most (31 per cent and 83 per cent, respectively) in Eurasia due to both cheaper output and cheaper imports.

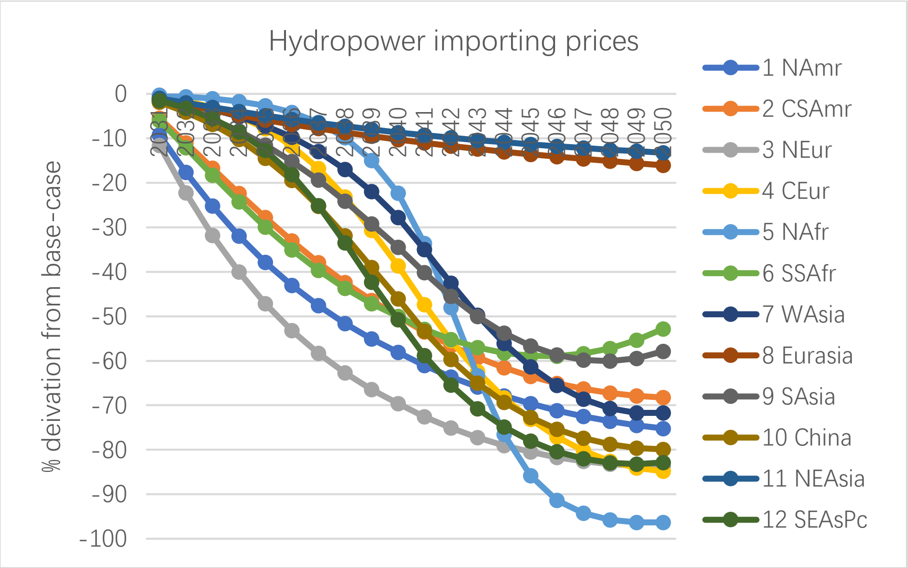

Figure 10: GEI's impact on hydropower importing prices

Source: authors' modelling results.

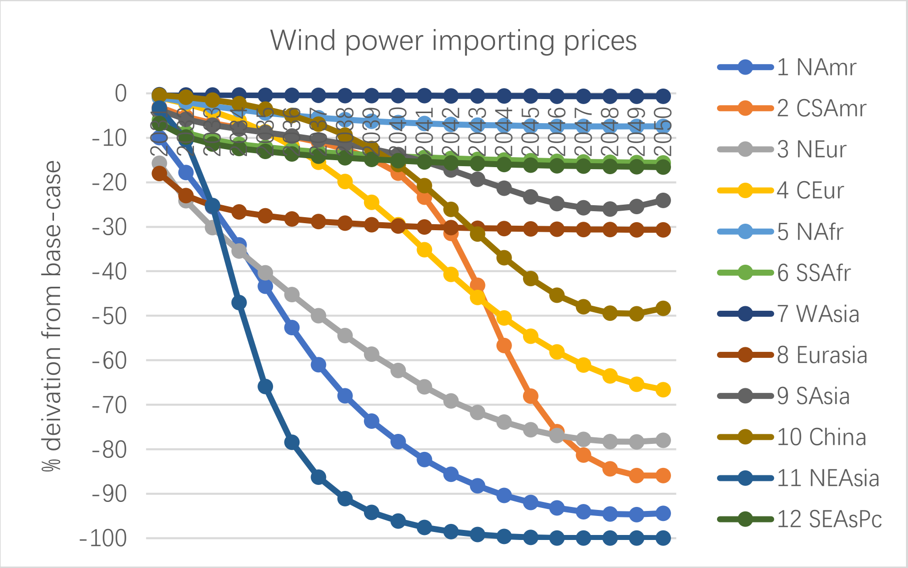

Figure 11: GEI's impact on wind power importing prices

Source: authors' modelling results.

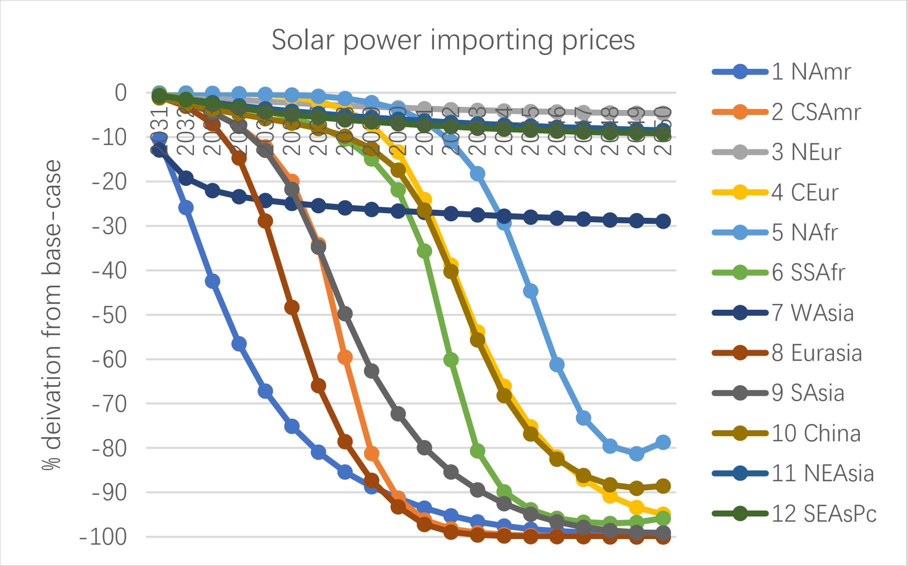

Figure 12: GEI's impact on solar power importing prices

Source: authors' modelling results.

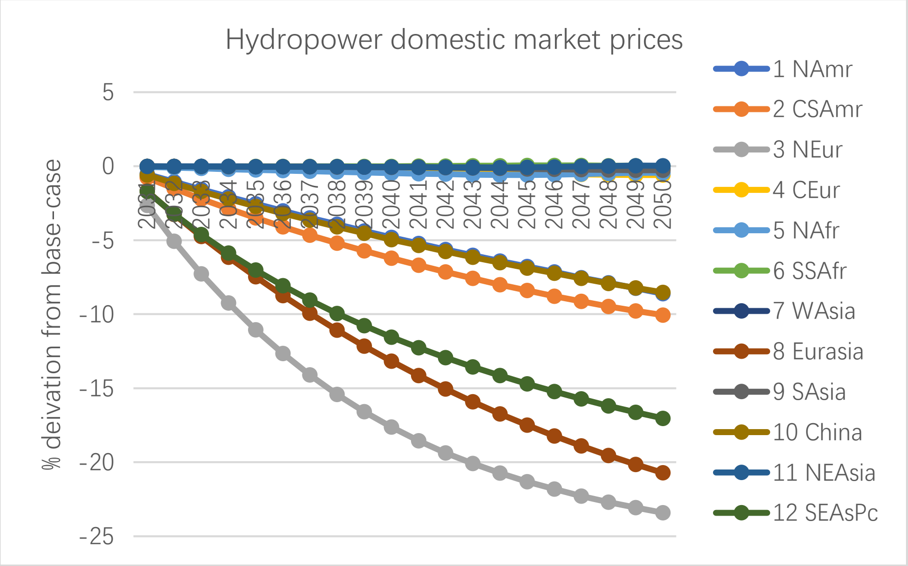

Figure 13: GEI's impact on hydropower domestic market prices

Source: authors' modelling results.

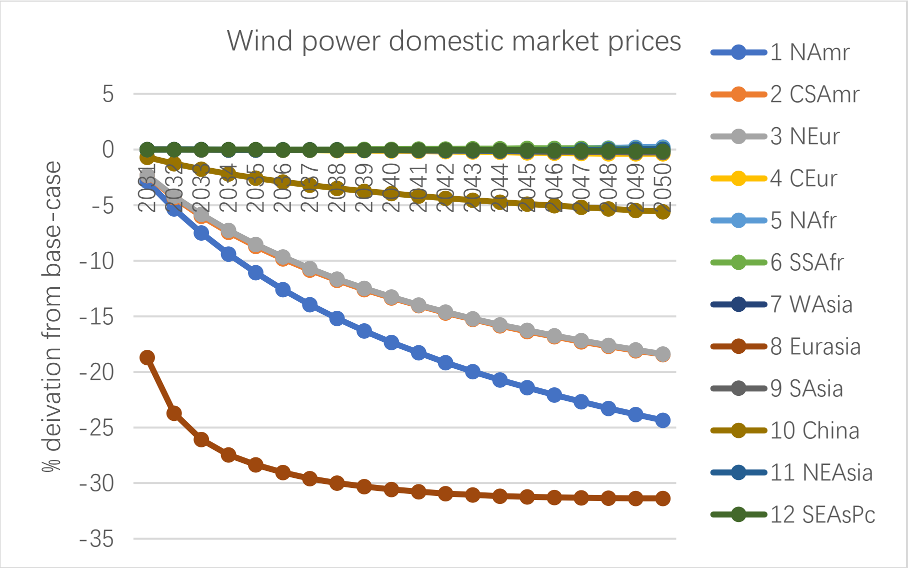

Figure 14: GEI's impact on wind power domestic market prices

Source: authors' modelling results.

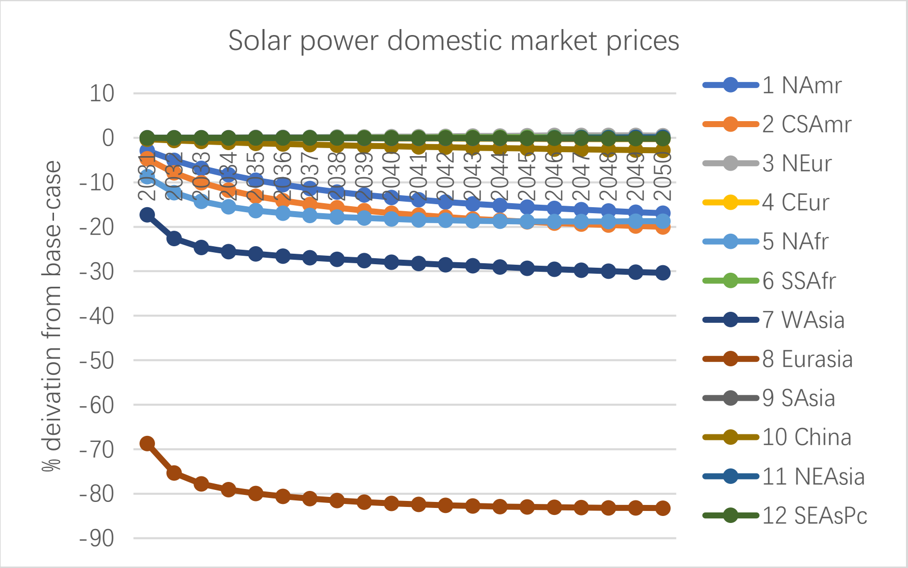

Figure 15: GEI's impact on solar power domestic market prices

Source: authors' modelling results.

Next, we show the results for the other parts of the energy sector (Figure 16). The world's total electricity output, as a result of lower prices, increase by 3.7 per cent from the base-case in 2050. Despite higher world economic growth having a positive output effect on all energy types – including fossil fuel energy, modelling results show that output for coal, oil and gas all fall (by 1.4 per cent, 0.2 per cent and 0.9 per cent, respectively). The fall in fossil fuel power (by 2.5 per cent), an important downstream user, is the reason for the reduction in these three traditional fossil energy types. Overall, total world primary energy, total world power generation and total world renewable power generation increase by 3.2 per cent, 6.5 per cent and 16.3 per cent, respectively.

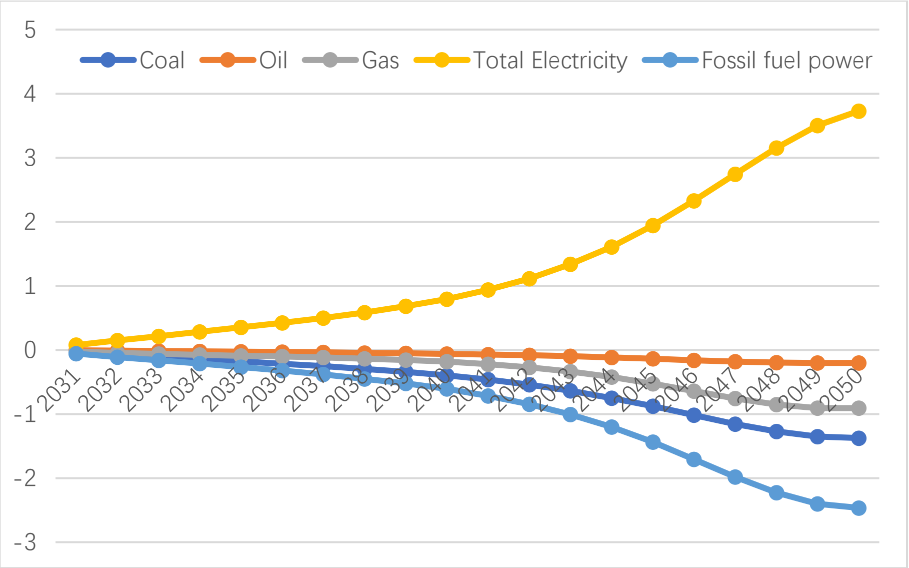

Figure 16: energy sector outputs, world total, by year.

Source: authors' modelling results.

Then, we show the changes in the world energy mix, in 2050 (Table 10). In primary energy, the shares of coal, oil and gas each fall by around 1 percentage point in the GEI scenario, and the share of renewable energy increases by nearly 3 percentage points. In total power generation, the share of fossil fuel power generation falls by 3.8 percentage points and the share of renewable power generation increases by 4.3 percentage points. The shares of hydropower, wind power and solar power in total power generation increases by 1.7, 1.0 and 1.9 percentage points, respectively.

Table 10: GEI's impact on fuel mix

Primary Energy	2050 NPS	2050 GEI	2050 GEI-NPS
Coal	19.7%	18.8%	-0.9%
Oil	25.6%	24.8%	-0.8%
Gas	26.2%	25.2%	-1.0%
Nuclear	5.6%	5.4%	-0.2%
Renewable	22.9%	25.8%	2.9%
Power generation	2050 NPS	2050 GEI	2050 GEI-NPS
Fossil fuel power	45%	41%	-3.8%
Nuclear power	9%	8%	-0.5%
Renewable power	47%	51%	4.3%
hydropower	14.5%	16.1%	1.7%
wind power	13.4%	14.5%	1.0%
solar power	14.5%	16.4%	1.9%
Other renewable power	4.4%	4.1%	-0.3%

Source: authors' modelling results.

As a result of faster renewable energy development and the substitution away from fossil fuels, the world economy becomes cleaner. This, on the one hand, has a negative effect on global CO_2 emissions. On the other hand, as global GDP increases, there is a positive output effect on global CO_2 emissions. Modelling results show that the negative substitution effect dominates the positive output effect and lead to a fall in global CO_2 emissions. Global CO_2 emissions fall by 0.72 per cent in 2050 (Figure 17).

Moreover, global emissions intensity of GDP also falls – by 2050 it is 1.05 per cent lower than it was in the base-case. Hence, modelling results suggest that the backbone network would decouple world CO_2 emissions from world economic growth.

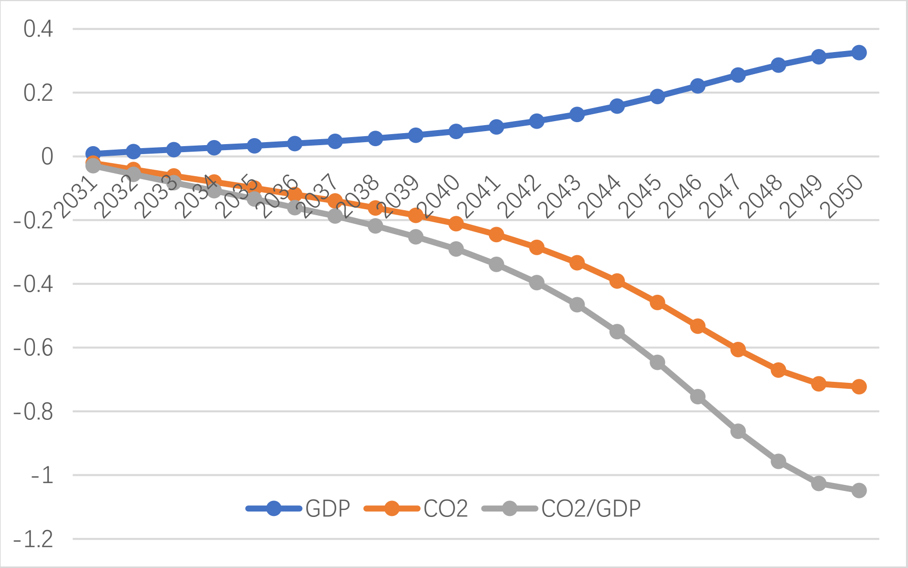

Figure 17: world CO_2 emissions, GDP, and emissions intensity of GDP.

Source: authors' modelling results.

6 Conclusion and policy implications

We analyse the social-economic implications of GEI development – using the specific plans for the GEI backbone network as a case-study. Major modelling efforts include: 1) incorporating the GTAP-power database into the GTAP-E model (configurating to 12 regions and 21 sectors), 2) constructing a new fuel-factor nesting structure, 3) estimating the constant elasticity of substitution (CES) parameters between the fossil fuel power generation and a non-fossil fuel power generation bundle, 4) fitting the model with MONASH-style dynamisms, 5) setting up a base-case (for years between 2011-2050) consistent with the New Policy Scenario in the World Energy Outlook 2018, and 6) designing and modelling the operation of the backbone network (for years between 2030 and 2050).

Modelling results suggest that, by 2050, comparing to the base-case, the backbone network will increase world GDP by 0.33 per cent. All regions represented in our analysis will benefit from connecting to this new network. Productivity improvement constitutes the majority of GDP improvement, followed increase in capital stock, and, in turn, in labour employment. All non-energy sectors will gain from GEI development. All fossil fuel energy sector, however, will be worse off - world outputs in coal, oil and gas will fall by 1.4, 0.2 and 0.9 per cent, respectively. The share of renewable energy in total electricity and total primary energy will increase by 4.3 and 2.9 percentage points, respectively. Global CO_2 emissions will fall by 0.72 per cent. CO_2 emissions intensity of GDP will fall by 1.1 per cent. Although the magnitudes of change are generally small at the global level, the directions of change show that stronger and sustained actions in GEI development are desirable.

Results vary among regions but are generally positive in all regions. North Africa, North Europe and Continental Europe will gain the most in GDP. North Africa benefits the most as it will become a hub of renewable energy production, consumption and trade. Capital growth will contribute more to GDP growth than labour will in North Europe – a GEI-exporting region; labour growth will contribute more to GDP growth than capital will in Continental Europe– a GEI-importing region. Regions that import renewable energy using the GBN will enjoy substantial falls in importing prices, and all regions will enjoy cheaper renewable energy. Although all non-energy sectors will gain on the global scale, some sectors may be worse off in some regions. Some tradables (e.g., Iron and Steel in West Asia) in slower-growing regions might be subject to strong import-substitution effects and see some slightly contraction.

Given the nature of modelling such a complex renewable power trading and production system, this study inevitably leaves areas for improvement. For example, one can always configure the model to finer details – that might allow more variations in results across sectors and regions. One might also expand the modelling years longer, although that might require longer projection phases for many regions and therefore reduces confidence in results. Some areas for improvement are related to the database and theoretical framework. For example, the existing model does not distinguish capital investment by sectors, and the model thus cannot show how much capital will be reallocated from fossil fuel to the renewable power sectors. Some limitations are due to the lack of information regarding GEI development itself. For example, we do not know who are going to finance the investment into the renewable sectors, so we cannot analyse the welfare changes among regions properly. Nevertheless, this study advances from the existing literature by adding much finer detail and much clearer definition for the base-case and the policy case. The current work can undoubtedly be a strong starting point for any future analyses in this field.

References

1. Bandoc, G., et al., *Spatial assessment of wind power potential at global scale. A geographical approach.* Journal of Cleaner Production, 2018. **200**: p. 1065-1086.

2. IEA, World Energy Outlook 2018. 2018.

3. Liu, Z., Chapter 6 - Innovation in Global Energy Interconnection Technologies, in Global Energy Interconnection, Z. Liu, Editor. 2015, Academic Press: Boston. p. 239-272.

4. Liu, Z., Chapter 7 - R&D on Global Energy Interconnection and Practice, in Global Energy Interconnection, Z. Liu, Editor. 2015, Academic Press: Boston. p. 273-342.

5. Bird, L., et al., *Wind and solar energy curtailment: A review of international experience.* Renewable and Sustainable Energy Reviews, 2016. **65**: p. 577-586.

6. den Elzen, M., et al., Are the G20 economies making enough progress to meet their NDC targets? Energy Policy, 2019. **126**: p. 238-250.

7. Pauw, W.P., et al., Beyond headline mitigation numbers: we need more transparent and comparable NDCs to achieve the Paris Agreement on climate change. Climatic Change, 2018. **147**(1): p. 23-29.

8. K.M, B., B. N.V, and A. M.A, *Cooperation of China and Russia in the Framework of the Asian Super Grid: Political and Legal Aspects.* International Journal of Economics & Business Administration (IJEBA), 2019. **VII**(1): p. 215-226.

9. Liu, Z., *Global Energy Internet.* 2015, Beijing: China Electric Power Press.

10. Li, J. and S. Jiang, *Global Energy Interconnection: an effective solution to climate challenges.* Global Energy Interconnection, 2018. **1**(4): p. 406-408.

11. Ongsakul, W., et al., An innovation idea for energy transition towards sustainable and resilient societies: Global energy interconnection. Global Energy Interconnection, 2018. **1**(3): p. 312-318.

12. Brinkerink, M., B.Ó. Gallachóir, and P. Deane, *A comprehensive review on the benefits and challenges of global power grids and intercontinental interconnectors.* Renewable and Sustainable Energy Reviews, 2019. **107**: p. 274-287.

13. Zong, H., *Global Energy Interconnection's social benefits mechanisms and estimation.* Fujian forum Social Science Edition, 2017(2017-8): p. 29-35.

14. Bompard, E., et al., World Decarbonization through Global Electricity Interconnections. Energies, 2018. **11**(7): p. 1746.

15. Jin, Y., et al., Research on the Economic and Social Benefits of the Global Energy Internet Based on the Computable General Equilibrium Model. Smart Grid, 2018. **46**(5): p. 1-8.

16. Wang, M., et al., Global Energy Interconnection: an innovative solution for implementing the Paris Agreement—the significance and pathway of integrating GEI into global climate governance. Global Energy Interconnection, 2018. **1**(4): p. 467-476.

17. Jiang, H., et al., The Comprehensive Benefit Analysis of Regional Energy Interconnection Based on System Dynamics Method. Global Energy Interconnection, 2019. **2**(1).

18. Feng, S., et al., Modelling GEI's social-economic implications - a case of China and its neighbouring countries. Global Energy Interconnection (Chinese), 2019. **2**(4): p. 376-383.

19. GEIDCO, *Global Energy Interconnection - the backbone network.* 2018.

20. Liu, Z., Chapter 4 - Supply and Demand of Global Energy and Electricity, in Global Energy Interconnection, Z. Liu, Editor. 2015, Academic Press: Boston. p. 101-182.

21. Nordhaus, W.D. and Z. Yang, *A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies.* The American Economic Review, 1996. **86**(4): p. 741-765.

22. Feng, S., et al., Towards a national ETS in China: Cap-setting and model mechanisms. Energy Economics, 2018. **73**: p. 43-

52.

23. Bergman, L., Oil Price Increases and Macroeconomic Instability: General Equilibrium Calculations on the Basis of Swedish Data. 1987.

24. Böhringer, C. and A. Löschel, Computable general equilibrium models for sustainability impact assessment: Status quo and prospects. Ecological Economics, 2006. **60**(1): p. 49-64.

25. Liu, Y., et al., Assessment of impacts of Hubei Pilot emission trading schemes in China – A CGE-analysis using TermCO2 model. Applied Energy, 2017. **189**: p. 762-769.

26. Mu, Y., et al., How will sectoral coverage affect the efficiency of an emissions trading system? A CGE-based case study of China. Applied Energy, 2018. **227**: p. 403-414.

27. Jorgenson, D.W., *Econometric general equilibrium modeling.* Journal of Policy Modeling, 2016. **38**(3): p. 436-447.

28. Antimiani, A., V. Costantini, and E. Paglialunga, The sensitivity of climate-economy CGE models to energy-related elasticity parameters: Implications for climate policy design. Economic Modelling, 2015. **51**: p. 38-52.

29. Burniaux, J.-M. and T. Truong, *GTAP-E: An Energy-Environmental Version of the GTAP Model*. 2002, Global Trade Analysis Project (GTAP): Department of Agricultural Economics, Purdue University, West Lafayette, IN.

30. Uzawa, H., *Production Functions with Constant Elasticities of Substitution.* Review of Economic Studies, 1962. **29**(4): p. 291.

31. Feng, S. and K. Zhang, *2018 fuel-factor nesting structures in CGE models of China.* Energy Economics, 2018. **75**: p. 274-284.

32. Stern and I. David, *INTERFUEL SUBSTITUTION: A META-ANALYSIS.* Journal of Economic Surveys, 2012. **26**(2): p. 307-331.

33. The Wold Bank, World Development Indicators.

34. Bank, T.W., World Development Indicators.

35. Statistics, C.N.B.o., *Annual statistics database*.

36. Fouré, J., A. Bénassy-Quéré, and L. Fontagné, *Modelling the world economy at the 2050 horizon.* Economics of Transition and Institutional Change, 2013. **21**(4): p. 617-654.

37. Guillemette, Y. and D. Turner, The Long View: Scenarios for the World Economy to 2060. 2018.

38. Li, J., F. Song, and X. Yu, *Research on Global Energy Interconnection backbone grid planning.* Global Energy Interconnection, 2018. **1**(5): p. 527-536.

Appendix 1: Mapping from original countries/regions in GTAP-power database to new 12 regions

New Regions	Original countries/regions
NAmr	Canada、United States of America、Mexico、Rest of North America
CSAmr	Argentina、Bolivia、Brazil、Chile、Colombia、Ecuador、Paraguay、Peru、Uruguay、Venezuela、Rest of South America、Costa Rica、Guatemala、Honduras、Nicaragua、Panama、El Salvador、Rest of Central America、Dominican Republic、Jamaica、Puerto Rico、Trinidad and Tobago、Caribbean
NEur	Denmark、Finland、Ireland、Sweden、United Kingdom、Norway、Rest of EFTA
CEur	Austria、Belgium、Cyprus、Czech Republic、France、Germany、Greece、Hungary、Italy、Luxembourg、Malta、Netherlands、Poland、Portugal、Slovakia、Slovenia、Spain、Switzerland、Albania、Bulgaria、Croatia、Romania、Rest of Europe
SSAfr	Benin、Burkina Faso、Cameroon、Cote d'Ivoire、Ghana、Guinea、Nigeria、Senegal、Togo、Rest of Western Africa、Central Africa、South Central Africa、Ethiopia、Kenya、Madagascar、Malawi、Mauritius、Mozambique、Rwanda、Tanzania、Uganda、Zambia、Zimbabwe、Rest of Eastern Africa、Botswana、Namibia、South Africa、Rest of South African Customs
NAfr	Egypt、Morocco、Tunisia、Rest of North Africa
WAsia	Baharain、Iran Islamic Republic of、Israel、Jordan、Kuwait、Oman、Qatar、Saudi Arabia、Turkey、United Arab Emirates、Rest of Western Asia
Eurasia	Estonia、Latvia、Lithuania、Belarus、Russian Federation、Ukraine、Rest of、Eastern Europe、Kazakhstan、Kyrgyztan、Rest of Former Soviet Union、Armenia、Azerbaijan、Georgia
SAsia	Bangladesh、India、Nepal、Pakistan、Sri Lanka、Rest of South Asia
China	China
NEAsia	Japan、Korea、Mongolia
SEAsPc	Australia、New Zealand、Rest of Oceania、Brunei Darusslam、Cambodia、Indonesia、Lao People's Democratic Republ、Malaysia、Philippines、Singapore、Thailand、Viet Nam、Rest of Southeast Asia、Rest of the World

Source: GTAP-power database and authors' compilation

Appendix 2: Mappings from original sectors GTAP-power database to 21 new sectors.

Agriculture sectors		Energy and mineral related sectors		Other manufacturing sectors		Power sectors		Services sectors	
New	Old	New	Old	New	Old	New	Old	New	Old
Agri	pdr	Coal	coa	OMF	cmt	Tnd	TnD	SER	gdt
Agri	wht	Oil	oil	OMF	omt	OtherP	NuclearBL	SER	wtr
Agri	gro	Gas	gas	OMF	vol	FFP	CoalBL	cns	cns
Agri	v_f	OMN	omn	OMF	mil	FFP	GasBL	trd	trd
Agri	osd	Oil_pcts	p_c	OMF	pcr	WindP	WindBL	tsp	otp
Agri	c_b	CRP	crp	OMF	sgr	HydroP	HydroBL	tsp	wtp
Agri	pfb	nmm	nmm	OMF	ofd	FFP	OilBL	tsp	atp
Agri	ocr	I_S	i_s	OMF	b_t	OtherP	OtherBL	SER	cmn
Agri	ctl	mtp	nfm	OMF	tex	FFP	GasP	SER	ofi
Agri	oap	mtp	fmp	OMF	wap	HydroP	HydroP	SER	isr
Agri	rmk			OMF	lea	FFP	OilP	SER	obs
Agri	wol			OMF	lum	SolarP	SolarP	SER	ros
Agri	frs			OMF	ppp			SER	osg
Agri	fsh			OMF	mvh			SER	dwe
				OMF	otn				
				OMF	ele				
				OMF	ome				
				OMF	omf				

Source: GTAP-power database and authors' compilation

Appendix 3: elasticity of substitution values

	σ_D	σ_M	σ_{VAE}	σ_E	σ_{NCOL}
1 Agri	2.39	4.87	0.26	1	2
2 Coal	3.05	6.1#	0.2	0	0
3 Oil	5.2	10.4	0.2	0	0
4 Gas	17.2	34.4	0.84	0	0
5 OMN	0.9	1.8	0.2	1	2
6 Oil_pcts	2.1	4.2	1.26	0	0
7 I_S	2.95	5.9	1.26	1	2
8 mtp	3.93	8.07	1.26	1	2
9 CRP	3.3	6.6	1.26	1	2
10 nmm	2.9	5.8	1.26	1	2
11 OMF	3.43	7.29	1.26	1	2
12 Tnd	2.8	5.6	0.5	0	0
13 FFP	2.8	5.6	0.5	0	0
14 HydroP	2.8	5.6	0.5	0	0
15 WindP	2.8	5.6	0.5	0	0
16 SolarP	2.8	5.6	0.5	0	0
17 OtherP	2.8	5.6	0.5	0	0
18 cns	1.9	3.8	1.4	1	2
19 trd	1.9	3.8	1.6	1	2
20 tsp	1.9	3.8	0.5	1	2
21 SER	1.91	3.83	1.26	1	2

Source: GTAP-E, authors' compilation

Appendix 4: method for estimating CES between fossil fuel power and non-fossil fuel power generation

We estimate σ_{GEN} for six large regions of the world, namely Asia and Pacific, North America, Central and South America, Europe, Africa and Eurasia[23]. We use IEA (2018) power generation data (by fuel) for all countries between 2000 and 2015[2]. As Feng and Zhang 2018 argued, parameters need to be estimated under compatible theoretical framework as the ones used the CGE models [31]. Hence our CES production function is specified in Eq. (1), which is the same as the ones used in the underlying model.

$$\ln Elec_{t,r} = \beta_{0,r} + \beta_{1,r} \ln \mathrm{FFP}_{t,r} + \beta_{2,r} \ln NFP_{t,r} + 0.5\beta_{11,r}\left(\ln \mathrm{FFP}_{t,r}\right)^2 + 0.5\beta_{22,r}\left(\ln NFP_{t,r}\right)^2 + \beta_{12,r}\left(\ln \mathrm{FFP}_{t,r}\right)\left(\ln NFP_{t,r}\right) \qquad \text{Eq. (1)}$$

$$\sigma_{GEN,r} = \frac{1}{1+\rho_r} = \frac{1}{1+\dfrac{\beta_{12,,r}(\beta_{1,r}+\beta_{2,r})}{\beta_{1,r}\beta_{2,r}}} \qquad \text{Eq. (2)}$$

In Eq. (1), Elec stands for the quantity of total power output. FFP and NFP stand for total fossil fuel power output and total non-fossil fuel power output, respectively. Subscripts t and r stand for time and region, respectively. By estimating β_1, β_2 and β_{12}, and using Eq.(2), we obtain the CES parameters for these seven regions. We then map these 6 regions to the 12 regions represented in our database (Table 3), and calibrate the model accordingly. Estimation results suggest that σ_{GEN} generally lie between 1.26 and 1.69. These results conform with the general finding that inter-fuel substitution values are typically between zero and two ([32]).

---

[23] We choose to estimate elasticities for 6 regions instead of the 12 in the model because, under the 12-regions classification, sometimes a region may only have a few countries (for example, North Africa, North Europe), and sometimes the countries in the same region may only have renewable energy data for a small number of years (for example, Sub-Saharan African countries). Hence, we use 6 large regions to overcome these problems.