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Report

Global Energy Interconnection: A scenario analysis based on the MESSAGEix-GLOBIOM Model

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Abstract

The concept of Global Energy Interconnection (GEI) proposed by Global Energy Interconnection Development and Cooperation Organization (GEIDCO) integrates smart grids, ultrahigh voltage (UHV) transmission and renewable energy access (solar, wind and hydro). Ultrahigh Voltage (UHV) lines could transmit renewable power from one world region to another with lower losses than current high voltage systems. In December 2019, the Global Energy Interconnection Development and Cooperation Organization (GEIDCO), International Institute for Applied Systems Analysis (IIASA) and World Meteorological Organization (WMO) published a report titled "Research Report on Global Energy Interconnection for Address Climate Change". In that report, two scenarios for Global Energy Interconnection are presented, consistent with limiting climate change to 1.5 and 2 degrees. These scenarios were limited to the GEI interconnections as concretely proposed by GEIDCO. This report provides an uncertainty analysis for the GEI scenarios, especially focusing on uncapping the GEI-interconnections to explore the potential for electricity transmission between world regions.

In order to further investigate the benefits of renewable electricity trade via UHV transmission lines, in this study we designed two new scenarios with uncapped transmission capacity of UHV lines by using IIASA's integrated assessment modeling (IAM) tool, the MESSAGEix-GLOBIOM model. Based on these scenarios, we find several insights: first, there exits more needs of electricity trade between the model regions than what the selected UHV projects can offer. This implies that new UHV transmission projects might need to be investigated. Second, renewable electricity trade by UHV transmission lines could facilitate higher production of renewable electricity. The more trade is realized, the more renewable electricity is produced. In addition, the renewable electricity trade could help the reduction of CO_2 emissions by boosting the global consumption of renewable electricity.

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1. Background

1.1 Concept of Global Energy Interconnection

The concept of Global Energy Interconnection (GEI) proposed by Global Energy Interconnection Development and Cooperation Organization (GEIDCO) includes three main components, namely smart grids, ultrahigh voltage (UHV) transmission and renewable energy access (solar, wind and hydro) (GEIDCO, IIASA and WMO, 2019). Smart grids are capable to integrate large-scale non-dispatchable renewable energy sources (RES), like solar and wind, and provide interactive service. UHV transmission lines (≥1000 kV AC or ≥±800 kV DC) can transmit power from remote areas to load canters over long distance (e.g., a few thousand kilometers) with low losses. With the commercialization of UHV transmission technology, the renewable energy previously consumed locally could be utilized by remote load centers. In summary, the GEI is to build a global platform for large-scale access and use of renewable energy and contribute to global energy transition required by climate targets of Paris Agreements – controlling the global temperature increase on average within 2℃ or even 1.5℃ by the end of the century.

1.2 Previous work

In December 2019, GEIDCO, IIASA and WMO published a report titled "Research Report on Global Energy Interconnection for Address Climate Change" (ISBN 978-7-5198-3222-3) (called GEIDCO-IIASA-WMO 2019 Report thereafter) (GEIDCO, IIASA and WMO, 2019). In this report, the contribution of two GEI scenarios on climate change mitigation are explored by using the integrated assessment modeling (IAM) tool, MESSAGEix-GLOBIOM. Two GEI scenarios, 2°C and 1.5℃, are presented in the GEIDCO-IIASA-WMO 2019 report, who were based on specific DC-type UHV projects planned by the GEIDCO globally, and these DC UHV projects are designed to transmit renewable power from one world region to another. Key characteristics of these two scenarios are presented below.

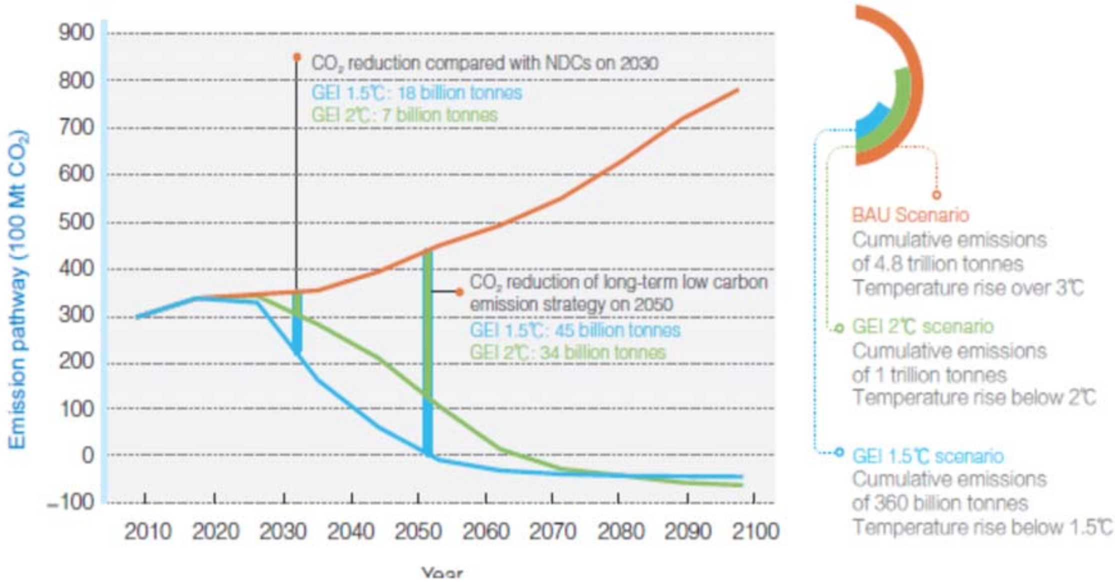


Figure 1: Mitigation pathways of GEI scenarios (MESSAGEix-GLOBIOM results)

The GEI scenarios are characterized by a high electrification rate, a high proportion of renewable energy, large-scale development of renewable energy, reliable system operation that advances the global energy system transition and provide systematic solution addressing climate change. The GEI scenarios indicate emission pathways of achieving 2°C (above 67% probability) and 1.5°C goals in the Paris Agreement (see Figure 1).

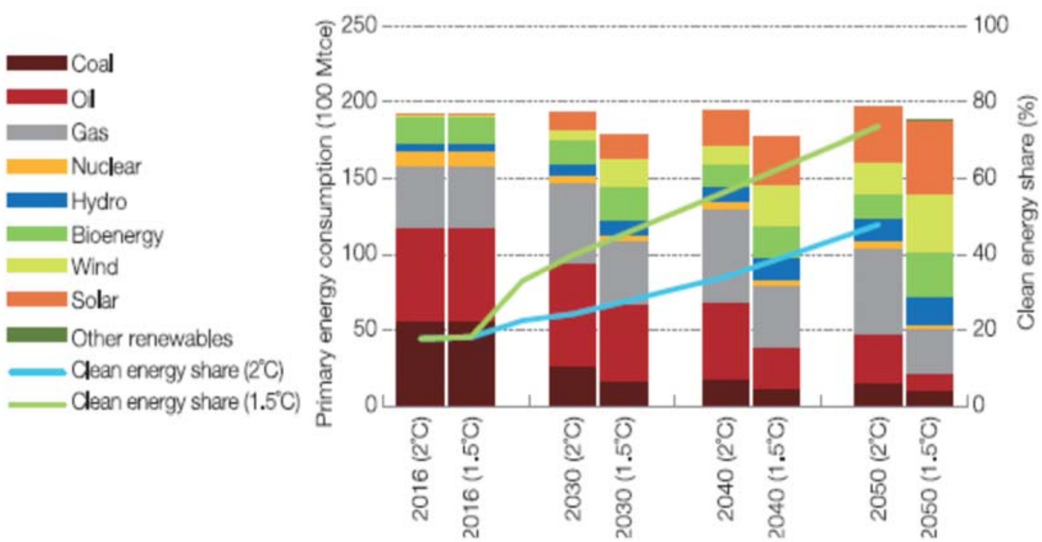


Figure 2: Total primary energy consumption and structure (MESSAGEix-GLOBIOM results)

For the GEI 2℃ scenario, the total global primary fossil energy consumption will reach the peak around 2025, and decline year by year. Specifically, total coal consumption drops sharply after reaching the peak around 2025, and for oil around 2030. The total natural gas consumption remains basically unchanged after reaching the peak around 2040. The scale of renewable energy exploitation expands year by year. Before 2050, renewable energy will hold a higher share in primary energy than fossil energy, reaching 50% in primary energy (the physical energy content method), which is twice the proportion of 2018 (see Figure 2).

In the GEI 1.5°C scenario, actions are taken to accelerate the in-depth clean replacement, mount the efforts in exploiting hydro, wind, photovoltaic and other renewable energy, and promote global consumption of clean electricity. Renewable energy quickly becomes the dominant energy source. The peak consumption of coal, oil and gas is brought forward in comparison to the 2°C scenarios and the decline rate is faster after reaching the peak. By 2050, the total fossil energy consumption will be 5 Gt standard coal equivalent, by which time renewable energy, overtaking fossil energy in 2030 as the dominant source, will take up 74% of primary energy consumption.

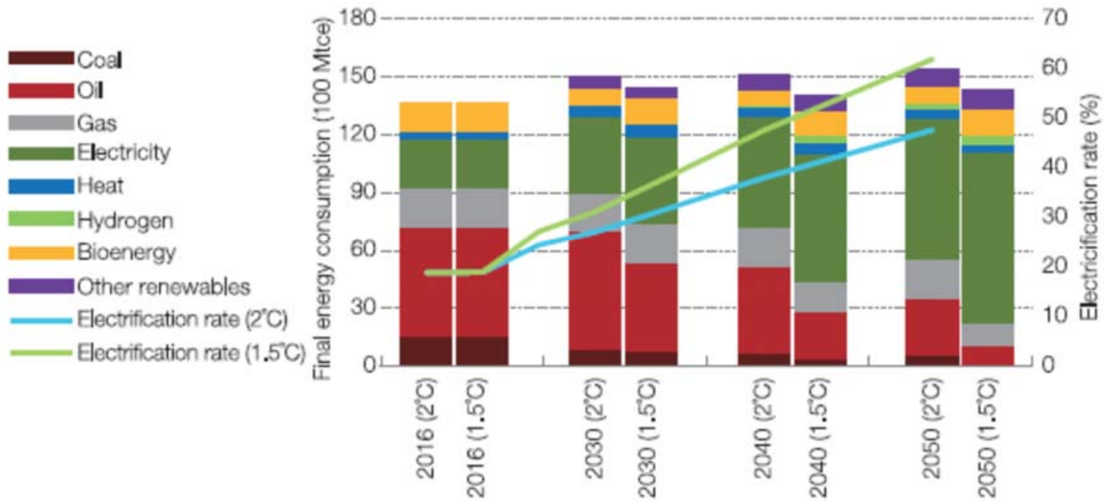


Figure 3: Total end-use energy consumption and structure (MESSAGEix-GLOBIOM results)

For the GEI 2°C scenario, total coal consumption drops sharply after peaking around 2025. The total natural gas consumption will remain basically unchanged after 2040. Oil use will remain basically unchanged after reaching the peak around 2020-2035. The total global electricity consumption grows year by year. By 2050, the proportion of electricity in end-use energy consumption increases to around 50% in 2050 (see Figure 3).

For the GEI 1.5°C scenario, the total end-use energy consumption will hit 14.3 Gt standard coal equivalent by 2050. Final fossil energy consumption continues to decline through speeding up the in-depth electricity replacement, and promoting global consumption of clean electricity. By 2050, fossil energy will take up 15% in end-use energy consumption, and global electricity consumption will increase to 70 PWh, accounting for around 65% in end-use energy (see Figure 3).

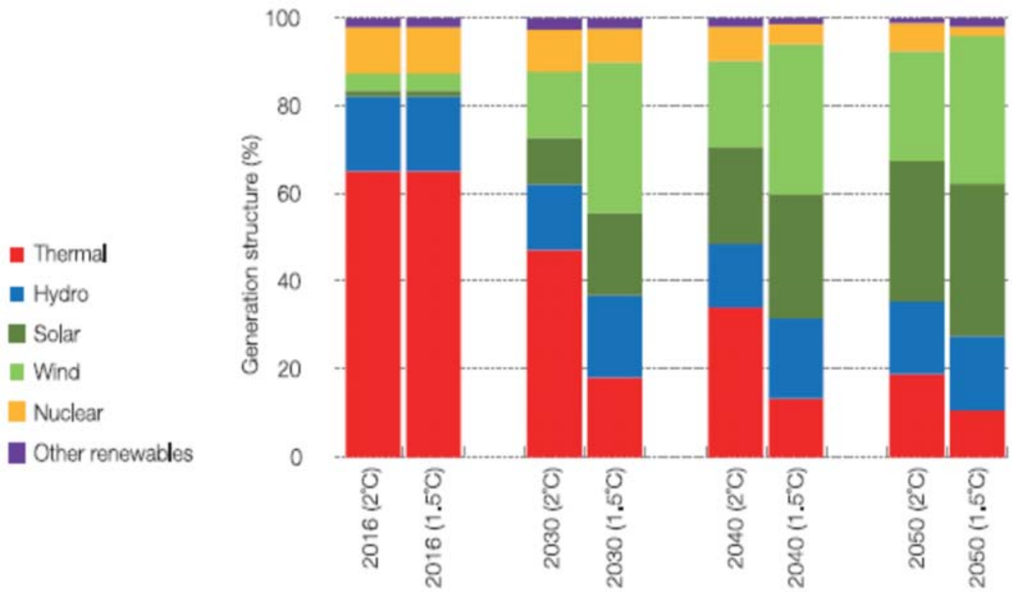


Figure 4: Global power generation structure (MESSAGEix-GLOBIOM results)

For the GEI 2°C scenario, in 2050 the power generated with renewable energy will exceed that with fossil energy from all standards, taking up more than 80% of the total power generation, of which wind power, hydropower and solar power account for 23%, 15% and 32% respectively (see Figure 4).

For the GEI 1.5°C scenario, in 2050, the renewable energy power generation will take up more than 90% of the total power generation, of which wind power and solar power together will account for over 68% (see Figure 4).

However, the UHV transmission lines investigated in these two scenarios are with capped transmission capacity, and therefore they might not be able to reveal the possible or optimal renewable power transmission potentials between the world regions.

1.3 Focus and structure of this report

As a follow-up study of the GEIDCO-IIASA-WMO 2019 Report, based on the previous GEI 2°C and 1.5°C scenarios we designed two new scenarios with uncapped transmission capacity to explore if there are more renewable power trade between world regions. This report is to present the findings from these "uncapped transmission capacity" scenarios.

In Section 2, the MESSAGEix-GLOBIOM model is introduced first and then we explain how we model the renewable electricity trade among world regions in the MESSAGEix-GLOBIOM model. The new scenario design is presented in Section 3 and modeling results are shown in Section 4. Section 5 summarizes the main findings from the new designed scenarios.

2. Methods

2.1 Introduction to the MESSAGEix-GLOBIOM model

MESSAGEix-GLOBIOM model is developed by the Energy, Climate and Environment (ECE) Program of International Institute for Applied Systems Analysis (IIASA). The model is a global energy-climate-economy system least-cost optimization model that can be used for medium-term to long-term energy system planning, energy policy analysis, and scenario development (Huppmann et al., 2019; Fricko et al., 2017). The code of the MESSAGEix-GLOBIOM model is open-source and available at: https://github.com/iiasa/message_ix; the model documentation is available at: https://docs.messageix.org/projects/global/en/latest/.

The model itself is a linked integrated assessment model (IAM) of MESSAGEix (energy systems model) and GLOBIOM (land use model) by including an emulator of GLOBIOM model into the MESSAGEix model. A typical model application is constructed by specifying performance characteristics of a set of technologies and defining a Reference Energy System (RES) that includes all the possible energy chains that MESSAGEix can access. Over the course of a model run, MESSAGEix determines how much of the available technologies and resources are actually used to satisfy a particular end-use demand, subject to various constraints (both technological and policy), while minimizing total discounted energy system costs over the entire model time horizon (from the first modeling year to 2110). The MESSAGEix-GLOBIOM model runs for every 5 years before 2060 and every 10 years after 2060 till 2110. It does this based on a linear programming, optimization solution algorithm.

The representation of the energy system in the MESSAGEix-GLOBIOM model includes vintaging of the long-lived energy infrastructure, which allows for consideration of the timing of technology diffusion and substitution, the inertia of the system for replacing existing facilities with new generation systems, and clustering effects (technological interdependence). Important inputs for MESSAGEix are technology costs and technology performance parameters (e.g., efficiencies, investment, fixed and variable O&M costs and lifetime). In addition to the energy system, the MESSAGEix model also tracks a full basket of greenhouse gases and air pollutants from both the energy and non-energy sectors.

There are 11 world regions in the MESSAGEix-GLOBIOM model (see Figure 5), including Sub-Saharan Africa (AFR), Centrally Planned Asia and China (CPA), Eastern Europe (EEU), Former Soviet Union (SU), Latin America & the Caribbean (LAM), Middle East & North Africa (MEA), North America (NAM), Pacific OECD (PAO), Other Pacific Asia (PAS), South Asia (SAS) and Western Europe (WEU).

Figure 5: Regions of the MESSAGEix-GLOBIOM model

2.2 Modeling renewable electricity trade in the MESSAGEix-GLOBIOM model

In the original MESSAGEix-GLOBIOM model, there is no electricity trade between model regions. In order to conduct the GEI studies, we added the feature of renewable electricity trade into the model based on the detailed data of UHV transmission lines across the MESSAGEix model world regions.

The UHV transmission projects are planned by GEIDCO. Among the GEIDCO planned UHV projects, we selected the UHV projects which fit in the regional division of the MESSAGEix-GLOBIOM model. The selected UHV projects are all DC type. We then parameterized the selected DC UHV projects, including sending and receiving locations, transmission capacity, capital cost, O&M cost, lifetime, transmission loss rate (depending on project's transmission distance), construction plan (first year in operation and rebuilding plan), and sources of renewable energy to be transmitted and their generation capacity potentials.

In details, each of the UHV transmission lines is added as an interconnection technology located in the exporting region. From an exporting region there are often several UHV lines to different destinations, thus the naming of these UHV interconnection technologies is designed to follow the rule of "elec_uhv_exp" plus "receiving region". For example, "elec_uhv_exp_sas" stands for the interconnection technology from a certain region (i.e., CPA, FSU, MEA or PAS in this study) to the SAS region.

When adding a new technology to the MESSAGEix-GLOBIOM model, one needs to define several parameters of the technology, usually including, at least, "input", "output", "technical_lifetime" (lifetime), "inv_cost" (capital cost), "fix_cost" (fixed O&M cost), "var_cost" (variable cost), etc. The "input" and "output" are used to define the energy efficiency and vintage possibility of the technology. Such data are provided by the GEIDCO based on their electricity sector modeling results.

Because for some regions, like the SAS and WEU in this research, the imported electricity could come from several exporting regions according GEIDCO's grid interconnection scheme, we introduced a second technology called "elec_uhv_imp", which is designed only for accounting purpose. First, the exporting interconnection technologies (e.g., "elec_uhv_exp_sas") will send the traded electricity to a global trading pool with a label of the final destination of "SAS". The destination label is realized by setting specific "level" in the model (e.g., the level is set as "elec_sas"); then the accounting technology "elec_uhv_imp" located in the SAS region will search all the electricity in the global trading pool to find all the electricity labeled with "elec_sas" and sum them up to calculate the total imported electricity to the SAS region.

As the UHV transmission lines in this study are direct current (DC) type interconnections. They are designed to transmit electricity from certain renewable energy power generation bases in an exporting region to the destination region. The foreseen renewable energy power base consists of three main technology types: PV, wind onshore and hydro.

In the MESSAGEix-GLOBIOM model, the power generation technology from PV, wind onshore and hydro are called "solar_pv_ppl", "wind_pv_ppl" and "hydro" respectively. As the renewable energy plants proposed by the GEIDCO for generating electricity to be transmitted by the UHV lines are usually in very large scales, and are not connected to the internal network in a region. Therefore, they could have different capital and O&M costs than the regular technology in the region. Accordingly, we added a new set of such power generation technologies to the model, namely "solar_pv_ppl_gei", "wind_pv_ppl_gei" and "hydro_gei".

In this sense, in this study there are two sets of renewable energy generating technologies in each region: a domestic set and an interconnection set. The domestic set is used to generate power for local use, while interconnection set is used for generating power for trading needs across regions. Both these sets of renewable power generation technology are allowed to use the full renewable resource potential of the region, therefore they will compete with each other for renewable resources that can be exploited for power generation.

In the MESSAGEix-GLOBIOM model, there are eight grades of solar and four grades of wind resource (depending on the regions, some regions may have fewer grades). The newly added interconnection set of renewable power technologies (i.e., solar_pv_ppl_gei" and "wind_pv_ppl_gei") is linked to all the grades of solar and wind resources by setting up the "relation_activity" in the model. The parameter of "relation_activity" in the MESSAGE model is used mainly for establishing required constraints for the optimization.

3. Scenario Design

In our GEI scenarios, there are four components, energy demand level, interconnection type, renewable cost and carbon tax. For the components of interconnection type and carbon tax, we also designed a few variants. Table 1 summarizes the variants of these components.

Table 1: Details of scenario design

Variant Types	Variants	Description
Energy demand level	SSP2	SSP2 energy demand
Interconnection type	noint	without grid interconnection
	int	with capped UHV transmission capacity based on GEIDCO plans
	openres	with uncapped UHV transmission capacity
Renewable cost	lc	low cost; using the PV cost from the LED scenario, hydro cost from SSP3 and the cost of all the other electricity generation technologies from SSP1
Carbon tax	15	15 US$2010/t$CO_2$ starting from 2030 and increasing at a rate of 5% per year; this carbon tax level could result in around 1,350-1,400 Gt cumulative carbon emissions during 2020-2100 (similar with 2℃ carbon budget)
	50	50 US$2010/t$CO_2$ starting from 2030 and increasing at a rate of 5% per year; this carbon tax level could result in a cumulative carbon budget during 2020-2100 around 450-480 Gt (similar with 1.5℃ budget)

Note: for the renewable cost, the references are LED (Grubler et al., 2018), SSP1 and SSP3 (van Vuuren et al., 2017; Fujimori et al., 2017; Riahi et al., 2017).

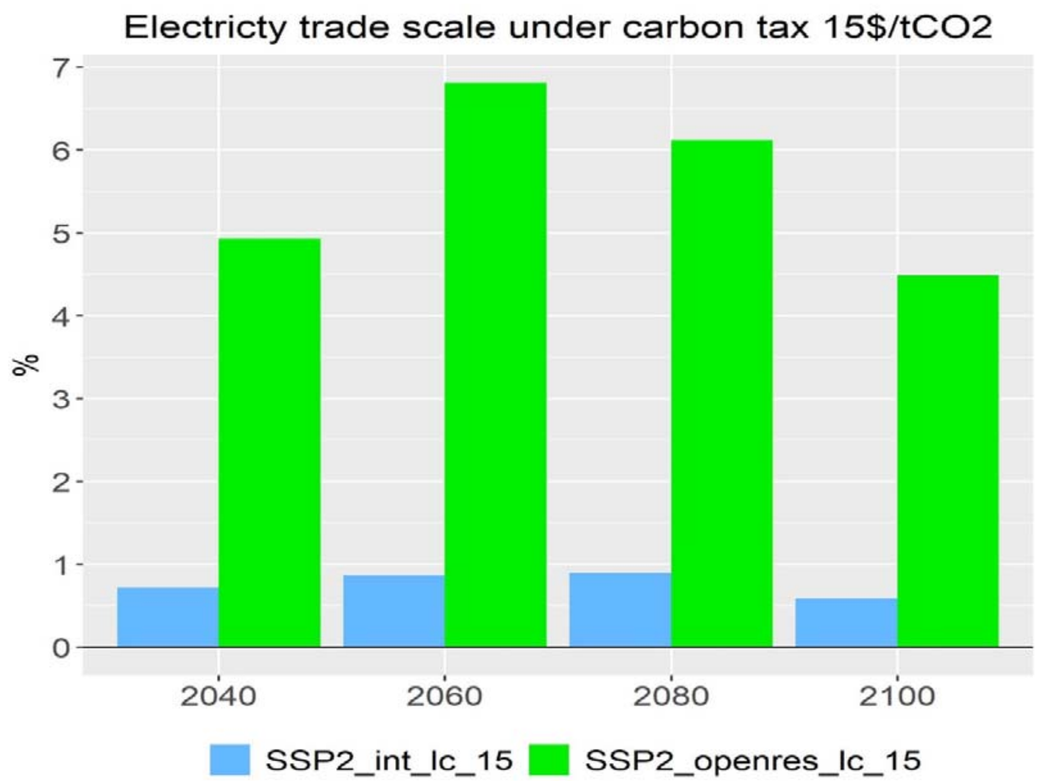
The scenario naming is based on the scenario variants, for example, a scenario called "SSP2_openres_lc_50" means using the SSP2 demand, uncapped UHV transmission capacity, low cost setup for the renewable power generation technologies and the 50 US$/t$CO_2$ of carbon tax.

In this study, we particularly focus on the analysis of the two uncapped scenarios "SSP2_openres_lc_15" and "SSP2_openres_lc_50" and the comparison between them and the capped scenarios "SSP2_int_lc_15" and "SSP2_int_lc_50".

4. Modeling Results

4.1 Renewable electricity trade scale

Compared to the two capped "int" scenario, the electricity trade under the two uncapped "openres" scenarios increases significantly (see Figure 6). With the carbon tax 15$/t$CO_2$, the electricity trade under the capped "int" cases is about 0.5-1.4% (in different years) of total electricity generation, while it becomes 4.4-6.4% under the uncapped "openres" case. A similar trend is also found with the carbon tax 50$/t$CO_2$. This implies that there is probably more needs of renewable electricity trade between world regions than what the selected UHV projects can transmit.



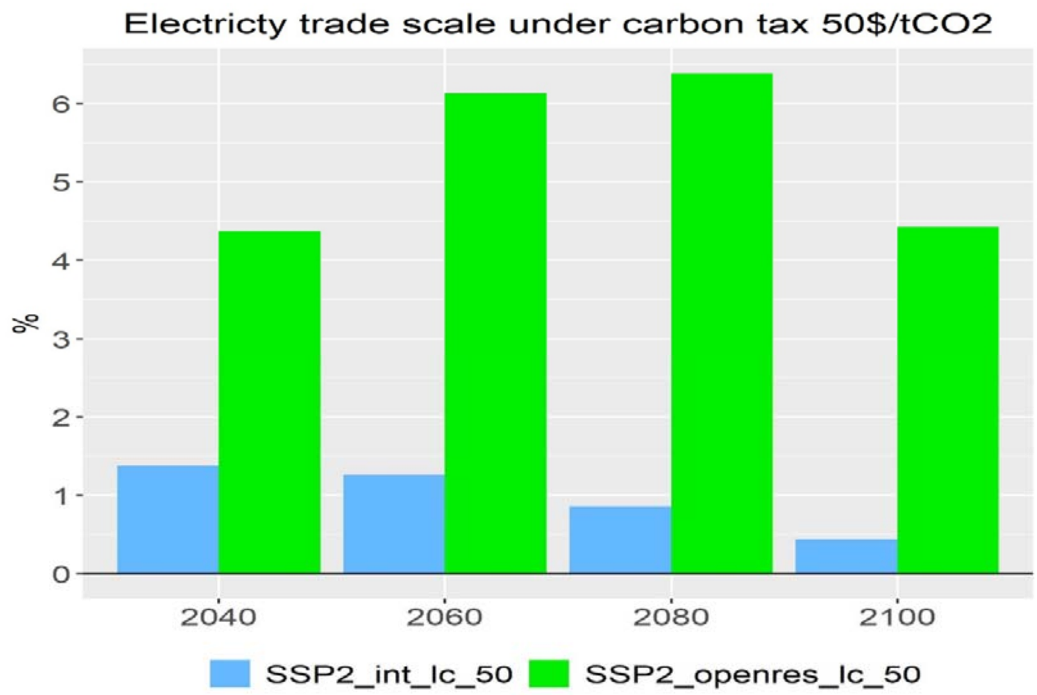
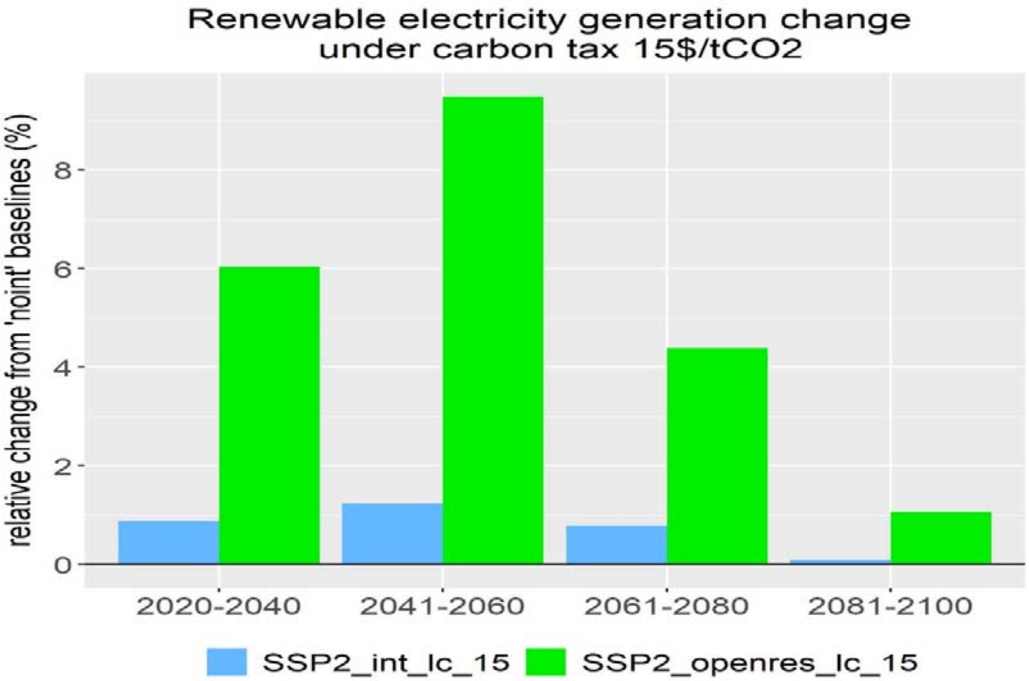


Figure 6: Electricity trade scale comparison between the capped "int" and uncapped "openres" scenarios

4.2 Renewable electricity generation

Renewable electricity generation (i.e., solar, wind and hydro) is also much higher in the uncapped "openres" cases (see Figure 7). With the carbon tax 50$/t$CO_2$, the renewable electricity generation in the uncapped "openres' case increases by about 3.4-8.2% (in different time periods) from the baseline case of without grid interconnection "noint", while such an increase is only about 0.3-1.3% in the capped "int" case. It shows the same trends with the carbon tax 15$/t$CO_2$.



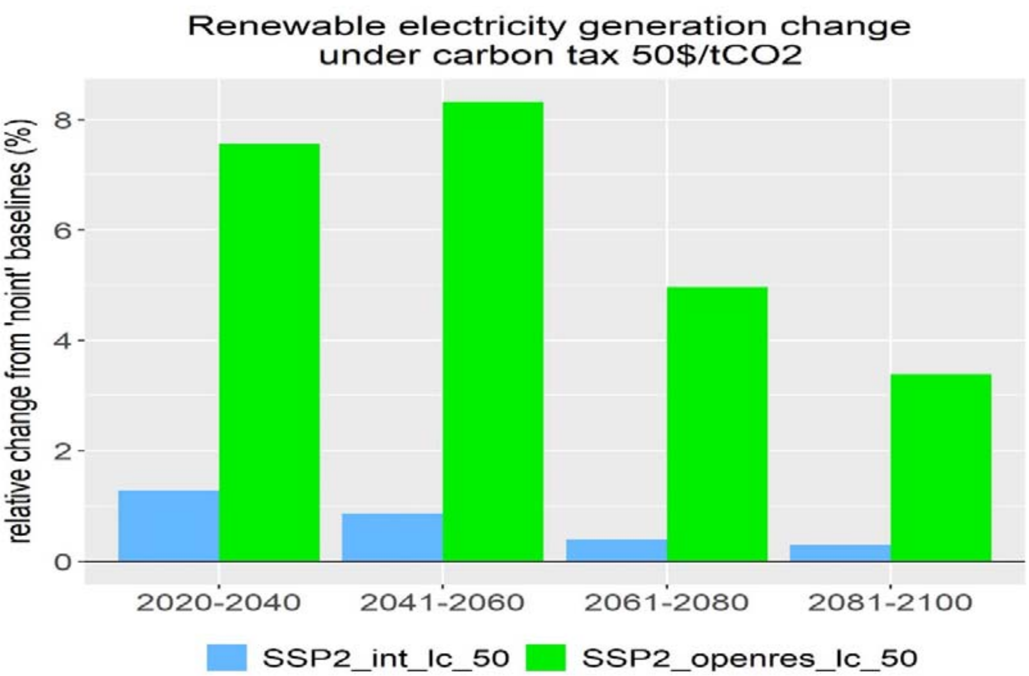
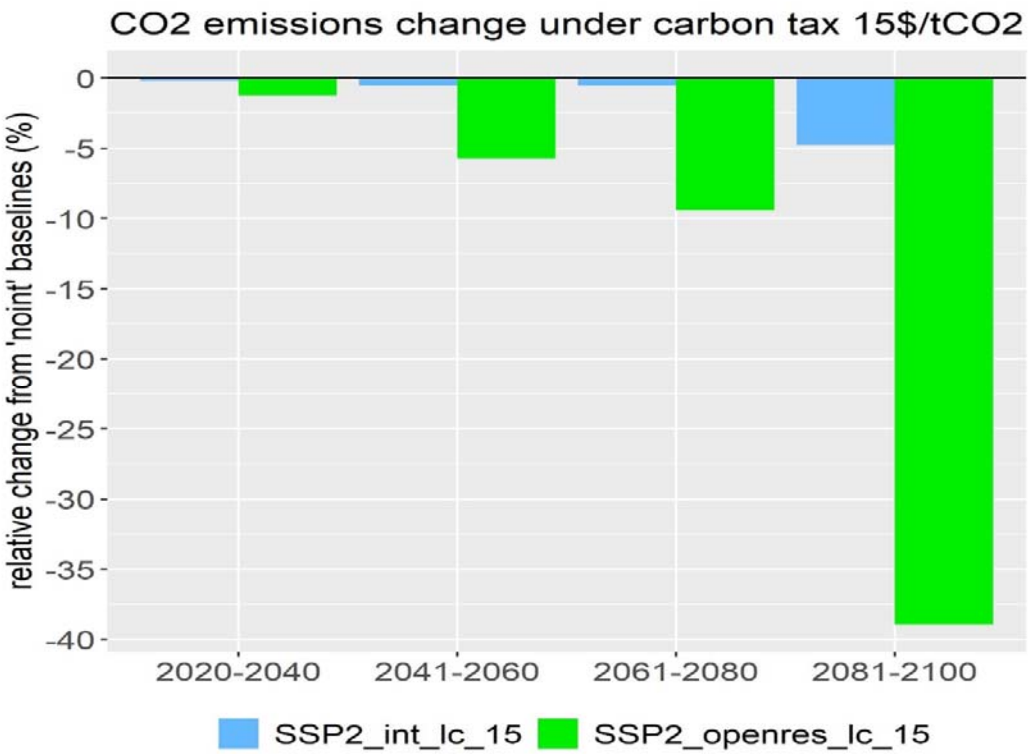


Figure 7: Renewable electricity generation comparison between the capped "int" and uncapped "openres" scenarios

4.3 CO_2 emissions

The consumption of more renewable electricity under the uncapped "openres" cases leads to less CO_2 emissions (see Figure 8). With the carbon tax 50$/t$CO_2$, the CO_2 emissions in the uncapped "openres" case is reduced by about 30% during 2060-2080 from the "noint" baseline, while the reduction is only about 2.5% in the capped "int" case. The large reduction happens in middle of century is because the selected UHV projects will be constructed partly in 2030 and in 2050. A similar trend is shown with the carbon tax 15$/t$CO_2$.



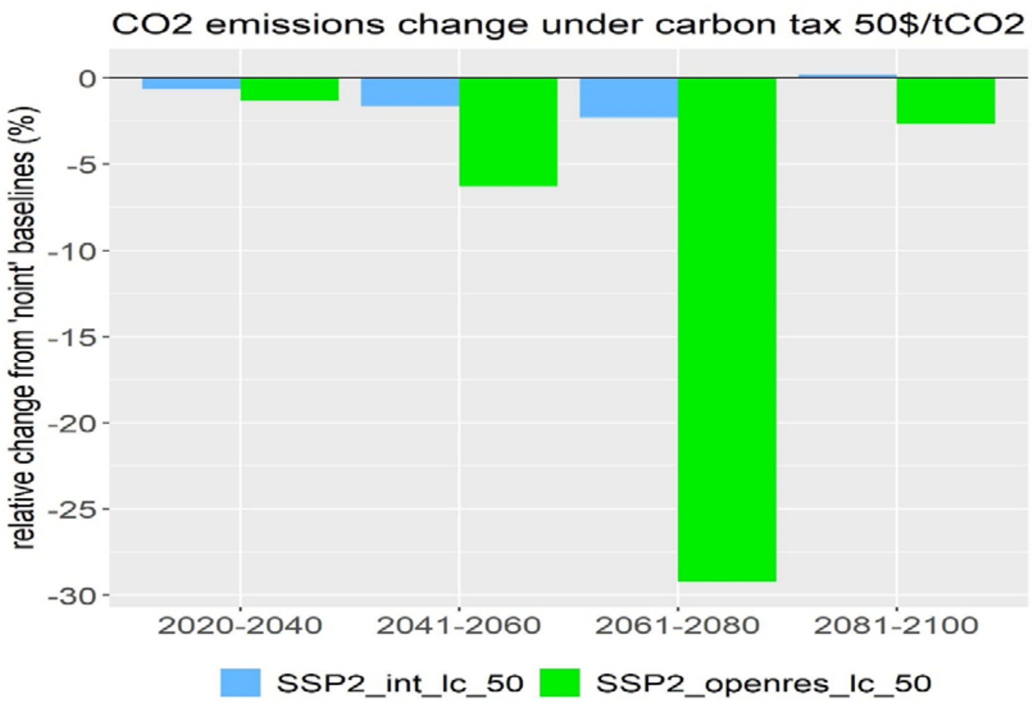


Figure 8: CO_2 emissions comparison between the capped "int" and uncapped "openres" scenarios

5. Main Findings

Several findings are observed from the above modeling results. First, we find a higher potential of electricity trade between the model regions than the currently planned UHV projects can offer. This implies that there is potential for new UHV transmission projects to be investigated. Second, renewable electricity trade by UHV transmission lines could facilitate higher production of renewable electricity. The more trade capacity is realized, the more renewable electricity is produced. Last, the renewable electricity trade could help the reduction of CO_2 emissions by boosting the worldwide consumption of renewable electricity consumption.

In summary, this study uses the well-established MESSAGEix-GLOBIOM model and explores the benefits of uncapped renewable electricity trade by UHV lines from a previous work done in the GEIDCO-IIASA-WMO 2019 Report. The findings reveal that the proposal of GEI, the integration of smart grids, UHV transmission and clean energy access, could to some extent contribute to meet the climate targets of Paris Agreements.

Reference

Fricko, O. et al. The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. Glob. Environ. Chang. (2017). doi:10.1016/j.gloenvcha.2016.06.004

Fujimori, S. et al. SSP3: AIM implementation of Shared Socioeconomic Pathways. Glob. Environ. Chang. (2017). doi:10.1016/j.gloenvcha.2016.06.009

GEIDCO, IIASA and WMO. Research report on global energy interconnection for addressing climate change. China Electric Power Press. (2019). ISBN 978-7-5198-3222-3

Grubler, A. et al. A low energy demand scenario for meeting the 1.5 °c target and sustainable development goals without negative emission technologies. Nat. Energy 3, 515–527 (2018).

Huppmann, D. et al. The MESSAGEix Integrated Assessment Model and the ix modeling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development. Environ. Model. Softw. (2019). doi:10.1016/j.envsoft.2018.11.012

Riahi, K. et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob. Environ. Chang. (2017). doi:10.1016/j.gloenvcha.2016.05.009

van Vuuren, D. P. et al. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Glob. Environ. Chang. (2017). doi:10.1016/j.gloenvcha.2016.05.008