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# Implications of intercontinental renewable electricity trade for energy systems and emissions

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A rapid global energy transition, including the ramping up of electricity generation from renewables, is needed to limit global warming to 2 °C or 1.5 °C. However, renewable resource endowments vary widely between regions, and renewable electricity is currently mainly used locally. Here we use a global integrated assessment model to explore the implications of renewable electricity trade via a set of planned direct-current-type ultra-high-voltage (UHVDC) transmission lines for global energy transition and climate change. We find that renewable electricity trade across large world regions via the underlying UHVDC interconnection can boost renewable electricity production and reduce 2020–2100 cumulative $CO_2$ emissions from the power sector up to 9.8%. Financial investments in the UHVDC lines are offset in the long term by reduced investments in other electricity-generation options, including nuclear and storage. Finally, we find that renewable electricity trade can substantially reduce air pollutant emissions in importing regions.

The Paris Agreement and mid-century carbon-neutrality goals call for an urgent global energy transition, which is expected to include a steep increase of renewable power generation[1,2]. The endowment of renewable energy sources (RESs) (solar photovoltaic (PV), wind and hydropower) varies across regions in terms of both quantity (total potential) and quality (capacity factor). Unlike fossil fuels, which are frequently transported and traded globally, RESs are commonly utilized only in local energy systems. Moreover, electricity demand varies considerably among world regions. A region with high electricity demand due to population and economic growth may not be endowed with sufficient RESs, whereas its neighbouring regions might have a surplus of electricity from RESs.

The advance of ultra-high-voltage (UHV) transmission technology over the past decade offers a solution for overcoming the technical barrier of trading renewable electricity across large world regions. UHV lines can transmit electricity over long distances (2,000–3,000 km) with relatively low losses (around 2–4% per 1,000 km depending on voltage levels)[3,4]. This technology has been commercialized since 2010. As of October 2021, 26 lines in China and one line in Brazil have been constructed with a total length of about 40,000 km (refs. [5,6]). UHV technology exists for both alternating-current (AC, ≥ 1,000 kV) and direct-current (DC, ≥ ± 800 kV). UHVAC transmission technology is usually adopted for synchronous networks within a single region or country, while UHVDC is adopted for remote, large-capacity and long-distance transmission. Recently, a global electricity interconnection network was proposed to transmit large-capacity renewable-based electricity to form an electricity-centred, renewable energy-dominant and interconnected energy system[3,7].

Various studies have explored the concept of global or regional grid interconnection (often called 'supergrids') alongside the need

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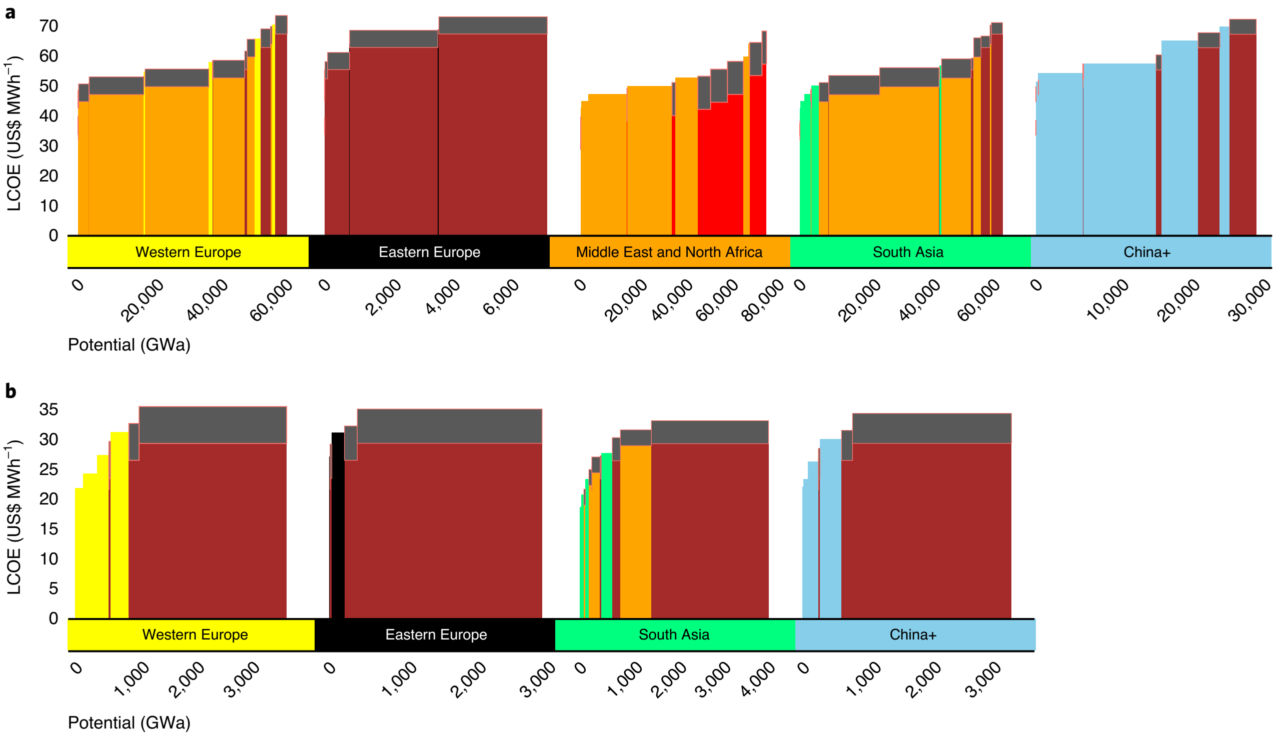

**Fig. 1 | Supply curves for solar PV and onshore wind in 2050 in different importing regions combined with the planned UHVDC lines. a**, Solar PV. **b**, Onshore wind. Definitions of the involved regions are available in Supplementary Table 2 in Supplementary Note 2. Each colour represents one world region. For each importing region, connected exporting regions are also shown. The grey markup represents the additional levelized cost of electricity (LCOE) of planned UHVDC transmission lines (shown on top of associated exporting regions). The capital costs, fixed operation and maintenance (O&M) costs and capacity factors of PV and onshore wind are from the 'standard cost' scenario (Methods and Supplementary Figs. 10 and 11 in Supplementary Note 4). The data for the potential and quality of PV and onshore wind in different regions are from the MESSAGEix-GLOBIOM model database (https://data.ene.iiasa.ac.at/cd-links), binned into eight and four quality grades for PV and onshore wind, respectively. To keep the figure concise, hydro is excluded from the figure. The unit 'GWa' stands for 'gigawatt years'. The figure for the 'low cost' variant is presented in Supplementary Fig. 90 in Supplementary Note 10. Costs are shown in 2010 US dollars.

to integrate considerable amounts of variable RESs (like solar and wind) into power generation. This includes conceptual investigation of technological feasibility and possible benefits of such interconnected power grids[3,8–15], such as demand and supply smoothing through area enlargement, cost-efficient power dispatch, lower curtailment and storage demand, lower price volatility, reduced operating reserves, improvement of supply diversity, environmental protection and acceleration of energy transition. Other studies have quantitatively explored the impacts of specific global or intra-continental grid interconnections on the electricity system itself using electricity-sector modelling[16–29].

Here we incorporate advanced transmission technology into a global integrated assessment model (IAM) to perform quantitative long-term scenario analyses on the role of global renewable electricity trade in the form of so-called point-to-grid connections on global energy transition and climate change mitigation. The linking of electricity-sector planning with an IAM allows us to assess the implications of renewable electricity trade across large world regions on the full energy-system transition, investments and relevant air pollutant and carbon emissions. We discover that renewable electricity trade across large world regions via the underlying UHVDC lines can increase renewable electricity production by up to 12.3% in 2050 and reduce 2020–2100 cumulative $CO_2$ emissions from the power sector by up to 9.8%. Investments in the UHVDC lines are offset in the long term by reduced investments in other electricity-generation options, including nuclear and storage. In addition, we find that renewable electricity trade could bring considerable co-benefits to importing regions, leading to important air-quality benefits and derived health effects.

## Underlying UHV transmission scheme and scenario design

In this study, based on scheme-level global grid-interconnection planning that includes 88 UHV projects and is developed by using a power sector model (GOPT, Grid Optimization Planning Tools)[7,30] (Methods and Supplementary Note 1), we analyse the impact of 26 UHVDC projects in the scheme that cross the borders of world regions represented in the global IAM, MESSAGEix-GLOBIOM (Model for Energy Supply Strategy Alternatives and their General Environmental Impact–Global Biosphere Management Model). These UHVDC projects transmit renewable power from large-scale renewable bases in an exporting region directly to the grids in an importing region. Each interconnection transmits a specific (mix of) RES-based electricity based on a detailed investigation into available RESs and feasible UHV lines behind the interconnection (Supplementary Table 1 in Supplementary Note 1). The included 26 UHVDC projects cross eight of the model's eleven world regions. The eight regions cover the continents of Eurasia and Africa, namely sub-Saharan Africa, China plus several neighbouring countries, eastern Europe, former Soviet Union, Middle East and North Africa, other Pacific Asia, South Asia and western Europe. These 26 projects include transmission from China and neighbouring countries to South Asia and from other Pacific Asia to South Asia; therefore, our study involves not only intercontinental but also intra-continental trade of renewable electricity. The eight regions account for about 87% of global population, 73% of gross domestic product, 76% of final energy consumption and 75% of electricity consumption[31,32]. The RES endowment varies in the involved eight model regions (Fig. 1). As an example, compared to its neighbouring regions, the Middle East and the former Soviet Union, the populous South Asia region has a much lower potential for PV and onshore wind (Fig. 1).

Using the MESSAGEix-GLOBIOM model (Supplementary Note 2) and adding the new feature of inter-regional electricity trade into the model (Supplementary Note 3), we conduct a scenario analysis to assess the impacts of the planned UHVDC interconnection on global energy transition and climate change mitigation.

In total, we design 48 scenarios for a large-scale sensitivity analysis. These scenarios are defined by variations in energy demand (low, medium and high demand), grid-interconnection type (no interconnection, capped interconnection, capped interconnection treating imported electricity as variable supply for the importing regions and uncapped interconnection without upper bound of transmission capacity and without prescribed mix of RESs), renewable investment costs (standard cost and low cost) and climate policy as defined by carbon price (2010 US\$15 $t^{-1}$ $CO_2$ and 2010 US\$50 $t^{-1}$ $CO_2$ + 5% per annum). For more, scenario design details are available in Methods and Supplementary Fig. 7 and Table 3 in Supplementary Note 4. To keep results manageable, we focus our results on three variants of grid interconnection ('no interconnection', 'capped interconnection' and 'uncapped interconnection') and energy demand at the medium level, while varying both renewable costs and climate policy assumptions. Analysis of all the other scenarios is included in Supplementary Notes 5–9.

## Renewable electricity trade

Renewable electricity trade differs between scenarios with capped interconnections and uncapped interconnections (Fig. 2). Compared with the capped cases, more renewable electricity is traded across regions in the uncapped cases, particularly to the South Asia region.

The share of traded renewable electricity in total electricity generation in Eurasia and Africa in 2050 will be 1.2–1.7% under the planned capped interconnection cases or 5.3–6.5% under the uncapped cases in which the upper limits of UHV transmission capacity and the prescribed mix of RESs are removed from model constraints (Fig. 3a,b). During the period 2020–2100, the cumulative share would be 0.8–1.5% for the capped cases and 4–5.5% for the uncapped cases. The trade shown under the uncapped cases implies that transmitting renewable electricity via the planned UHVDC lines is economical, given the different cost of renewables between regions.

## Renewable electricity generation

The opportunity to trade renewable electricity over long distances via UHVDC lines make RESs more economically viable (Fig. 3c,d). Compared with the relevant 'no interconnection' baseline scenarios, the scenarios with capped interconnection indicate higher renewable electricity generation in 2050 of 1–2.3%. Without capping UHV transmission capacity between regions, the renewable electricity production in 2050 increases to 9.3–12.3%. This implies that renewable electricity trade across large world regions via UHVDC interconnection can boost RES-based electricity generation and help exploit renewable resources that would otherwise be unused.

## $CO_2$ emissions

Analysis of the $CO_2$ emissions changes between scenarios with and without renewable electricity trade reveals two main findings (Fig. 3e,f): first, renewable electricity trade across large world regions reduces $CO_2$ emissions and second, more renewable electricity trade leads to stronger reductions in $CO_2$ emissions. We compared the relative changes of $CO_2$ emissions from relevant 'no interconnection' baselines to the four scenario sets discussed in this paper. In the capped interconnection cases, in which 0.8–1.5% of total electricity generation over 2020–2100 is traded across the eight regions in Eurasia and Africa, cumulative $CO_2$ emissions over the same period are reduced by 0.4–1.2%. Cumulative $CO_2$ emissions could be further reduced by 1.8–5.5% or 19–55 Gt $CO_2$, as shown in the uncapped interconnection cases, with trading equalling 4–5.5% of total electricity generation during the 2020–2100 period. It is worth noting that part of the studied 26 UHVDC projects are planned to be in operation by 2030 and the rest by 2050; therefore, if we calculate the 2030–2100 cumulative $CO_2$ emissions instead of the 2020–2100 cumulative, the reduction is larger, about 2.4–11.6% in the uncapped interconnection cases.

In addition, if we measure the 2020–2100 cumulative $CO_2$ emissions from only the energy sector and the electricity sector, the emissions would reduce by up to 1.8–6.4% and 6.4–9.8% in the uncapped interconnection cases, respectively. This indicates that grid interconnection via UHVDC lines can facilitate the sharing of remote high-quality RESs at a global level (namely a better configuration of global RES use in electricity generation), resulting in lower $CO_2$ emissions.

## Investment in the energy-supply sector

Totalling across Eurasian and African regions, we find that the benefits of global renewable electricity trade across large world regions will not require substantial changes in total cumulative investment in energy supply for the period 2020–2100 (Fig. 4a,b). In the capped interconnection cases, for all four scenario sets with different renewable cost (low cost and standard cost) and carbon price assumptions (US\$15 $t^{-1}$ $CO_2$ and US\$50 $t^{-1}$ $CO_2$), cumulative global investments over the period 2020–2100 are reduced by 0–0.2% compared with 'no interconnection' cases. In the uncapped interconnection cases, such investments are reduced by 1–1.3% in three sets of scenarios ('low cost with carbon price 15', 'low cost with carbon price 50', 'standard cost with carbon price 15'). The only exception is the scenario 'standard cost with carbon price 50' (that is, higher renewable cost and tighter climate policy), wherein investment increases by 0.7%.

To analyse the underlying changes in depth, we zoom into the structure of investments within the electricity sector between a scenario with high renewable electricity trade and its respective 'no interconnection' baseline, namely the scenarios of 'uncapped interconnection_low cost_50' and 'no interconection_low cost_50' (Fig. 5). We find that although the cumulative (2020–2100) investments in grids (transmission and distribution) in the uncapped interconnection case are higher (+ US\$1,800 billion) than those in the 'no interconnection' baseline scenario, the cumulative investments in the power sector are lower in the uncapped interconnection case (−US\$1,031 billion). This is because of lower investments in fossil power production (−US\$244 billon), electricity storage (−US\$751 billion), nuclear (−US\$988 billion) and renewables (−US\$880 billion) in the uncapped interconnection case. The lower investment in renewables in the uncapped interconnection case shows the benefits of utilizing remote high-quality RESs at a global level. In short, over the full century, the investment in UHVDC transmission lines could be offset in the long term by the reduced investment in other electricity-sector infrastructures. However, the timing of investment shows that building power grid interconnections requires additional short-term (2020–2040) investment, followed by reduced investment in the long term (2040–2100) (Figs. 4a,b and 5). This indicates that the investment mechanisms to finance a renewable electricity trade network need to depend on a long-term outlook for the global electricity system.

A global interconnection network also leads to shifts in energy-system investment across regions. Here we take advantage of the broad energy-system definition of the IAM and compare the investments in total energy supply between the scenarios with

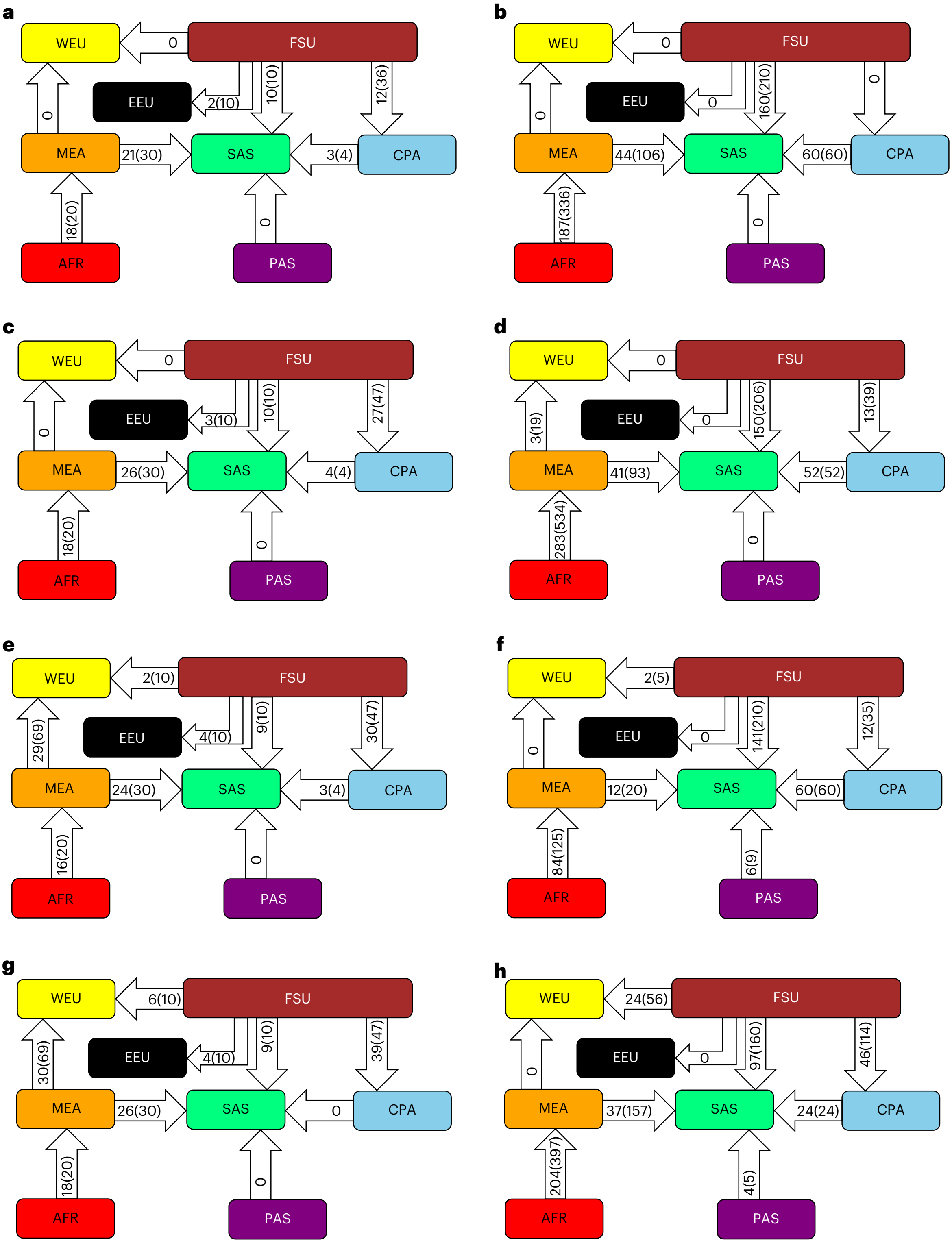

**Fig. 2 | Renewable electricity trade across large world regions under scenarios with different assumptions of interconnection type, renewable cost and climate policy.** **a**, Capped interconnection_low cost_15. **b**, Uncapped interconnection_low cost_15. **c**, Capped interconnection_low cost_50. **d**, Uncapped interconnection_low cost_50. **e**, Capped interconnection_standard cost_15. **f**, Uncapped interconnection_standard cost_15. **g**, Capped interconnection_standard cost_50. **h**, Uncapped interconnection_standard cost_50. The scenario naming is a combination of interconnection type (capped and uncapped), renewable cost (standard and low cost) and climate policy (US\$15 $t^{-1}$ $CO_2$ and US\$50 $t^{-1}$ $CO_2$ as the carbon price). More details on these assumptions are available in Supplementary Table 3 in Supplementary Note 4. The numbers outside and inside a parenthesis on an arrow stand for the average and the peak amount of yearly renewable electricity trade, respectively, during 2030–2100 between two regions with the unit of 'gigawatt years'. The width of arrows symbolically represents the trade volume. The number zero indicates either no trade at all or a very small amount of trade with the unit of 'gigawatt years'. Each box represents a world region, namely AFR (Sub-Saharan Africa), CPA (Centrally Planned Asia and China), EEU (Eastern Europe), FSU (Former Soviet Union), MEA (Middle East and North Africa), PAS (Other Pacific Asia), SAS (South Asia), and WEU (Western Europe). Details of these world regions are available at https://docs.messageix.org/projects/global/en/latest/overview/spatial.html.

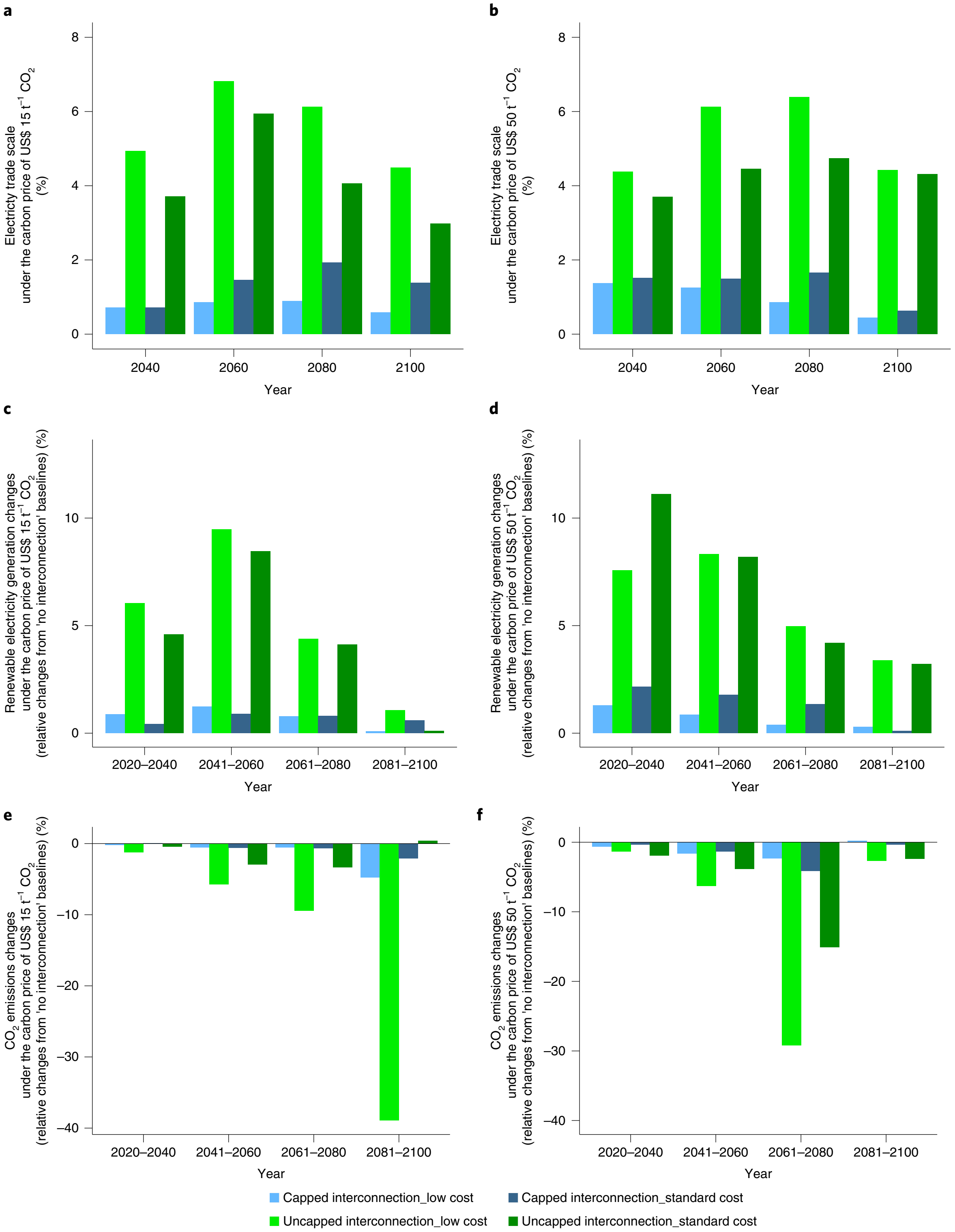

**Fig. 3 | Electricity trade, renewable electricity generation and $CO_2$ emissions under various scenarios. a**, Electricity trade scale under the carbon price of US\$15 $t^{-1}$ $CO_2$. **b**, Electricity trade scale under the carbon price of US\$50 $t^{-1}$ $CO_2$. **c**, Changes in renewable electricity generation relative to 'no interconnection' baselines under the carbon price of US\$15 $t^{-1}$ $CO_2$. **d**, Changes in renewable electricity generation relative to 'no interconnection' baselines under the carbon price of US\$50 $t^{-1}$ $CO_2$. **e**, Changes in $CO_2$ emissions relative to 'no interconnection' baselines under the carbon price of US\$15 $t^{-1}$ $CO_2$. **f**, Changes in $CO_2$ emissions relative to 'no interconnection' baselines under the carbon price of US\$50 $t^{-1}$ $CO_2$. With a carbon price of US\$15 $t^{-1}$ $CO_2$, the scenarios are about 2 °C scenarios, while with a carbon price of US\$50 $t^{-1}$ $CO_2$, they are about 1.5 °C scenarios. The carbon price is in 2010 US dollars.

and without grid interconnection for a typical importing region (Fig. 4c,d) and exporting region (Fig. 4e,f). We find that total investments for exporting regions increase, while they are decreasing for importing regions. More specifically, compared to the 'no interconnection' case, a breakdown analysis of investment in the electricity sector shows that the cumulative investment (2020–2100) in

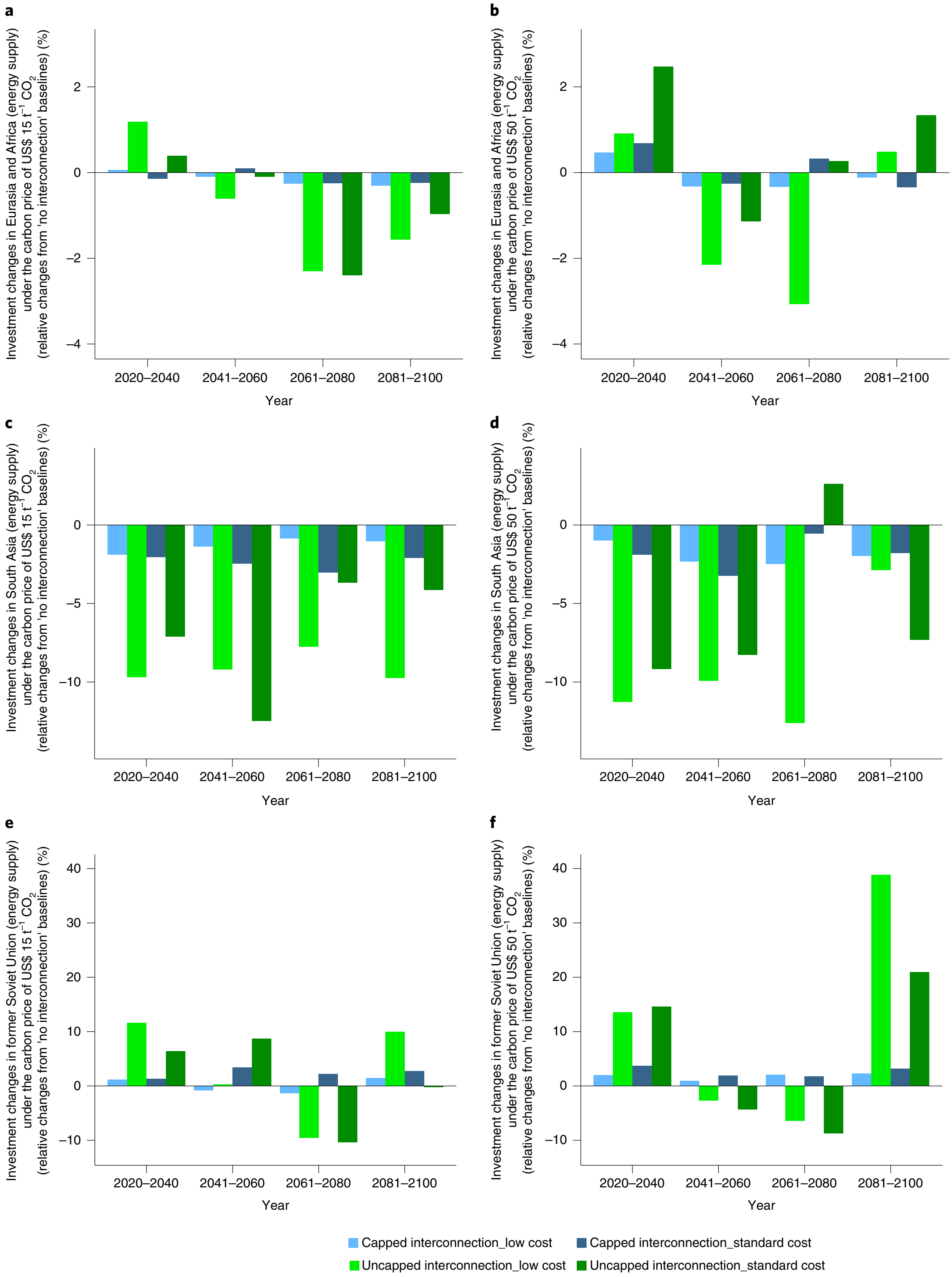

**Fig. 4 | Changes of investment in energy-supply sector with renewable electricity trade. a**, Changes under the carbon price of US\$15 $t^{-1}$ $CO_2$ in Eurasia and Africa. **b**, Changes under the carbon price of US\$50 $t^{-1}$ $CO_2$ in Eurasia and Africa. **c**, Changes under the carbon price of US\$15 $t^{-1}$ $CO_2$ in South Asia. **d**, Changes under the carbon price of US\$50 $t^{-1}$ $CO_2$ in South Asia. **e**, Changes under the carbon price of US\$15 $t^{-1}$ $CO_2$ in the former Soviet Union. **f**, Changes under the carbon price of US\$50 $t^{-1}$ $CO_2$ in the former Soviet Union. All changes are relative from the relevant 'no interconnection' baselines. The carbon price is in 2010 US dollars.

grids increases in the uncapped interconnection case for both the electricity importing and exporting regions (Fig. 5). However, the investments in other electricity infrastructures (fossil, renewables, energy storage and nuclear) are very different for the two types of regions, increasing in the exporting region while decreasing in the importing region (Fig. 5). This highlights the need for a cooperative

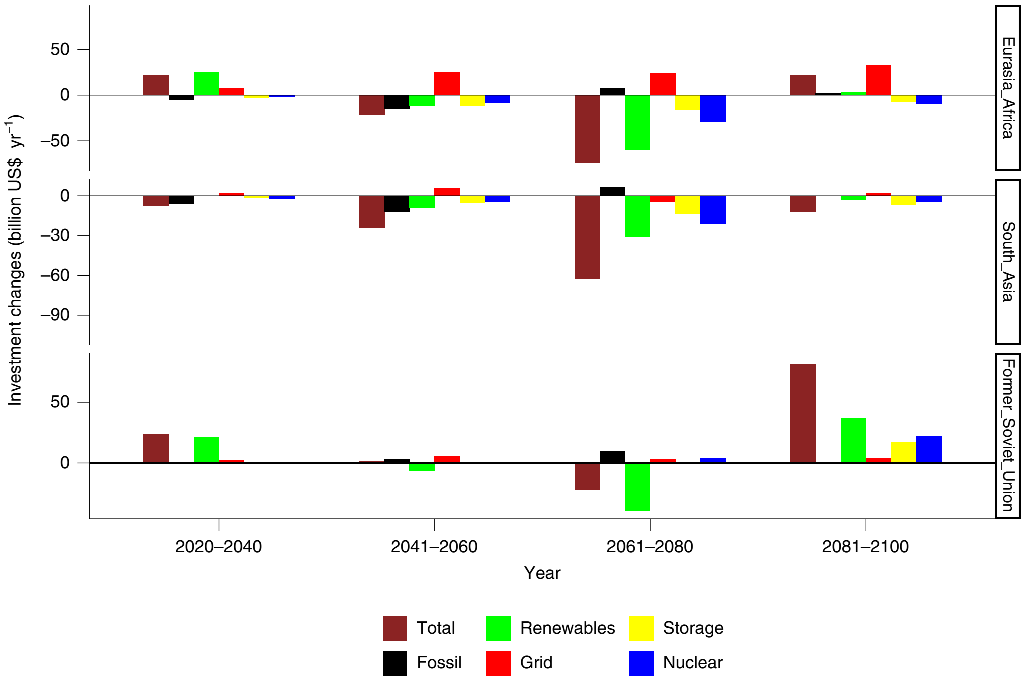

**Fig. 5 | Changes of investment breakdown in the electricity sector.** The changes are between an 'uncapped interconnection' scenario and a 'no interconnection' baseline scenario with the same assumptions of renewable cost (low cost) and carbon price (2010 US\$50 $t^{-1}$ $CO_2$) in Eurasia and Africa, South Asia and the former Soviet Union.

framework to allow both importing and exporting regions to benefit from the renewable electricity trade with the introduction of grid interconnection.

## Regional trade-offs and co-benefits

The broad energy-system definition of the MESSAGEix-GLOBIOM model allows us to analyse the trade-offs and co-benefits of renewable electricity trade across the eight model regions reviewed in this study. Generally, fossil-based electricity generation is replaced by imported renewable electricity for the importing regions, while exporting regions increase their generation of renewable electricity (Fig. 6). Results for all individual regions are included in Supplementary Note 9. Here we focus on South Asia and the former Soviet Union. South Asia is a dominant electricity-importing region with high electricity demand, owing to its large population and continued economic growth. In contrast, the former Soviet Union region is a dominant electricity-exporting region that is rich in PV and wind resources (for example, PV in Central Asia and wind in the Arctic areas). Here we discuss the regional benefits and trade-offs of renewable electricity trade by exploring the power-generation mix in the two regions (Fig. 6) and specifically the $CO_2$, $NO_x$ and $SO_x$ emissions in the South Asia region (Fig. 7).

For the South Asia region, we find that imported electricity mainly replaces coal power generation (Fig. 6a, using the year of 2050 as an example). The relative changes in coal power generation in 2050 from relevant 'no interconnection' baselines range from −2% to −39% for capped interconnection cases and from −81% to −91% for uncapped interconnection cases, the higher ends being achieved with lower renewable costs.

In the former Soviet Union region, electricity generation rises as more electricity gets exported to its neighbouring regions, and the increased power generation mainly comes from renewables (Fig. 6b, using the year of 2050 as an example). Renewable electricity generation (hydro, PV and wind) in this region in 2050 increases by about 13–45% for the capped interconnection cases and 95–197% for the uncapped interconnection cases, but with the higher ends achieved with higher renewable costs. This implies that when the cost of renewables is higher, the former Soviet Union region might export more renewable electricity because of its rich and high-quality RESs. In addition, we also observe that when renewable costs increase (that is, from low cost to standard cost cases), the share of nuclear power in the region's power mix increases substantially.

As a result of these changes in the power system, we observe lower emissions of greenhouse gases and air pollutants ($CO_2$, $NO_x$ and $SO_x$) in South Asia (Fig. 7). In detail, compared with the relevant 'no interconnection' baselines, we find modest reductions in emissions of $CO_2$ (1.2–4.3%), $NO_x$ (0.9–1.4%) and $SO_x$ (0.3–3.2%) cumulatively during 2020–2100 in the capped interconnection cases. In the uncapped interconnection cases, these emissions reductions are more considerable, as more renewable electricity is imported into South Asia from its neighbouring regions, displacing domestic fossil electricity production. The reduced $CO_2$ emissions between scenarios with and without grid interconnection range from 7.1% to 23.7%, from 5% to 15.2% for $NO_x$ emissions and from 2.3% to 13.3% for $SO_x$ emissions. The higher ends of these ranges are generally achieved with assumptions of lower renewable costs and more stringent climate policies.

In short, we conclude that renewable electricity trade across large world regions could bring substantial co-benefits to electricity-importing regions, and their importance depends strongly on the scale of trade. Lower renewable power-generation costs and tighter climate policies improve the magnitude of such co-benefits.

## Discussion

The scenarios presented in this study analyse the effects of renewable electricity trade between eight large world regions on climate change mitigation (covering Eurasia and Africa). It needs to be noted that in this study, our investigation of renewable electricity trade and its impacts on climate change mitigation is based on only 26 planned UHVDC projects in Eurasia and Africa. It also should be

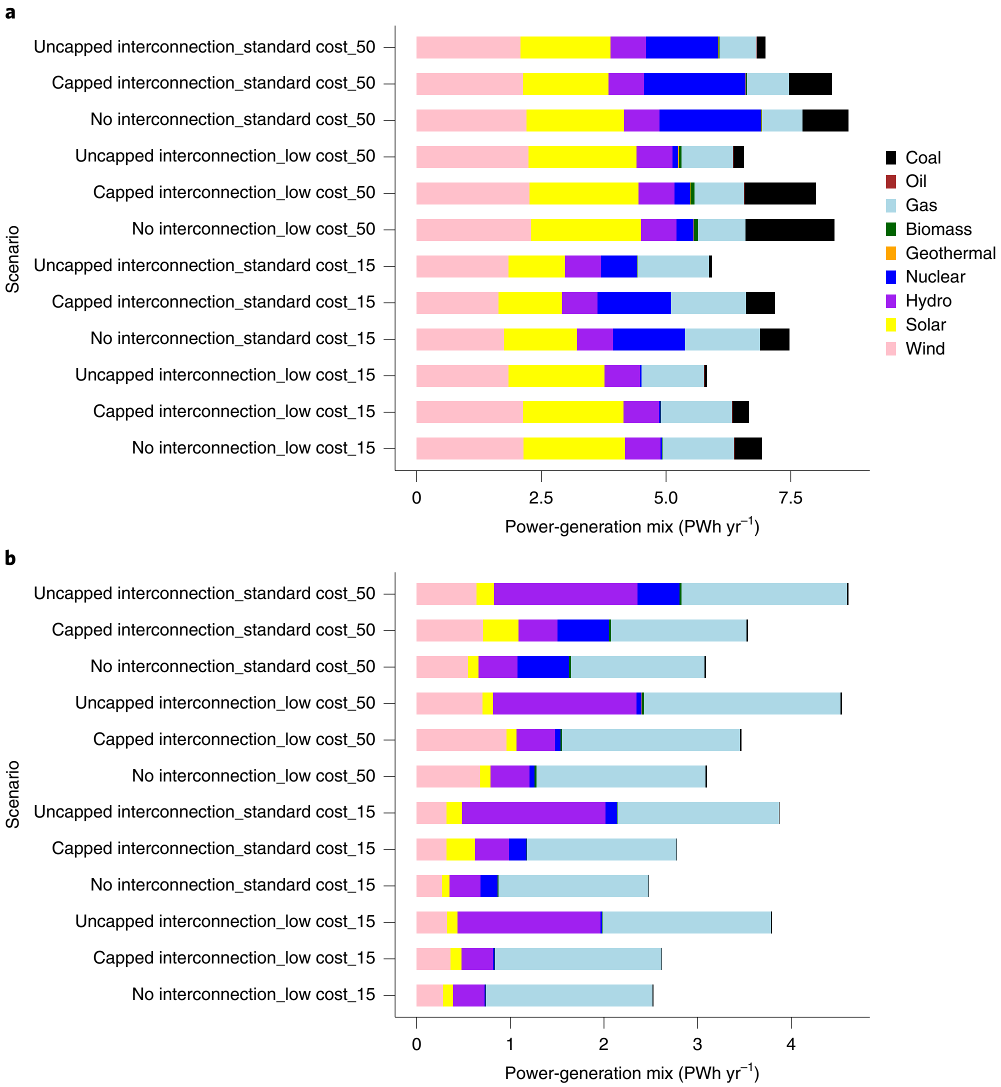

**Fig. 6 | Impacts of renewable electricity trade across large world regions on regional power-generation mix. a**, Power-generation mix in South Asia in 2050 under various scenarios. **b**, Power-generation mix in the former Soviet Union in 2050 under various scenarios.

noted that there exists considerable benefits from renewable electricity trading within these large regions that are not covered in this study. However, we have used an optimistic parameterization of the integration of variable RESs, assuming a strong intra-regional grid and reflecting that the intra-regional grid is expanded first before intercontinental power lines are built. Although based on a limited number of UHVDC projects, we found that such a grid-interconnection scheme could contribute considerably to reducing global $CO_2$ emissions, up to 55 Gt (2020–2100 cumulative). The attractiveness of renewable electricity trade in the power system also depends strongly on the available and acceptable alternative mitigation options. In scenarios where nuclear and/or CCS (carbon capture and storage) are excluded, we find stronger increases in renewable electricity trade, adding up to about 10–11% of global electricity production cumulatively during 2020–2100 (Supplementary Table 7 in Supplementary Note 5).

There are several important practical barriers to realizing global renewable electricity trade that may hamper the development of such a global interconnection network. For example, the difficulty of integrating different types of power market could complicate interconnections; high initial capital investment, design of proper financing and cost sharing mechanism, land use and public acceptance are other important barriers[3]. A potentially large technical barrier is operating high variable renewable energy (VRE) grids globally (a scale such as 50% in 2050 and 80% in the end of century, as shown in this study). Moreover, geopolitical considerations, energy security and import dependence could also be a challenge to realizing the interconnections discussed in this paper[19,33–35]. However, our research indicates that the potential benefits of large-scale renewable electricity trade across large world regions can contribute considerably to global energy transition and carbon neutrality, identifying reasons to work towards overcoming these barriers.

## Conclusions

This paper explores the implications of renewable electricity trade across large world regions for global energy transition and climate change mitigation. The trade is implemented via 26 scheme-level planned UHVDC projects that transmit renewable electricity from large-scale renewable bases to remote demand centres (that is, the so-called ‘point-to-grid’ interconnections). We parameterized these UHVDC projects derived from electricity-sector planning and reflected them into the MESSAGEix-GLOBIOM integrated assessment modelling framework to conduct long-term scenario analyses for eight large world regions, covering Eurasia and Africa.

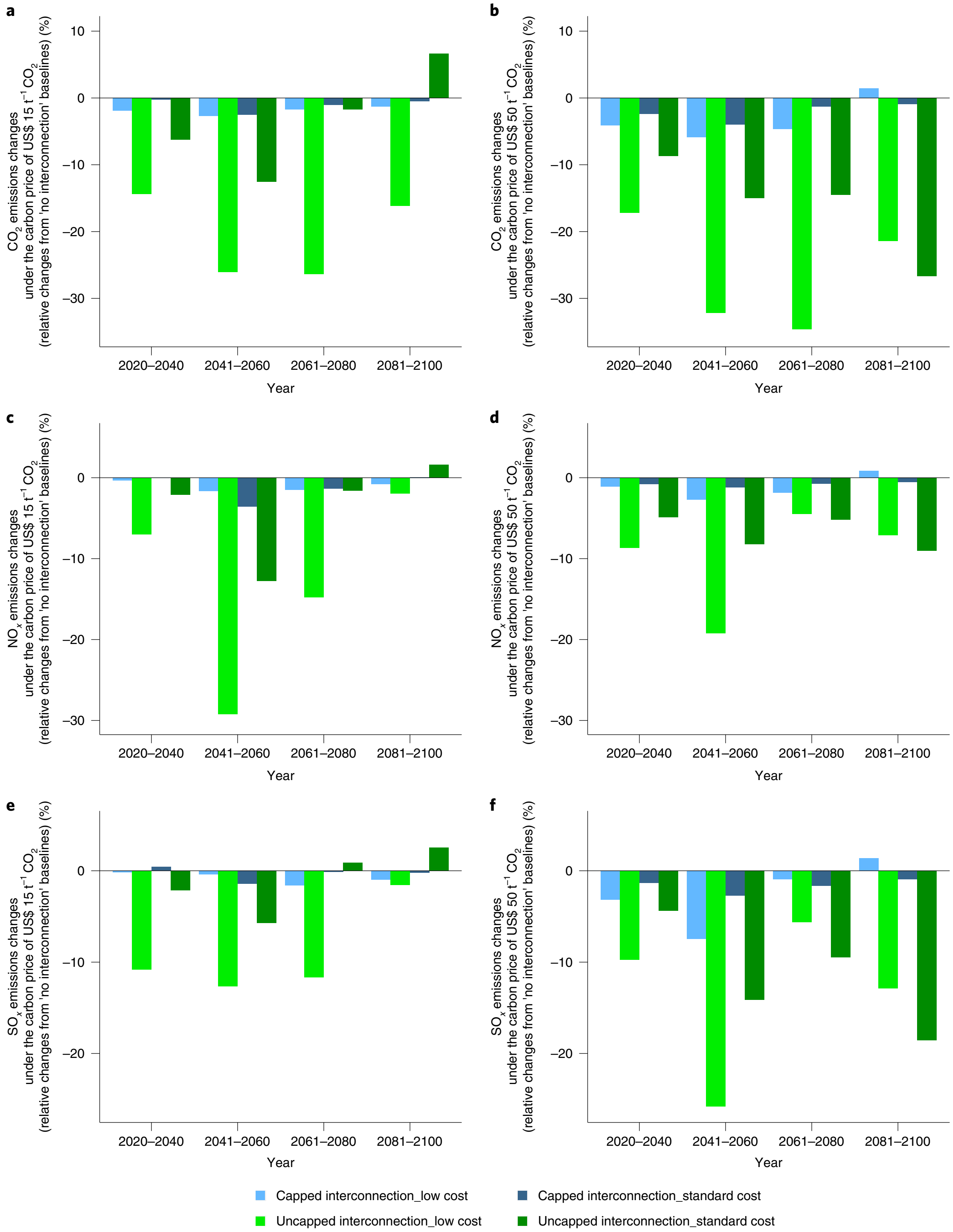

**Fig. 7 | Impacts of renewable electricity trade across large world regions in South Asia on the region's $CO_2$, $NO_x$ and $SO_x$ emissions.** The emissions are from the energy sector. **a**, $CO_2$ emissions changes relative to 'no interconnection' baseline scenarios under the carbon price of US\$15 $t^{-1}$ $CO_2$. **b**, $CO_2$ emissions changes relative to 'no interconnection' baseline scenarios under the carbon price of US\$50 $t^{-1}$ $CO_2$. **c**, $NO_x$ emissions changes relative to 'no interconnection' baseline scenarios under the carbon price of US\$15 $t^{-1}$ $CO_2$. **d**, $NO_x$ emissions changes relative to 'no interconnection' baseline scenarios under the carbon price of US\$50 $t^{-1}$ $CO_2$. **e**, $SO_x$ emissions changes relative to 'no interconnection' baseline scenarios under the carbon price of US\$15 $t^{-1}$ $CO_2$. **f**, $SO_x$ emissions changes relative to 'no interconnection' baseline scenarios under the carbon price of US\$50 $t^{-1}$ $CO_2$. The carbon price is in 2010 US dollars.

We find that there is a large potential for trading renewable electricity in the studied Eurasia and Africa region, up to 4–5.5% of the region's cumulative (2020–2100) electricity production. Compared with the 'no interconnection' baselines, such trade could facilitate the increased use of remote high-quality renewable resources for electricity generation (for example, up to 9.3–12.3% of the increase in renewable power production in 2050) and reduce $CO_2$ emissions by up to 1.8–5.5% between 2020–2100 (about 19–55 Gt $CO_2$) or $CO_2$ emissions from the power sector by up to 6.4–9.8% in the same period without substantial changes in cumulative investments in the energy-supply sector. The high end of these ranges is achieved in scenarios with optimistic renewable costs and tight climate policy.

In the electricity-sector investment breakdown analysis for one of our scenarios with higher renewable electricity trade from its relevant 'no interconnection' baseline scenario, we find that the 2020–2100 cumulative investment in UHVDC transmission lines (about + US$1,800 billion) could be largely offset in the long term by the reduced investment in other electricity-sector infrastructures at the global level, including fossil (−US$244 billion), energy storage (−US$751 billion), nuclear (−US$988 billion) and renewables (−US$880 billion). The substantial investment decrease in renewables implies the benefits of sharing remote high-quality RESs at a global level, while the similar-scale investment decrease in nuclear indicates that the renewable electricity generation promoted by trading them across large world regions could well replace the measure of nuclear power for achieving 2 °C or 1.5 °C climate goals. We also find that renewable electricity trade could bring important co-benefits to electricity-importing regions, such as South Asia, by promoting the phase out of coal power generation, leading to important air-quality benefits and derived health effects.

By analysing the use of emerging UHVDC transmission technology to realize renewable electricity trade across large world regions, this study explores an option to address climate change challenges. Through building advanced transmission infrastructure to form a global super grid, remote high-quality renewable energy sources that previously could be exploited only locally would become available for use in distant load centres and help less resource-endowed countries in reaching net-zero carbon emissions. On top of the point-to-grid-interconnection studies in this research, global grid expansion through area enlargement and grid-to-grid interconnections, could further support the global electricity system through demand and supply smoothing, variability balancing of renewable electricity, reduced operating reserve requirements and lower curtailment and storage.

# Methods

## Modelling tools

This study is based on linking electricity-sector planning results with integrated assessment modelling (IAM) (Supplementary Fig. 6 in Supplementary Note 3). The former provides key data inputs to the latter. First, UHV transmission lines are planned for trading renewable electricity across countries and regions based on electricity-sector modelling using the GOPT model[36–42]. Then, we use the global IAM framework, MESSAGEix-GLOBIOM (https://docs.messageix.org/projects/global/en/latest/), to conduct scenario analysis on the impacts of renewable electricity trade across large world regions via the planned UHV interconnection on global energy transition and climate change mitigation.

## Electricity-sector planning

The UHV interconnection planning is based on the GOPT electricity-sector model[36–42]. This model includes both the modules of 'generation expansion planning' and 'power system operation simulation', and it is particularly developed to analyse the operating modes of a power system with high variable renewable energy (VRE) integration. It could conduct the year-round power system operation simulation and is able to investigate the impact of VRE on hourly dispatch.

First, based on the existing power grid system in each country or region, the power-generation expansion-planning module is utilized to model the required power-generation capacity for meeting the projected power demand in the future[43–46]. Second, under new cross-border power-interconnection constraints (for example, international connections), the operation simulation module working together with the expansion-planning module finds the lowest power system construction and operating cost by balancing the planned power capacity and the typical operation needs of the power system. In the operation simulation, ten typical days in a target year are selected, including the two days with maximum load in both summer and winter and one work day and one weekend day in each of the four seasons (that is, spring, summer, fall and winter)[47]. Then, under certain power operation constraints (for example, operation regulations, balance of load, generator ramping rates, generation reserve), the operation simulation module is employed to model the operation strategies, annual operation hours and generation mix for transmission. On the basis of the above modelling results of each country or region in the world and extensive field investigation, the direction and scale of renewable electricity trade between different countries and regions in the world are identified (that is, the power flows between the exporting countries/regions with rich renewable sources and power-generation capacity and the importing regions of power-load centres). According to the transmission distance and volume, needs for synchronous interconnection and the frequencies and voltage levels of grids in different countries and regions, AC or DC type of UHV transmission lines are planned for transmitting renewable electricity across countries or regions[30,43,48]. In total, 88 UHV transmission projects are planned globally based on the electricity-sector modelling. Details are presented in Supplementary Note 1.

## IAM

MESSAGEix-GLOBIOM 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[49,50] (Supplementary Note 2).

MESSAGEix-GLOBIOM model is a linked integrated assessment model 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 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 modelling year to 2110).

The MESSAGEix-GLOBIOM model runs for every ten years until 2110. It does this based on a linear programming, optimization solution algorithm. The representation of the energy system 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 (for example, 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 other radiatively active gases—$CO_2$, $CH_4$, $N_2O$, $NO_x$, volatile organic compounds, CO, $SO_2$, black carbon (BC), organic carbon (OC) and so on—from both the energy and non-energy sectors (for example, deforestation, livestock, municipal solid waste, manure management, rice cultivation, wastewater and crop-residue burning).

From the 88 planned UHV transmission projects derived from electricity-sector planning, we selected 26 UHV-type projects to be further analysed in the MESSAGEix-GLOBIOM model. This is mainly because of the spatial resolution of the MESSAGEix-GLOBIOM model that has only 11 world regions (Supplementary Fig. 4 and Table 2 in Supplementary Note 2). The 26 selected UHV projects cross the borders of eight world regions in the MESSAGEix-GLOBIOM model (covering Eurasia and Africa). Serving for the research purpose of this study, the selected 26 UHV projects are all direct-current (DC)-type ones and designed to transmit renewable power generated from certain renewable bases (solar, wind and hydro) to certain regions (usually electricity-demand centres).

The original MESSAGEix-GLOBIOM model does not include the feature of electricity trade across different model regions. In this study, we specifically added such a feature into the MESSAGEix-GLOBIOM model based on the data of planned UHV transmission lines derived from the electricity-sector planning (Supplementary Note 3). On the basis of the electricity-sector planning results, we parameterized the selected 26 UHVDC projects into the MESSAGEix-GLOBIOM model, including sending and receiving regions, transmission capacity, capital cost, O&M cost, lifetime, transmission loss (depending on project's transmission distance), construction plan (first year in operation and rebuilding plan) and connected renewable energy sources and their generation capacity and so on.

In addition, in the MESSAGEix-GLOBIOM model, grid development is represented within each model region as part of the variable renewable electricity integration formulations. For consistency reasons, we have assumed that an inter-regional power grid will not be widely built without exploiting the options to improve the grid network within each region itself. We have reflected this situation in this study by using the most optimistic within-region parameterization for the variable renewable integration, based on the low energy demand (LED) scenario[51]. By doing so, we evaluate the added value of the inter-regional electricity trade against a situation with improved grid connections within each model region.

### Scenario design for sensitivity analysis

We designed a total of 48 scenarios for sensitivity analysis to check the robustness of our findings. All scenarios start from the CD-LINKS (Linking Climate and Development Policies—Leveraging International Networks and Knowledge Sharing) NPi (currently implemented National Policies) scenario (https://data.ene.iiasa.ac.at/cd-links), which assumes an implementation and continuation of current policies. The year 2020 (before the COVID-19 pandemic) is fixed to be the same across all scenarios, and the first modelling year is 2030. For each scenario, we include four important components, namely energy demand, grid-interconnection type, technology cost and carbon price. Each component has several variants—three for demand, four for grid-interconnection type, two for technology cost and two for carbon price (Supplementary Table 3 in Supplementary Note 4).

The three demand variants are prepared based on Shared Socioeconomic Pathways (SSPs). The SSPs (SSP1–5) create a framework indicating how the future may evolve under a consistent set of assumptions. Our three demand variants, 'low demand', 'medium demand' and 'high demand', are derived from SSP1 (the Green Road), SSP2 (Middle of the Road) and SSP3 (a Rocky Road)[50,52–55]. We generated the 'medium demand' based on SSP2, 'low demand' based on SSP1 and SSP2 and 'high demand' based on SSP3 and SSP2. For the last two demand categories, we applied the SSP1 and SSP3 energy intensities respectively with the SSP2 socio-economic assumptions. In this way, these three demand levels are based on the same population and gross domestic product projections and are thus more comparable.

We devised four variants of grid-interconnection type for trading electricity across regions, namely 'no interconnection', 'capped interconnection', 'capped interconnection treating imported electricity as variable supply' and 'uncapped interconnection'. The variant 'no interconnection' means 'without renewable power trade across regions', so it is the baseline scenario. In the two variants of capped interconnection, we applied two constraints, namely maximum transmission capacities of the planned UHV lines and the power-generation mix connecting to them from different RESs. The only difference between the two variants is that we treat the traded electricity as 'stable supply' or 'variable supply' for importing regions. 'Variable supply' means that if the electricity is generated from intermittent RESs like PV or wind, additional flexible power-generation capacity (for example, gas, storage) is required for importing regions[56,57]. The assumption of 'stable supply' means that the supply of electricity through the UHV interconnection is predictable and reliable so that no additional flexible generation capacity is needed to compensate imported renewable electricity in the importing region. Different from the two variants of capped interconnection, in the 'uncapped interconnection' variant, we removed the two constraints of transmission capacity and prescribed renewable power mix. This means that in the 'uncapped interconnection' variant, the optimization model MESSAGEix-GLOBIOM itself determines the amount and sources of renewable electricity being traded across regions. This means that the UHV interconnections can be fed by model-determined shares of solar, wind or hydropower-generated electricity and consequently can either become a source of network flexibility (in the case of hydropower) or require flexible capacity (in the case of PV and wind) in the importing regions.

We designed two levels of technology cost (including capital and fixed O&M cost) for the power-generation technologies included in the MESSAGEix-GLOBIOM model. The two levels are called standard cost and low cost. Standard cost uses the cost data from the SSP2 baseline marker scenario[50]. Low cost stands for a scenario with lower renewable power cost but higher non-renewable power cost. In detail, we structured the 'low cost' scenarios by using the lowest costs of renewable power-generation technologies (that is, PV, wind and hydro) from the SSP1 and SSP3 baseline marker scenarios and the low energy-demand scenario[51–53]. For non-renewable power-generation technologies, the costs in the 'low cost' scenarios are derived directly from the SSP1 cost assumptions[52] (Supplementary Figs. 10–21 in Supplementary Note 4).

We also assumed two carbon price variants, '15' and '50', standing for US\$15 $t^{-1}$ $CO_2$ and US\$50 $t^{-1}$ $CO_2$, respectively (2010 US\$). These carbon prices become effective in 2030 and increase by 5% per year. Our results show that with the SSP2 energy demand, the cumulative (2020–2100) global $CO_2$ emissions with the two carbon prices of US\$15 $t^{-1}$ $CO_2$ and US\$50 $t^{-1}$ $CO_2$ will be about 1,350–1,400 Gt and 450–480 Gt, respectively, depending on specific trading interconnections and technology costs. These two levels of $CO_2$ emissions are roughly equivalent to the carbon budgets for limiting global warming to less than 2 °C and 1.5 °C, respectively, with a 50% likelihood by the end of the century[58].

The naming of the scenarios is the combination of the four components adopted in the order of 'demand_interconnection type_renewable cost_carbon price'. As an example, a scenario called 'medium demand_uncapped interconnection_low cost_50' means that it uses the medium level of demand (that is, SSP2 demand), uncapped interconnection type of grid interconnection, low cost setup for renewable power-generation technologies, and a carbon price of US\$50 $t^{-1}$ $CO_2$.

In the main text of this article, we limit our analysis to the 'medium demand' scenarios and use the four extreme ends of this scenario family to demonstrate our findings. In other words, we use four scenario sets of 'low cost with carbon price 15', 'standard cost with carbon price 15', 'low cost with carbon price 50' and 'standard cost with carbon price 50' to discuss the effects of different grid-interconnection variants on electricity transmission and climate change mitigation. Among the four grid-interconnection variants (namely 'no interconnection', 'capped interconnection', 'capped interconnection treating imported electricity as variable supply' and 'uncapped interconnection'), we found that the differences between the two capped interconnection variants are quite small, particularly when comparing them to the other two variants, 'no interconnection' and 'uncapped interconnection'. To make figures and discussion more concise in the main text, we dropped relevant analysis of the 'capped interconnection treating imported electricity as variable supply' variant here but include it in Supplementary Note 5.

## Data availability

All scenarios used in this paper are available in the online database https://data.ece.iiasa.ac.at/gei.

## Code availability

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/.

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## Author contributions

F.G. and B.J.v.R. conceived the research, carried out the analyses and analysed the results. X.C. analysed techno-economic parameterizations of global UHV lines. All authors contributed to writing the manuscript and developing the figures.

## Competing interests

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## Additional information

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