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Modeling of energy transformation pathways under current policies, NDCs and enhanced NDCs to achieve 2-degree target

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HIGHLIGHTS

- Existing energy policies' impacts on long-term CO2 mitigation is limited.
- Delayed NDC enhancement might result in significant reduction on energy service.
- Early enhancement with carbon trading could effectively reduce the system cost.
- Cost-optimal enhancing plan requires huge investment in developing regions.

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ABSTRACT

CO2 mitigation in the global energy system is critical in tackling climate change, each region should design its long-term strategies and implement policies accordingly to promote the energy transformation. To evaluate the impacts of existing energy policies and propose possible enhanced NDCs (Nationally Determined Contributions), this paper applied a 14-region global model to explore the transitions of the global and regional energy system. With the modelling of early and late NDCs enhancing plan for 2-degree target, the required energy transition of each plan was analyzed, together with the vital challenges and potential economic impacts. Model results show: 1. Existing energy policies can reduce the annual emission growth rate to 0.6% for 2015 – 2020, while their influence on long-term mitigation is limited; 2. If enhanced NDCs begin from 2030 onwards after realizing current goals, 2-degree target would become quite challenging in later period, some regions will have to cut the energy service drastically; 3. With the assumption of early enhancement and free carbon trading in the cost-optimal enhancing plan, the total cost of global energy system could be reduced by 10% in 2050, compared with the former plan; 4. Under this cost-optimal enhancing plan, developing regions may face great challenges in short to medium term, 122% of additional investment should be put in power sector in 2030, international support on both technology and finance would be essential.

1. Introduction

Tackling climate change is a global and long-term challenge, and it requires each region to design its mitigation roadmap and implement policy instruments accordingly. To make the likelihood of achieving the 2-degree target higher than 50%, the cumulative CO2 emissions for the whole world should be limited to 960 – 1430 Gt from 2010 to 2100 [1], while the historical data shows that the global annual CO2 emission from fuel combustion has reached 32 Gt in 2016 [2].This means that fuel combustion might exhaust all the remaining budget within 30 – 45 years even if the annual CO2 emission will no longer rise. Therefore, to reduce CO2 emissions from fuel combustion is becoming increasingly urgent and critical.

To better coordinate the cooperation of all parties, a new climate governance mode which combines the National Determined Contributions (NDCs) and regular global stocktakes has been set in Paris Agreement. The NDC registry page of UNFCCC website stated that 181 parties have submitted their NDCs [3], and the year 2023 is expected to be first stocktake year. This paper aims to make explorations on two topics: what mitigation impacts can be brought by existing policies and whether they are in line with current NDC goals; how large is the gap between current NDC goals and the long-term 2-degree target and how the current NDCs could be enhanced towards it.

Great effort has been put to study the impacts of energy policies. Early policy assessments were mainly conducted with policy assumptions rather than policy reviews, and most of them focused only on one

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specific type of policies. In recent years, a few studies were conducted to evaluate the impacts of ongoing policies. Braun et al examined the effectiveness of four policies on CO2 emission reduction, and estimated their mitigation potential for 2020 and 2030 [4]. Fekete et al. identified several good practice policies that are currently implemented in individual countries, and stated that great CO2 mitigation potential exists if they can be applied worldwide [5]. Similarly, Den Elzen et al. analyzed the mitigation impacts of good practice policies for 11 major regions, and estimated the emissions in 2030 assuming these policies can be enhanced and promoted across regions [6]. By investigating regional policies, these studies highlighted the significance of good policy sharing. However, as the impacts of the combination of micro policy instruments including efficiency standards could be quite complex, these studies mainly held the focus on policies that are generally important for most regions. To evaluate the mitigation effort for each region, analyses involving a technology-rich energy system and more regional differences is of great importance.

As for long-term mitigation strategy, 2-degree target and current NDCs have attracted lots of attention from research community in recent years, and a few studies have already pointed out the necessity of NDCs' further enhancement. Rogelj et al. compared multiple emissions pathways for current NDCs and 2-degree targeted, stated that scenarios with NDCs emission 2030 will have a lower possibility to reach 2-degree target, even with rapid reduction in post-2030 period [7]. Millar et al. pointed out that the emission in 2030 should be lower than current level to be in line with RCP2.6 pathway, meanwhile a rapid reduction after 2030 is required [8]. Hof et al analyzed the abatement costs of achieving both NDCs and long-term climate targets, concluded that the cost under 2-degree target would be over three times higher than under NDCs in 2030 [9]. Benveniste et al. analyzed the global greenhouse gas emissions in 2030 with the implementation of current NDCs, and highlighted that an ambitious enhancement is required to avoid the hardly feasible decarbonization rates after 2030 [10].

However, only a few studies have made exploration on how the NDCs can be enhanced. Assuming a global uniform carbon tax, Van Soest et al. analyzed the required mitigation if 2-degree mitigation starts from 2020, 2025 and 2030, and presented the emission gaps between NDCs and cost-optimal 2-degree scenario in 2030 [11]. Winning et al. also adopted the uniform carbon tax method, compared the 2-degree mitigation requirements for scenarios with current NDCs and early ambitious actions, and highlighted the importance of negative emission technologies for the delayed enhancement [12]. Taken current NDCs as a start point, Rose et al. designed different emission reduction from 2030 to 2050, examined the global mean temperature of these scenarios, and compared them with the cost-optimal 2-degree scenario [13]. With similar method, Holz et al. designed different mitigation rates for developed and developing regions respectively from 2030 onwards, presented the expected mitigation rates for 2-degree target [14]. Du Pont et al. considered five burden-sharing principles, analyzed major regions' emission pathways if the 2-degree budget is allocated from 2010 and 2030 (after achieving current NDCs) [15]. Kriegler et al. proposed four plans on the policy enhancement for 2-degree target, and analyzed the emission pathways and impacts of these plans with REMIND-MAgPIE model [16]. These studies provided valuable information on the NDCs enhancement, while certain limitations still exist. Firstly, most studies focused on the emission pathways and temperature rises, and lots of them were conducted from a global perspective, while the information on the regional energy transition is lacking. Secondly, most enhancing proposals chose to enhance the mitigation plan independent of existing NDCs, either adopted the uniform carbon tax method or assumed different reduction rate. However, individual regions may still take current NDC goals as reference when they are trying to design the future plans, it is necessary to explore the potential impacts of NDCs' continuous enhancement.

Therefore, to provide more information for the coming global stocktake, this paper applied a technology-rich model to analyze the overall impacts of existing policies. And we designed the enhancement plan considering current NDCs' continuation and also cost-effective optimization, presented the required transitions and challenges for regional energy system under these enhancing ideas.

Based on the investigation and evaluation of existing energy policies and current NDCs, this paper proposed a scheme to enhance NDCs for all regions after they finished current commitment at 2030, and analyzed the key challenges for global and regional energy system transition with a 14-region Global TIMES model. Besides, exploration was made on an ideal enhancing plan which begins since 2020 and assumes full carbon trade between regions. Section 2 gives a brief introduction on methodology used in this paper, which includes Global TIMES model and scenarios design; Section 3 presents the main results, which includes CO2 emission pathways and the key features of required energy system transitions; Section 4 makes the conclusion, related discussions are also conducted in this section.

2. Methodology

2.1. Global TIMES model

Global TIMES model is a bottom-up energy system model developed by Tsinghua University, which covers a period of 2010–2050 with a five-year interval [17–19]. As shown in Table 1, the whole world is divided into 14 regions, which allows the introduction of techno-economic characteristics on the regional energy system. Besides, TIMES model provides several different types of parameters and user-defined constraints, therefore diversity forms of energy and climate policies including emission taxes and advanced technology promotion can be described in the policy scenarios, which makes it possible to analyze the energy transformations and energy-related CO2 emission pathways under both regional and global level policies. If there is no specific explanation, CO2 emission in this paper only refers to CO2 emission from energy consumption.

The reference energy system decides the core structure of a TIMES model [20], and the basic structure of China TIMES model has been taken as reference for the design of Global TIMES [21–30]. To provide detailed representation for energy flows covering energy extraction, processing, transmission and end-use, 6 interrelated energy sectors have been constructed: upstream, power, agriculture, building, industry and transportation sector. Upstream sector contains energy supply processes including fossil fuel mining, petroleum refining and heat generating, etc. In power sector, abundant technologies including thermoelectric technology, hydropower technology, renewable energy generation technology have been described [17]. In building sector, residential and commercial subsector have been constructed separately, with the consideration of basic energy service demand including space

Table 1
Model regions.

Model region code	Description
AFR	Africa countries
ANZ	Australia and New Zealand
CAN	Canada
CHN	China
EEU	East Europe countries (excluding countries ever in former Soviet Union)
FSU	Countries ever in former Soviet Union
IND	India
JAP	Japan
KOR	Korea
MEA	Middle Eastern countries
LAM	Latin American countries
ODA	Other developing Asian countries
USA	The United States of America
WEU	Western Europe countries

heating, space cooling, lighting, electric appliances and cooking [18,31]. Energy-intensive industries including steel, paper, nonferrous, nonmetal and chemical industry have been modelled in industry sector [19,32]. Transportation sector considers both passenger and freight traffic demand, and various transportation modes including air, ship, railway and road have been provided [33].

With the technology-rich basis of Global TIMES model, multiple technology policies including efficiency standards and promotion targets can be introduced for the policy impact analysis. Moreover, this technology-rich feature also makes it possible to realize active competition within each sector, therefore details in energy transformation can be discussed. To decide the techno-economic parameters and describe the technical progress, we introduced a exogenous cost curve for each technology, and a few reports and databases for technology projection have been taken as Ref. [34–37]. However, it is worth mentioning that the fuel price fluctuation and governmental subsidies were not considered in model development. By conducting scenario run, the model aims to find the least expensive technology mix to satisfy the projected energy service demand [20]. Take power sector for instance, with the consideration of both traditional technologies like subcritical coal-fired generating technology and advanced technologies like solid biomass CCS generating technology, the model could make different investment decisions to meet with different energy or climate policies.

2.2. Scenario design

4 scenarios were established in this research: REF, POL, 2C-NDC and 2C-OPT, as shown in Table 2.

REF scenario is introduced as a baseline, which describes a future that few significant changes will happen to the global energy system, and its socio-economic development would also follow middle of the road trajectory (SSP2) from Shared Socioeconomic Pathways [38].

To evaluate the impacts of existing policies, in POL scenario, we described major energy policies for each region. Most regional policies are collected from online databases: New Climate policy database [39], Addressing Climate Change policies and measures database [40], Global Renewable Energy IEA/IRENA Joint policies and measures database [41] and Energy Efficiency policies and measures database [42]. The policy collection covered both climate related policies such as renewable promotion and other energy policies including fuel and technology standard. Considering the model functions, these policies are filtered and those can be described in the model are classified as energy supply, energy efficiency, energy structure, new technology and renewable promotion, etc. In addition to the impact evaluation, POL scenario is also used to project the energy system in 2020, providing a baseline for the ideal enhancing plan of 2-degree target.

To introduce 2-degree target in energy system model, RCP 2.6 emission pathway in IPCC Fifth Assessment Report has been taken as Ref. [1]. This pathway is described as likely to realize the 2-degree target, and it provides carbon budget ranges for 2010 – 2050 and 2010 – 2100. In this research, the 2-degree carbon budget for the global energy system is chosen to be 1000 Gt between 2010 and 2050. For current NDCs, CO2 emission cap for each model region are calculated according to the official documents from the NDC registry page of UNFCCC website [3].

2C-NDC scenario describes a mitigation pathway that current NDCs would be obeyed until 2030 and then further enhancement would begin. This scenario contains two stages of model run: firstly, the pre-2030 emissions will be in line with current NDCs; secondly, for 2030 – 2050, the mitigation pathway for each region is calculated exogenously and put into the model as emission constraint. Several assumptions have been made for the enhancement plan after 2030:1. regions with a per capita GDP of over 1000 USD (2005 constant price) should start the absolute mitigation; 2. for those who already have absolute mitigation commitments, the benchmark is set to be the average annual reduction rate of its current NDCs; 3. for those who do not, the reduction rate of Former Soviet Union region and Korea are taken as the benchmark for regions with a per capita GDP of between 1000 and 2500 USD and over 2500 USD respectively. Then, to meet the mitigation requirements of 2-degree target, we gradually increased the reduction rate for every region at the same multiple, and decided the required enhancement when the cumulative emission is close to the carbon budget of 2-degree target.

2C-OPT is another enhancing plan for 2-degree target, which describes a cost-optimal solution. The targeted enhancement would begin in 2020 and the mitigation pathway of each region is decided by the model optimization. During the optimization, an endogenous uniform carbon price for all regions will be generated, indicating that this plan could represent a global cost-optimal plan by realizing free carbon trading between regions.

3. Results

3.1. Current policies and NDCs' impacts on global energy system

In recent years, many regions have implemented policies and measures to promote the low-carbon energy transition, the impacts of the combination of existing policies mix are to be analyzed though.

Existing policies could have significant impacts on the pre-2020 CO2 emission growth. As the energy demand grows, the global CO2 emission from fuel combustion increased by 39% from 2000 to 2015, with an annual growth rate of over 2% [2]. In REF scenario, this increasing trend is expected to continue, the CO2 emission may reach 35 and 55 Gt in 2020 and 2050 respectively. However, with the implementation of energy policies, the emission growth could be greatly slowed down in the short term. In POL scenario, the CO2 emissions are expected to be 33.4 Gt in 2020, indicating the annual growth rate will be only 0.6% during 2015–2020, as shown in Fig. 1(left).

With the intensive effort on energy transformation, China may be able to see big progress in near future. From 2015 to 2020, the annual emission growth rate is only 0.2% in POL scenario, which means the emission growth is almost stagnant during this period. Without these policies, a 2% increase in annual CO2 emission is expected to occur in REF scenario. Among all the policies considered in this research, renewable energy target is most effective to reduce the short term CO2 emissions for China. By implementing renewable promotion target for 2020 [43], over 800TWh of electricity generation could be provided by these additional units, which could lead to 20% reduction of coal consumption in power sector, compared with REF scenario. However, 2020 target can only have limited effects on the sustainable growth of renewable power, other measures on improving the cost disadvantage would be necessary. If the cost reduction goal for solar and wind power

Table 2
Scenarios of this research.

Scenario name	Description
REF	Reference scenario.
POL	Reference scenario with the consideration of regional energy policies.
2C-NDC	2-degree scenario, the NDC enhancement will begin from 2030 onwards, current regional goals will be taken as reference for enhancement.
2C-OPT	2-degree scenario, the NDC enhancement will begin from 2020 onwards, and free carbon trading between regions is allowed.

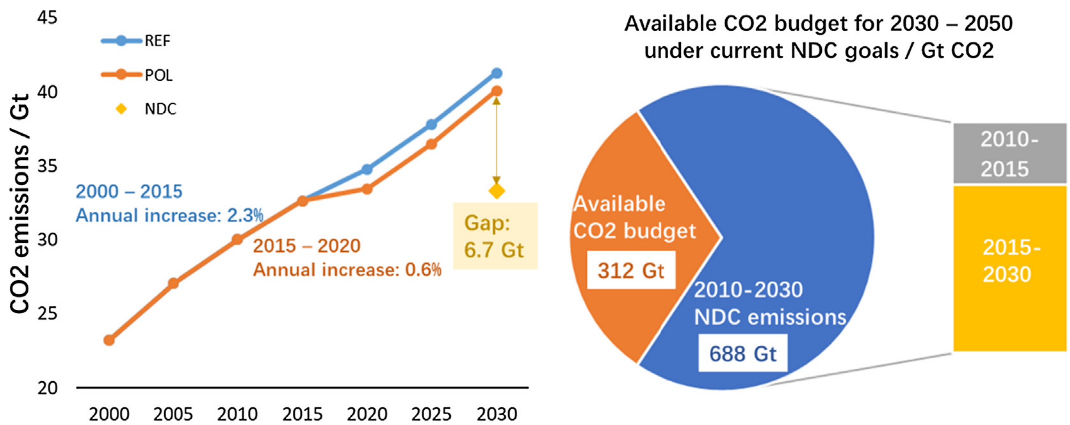

Fig. 1. CO2 emissions from global energy system (left) and carbon budget allocation under 2-degree target with current NDC goals (right).

can be achieved by 2020 and 2025 [43], they may be able to provide nearly 15% of the total electricity generation by 2050.

Although existing policies can greatly influence the per-2020 emission, they are not sufficient for current NDC goals. After 2020, the annual emission growth rate would increase to 1.6% again in POL scenario. In 2030, the global CO2 emission may reach 40 Gt, 6.7 Gt higher than the expected value of NDCs. To achieve the NDC goals, most regions would need more policy support for low-carbon energy transition, specifically, the U.S. is one of the regions with the biggest emission gap between current policies and NDC goal [44].

Affected by the withdrawal from Paris Agreement, the U.S. is now facing an uncertain future in climate mitigation. Nevertheless, if the current NDC is still valid, much effort will be required to close the emission gap. Compared with its NDC mitigation goal, an emission reduction of nearly 1 Gt CO2 is required by 2025 in POL scenario, more mitigation effort would be necessary. Take power sector as an instance, the Clean Power Plan stated to reduce the emissions from power generation by 32% in 2030, compared with 2005′s level. To realize the NDC goal, this reduction should be expanded to 42%, and the electricity generation from solar and wind is expected to be doubled from 2020 to 2030. In 2030, 76% of more investment on power sector is required to support these changes, compared with POL scenario.

Moreover, to realize 2-degree target, there is still a long way to go even if all current NDC goals can be achieved by 2030. Under current NDC goals, the cumulative CO2 emission between 2010 and 2030 will reach 688 Gt. And if each NDC's decrease rate (for both absolute emission and emission intensity) could keep constant in the following years, the cumulative CO2 emission from 2010 to 2050 will reach 1360 Gt. According to IPCC's conclusion [1], this extension is possibly in line with RCP4.5 trajectory, which has a likelihood of less than 50% to realize 2-degree target. With the 2-degree carbon budget assumed in this research, the available CO2 budget for 2030–2050 is only 312 Gt, indicating the mitigation action in these 20 years should be much more ambitious than before.

3.2. NDC enhancement for 2-degree target based on current NDCs

Based on current NDCs, this paper proposed a straightforward enhancing strategy for 2030 – 2050 under 2-degree target, as shown in Fig. 2. The details are explained in Section 2.2.

The former emission reduction rate needs to be increased by 4.6 times if the NDC enhancement begins at 2030. Take Western Europe as an instance, between 2010 and 2030, the annual emission reduction rate is around 1.8% to achieve its NDC goal, and from 2030 onwards, the emission need to be reduced by 10% every year in 2C-NDC. By 2050, the global CO2 emission is expected to decrease by 65% from 2030′s level and reach 11.6 Gt. To achieve this mitigation, the share of renewables in global primary energy demand should reach 43% in 2050, indicating rapid changes in the energy system is required, as this share is only 20% in 2030.

3.2.1. Severe challenges for developed regions

The developed regions would face serious mitigation challenges in 2C-NDC plan. Since most developed regions have already promised rapid reduction on absolute CO2 emission in current NDCs, the following enhancement could be very challenging. Under this proposal, Australia and New Zealand, Canada, Japan, Korea, the U.S. and Western Europe together are expected to account for only 7% of the world total CO2 emissions by 2050 (see Fig. 2), while their share in POL scenario is 22%. In 2C-NDC scenario, the CO2 emission in Japan, the U.S and Western Europe would be reduced by 97%, 95% and 93% by 2050, compared with POL scenario. With such big drops, great transitions in the energy system would become essential for these regions.

For many developed regions, the enhanced NDC goal may be unachievable without significant reduction on energy service demand, especially in the later stage. As mentioned above, many developed regions would experience rapid emission decrease after 2030. For some regions, the emission space is extremely limited in the later period and the required emission reduction may beyond the mitigation potential of the energy system. Therefore, except for deep decarbonization in the energy system, other measures on reducing the energy service demand would also be necessary, especially for hard-to-abate sectors including heavy industry. From model results, by 2050, there would be six regions who are expected to have over 50% of energy service demand reduction in industry sector: Australia and New Zealand, Canada, Japan, Korea, the U.S. and Western Europe.

The cutting on energy service indicates two problems: insufficient energy supply and great welfare loss. On one hand, the reason for energy service reduction is: when the existing infrastructure's activity is restrained by emission constraint, the newly additional capacity is either too expensive or too limited to satisfy the baseline energy service. Take Japan for instance, compared with REF scenario, the energy service demand for both industry and building sector would decrease by over 20% in 2035, within only 5 years of the deep decarbonization. This sharp reduction will come at the expense of less industrial output and poorer energy access of people's daily life. On the other hand, the energy service reduction would result in welfare loss, as the sum of suppliers' and consumers' surpluses will be reduced when the supply price for a same commodity increases. For Japan, compared with REF scenario, the industrial energy service demand would reduce by 69% by 2050, as industry sector is hard to decarbonize in most regions. And the reduction in transportation sector and building sector would be 21% and 27% respectively, as shown in Fig. 3. As a result, the welfare loss brought the energy service demand reduction in Japan may reach 2.6% of its GDP by mid-century.

Meanwhile, a series of transitions towards low-carbon energy

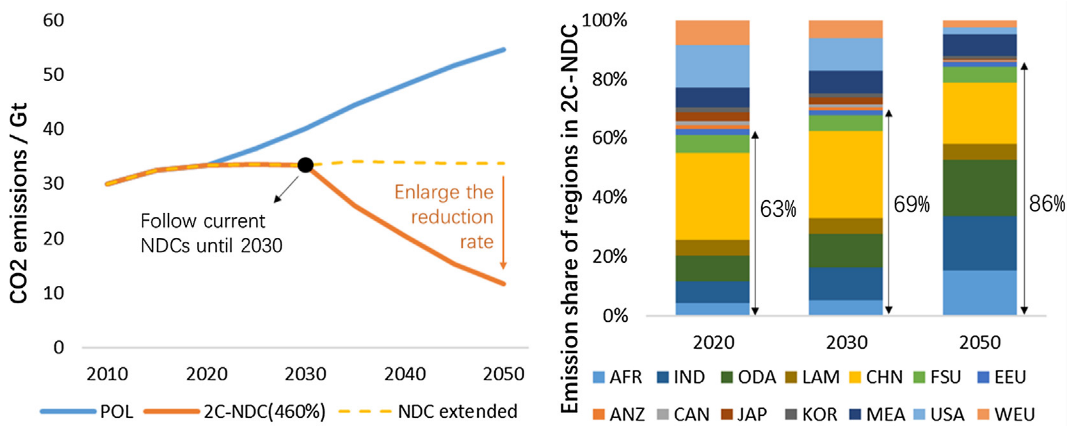

Fig. 2. Global CO2 emission in POL and 2C-NDC scenarios (left) and model regions' emission share (right).

system would also be necessary.

Among all the end-use sectors, building sector is expected to take the lead to realize zero-emission before mid-century. In 2C-NDC scenario, fossil fuels should be completely phased out in building sector since 2040 for the following regions: Australia and New Zealand, Canada, Japan, the U.S. and Western Europe. Therefore, rapid electrification together with renewable promotion would be necessary to provide energy supply. For Japan, geothermal and solar only account for 6% of building sector's total final energy consumption in 2030, and this share should increase by over 1% every year between 2030 and 2050, implying a rapid change in building sector's energy consumption mode.

With the large building stocks in developed regions, there could be obstacles to change the energy consumption modes especially in the early stage, since there is already much existing equipment for heating and hot water. Policy support such as specific subsidy to reduce the initial investment may be helpful.

For most developed regions, power sector is required to be carbon neutral by 2050, but the least-expensive power generation structure may vary a lot among regions for the big differences in their natural endowment. As a water-rich country, Canada may use more hydropower to reduce generation from fossil fuels, by 2050, hydropower may provide 68% of its total electricity demand. In addition, intermittent energy including solar is expected to be widely used to replace the oil-fired power generation in remote regions, the exploration on microgrid may contribute a lot in this transition. While for Japan, with the limited natural resources, gas thermal power technology with CCS would become the second biggest power source in 2050, accounting for 29% of the total electricity generation, which is only after nuclear power technology. In 2017, over 97% gas consumption in Japan was imported as liquefied natural gas, with this large share in electricity supply, targeted policy measures might be necessary for long to deal with the uncertainty in gas trade and price. And in other developed regions, promoting renewables including solar and wind would be a common trend, the share of solar and wind power in electricity generation would be over 35% in 2050 on average. With this promotion, it is worth noticing that the volatility of solar and wind production could bring more challenges for the grid operation.

Power structure improvement needs to install large-amount of low-carbon power plants, which results in huge investment demand. Benefiting from its hydro-dominated power structure, Canada is expected to have a relatively smooth transformation in power sector, in 2050, the installed capacity of non-fossil power plant may only have 20% of an increase from POL scenario. As a result, only 8% of more investment in power sector would be required in 2C-NDC scenario. While the additional investment would be even higher in other regions. For Japan, with 80% increase in non-fossil power capacity in 2050, 19% of more investment in power sector should be necessary.

In summary, if the current NDCs are not going to be enhanced until 2030, developed regions may face challenging mitigation tasks and significant economic cost in post-2030 period.

3.2.2. Required changes in developing regions

Under 2C-NDC scenario, as developing regions could participant in the deep mitigation later than developed regions, they might be able to conduct energy transformation in a more gentle way.

By mid-century, China and India are expected to make the biggest contributions in the absolute mitigation, while their emission cutting share from POL scenario are smaller than most developed regions. In the coming decades, energy demand and CO2 emissions in developing

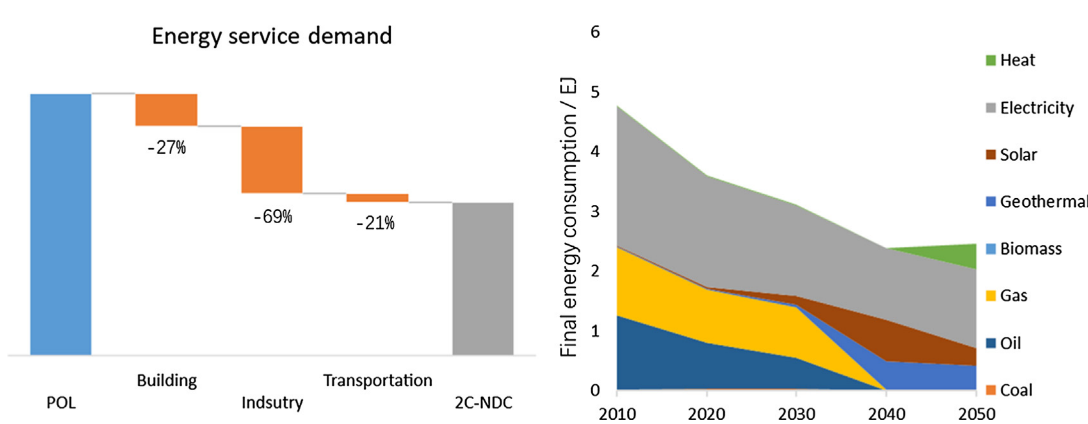

Fig. 3. Energy service demand changes for Japan in 2050 (left), final energy consumption in Japan's building sector (right).

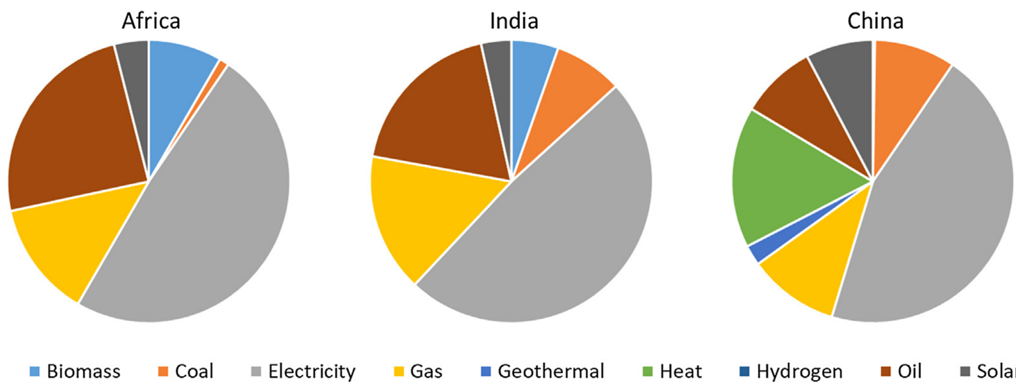

Fig. 4. Final energy structure in 2050 for Africa, India and China.

regions are expected grow rapidly as the economy develops. In POL scenario, China, India, Africa and other developing Asian countries together may account for over 60% of the global CO2 emission by 2050. Since many developing regions haven't set an absolute mitigation goal yet, they might have certain emission growth space before 2030 and also a more gentle mitigation process after. As the biggest emitters in 2050, China and India may contribute 30% and 12% of the total CO2 emission reduction from POL scenario, and their cutting share from POL scenario is 84% and 70% respectively. Considering most developed regions have a share cutting of over 95%, it is indicated that energy transitions in developing regions may be not as drastic as in developed regions.

To achieve the enhanced NDC goals, to increase the electrification level in end-use sectors is the most significant transition for developing regions. In POL scenario, most developing regions would have an electrification level of less than 25% by mid-century. And great improvements would occur to meet the required CO2 emission reduction in the energy system. In 2C-NDC scenario, electricity is expected to provide 45 – 48% of the final energy consumption for all developing regions in 2050, as shown in Fig. 4. The increasing electrification level could greatly reduce the consumption of fossil fuels in end-use sectors, therefore reducing the direct CO2 emission. Take India for instance, in 2C-NDC scenario, the final consumption of fossil fuels would decrease by 56% from 2030 to 2050, which could lead to 66% of CO2 emission reduction in 2050, compared with POL scenario.

Under the rapid electrification, a low-carbon power generation system would be especially important for overall CO2 mitigation. With slower decarbonization process, the power sector in developing regions may still emit certain amount of CO2 by mid-century, while the large reduction on carbon intensity of power generation is also essential. For India, from 2030 to 2050, the carbon intensity should be declined by 9% every year in this scenario. To meet the growing electricity demand with declining carbon intensity, renewables including hydro, solar and wind would be promoted and contribute 11% of the total electricity generation in 2050. More importantly, the fossil fuel generation with CCS are becoming the major power source, their share in total generation may be beyond 60% since 2045, indicating over 500 GW of the capacity should be installed within 10 years. In this case, by 2045, the annual power system investment in 2C-NDC scenario may be 216% higher than in POL scenario.

With 2C-NDC plan, all developing regions are required to realize low-carbon transition in the energy system within 20 years. Although their mitigation tasks are not as urgent and drastic as developed regions, it would still be quite challenging to meet the huge investment demand brought by CO2 emission reduction goal.

3.3. Ideal enhancement under cost-effective optimization

To explore the ideal enhanced NDC pathways under the cost-optimal principle, 2C-OPT plan is introduced, as introduced in Section 2.2.

Compared with current NDC goals, in 2030, 18% of further CO2 reduction should be achieved in the global energy system. In 2C-OPT scenario, the CO2 emission would peak at around 2020 with a peak value of 34 Gt, then begin to decrease at an annual rate of 2.1% and reach 18 Gt by 2050 (see Fig. 5). In 2030, 6 Gt of additional emission reduction is required on the basis of current NDCs. This additional reduction requires the effort from all regions, both developed regions and developing regions should enhance the current mitigation goal from now on. Among all the regions, other developing Asian countries, India, Middle East and China are expected to make the biggest contributions to fill the gap between current NDCs and 2C-OPT plan, accounting for 25%, 18%, 13%, 10% of the total emission reduction respectively.

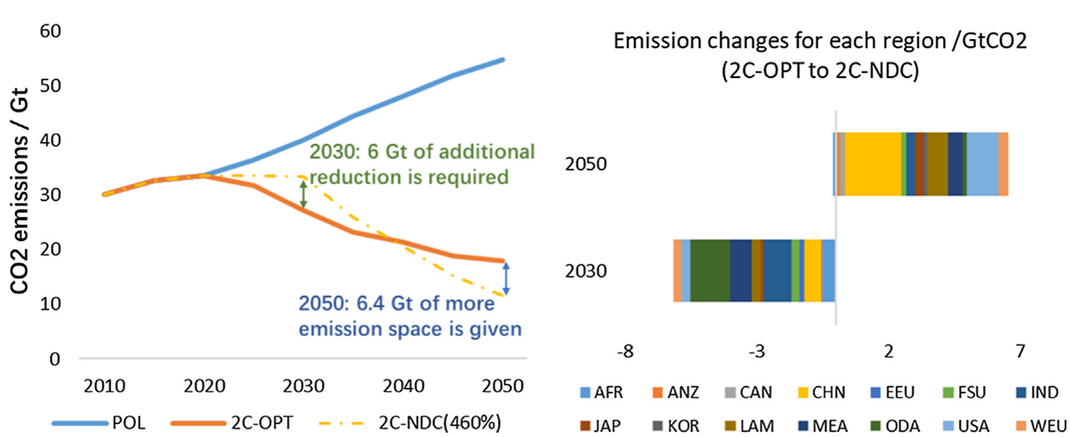

Fig. 5. Global CO2 emission in POL, 2C-NDC and 2C-OPT scenarios (left) and emission changes between 2C-OPT and 2C-NDC scenarios (right).

3.3.1. Major transitions in energy system

As the enhancement begins earlier, more and deeper low-carbon transitions in global energy system may become possible in the next decades.

Power sector is expected to be the biggest contributor for global CO2 mitigation, and it is possible that no more CO2 emissions would come from power generation by mid-century. With current policy, the CO2 emission from power sector would be around 13.3 Gt by 2020. Then, it is expected to gradually decrease to 7 Gt and less than 1 Gt in 2030 and 2050 respectively. To realize this deep decarbonization, and the promotion of renewables should be gradually accelerated. From 2020 to 2025, the annual capacity additions for solar PV and wind power will be around 300 and 340GW, which should be achievable since the installed capacity of solar and wind power in 2017 is over 98 GW and 52 GW respectively [45]. While after 2035, more challenges might arise, as the required annual capacity addition could reach 160 GW and 110 GW for solar and wind power. By 2050, non-fossil fuels may account for 66% of the total electricity generation, beside the renewable promotion, CCS technology may also become increasingly important.

From 2020, most regions need to be very cautious about new investment decisions on fossil-fuel power plants, unless the plants are equipped with CCS technologies. Currently, coal-fired power is the biggest electricity source and generates nearly 40% of the global electricity [2], while model result suggests no more traditional coal-fired power units should be built since 2020. By 2050, only 9.8% of coal-fired electricity generation would come from units without CCS technology. For regions like China and India, which has high dependence on coal-fired power, their former development plans on traditional coal-fired power plants should be reevaluated. Considering their growing electricity demand, it may be not realistic to completely stop building coal-fired plants right now, then, another possible approach is to equip the capture-ready function for all new plants. The situation is similar for oil-fired and gas-fired power technologies, it is also uneconomic to build new plants without CCS since 2020.

Biomass CCS technology could play a vital role in meeting the 2-degree carbon budget. In 2C-OPT scenario, the biomass CCS technology is expected to be used for electricity generation since 2030 and could generate 6.8% of total electricity by 2050, as shown in Fig. 6. As a result, a total of 55 Gt of negative emissions can be brought during 2030 to 2050. Among all the regions, the U.S. may become the pioneer on promoting biomass CCS power generation technologies, a 50 GW of installed capacity may be achieved in 2035. Although starting later, China should plan a rapid promotion from 2035 to 2050, with over 10 GW of the annual capacity addition. To improve the cost effectiveness of biomass CCS technologies, more R&D investment and pilot projects should be necessary in next decade. Besides, bioenergy has a competitive relationship with normal crops for the limited land and water resources, scientific planning on the coordination of energy crop and food crop is essential for the sustainable development. (See Fig. 7).

In 2C-OPT plan, drastic cut on energy service can be avoided, since great energy transformation is more achievable to supply low-carbon energy for end-use sectors.

Fossil-fuel consumption will should be gradually transferred to heavy industries and road transportation. Under the cost-effective optimization, the growth on fossil-fuel consumption will be rapidly slowed down, and most of the remaining consumption would happen in industry and transportation sector. By 2030 and 2050, coal consumed in industry sector would account for 82% and 94% of its final consumption, since certain industrial inputs that are hard to be replaced by other products. For example, in 2050, over 20% and 40% of coal will be consumed to provide feedstock and process heat for heavy industries including steel and chemical industries. As for oil, over 70% of its consumption will happen in transportation sector in 2050, as the alternatives including electricity and hydrogen are still expected to have relatively high cost under current projection.

With the decreasing fossil-fuel consumption, secondary energy would become the major energy source in end-use sectors by 2050. In 2C-OPT scenario, the growth of final energy demand should be greatly slowed down, while the final energy will still increase by 10% and 28% in 2030 and 2050, compared with 2020′s level. To satisfy the energy demand, more secondary energy will be used to replace fossil-fuel. In 2050, the electricity is expected to provide 40% of the global final energy, implying the continuous investment on the power capacities. For developing regions, great challenges would arise to provide continuous energy. On the one hand, as their energy demand would increase rapidly in the next decades, higher growth in electricity generation is required. Take Africa as instance, the electricity demand should increase by 169% from 2020 to 2030. On the other hand, they will also need lots of infrastructures and appliances to achieve this transition, which will also require intensive effort.

3.3.2. Potential economic impacts

The early enhancement and free carbon trading in 2C-POT plan could lead to great reduction on the mitigation cost. From a global perspective, the energy system cost in 2C-OPT scenario may reduce by 10% in 2050, compared with 2C-NDC scenario. Firstly, the early enhancement could help to avoid sudden and drastic changes in the energy system, gradual investment shifts from carbon-intensive infrastructures to low-carbon technologies should be achievable with early planning. Secondly, the free carbon trading makes it possible to fully tap the potential of relatively cheap mitigation options. For example, if the energy efficiency of developing regions can be greatly improved, the mitigation potential can be tapped at a lower cost than to deploy biomass CCS in developed regions.

Especially, the mitigation burden could be partly eased for developed regions, compared with the 2C-NDC proposal. As mentioned in Section 3.2.1, in 2C-NDC scenario, most developed regions need to

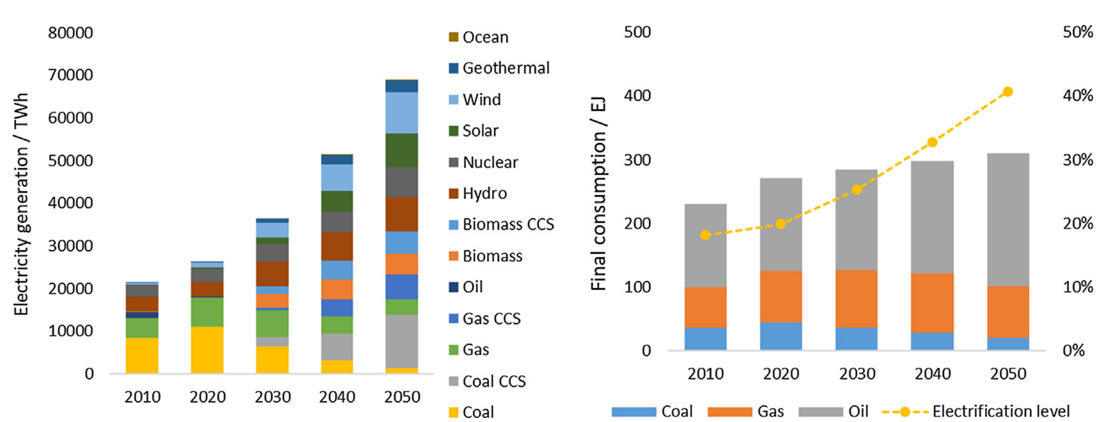

Fig. 6. Global electricity generation (left), final consumption of fossil fuels and electrification level in global end-use sectors (right).

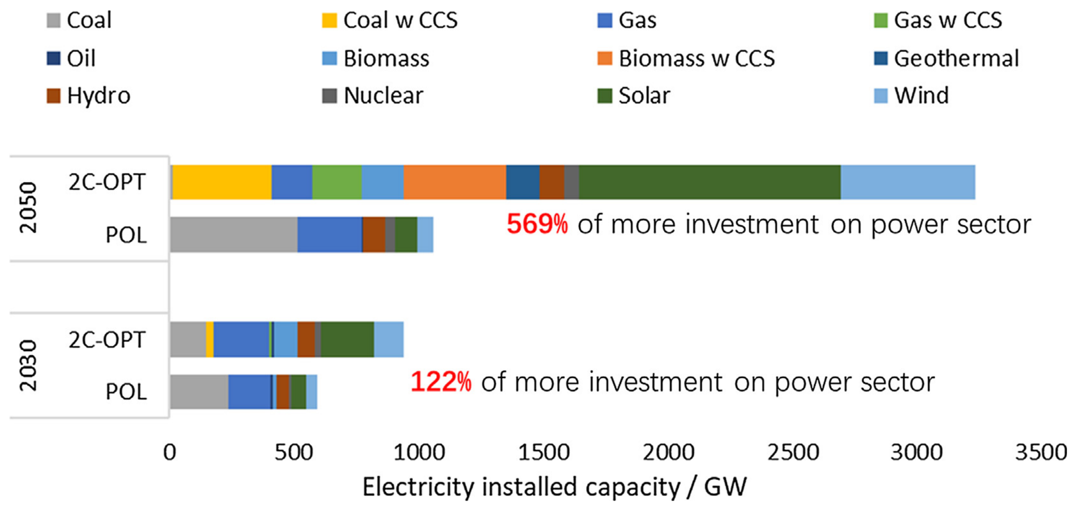

Fig. 7. Electricity installed capacity in 2030 and 2050 for India.

realize an emission-cutting share of 85 – 95% by 2050, compared with POL scenario. While the cutting share of CO2 emission could be reduced to less than 70% in 2C-POT scenario, which would lead to less drastic changes in energy service demand and energy supply system. The system cost reduction in developed regions could be even more than the global average level, take the U.S as an instance, nearly 30% of reduction should be possible in 2050.

Meanwhile, developing regions need to face more challenges on both technical and economical level, especially in the near future. Under 2C-OPT plan, developing regions are expected to begin the mitigation much earlier than 2C-NDC plan, international support on both technology and finance would be necessary. Take Africa as an instance, in 2030, its emission is required to be 30% lower than 2C-NDC scenario. On the one hand, the deployment of new technologies is necessary to realize the CO2 mitigation in the energy system, while some developing regions may not have access to advanced technologies yet. Besides, the improvements on related infrastructures would also require technology support. For example, solar and wind are intermittent and most often stochastic, a flexible power grid with energy storage and dispatch solutions would be essential with their deployment. On the other hand, the required investment for these low-carbon transitions could beyond the affordability of some regions. For India, with the increasing capacities of renewables in near future, in 2030, the investment in power sector would be 122% higher than in POL scenario, the transition could become infeasible if India cannot get any international financial support.

A reasonable and shared carbon pricing method is necessary for the deep decarbonization in the global energy system, the carbon price may reach 1000 $/tCO2 by 2040. One major premise of 2C-OPT plan is that free carbon trading between regions could be achieved with a uniform carbon price for all regions. In 2C-OPT scenario, this carbon price should be around 330 $/tCO2 at 2025, then rapidly increase to over 1000$/tCO2 by 2040, implying 40$ of increase for each year. It is not easy to establish a uniform carbon price for all regions, especially within a short time period, and this high price could also be extremely challenging to achieve. Therefore, other policy instruments may also be essential to supplement the pricing approach.

4. Conclusions and discussions

By introducing energy policies, NDC goals and long-term climate targets into Global TIMES model, this paper presented insights on the current mitigation progress and the remaining gap on 2-degree target. Furthermore, energy transformation challenges to fill this gap were analyzed with the consideration of two possible enhanced NDCs.

Model results shown that the existing energy policies could have significant impacts on pre-2020 emissions, while it is also clear that policies covering more fields and longer periods would be necessary to achieve NDC goals. With the implementation of existing policies, between 2015 and 2020, the annual increase rate of global energy-related CO2 emission could be reduced to 0.6% from 1.3% in REF scenario. In regions with intensive policies, the short-term impacts would be even greater, while these policies' long-term impacts are expected to be limited. For China, with multiple policies covering the recent few years, no significant emission growth will occur before 2020, but a rapidly growing trend will occur again after 2020 as the economy develops. By 2030, the global CO2 emission gap between POL scenario and NDC goals may reach 7 Gt, indicating more effort is required for current NDCs.

Moreover, the necessity of enhanced NDCs has been highlighted. With the assumption that NDCs level of ambitious can be maintained to mid-century, the cumulative CO2 emission between 2010 and 2050 would reach 1360 Gt, which could lead to a likelihood of below 50% to achieve 2-degree target [1]. This result indicated, to realize global 2-degree target, there is still a long way to go even if the current NDC goals should be achieved by 2030.

This research analyzed the energy transformation under two NDCs enhancing method. Although it is not realistic to propose a NDCs enhancement that applied to all regions at present, to explore the consequences and challenges of possible enhancing ideas is still of great importance, as it could provide reference for the future designing for the enhancement.

If the enhancement begins at 2030 after realizing the current NDCs, energy system would have to face drastic changes in the next 20 years, especially for the developed regions. 2C-NDC scenario has been analyzed with two major assumptions: enhancement will not begin until the current NDCs are being realized at 2030; the further enhancement will be designed based on current NDCs of each region. In this scenario, developed regions would face serious mitigation challenges which may result in energy service reduction by a large amount. Take Japan for instance, compared with POL scenario, the CO2 emission needs to be reduced by over 95% in 2050. Despite the deployment of CCS technology, its energy service demand would also need to be cut, and a welfare loss of 2.6% of annual GDP may be caused by 2050.

With the ideal assumption that the enhancement begins at 2020 with free carbon trading across regions, the mitigation pressure in later stage could be greatly eased. In this research, a cost-effective enhancement plan (2C-OPT) has been generated by Global TIMES model. Compared with 2C-NDC plan, in 2050, 2C-OPT plan could reduce the total cost of global energy system by 10%, and the energy service cut in most developed regions could be controlled within 20%. In this plan, developing regions are expected to make bigger mitigation contributions, mainly because the free carbon trading makes it possible to tap the relatively cheap mitigation potential in developing regions. While it is worth noticing that developing regions may face huge challenges both on technology and finance, especially in the near future, international technical cooperation and financial support would become critical.

2C-OPT plan would need higher mitigation ambitious in near future and free carbon trade across different regions. In 2030, 7 Gt of reduction is required in 2C-OPT scenario, compared with 34 Gt of CO2 emission under current NDCs. Power sector is expected to have the fastest mitigation, which would require the huge investment on renewable power plants or CCS power plants, even in developing regions. Take India for instance, the power system investment could increase by 122% in 2030, comparing with POL scenario. Moreover, international carbon trading is also vital. Many developing regions may not have enough capability to tap their mitigation potential, and the weak financial ability is one of the reasons. And if free carbon trading could be conducted, developing regions could gain profits from it to support the low-carbon energy transitions, and developed regions may be able to make mitigation contributions at a lower cost. However, to establish the international carbon market and achieve a reasonable price within a short time can be extremely challenging, other supplementary policy instruments such as shared energy standards could also be essential.

It is worth noticing that this paper has certain limitations, which may need more exploration in future research. Firstly, technical progress was described exogenously at present, while the ambitious mitigation could help to promote new and renewable energy, to introduce endogenous technological progress in model will be essential in future. Secondly, the energy service demand of each region were projected based on SSP2 trajectory, which includes the projection on international trade. However, the future trade pattern may change greatly under 2-degree target, more insights could be provided with introduction of trade models and Global Trade Analysis Project (GTAP) database in further research. Thirdly, this paper only focused two straightforward methods for NDCs enhancement, and burden sharing issues including capacity and responsibility have not been discussed. To further explore NDCs enhancement, more analyses considering multiple burden sharing principles and political factors should be necessary.

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