Renewable and Sustainable Energy Reviews 149 (2021) 111336

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Comparison of sectoral low-carbon transition pathways in China under the nationally determined contribution and 2 °C targets

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ARTICLE INFO

Keywords:
Low-carbon transition
Sectoral comparison
Nationally determined contribution
2 °C target
China
Energy system model

ABSTRACT

National climate targets must be decomposed into key areas to guide mitigation actions. This paper presents a comparative study of China's low-carbon transition pathways at the sectoral level under the nationally determined contribution (NDC) and 2 °C targets, using the energy system model and detailed sectoral information. The results show that each sector plays different roles in terms of emission trends, mitigation potentials, technology roadmaps, investment requirements, and mitigation costs. The power sector is expected to contribute around 50% of the total mitigation. The industry sector has better cost-effective performance, with high mitigation potential and low investment requirement. By contrast, the transport and power sectors account for around 90% of total investment demand. The building and transport sectors have substantial mitigation opportunities that can be realized through technologies with negative mitigation costs. Conversely, the industry sector faces challenges in promoting carbon capture and storage, which has the highest mitigation cost. Compared with the sectoral transition pathways under the NDC target, the 2 °C scenario requires a rapid near-term decarbonization of the power sector and additional emission reductions in end-use sectors. This decarbonization is possible through comprehensive deployment of advanced low-carbon technologies as well as measures that increase investments in low-carbon infrastructure and decrease investments in fossil fuel-based technologies in the power and transport sectors. Therefore, it is important to thoroughly understand the sectoral transition pathways under different climate targets in order to coordinate inter-sectoral actions and resources in a cost-effective manner.

1. Introduction

China is seeking low-carbon transition pathways to achieve the peaking target (to peak national CO_2 emissions around 2030, while making best efforts to peak early) of its nationally determined contribution (NDC) [1]. Simultaneously, it is preparing a long-term low-carbon strategy to comply with the requirements of the Paris Agreement [2]. Detailed sectoral development roadmaps—by decomposing the national target into key areas—can help achieve this goal. Developing these roadmaps involves determining strategic priorities and coordinating mitigation actions across sectors as well as time periods. Therefore, a quantitative assessment of low-carbon transition pathways at the sectoral level, especially through comparison, is necessary, to provide valuable input to policy makers.

Several studies have examined the mitigation potentials of different sectors, especially from the policy or technology perspectives. Various policies have been investigated, including those on fuel economy standard [3], fossil fuel and carbon emission tax [4], public transport promotion, and urban form planning [5] in the transport sector; building codes [6,7], heat metering system retrofitting, and total floor space control [8] in the building sector; de-capacity (removal of excess capacity) of energy-intensive industrial sectors [9] and carbon pricing [10] in the industry sector; and, finally, mandatory renewable targets, green dispatch [11], and carbon emission trading schemes [12,13] in the power sector. By contrast, technology development and mitigation potential estimation are at the center of other streams of sectoral studies, such as the deployment of electric vehicles [14]; natural gas and fuel cell vehicles [15]; energy-efficient home appliances promotion [7,16]; solar heaters; integrated photovoltaic application [17]; renewable power

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https://doi.org/10.1016/j.rser.2021.111336
Received 31 May 2020; Received in revised form 14 May 2021; Accepted 7 June 2021
Available online 15 June 2021
1364-0321/

List of abbreviations

CCS	Carbon capture and storage
EJ	Exajoules
EVs	Electric vehicles
Gt	Gigaton
LC	Low carbon
LEAP	Low emissions analysis platform
m^2	Square meter
NDC	Nationally determined contribution
PECE	Program of Energy and Climate Economics
PV	Photovoltaic
TWh	Terawatt hour
USD	United States dollar

generation [18]; and flexible thermal power plants [19]. There also exist studies on the low-carbon transition pathways of some energy-intensive sub-sectors such as iron and steel [20], cement [21–23], road transport [15], freight [24] and passenger transport [25], and residential buildings [26].

Although both the policy and technology perspectives are applied when evaluating the mitigation effects of specific policies and technologies, these are generally not intended to support the national climate target. The results of studies on emission pathways may vary substantially, such as the projections that CO_2 emissions could peak around 2030 [14] or between 2040 and 2045 [3] for the transport sector and between 2030 and 2040 [10], or as early as 2025 [9], for the industry sector. It is difficult to draw consistent conclusions from individual sectoral studies on how much each sector will contribute to the national target.

A few sectoral studies have tried to connect sectoral pathways and the national target: For example, Pan et al. [27] and Jiang et al. [28] assessed the decarbonization pathway for the transport sector based on estimated national residual carbon budgets or the emissions trajectory consistent with global 2 °C and 1.5 °C targets. Zhang et al. [29] and Lugovoy et al. [30] evaluated the transition roadmap toward long-term zero emissions in China's power sector.

Another common approach is to use a global uniform carbon price simulated by global modeling exercises (mostly the integrated assessment model) to investigate the mitigation roadmap for a target sector [7, 10,31]. The feasibility of the sector's roadmap remains questionable, however, as the circumstances of other sectors are not fully considered in the simulation. Without analyzing other sectors, it is difficult to determine how the target sector will transform in a way that is coordinated with the evolving pathways of other sectors, and how all sectors will contribute to achieving the national climate target. An integrated assessment that includes all sectors is necessary to juxtapose the overall low-carbon target against each sector's characteristics, and thus optimize sectoral development pathways.

System-wide low-carbon transition roadmaps for China based on the energy system or integrated assessment model are a popular fixture in the literature [32–34]. Some overall development indicators, such as total energy consumption, emission trends, non-fossil fuel ratio, overall peaking time, annual emission reduction rate [35,36], and key technologies [37,38], have been produced as well. Several sectoral results, such as fuel demand, CO_2 emissions, and the energy mix of sectors [39, 40], have been useful for policymakers tasked with diagnosing key mitigation sectors and identifying related conditions for achieving the national target. However, these sectoral results usually have been used as supplementary information to support the major findings on the overall pathway [41]—for example, to exemplify the general growth trend of non-fossil fuel consumption through comparisons between reference scenarios and low-emission scenarios in sectors [42,43]. This is not enough to support the government's decision-making on how to decompose national target and coordinate mitigation actions at the sectoral level. A more dedicated sectoral analysis is necessary to produce detailed results on sectoral transition pathways.

Acknowledging the research gaps and China's crucial role in achieving the global climate target, this study aims to conduct a comprehensive analysis of China's sectoral mitigation pathways, using the energy system model and detailed sectoral information. This research will be conducted in a comparative manner, with a focus on sectoral emission growth trends, mitigation potentials, technology options, investment requirements, and mitigation costs, to ultimately identify the different roles and contributions of various sectors as well as the cost-effective mitigation opportunities within and across sectors at different stages. The sectoral transition pathways under the NDC and 2 °C climate targets are also compared, to identify the change in the performances of each sector. The results will provide valuable insights for policymakers on ways to decompose the national climate target, coordinate actions, and make cost-effective investments across sectors in different periods and under different climate target constraints.

2. Methodology

2.1. Program of Energy and Climate Economics-LIU

To develop a low-carbon transition roadmap for China, this study applied the *Program of Energy and Climate Economics-LIU* (PECE-LIU)—a simulation model based on the low emissions analysis platform (LEAP) [44]—with a base year of 2015. Instead of replicating the energy system at the national level, this study constructs a high-resolution model structure, with both final energy demand and energy transformation processes simulated at the sectoral level to capture the characteristics of China's energy system (Fig. 1).

The final energy demand module consists of major end-use sectors, including industry, transport, building, agriculture and others. Each sector is further decomposed into several energy-consuming divisions. For example, in the industry sector, energy-intensive industries such as iron and steel, cement, aluminum, and chemicals are modeled independently. In the building sector, in addition to residential and commercial buildings, which are the regular modeling paradigm in large-scale global models [45,46], northern urban heating—which accounts for a quarter of the energy demand in China's building sector—is simulated separately [47]. Residential buildings are classified into urban and rural to differentiate their energy consumption patterns. The transport sector is divided into passenger and freight, which is further divided into six types of transportation modes and eleven types of vehicles [48].

The energy service demand is developed with the same level of detail for each end-use sector. Various types of energy services—including outputs of major energy-intensive industrial products, different floor spaces by building type and household sizes by resident, person-kilometers traveled for passenger transport, ton-kilometers traveled for freight transport, vehicle ownership, and value added in the rest of the sectors—are considered, so as to match the sectoral structure of the final energy demand module. This feature of the model enables the identification of the sources and contributions of each energy service demand in determining the future energy consumption and carbon emissions growth in each sector.

The transformation module comprises the power generation, heat production, coking and gas works, and refinery sectors to provide a wide range of final energy products from different primary energy sources. Ten types of fuels, including both fossil fuel and non-fossil fuel sources, and thirty-seven types of power generation technologies are modeled for the power sector. Among these, coal-fired power plants are divided into six types of unit groups, which allows us to simulate the coal phase-out in the low-carbon transition process at unit level. With such sectoral details, the PECE-LIU can generate sector-wise energy transition and

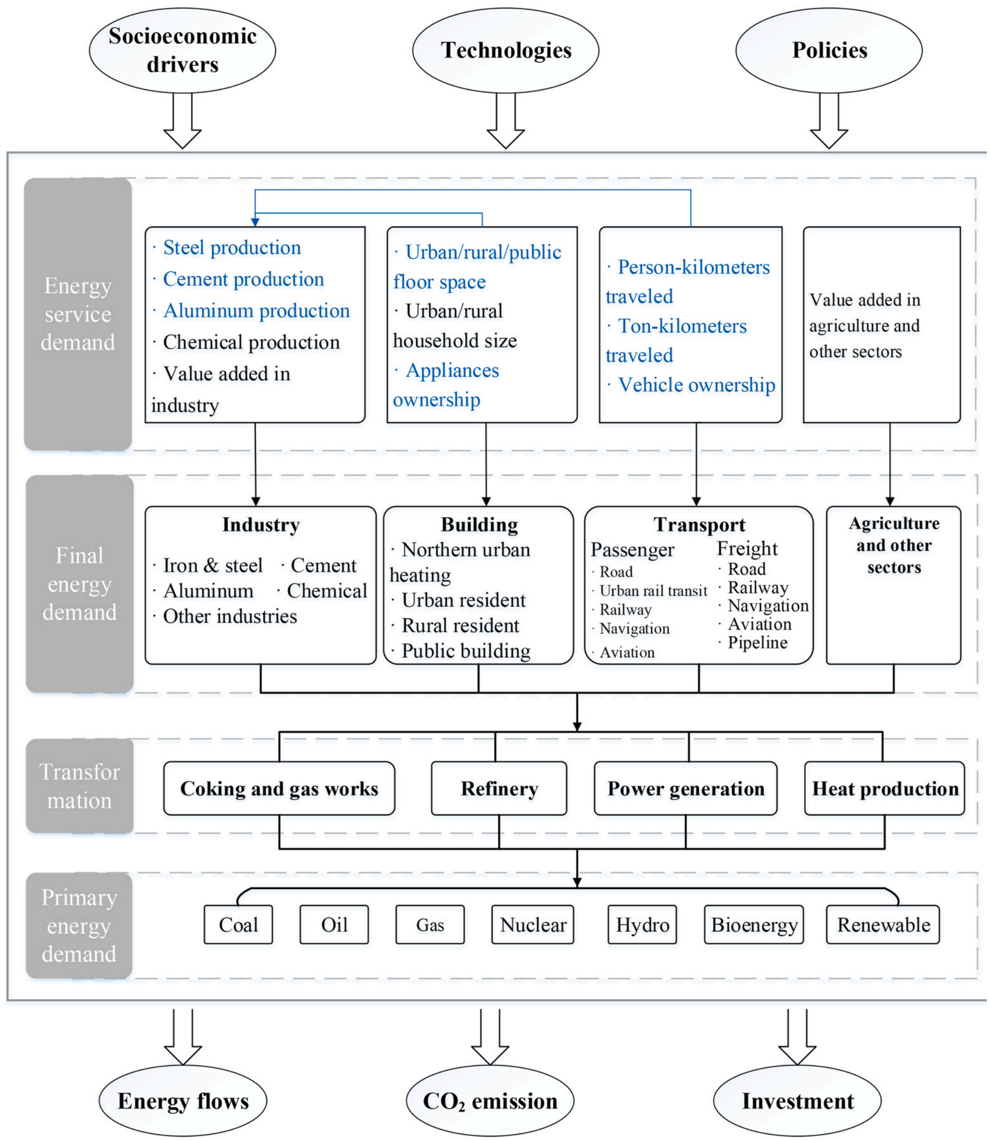

Fig. 1. Program of Energy and Climate Economics-LIU model framework.

CO_2 emission pathways for China. It can be successfully exploited to investigate the long-term low-carbon development roadmap for each sector [49–52].

Apart from the detailed sectoral structure, this study also develops a database with abundant technical and cost parameters for a total of 406 types of technologies covering all sectors in PECE-LIU. Doing so enables the model to not only investigate the mitigation potential under different technological development trends by sector, but also evaluate the corresponding mitigation cost as well as investment requirement. This important feature allows cost-effectiveness comparisons of mitigation opportunities within and across sectors.

Model runs are driven by the energy service demands in four end-use sectors, which are determined based on socio-economic factors such as GDP, population, and urbanization rate. Both GDP and GDP per capita act as key drivers of energy service demand in the building and transport sectors, as well as future added value in the industry sector. The population and urbanization rate determine the total volume of energy service demand and its distribution between rural and urban areas. In particular, a stock-based method is used to determine the future outputs of crude steel, cement, and aluminum based on the development of major consuming industries such as the construction industry (which is associated with total building floor space and transport infrastructure mileage) and the electrical appliances and automobile manufacturing industries (which are related to various home appliances and vehicle ownership). Liu et al. [53] share a detailed method for evaluating the three industrial outputs. With this strengthened connection among the end-use sectors, the interaction simulation between industry and socio-economic drivers improves, thus reducing the uncertainty in projecting energy service demand in China's biggest energy-consuming sector.

After the evaluation of energy service demand, the amounts of final and primary energy consumption to provide such services are derived based on the energy intensities of a combination of technology portfolios according to the diffusion rates of future technologies, which are, in turn, determined by policies, targets, and the assessed technology potential under different scenarios. Simultaneously, the marginal abatement cost of each technology is calculated using the result of net additional cost (increased capital and operation cost minus fuel expense saving vis-à-vis the baseline scenario) divided by accumulated amount of reduced CO_2 emissions during the technical lifetime. The capital investment requirement by technology as well as the sectoral summary results are also provided.

2.2. Scenarios and assumptions

2.2.1. Scenario setting

A climate target-driven approach was adopted in scenario setting. The baseline scenario describes a future under current policies. This scenario reflects the current development trend of slow technology improvement without substantial changes in energy structure; it is used as a reference for comparing the mitigation efforts and investment needs in other scenarios. The NDC scenario considers implementing the targets of China's NDC by 2030, including the CO_2 peaking target around 2030, carbon intensity reduction by 60–65% vis-à-vis 2005 levels, and achieving a 20% non-fossil fuel ratio. A series of "five-year-plans" for each sector are also considered in order to guide the development trend in the short term. The "low carbon" scenario (LC) considers the long-term 2 °C climate target, and determines the related requirements for decarbonization in each sector [37,54]. By comparing the baseline, NDC, and LC scenarios of sectoral pathways, the different roles of each sector in terms of emission contributions, mitigation potentials, technology roadmaps, investment requirements, and mitigation costs, as well as the changes in roles under different targets, can be understood.

2.2.2. Assumptions

The energy service demand projections for each sector were developed using the same set of key socio-economic driving forces, given China's specific development background. Future GDP per capita in 2050 was assumed to reach the current average level of developed countries, which is the long-term strategy target set by the central government [55]. The total population trend was based on a report by the United Nations Population Division, and special attention was given to the ongoing urbanization process in China. Currently, 60.6% of the population lives in urban areas [56]. In the long term, between 2014 and 2050, more than 300 million rural Chinese are expected to migrate to urban areas, with the urbanization level mirroring that of most developed countries [53]. This will have great implications in terms of both improvement in living conditions as well as changes in the energy-use patterns of all residents.

It was assumed that the quality of life in urban areas will continue to improve with income growth, and this includes better heating and cooling conditions in residential buildings, especially in the southern area, where there is no concentrated heat supply. Rural-to-urban migrants will move up the energy ladder and switch to the energy-use patterns of local urban residents after arriving in the city. The living standard gap between rural and urban residents will decrease significantly in the long term, and people will travel for longer distances and more frequently using a combination of various transportation modes. As a result, the construction of national transport infrastructure and buildings will continue, in order to meet the growing demand for more living space and longer travel distances. Residents' rising income will also lead to an increase in the ownership of appliances and vehicles, which, together with infrastructure construction, will drive the demand for industrial materials. The future outputs of crude steel, cement, and aluminum are expected to remain high till 2050, without significant reduction. Key assumptions and estimation results are provided in Table A.1.

Different climate targets also imply different technology innovation and penetration rates. In the baseline scenario, the technology development speed is assumed to follow historical trends, without significant improvement. In the NDC scenario, both energy efficiency and clean, renewable technologies will be promoted at the speed required by a series of sectoral plans in the short-to-mid-term, such as the capacity addition targets of Photovoltaic (PV), wind, and coal power plants in the "13th five-year plan for power sector development" [57]; energy efficiency goals for major energy-intensive industrial products [58–61]; fuel standard improvement schemes; and new energy vehicle promotion plans [62].

In the LC scenario, all technologies at different stages of development will be promoted to their full potential to meet the long-term 2 °C target. To facilitate the comparative analysis, 406 technologies were classified into six groups, namely, energy efficiency, energy mix adjustment in end-use sectors, non-fossil fuel power generation, industrial production process change (with a focus on the deployment of the electric arc furnace in iron and steel production), carbon capture and storage (CCS), and lifestyle changes in terms of shift in travel behavior. Technology penetration rates under different scenarios were assumed based on historical trends, policy targets, and the literature on various technology development roadmaps [63–70]. The detailed assumptions on the future development of the six technology groups under the baseline, NDC, and LC scenarios are outlined in Table A.2. Although developed with 2015 as the base year, the parameters were updated based on the availability of data. Therefore, the energy demand and CO_2 emissions of the three scenarios were calibrated to be consistent with official data until 2019.

3. Results

3.1. CO_2 emission trends by sector

3.1.1. CO_2 emission growth contributions by sector

Emission trends vary across scenarios. In the baseline scenario, total CO_2 emissions are projected to show no sign of peaking till 2050, when they are expected to rise by 81% compared with their level in 2015 (Fig. 2). When taking current policies and targets into consideration, in the NDC scenario, total CO_2 emissions in China are likely to peak around 2030, after which, emissions will decrease at an annual rate of 1.6% and reach 77% of the 2015 level in 2050. To limit the rise in global temperature to less than 2 °C in the long term, total CO_2 emissions will have to peak much earlier, between 2020 and 2025, and then decline at an accelerated rate of 2.1% annually, to reach 41% of the 2015 level in 2050.

The power, industry, and transport sectors are the largest emission contributors, and are together projected to account for 87–89% of CO_2 emissions growth before peaking in all the scenarios. Without rapid technological development, the power and industry sectors are likely to dominate the total emissions increase, each contributing 40% and 22%, respectively, of the total emissions increase in the baseline scenario.

The NDC and LC scenarios are expected to see significant contribution from the transport sector, accounting for, respectively, 73% and 41% of emissions growth before peaking, indicating the important role of the driving forces of urbanization and income rise in generating demand for longer travel in the transport sector. After the peaking of total CO_2 emissions, compared with the decreasing emissions in the power and industry sectors, emissions in the transport and building sectors are projected to continue growing, before reduced emissions from technological improvement outweigh the increased emissions from rising demand. From the perspective of emissions growth contribution by sector, before peaking, the power and industry sectors are likely to be at the center of emission control actions, while after peaking, emission control efforts should focus on the transport and building sectors.

Regardless of climate targets, the industry sector is expected to always play a key role in total CO_2 emissions, with an emission ratio of above one-third in all the scenarios. In the baseline scenario, the proportion of emissions from the industry sector is likely to experience gradual decline, from 43% in 2015 to 34% in 2050, owing to rapid emissions growth in other sectors. In the NDC and LC scenarios, the industry sector is projected to account for an increasing proportion of total CO_2 emissions, reaching 45% and 54%, respectively, by 2050. This indicates the difficulties in decarbonizing this sector. The power sector is projected to move in the opposite direction, with the proportion of emissions rising from 35% in 2015 to 37% in 2050 in the baseline scenario, while decreasing sharply to only 11% and 10% in the NDC and LC scenarios, respectively, because of the phasing out of coal and the deployment of renewable power technology. Both the transport and building sectors are likely to play a major part in total CO_2 emissions,

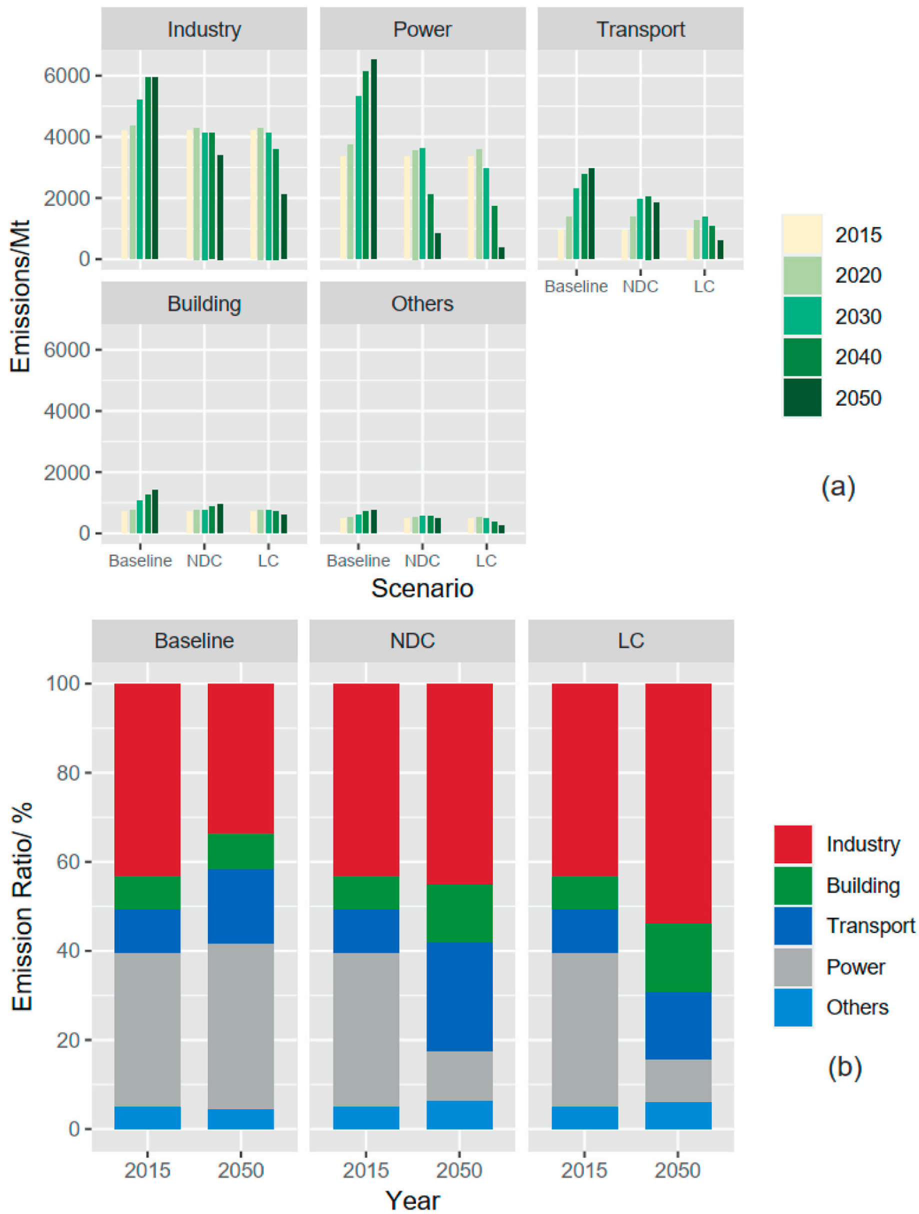

Fig. 2. CO_2 emissions trends (a) and emission ratio (b) by sector and scenario. Note: "Others" includes agriculture and other sectors in the end-use sector, heat production, coking and gas works, and refinery.

with emission ratios rising from 7% to 10% in 2015, respectively, to 13% and 24% in 2050 in the NDC scenario and 16% and 15% in the LC scenario, respectively.

3.1.2. CO_2 emission mitigation potential by sector

The emission reduction potential and mitigation requirements by sector can be demonstrated through scenario comparisons. As shown in Fig. 3, the CO_2 emissions in 2050 are estimated to reduce by 57% (from 17.6 Gt to 7.5 Gt) from the baseline scenario to the NDC scenario, with cumulative emission reduction of 163.7 Gt.

In the LC scenario, CO_2 emissions in 2050 are projected to reduce further to 3.9 Gt, with cumulative emissions of 220 Gt of CO_2 during 2015–2050. Among the different mitigation channels, the power sector is the largest contributor, and can potentially account for 55% of total mitigation in the NDC scenario compared with the baseline scenario, and 47% of the total mitigation in the LC scenario compared with the baseline scenario.

The industry sector is the second largest source of emissions

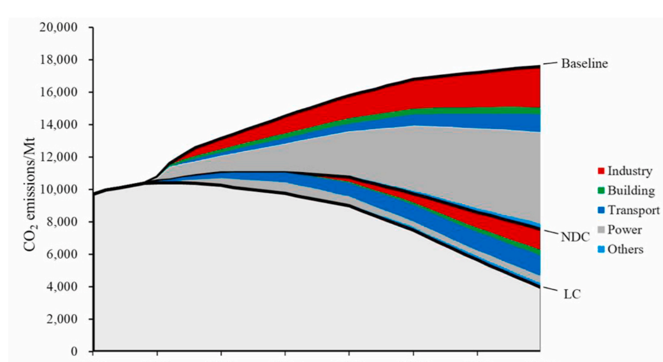

Fig. 3. CO_2 emission mitigation potential by sector and scenario.

reduction, reducing total emissions by 26% in both the NDC and LC scenarios compared with the baseline scenario. An increase in mitigation can be achieved through enhanced measures in the transport sector, which can eliminate 16.7 Gt of CO_2 emissions in the NDC scenario, compared to baseline (accounting for 10% of total mitigation), while an additional 23.1 Gt of CO_2 can be further eliminated in the LC scenario, compared to NDC (accounting for 18% of total mitigation from the baseline to LC scenario). The building and other sectors could each contribute to 6% and 3% of emission reductions, respectively, from the baseline to LC scenario. Thus, the mitigation potential by sector can be used as an important reference by the government when setting emission reduction targets for each sector under different climate targets.

The different overall emission pathways, including peaking time and post-peaking mitigation rates, under different climate targets imply different emission transition roadmaps for each sector. Even though the future outputs of the industry sub-sectors (crude steel, cement, and aluminum) are projected to stay at high levels, the CO_2 emissions curve of the largest emitting sector may bend and peak in or shortly after 2020 with the existing energy-efficient technologies (Fig. 4), laying the foundation for early peaking in the NDC and LC scenarios. The emission reduction rates after peaking are projected to accelerate in the LC scenario at 1.7% annually compared with 0.7% annually in the NDC scenario, reaching half of the 2015 emission levels in 2050.

Opportunities also exist in the power sector—as the CO_2 emissions in the NDC scenario peak around 2025—which, together with the industry sector, is key to supporting the national peaking target of 2030 in the NDC. In the LC scenario, with strict measures to control coal power plant addition after 2020, the power sector may peak earlier, in or shortly after 2020, which is key for realizing the early-peaking requirement (2020–2025) based on the long-term 2 °C target. After peaking, the power sector is likely to experience rapid decarbonization with the phasing-out of coal, reaching about 22% and 11% of the 2015 levels in 2050 in the NDC and LC scenarios, respectively. The early peaking in the industry and power sectors not only provides opportunities for achieving national peaking targets, but also leaves more emission budgets for other sectors that are witnessing rapid development. Driven by growing travel demand, CO_2 emissions in the transport sector can only peak by around 2038, but no signs of peaking are expected in the building sector until 2050.

As required by the strict emission budget constraints in the LC scenario, all possible mitigation measures need to be employed to move the peaking time forward till before 2030 in both the sectors, with the peaking of CO_2 emissions occurring by around 2026 in the transport sector and 2027 in the building sector. This provides implications on how to manage emission pathways by sector in terms of peaking time and mitigation rates that are consistent with national climate targets.

3.2. Transition pathway by sector

3.2.1. Energy transition pathway by sector

Realizing the mitigation pathways involves a fundamental shift in energy structure, with each sector playing a different role in the energy transition process (Fig. 5). Total coal consumption in 2050 will witness a dramatic decrease of 73% and 77%, respectively, in the NDC and LC scenarios, compared with the baseline level. As a result, coal's proportion in total primary energy demand in 2050 is likely to decline from 55% in the baseline to 19% in the NDC and 17% in the LC scenario. The power sector is the most important actor in phasing out coal, by reducing the use of 63–64 EJ (EJ) of coal in 2050, which may account for 62–64% of total coal reduction. It is followed by the industry sector, which may contribute to around 30% of the total reduction in both the NDC and LC scenarios compared with the baseline consumption level. By substituting some coal for heating, the building sector can contribute 6% and 10% of total coal reduction in the NDC and LC scenarios, compared with the baseline scenario, by avoiding 6 and 10 EJ of coal, respectively.

Owing to coal demand for industrial processes and high temperature heating, in 2050, 83% of residual coal consumption is likely to be concentrated in the industry sector in the LC scenario.

Total oil consumption is expected to rise to 58 EJ in 2050 in the baseline scenario (2.5 times the 2015 level), with the transport and industry sector each accounting for 71% and 23% of total demand, and the remaining demand arising from the building and other sectors.

From the baseline to NDC scenario, total oil consumption in 2050 is likely to reduce by 22 EJ. The transport sector can contribute 72% of the total reduction through deployment of energy-efficient engines and electric vehicles (EV), which is not surprising, because of its dominant role in total oil consumption.

The second largest contributor is the industry sector, which may account for 22% of the total reduction. To realize the long-term 2 °C target, an additional 18 EJ of oil consumption will need to be avoided, especially in the transport sector, through the promotion of more advanced technologies and demand-side measures, such as the use of biofuel in heavy road transport, navigation, and aviation, as well as public transport promotion. This may result in 68% reduction in total oil demand in 2050 in the LC scenario vis-à-vis the baseline scenario, with 84% of this reduction being contributed by the transport sector. After the transition, the industry and transport sectors both account for about 45% of oil consumption.

In contrast to the declining trend in coal and oil consumption, natural gas demand is expected to climb up all the way from the baseline to

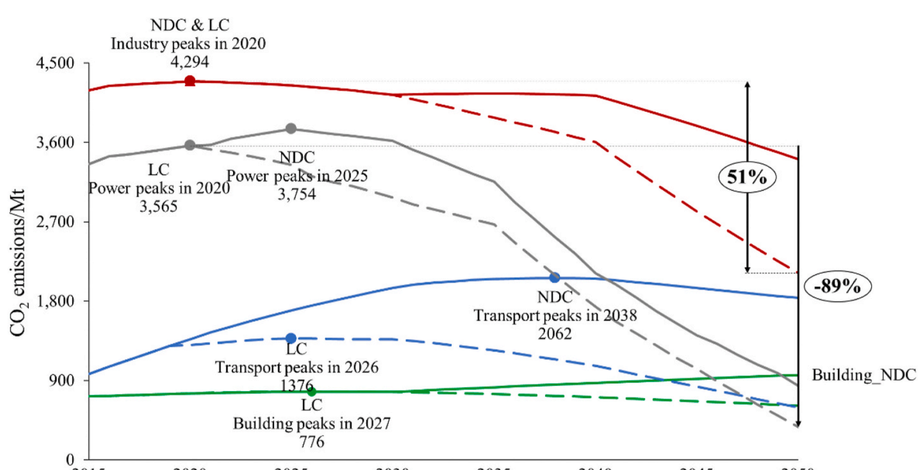

Fig. 4. Peaking pathways by sector under different scenarios. Note: As emissions from other sectors is too small compared to the industry, building, transport, and power sectors, their value is not included in this figure.

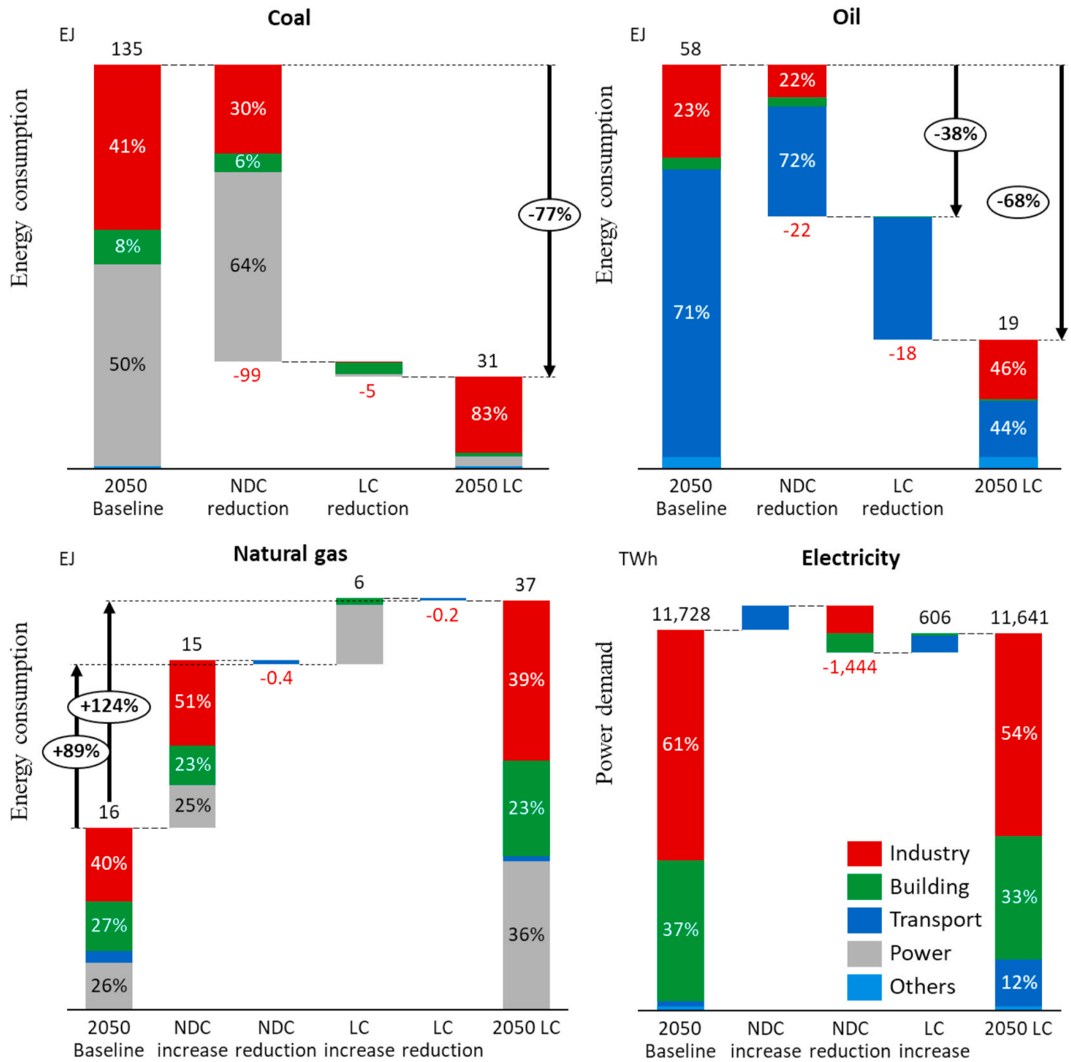

Fig. 5. Energy transition pathways by energy type and sectoral contributions under different scenarios.

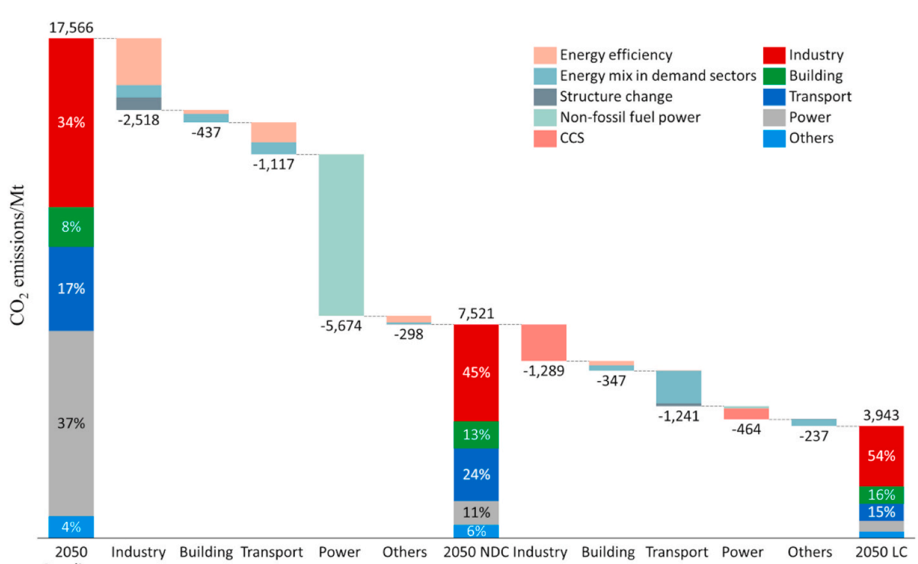

Fig. 6. Mitigation pathway by sector and technology under different scenarios.

NDC scenario and more than double in the LC scenario. As shown in Fig. 5, natural gas consumption in 2050 is projected to rise by 89% in the NDC and by 124% in the LC scenario compared with the baseline level. Serving as an important alternative to coal in boilers, power generation, and building heating, the natural gas demand of the industry, power, and building sectors is likely to witness a substantial increase in the LC scenario, accounting for 37%, 44%, and 19% of total gas growth compared to baseline, respectively.

Electrification is another important factor in the low-carbon transition of the energy system. The share of electricity in total final energy demand (electrification rate) in 2050 is likely to rise from 23% in the baseline scenario to 30% and 34% in the NDC and LC scenarios, respectively. The total electricity consumption levels are similar between scenarios (Fig, 5), but there are structural changes across scenarios. Power demand in the building and industry sectors is projected to decline in both the NDC and LC scenarios as a result of the improved efficiency of boilers and appliances, while electricity consumption in the transport sector is estimated to rise by more than seven times in 2050 in the LC scenario compared with the baseline scenario. This may lead to a substantial increase in its ratio in total power demand, from only 1% in baseline to 12% in the LC scenario.

3.2.2. *Technology roadmap by sector*

Low-carbon technology development and deployment is key to realizing mitigation targets. Different climate targets indicate different technology options by sector. In the transition pathway from baseline to NDC (Fig. 6), in 2050, among all the measures, non-fossil fuel power generation in the power sector contributes to the highest mitigation, that is, 100% of total emission reduction in the power sector and 56% of national mitigation potential. Energy efficiency is key for mitigation technology in end-use sectors, which can reduce 65% and 61% emissions in the industry and transport sectors, respectively. Energy mix adjustment technologies in end-use sectors, including coal replacement by clean energy boilers in the industry sector and fuel replacement by EVs in the transport sector, are important as well. These can lead to decreases in emissions of 18% and 39%, respectively, in the two sectors. An energy structure change from coal-based heating systems to other clean energy sources can also play a key role, and contribute to 71% of total mitigation potential in the building sector. Moreover, a production structure change in the steel producing process can contribute to an additional 17% mitigation in the industry sector through coal reduction.

To achieve a more stringent climate target in the LC scenario, both the industry and transport sectors will have to play increasingly important roles in decarbonizing the energy system. The two sectors can individually contribute an additional emission reduction of 1289 Mt and 1241 Mt in 2050, respectively, accounting for a combined 71% of the total mitigation requirement from the NDC to LC scenarios, followed by 13% from the power sector, 10% from the building sector, and 6% from other sectors.

The major technology options also change under lower emission targets. As energy efficiency technology has almost been deployed to its full potential in the NDC scenario, advanced low-carbon technologies and renewable energy become more important in the LC scenario. Key and emerging options include 90% penetration of EVs by 2050, promotion of biofuel utilization in navigation and aviation, rapid deployment of renewable energy generation, and a higher proportion of clean energy in heating in the building sector. Moreover, technology that is under development, such as CCS, is key to decarbonizing the industry and power sectors in the long term, while a low-carbon lifestyle in public transport can contribute toward the mitigation of an additional 92 Mt CO_2 in the transport sector.

3.3. *Investment requirement and mitigation cost by sector*

3.3.1. *Investment requirement by sector*

Higher investment is required when applying more stringent policies. As shown in Fig. 7, the cumulative capital investment in 2015–2050 is projected to increase from USD 1969 billion in the baseline scenario to USD 3327 billion in the NDC scenario, and to grow further to USD 4210 billion in the LC scenario. The transport and power sectors dominate both total investment demand and additional investment between scenarios, accounting for around 90% of both total capital investment in each scenario and investment additions from baseline to NDC and from baseline to LC.

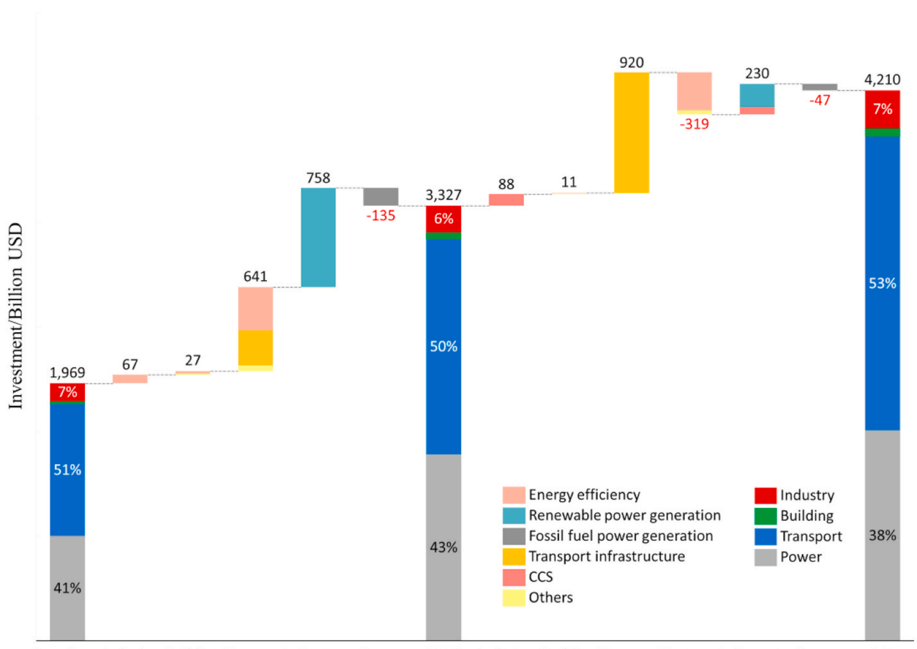

Fig. 7. Accumulated capital investment by sector under different scenarios. Note: 2015 constant price level. Investments for a production structure change in the iron and steel industry toward higher use of the electric arc furnaces are not calculated owing to data limitations. Investment demand in other sectors is not estimated for the same reason. "Others" indicates investment required to shift the energy structure in end-use sectors, such as investment in EVs and heat pumps.

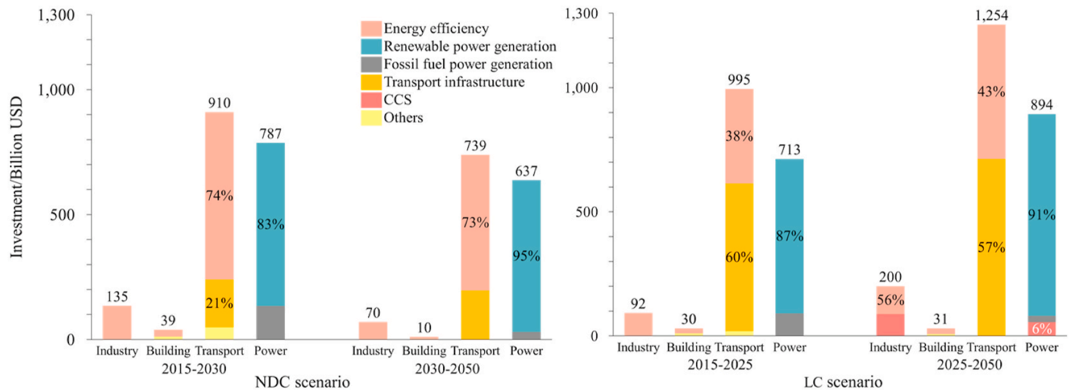

Fig. 8. Cumulative capital investment before and after peaking by sector.

Energy efficiency and infrastructure are the two largest investment areas (Fig. 8); the former dominates total investment requirement in the industry and building sectors, while the latter forms the entire investment demand in the power sector. The two types of investment constitute the major part of total investment in the transport sector. There is a structural shift in investment before and after peaking, with a growing share of investment in infrastructure in both the transport and power sectors, owing to enhanced investment in charging facilities for EVs and the addition of renewable power capacity. The rapid deployment of EVs and promotion of public transport through urban rail transit construction in the LC scenario is expected to increase the share of infrastructure investment requirement substantially to over 50% in the transport sector. In both the industry and power sectors, CCS investment in the post-peaking period is key to further decarbonizing the two sectors, as required by the 2 °C target.

The investment pattern in each sector can not only vary between the mid- and long-term periods, but also across scenarios. A detailed comparison of the investment by technology for each sector across the different scenarios was conducted. The results (Fig. 7) show that, from the baseline to NDC scenario, with renewable power generation technology being promoted in the NDC scenario, a large investment (USD 758 billion) is required for constructing renewable power plants. However, with lower power generation from coal power plants, less money (USD 135 billion) will be invested in coal-fired power projects in the NDC scenario compared with the baseline scenario. Similarly, another USD 47 billion is likely to be saved in coal power plant investments to meet the long-term 2 °C target in the LC scenario.

Rapid growth in the EV penetration rate in the LC scenario indicates less ownership of internal combustion engine vehicles, resulting in less investment for improving the fuel standard of traditional internal combustion engines. The apparently different—sometimes even contradictory—investment patterns across scenarios exemplify the importance of sectoral decomposition of long-term climate targets as well as scenario comparisons. Doing so will strengthen the government's ability to optimize the technology roadmap—investment arrangement—thus avoiding potential stranded assets caused by overinvestment in fossil fuel-based technology or infrastructure, which may impede the process of low-carbon transition because of the carbon lock-in effect.

3.3.2. *Mitigation cost by sector*

Mitigation cost is also a very important factor that can be used to represent the relative difficulties in mitigation in each sector. The marginal abatement cost curve in 2050 in Fig. 9 indicates that almost all technologies in the transport sector, most technologies in the building sector, and a large proportion of technologies in the industry sector have negative marginal abatement costs. Thus, net incomes can be achieved by applying these technologies through higher energy cost savings compared with additional capital and operational investment.

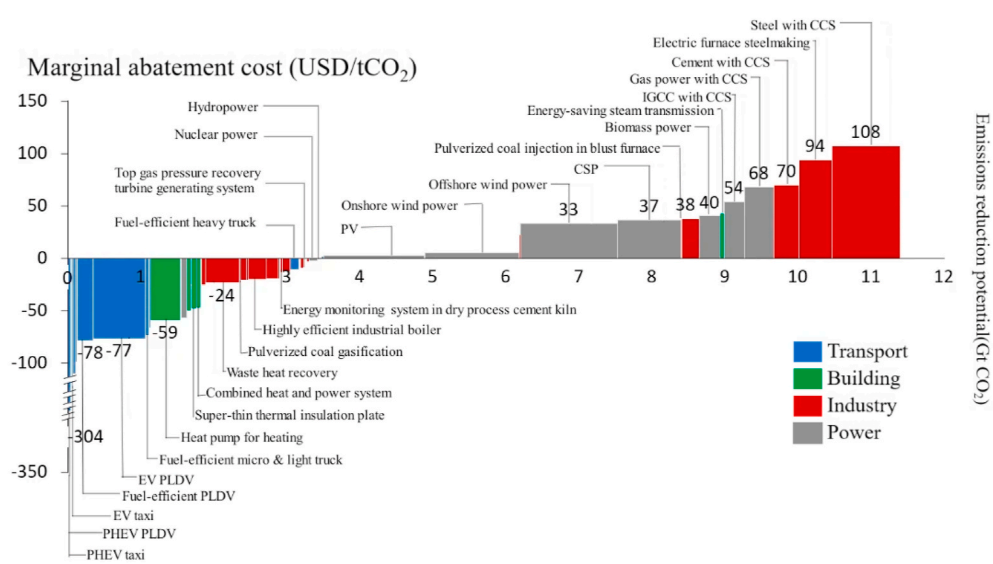

Fig. 9. Marginal abatement cost curve in 2050 under the LC scenario. Note: Owing to lack of data, marginal abatement costs of transport infrastructure (charging facilities and urban rail transit); biofuel in vehicles, navigation, and aviation; and some energy-structure change equipment (such as electric arc furnaces, natural gas boilers in the industry sector, and solar water heaters in the building sector) are not calculated.

Almost all power generation and parts technologies in the industry sector have positive marginal abatement costs. The technologies with negative marginal abatement costs can contribute 35%, 77%, 54%, and 4% of the total mitigation potential in the industry, building, transport, and power sectors, respectively. However, with a carbon price of 5 $\$/tCO_2$, 47% of the mitigation potential becomes feasible in the power sector. By contrast, more than 45% of the mitigation potential in the industry sector is possible only when carbon price is as high as 108 $\$/tCO_2$. This implies that a large proportion of mitigation potentials in the building sector and more than half in the transport sector can be realized relatively easily. Appropriate policies need to be formulated to promote the adoption of low-carbon technologies in the power sector, while enhanced policies are further needed to provide strong support for decarbonization in the industry sector.

From a technological perspective, energy-efficient technologies in all sectors generally have negative marginal abatement costs, which should be the top priority for promotion. For example, fuel-efficient light-duty vehicles (including private cars, taxis, and official cars) have a marginal abatement cost as low as -78 to $-99\$/tCO_2$. The marginal abatement cost of super-thin thermal insulation plates in the building sector is around $-50\$/tCO_2$. The abatement costs of most energy-efficient technologies in the industry sector (including highly efficient boilers and top gas recovery turbine generating systems) are in the range of -13 to -25 $\$/tCO_2$. Plug-in hybrid electric vehicles have the best economic performance, with a marginal abatement cost of around -300 $\$/tCO_2$. While PV and onshore wind power technologies are likely to become competitive in the long term, advanced renewable energy generation technologies, such as offshore wind power and concentrated solar power generation technologies, are expected to have positive marginal abatement costs by 2050. CCS in the industry and power sectors are assumed to remain the most expensive mitigation choices in the long term. In this regard, when formulating technology development roadmaps at the sectoral level, if economic performance is taken as a key indicator, the promotion of energy-efficient technologies and EVs should be the priority, followed by renewable power generation technologies, and finally CCS deployment, which needs the strongest policy support.

4. Discussion

The study's results reveal that various sectors perform differently under different climate targets in terms of emissions contribution, mitigation potential, mitigation cost, and investment requirement. This finding will serve as a valuable reference for the government when deciding on the appropriate decomposition method of the overall target. For example, the mitigation potential by sector can be used as weight to determine the amount of relative reduction in emissions for each sector. The mitigation cost by sector, in ascending order, indicates those sectors that need to start mitigation immediately and those that need further policy support or a proper market environment before achieving their full emission reduction potential. The dynamic roles of each sector over time and the detailed technology evaluation results are also important information for the government when developing mid-to-long-term action plans and strategies with regard to technology development and investment.

In the following text, the different aspects and performances of each sector are summarized to provide a comprehensive assessment result. The power sector performs the best in terms of total mitigation potential, the industry sector has better cost-effective performance with both high mitigation potential and low investment requirement, and the transport and power sectors are expected to account for around 90% of total investment demand. The building and transport sectors have substantial mitigation opportunities that can be realized through technologies with negative mitigation costs, while the industry sector faces challenges in promoting CCS, which has the highest mitigation cost.

One key finding of this study that has seldom been discussed before is that different climate targets imply different technology roadmaps and investment arrangements, which may sometimes conflict. Taking the power sector as an example: In the baseline scenario, coal power plants are a preferred option when constructing new power plants till 2050. In the NDC scenario, no new coal power plants will be allowed after 2025 according to the NDC peaking target. In the LC scenario, coal power plant construction will stop after 2020 to adhere to a more stringent climate target. Similarly, in the transport sector, as EVs achieve greater penetration, less money will have to be invested in developing energy-efficient internal combustion engines. This leads to very different investment arrangement among the scenarios. For example, in the baseline scenario, most of the investment in the power sector is likely to be on coal power plants, while in the NDC and LC scenarios, most of it is expected to be devoted to non-fossil fuel power plants such as solar PV and wind.

The different investment requirements across scenarios emphasize the importance of decomposing the target at the sectoral level and aligning long-term targets with short-to mid-term actions. This will not only improve the feasibility of the overall target, but also avoid unnecessary waste of resources. Compared with the baseline scenario, the NDC pathway can save a total of USD 135 billion in coal power plant investment. The LC roadmap will further reduce investments of USD 289 billion in fuel-efficient engines and another USD 47 billion in coal power plants. Otherwise, without considering a long-term target, the current investment pattern may endanger the ability to achieve climate targets by locking the energy system on to a fossil fuel-dependent path and creating financial risk for the whole economy through stranded assets. It is also worth noting that, besides the NDC and 2 °C targets, other important climate targets, especially the 1.5 °C target and the recently announced 2060 carbon neutrality target, should also be considered, as they may entail new technology not included in previous research (such as hydrogen). This may result in new investment patterns that are different from both the NDC and 2 °C scenarios. However, the 1.5 °C and carbon neutrality scenarios are not considered in this study and are left to future research.

5. Conclusions

This study conducts detailed comparisons of low-carbon transition pathways at the sectoral level in China under the NDC and 2 °C targets. The results show that each sector plays very different roles in terms of future CO_2 emissions trends, mitigation potentials, technology roadmaps, investment requirements, and mitigation costs. The sectors' performances also change under different climate targets. Table 1 provides an overview of the similarities and differences in the characteristics of the sectoral transition pathways under the NDC and 2 °C targets, some of which are highlighted here.

First, as the current largest sources of emissions, the industry and power sectors are major contributors to emissions growth in the near term, especially before peaking, while the transport and building sectors are expected to dominate the emissions increase in the long term owing to urbanization and rising incomes. The power sector has the largest mitigation potential, followed by the industry sector. The early peaking in the industry and power sectors before 2025 is fundamental to realizing the national peaking target.

Second, when transforming the energy system, the power and industry sectors play key roles in phasing out total coal consumption, while the transport sector dominates the effort to reduce oil consumption. Non-fossil fuel power generation can contribute around half of total mitigation, followed by energy efficiency and energy mix adjustment technologies in end-use sectors.

Third, the transport and power sectors are estimated to account for around 90% of total capital investment requirements, owing to the infrastructure-dependent nature of the two sectors. There is a structural shift in investment before and after peaking, with a growing share of investment in infrastructure in both the transport and power sectors, which is a result of enhanced investment in charging facilities for EVs

Table 1
Key characteristics of sectoral low-carbon transition pathways and comparisons between NDC and 2 °C targets.

Key sectoral characteristics	Differences between NDC and 2 °C targets
CO_2 emissions trend by sector: Power, transport, and industry sectors are estimated to dominate total CO_2 emissions growth before peaking, while transport and building sectors are expected to be major contributors after peaking. Future share of emissions from the industry sector is likely to rise to around 50%, becoming the largest source of emission, followed by increasing shares from building and transport sectors, while power sector may witness significant decline in emission ratio. The power and industry are the largest mitigation sectors; their early peaking is key for realizing the national peaking target.	Compared with the NDC transition pathway, where there is no sign of peaking in the building sector and late peaking in transport sector, under the 2 °C target constraint, the peaking time of both the building and transport sectors need to be achieved before 2030, with accelerated mitigation rates after peaking in all sectors.
Transition pathway by sector: Power sector plays a leading role in reducing total coal consumption by phasing out coal power plant, followed by industry sector, while the transport sector dominates the reduction in oil consumption. Non-fossil fuel power generation is the most important mitigation technology, which can contribute to around half of total mitigation, followed by energy efficiency and energy mix adjustment technologies in end-use sectors. CCS application, production process shift, and low-carbon lifestyle are also important measures in decarbonizing industry, power, and transport sectors.	As energy-efficient technology has been deployed to almost its full potential in the NDC pathway, the 2 °C pathway will depend more on renewable technologies, advanced low-carbon technologies, and demand management measures, including higher penetration rate of renewable power to phase out coal in the power sector, rapid deployment of EVs and biofuel in transport sector, CCS application in industry and power sectors, and public transport promotion.
Investment requirement and mitigation cost by sector: Transport and power sectors together account for around 90% of both total capital investment requirement and additional investment across the scenarios. Energy efficiency dominates investment requirement in the industry and building sectors, while infrastructure accounts for the entire investment demand in the power sector. There is a growing share of investment in infrastructure in transport and power sectors after peaking.	Under the 2 °C pathway, the investment share of infrastructure is projected to increase substantially to over 50% in the transport sector owing to rapid deployment of EVs charging facilities and urban rail transit construction. CCS investment will be key to decarbonize both the industry and power sectors in the post-peaking period.
A majority proportion and over half of the mitigation potential that have negative marginal abatement costs can be easily realized in building and transport sectors. Most mitigation technologies in the power sector have positive marginal abatement costs, which may need appropriate support from the government. The strongest policies will be needed to decarbonize the industry sector, which has the highest abatement cost for CCS.	Investment patterns differ significantly between NDC and 2 °C pathways, where more investment in renewable energy generation technologies and low-carbon transport infrastructure is needed under the 2 °C target, while less money is required for coal power plant and fuel-efficient internal combustion engines.

and the addition of renewable power capacity. Energy-efficient technologies and EVs in end-use sectors have negative marginal abatement costs, with the potential to be easily realized. Most low-carbon power generation technologies in the power sector have positive mitigation costs that need a higher carbon price or appropriate government support, while CCS has the highest mitigation costs, and may need the strongest policy support.

There are also some important differences between the NDC and 2 °C pathways. *First*, the 2 °C pathway requires reaching the national CO_2 emissions peak around 2020–2025, which is five to ten years earlier than NDC peaking target. This requires a profound near-term decarbonization of the power sector compared to that in the NDC scenario (five years earlier in peaking), and additional emission reductions in the building and transport sectors, in order to move forward the peaking time of both sectors to before 2030. The much lower emission level by 2050 in the 2 °C pathway also implies accelerated mitigation rates after peaking in all the sectors.

Second, as the mitigation potential of energy-efficient technologies has largely been exhausted in the NDC scenario, the 2 °C pathway requires comprehensive mitigation measures and depends more on advanced low-carbon technologies, including higher renewable power generation, CCS application in the power and industry sectors, EVs and biofuels in the transport sector, and demand management through public transport promotion.

Fourth, in addition to higher total investment requirement in the 2 °C scenario vis-à-vis the NDC scenario, significant differences in investment patterns exist between the two pathways. The 2 °C pathway requires a higher proportion of low-carbon infrastructure investment, including renewable power plants, charging facilities for EVs, urban rail transit, and CCS on the one hand, and less investment in fossil fuel-based technology, such as coal-fired power plants, and efficient fuel combustion engines on the other.

The findings of this paper highlight the importance of decomposing the national target by sector for the government. A comprehensive understanding of the different roles of each sector in the transition pathways will enable policymakers to prioritize key areas, determine targets by sector and period, and coordinate mitigation actions and resource allocation across sectors in a cost-effective way.

One key finding from the scenario comparison is that the mitigation pathway by sector between the NDC and 2 °C scenarios cannot be undertaken in a simple, linearly strengthening manner. Caution should be exercised in identifying the different technology roadmaps and implied investment patterns for the two pathways. The apparent differences in investment structure between the NDC and 2 °C scenarios implies that it is very important to set a long-term climate target and align the long-term goal with near-to mid-term actions to avoid wasting money and prevent the possible risk of a carbon lock-in effect caused by current fossil-fuel investments.

Credit author statement

Junling Liu: Conceptualization, Methodology, Formal analysis, Writing – original draft, Revision. Mingjian Yin: Investigation, Visualization. Qinrui Xia-Hou: Investigation, Visualization. Ke Wang: Conceptualization, Supervision. Ji Zou: Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (grant number 72004043); Shenzhen Low Carbon City Big Data Engineering Laboratory (grant number ShenzhenDRC[2017]1089); and the Discipline Construction Program on Combating Climate Change and Low Carbon Economics of the Harbin Institute of Technology, Shenzhen, China (grant number ShenzhenDRC[2018]725).

Appendix

Table A.1
Key assumptions for energy service demand

Sector	Energy service demand	2015	2050
Industry	Crude steel output (million ton)	804	766
	Cement output (million ton)	2359	2094
	Aluminum output (million ton)	31	47
Building	Urban household size (people/household)	2.8	2.7
	Rural household size (people/household)	3.8	3.0
	Urban residential building floor space (billion m^2)	21.9	70.8
	Rural residential building floor space (billion m^2)	23.8	14.8
	Public building floor space (billion m^2)	11.6	22.1
	Appliance ownership (million)	1305	2479
Transport	Person-kilometers traveled (billion)	9717	24,265
	Ton-kilometers traveled (billion)	17,836	77,085
	Vehicle ownership (million)	163	605

Source [49–51]:

Table A.2
Assumptions for each sector by scenario

	Baseline	NDC	LC
Industry	**Energy efficiency:** 5–12% increase by 2050 to reach the current levels of developed countries **Energy mix:** maintains current status **Production process:** maintains current status **CCS:** no application	**Energy efficiency:** 8–30% improvement by 2050 to become the world leader **Energy mix:** 36–63% coal substituted by gas and electricity in boilers **Production process:** 33% of crude steel output from electric steel-making process **CCS:** no application	**Energy efficiency:** deployed to full potential **Energy mix:** coal substituted by gas, electricity to full potential **Production process:** the same as NDC **CCS:** to be applied in the iron and steel and cement industries after 2030
Building	**Energy efficiency:** improves slowly **Energy mix:** no change.	**Energy efficiency:** overall energy efficiency to double by 2050 **Energy mix:** coal substituted by gas and electricity in heating	**Energy efficiency:** deployed to full potential **Energy mix:** coal substituted by gas, electricity, and heat pump for heating and rural residents
Transport	**Energy efficiency:** 17–30% improvement in fuel economy **Energy mix:** no change **Lifestyle:** no change	**Energy efficiency:** to become the world leader **Energy mix:** EV ownership to reach five million and twenty-five million by 2020 and 2030, respectively, and 41% market penetration rate by 2050 **Lifestyle:** travel mode dominated by private vehicles	**Energy efficiency:** to become the world leader **Energy mix:** EVs to become cost competitive after 2020 and reach 90% market share by 2050; biofuel deployed in coaches, freight vehicles, navigation, and aviation **Lifestyle:** public transport mode developed to full potential
Power	**Energy efficiency:** 9% improvement in thermal power plant **Power generation mix:** dominated by coal power plant **CCS:** no application	**Energy efficiency:** 9% improvement in thermal power plant **Power generation mix:** no new coal power plant to be added after 2025; renewables like solar and wind to be promoted rapidly **CCS:** no application	**Energy efficiency:** the same as NDC **Power generation mix:** no new coal power plant to be added after 2020; renewables like solar and wind energy to be promoted rapidly **CCS:** to be applied in coal and gas power plants after 2030

Note: The technology development assumptions for the baseline scenario are based on historical trends. For NDC and LC scenarios, short-to-mid-term sectoral climate-related targets (such as those announced in China's NDC and a series of "five-year plans" for different sectors) are used as references to set several technology development assumptions. The rest of the assumptions are simulation outcomes of the emission target implied in the scenarios, that is, the 2030 peaking target in NDC and 2050 emission level required by the 1.5 °C target.

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