RUC-MESSAGEix-China (RMC)

Model Documentation

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Dec, 2024 (Updating)

1. Overview

1.1. Background

The RUC-MESSAGEix-China (RMC) model is an energy-economy-environment (E3) integrated assessment model for China based on the open-source modelling framework MESSAGEix (IIASA ECE Programme, 2020). It has been co-developed and maintained by Prof. Zhou Wenji's group at the School of Applied Economics, Renmin University of China and Prof. Ren Hongtao at the School of Business, East China University of Science and Technology.

1.2. Basic principles

The RMC model is based on the globally renowned integrated assessment modelling framework MESSAGEix, which is developed and maintained by the International Institute for Applied Systems Analysis (IIASA), and widely used for integrated assessment models (IAMs) and energy system models (ESMs) (IIASA ECE Programme, 2020). MESSAGEix is highly flexible and suitable for constructing local, national, multi-regional, or global energy system models, and can reflect the dynamic evolution of energy systems over multiple periods and incorporates rich technological details. While typically used for analyzing energy systems at regional levels, this framework can also be applied to study individual energy sectors, such as electricity or heat.

As an optimization modelling framework, its mathematical principle involves an overall objective function to minimize the total discounted system cost over the whole modelling horizon, which aggregates the costs of all energy technologies, including investment and operating costs of technologies, extraction costs of exhaustible resources and generation costs of renewable energy, emission taxes, and other expenditures. In addition, constraints can be added as needed, such as limiting total carbon emissions from the energy system (or carbon emissions from individual technologies).

More features and functions of MESSAGEix can be found from its online documentation (https://docs.messageix.org/en/latest/index.html) and related literatures, e.g. (Huppmann *et al.*, 2019) . The source code is available from the Git deposit website (https://github.com/iiasa/message_ix)

1.3. Spatial-temporal resolution

The RMC model currently covers 31 province-level administrative regions in mainland China, accounting for the energy system structure, economic development pattern, and resource endowment etc. at the provincial scale.

To assess the systemic impact of China's carbon-neutral goals, the current version of RMC is calibrated to 2022 and has a modelling horizon from 2025 to 2060 with a five-year time interval. Thanks to the flexibility of the MESSAGEix framework, both the time range and time step can be adjusted to meet various research needs.

2. Socio-economic drivers

Population and economic development levels exert profound influences on the capacity to mitigate and adapt to climate change (O'Neill *et al.*, 2014). Demographic change and economic growth are the key determinants of future energy demand in the RMC model, and are exogenous to the model.

2.1. Population

The demographic change for each region is calculated with reference to the projection from Chen et al and the United Nations World Population Prospects (Chen *et al.*, 2020; UN DESA/Population Division, 2024). Chen et al. estimated China's provincial population from 2010 to 2100 by age (0–100+), sex (male and female) and educational levels (illiterate, primary school, junior-high school, senior-high school, college, bachelor's, and master's and above) under five shared socioeconomic pathways (SSP1-5). Our study uses the SSP2 projection, which represents an intermediate path where future development follows the historical pattern (O'Neill *et al.*, 2017). As the projection from Chen et al. starts 2010 and does not include the latest trend, the data from the National Bureau of Statistics (NBS) and the demographic projection for the whole country from UN World Population Prospects are used to calibrate and update the province-level projections. The results show that China's national population peaks at 1.4 billion people in 2021, and slowly declines thereafter, falling to 631 million by the end of the century. Fig. 2 shows the calibrated population change for each region in the model. Align with the original results from (Chen *et al.*, 2020), the calibrated demographic results differentiates between rural and urban demographics, and additionally taking into account varying household income levels and energy consumption structures.

Figure 1 Provincial trends of total population in China from 2020 to 2100

2.2. Economic growth

The future economic growth at the provincial level used in the model is obtained from the GDP projections from in relevant literature (Bai and Zhang, 2017; Leimbach *et al.*, 2017; Christensen, Gillingham and Nordhaus, 2018; Pan *et al.*, 2020; Jing *et al.*, 2022; Yang *et al.*, 2024). The changes in GDP per capita in each region can be further derived from on the projections of population and GDP. The average income is projected to grow by a factor and exceed 100 thousand USD/capita by the end of the century. Figs. 3 and 4 depict a future of progress where the provinces achieve significant economic growth, with convergence of income per capita across different regions.

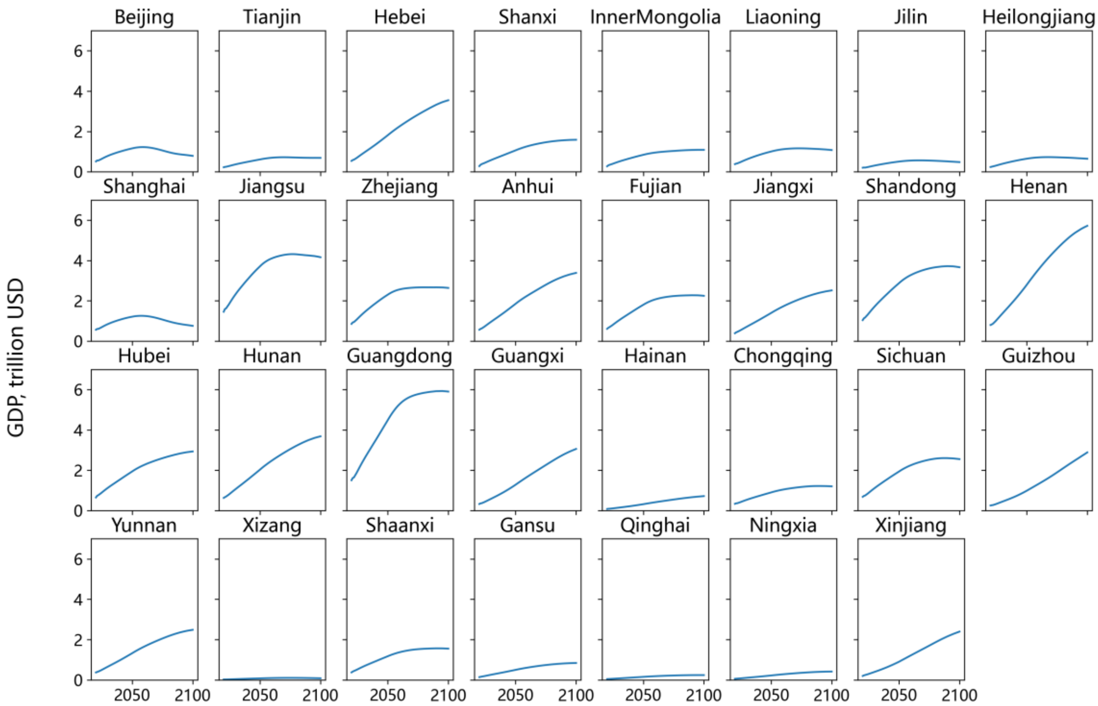

Figure 2　Provincial trends of GDP in China from 2020 to 2100

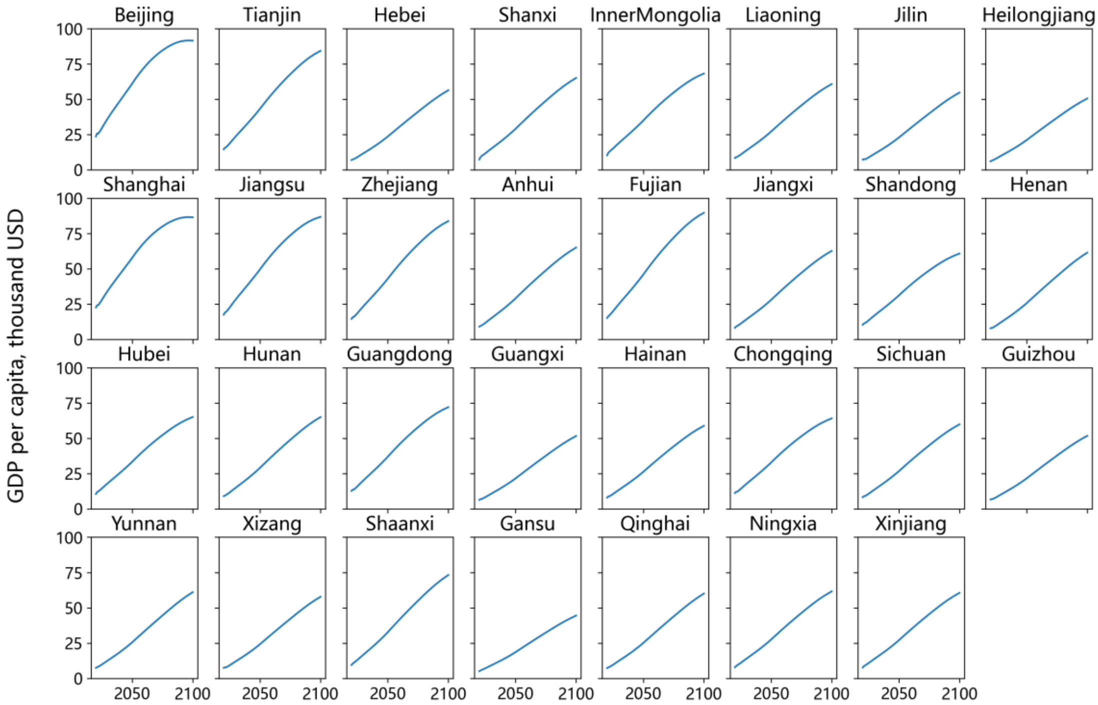

Figure 3　Provincial trends of GDP per capita in China from 2020 to 2100

3. The Reference Energy System

The energy system constructed in the RMC model covers a complete macro energy system, including: primary energy extraction, secondary energy processing and conversion, and final energy consumption. Fig. 4. illustrates a simplified energy system in its full coverage of the three stages, while a complete set of technologies and the energy flow between regions are not easy to show.

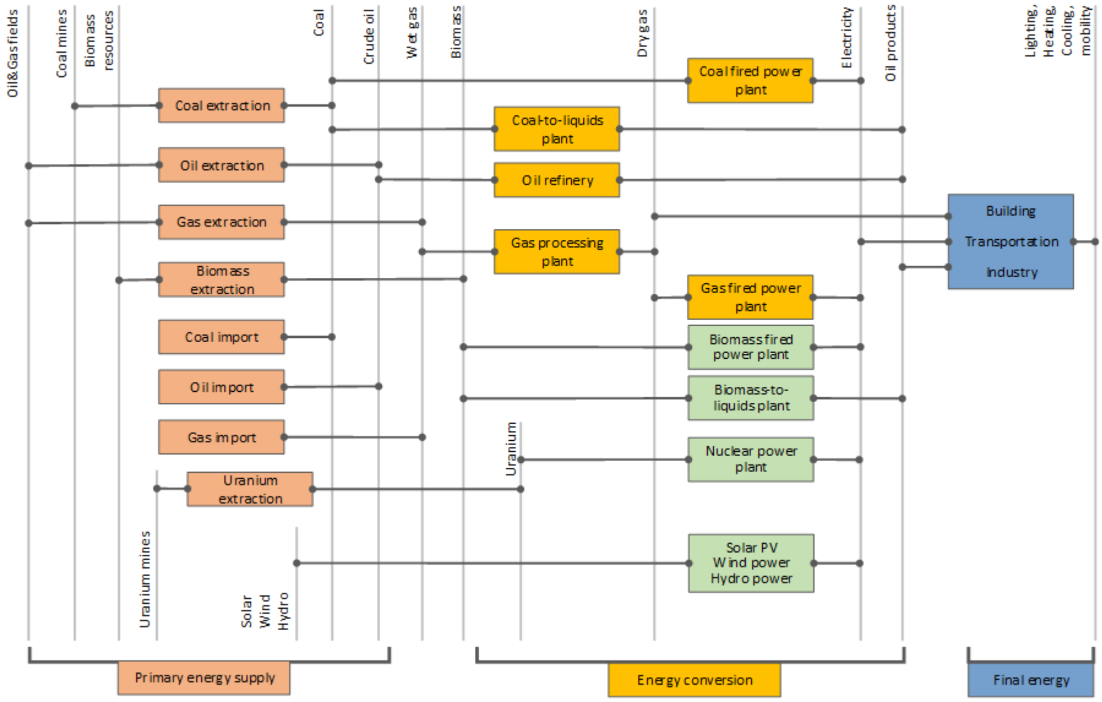

Figure 4 A simplified reference energy system

In total, the current version of the model involves over 400 energy technologies from resource supply to final consumption. It encompasses the full spectrum of energy supply: upstream resource extraction (resource supply), midstream processing and conversion (power plants, refineries, coking plants, etc.), energy transmission, import and export. Energy demand sectors include the three major final energy consumption sectors: industry, buildings, and transportation. Energy demand, represented as useful energy in the model, is exogenously determined with consideration of socio-economic development projections.

3.1. Energy resource endowments

3.1.1. Fossil fuel reserves and resources

The accessibility and cost of fossil fuels play a critical role in shaping the future of the energy sector, thereby directly impact the nature of future climate mitigation challenges. It is imperative to understand the changes in the availability of fossil fuels and their extraction costs. The assumptions on fossil energy resources in RMC are derived from a variety of sources, including national and global databases such as NBS and the United States Geological Survey (USGS), as well as reports and forecasts from diverse energy research institutes and organizations.

Table 1 shows the calculated fossil fuel resources in the RMC model for 2022. Fig. 5 shows these resource estimates as cumulative resource supply curves. Estimating fossil fuel reserves is built on technological assumptions. With an improvement in technology, the amount that may be considered a 'reserve' vs. a 'resource' can actually vary widely.

'Reserves' in this model refer to the quantities of fossil fuels that have been confirmed to exist through geological assessment with a significant degree of certainty regarding their existence (proven, probable, or possible) and can be commercially extracted under current economic and technological conditions. 'Resources', a broader concept than 'reserves', including those that have not yet been discovered, as well as those that are technologically unfeasible or economically unviable, but might be recoverable in the future, as well as those quantities that are geologically possible, but yet to be found.

Table 1 Calculated results of China's fossil fuel resources in the RMC model

Category	**Resources (ZJ)**
Coal	40
Conventional Oil	0.8
Unconventional Oil	0.6
Conventional Gas	1.6
Unconventional Gas	1.3

China's coal resources account for approximately 90% of total fossil resource estimates. Oil and natural gas are relatively scarce, with 1.4 ZJ and 2.9 ZJ resources respectively.

Drawing from multiple sources of information, mainly from some literatures and reports (McGlade and Ekins, 2015; China National Administration of Coal Geology, 2016; Li, 2019; Welsby *et al.*, 2021; Ministry of Natural Resources of the People's Republic of China, no date), the supply costs of fossil fuels across the country have been estimated. Fig. 5 presents the cumulative national resource supply curves for coal, oil and gas in the RMC model. The resources represented by different color shades indicate different resource categories.

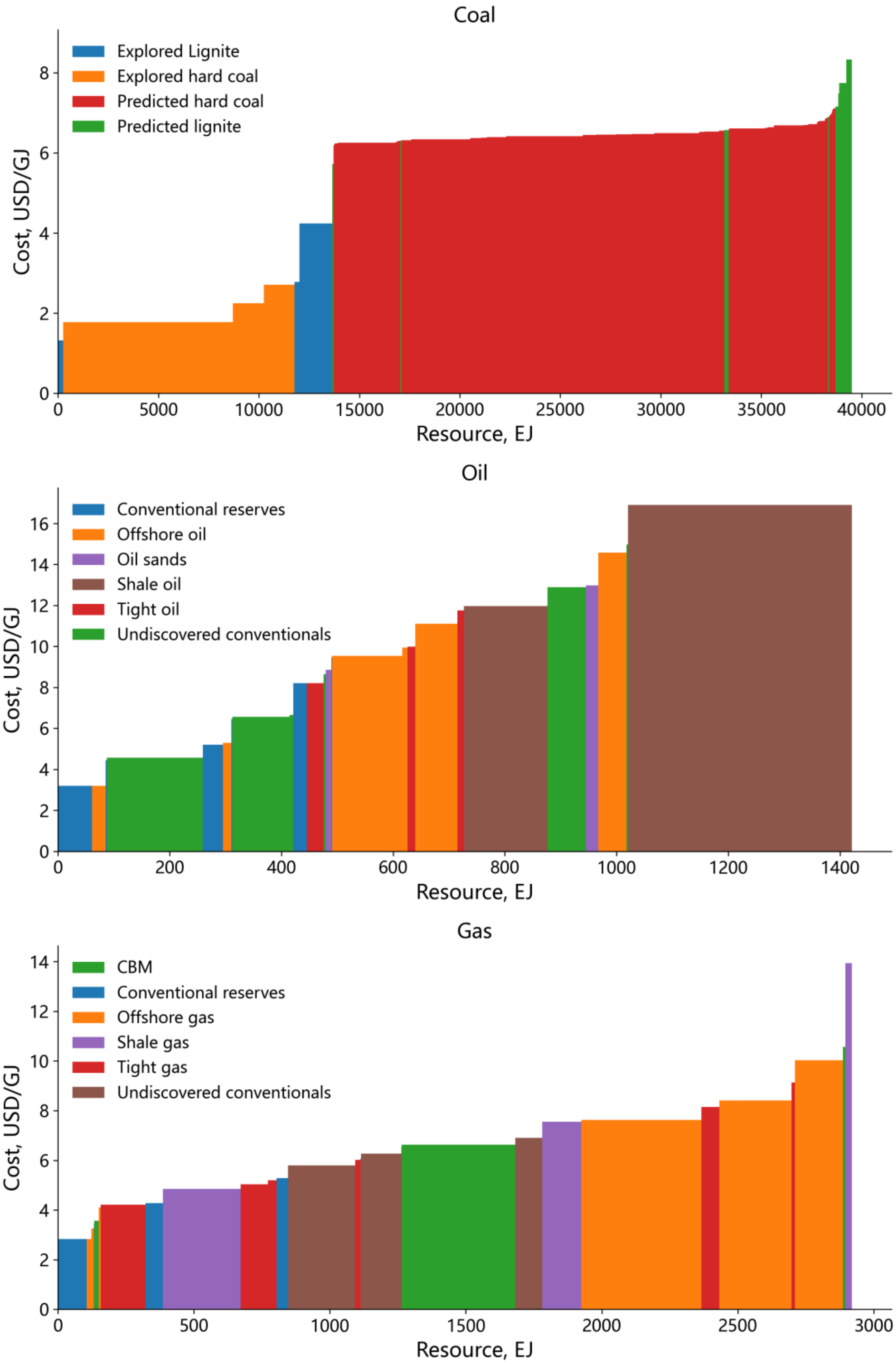

Figure 5　Cumulative national resource supply curves for coal (top), oil (middle), and gas (bottom) in the model

Coal is the largest and most widely distributed fossil fuel resource in China. Every province except Shanghai has coal resources. In terms of spatial distribution, coal resources are more abundant in the north than in the south. Xinjiang and Inner Mongolia are the two regions with the largest coal resources, followed by Shanxi and Shaanxi. These four provinces in the north account for approximately 79% of the country's coal resources collectively. The distribution of conventional oil is also mainly in the northern regions such as Xinjiang, Gansu, Shaanxi, Heilongjiang, and Shandong, all possessing more than 1 Gt of conventional onshore resources. Coastal provinces including Hainan, Tianjin, and Guangdong possess offshore oil resources. Unconventional oil, primarily in the form of shale oil, is highly concentrated and mainly distributed in Liaoning, Xinjiang, and Jilin. The distribution patterns of conventional and unconventional natural gas are similar, with Sichuan, Shaanxi, and Inner Mongolia rich in both resources. Thanks to its developed coal industry, Shanxi and Inner Mongolia also have a significant amount of coalbed methane (CBM) resources. Hainan and Guangdong have large offshore natural gas resources that are yet to be exploited. Figs 6-13 show the regional distribution of different resource categories.

Figure 6 Regional distribution of remaining recoverable explored coal resources (Gt)

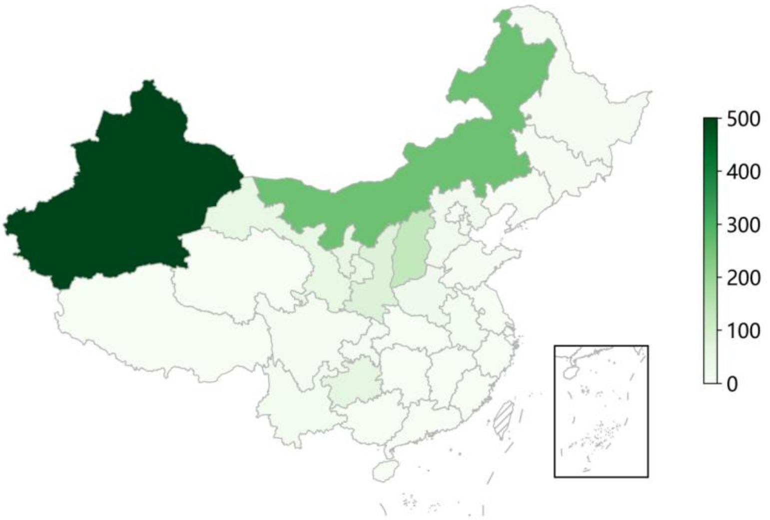

Figure 7 Regional distribution of remaining recoverable predicted coal resources (Gt)

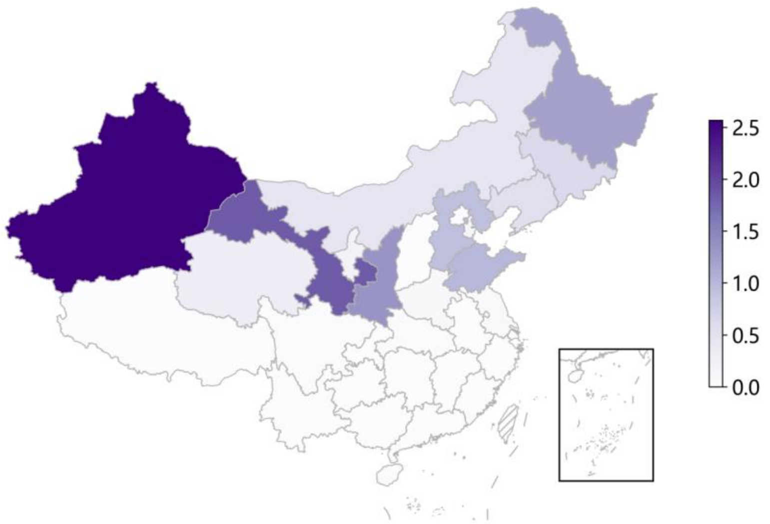

Figure 8 Regional distribution of remaining recoverable conventional onshore oil (Gt)

Figure 9 Regional distribution of remaining recoverable offshore oil (Gt)

Figure 10 Regional distribution of remaining recoverable unconventional oil (Gt)

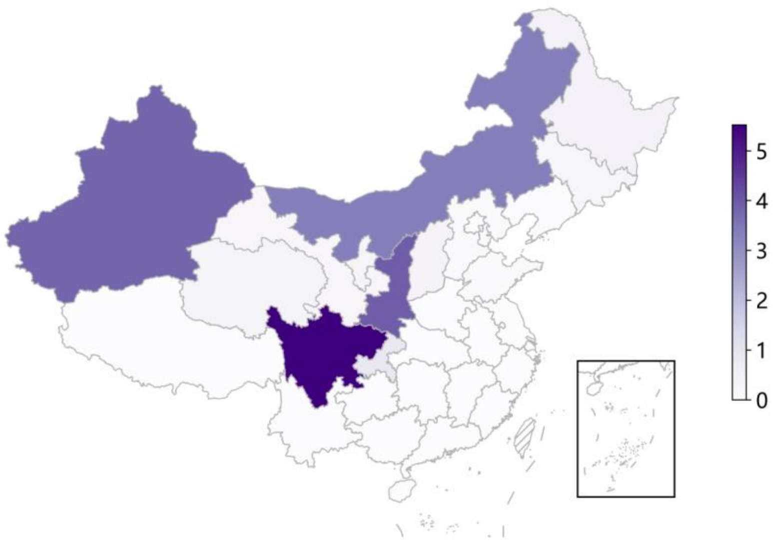

Figure 11 Regional distribution of remaining recoverable conventional onshore gas (Tcm)

Figure 12 Regional distribution of remaining recoverable offshore gas (Tcm)

Figure 13 Regional distribution of remaining recoverable unconventional gas (Tcm)

3.1.2. Biomass resources

Biomass energy is a potentially important renewable energy resource in the RMC model. This includes both commercial and non-commercial use. Commercial refers to the use of bioenergy in, for example, power plants or biofuel refineries, while non-commercial refers to the use of bioenergy for residential heating and cooking, primarily in rural households. The estimates of the national biomass resource potential in the model combines multiple sources (Zhang, 2018; Hanssen *et al.*, 2020; Kang *et al.*, 2020; Nie *et al.*, 2020; Biomass Energy Industry Promotion Association *et al.*, 2021; Tian *et al.*, 2021; Biomass Energy Industry Promotion Association and Energy Foundation, 2023; Wang Rui *et al.*, 2023). The biomass resources in the model include agricultural residues, forestry residues, energy crops, municipal sewage, municipal solid waste and animal manure.

Table 2 shows the total volume, collectable volume and energy utilization potential of China's biomass resources in the RMC model. The energy use potential is the amount obtained by deducting non-energy uses from the collectable volume. Relying on developed agriculture and animal husbandry, more than 60% of national total biomass resources come from agricultural residues and animal manure. In southern provinces such as Guangxi and Yunnan, abundant forest resources also provide considerable potential for biomass development. It is noteworthy that despite the substantial potential for growing energy crops across the country, the associated market and industry systems remain underdeveloped. Consequently, it is anticipated that a considerable period will be required for these crops to emerge as the primary source of biomass utilization within China.

Table 2 The scale and utilization potential of biomass resources in China (EJ)

Category	Total resource	Collectable resource	Energy use potential
Agricultural	15.3	13.3	4.2
Animal manure	22.7	22.7	7.6
Energy crops	16.0	16.0	16.0
Forestry	5.9	5.9	2.6
Municipal sewage	0.2	0.2	0.2
Municipal solid waste	1.7	1.7	1.7

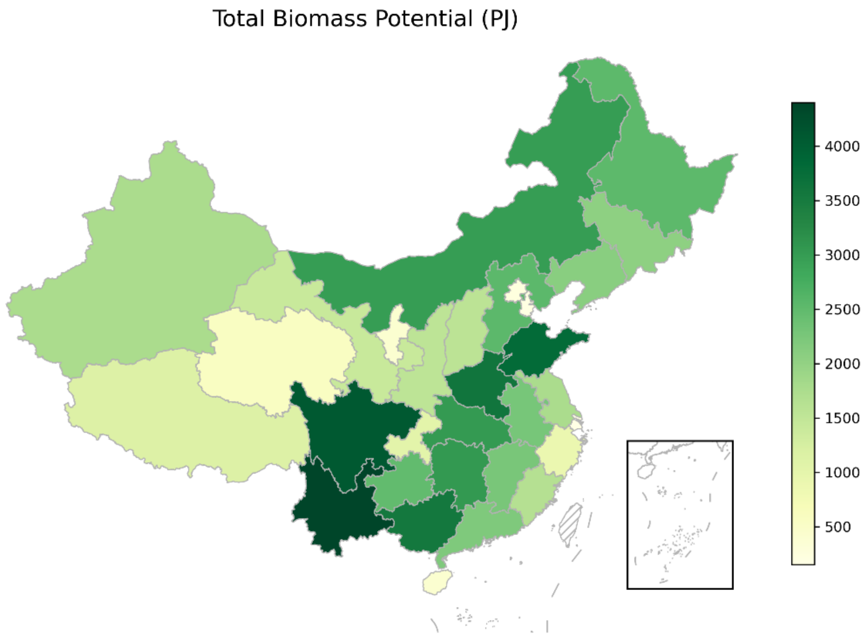

Figure 14 Regional distribution of biomass resources (PJ)

3.2. Power System

The RMC model covers a full range of electricity generation, transmission and storage in and between the 31 provinces' power systems. It can run with an annual time resolution consistent with other modules and or be soft-linked with a dedicated power system model CPOST with an hourly resolution (8760 hours for a modelled year) to capture more detailed features in the power system. The spatial resolution and technologies in the power system are consistent between RMC and CPOST. Description of the CPOST model is available from its documentation.

3.2.1. Generation technologies

The power system encompasses a variety of power generation technologies, including fossil fuel-based generation, nuclear, and renewable energy like hydro, wind, solar and biomass power generation, along with energy storage and transmission facilities.

In coal-fired power generation, there are advanced technologies such as large ultra-supercritical and supercritical units, as well as relatively low-efficient subcritical technologies. For gas-fired power generation, it includes large combined cycle gas turbine (CCGT) units and conventional open-cycle gas turbine (OCGT) power generation technologies. The system has also taken into account the integration of carbon capture and storage (CCS) technology within power generation units. The following shows the list of generation technologies including both fossil and renewables in the model.

- Coal w/o CCS: ultra-supercritical units (USC), supercritical units (SC), and subcritical units (Sub-C);
- Coal w/ CCS: ultra-supercritical units with CCS, supercritical units with CCS;
- Gas w/o CCS: combined cycle gas turbine (CCGT) and open cycle gas

turbine (OCGT);

- Gas w/ CCS: CCGT with CCS and OCGT with CCS;
- Biomass w/ CCS;
- Biomass w/o CCS;
- Solar: centralized/distributed photovoltaic (PV) power station and solar thermal power plant (concentrated solar power, CSP);
- Wind: onshore/offshore wind;
- Nuclear.

Note that CCS is treated as an ‘add-on’ technology to the parent technology, e.g., coal-fired ultra-supercritical units or biomass power plants. More details on how CCS is modelled can be found in the MESSAGEix document.

3.2.2. Capital costs

Table 4 shows the cost trajectory of power generation technologies in a baseline scenario with references to a number of studies (McElroy *et al.*, 2009; Lu *et al.*, 2021; IEA, 2022, 2023b, 2023a, 2024; National Bureau of Statistics of China, 2022, 2023, 2024; Wang *et al.*, 2022; China Meteorological Administration, 2023; Ember, 2023; CEIC, 2024; Dianchacha, 2024; EMBER, 2024).. The model allows for adjustments to the cost of each specific generation technology in different scenario designs.

Table 3 Capital cost assumptions for generation technologies in RMC (unit: US$/kW)

Capital Cost	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**2055**	**2060**
Biomass w/ CCS	1679.0	1460.0	1412.0	1304.0	1206.7	1138.7	1099.0	1087.1	1086.0
Biomass w/o CCS	1320.0	1200.0	1161.0	1073.2	994.1	938.8	906.6	896.9	896.0
Coal w/ CCS	1139.3	1085.0	1058.7	999.5	946.2	908.9	887.1	880.6	880.0
Coal w/o CCS	712.3	698.3	690.8	673.8	658.5	647.8	641.5	639.7	639.5
Gas w/ CCS	1086.8	1035.0	1013.8	966.2	923.3	893.2	875.7	870.5	870.0
Gas w/o CCS	650.3	637.5	635.3	630.2	625.6	622.5	620.6	620.1	620.0
Hydro	1632.0	1600.0	1573.8	1514.8	1461.7	1424.5	1402.8	1396.3	1395.7
Nuclear	2754.0	2700.0	2628.8	2468.4	2324.2	2223.2	2164.3	2146.6	2145.0
Solar: CSP	1485.0	1350.0	1311.5	1224.8	1146.8	1092.3	1060.4	1050.9	1050.0

Solar: PV	919.1	835.5	810.1	753.1	701.8	665.8	644.9	638.6	638.0
Storage: Pumped-hydro	1422.0	1350.9	1332.6	1291.6	1254.6	1228.7	1213.6	1209.1	1208.7
Storage: Battery	950.0	902.5	841.2	703.3	579.2	492.3	441.6	426.4	425.0
Wind: Offshore	2519.0	2290.0	2201.0	2000.9	1820.7	1694.6	1621.1	1599.0	1597.0
Wind: Onshore	1309.0	1190.0	1130.8	997.7	877.8	793.9	745.0	730.3	729.0
Transmission: UHV	346.5	329.18	324.73	314.72	305.71	299.41	295.73	294.62	294.53

3.3. Other energy conversion

Similar to the power system, a number of district heating technologies based on fossil and renewable energy sources are considered in the RMC model. These heating plants feed low temperature heat into the district heating system that is then used in the end-use sectors.

Beyond electricity and centralized heat generation, there are three further subsectors of the conversion sector represented in the model, namely, liquid fuel production, gaseous fuel production and hydrogen production.

In addition to oil refining, the main supply technology for liquid fuels currently, the model also encompasses a variety of alternative pathways for producing liquid fuels from diverse feedstocks, such as coal liquefaction, gas-to-liquids technologies, and biomass-to-liquids technologies, with and without the integration of CCS. Gaseous fuel production technologies cover biomass gasification and coal gasification. Hydrogen production include gasification processes for coal and biomass, steam methane reforming from natural gas and hydrogen electrolysis.

3.4. Technological advancement

In the RMC model, technological advancements are considered as exogenous factors and vary across scenarios. However, related studies have been conducted to incorporate the endogenous aspects of technological change through learning curves within energy-engineering models, as well as to examine how technology costs are influenced by market structures.

Cost and performance parameters, such as conversion efficiencies and emission factors, are typically sourced from the extant engineering studies. At the same time, alternative projections for costs and performance are formulated to account for a broad spectrum of uncertainties that significantly impact the model results for the future.

3.5. Energy demand

Energy service demands from end-use sectors such as industry, transportation and residential/commercial are calculated with socio-economic development projections and exogenous to RMC. These demands are generated through the utilization of a scenario generator implemented in Python. The scenario generator correlates historical GDP per capita to final energy demands at the regional level and extrapolates the sectoral energy service demands into the future leveraging projections of GDP and population growth. The scenario generator runs regressions on the historical datasets to establish the relationship for each of the 31 RMC regions between the independent variable (GDP per capita) and factor such as total final energy intensity, shares of final energy among several energy end-use sectors, and shares of electricity use between the industrial and residential/commercial sectors. With the input parameters, both the final energy intensity and the sectoral distribution can be projected.

Sector-specific models are under development and expected to soft-link with the RMC in the near future.

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