We deeply appreciate the detailed and constructive comments provided by the three anonymous reviewers. Following their suggestions and comments, we have extensively revised the manuscript and provided a point-to-point response to each comment. The original comments are in **bold** font, our response is in regular font, and the changes in the text are in blue.

## Comment 2

**Sang et al develops a regional system dynamics model to represent coupled human natural systems in the Yellow River Basin, integrating population, economy, energy, food, water, land, carbon, and climate processes to explore historical dynamics and future baseline projections. Overall it looks good, with extensive explaination of the model structure and some illustrative results. However, my main concern is that the human dimension, especially the energy sector, is relatively weakly specified to support the strong claims made about cross sector dynamics in this coupled framework. Because energy use is tightly linked with economic activity, water demand, food production, and carbon emissions, a simplified or poorly validated energy representation risks propagating bias across the entire system. So it's unclear to me whether the projected interactions among energy, water, food, and carbon are internally consistent or robust, especially in the future projections that are central to the paper's conclusions.**

**Response:** We appreciate the reviewer's concern regarding the energy sector specification. We acknowledge that the energy module is simplified to balance overall system complexity; however, we have verified its robustness by extending the validation with recent data (2021–2024), which demonstrates a good match with extended historical data. Furthermore, since the energy sector accounts for a relatively minor fraction of total basin-wide water consumption compared to agriculture (>70%), this simplification does not propagate significant bias to the study's core human–water interaction conclusions. We have refined the description of the energy logic and explicitly discussed limitations, such as electrification trends, as priorities for future model iterations in the revised manuscript.

1. **First, A key issue is the system boundary of the energy sector. Although an energy module is included, the model appears to explicitly represent only electricity, while other major energy uses, particularly in industry, are treated in a highly aggregated manner. This is problematic because non electric energy use and structural change in industry are major drivers of both emissions and water demand. In addition, important indirect effects are not clearly represented. For example, electrification trends such as electric vehicle deployment would increase electricity demand while reducing oil consumption, yet such substitution dynamics are not discussed. Similarly, changes in industrial energy structure could feed back to economic output and water use, but it is unclear how these interactions are captured. Given the stated goal of representing coupled human natural systems, it is important for the authors to clarify how these cross sector linkages are treated and how sensitive the results are to the simplified energy boundary.**

**Response:** We acknowledge that compared to dedicated bottom-up energy models, such as those included in IAMs, the energy sector in the CHANS-SD-YRB 1.0 model has been simplified to balance the complexity of the coupled human-natural system in the YRB. Given the breadth of human-nature interactions in the study region, a model could not exhaust every interaction and pathway. Therefore, the current model focuses on simulating the basin's human–water interactions through water supply and demand perspectives, with necessary simplifications made for certain processes and sectors. We completely agree that electrification (e.g., EV deployment) and AI data center are critical emerging trends for energy consumption growth in recent years. While electrification alters the energy mix, its direct impact on the water balance of the Yellow River Basin is of secondary compared to agricultural and ecological water demands. We fully recognize the importance and incorporating these mechanisms into a more detailed energy substitution module (reflecting trends like EV adoption) can expand model's capability for simulating finer-scale energy-water nexus dynamics, which we will consider for the next major release of the model.

The reviewer correctly points out that industry and energy structure affect water demand. In the Yellow River Basin, water withdrawal is overwhelmingly dominated by agriculture (>70%) whereas industrial water withdrawal only accounts for 12% in 2024. Although thermal power is the most water-intensive in energy source sector, its share in total basin-wide water consumption is relatively small, and in many years, even zero. (data from China Water Resources Bulletin http://www.mwr.gov.cn/sj/#tjgb). Moreover, there is a lack of long-term data on specific industry sectors and their water withdrawal, making explicitly modeling industry sectors and their structural changes difficult. Given the data constraint, the aggregated approach for the energy structure is a practical design choice to satisfy our modeling goal to capture the main driver of water pressure. In the current model, the feedback loop from changing energy structure to economic output and water use is not explicitly represented. The model employs a demand-driven logic for the energy sector, where energy supply is assumed to meet the demand generated by economic activities. Therefore, we do not currently simulate scenarios where energy shortages or structural constraints restrict GDP growth.

In response to these comments, we have incorporated a new subsection into the Discussion. The revised texts are shown below:

For human processes, the Energy and Economy sectors could be refined to model more detailed industry subsectors and emerging trends in energy demand driven by electrification.

2. **Second, the description of the energy sector in Section 2.2.3 is unclear. The statement that "coal, oil, and gas consumption are derived from linear relationships between historical sectoral GDP" and corresponding consumption is ambiguous. It is not clear whether this refers to total final energy consumption or only to fuels used for electricity generation. More**

**importantly, a linear extrapolation based on historical GDP trends is unlikely to be appropriate for long term projections under ongoing structural change, efficiency improvements, and decarbonization. The manuscript also does not clearly explain how total energy demand evolves over time or how energy intensity changes are represented. Besides, electricity generation shares are imposed exogenously based on Li et al. 2024, which makes the future pathway highly deterministic. The underlying policy assumptions and narratives are not clearly described. So Figure 16 would benefit from validation against recent historical data before 2025 and comparison with ranges reported in the literature. In particular, the emerging nuclear capacity around 2030 requires stronger justification in terms of feasibility and policy assumptions in China's context.**

**Response：** We apologize for the lack of clarity in the description of the *Energy* sector. As for the ambiguity regarding coal, oil, and gas consumption, these fossil fuels refer to consumption by production of industry and service sectors, which is derived from their relationship with sectoral GDP. Fossil fuel consumption for electricity generation by thermal power is separately calculated based on total electricity consumption and the generation mix. These two constitutes the total coal, oil, and gas consumption.

We have significantly revised the description of the energy sector in Section 2.2.3 and provided detailed description in the Supporting Information Section S2.4:

The fossil fuel consumption by economic production of industry and service sectors is modeled as a linear function of sectoral GDP based on historical data (Equations S25-S27).

The detailed information in the Supporting Information is shown below:

Coal (Equation S25), oil (Equation S26) and gas (Equation S27) consumption by economic production of industry and service sectors are obtained from the linear fit of historical sector GDP and related consumption,

$$Coal_{con} = TP \times Share_{coal} \times Coef_{ESC} \times Coef_{SCC} + Para_{IC} \times GDP_{ind} + Const_{IC} \quad \text{(S25)}$$

$$Oil_{con} = TP \times Share_{oil} \times Coef_{ESC} \times Coef_{SCO} + Para_{ISO} \times (GDP_{ind} + GDP_{ser}) + Const_{ISO} \quad (S26)$$

$$Gas_{con} = TP \times Share_{gas} \times Coef_{ESC} \times Coef_{SCG} + Para_{ISG} \times (GDP_{ind} + GDP_{ser}) + Const_{ISG} + Pop_{rural} \times PCG_{rural} + Pop_{urban} \times PCG_{urban} \quad (S27)$$

where $TP$ is the thermal power generation; $Share_{coal}$, $Share_{oil}$ and $Share_{gas}$ are the proportion of coal, oil and gas in thermal power generation; $Coef_{ESC}$ is the standard coal conversion coefficient of electricity, $Coef_{SCC}$, $Coef_{SCO}$ and $Coef_{SCG}$ are the conversion coefficients of standard coal, coal, oil and gas, which are derived from General Principles for the Calculation of Comprehensive Energy Consumption (GB/T 2589-2008, GB/T 2589-2020); $Para_{IC}$ and $Const_{IC}$ represent the slope and intercept derived from the linear fit of historical industry GDP and coal consumption. Similarly, $Para_{ISO}$, $Const_{ISO}$ and $Para_{ISG}$, $Const_{ISG}$ denote the corresponding parameters for oil and gas, respectively. Notably, these parameters were estimated using a piecewise linear regression with distinct coefficients for the pre- and post-2010 periods to capture the structural changes around 2010 driven by socio-economic shifts. $Pop_{rural}$ and $Pop_{urban}$ are rural and urban population, from *Population* sector, $PCG_{rural}$ and $PCG_{urban}$ are the per capita natural gas consumption in rural and urban areas from the China Energy Statistical Yearbook (NBSC, 2020a).

Regarding the concern about "linear extrapolation," we acknowledge that a single linear trend cannot capture long-term decarbonization. Future decarbonization scenario can be designed by adjusting this parameter. For historical period, we employed a piecewise linear regression approach with a structural break around 2010. The change in slope after 2010 explicitly captures the decoupling trend between economic growth and energy consumption (i.e., efficiency improvements and structural change).

Total energy demand is driven by socio-economic development. Electricity demand is calculated based on sectoral electricity intensities, while fossil fuel demand (coal, oil, gas) is derived from linear relationships with sectoral GDP, where the coefficients serve as proxies for the marginal energy intensity of production activities. These parameters are calibrated at the provincial level to capture spatially divergent trends.

Since future energy structure changes are uncertain, we used electricity generation shares projection following the carbon neutrality goals of China by Li et al. (2024) in the future baseline scenario. China's energy transition is heavily driven by top-down state planning (i.e., Carbon Peaking and Carbon Neutrality Goals), modeling these shares as exogenous policy targets allows us to simulate the specific impact of fulfilling national strategic goals, rather than relying on a market-clearing mechanism which might misrepresent China's regulated energy sector.

Regarding the validation period, we found that electricity generation data is available up to 2024, while fossil fuel consumption data (coal, oil, and natural gas) is currently only published up to 2022. We have collected these latest datasets and compare our simulation results against this extended historical period (2021–2024 for electricity, 2021–2022 for fossil fuels). Please refer to the response to the next question for the figure.

3. **Third, the paper emphasizes the regional and spatially explicit nature of the CHANS SD YRB model, but this advantage is not fully demonstrated in the results. Although Figure 1 highlights spatial resolution across provinces and sub basins, many subsequent figures are conceptual diagrams rather than quantitative outputs. Model validation for energy variables ends in 2020, and maybe there are more recent to validate, such as 2021-2024? It would be important to show how near term projections after 2020 compare with observations, particularly for electricity generation and fuel consumption. Also, author may consider presenting and validating provincial level energy results beyond more aggregated models.**

**Response:** Thank you for the comments.

We would like to clarify that the regional and spatially explicit nature is a core feature of our model and the simulation results. The results are not merely aggregated; they maintain spatial resolution throughout the simulation. As shown in the "Results" section, the human sectors' outputs (e.g., economic and population metrics) are presented for the nine provinces, while the natural sectors' outputs (e.g., runoff) are validated and projected at the sub-basin level (up-, mid-, and downstream). The future scenario results explicitly display trajectories for both the aggregate Yellow River Basin and the individual nine provinces.

Regarding the validation period, this study was initiated in 2022. At that time, the official statistical yearbooks for all nine provinces were only available up to 2020 due to the standard 2-year lag in regional data publication in China. While some fragmented national data for 2021–2024 exist, integrating inconsistent datasets would compromise the model's internal coherence. Therefore, we maintained 2020 as the uniform cutoff for calibration to ensure data consistency across all sectors.

In response to the reviewer's suggestion, we attempted to collect more recent data for *Energy* sector covering the period 2021–2024. However, the official statistics are currently limited. The data for electricity generation are available for the full 2021–2024 period, consumption data for coal, oil, and natural gas are only available for 2021–2022. These available historical statistical data after 2020 are added in the comparison with the simulation results in Figure 1. The simulation results show good agreement with the extended historical data in terms of both trends and magnitudes.

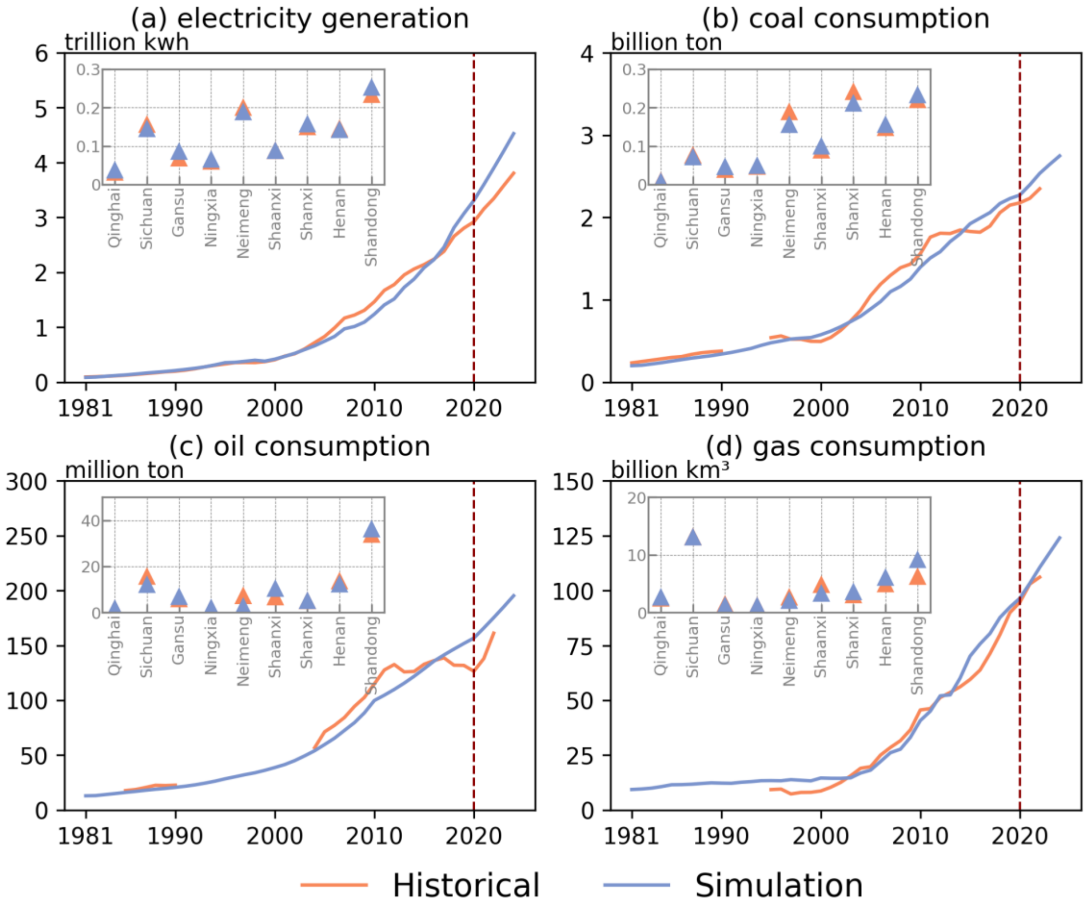


Fig.1 Validation of variables in *Energy* sector during historical period of 1981-2024. Pink triangles in the upper left sub-image represents the average of historical and simulation value in 1981-2024 of each province in the YRB.

We agree that provincial validation is crucial, which is included in the inset of Figure 1. The triangular markers represent the comparison between the simulated means and the historical statistical data for each of the nine provinces. This visualization explicitly shows the model's performance at the provincial level, demonstrating its capability to capture regional variations beyond the basin level.

4. **Lastly, there are several clarity issues that should be addressed. The meaning of "fire" in the energy sector in Figure 2 is unclear. In addition, the term "per capital" appears repeatedly in the text and figures and should be corrected to "per capita" throughout the manuscript.**

**Response:** Thank you for the comments.

We apologize for the typographical errors in the manuscript. We have corrected them in the revised version. Specifically, the label 'fire' in Figure 2 has been updated to 'Thermal Power', and all instances of 'per capital' have been corrected to 'per capita' throughout the text.

The revised Figure 2 is shown below:

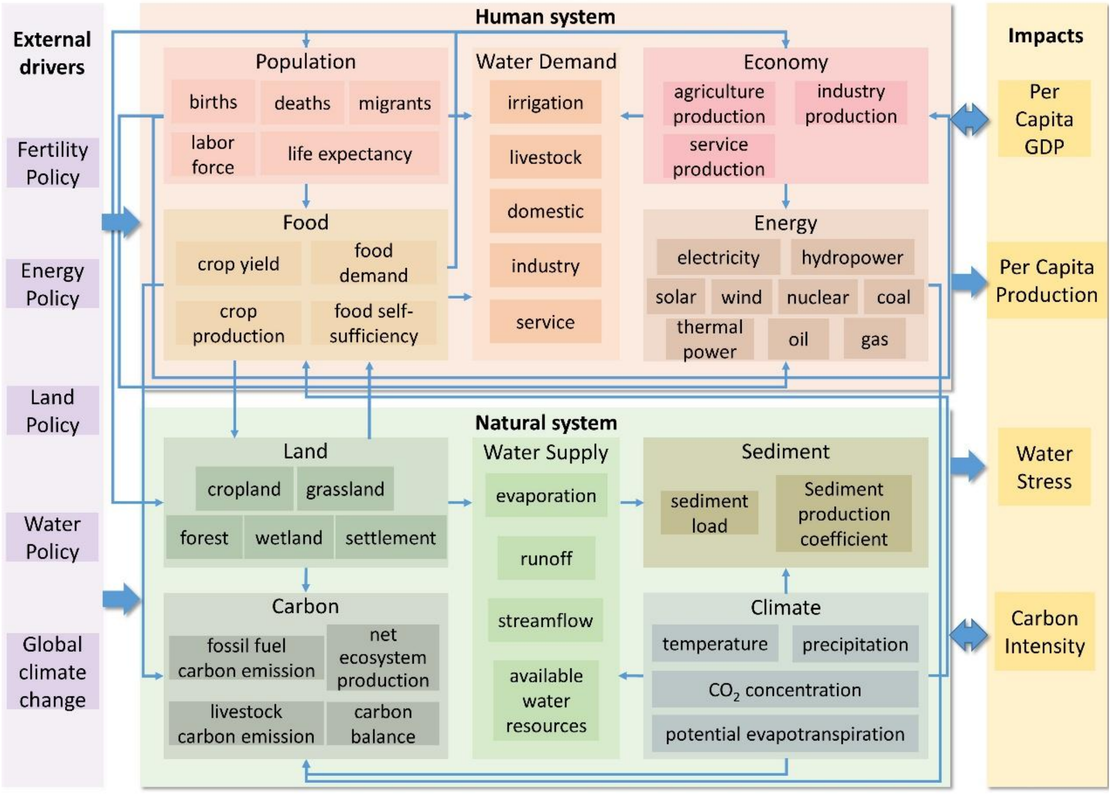


Fig.2 (Fig.2) Structure of the CHANS-SD-YRB, which shows sectors of human and natural systems, their key processes and interactions.

**References:**

Li, M., Shan, R., Abdulla, A., Virguez, E., and Gao, S.: The role of dispatchability in China’s power system decarbonization, Energy Environ. Sci., 17, 2193–2205, https://doi.org/10.1039/D3EE04293F, 2024.

National Bureau of Statistics of China (NBSC), China Energy Statistical Yearbook, https://data.cnki.net/yearBook?type=type&code=A, 2020.