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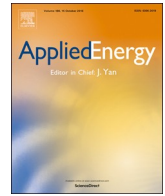
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Decarbonizing China's energy system – Modeling the transformation of the electricity, transportation, heat, and industrial sectors

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HIGHLIGHTS

- China's Nationally Determined Contributions do not comply with the Paris Agreement.
- Overall coal usage needs to decrease by 60% (2 °C) or even 100% (1.5 °C) by 2050.
- 100% Renewable energies are cost-efficient to decarbonize the electricity sector.
- Sector coupling increases the electricity demand by 100% (2 °C) to 400% (1.5 °C).
- Incentives for local actors are needed for a sustainable low-carbon transformation.

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ABSTRACT

Growing prosperity among its population and an inherent increasing demand for energy complicate China's target of combating climate change, while maintaining its economic growth. This paper, therefore, describes three potential decarbonization pathways to analyze different effects for the electricity, transport, heating, and industrial sectors until 2050. Using an enhanced version of the multi-sectoral, open-source Global Energy System Model, enables us to assess the impact of different CO₂ budgets on the upcoming energy system transformation. A detailed provincial resolution allows for the implementation of regional characteristics and disparities within China. Conclusively, we complement the model-based analysis with a quantitative assessment of current barriers for the needed transformation. Results indicate that overall energy system CO₂ emissions and in particular coal usage have to be reduced drastically to meet (inter-) national climate targets. Specifically, coal consumption has to decrease by around 60% in 2050 compared to 2015. The current Nationally Determined Contributions proposed by the Chinese government of peaking emissions in 2030 are, therefore, not sufficient to comply with a global CO₂ budget in line with the Paris Agreement. Renewable energies, in particular photovoltaics and onshore wind, profit from decreasing costs and can provide a more sustainable and cheaper energy source. Furthermore, increased stakeholder interactions and incentives are needed to mitigate the resistance of local actors against a low-carbon transformation.

1. Introduction

China plays a very important role for the global low-carbon energy transformation. It is the second-largest economy, as well as one of the major producers of solar photovoltaics (PV) modules and wind turbines [1,2]. Furthermore, China has shown substantial growth in energy demand in the past and is likely to continue this trend in the future, i.e., already being the largest emitter of greenhouse gases (GHG) worldwide (see Boden et al. [3,4] and Ahmad et al. [5]).

Relevant research shows that China is able to reduce emissions in its power sector and achieve the target of peak coal consumption set by itself (compare Zhou et al. [6] and Liu et al. [7]). The transformation of the Chinese power sector is analyzed in studies by Liu et al. [7], He et al. [8], Liu et al. [9], and Liu et al. [10]. Still the aforementioned studies have their focus on the power system with little to no detail of other sectors. Hence, we propose a multi-sectoral approach for modeling the Chinese energy system with an open-source energy system model. An analysis of different pathways for a decarbonization of the

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Nomenclature			
<i>Abbreviations and Descriptions</i>			
CCS	Carbon Capture, and Storage	GHG	Greenhouse gases
CO ₂	Carbon Dioxide	GDP	Gross Domestic Product,
CPC	Communist Party of China	IAM	Integrated Assessment Model
dynELMOD	Dynamic Investment and Dispatch Model for the Future	NBS	National Bureau of Statistics of China
	European Electricity Market	NDC	Nationally Determined Contribution
FYP	Five-Year-Plan	OSeMOSYS	Open Source Energy Modelling System
GENeSYS-MOD	Global Energy System Model	PV	Photovoltaics
		RES	Renewable energy sources
		SDG	Sustainable Development Goal
		TIMES	The Integrated MARKAL-EFOM System
		UN	United Nations

sectors electricity, transportation, heat, and industry is carried out. The paper aims to bridge the gap between the different sectoral analyses and to provide a novel, holistic, view on the decarbonization pathways for the Chinese energy system in light of current climate policies.

The paper is structured as follows: Section 2 gives an overview and characterization of the Chinese climate and energy policy in the global context of the Paris Agreement and Sustainable Development Goals (SDGs). The relevant literature, the research question, and the research gap are presented in Section 3. Following, Section 4 gives an overview of the methodology and a description of the key assumptions and data for modeling the Chinese energy system. Furthermore, the characterization and limitations of the utilized model are presented in this Section. The main results are depicted in Section 5. To complement the modeling work, the barriers for a transformation are presented in Section 6. The paper concludes with recommendations in Section 7 and a conclusion in Section 8.

2. Characterization of the Chinese climate and energy policy

On a global scale, the political urgency of reducing GHG emissions is shown in the Paris Agreement, which aims to limit global warming to well below 2 °C. A temperature rise beyond this figure would lead to severe environmental and economic risks, as stated by Stern [11]. The announced withdrawal of the United States of America from the Paris Agreement [12] and the unclear development in the European Union [13] increase the importance of China's role in international climate policies.

To comply with the Paris Agreement, China has underlined its ambition to set an end to the ever-rising consumption of coal, with an expected peak in 2030 or earlier [14]. Currently, China's coal consumption stayed comparably stable over the last years and the share of coal on the overall energy mix is slightly decreasing each year (compare National Bureau of Statistics of China (中华人民共和国国家统计局) [15] and Deha [16]). Among other goals, China especially targets to decrease its carbon intensity by 60% in comparison to 2005 and to achieve a total installed capacity of wind and solar power of 200 GW and 100 GW, respectively, by 2020. At the beginning of 2019, China

had an installed capacity of 174 GW solar PV and thus already surpassed its initial goal for 2020 by 74% [17]. Also, a recent study by Zhou et al. [6] shows that China's CO₂ emissions are able to peak in 2025, as compared to its own NDC (peak CO₂ emissions in 2030).

In stark contrast to its promising Nationally Determined Contributions (NDCs), China's energy system is still dominated by coal and other fossil fuels. The majority of its coal is being consumed in the industrial and heating sectors – making a decarbonization more difficult than in most other countries, as shown in Fei [18]. The burning of fossil fuels is the primary cause of air pollution, which not only poses a risk to the environment, but also causes a multitude of health problems. Hence, as stated by Fuso Nerini et al. [19] and McCollum et al. [20], a reduction in coal usage will also decrease local air pollution-related issues in China. Thus, a reduction in coal usage contributes to reaching the Sustainable Development Goals (SDGs) of the United Nations (UN). In line with its NDCs proposed to UN, China has published its 13th Five-Year-Plan (FYP) [21], covering short- to medium-term goals of the country from 2016 to 2020, ranging from socio-economic, over industrial, and infrastructural, to environmental aspects. Naturally, both commitments go hand in hand, as a pledge to keeping the 13th FYP on a national level also means achieving its NDCs proposed to the UN.

On the policy side, China can be divided into six vertically subordinated governmental layers: Central, provincial, city, district, town, and village levels, as shown in Dai [22]. These are involved in the implementation process of commands and guidelines within the FYPs by the national leadership in Beijing. On each level, the distinct authority has its own scope to fulfill these commands. Most policies are primarily within the provincial or city level and include detailed target implementations and resource allocations. Within the 13th FYP, the Chinese government tries to re-centralize the federal energy structure of the previous decades to avoid possible struggles caused by clean energy drafting of weaker ministries (compare Arent et al. [23]).

In the north, the country still features vast coal deposits, mostly found in the Inner Mongolia Autonomous Region and the Shanxi province. China's abundance of renewable energy sources (see Fig. 1) will allow and accelerate its transformation towards a sustainable energy system (compare Liu et al. [10]). As for variable renewable energy

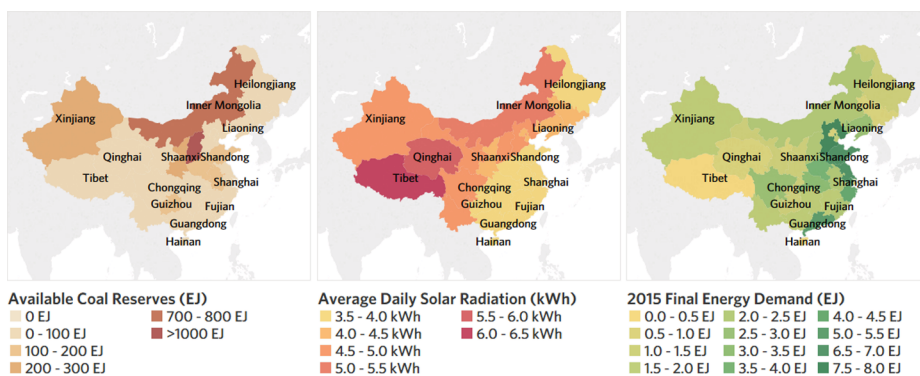


Fig. 1. Overview of available coal reserves (in EJ) as well as solar radiation (in kWh/d) and final energy demand (in EJ) per Chinese province. There is a regional disparity in the availability of energy sources and demand centers. Although not displayed in this picture, neither wind and hydro-power potentials are available in high energy-consuming provinces.

sources (RES), sizable solar PV potentials are mainly aggregated in the central-west and central-south (as analyzed by He and Kammen [24]), while onshore wind potentials are primarily situated in the Inner Mongolia Autonomous Region (see He and Kammen [25]). Given the enormous electricity demand in the population-dense coastal-east, large investments into expanding the electricity network are to be expected throughout the decarbonization process of the power sector, as depicted by He et al. citeGangHeSWITCHChina2016 and Christian Breyer et al. [26].

3. Status quo of relevant literature

Concerning the decarbonization of energy systems, a large variety of studies is available. However, most studies are focusing on a global energy system with little to no regional detail. Deng et al. [27] use an Integrated Assessment Model (IAM) to analyze the possibility of transitioning to a global sustainable energy system. They present a feasible pathway for reaching 95% sustainable energy supply in 2050. The importance of technology diffusion of renewable energy sources, such as solar PV or wind, for reaching the climate goals of the Paris Agreement is shown by an analysis by Huang et al. [28]. Further global studies look at 100% renewable energy systems. Only looking at the power sector, Bogdanov et al. [29] shows the possibility of reaching an energy system based on 100% renewables. Similar findings are concluded by Löffler et al. [30] and Tokimatsu et al. [31]. Both also include other sectors apart from the power sector to provide further insights into the transformation of the global energy system. The importance of extending classic power system models by incorporating interlinked sectors is shown by Pursiheimo et al. [32]. This importance is also reflected by the extensive global study of a 100% renewable energy system provided by Ram et al. [33]. Overall, the feasibility of an electricity system based solely on renewable energies is currently extensively discussed (compare Heard et al. [34] and Brown et al. [35]).

Also, various studies exist which focus on different regions of the World in detail. Jacobson et al. [36] showed that for the United States, a 100% renewable power system, solely based on hydropower, solar PV, and wind power is technically and economically feasible. Similar findings regarding the power system are provided in a study by Connolly et al. [37] and Child et al. [38] for Europe. In the context of a 100% renewable European energy system, Steinke et al. [39] analyze the trade-offs between grid and storages and conclude that investments into both technologies are needed. Kasperowicz et al. [40] reviewed technical optimization vs. economical optimization in the context of a 100% renewable energy system and argued that large-scale installment of batteries could increase the stability of an energy system. Also regarding Europe, Gerbaulet et al. [41] show that reduced foresight in energy system models can lead to a substantial amount of stranded assets. The assumption of decreasing or increasing energy efficiency is also highly relevant when looking at different energy systems models. Tvaronavičienė et al. [42] showed within their analyses that especially for their selected European countries, the energy intensity would not decrease considerably until 2050. They claim that mostly behavioral aspects lead to this aspect. Apart from Europe or the United States, other regional studies are available. For Germany, Müller et al. [43] present a modeling framework for multi-modal energy systems. In their work, they show that sector-coupling, specifically the electrification of heat and mobility, is needed to reach Germany's climate targets, a result also highlighted by the recent study of Bartholdsen et al. [44]. Furthermore, a multi-sectoral study with similar findings is available for India (compare Lawrenz et al. [45]).

Apart from the aforementioned regional studies, some energy system analyses targeting China are available. An assessment of a renewable power system is conducted by Liu et al. [10]. They show that China is currently in a phase of rapid technological deployment and that China has an abundant potential of renewable energy sources. Thus, they conclude that a 100% renewable power system is not

unreasonable. Christian Breyer et al. [26] also looked at the transformation of the power system in China. By aggregating China into larger regions and including neighboring countries, they showed that whole North-East-Asian region could be transformed to use 100% renewables in the power sector. Their results furthermore highlight that implementing an area-wide power grid infrastructure reduces the need for excess power generation capacities and thus further decreases the total system costs. He et al. [8] present a systems approach for a decarbonization of the Chinese power system. They show that for China, substantial reductions in GHG emissions from 2030 on are needed in order to stay below 2 °C. Also, large extensions in the power grid infrastructure are required to reach an 80% carbon reduction in 2050. More recently, Liu et al. [9] presented a cost-optimal design of a simplified, highly renewable Chinese electricity network. They show similar findings regarding the needed grid expansion, compared to He et al. [8]. Most importantly, long-range power transmission is required, given China's regional disparity of renewable resource availability and demand centers. Endogenously incorporating the electricity requirements from other sectors (industry, building, transport, and agriculture) to an energy system, Liu et al. [7] showed that the future development of coal power plants is a crucial factor in determining the time of the emissions peak and thus for reaching China's NDCs. Zhang et al. [46] aggregated China into seven regions and analyzed the development of the Chinese power system until 2050. They also showed that China's CO₂ emissions are able to peak in 2030. Looking at the requirements for China's renewable energy transition, Wang et al. [47] showed critical minerals and rare earths may be limiting the deployment of both wind and solar PV. They argue that the transformation of China's power system has to be more in line with China's critical mineral endowment. Also, several studies, specifically analyzing the requirements, impacts, or complementarity of solar PV and wind are available. Tu et al. [48] state that the profitability of onshore wind and solar PV is highly depended on the feed-in-tariff. With the current prospect of a diminishing feed-in-tariff, the profitability of solar PV and onshore wind will decrease. Also, Tu et al. [49] identified carbon pricing as a primary factor for reaching grid parity in China. The importance of coordinated operation or combined wind-PV-thermal dispatch is presented in different studies by Zhang et al. [50], Tan et al. [51], Sun and Harrison [52], and Ren et al. [53]. Summarizing, the current literature regarding the Chinese power sector acknowledges the role of solar PV as driving forces for decarbonization of the Chinese energy system, although Zhou et al. [54] argues that the intermittency of these variable renewables likely increases the electricity costs.

Overall, most studies conclude that significant investments into low-carbon energy technologies are needed to fulfill the Paris Agreement, and even more to reach a maximum global warming of 1.5 °C as shown by McCollum et al. [55]. Also, many studies targeting a limitation of global warming to 2 °C and below rely on a substantial use of Carbon Capture and Storage (CCS) (compare Huang et al. [28]). Contrary, other articles conclude that there is still a possibility of staying well below 2 °C without an abundant deployment of CCS [56]. This is especially important, as large-scale deployment of CCS and investment into CO₂ infrastructure is rather unlikely [57]. Overall, the role of CCS and other negative-emission technologies for the future energy system transformation is very uncertain (see Minx et al. [58]).

Regarding China, He et al. [59] review the four key drivers that dominate China's energy transformation: resource potential, technology advancement, air pollution control and policy, as well as reform of the power sector. They conclude that China's energy demand can largely be powered by RES, given its vast resource potential in solar and wind (compare He and Kammen [25] and He and Kammen [24]). The government, on the other hand, is still heavily invested in both traditional and more advanced, less pollutant technologies. In general, especially solar PV has seen substantially decreasing prices in the last years, which was mainly enabled by the comparative advantage and low market entry barriers in China, as stated by Zhu et al. [60].

While, in general, 36.2% of China's total CO₂ emissions can be allocated to the operation of coal-fired power plants in the power and heating sectors [61], the emissions per downstream sector (manufacturing, construction, etc.) are often unclear. A recent survey of Bai et al. [61] looks at the CO₂ emissions embodied throughout the industrial supply chain in China. By mapping inter-industrial CO₂ flows across 30 Chinese industrial sectors, the study finds that around 29.8% of all CO₂ emissions of 2012 are resulting from rapid urbanization in recent years. Instead of capping CO₂ emissions in upstream sectors (energy generation, exploitation of resources), they propose that a cost-effective and significant reduction in CO₂ emissions can be achieved through adopting stronger incentives for more efficient and sustainable material manufacturing and energy use in downstream industries.

A recent joint report by Agora Energiewende and the China National Renewable Energy Center [62] confirms the widely established consensus that China can achieve a 50% share in renewable energy integration by 2030. In addition to expanding existing wind and solar power capacities by 35 GW and 65 GW respectively, fundamental challenges in China's present energy mix have to be addressed, i.e., over-capacities in coal-fired assets and the lack of accessibility for (new) market participants [62]. Furthermore, the continued construction of coal-fired power plants by the Chinese government leads to high risks of stranded assets in the power sector [18].

Overall, previous studies have shown that in order to reach the agreed-upon goal of a maximum mean temperature increase of 2 °C, extensive expansions of renewable generation capacities are required, and that large-scale installment of nuclear power may not be an economically feasible alternative, as depicted in the works of Huang et al. [28], Löffler et al. [30], He et al. [8], Bogdanov et al. [29], or Christian Breyer et al. [26].

However, most of the previously mentioned studies, including all Chinese ones, target only the power sector, omitting crucial effects due to sector-coupling (compare He et al. [8], Huang et al. [28], Liu et al. [9] or Bogdanov et al. [29]). Despite the efforts of Liu et al. [7] to expand their power system model by introducing the electricity requirements of other sectors, a full view of other sectors and their corresponding sector-coupling potentials are omitted in this study. Also, although Ram et al. [33] published an extensive study of analyzing 100% renewables on all sectors, only one distinct scenario has been analyzed, and China has only be looked at in aggregated larger regions. The same is observed in the paper by Löffler et al. [30]. It shows the importance of including sector-coupling to an energy system model and also elaborates the possibility of 100% renewables across all sectors. Still, they have a less detailed heating sector (compare Section 4), transportation sector (see Burandt et al. [63]) and a rather rough time-aggregation while modeling only large, aggregated regions.

As of now, a comprehensive analysis of the roles of the different sectors, including electricity, industry, buildings, as well as transport, on a technological level, with possible electrification potentials for China on a detailed regional level of aggregation is missing in the literature. We, therefore, propose a multi-sectoral, bottom-up, techno-economic approach with an accurate regional aggregation for China at provincial resolution. The research tries to provide insights for the following research question: *How does the Chinese energy system in general, and specific sectors in particular, transform by applying different CO₂ budgets?*

4. Methodology

Overall, energy system models can be broadly divided into techno-economic (bottom-up) and macroeconomic (top-down) models, compare Herbst et al. [64]. Techno-economic models permit separating the energy system into different technologies, processes, and interdependencies across energy carriers. This ability to divide the energy system into smaller technology blocks allows the model to internalize the impact of specific policies in each subdivision and to optimize the

relationships between sectors, technologies, and regions. On the opposite, techno-economic models neglect severe market imperfections and obstacles in many final energy sectors. Macroeconomic models, on the other hand, sacrifice detailed technical information for a better macroeconomic representation. They try to depict the whole national or regional economies while looking at aggregated effects of climate, energy, or societal change, while attempting to capture links between the energy sector, the economy, and society. The separation between techno-economic and macroeconomic models resulted in the need to develop a new set of models that internalize the advantage of both approaches. Compared to those two categories, Dagoumas and Kolt-saklis [65] review models for integrating renewable energy in the generation expansion planning in three types: *Optimization Models*, *General/Partial Equilibrium Models*, and *Alternative Models*. According to Dagoumas and Kolt-saklis [65], Optimization models are considered as robust models, as they incorporate in detail the techno-economic characteristics of the power system. These models are able to analyze regional and national policies due to their level of detail (regarding technologies, regional aggregation, or temporal resolution).

An important example of techno-economic optimization models is the MARKAL model, developed by the International Energy Agency [66]. While MARKAL belongs to the group of optimization models, recent modules try to bridge the gap between the techno-economic and macroeconomic models [67], one of them being TIMES (The Integrated MARKAL-EFOM System). TIMES combines a technical engineering with an economic approach, thus merging the characteristics of both [68].

To analyze the effect of different CO₂ budgets on the development of the Chinese energy system, we use an enhanced version of the Global Energy System Model (GENeSYS-MOD) [30]. GENeSYS-MOD is a linear cost-optimizing model based on the Open Source Energy Modelling System (OSEMOSYS) [69,70], offering endogenous optimization of different demand sectors assuming an omniscient central planner. Overall, GENeSYS-MOD is similar to the TIMES model regarding its modular structure and general modeling paradigm. The key advantage of GENeSYS-MOD is the open-source approach of code and data. The capacity of GENeSYS-MOD to subdivide the energy system into sectors, technologies, and regions; its ability to account for sector coupling; and its high degree of technological features are necessary characteristics of a model attempting to understand the consequences of exogenous variations in energy and climate policies on each supply option, energy sector, and modeled region.

In this article, we look at the sectors *Power*, *Buildings*, *Industry*, and *Transport* on a provincial level with a reduced hourly time-series. The results of this quantitative method were verified by a combination of expert elicitation and literature research.

Compared to the version of the model presented in Löffler et al. [30] and Burandt et al. [63], several new additions have been made. Firstly, to better represent the need for flexibility options, ramping, together with ramping costs, has been added to the model. Eq. (1) defines the upward and downward production change ($g_{y,l,t,f,r}^{\Delta+}$ and $g_{y,l,t,f,r}^{\Delta-}$) as difference in the generation per technology ($g_{y,l,t,f,r} * YS_{y,l}$) between the current and the previous time-step l . This equation is set up for all years $y \in Y$, time-steps $l \in L$, technologies $t \in T$, fuels $f \in F$, and regions $r \in R$.

$$g_{y,l,t,f,r} * YS_{y,l} - g_{y,l-1,t,f,r} * YS_{y,l-1} = g_{y,l,t,f,r}^{\Delta+} - g_{y,l,t,f,r}^{\Delta-} \quad \forall y,l,t,f,r \quad (1)$$

The up- and downward change in production is limited by the yearly capacity $tcap_{y,t,r}$ denoted by the availability factor $AF_{y,t,r}$ of each technology t in each year y and time-step l . To convert the capacity to an limit for the amount of energy, the previous term is multiplied by factor that determines the maximal energy that could be produced by one unit of capacity in one year (CTA_t). Furthermore, the up- and downward change is limited by exogenous defined ramping factors $RF_{r,t,y}^+$ and $RF_{r,t,y}^-$. These factors define how much of the built capacity can be activated or deactivated in each time-step, see Eqs. (2) for the upward

ramping limit and (3) for the respective downward ramping limit.

$$g_{y,l,t,f,r}^{\Delta+} \leq tcap_{y,t,r} * AF_{y,t,r} * CTA_t * RF_{r,t,y}^+ * YS_{y,l} \quad \forall_{y,l,t,f,r} \quad (2)$$

$$g_{y,l,t,f,r}^{\Delta-} \leq tcap_{y,t,r} * AF_{y,t,r} * CTA_t * RF_{r,t,y}^- * YS_{y,l} \quad \forall_{y,l,t,f,r} \quad (3)$$

Furthermore, Eq. (4) adds costs for each unit of energy that has been changed between timeslices (ramped up or down) by applying a cost factor $RCF_{r,t,y}$ on the energy changed. Coal power plants have comparably high and natural gas relatively low costs, and thus, coal power plants will be encouraged to serve as base-load power plants. Contrary, natural gas is used for handling variability and intermittency of RES, together with storage technologies. The annual ramping costs $rc_{y,t,f,r}$ are discounted to the base year ($rc_{y,t,f,r}^D$) and included in the objective of the model as depicted in Eq. (5).

$$rc_{y,t,f,r} = \sum_l (g_{y,l,t,f,r}^{\Delta+} + g_{y,l,t,f,r}^{\Delta-}) * RCF_{r,t,y} \quad \forall_{y,t,f,r} \quad (4)$$

$$rc_{y,t,f,r}^D = \frac{rc_{y,t,f,r}}{(1 + DR)^{y-y_{first}+0.5}} \quad \forall_{y,t,f,r} \quad (5)$$

The annual discounted ramping costs are added to the total discounted technology costs $ttc_{y,t,f,r}$, together with discounted variable and fixed operating costs $oc_{y,t,r}^D$, discounted capital expenditures $ci_{y,t,r}^D$ and discounted emission costs $ep_{y,t,r}^D$ (compare Eq. (6)). Finally, as seen in Eqs. (7) and (8), the sum of all technology costs and storage costs $tsc_{y,s,r}^D$ are added to the objective function. This displays the modular structure of GENeSYS-MOD. Although several equations and parameters are added to the original model, only one equation has to be changed to incorporate this new functionality to the model. In general, all key parts of OSeMOSYS and GENeSYS-MOD are formulated in distinct blocks. For an overview of the major blocks of functionality of GENeSYS-MOD, please refer to Appendix B.

$$ttc_{y,t,r}^D = oc_{y,t,r}^D + ci_{y,t,r}^D + ep_{y,t,r}^D + sv_{y,t,r}^D + rc_{y,t,r}^D \quad \forall_{y,t,r} \quad (6)$$

$$tc_{y,r}^D = \sum_t ttc_{y,t,r}^D + \sum_s tsc_{y,s,r}^D \quad \forall_{y,r} \quad (7)$$

$$\text{minimize} \quad \sum_{y,r} tc_{y,r}^D + \sum_{y,r} atc_{y,r}^D + \sum_{y,f,r,rr} ncc_{y,f,r,rr}^D + \sum_{y,f,r} acc_{y,f,r}^D \quad (8)$$

The remainder of the model formulation is well presented in other articles. Hence, for further information of the model and the model formulation, please refer to Howells et al. [69], Löffler et al. [30], and Burandt et al. [63]. A list of used symbols in this mathematical formulation can be found in Appendix B.1.1. Also, a mathematical formulation in line with the OSeMOSYS- or GENeSYS-MOD-style of defining equations is presented in Appendix B.1.2.

Furthermore, as the introduction of ramping needs a more detailed time resolution, the approach using representative time-slices was changed in favour of (reduced) hourly time-series as used by the *Dynamic Investment and Dispatch Model for the Future European Electricity Market* (dynELMOD), presented by Gerbaulet and Lorenz [71] and Gerbaulet et al. [41]. This time-series reduction algorithm works in three steps. First, every n th hour of a full hourly time-series is chosen, starting at a given starting-hour. Additionally, the 12 or 24, depending on target resolution, consecutive hours with the lowest renewable infeed are added. This reduced time-series is smoothed with a moving-average function in the next step to decrease the artifacts and jumps of the new time-series. The window width is defined by hand for each technology. The third step scales the new time-series with a discontinuous non-linear program. For a detailed description of this process, please refer to Gerbaulet and Lorenz [71] and Gerbaulet et al. [41].

Due to memory and computation time constraints, a time-series based on each 73th hour was chosen, resulting in 120 time periods. Hence, five consecutive days with a hourly resolution and yearly

characteristics have been calculated.¹

Additionally, to better accommodate the importance of the industry in China, the preexisting structure of high-temperature and low-temperature heat as depicted in Löffler et al. [30] has been altered. The new structure features four different temperature ranges with a more distinct differentiation in industrial (0–100° C, 100–1000° C, and > 1000° C) and residential heating (0–100° C). For this new representation, a large variety of new technologies has been implemented to allow for alternative options to decarbonize industrial processes of more than 1000° C, as electrification poses only limited options for these cases. This new structure allows for a better illustration of sectoral CO₂ emissions, and thus allows for a more detailed analysis of the importance of the industry for a decarbonization of an energy system. This representation is of high importance, as the energy-intensive high-temperature industry (e.g., steel-making, aluminum production) has a large influence and importance for China [15].

4.1. Key assumptions and data

For this analysis, nearly all first-level administrative divisions, such as provinces, municipalities, autonomous regions, and special administrative regions are included. Due to missing interconnections and the difficult political status, Taiwan has been excluded from this case-study. In total, 33 nodes were considered in the model.

Most meta data on China's demographic, economic, and industrial situation, including historic population growth, energy consumption by sector, energy composition, and fossil fuel deposits are publicly available and provided by the National Bureau of Statistics of China (NBS) [15].

Cost-assumptions, efficiencies, and lifetimes of most technologies are stated in Burandt et al. [63]. The newly included technologies for the industry are based on Fraunhofer et al. [72]. Hourly capacity factors of solar PV, wind, and heat pumps were calculated based on a 50x50km grid of *renewables.ninja* [73] from the meteorological year of 2015. The resulting data-points have been ordered in three categories for each province. Afterwards, the average for each province and each category has been calculated and included in the model. In order to take account of the limitations and linearity of the model, the hourly capacity factors for RES stay constant over the years. Hence, no increasing efficiencies for PV are being accounted for. Also, the amount of calculated time-steps has a direct effect on the installed storage capacities, which are reduced according to their fraction of a year. Overall, possible over-estimations of renewable energy sources, heat pumps, and storages due to the rather rough timely resolution are reduced through the previously mentioned measures. Potentials of solar PV and wind are taken by He and Kammen [24,25].

4.2. Scenario analysis

This study looks at the effect of different carbon budgets on the Chinese energy system. Therefore, the main scenarios that where analyzed impose these different budgets. To reflect the global and regional ambitions of reducing GHG emissions, we introduce a *Paris Agreement* scenario, which features a total carbon budget of 293.184 GtCO₂ from 2015 onwards and correspondences to a 2° C pathway. This scenario is compared to an *Ambitious* scenario with only 115.081 GtCO₂ (a 1.5° C pathway) and a *Limited Effort* scenario. The latter has no assigned CO₂ budget and serves as a benchmark for the other scenarios. The budgets for China were calculated using the corresponding global budgets from Rogelj et al. [74]. As there are currently no direct binding CO₂ targets for any country, allocating the global budget is possible in multiple ways. Possible indicators are the gross domestic product (GDP),

¹ The final model calculation used about 75 GB of RAM for each scenario and sensitivity run and took about 6–7 days calculation time.

population, or emissions. In regard of allocating a global budget by emissions, a differentiation between historic or current emission is most common. In a study analyzing Europe, Hainsch et al. [75] showed that allocating CO₂ to European countries by using the current emissions is closest to an optimal allocation used by a central planner with perfect foresight. Therefore, we are using China's current emissions (from the year 2015) as key indicator to calculate the share of the global budget it is allowed to emit. Changing the indicator for allocation to GDP would decrease China's budget by 33%; an allocation by population by 47%.

All scenarios have a fixed base year of 2015 and planned and commissioned power plants are equally included in all scenarios. The targets of the current FYP of the Chinese government are included as boundaries in the model until 2020. Also, future outlines, as, for example, political efforts of increasing electric-vehicle transportation in city-states (i.e., Beijing, Shanghai) are also considered in the modeling work. Furthermore, all scenarios are calculated with and without the possibility to invest in CCS due to the uncertainty of its technological availability. Regarding the macroeconomic assumptions, all scenarios share the same base-line. The demands for each fuel per province were obtained from National Bureau of Statistics of China (中华人民共和国国家统计局) [15]. Hereby, we allocated the demand of the different industrial branches to their corresponding temperature-range². The demand growth for each different sector until 2050 was obtained from the 2017 World Energy Outlook [76], which has a particular focus on China.

4.3. Model calibration and validation

The model has been calibrated to the base-year 2015. Capacities and production in the sectors electricity, industry, and buildings are fixed for the base year. For the transportation sector, the final energy demand and modal shares are fixed. The calculated results of the power sector were compared to similar studies by [8] and Christian Breyer et al. [26] to find possible flaws.

4.4. Model characterization and limitation

As a pure techno-economic bottom-up model, GENeSYS-MOD lacks features of macroeconomic models. Hence, a strong dependency on assumptions regarding growth (e.g., GDP, population) can be observed when utilizing the model. Also, technology development is set exogenously, and thus the results depend on given cost-estimates. The past has shown that especially RES and storages were highly underestimated, as depicted by Metayer et al. [77] and Mohn [78]. We researched all recent literature and interviewed experts to achieve realistic cost estimates. For a broader picture of the whole energy-economic system, linking of bottom-up techno-economic and top-down macroeconomic models is needed in future works, as suggested by Crespo del Granado et al. [79]. This is especially needed for varying macroeconomic parameters per scenarios as these parameters (i.e., GDP) naturally change with deployment of different technologies. Still, a primary challenge of linking top-down to bottom-up models is the inconsistency in behavioural assumptions, treatment of temporal resolution, sectoral aggregation, or regional coverage.

Also, future analyses have to look at other pollutants apart from CO₂, as especially methane leakage becomes an essential factor when coal is replaced by natural gas to reduce emissions (compare Alvarez et al. [80]). This is, however, not accounted for within this paper and would likely reduce the role of natural gas.

Furthermore, the model assumes an omniscient social-optimal planner and hence neglects local actors and barriers mentioned in the

paper. Nevertheless, China's consequent FYPs, from a central planners perspective, have proven to be a particular case for China, compared to other countries, when applying optimization models (compare Section 6).

Additionally, the years and sectors are all calculated with an integrated approach until 2050 with perfect foresight. This integrated approach leads to new insights about the optimal use of resources in certain sectors, but neglects market- and concurring effects. Nevertheless, the multi-sectoral approach utilized in this paper generates more insights about the role of sector coupling and future developments of the whole energy system than pure power market models.

Furthermore, although significant model improvements regarding possible over-estimation of RES have been undertaken, the model still lacks a full hourly resolution. However, Welsch et al. [81] compared an enhanced version of OSeMOSYS to a full hourly TIMES model and showed that the results only differ slightly. Overall, we believe that the modifications of the version of GENeSYS-MOD in this article allow for a good qualitative analysis to present a low-cost decarbonization pathway given general computational limitations (e.g., model size, computation time, data restrictions). An alternative to using a reduced time-series would be using representative hours instead. A notable example for generating representative days for an application in long-term models would be the algorithm presented by Nahmmacher et al. [82]. They propose a hierarchical clustering algorithm for obtaining representative days with different hourly aggregation and conclude that using six representative days with eight time-slices per day (every 3 h aggregated) are sufficient for analyzing long-term strategies with their model for Germany. Therefore, future works with GENeSYS-MOD focusing on this region could also compare the application of representative hours with reduced and full hourly time-series.

Lastly, we want to point out that the model results should not be interpreted as forecasts, but as a source of valuable insights to transform China's energy system in line with the agreed upon international climate goals. This paper concentrates only on the development needed for complying with the Paris Agreement within the time-frame until 2050. As this time-frame is very ambitious, developments after 2050 have to be considered in future modeling works.

5. Impact of CO₂ Limits on the Chinese Energy System

This section presents the main results of the different scenarios and sectors. As shown in Fig. 2, the application of a CO₂ budget has a notable impact on the shape of the power transformation in China. The need for electrification in interlinked sectors leads to a vastly increased demand for electricity. This demand will primarily be fulfilled by the substantial introduction of renewable energy sources like onshore wind and solar PV. Even throughout the *Limited Effort* pathway, solar PV will take a significant role. Especially in north-eastern China, this can be traced back to high regional insolation with an overall projected decrease in capital costs. Only in the *Ambitious* scenario, breakthrough-technologies, such as methanized synthetic gas or hydrogen (H₂) are used in the power sector.

Even under strict CO₂ budgets, more costly climate change mitigation technologies such as CCS only play a minor role. Overall, the need for electrification under a strict CO₂ budget leads to a doubling of the final electricity demand. In the *Ambitious* scenario, the power produced by coal-fired power plants needs to be vastly reduced by 2025 to meet the climate target of 1.5 °C. This phase-out will imminently result in large amounts of stranded assets, as most of the existing coal capacities in China have been newly constructed or recently modernized [18]. In general, large investments in solar PV plays a primary role in reaching the ambitious targets of the Paris Agreement. More significantly, the high degree of electrification to stay below 1.5 °C results in even higher additions of solar PV. Also, onshore wind sees more deployment in the the *Ambitious* scenario compared to the other scenarios. In the model

² E.g., steel-making and aluminum production need temperatures of more than 1000 °C, whereas the (non-electricity) energy demand for food-production was allocated to the low-temperature range.

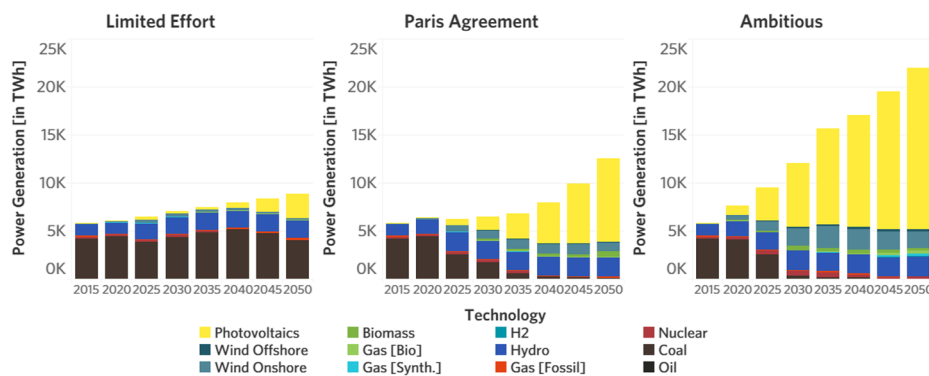


Fig. 2. Comparison of yearly power generation by technology in TWh in different decarbonization pathways. With a more limited CO₂ budget, a phase-out of coal in the power sector and increasing electricity demand due to sector-coupling can be observed.

results, the large variability and intermittency of renewables is mostly covered by inter-regional trade instead of large investments into storage technologies.

Second to the power sector, the industry sector faces significant changes after applying a CO₂ budget (see Figs. 3 and 4). Without any limit, coal still keeps the predominant role in the industry sector, as seen in Fig. 3. Only in the more ambitious scenarios, the usage of coal declines throughout the periods. The strict limit in the *Ambitious* scenario leads to a nearly complete phase-out of coal in the industry sector by 2050. This phase-out is accompanied by higher usage of gas- and biomass-based heating. In the second quarter of the century, hydrogen and geothermal play a more significant role in decarbonizing the industry sector. Overall, as seen in the *Ambitious* scenario, biomass together with hydrogen and methanized synthetic gas are key to decarbonize the industry sector. Nevertheless, a large degree of electrification is required, which is most cost- and emission-efficient when the power sector is already decarbonized. To reach the targets of the Paris Agreement, coal can still play a primary role within the industry sector, as most of the GHG reductions are achieved in the power and transportation sectors. On the other hand, slower developments in the power system can be offset by more ambitious measures in the industry or buildings sector.

In general, the buildings sector (compare Fig. 4) sees a reduction in the use of conventional energy sources in all scenarios. Still, conventional residential heating by coal and natural gas plays a significant role in the *Limited Effort* and *Paris Agreement* scenarios. In those two scenarios, electrification takes place at a later time, when price and emission intensity of electricity decrease due to the introduction of more renewable energy sources to the power system. Under a very strict CO₂ budget, a substantial increase in capacities of biomass- and hydrogen-based heating, combined with a phase-out of conventional energy carriers lead to a decarbonized buildings sector from 2040 onward.

In general, the increase of electrification in the residential heating sector does not increase significantly in all scenarios. Overall, decarbonization targets in this sector are mostly achieved by shifting to gas-based energy carriers (first natural gas, later bio- and synthetic gas).

In the transportation sector, petro-fuels still play the primary role in the *Limited Effort* scenario. Only under stricter CO₂ budgets, electrification and large-scale introduction of biofuels pose alternatives to conventional transportation. Again, biomass and biofuels are very flexible fuels for a decarbonization of this sector. Moreover, hydrogen-based transportation can be observed in the *Paris Agreement* and *Ambitious* scenarios.

Overall, the least cost decarbonization pathway for the *Ambitious* scenario leads to an energy system based on nearly 100% RES. In reverse, targeting an energy system based on 100% RES for 2050 can pose a possible way for China to stay well-below 2 °C and even reach a 1.5 °C goal. The overall possibility of a 100% renewable energy system has already been assessed in studies by Löffler et al. [30], Christian Breyer et al. [26], Brown et al. [35], or Bogdanov et al. [29] (compare Section 3). Nevertheless, those studies only have a small focus on sector-coupling and deep decarbonization of the complete energy system and do not offer a detailed representation of regional characteristics of China as presented in this paper.

While coal undeniably dominates the power and industrial sectors today, applying strict climate targets require a reduction in coal usage throughout all sectors. In the *Paris Agreement* scenario, the peak of coal consumption is to be expected in 2020 (compare Fig. 5). Also, as previously pointed out, to reach the targets of the *Paris Agreement*, coal usage has to be reduced extensively, but it can still play a role in certain sectors. Contrary, the *Ambitious* scenario implies an even earlier decrease to comply with its very strict CO₂ budget. Even the *Limited Effort* scenario results in a plateau of coal consumption in 2040, followed by a slowly reduced demand due to the projected cost-competitiveness of

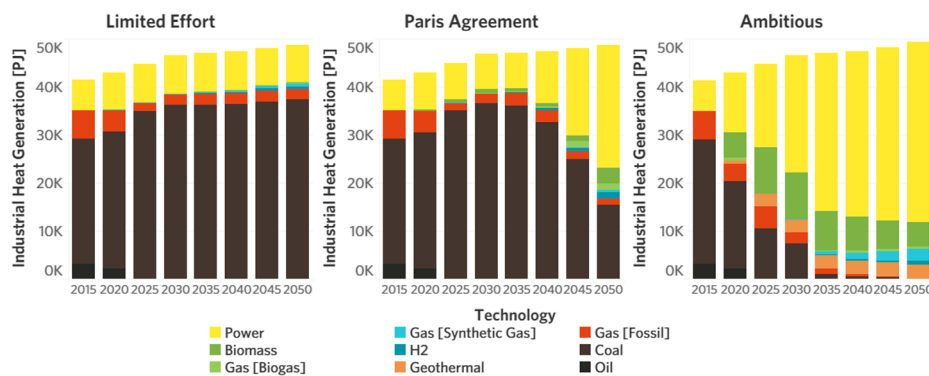


Fig. 3. Yearly industrial heat generation in PJ per technology and scenario. Even under a compliance to the Paris Agreement, coal will keep its dominant position in the Chinese industry.

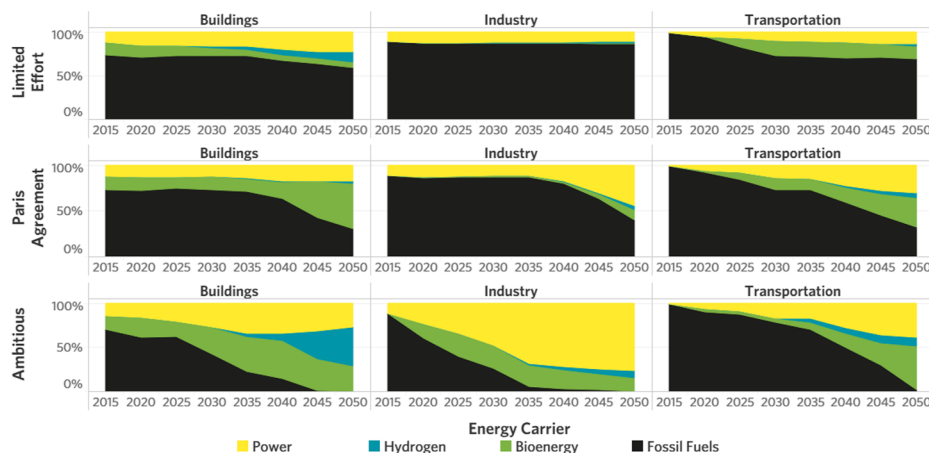


Fig. 4. Shares of consumed energy in percent of total consumption in different sectors and scenarios. The industry sector will be the most impacted energy consuming sector when applying a CO₂ budget.

renewable energy technologies and the accompanying decrease in electricity price. Overall, the target of the Chinese government to peak emissions in 2030 is, therefore, not ambitious enough to stay in line with a global target of 2 °C and below.

Looking at the regional distribution of power generation shares (compare Fig. 6), the decarbonization of the power system in China will require substantial grid extension measures (nearly doubling the total power transmission capacity from 2020 until 2050 in the Paris Agreement scenario). This can be traced back to the regional disparity of resource distributions. Being a region with high irradiation, Inner Mongolia will become the dominant power-generating province in China. He et al. [8] present similar findings. Also, the large regional extension of China enables the regional power trade to balance out the variability of renewables in the more ambitious scenarios. Still, this significantly increases the need for power grid extensions. Also, the regional disparity in the availability of biomass results in a significant increase in biomass, hydrogen, biogas, and synthetic methane trading in the Paris Agreement and Ambitious scenarios.

Additional sensitivity analyses have been carried out, looking at the variety of different cost-assumptions. In general, the most significant drivers in the Paris Agreement and Limited Effort scenarios are costs of storages, solar PV, and coal. Costs-assumptions have little to no impact on the Ambitious scenario. Another significant driver for the results of the scenarios with a CO₂ budget are the potentials of solar PV and wind. Especially a higher availability of solar PV leads to decreased grid extension and higher utilization of PV, even in the Limited Effort scenario. The results of the sensitivity analysis also show a significant impact of final energy demand projections on the development of the energy system. Lastly, the impact of CCS was comparably small with only some

utilization in the high-temperature industry sector.

Compared to other studies targeting the transformation of the Chinese energy system, an advantage of including other sectors in the power system analysis, as well as a higher regional aggregation can be shown. Compared to the recent results by Liu et al. [7], a similar peak of coal consumption in the Paris Agreement scenario compared to their C2020-renw scenario can be seen. Contrary, the Ambitious scenario needs even further emission reductions as presented in their paper. This is due to the different modeling approaches deployed. Whereas Liu et al. [7] analyze the effect of different peaking-periods for the Chinese power system, we apply CO₂ budgets to all sectors of the energy system.

The optimal long-term generation and transmission structure of China’s electricity system is analyzed by Zhang et al. [46]. Here, they assume a strong increase in power demand across most regions (roughly an increase by 70% compared to 2015). Although being an important paper with their analysis, they still neglect the strong impact of sector-coupling and electrification on future power demands. As shown in the work presented here, the need for deep decarbonization (i.e., within the Ambitious scenario) leads to a substantial increase in power demand. The Ambitious scenario sees a 400% increase between 2015 and 2050. On the other hand, the electrification of transport and industry in the Paris Agreement only accounts for an increase of 110%. Finally, without any efforts to decarbonize other sectors, the power demand will increase even less than projected by Zhang et al. [46]. Overall, this highlights the importance of future power system models to incorporate other sectors with their corresponding sector-coupling and electrification potentials.

He et al. [8] analyzed various scenarios with different demand projections. Although no inter-sectoral effects are included in their

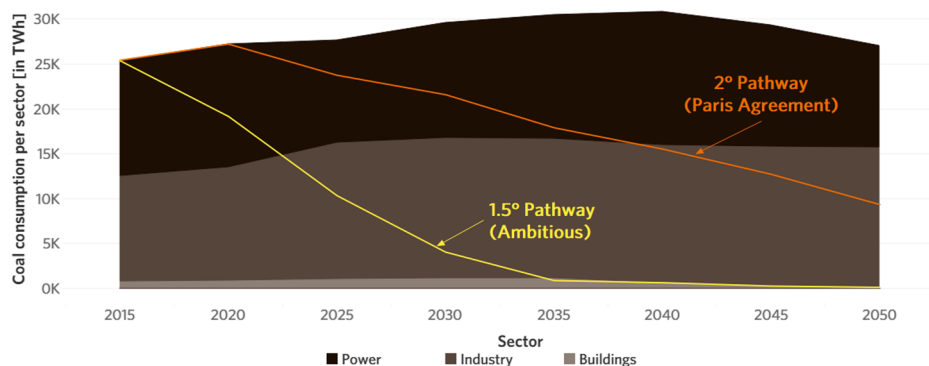


Fig. 5. Coal consumption in TWh per sector in the Limited Effort pathway with coal consumption of other pathways as comparison. Under strict CO₂ budgets, the usage of coal needs to be reduced.

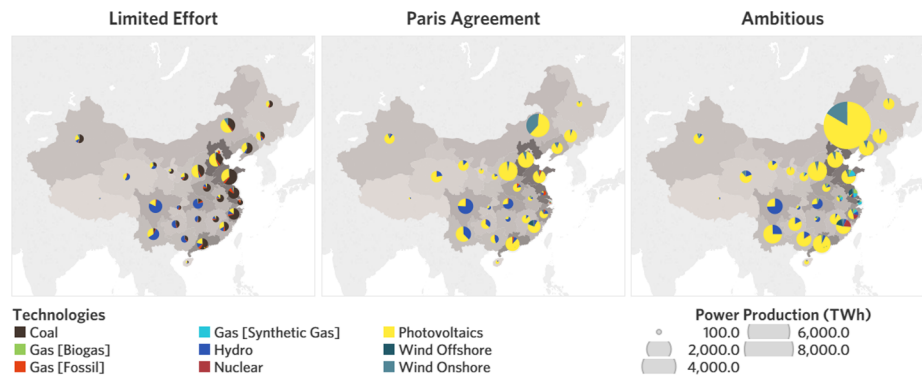


Fig. 6. Regional power production shares in 2050 in the different pathways. Provinces with high demand are highlighted with darker background color. Grid extension and power production outside of demand centers will likely increase by applying a more limited CO₂ budget.

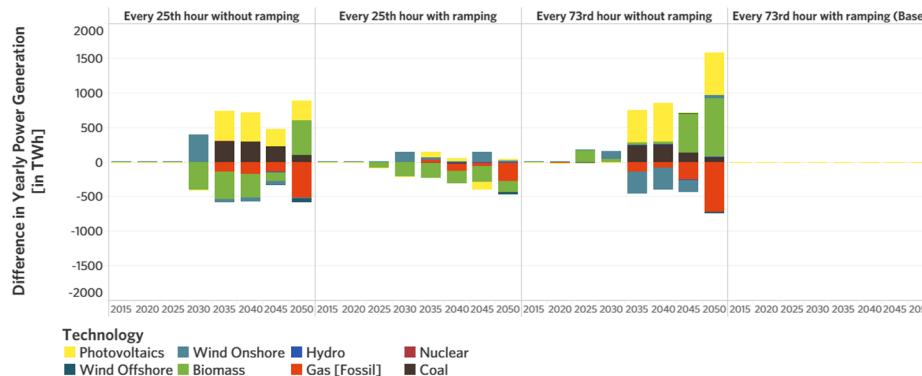


Fig. 7. Difference of power production per year and sensitivity for an artificially aggregated Chinese power system compared to the base scenario. Smaller time-series than those used for the main scenarios only have small effects on the results.

analysis, the deployed scenarios show similar trends as the results presented in our assessment of decarbonization pathways. Again, due to our multi-sectoral approach of modeling the Chinese energy system, we see different demands than projected in their scenarios and have an improved assessment of the need for electricity under different decarbonization pathways. Still, we conclude similar findings regarding the need for increased transmission structure and the importance of the Inner Mongolia province for the decarbonization of the Chinese energy system.

Lastly, assessing the additions and enhancements of GENeSYS-MOD included in the version presented in this paper, please refer to Fig. 7 and 8.

In Figs. 7 and 8, four different sensitivities are presented for an artificially aggregated Chinese region for the Paris Agreement scenario³. For this sensitivity analysis, trade routes between the provinces, as well as regional different renewable potentials have been omitted for more comparable results.

Fig. 7 presents the difference between the sensitivities in the yearly power production for this aggregated region. The sensitivity scenario calculating every 73th hour with ramping constraints was used as a baseline. As shown in this Figure, the reduction from every 73th to every 25th hour for the selection of the final time-series does not significantly impact the results, especially in the first years of the modeled period. Deactivation or activation of the newly added ramping equations (see Section 4), on the other hand, changes the results. For the yearly power production, a decrease of natural-gas usage in the later model periods can be observed when the ramping constraints are deactivated. Also, removing these constraints leads to a prolonged

³ All demands, potentials, and capacities are summed up and the load per time-slice and capacity factors have been averaged.

relevance of coal in the power system. A more significant change for adding the ramping constraints can be seen in the yearly dispatch, compare Fig. 8.

Overall, the impact of the ramping constraints has mostly an effect on baseload technologies. Without these constraints, nuclear, coal, and biomass generation technologies can completely activate or deactivate their full capacity from one hour to another. This leads to significant peaks in the generation of said baseload technologies. In systems with high shares of renewables, the removal of ramping constraints decreases the need for storages and reduces the amount of curtailed energy.

Finally, assessing the importance of highly detailed regions is highlighted by comparing Figs. 7 and 2. The need for flexibility in the power system is mostly covered by the different regional availability of renewable energy source (mostly solar PV). Also, Biomass is used to decarbonize the transportation and residential sectors and not in the power sector due to the implemented boundaries of overall usage. The artificially aggregated Chinese region presented in Fig. 7 has an overall reduced need for power-, biomass-, and coal-trade between the regions and thus reduced costs and higher availability for those energy carriers. Although this phenomenon can be offset by a more detailed regional aggregation with weighted averages of capacity factors and hourly load, the effect of balancing the power grid through the trade of electricity can only be captured with a high regional resolution.

6. Barriers for a Decarbonization of the Chinese Energy System

Despite displaying enormous potentials of RES and an urgent need to decarbonize its energy system to stay in line with the Paris Agreement, China will face a variety of barriers, challenges, and obstacles.

Present-day China still suffers from high social inequality and

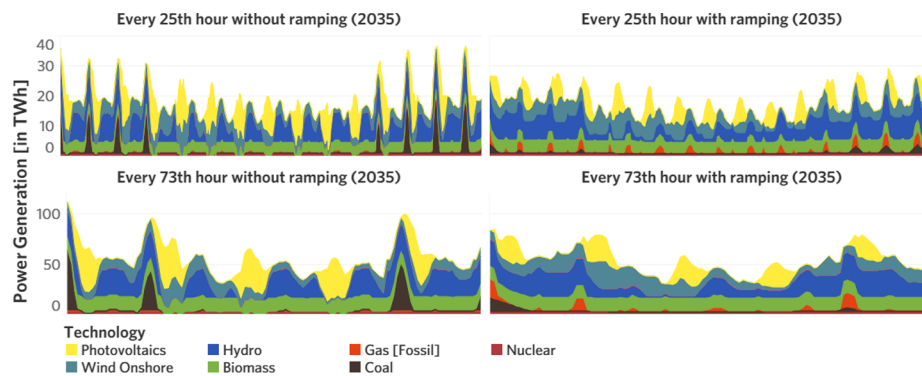


Fig. 8. Yearly dispatch in different sensitivity assessments. Without ramping constraints, significant peaks in activating and deactivating of nuclear, coal, and biomass can be seen.

poverty in various regions, as well as economic underdevelopment, despite the booming industrial centers, conglomerated in eastern, coastal regions. Incisive environmental targets, which allegedly restrict economic development, can, therefore, be difficult to explain to the local society, whose private welfare is often highly dependent on a single and emission-intense, industrial, local enterprise. Another aspect regarding societal opinion and barriers is the change of behavior within the Chinese culture, with increasing levels of prosperity, especially in industrial centers. Following the model of western countries, many Chinese strive for a modern and comfortable lifestyle with a stronger focus on consumption (compare Wang et al. [83]).

In public opinion, reducing emissions and the compliance to strict environmental restrictions is linked to consumption waivers and an obstruction to personal development. This opinion displays a significant lack of public information campaigns to show the importance of combining economic growth on all social levels with the needed emission reduction.

This can be seen by the obstacles that the Chinese government faced trying to decarbonize the heating sector by replacing coal with gas as a heating source between 2016 and 2017 Meng and Mason [84]. Also, as China's source for heating has largely been coal, a fuel-switch to gas would imminently result in a higher dependence on gas and liquid natural gas (LNG) imports from Russia and the USA, see Dong et al. [85] and 李春莲 [86]. Thus, concerns about energy security related issues occur. With import shares of up to 39% in 2017, this will significantly strain the national pipeline infrastructure and limited storage capacities. On the population side, especially elderly people in rural areas were met with difficulties in a transformation to gas based (cooking) facilities (compare Hao [87]).

On the policy side, considering China's division of tasks on a national (policy making) and provincial (policy implementation) level, inconsistent and relaxed implementation of policies like the emission trading system on a provincial level may deflect their initial purpose, as depicted by Duan and Zhou [88]. Furthermore, the previous methods for ensuring the implementation of policies on a local level may have proven to be effective in the past, but it might be problematic when implementing environmental policies, as these are characterized by time lags, as shown by Kostka and Hobbs [89] and Kostka and Mol [90]. Thus, local leaders might not see an incentive on the short term of the deployment of environmental policies. Hence, inefficiencies and delayed implementations on a provincial level might occur. As China's FYP targets are only binding within the short term, the Chinese energy transformation is highly dependant on the current agenda of the ruling Communist Party of China. As measurements are initiated and coordinated on a governmental level, investments into renewable energy technologies driven by the market are missing.

While China's shift towards green, sustainable energy production and consumption, as well as choices regarding the economy, are primarily initiated and driven by the national government, the demand of

the Chinese people for RES is slowly increasing. However, private companies and institutions leading the energy transformation are still to emerge, and incentives for the private sector need to be developed. This shows that the national target is only achievable when local entities understand the necessity for decarbonization and no disadvantages occur for the local actors.

7. Recommendations

China is and will be one of the main drivers for the transformation of the global energy system. While being the world's second-largest economy and the largest emitter of greenhouse gases worldwide, China has committed itself to fight climate change and to reduce its consumption of coal with their NDCs. Large shares of renewable power generation capacities have been installed in China in recent years, as depicted in Table 1, whereas the installment of new coal power plants decreased.

In the period from 2015 to the first quarter of 2019, 145 GW of conventional thermal generation capacities have been added to the Chinese power system. In the same period, around 260 GW of renewable energy sources have been installed, not including biomass and geothermal assets⁴. This increase in generation is also reflected in the actual yearly power generation, where the share of renewable technologies grows steadily.

Still, China has to push for additional efforts to reach their own NDCs, and even more to emerge as a leading country of the global low-carbon transformation. The results in this paper indicate that decarbonization of the industry and buildings sector is mostly depending on the power sector being carbon-free until 2050. Also, the decarbonization of the transportation sector has made progress but still needs to improve to meet all climate targets. With the ongoing addition of new coal-fired assets, electrification and decarbonization of the industry sector has to be promoted further, if the global target of the Paris Agreement is taken seriously. Also, the target of China's NDC of peaking emissions in 2030 is not compliant to a global CO₂ budget corresponding to the Paris Agreement. Targets for renewable generation and supporting actions in all sectors should be considered to comply with the Paris Agreement. Using different allocation schemes for the global CO₂ budget, as outlined in Section 4.2, would further decrease the available budget for China. This would, in turn, create the need for even higher ambitions to comply with the Paris Agreement.

Also, the time-frame until 2050 highlights the very ambitious efforts needed for complying with the Paris Agreement. With more postponed actions in the first half of the 21st century, a view at the second half until 2100 is needed. Still, significant investments into renewable

⁴ The yearly and quarterly reports of the China Electricity Council do not include information on these technologies.

Table 1

Capacity in GW and yearly generation in TWh of main electricity generation technologies in China. The share of conventional, thermal, power generation capacity is decreasing over the last years with substantial amounts of renewable energy sources added each year. Data source: China Electricity Council [91]

Capacity in GW						
Technology	2015	2016	2017	2018	2019 (Q1)	Change '15-'19
Thermal	1005.54 (67%)	1060.94 (66%)	1106.04 (64%)	1143.67 (62%)	1150.28 (60%)	+ 14%
Hydropower	319.54 (21%)	332.07 (20%)	341.19 (20%)	352.26 (19%)	354.86 (19%)	+ 11%
Solar	42.18 (3%)	76.31 (5%)	130.25 (7%)	174.63 (9%)	179.83 (9%)	+ 326%
Wind	130.75 (9%)	147.47 (9%)	163.67 (9%)	184.26 (10%)	217.88 (12%)	+ 67%
Generation in TWh						
Technology	2015	2016	2017	2018	2019	Change '15-'18
Thermal	4186.80 (76%)	4327.32 (74%)	4587.70 (74%)	4923.10 (73%)	-	+ 18%
Hydropower	1111.70 (20%)	1174.88 (20%)	1194.70 (19%)	1232.90 (18%)	-	+ 11%
Solar	38.50 (1%)	66.523 (1%)	117.80 (2%)	177.50 (3%)	-	+ 361%
Wind	185.30 (3%)	240.86 (4%)	304.60 (5%)	366.00 (5%)	-	+ 98%

energies, energy efficiency, and promoting electrification of non-power sectors are required.

Furthermore, the current importance of local actors imposes social, political, and economic barriers for a successful transformation of the Chinese energy system. Hence, it is critical that these barriers have to be tackled by the Chinese government through interaction with stakeholders. Furthermore, to mitigate local resistance against a low-carbon transformation, additional incentives for private companies, institutions, and individuals have to be developed and introduced by the Chinese government.

8. Conclusion

In this paper, we analyzed the development of the Chinese energy system until 2050 under different CO₂ budgets. Our focus on sector-coupling and decarbonization pathways provide several additions for the existing literature. From a modelers perspective, we have shown that it is essential to add interconnections between sectors to have better estimations about the electricity demand increase corresponding to electrification and other decarbonization and sector-coupling measures. Also, a detailed regional level of aggregation is needed for assessing the power system balancing effects of inter-regional power trade.

The usage of CO₂ budgets leads to following insights about the Chinese energy system: Firstly, coal usage has to be reduced drastically to comply with a carbon budget that is in line with the Paris Agreement. Furthermore, for a cost-efficient decarbonization of the industry and buildings sectors, the power sector has to be transformed first. The speed and composition of the energy transformation in the power and industry-sector are highly sensitive to different carbon budgets. Lastly, staying well below 1.5 °C will require immediate decarbonization measures in all sectors, and an introduction of breakthrough-technologies. Also, results indicate that an energy system based on nearly 100% renewable energy sources by 2050 is needed for limiting global

Appendix A. Data

This section presents some additional key data for the analysis. More supplementary data is provided in the *Mendeley Data* repository provided by Burandt [92].

warming to 1.5 °C. Overall, the current Nationally Determined Contributions proposed by the Chinese government are not sufficient enough to comply with a global CO₂ budget in line with the Paris Agreement.

Further research should examine the effect of different energy demand forecasts on the transformation of the Chinese energy system. Also, including the neighboring countries would enable to measure possible synergies of international co-operation to foster a global decarbonization pathway in line with agreed on climate targets.

Data availability

The authors will publish the available data, which is under no copyright limitations, as well as the model code. This is to allow others to verify the results and examine possible additional scenarios. For now, the authors are willing to share the code and data after a reasonable request. Selected key data can be found in Burandt [92].

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A.1. Technology costs

See Table A.1.

Table A.1

Capital costs of main electricity generating technologies in M€/GW. Data based on European Commission et al. [93], Gerbaulet and Lorenz [71], Ram et al. [33], and Burandt et al. [63].

	2015	2020	2025	2030	2035	2040	2045	2050
Utility PV	1020	790	695	600	525	450	410	370
Onshore Wind	1250	1150	1060	1000	965	940	915	900
Offshore Wind	3500	2637	2200	1936	1800	1710	1642	1592
Geothermal	5250	4970	4720	4470	4245	4020	3815	3610
Biomass Thermal Plant	2890	2620	2495	2370	2260	2150	2050	1950
Hydropower (Large-Scale)	2200	2200	2200	2200	2200	2200	2200	2200
Hydropower (Small-Scale)	4400	4480	4490	4500	4500	4500	4500	4500
Coal-Fired Thermal Plant	1600	1600	1600	1600	1600	1600	1600	1600
Gas-Fired Thermal Plant	650	636	621	607	593	579	564	550
Oil-Fired Thermal Plant	650	627	604	581	559	536	513	490
Coal-Fired CHP	2030	2030	2030	2030	2030	2030	2030	2030
Gas-Fired CHP	977	955	934	912	891	869	848	826
Oil-Fired CHP	819	790	761	733	704	675	646	617

A.2. Ramping parameters

See Table A.2.

Table A.2

Capital costs of main electricity generating technologies in M€/GW. Data based on European Commission et al. [93] and Gerbaulet and Lorenz [71].

	Ramping Up	Ramping Down	Ramping Costs in €/MWh
Hydropower (Large-scale)	25%	25%	50
Biomass Power Plant	4%	4%	50
Nuclear Power Plant	1%	1%	200
Coal-Fired Thermal Plant	4%	4%	50
Gas-Fired Thermal Plant	20%	20%	20
Oil-Fired Thermal Plant	6%	6%	50

A.3. Fuel costs

See Table A.3.

Table A.3

Import fossil fuel cost in M€/PJ and domestic costs of hard-coal in primary coal-exporting provinces, based on International Energy Agency [76] and He et al. [8].

	2015	2020	2025	2030	2035	2040	2045	2050
Oil [Import]	7.12	10.18	11.02	11.86	11.37	10.88	8.99	7.11
Coal [Import]	4.50	4.57	4.54	4.50	4.35	4.19	4.07	3.94
Nat. Gas [Import]	8.81	8.15	9.00	9.86	9.90	9.95	10.00	10.05
Coal [Inner Mongolia]	0.81	0.82	0.82	0.82	0.78	0.75	0.73	0.71
Coal [Shaanxi]	1.54	1.56	1.55	1.54	1.49	1.43	1.39	1.35
Coal [Ningxia]	1.58	1.60	1.59	1.58	1.52	1.47	1.43	1.38
Coal [Guizhou]	3.60	3.65	3.62	3.60	3.47	3.35	3.25	3.15

A.4. Demand

See Table A.4.

Table A.4

Sector-specific demands, based on International Energy Agency [76] and National Bureau of Statistics of China (中华人民共和国国家统计局) [15].

	2015	2020	2025	2030	2035	2040	2045	2050
Power [PJ]	9858	10,775	11,590	12,404	12,753	13,101	13,264	13,426
Industry (High) [PJ]	23,061	24,342	25,374	26,406	26,620	26,833	27,211	27,588
Industry (Medium) [PJ]	12,890	13,607	14,183	14,760	14,880	14,999	15,210	15,421
Industry (Low) [PJ]	5307	5602	5840	6077	6126	6175	6262	6349
Buildings [PJ]	12,096	12,952	13,794	14,637	15,341	16,045	17,717	18,510
Freight-Mobility [gtkm]	15,667	19,699	23,716	27,704	31,636	35,324	38,288	39,643
Passenger-Mobility [gpkm]	2838	3360	3930	4499	4684	4870	4918	4967

A.5. Renewable capacity factor

See Fig. A.9.

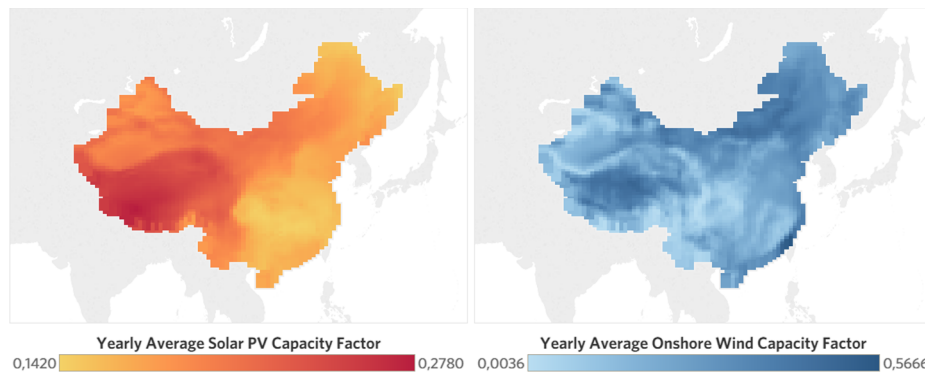


Fig. A.9. Presentation of the yearly average capacity factors for onshore wind and solar PV per data point in a 50x50km grid.

Appendix B. GENeSYS-MOD: blocks of functionality

This section shortly describes the main components of GENeSYS-MOD. In similar manner to the original OSeMOSYS formulation, all additions have been formulated as mostly separated blocks, as depicted in Fig. B.10.

In general, OSeMOSYS features several blocks of functionality that can be modified or expanded individually. Each of these blocks consists of one or multiple equations. In total GENeSYS-MOD considers 122 individual mathematical equations each set up for a variety of different sets. The main characteristics of an energy system are represented with energy balances (i.e., demand equals production plus/minus trade and storages) and capacity adequacies for all energy carriers. Yearly capacity addition limits, as well as total limits for capacities or technology activity, implement

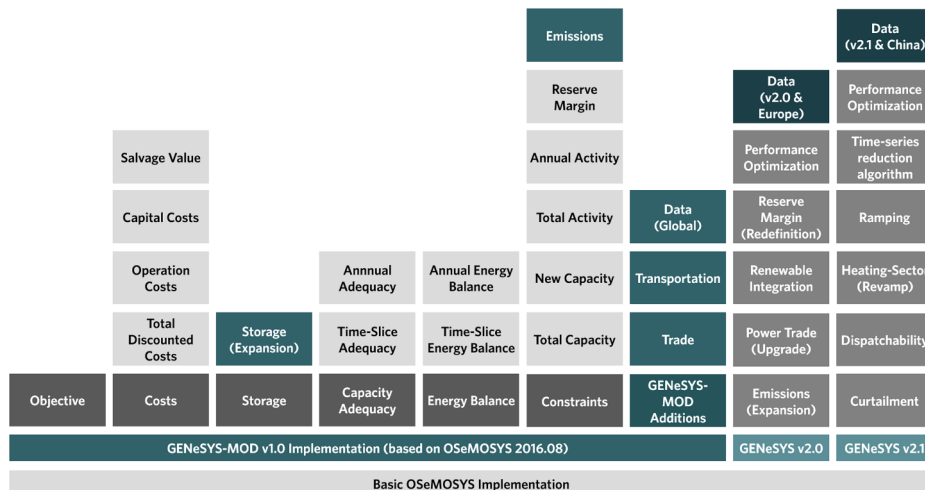


Fig. B.10. Simplified block structure of OSeMOSYS and GENeSYS-MOD. The grey blocks on the right side represent recent additions to GENeSYS-MOD.

technological, economic, or physical boundaries of the analyzed system. Storages are modeled different from other technologies and thus feature their own block. The mathematical formulation of storages has been improved within GENeSYS-MOD compared to the basic OSeMOSYS formulation. Also, GENeSYS-MOD features an overhauled trade of energy carriers (e.g., electricity) with losses, costs, and endogenous capacity expansion. Additional equations for transportation carriers limit modal shifts between transportation services (e.g., air to rail). More recently, the power trade, as well as the integration of renewable generation technologies, has been expanded. For more detail regarding the additions of GENeSYS-MOD please refer to Löffler et al. [30] and Burandt et al. [63].

B.1. Mathematical formulation

This appendix gives an overview over the sets, variables, and parameters used in the mathematical formulation in Section 4. These lists do not include all variables or parameter used by OSeMOSYS or GENeSYS-MOD. For a more comprehensive overview, please refer to Howells et al. [69], Löffler et al. [30] and Burandt et al. [63].

B.1.1. Sets, variables and parameters

Sets		
Set		Description
$l \in L$		Timeslices (hours)
$y \in Y$		Years
$t \in T$		Technologies
$f \in F$		Fuels
$s \in S$		Storage-Technologies
$r, rr \in R$		Regions (provinces)

Superscripts		
Superscript		Description
<i>first</i>		Denotes the first entry in a set
<i>D</i>		Denotes discounted costs

Variables		
Variable	OSeMOSYS-Style Name	Description
<i>tc</i>	TotalCost	Sum of technology and storage costs
<i>ttc</i>	TotalTechnologyCosts	Sum of operating-, investment-, emission-, and ramping-costs minus the salvage value for any technology
<i>tsc</i>	TotalStorageCost	Sum of fixed, variable, investment, emission, and ramping costs minus the salvage value for any storage
<i>atc</i>	AnnualTotalTradeCosts	Yearly costs for trading fuels between regions
<i>acc</i>	AnnualCurtailementCost	Yearly costs for curtailment
<i>ncc</i>	NewTradeCapacityCosts	Costs for added power trading infrastructure
<i>oc</i>	OperatingCost	Sum of fixed and variable costs
<i>ci</i>	CapitalInvestment	Capital expenditures
<i>ep</i>	TechnologyEmissionsPenalty	Emission penalty or costs
<i>sv</i>	SalvageValue	Salvage value of technology t in year y
<i>rc</i>	AnnualProductionChangeCost	Annual ramping costs
<i>tcap</i>	TotalCapacityAnnual	Total existing capacity of a technology in given region and year
<i>g</i>	RateOfProductionByTechnology	It represents the quantity of fuel f that technology t would produce in one mode of operation and in time slice l, if the latter lasted the whole year
$g^{\Delta+}$	ProductionChangeUp	Upwards change of generation
$g^{\Delta-}$	ProductionChangeDown	Downwards change of generation

Parameters		
Parameter	OSeMOSYS-Style Name	Description
<i>AF</i>	AvailabilityFactor	Maximum time a technology can run in the whole year, as a fraction of the year
<i>CTA</i>	CapacityToActivityUnit	Conversion factor relating the energy that would be produced when one unit of capacity is fully used in one year
RF^+	RampingUpFactor	Fraction of capacity that can be activated each hour
RF^-	RampingDownFactor	Fraction of capacity that can be deactivated each hour
<i>YS</i>	YearSplit	Duration of a modelled time slice, expressed as a fraction of the year
<i>RCF</i>	ProductionChangeCost	Costs for changing one unit of energy
<i>DR</i>	DiscountRate	Discount rate for determining discounted costs that are included in the objective function

B.1.2. Mathematical formulation with OSeMOSYS-style names

$$\begin{aligned}
 &RateOfProductionByTechnology_{y,l,t,f,r} \cdot YearSplit_{y,l} - RateOfProductionByTechnology_{y,l-1,t,f,r} \cdot YearSplit_{y,l-1} \\
 &= ProductionChangeUp_{y,l,t,f,r} - ProductionChangeDown_{y,l,t,f,r} \quad \forall y, l, t, f, r
 \end{aligned}
 \tag{B.1}$$

$$\text{ProductionChangeUp}_{y,l,t,f,r} \leq \text{TotalCapacityAnnual}_{y,t,r} \cdot \text{AvailabilityFactor}_{y,t,r} \cdot \text{CapacityToActivityUnit}_t \cdot \text{RampingUpFactor}_{r,t,y} \cdot \text{YearSplit}_{y,l} \quad \forall y, l, t, f, r \quad (\text{B.2})$$

$$\text{ProductionChangeDown}_{y,l,t,f,r} \leq \text{TotalCapacityAnnual}_{y,t,r} \cdot \text{AvailabilityFactor}_{y,t,r} \cdot \text{CapacityToActivityUnit}_t \cdot \text{RampingDownFactor}_{r,t,y} \cdot \text{YearSplit}_{y,l} \quad \forall y, l, t, f, r \quad (\text{B.3})$$

$$\text{AnnualProductionChangeCost}_{y,t,f,r} = \sum_l (\text{ProductionChangeUp}_{y,l,t,f,r} + \text{ProductionChangeDown}_{y,l,t,f,r}) \cdot \text{ProductionChangeCost}_{r,t,y} \quad \forall y, t, f, r \quad (\text{B.4})$$

$$\text{DiscountedAnnualProductionChangeCost}_{y,t,f,r} = \frac{\text{AnnualProductionChangeCost}_{y,t,f,r}}{(1 + \text{DiscountRate})^{y - \text{StartYear} + 0.5}} \quad \forall y, t, f, r \quad (\text{B.5})$$

$$\begin{aligned} \text{TotalDiscountedCostByTechnology}_{y,t,r} &= \text{DiscountedOperatingCost}_{y,t,r} + \text{DiscountedCapitalInvestment}_{y,t,r} + \text{DiscountedTechnologyEmissionsPenalty}_{y,t,r} \\ &+ \text{DiscountedAnnualProductionChangeCost}_{y,t,r} - \text{DiscountedSalvageValue}_{y,t,r} \quad \forall y, t, r \end{aligned} \quad (\text{B.6})$$

minimize z

$$\begin{aligned} = & \sum_{y,r} \left(\sum_t (\text{TotalDiscountedCostByTechnology}_{y,t,r}) + \sum_s (\text{TotalDiscountedStorageCost}_{y,s,r}) + \text{DiscountedAnnualTotalTradeCosts}_{y,r} + \right. \\ & \left. \sum_{f,rr} (\text{DiscountedNewTradeCapacityCosts}_{y,f,r,rr}) + \sum_f (\text{DiscountedAnnualCurtailmentCost}_{y,f,r}) \right) \end{aligned} \quad (\text{B.7})$$

Appendix C. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.apenergy.2019.113820>.

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