

Motives beyond markets

State ownership, stranded assets, and decarbonisation in the power sector

Alex Clark

Thesis submitted for the degree of Doctor of Philosophy

Trinity Term 2023

Hertford College

Smith School of Enterprise and the Environment, School of Geography and the Environment

and

Institute for New Economic Thinking at the Oxford Martin School

University of Oxford

This thesis is dedicated to the memories of

Joy Clark, Bruce Nightingale, and Diana Nightingale

Acknowledgements

Work on this thesis began in a society untouched by the COVID-19 pandemic. In some ways, the world that has emerged from it is radically different, and in others it has – fortunately and unfortunately – remained much the same. For their guidance, patience and encouragement throughout a difficult time in which to be a graduate research student, thank you to my supervisors Ben Caldecott and Cameron Hepburn. Zena, thank you for being my foundation – for being the source of belief, kindness and love that saw me sail through the highs and lows. I still have so much to learn from you. Mum and Dad, Emily and Ben, you made it all possible, and you make it all worthwhile. For taking the time to carefully read and comment on the material in this thesis as it came together, and offer constructive input at different stages, my thanks to Alex Money, Tom Hale, Doyne Farmer, and the several anonymous peer reviewers of the published thesis papers. Additional thanks to Alex Money, and to Kevin Gallagher, for agreeing to serve as assessors, and to Henry Lee for inviting me back to the Harvard Kennedy School after such a lengthy interval.

To my co-author Philippe Benoit, I am grateful to have developed such a fruitful collaboration in which we have challenged, and learned from each other. Additional thanks to Moritz Schwarz, Arjuna Dibley, and Weirong Zhang. I have been fortunate to work alongside many other brilliant researchers and colleagues over the process of undertaking this degree across the Smith School of Enterprise and the Environment, INET Oxford, Oxford Martin School, Global Development Policy Center at Boston University, and Environment and Natural Resources Program at the Harvard Kennedy School. Particular thanks to Matt Ives for making this project possible via the EEIST research consortium, to Pete Barbrook-Johnson for his leadership, and to Simon Sharpe for his vision. For their friendship and intellectual companionship, thanks to Sugandha Srivastav, Tim Dobermann, Brian O’Callaghan, Annabelle Wainer, and Krister Koskelo. For their support and encouragement in the very beginning, thank you to Donovan Escalante, Barbara Buchner, and Dario Abramskiewn. I acknowledge financial support from, among others, the Sustainable Finance Group; INET Oxford (via BEIS and CIFF); the Blavatnik School of Government, Hertford College, the National Environment Research Council, and Boston University.

Abstract

State-owned enterprises (SOEs) will play a central role in the decarbonisation of the global economy. They are also the dominant type of actor in the power sector by both installed power generation capacity and investment, with China accounting for the largest share. Despite their obvious prominence, SOEs remain an understudied element in climate policy analysis, design and implementation. The papers in this thesis begin to address this research gap, focusing on state-owned power companies (SPCs). The three papers employ, respectively, comparative case study analysis, a modified version of discounted cash flow analysis, and microsimulation techniques. Together, they make some initial progress towards more explicit integration of SOEs and government shareholders into climate policy research. Paper 1 develops a framework for analysing how SPCs' characteristics and the context in which they operate affects their response to government interventions. It finds that SPCs can, under certain circumstances, be more effective conduits for climate policy than private companies, and that market-wide policies may have less effect on SPCs than on their privately-owned counterparts. Paper 2 adapts and extends traditional stranded asset analysis to consider cases in which the asset owners are SOEs, focusing on coal power in China. It concludes that new coal power investments by Chinese SOEs are unlikely to deliver positive economic returns, and that dispatchable renewable power will soon be economically competitive as an alternative even without accounting for the social cost of carbon. Paper 3 simulates the effect of thermal coal phase-out in China on employment and tax revenue in the thermal coal value chain. The results show that delaying coal phase-out cannot prevent losses in employment and tax revenue in China's coal sector from being realised, and that these losses are both geographically concentrated and associated with a small number of large SPCs. Overall, this thesis demonstrates the importance of explicitly accounting for SOEs both in formulating climate policies and analysing their effects.

Thesis Papers

1. **Decarbonization in state-owned power companies: lessons from a comparative analysis**

Journal of Cleaner Production

Philippe Benoit, Alex Clark, Moritz Schwarz and Arjuna Dibley

2. **Government Shareholders, wasted resources and climate ambitions: why is China still building new coal-fired power plants?**

Climate Policy

Alex Clark, Philippe Benoit and Jonathan Walters

3. **Estimating the Employment and Fiscal Consequences of Thermal Coal Phase-out in China**

Energies

Alex Clark and Weirong Zhang

Supervisors

Professor Cameron Hepburn, Professor of Environmental Economics at the Smith School of Enterprise and the Environment, and the Institute for New Economic Thinking at the Oxford Martin School University of Oxford

Dr Ben Caldecott, Associate Professor of Sustainable Finance at the Smith School of Enterprise and the Environment, University of Oxford

Examiners

Internal Examiner

Dr Alex Money, Director of Innovative Infrastructure Investment Programme at the Smith School of Enterprise and the Environment, University of Oxford

External Examiner

Professor Kevin P. Gallagher, Professor of Global Development Policy, Frederick S. Pardee School of Global Studies, Boston University

Contents

1. Introduction.....	1
a. State-owned enterprises and climate change.....	1
b. SOEs in the power sector.....	4
c. Contributions.....	8
2. Literature Review.....	11
a. Theoretical underpinnings.....	11
b. Governments’ net zero commitments.....	14
c. State ownership and the power sector.....	18
d. Stranded asset risks and state ownership.....	24
3. Outline of the Thesis Papers.....	28
A note on research design.....	28
Paper 1: State-owned power companies and decarbonisation.....	32
Motivation and research question.....	32
Methods.....	33
Results.....	35
Limitations.....	36
Paper 2: Government shareholders and stranded assets.....	40
Motivation and research question.....	40
Theory.....	41
Methods.....	44
Results.....	46

Limitations	47
Paper 3: The effects of coal phase-out on employment and fiscal revenue in China	50
Motivation and research question	50
Methods.....	51
Results	52
Limitations	53
4. Policy Implications	58
5. Extensions and Future Work.....	60
a. Improvements in data availability	60
b. Investigating the political economy of government- SPC relationships.....	64
c. Exploring additional sectors, geographies, and scenarios.....	66
d. Accounting for overseas assets and investments	69
6. Conclusion	71
a. Overview of main findings.....	71
b. Looking ahead: towards including SOEs in climate policy design and analysis.....	73
7. References.....	79
A1. Paper 1: State-owned power companies and decarbonisation	91
A2. Paper 2: Government shareholders and stranded assets.....	131
A3. Paper 3: The effects of coal phase-out on employment and fiscal revenue in China	157
A4. Additional work and related publications	200
Appendix References	204

Abbreviations

For abbreviations of Chinese province names, see Appendix 3, p. 27 of the attached offprint.

ABM	agent-based model
B	Baseline (scenario)
B2C	Below 2 Degrees Celsius (scenario)
BEIS	Department of Business, Energy and Industrial Strategy (United Kingdom)
bn	billion
BRI	Belt and Road Initiative (China)
BUMN	Ministry of State-owned Enterprises (Indonesia)
C	celsius
C50	50% decline in carbon dioxide emissions 2015-2030 (scenario)
C80	80% decline in carbon dioxide emissions 2015-2030 (scenario)
CapEx	capital expenditure
CBIRC	China Banking and Insurance Regulatory Commission
CCNG	combined cycle natural gas
CCS	carbon capture and storage
CDB	China Development Bank
CEIT	Central Environment Inspection Team (China)
CELCEP	China Energy and Low-Carbon Economy Programme
CFE	Comisión Federal de Electricidad
CGEP	Center on Global Energy Policy (Columbia University)
CIFF	Children's Investment Fund Foundation
CNY	Chinese yuan (currency)
CO ₂	carbon dioxide
COVID-19	coronavirus disease (2019)
COP	Conference of Parties to the UNFCCC (see abbreviation)
DFI	development finance institution
DSGE	dynamic stochastic general equilibrium
DISCOM	electricity distribution company (India)
ECA	export credit agency

EDF	Electricité de France
EEIST	Economics of Energy Innovation and Systems Transition
EIRR	economic internal rate of return
ENPV	economic net present value
EPC	engineering, construction & procurement
EPT	Environmental Pollution Tax (China)
ERA	Energy Regulator Act (ERA)
ETS	emissions trading scheme
EU	European Union
Exim Bank	Export-Import Bank of China
FCDO	Foreign Commonwealth & Development Office (United Kingdom)
FIRR	financial internal rate of return
FNPV	financial net present value
FY	financial year
FYP	Five-Year Plan (China)
GCPT	Global Coal Plant Tracker
GDP	gross domestic product
GHG	greenhouse gas
GTCO _{2e}	gigatonne of carbon dioxide equivalent
GW	gigawatt (billion watt)
HA	Higher Ambition (scenario)
HHI	Herfindahl-Hirschman Index
IAM	integrated assessment model
IDFC	International Development Finance Club
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IMF	International Monetary Fund
IPP	independent power producer
JETP	Just Energy Transition Partnership
JTT	Just Transition Transaction
KEPCO	Korea Electric Power Corporation

kcal	kilo-calorie
kg	kilogramme
KPI	key performance indicator
kWh	kilowatt-hour (thousand watt-hour)
LCOE	levelised cost of electricity
LNG	liquefied natural gas
LR	load factor restriction
Mt	million metric tonnes
Mtce	million tonnes of coal equivalent (China)
MW	megawatt (million watt)
MWh	megawatt-hour (million watt-hour)
NEA	National Energy Act (South Africa)
NEI	National Energy Investment Group (also known as China Energy or CHN Energy)
NDRC	National Development and Reform Commission
NERC	National Environment Research Council
NHPC	National Hydroelectric Power Corporation (India)
NDC	Nationally Determined Contributions
NOC	national oil company
NO _x	nitrogen oxide
NPV	net present value
NREL	National Renewable Energy Laboratory (United States)
NT	No Transition (scenario)
NTPC	NTPC Limited (formerly National Thermal Power Corporation Limited)
O&M	operations and maintenance
OECD	Organisation for Economic Co-operation and Development
PLN	Perusahaan Listrik Negara
PM _{2.5}	particulate matter (particle diameter 2.5 microns or less)
POSCO	POSCO Korea (formerly Pohang Iron and Steel Company) (South Korea)
PPA	power purchase agreement
PPF	public pension fund
R	Rapid renewable cost declines (scenario)

SASAC	State-owned Assets Supervision and Administration Commission
SCP	shadow carbon price
SO ₂	sulphur dioxide
SOE	state-owned enterprise
solar PV	solar photovoltaic
SP	Stated Policies (scenario)
SPC	state-owned power company
SPIC	State Power Investment Corporation
SWF	sovereign wealth fund
PEMEX	Petróleos Mexicanos
R&D	research and development
RMB	Chinese Renminbi (equivalent to Chinese yuan, CNY)
t	metric tonne
T&D	transmission and distribution
tce	tonne of coal equivalent
TW	terawatt (trillion watt)
TWh	terawatt-hour (trillion watt-hour)
ULE	Ultra-Low Emissions Standard (China)
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
US	United States of America
USD/US\$	United States dollars
VAT	value-added tax
WEPP	World Electric Power Plants database (S&P)
WTP	willingness-to-pay

1. Introduction

a. State-owned enterprises and climate change

State-owned enterprises (SOEs) are widely acknowledged as major components of the global economy and an unavoidable empirical reality. As Whincop (2016) observes in *Corporate Governance in Government Corporations*, “Whether one likes it or not, the state-owned enterprise ... remains an important part of the economic apparatus of virtually every country.” Highlighting the role of SOEs in developing and emerging economies, he goes on to note that they are particularly prominent in “jurisdictions which have yet to develop strong markets, and rely on greater levels of public ownership to overcome weak property rights.” The International Monetary Fund (2020) also finds that SOEs today occupy a central role in infrastructure investment and construction in emerging markets and low-income developing countries, often with state-owned financial institutions as the corresponding lenders and underwriters.

A significant share of global economic activity, and the greenhouse gas (GHG) emissions (henceforth ‘emissions’) arising from it, is directly associated with SOEs under the explicit control of national and subnational governments. The presence of SOEs is most salient in high-carbon, capital-intensive industries, particularly power (i.e. electricity generation), oil and gas, cement and steel (Clark & Benoit, 2022; Mayer & Rajavuori, 2017; Prag, Röttgers, & Scherrer, 2018). A conservative and incomplete aggregation of emissions from SOEs – defined as firms in which governments hold more than 50% of voting shares – finds that they account for at least 7.49 billion tonnes of carbon dioxide equivalent (GTCO_{2e}) in annual direct (‘Scope 1’) emissions alone, representing approximately 15% of global annual emissions from all sources. If estimated emissions, based on production data combined with emissions intensities, are included, this figure rises to 8.87 GTCO_{2e} – approximately 18% of global emissions. Adding indirect upstream and downstream (Scope 3) emissions raises the total to over 12.5 GTCO_{2e}, close to one quarter of the global total (Clark & Benoit, 2022). Nonetheless, SOEs remain

conspicuously absent from mainstream research on the design, effectiveness, and governance of climate policies and the decarbonisation of national economies.

Straddling elements of government and private enterprise alike, SOEs will play an indispensable but critically under-researched and not well-understood role in any trajectory towards a decarbonised economy. In academic research on national and global decarbonisation pathways, SOEs are almost entirely overlooked as key targets of industrial policies, market-based climate policy mechanisms, or any other systematic effort to decarbonise national economies. Within literatures on the economics of climate change and modelling of transition pathways to a net zero-emissions economy, policy-relevant output is still dominated by integrated assessment models (IAMs) based on generalised assumptions of firms' structures and behaviours (Farmer, Hepburn, Mealy, & Teytelboym, 2015; Peng et al., 2021). While substantial progress has been made towards incorporating more robust representations of decision-making under uncertainty, bounded rationality in individual decision-making, and features of complex adaptive systems with heterogeneous agents, firms are still widely conceptualised in economic models as self-interested rational actors with solely profit-maximising objective functions. Given this focus on idealised private markets for goods, services and capital, it is unsurprising that climate policy discourse has focused on market-based mechanisms and regulatory initiatives as the primary means of motivating changes in firm activity. This reflects a prevailing norm that states' function is to set and enforce rules for free competition between private firms, rather than intervening directly in firm behaviour (Cullenward & Victor, 2020).

If SOEs were marginal components of global economic activity, or small contributors to emissions, it might be reasonable to assume that all firms are indeed, to a first approximation, rational profit-maximisers. As Clark and Benoit (2022) show, however, SOEs' role is far from marginal. Through SOEs, governments today are playing a direct role in allocating large amounts of capital towards investments in emissions-intensive physical asset stocks, and the financing and operation of existing asset stocks. Underlying these physical assets are both historical emissions associated with their activities to date, and 'committed' emissions based on expected future activities up to the asset's retirement. At the same time, SOEs – even those in which governments' direct shareholding is nominal

– may conceivably operate at greater distance from market forces and less distance from government, and with a different relationship to both of them, than the profit-maximising private firms generally represented in the IAMs and other technoeconomic models which currently inform the design and execution of climate policies. If it is true that capital allocation in an SOE is less subject to market forces, and subject to different rules, than its privately held peers, it follows that the same is true for their historical and future emission profiles.

Even if there is no significant difference in how SOEs allocate capital in comparison to their peers, scholars including Shleifer (1998) and Megginson and Netter (2001) have suggested that SOEs are sufficiently different from their privately-owned counterparts that they deserve to be analysed as a distinct category of organised activity. If SOEs do differ systematically from private firms, any model results and policy prescriptions that assume all firms act homogeneously and to maximise profits are necessarily biased. This limits these models’ usefulness in understanding or explaining SOEs’ historical activities. It also runs the risk of under- or over-estimating aggregate economy-wide responses to climate policies, with corresponding effects on decarbonisation outcomes. It is certainly possible that existing models fundamentally misrepresent the role of state-owned firms in the economy to the extent that they exclude factors such as national economic growth, employment targets and service delivery imperatives from their definitions of SOEs’ objective functions. For state-led economies, this may have major implications for macroeconomic policy in general, and decarbonisation policy in particular.

Despite the empirical significance of SOEs, there is far less data – particularly structured data – available on the universe of SOEs than on that of publicly traded firms. There are large literatures on the history, politics, industrial economics, political economy, sociology and management of SOEs in general across a wide range of contexts. All of them are potentially helpful for understanding the historical context, structure and contemporary behaviour of SOEs. The most relevant strands for the purposes of this research, however, are those that deepen our understanding of how SOEs make decisions. Scholars of corporate governance and law have found, for instance, that the legal structures which regulate relationships between governments and SOEs, as well as the market power of SOEs, also affect the degree of formal and informal control the state can exert over them (Belloc, 2014; Dibley,

2021; Su, Wan, & Song, 2018). Milhaupt and Pargendler (2019) find that governments often provide their SOEs with financing at below-market rates. This gives them greater flexibility in pursuing objectives other than profit maximisation and in some cases, an advantage over international or domestic competitors. Other researchers have claimed that conflicts between profit motivations and mandates to pursue other policy-related goals inherently limit SOEs' capacity to invest in innovative technologies (Tirole, 1994), and by extension, to strengthen long-term productivity growth (Hart, Shleifer, & Vishny, 1997; Shleifer, 1998) – although more recent work has started to challenge these findings (Belloc, 2014; Dibley, 2021; Steffen, Karplus, & Schmidt, 2020). See Section 2 for a more detailed discussion of the relevant literature.

Despite the rich and varied scholarship on SOEs in general, there is very little published work focusing on SOEs' contributions to GHG emissions and still less on their role in delivering on their government shareholders' pledges to transition to net-zero emissions economies. However, there are firm foundations for considering SOEs to be distinct in theory and practice from their privately-owned peers, and for beginning to identify the sources of some of these differences. The authors cited above collectively identify the clearest sources of divergence across SOEs to be the cost of (and access to) financing; mandate; corporate and legal structure; investment strategy; market power; and political context. Nevertheless, scholars have yet to succeed in developing a robust model of SOE decision-making, either in general or for specific sectors.

b. SOEs in the power sector

SOEs are the dominant type of actor in the power sector, controlling 61% of existing global electricity generation capacity and accounting for 52% of planned future capacity in 2017 (Prag et al., 2018). Clark and Benoit (2022) find that the power sector contributes 85% of estimated total direct emissions from SOEs. In addition, rapid and complete decarbonisation of power generation is necessary – albeit not sufficient – for the Paris Agreement's objectives to be met (International Energy Agency,

2021). Power is also a sector in which pre-existing data on physical assets and corporate owners is relatively widely available and consequently, research questions are more tractable.

These characteristics became a more important consideration for the work represented in this dissertation when the advent of the COVID-19 pandemic made international travel, especially to China, impossible for an indeterminate period early in 2020. Having previously planned to conduct interview-based primary research, the constraints imposed by the pandemic required me to reformulate core research questions such that they could be satisfactorily addressed with existing data, with or without the support of collaborators based in China (see Section 3, ‘A note on research design’ for further discussion on this point). Taking data availability and practical considerations into account, the power sector therefore presented a useful and logical entry point for studying the role of SOEs in economy-wide decarbonisation.

The extant literature on the state-owned power companies (SPCs) that are the focus of this dissertation is largely limited to studies incorporating a narrow range of input data, and to individual case studies (Bellas & Nentl, 2007; Steffen et al., 2020; Tönurist, 2015). An econometric study of SOEs’ asset portfolios and investments by Prag et al. (2018) is one of few to make use of large quantitative datasets and statistical methods. The ‘state-of-the-art’ in this field reflects the challenges faced in making theoretical or empirical claims on SOEs and their role in net zero transitions that can be generalised or reproduced. Quantitative research methods and formal modelling tools are commonly deployed to enrich our understanding of the behaviour of firms and their response to policy stimuli in the context of economy-wide decarbonisation.¹ The relative absence of data and the deeply heterogeneous, historically grounded and inherently political nature of SOEs makes them a difficult target for these methods. Given the heterogeneity SOEs exhibit across the aforementioned characteristics, it is at present unrealistic to build a formal, generalised model of SOE behaviour on this basis. Indeed, the existing literature provides a very limited basis for attempting to construct a ‘theory

¹ Data availability has improved even since the research in this dissertation was conducted and possible quantitative extensions are explored in Section 6.

of the state-owned firm’ as a complement to the general ‘theory of the firm’, particularly given that the decision-making rules being followed by this heterogeneous group may be so varied as to resist any generalised classification of SOEs. At this stage in the research agenda on SOEs, there is still much to do, both to (i) understand sources of variation across SOEs and the dynamics of interactions between states, SOEs, markets and private firms, and (ii) generate testable conjectures on the basis of observed patterns or shared characteristics. This dissertation aims to be to fill this gap, motivated by SOEs’ central role in decarbonisation and the concern that existing technoeconomic models’ failure to account for state ownership may be generating biased or otherwise misleading results with major consequences for climate policy design and execution.

In summary, there is a clear case for further investigation into the implications of state ownership for power sector decarbonisation, and how this maps to the financial and non-financial risks and opportunities associated with this transition, both at the level of individual assets and across the sector as a whole. In attempting to address the clear and empirically consequential gap within existing research on the economics and policy of decarbonisation, the thesis papers of which this dissertation is composed focus on addressing several distinct aspects of the role of SPCs in the transition towards ‘net zero emissions’ in the power sector. In this context, ‘net zero’ refers to achieving a balance between flows from sources of greenhouse gases, and sinks thereof, such that the net contribution to total stock over a given period – typically one year – is zero.

The first paper aims to construct an improved understanding of the relationship between SPCs and decarbonisation in the power sector through a comparative analysis of major SPCs in six countries, the options available to government (in its dual role as policymaker and shareholder) for influencing their activities, and how SPCs’ characteristics may affect their responses to government action. The remaining two papers are applied specifically to the role of state-owned coal industries in the Chinese economy. China is the world’s largest national emitter and consumer of electricity, with a high degree of dependence on the coal sector for economic growth, a heavily-regulated electricity sector and a ubiquitous state presence in the major industrial sectors – including but not limited to coal mining, oil and gas, power, steel, and cement. China’s government has also committed to achieving economy-wide

carbon neutrality (referring to net zero carbon dioxide emissions, but not necessarily other GHGs) by 2060 and peaking national emissions before 2030. This places China's SOEs in a central position of responsibility in executing a transition from a highly-carbon intensive economy to effectively a net zero economy in less than four decades, on a historically unprecedented scale.

The second thesis paper uses a *pro forma* analysis of a proposed investment in a new coal-fired power plant in China to investigate how state ownership of power generation assets and the upstream and downstream industries associated with them is relevant to the decision whether or not to invest. It examines the net country-level economic benefits (henceforth simply 'economic'), and project-level financial benefits (henceforth, 'financial'), respectively, of continuing to build new coal plants domestically in light of a moderate but overwhelmingly likely tightening of climate policy during the plant's operating lifetime. It engages with the existing literature on stranded asset risks in China to show that an economic framing (as opposed to solely a financial one) of such investments – particularly pertinent where the corresponding value chain is as comprehensively state-owned as it is in China – can be used to better model and understand government decision-making. The same framing can also better highlight the economic risks of continuing to expand coal power investment in China.

The third paper offers a methodologically different and more applied approach to the same core ideas developed in the first two: namely, that non-financial objectives are important considerations for government, and that these objectives are more directly relevant to firm-level activities when those firms are directly state-owned. Using an asset-level dataset of Chinese coal plants and mines, it models the effects of phasing out thermal coal power in China on employment and fiscal revenue from the coal industry, two aspects of relevance to China's government as it navigates pathways towards achieving its stated policy goals. Employing a range of scenarios, it analyses the results at the national level, but also explores inter-provincial dynamics, and the role of specific SPCs in accelerating or slowing losses in jobs or tax revenues from coal as the industry declines.

The remainder of this synthesis document is structured as follows. Sections 1(a) and 1(b) – this section – introduce the dissertation and place it in context. Section 1(c) outlines the contribution of the

three thesis papers to our knowledge and understanding of the role that SOEs play in climate policy generally, and the decarbonisation of the power sector specifically. Section 2 provides an overview of the relevant literature and theoretical perspectives underpinning the thesis papers. In Section 3, a summary of each of the thesis papers is presented, along with an overview of their limitations. Section 4 considers the policy implications of the body of work in this dissertation. In Section 5, possible extensions and avenues for future research are explored. Section 6 concludes and outlines the contours of a possible future research agenda. In addition, four appendices are attached to this document (A1, A2, A3 and A4). The first three contain offprints of the thesis papers as they appear in the peer-reviewed academic journals in which they have been published, along with the supplemental material provided as appendices to each publication. The first page of each appendix also details the respective contributions of the authors to each of the papers. The final appendix provides an overview of other published work that is related to the thesis papers but not submitted as formal components of this dissertation.

c. Contributions

The literature on SOEs' and SPCs' role in decarbonisation is still nascent. A well-developed framework for modelling and predicting SOE decision-making does not exist either in general, or in the specific context of climate policy. The three thesis papers investigate different angles of the 'SPC problem' and use a combination of deductive and empirical tools, theoretical constructs, and data analysis to do so. Together they lay a theoretical foundation (Paper 1 and 2) and empirical foundation (Paper 3) for continued research into what the decarbonisation-relevant characteristics of SPCs are, and in particular how both SPCs themselves and their government shareholders may be motivated by factors other than the price and market signals traditionally used to guide quantitative modelling of firms' real-world decision-making. This work aims to make some initial sector-specific inroads into the empirical challenge that state ownership presents in the context of the transition to a net zero-carbon economy.

Paper 1 draws on existing research on SOE decision-making, in combination with a meso-level comparative analysis of a small sample of representative SPCs in China (SPIC), India (NTPC), Mexico (CFE), South Korea (KEPCO), South Africa (Eskom), and Indonesia (PLN). It develops a framework for assessing how their shared and divergent characteristics – and those of the markets in which they operate – might affect their response to measures taken by their government shareholders. It also considers the implications of these relationships for the effective implementation of sector-wide decarbonization strategies. In so doing, it questions some of the central – but often not explicitly justified – normative and positive assumptions underpinning decarbonisation pathways as represented in the results of technoeconomic modelling exercises. The first assumption is that all firms, including SOEs, will (a positive claim) and should (normative) maximise profits. The second is that governments will (positive) and should (normative) confine themselves to legislative and regulatory roles. While Paper 1 is not designed to support a quantitative recalibration of formal modelling to account for the relaxation of these assumptions, it does strengthen the theoretical and empirical bases for claiming that decarbonisation pathway modelling is both positively and normatively divergent from the assumptions that typically underpin transition pathway modelling exercises.

Continuing in a similar vein, Paper 2 makes a theoretical contribution to extending concepts and debates in stranded asset estimation and measurement frameworks to better account for state-owned assets. Existing frameworks for estimating stranded asset risks are built on the assumption that the assets in question are owned by private firms seeking to maximise financial returns. The paper adapts this standard framework to more convincingly describe contexts in which considerations other than private profit influence decisions on future and existing investments, such as those where the asset owner is an SOE, and/or the upstream and downstream value chain are under state control. This exercise provides some preliminary explanations for the otherwise surprising observation that China is continuing to build coal-fired power plants that are unlikely to deliver financial profits, despite its clear policy commitment to carbon neutrality.

Paper 3 develops a bottom-up model that estimates the employment and tax revenue impact of the transition away from a coal-heavy power generation asset base in China, an economy both

dominated by SOEs and explicitly committed to decarbonisation. Besides being one of the first empirical studies to construct a model of the Chinese coal sector at the asset-level by compiling multiple publicly available sources of data, it is also a useful complement to existing macro-level modelling approaches. Such approaches are capable of reflecting general equilibrium effects of changes in one sector on others (and on macroeconomic indicators) but their ability to resolve changes at sub-provincial level, and certainly asset-level, is very limited. The asset-based approach developed here, while limited to the thermal coal value chain, is a useful addition to top-down modelling and can become more useful as it extends into other sectors and embraces greater complexity (see Section 5).

Further study of SOEs in the power sector, and other high-emitting sectors, can help researchers and policymakers to understand how generalisable the findings of the work in this dissertation are, how feasible it is to represent SOEs in formal modelling, and where more theoretical and applied research is needed to understand SOEs' (and SPCs') role in decarbonisation in more detail and with more precision. Methodological innovations and the creation of new datasets may also expand the possibilities for testing the conjectures developed in this work. Indeed, the scope for further work in this field is very broad and has the potential to make exciting and practical contributions to designing effective energy transition policy.

2. Literature Review

Each of the thesis papers herein contains a dedicated literature review. This section summarises some of the key findings in the wider literature on complexity theory, climate policy, and state-owned enterprises, both in general and in the specific context of state-owned power companies and decarbonisation. Many of the works referenced in this section are also cited in the thesis papers' respective literature reviews. It also provides an overview of the literature consulted in the process of identifying appropriate research designs and developing the theoretical perspectives underpinning the work conducted in this dissertation.

a. Theoretical underpinnings

The theoretical tools and perspectives employed in this dissertation stem from a view of economic decision-making and socio-economic relations as exhibiting key features of a complex adaptive system. In such a system, incentives and power relations between agents influence their individual behaviour. The boundaries around each agent (reflecting their ability to interact with other agents), and the emergent dynamics from the resulting interactions between agents, can change the nature of the system over time (Arthur, 1995; Beinhocker, 2007). Features of complex systems that do not typically feature in orthodox economic modelling approaches, but are particularly relevant to modelling interactions within and between human and ecological systems, include interdependency between agents; heterogeneous agents each with different utility functions; preferences that change over time and in response to others' actions; and a thorough mapping of feedback mechanisms (in which a stimulus to one part of the system can directly or indirectly affect other components of it, and in some circumstances 'tip' a system from one stable state into another, or into an unstable self-reinforcing positive feedback loop (Balint et al., 2017; Farmer et al., 2019; Farmer et al., 2015; Mattauch & Hepburn, 2016)).

This theoretical perspective explicitly allows for many of the key assumptions underpinning the standard free market model of incentives and actions to be relaxed in pursuit of a more realistic

understanding of how agents' preferences are shaped and what phenomena emerge from their individual and collective actions. The most important of these assumptions are (i) rational decision-making, in which agents with exogenously determined, fixed preferences maximise utility subject to their budget constraint; and (ii) free mobility of capital – including human capital. The foundational features of SOEs – namely that they (i) can have complex objective functions that are not purely profit-maximising, not well-defined and change over time, and (ii) can limit the ability of capital to flow to where it is theoretically most productive (whether inside or beyond the government shareholder's borders) through their use as instruments of industrial and developmental policy – suggest that the model of behaviour central to free market economics may not be appropriate in describing SOEs as agents in economic systems. In the context of this research (SOEs and power sector decarbonisation), empirical data on the structure and dynamics of economic relationships between SOEs, governments, and markets, can undermine the case for retaining many of the core assumptions of a free market model in at least five ways.

First, in power markets and energy value chains in which the state features heavily as an asset owner and manager, as well as a political entity, the assumption of atomistic, profit-maximising firms is unlikely to hold. In cases where a large proportion of the power sector is state-owned, the free-market model may diverge very substantially from observed activity both in terms of outcomes, and the decision-making heuristics explaining them.

Second, SOEs can be different not just from private firms, but also from each other, depending on their own characteristics, as well as their strategic significance and political value to individuals or the state. In the Chinese context on which much of this work focuses, these differences can arise from differences in what the SOE produces and the markets in which it competes, where it is located, the political and historical context in which it is embedded, whether it is owned by national or local governments, whether it features listed subsidiaries or not, and myriad other factors that are not yet fully understood. This potential for widespread heterogeneity further complicates any effort to model firms in the power sector on the basis that they are (even approximately) identical.

Third, the key assumption of free markets – that is, perfect competition – is unlikely to be a realistic representation of cases where power markets are either under the monopoly control of a single state-owned entity, or where the majority of market share is held by state-owned companies ultimately under government control. Additional market distortions induced by price controls and subsidies, and other factors contributing to preferential treatment for SOEs, such as privileged access to financing, would further differentiate the competitiveness and incentives of state-owned and private agents even if they had the same objective functions.

Fourth, any restrictions on capital mobility implied or mandated by state ownership limit the free movement of capital assumed in basic free market models (e.g., where certain pools of capital are restricted to SOEs) and can either constrain or facilitate the reallocation of resources towards the most profitable or socially beneficial uses possible.

Finally: the existence of SOEs further complicates the calculus of governments engaging in decision-making under uncertainty when designing climate policies. With respect to designing policies for decarbonisation, uncertainty predominantly refers to government having limited information on (i) the fixed and marginal costs faced by firms that would determine such firms' responses to market-based mechanisms; and (ii) the true social cost of carbon, both of which are fundamental to the design of carbon trading and/or pricing regimes. These sources of uncertainty are not necessarily made less relevant by the existence of SOEs. Indeed, in some respects, the presence of SOEs may reduce uncertainty, as government may be able to access more information on the fixed and marginal costs faced by the firms for which it is a direct shareholder. But where SOEs diverge from idealised profit-maximising private firms, their presence can increase uncertainty, since their response to a given policy may be driven by a combination of factors (e.g. a service delivery mandate, employment targets, incentives of managerial staff), of which profit maximisation is only one.

In summary, the presence of SOEs in market economies appears to be more consistent with the characteristics of complex system frameworks than idealised free market modes. This is not to say that the latter are not useful: they can still provide helpful approximations or theoretical baselines against

which the actual performance of economic systems can be assessed and policies can be calibrated. However, there are several core assumptions of free market models that are unlikely to approximate reality, given the dominant presence of SOEs across several sectors critical to decarbonisation, not least in the power sector.

By contrast, some of the central tenets of complex systems analysis resonate powerfully with the SOE context, particularly the notions that preferences are endogenously determined, and that the tools of network analysis (formally described in graph theory) can help to explain how these preferences are formed and the influence of resulting decisions on other agents in a network. Additionally, SOEs exhibit a high level of heterogeneity driven not only by their political-economic context, but also by their political and historical background, the features of the markets in which they operate and a range of other possible factors explored in more depth in the first of the thesis papers. In light of this, the features of complex systems modelling may well be better suited to describing how economic systems operate than the free market framework. This possible divergence between the theoretical and empirical has potentially significant implications for policy design and implementation.

However, while the view of economies as complex adaptive systems appears more appropriate than the free market paradigm, limited availability of detailed quantitative or other machine-readable data on SOEs curtails the use of many of the data-intensive, network-driven modelling approaches that feature prominently within the disciplines of complexity science and economics. The papers in this dissertation alone cannot address the fundamental problem of insufficient data; but the central insights of complex systems theory (most notably heterogeneous agents, endogenous preferences, and feedback effects) provide the foundation on which the research questions addressed in this dissertation are built.

b. Governments' net zero commitments

The decision document of the 21st Conference of Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) in 2015 – generally referred to as the ‘Paris Agreement’ – marked a decisive shift away from the top-down model of national greenhouse gas

emissions controls embedded into the Kyoto Protocol of 1997, to a more flexible multi-level approach, characterised by voluntary commitments by national governments (in the form of Nationally Determined Contributions), and periodic global assessments of progress against them. The Paris Agreement's core goal is to deliver "well below" 2°C average global temperature rises over pre-industrial levels by 2100, with an additional aspirational goal of 1.5°C (UNFCCC, 2015).

In principle, an array of non-governmental organisations, civil society groups, media organisations, and even businesses in some cases, would act as coordinators and enforcers of accountability against these declarations, complementing the role of the UNFCCC and the governmental signatories of the Paris Agreement. The Marrakech Partnership for Global Climate Action, established after COP22 in 2016, accelerated efforts to track and report progress on a growing set of parallel pledges made by non-state actors ranging from subnational governments and authorities to large corporations. It is not yet clear whether the institutional architecture underlying the Agreement is sufficient – or arguably, necessary – to deliver on these targets. Since its entry into force in 2016, however, a large and growing number of governments have made formal pledges – ranging from policy announcements to binding legislation – committing their national economies to reaching net zero emissions by a given year. Meanwhile, the performance and cost of low-carbon technologies relative to their high-carbon equivalents has improved significantly and is expected to continue to do so, particularly in areas critical to decarbonisation such as clean electricity generation, zero-emissions hydrogen production, and long-duration battery storage (Way, Ives, Mealy, & Farmer, 2022).

The world's governments are increasingly making net zero commitments in policy and law (referring in this context to the achievement of net zero emissions within a national territory by a certain date, and maintaining negative or zero emissions thereafter) in the coming decades. Sweden became the first country to legislate for a pre-2050 net zero target in 2017. The share of global emissions covered by a governmental net zero pledge subsequently rose from 16% in 2019 to 68% in 2021 (Hans, Kuramochi, Black, Hale, & Lang, 2022). As of January 2023, 133 national governments representing 87% of global GHG emissions, 91% of GDP, and 80% of the global population, have made commitments to achieving net zero across their entire national economies. These commitments are

enshrined in law in twenty-two countries. A further eight countries claim to have already achieved net zero emissions, with 21 others having made formal pledges, and 81 referring to net zero emissions targets in published policy documents (Energy & Climate Intelligence Unit, Data Driven Envirolab, New Climate Institute, & Oxford Net Zero, 2023).² Among the top 20 global emitters (Table 1), six have enshrined a net zero target in law, seven more in policy documents, and three more have made declarations or pledges. Of the remaining four, three have a target under discussion.

Table 1. National net zero emissions commitments, ranked by estimated annual GHG emissions. Source: Energy & Climate Intelligence Unit et al. (2023), author's analysis. P = In policy document, L = In law, D = declaration or pledge, UD = under discussion.

Rank	Country	Target status	Population (million)	GDP (real, US\$ billion)	GHG emissions (GtCO ₂ e)	Target Year
1	China	P	1,426	24,861	12.1	2060
2	US	P	337	20,932	5.8	2050
3	India	D	1,408	9,301	3.4	2070
4	Indonesia	UD	274	3,246	2.0	2060
5	Russia	L	145	4,080	1.9	2060
6	Brazil	D	214	3,128	1.5	2050
7	Japan	L	125	5,124	1.1	2050
8	Iran	-	82	1,131	0.8	2030
9	Canada	L	38	1,832	0.8	2050
10	Saudi Arabia	P	36	1,594	0.7	2060
11	Germany	L	83	4,400	0.7	2045
12	Mexico	UD	127	2,416	0.7	2050
13	South Korea	L	52	2,283	0.7	2050
14	Australia	P	26	1,269	0.6	2050
15	South Africa	D	59	788	0.6	2050
16	Turkey	P	85	2,658	0.5	2053
17	Pakistan	UD	231	1,324	0.4	2050
18	Vietnam	P	97	1,032	0.4	2050
19	Thailand	P	72	1,223	0.4	2065
20	UK	L	67	3,086	0.4	2050

Although progress on policy design and implementation for net zero varies substantially across countries, there is a clear emerging consensus among policymakers on targeting net zero emissions

² Note that these figures differ from those reported on the Net Zero tracker website at the time data was accessed, because European Union (EU) emissions and GDP are incorrectly double counted with those of its member states. The figures here treat EU countries as individual states. Additionally, emissions for the Democratic Republic of Congo are overstated by a factor of 100 in the Net Zero tracker.

within their national economies. The fact that existing declarations, policy statements and legislation cover the vast majority of global population, economic activity and emissions, implies an economic, social, and technological transition of unprecedented scale and depth over the next three to four decades. Successfully executing this transition will require substantial acceleration in markets' reallocation of capital towards zero-emissions activities and away from high-carbon activities, as well as a suite of major technological advances and the early retirement or stranding of at least some existing infrastructure and resources (Curtin et al., 2019; International Energy Agency, 2020b, 2021; McGlade & Ekins, 2015; Mercure et al., 2018; Pfeiffer, Hepburn, Vogt-Schilb, & Caldecott, 2018).

In parallel to commitments by national governments and complementary commitments by a wide range of subnational government actors, a range of additional initiatives have emerged making use of variations on net zero rhetoric and principles. Companies in publicly traded and private markets for capital, goods and services, are starting to make individual pledges and in some cases associate themselves with groups claiming to have net zero ambitions or be compliant with voluntary standards. The significance of these pledges, in terms of absolute emissions reductions in the real economy, is uncertain and subject to a range of nuances and caveats. Their total contribution to the realisation of the Paris goals (or even to the more specific goal of net zero) in principle and in practice are not yet clear. A large and growing research community is working to understanding what national, subnational and corporate net zero targets entail in reality, how they are and should be governed, and what policies and corporate actions are necessary in order to realise them.

Most notable for the work in this thesis is the observation that SOEs have a non-marginal presence in emissions-intensive sectors in all of the top five emitting economies, and eighteen of the top 20 (the only exceptions being Japan and the UK). SPCs play a particularly central role in electricity generation in China, India, Indonesia, Canada, Saudi Arabia, Mexico, South Korea, South Africa, Vietnam, Pakistan, and Thailand (from database generated for Clark & Benoit, 2022).

c. State ownership and the power sector

The empirical and theoretical study of state ownership of productive enterprises, referred to variously as public enterprises, government commissions, and elements of state capitalism, is rich and broad. Appropriately determining the scope, extent and nature of direct government participation in the ecosystem of organised economic activities has been an active scholarly debate and a highly relevant policy issue for many decades. Indeed, in his discussion of “public enterprise systems”, Wattenhall (1985) reminds us that “scholars and thinkers now mostly forgotten” had already been engaged in detailed discussion of state-owned capital assets, enterprises and the form they should take for nearly a century by the mid-1980s. Contrary to contemporary perceptions in the economic discourse, Millward (2011) further contends that SOEs are often mischaracterised as primarily a socialist device for curtailing excessive worker exploitation, and a means of “overcoming problems of natural monopoly”, showing instead that SOEs have historically played more significant roles as tools of social and political integration, national security and strategic resilience, and economic growth, “with regulatory failures and socialist pressures playing a more subsidiary and/or occasional role”.

The end of the Cold War accelerated a wave of privatisation already under way in Western Europe and extended it to the former Soviet economies. As noted by Belloc (2014) and Bernier (2014) this was accompanied by influential theoretical and applied scholarship extolling the virtues of the private corporation as a model of economic organisation, and highlighting the perceived inefficiencies and political gaming associated with SOEs (Boycko, Shleifer, & Vishny, 1996; Hart et al., 1997; Shleifer, 1998; Shleifer & Vishny, 1998).

A survey of empirical studies conducted in the early 2000s suggest that the privatisation efforts of the preceding years enjoyed a degree of success in terms of improving the efficiency, profitability, and the returns seen by investors from private firms that were formerly SOEs (Megginson & Netter, 2001). More recent scholarship on SOEs, however, is increasingly questioning the findings of this earlier literature, reconsidering what SOEs are ‘for’, and the corresponding metrics of success. Where previous scholars focused primarily on notions of efficiency and profit, more recent work has sought to understand the role of state ownership in catalysing innovation and the adoption of new technologies.

This discourse has increased in relevance as the need to undertake major technological transitions across multiple sectors to meet climate ambitions has become manifest.

Recognising this trend, Florio and Fecher (2011) made an explicit call for a new research agenda on SOEs and their role in the 21st century. In the following years, a number of important studies advanced the discussion on the relationship between firm performance (including innovation) and state ownership. Belloc (2014), for instance, argues that where SOEs are inefficient relative to their private peers, this is “not due to state ownership per se”, but a function of other conditions that SOEs are likely to exhibit. He further finds that corporate governance reforms to limit political interference and corruption may be more successful than privatisation in improving firm efficiency. The notion that privatisation is not the only adaptive tool available to SOEs is lent further support in an analysis by Chandra (2018) showing how SOEs in India’s coal industry have successfully adapted to accommodate multiple significant changes in the policy environment they face.

Other work suggests that regardless of the potential merits of privatisation, “many governments (and their constituencies) remain reluctant to privati[s]e firms in nationally strategic sectors” (Musacchio, Lazzarini, & Aguilera, 2015) and research agendas must account for this reality in exploring the causes of heterogeneity in firm performance across the various forms of state participation in firms, ranging from full nationalisation to minority stakes and strategic support to specific industries (Musacchio & Lazzarini, 2014; Musacchio et al., 2015). In an illustration of why this perspective matters, Inoue, Lazzarini, and Musacchio (2013) find, in a study of Brazilian firms, that minority state ownership can have positive effects on performance-relevant variables, such as return on assets – but that this is largely conditional on which public entities hold the shares, and the extent to which local market, capital and labour institutions are developed. This foreshadows a similar argument advanced by Milhaupt and Zheng (2015) with respect to SOEs in China.

Interesting results have also emerged from recent literature specifically examining SOEs and innovation, with some such as Bernier (2014) calling for research to go beyond “the governance of these institutions or the particularities of ownership” to consider public enterprises as policy instruments

for entrepreneurship. Indeed, Sterlacchini (2012) finds that reductions in research and development (R&D) expenditure among electric utility firms from 1990-2004 was much more pronounced for privatised and newly-privatised utilities than state-owned counterparts. Meanwhile, Tönurist and Karo (2016) argue that SOEs can be important actors in the implementation of national innovation policies. In their work on the “entrepreneurial state”, Mazzucato (2018) and Mazzucato and Semieniuk (2017) make a more general argument for public financing of innovation, including through SOEs, as a means of creating and shaping new markets rather than simply regulating them.

In the environmental and resource economics subfield, Hertog (2010) questions the well-known ‘resource curse’ hypothesis by highlighting the experiences of large SOEs in successful contemporary rentier states (predominantly large oil exporters). Moving closer to the topic of interest to this thesis, namely SOEs’ role in addressing climate change, Hsu and Liang (2017) find that large SOEs in emerging economies are on average more engaged in environmental issues than their private counterparts, indicating that they may be more able or willing to deal with environmental externalities, although more research is required to understand more clearly why this is the case. In the policy literature, an OECD (2022) “stocktaking report” collects and analyses data on the integration of climate change considerations by SOEs through a voluntary questionnaire based on the OECD’s already-established Guidelines for Corporate Governance of SOEs.

There also exists a very substantial literature on the governance and political economy of SOEs in China specifically. This is unsurprising, given their central role not only in propelling the country’s unprecedented speed and scale of development over the last half century, and the more recent rapid extension of Chinese SOEs’ international footprint. Indeed, the dominance of SOEs in China is such that any analysis of firm behaviour or industrial economics in China necessarily requires accounting for SOEs. While the literature is consequently far too large to survey in depth, key findings from recent literature are generally consistent with the broader SOE canon. For instance, Belsie (2019) shows that SOEs see higher wages and better working conditions than their private (often much smaller) counterparts, suggesting that they play a social as well as financial role; and Milhaupt and Zheng (2015) argue, in tandem with claims in the wider literature, that there is no sharp analytical distinction to be

made between SOEs and non-SOEs in China and that government control over firms is perhaps better explained as “capture of the state” by corporate interests than it is by government ownership of those interests alone. In subsequent work, Milhaupt (2020) and Lin, Lu, Zhang, and Zheng (2020) review China’s experience with SOEs, identifying tensions between ‘sound’ corporate governance practices and the non-financial industrial policy goals that they are – implicitly or explicitly – often tasked with promoting. The environmental role of China’s SOEs has not escaped scholarly attention, as evidenced by work on the political economy of the Three Gorges Dam project in the 2010s (Webber, 2012). There is a large body of work on China’s energy transition, and particularly its development of renewable energy sources, but only more recently have scholars begun to explicitly examine the intersection of state ownership and progress on climate policy targets, including SOEs’ role in accelerating the deployment of wind power in China (Zhu, Qi, Belis, Lu, & Kerremans, 2019).

A review of the relevant literature shows that SOEs have been the subject of scholarly attention for well over a century, across multiple fields of inquiry and national contexts. Despite recent work linking SOEs to decarbonisation indirectly through their role as entrepreneurs and innovators, the literature explicitly linking SOEs to climate policy remains relatively thin, particularly for those operating in the power sector. This is a striking omission given the dominance of SPCs in the power sector in a number of large economies, most notably China. This may partly be a function of the lack of comparable, detailed, audited and publicly available corporate data on most SPCs and financial SOEs, restricting the literature largely to discrete case studies, with only a handful of studies employing statistical and econometric techniques to identify more general features of the relationship between state ownership and observed variables such as efficiency (Fungáčová, Klein, & Weill, 2020) and the share of renewable energy in total investment (Prag et al., 2018). Nevertheless, the study of economic and market dynamics in the power sector has yet to properly account for two key empirical facts, with major consequences for the underlying assumptions that drive key results and inform understanding of decarbonisation pathways.

The first point of empirical divergence from the version of reality implicit in the existing stranded asset literature is the degree of government control over power companies, and therefore their

asset portfolios. Over half of the world's electricity generation capacity is controlled by SPCs under majority public sector ownership. SOEs controlled 61% of installed electricity generation capacity globally in 2017 and accounted for 52% of planned future capacity. In the same year, they financed 55% of global thermal power investment (Prag et al., 2018). Three-quarters of global energy investment is estimated to be made either through SOEs, or in the form of private investment directly enabled by government policies (International Energy Agency & OECD, 2017). In some cases, these SOEs are publicly listed companies with a proportion of shares freely traded on stock markets; in others, they are unlisted companies; and in still others, they are partnerships between regional governments or governments of multiple countries.

As already noted, very little of the well-established and varied literature on SOEs across multiple disciplines considers how state ownership of firms in the power sector interacts with decarbonisation specifically. Some of the findings in the SOE literature do, however, provide a useful and relevant grounding for the work pursued in this dissertation. Some studies suggest that the mere presence of government as shareholder in a company is not necessarily the main indicator, or even a relevant one, in predicting how it might act (Benoit, 2019; Mayer & Rajavuori, 2017; Mayer, Rajavuori, & Fang, 2017). Older studies of SOEs conducted in the 1990s suggest that their objective functions were indeed – even at the time – determined by a number of factors other than profit maximisation (Holmstrom & Milgrom, 1991; Shleifer & Vishny, 1998). More recent work suggests that government owners have a significant degree of control over the cost of finance for SOEs and the distribution of real and financial resources among them (Milhaupt & Pargendler, 2019). Other scholars find that the legal context, and the relative market power of SOEs and private firms, affects the degree to which governments can dictate the behaviour of an SOE (Belloc, 2014; Dibley, 2021; Su et al., 2018); and that SOEs, far from presenting an additional constraint on decarbonisation, may in fact be vehicles for accelerating the process (Mazzucato & Semieniuk, 2017; Steffen et al., 2020; Sterlacchini, 2012).

The second point of divergence is that, state ownership aside, power markets in the jurisdictions with the largest fossil capacity and highest growth rates remain highly regulated and subject to significant price and incentive distortions that largely serve to protect fossil fuel generation from free

market forces. These factors are particularly prevalent for coal power generation, the most carbon-intensive form of electricity generation and the largest source of power globally. Of the world's currently operating coal plants, an estimated 93% are operating in markets with price or quantity controls, typically in the form of long-term guaranteed revenue streams, capacity payments, regulated equity returns, or government mandates to provide power at fixed or heavily regulated prices (Bodnar et al., 2020). These and other distortions to the free-market paradigm may allow coal and other fossil fuel plants or related infrastructure to remain competitive, even profitable, when renewables are cheaper on a cost basis, and can be accompanied by powerful incentives to avoid breaking contracts due to the legal, financial, or political consequences (Boston University Global Development Policy Center, 2022; Gelpert, Horn, Morris, Parks, & Trebesch, 2021; Tienhaara & Cotula, 2017). Further market distortions can appear at the sectoral level in the form of electricity price subsidies, fossil fuel production and consumption subsidies, and tax credits.

Among the jurisdictions in which state ownership and market distortions loom largest, China is by far the most prominent. In 2021, the country became host to over half of the world's operating coal power generation capacity for the first time. China accounted for 75% of global commissioned coal capacity in 2020, and 85% of capacity in the planning stages (Shearer & Myllyvirta, 2021) – although this latter share may yet be substantially reduced following the Chinese government's announcement in September 2021 that it would no longer provide finance for new coal capacity outside China. Of China's domestic coal power capacity, 94% was estimated to be under government control in 2015, either through SOEs or government-sponsored joint ventures (Hervé-Mignucci & Wang, 2015). China's electricity system is highly regulated, with coal prices subject to price controls, and electricity prices subsidised by the state (Gençsü & Chen, 2019). Restrictions on competition in the power sector, managerial incentives misaligned to long-term firm performance, and the politicisation of corporate governance, present further structural and practical obstacles to establishing competitive, liberalised power markets (Leutert, 2016). Any comprehensive attempt to understand and model the trajectory of electricity generation must, therefore, account for China, given its share of global electricity generation capacity and corresponding emissions – as well as for the other high-emitting

countries in which SPCs are prominent, as described in Section 2(b). In turn, any such attempts should explicitly consider how the prevalence of SPCs in these countries – particularly China – affects the design and cost of policies intended to decarbonise electricity supplies.

d. Stranded asset risks and state ownership

The implications of the transition to net zero for the market (financial) value of current and future stocks of greenhouse gas-emitting assets are highlighted in a well-established literature on ‘stranded assets’. According to the most accepted definitions in the literature, asset stranding occurs when an asset’s value is permanently impaired (Caldecott, Dericks, et al., 2017). In the context of the environment and climate change, the term is most commonly used to describe shareholders of (or lenders to) fossil fuelled power plants forced to accept irreversible financial losses as a result of climate policies, environmental change (including climate change), technological advances, or a combination of all three. The owners and/or creditors of the companies operating the assets suffer from stranding when they observe “unanticipated or premature write-downs, devaluation or conversion to liabilities” of these assets (Caldecott, Howarth, & McSharry, 2013). The term ‘stranded asset’ is also used in association with fossil fuel resources (oil, gas, and coal reserves), industrial manufacturing assets (power plants, steel plants, cement plants), and even vehicles (ships, trucks, aeroplanes, cars). For the purposes of this dissertation, the term is used only in reference to the power sector, in the form of power plants generating electricity from the combustion of fossil fuels.

Accounting for state ownership has an important bearing whether existing conceptions of stranded assets are still appropriate when government is the asset owner. Researchers have employed a range of approaches to estimate the extent and value of stranded assets in the power sector. One such approach measures foregone generation – that is, ‘electricity not generated’ by a power plant or portfolio of plants compared to a baseline, given a set of constraints (e.g. a cap on cumulative carbon emissions, or optimising for levelized cost of electricity (LCOE)). The magnitude of asset stranding is then

expressed in terms of forgone electricity generation, typically in TWh (Lu, Cohen, Smith, & Pfeiffer, 2022; Pfeiffer, 2018; Pfeiffer, Millar, Hepburn, & Beinhocker, 2016).

An alternative approach (and the methodological basis for Paper 2) is to treat the expected financial return on a plant when it is built as the baseline. For coal plants, this typically means assuming an operating lifetime of thirty years or more, at a relatively high load factor. The stranded asset value is then measured as the difference between either (i) the expected return on the plant, or (ii) the return required to fully recover the initial investment; and the return expected to be realised under a given scenario. The stranded asset risk of a portfolio of assets in a given scenario is the total expected loss to be incurred by investors in the power plants compared to the chosen baseline (Caldecott, 2019; Caldecott et al., 2016).

For a complex portfolio of assets in which dispatching one set of power plants has an impact on others (such as a national or regional electricity grid), estimating the relative stranding exposure of each asset requires devising a set of rules governing how individual plants are affected, which in turn solve the problem of how total forgone electricity generation is distributed across individual power plants. One approach for these cases is to optimise the dispatch of different electricity sources on the basis of short-run marginal costs (the merit order dispatch system generally used in liberalised electricity markets), and to consider plants to be no longer operating due to a lack of viable markets once long-run marginal costs permanently exceed revenue, which can be the result of factors including but not limited to climate policies, such as declining renewable energy costs leading to the displacement of existing fossil fuel generation (Gray & Sundaresan, 2020a, 2020b). A second approach, employed by Caldecott, McCarten, and Triantafyllidis (2018) to identify assets in a portfolio that are at high relative risk of stranding under different constraints, combines estimates of marginal abatement costs and cumulative committed emissions, to determine whether or not investments in abatement for existing fossil assets are competitive against alternative options (such as renewable energy generation), and which remaining unabated assets in the given portfolio are incompatible with given carbon budgets once any abatement decisions are taken. This framework offers flexibility on how to prioritise uncompetitive assets for (early) retirement – on the basis of efficiency, marginal operating cost, age,

emission intensity, technology type, or other combinations of variables. Once placed in order, those assets within the cumulative carbon budget are considered to be subject to lower stranding risk, although the binary nature of the result is somewhat artificial.

Asset stranding estimates can also be derived from least-cost optimisation models for a given electricity grid. Economic modelling of the power sector at the global level (Ives et al., 2021; Mercure et al., 2018; Way et al., 2022) shows increasingly clearly that this approach leads to the conclusion that meeting marginal demand with renewable capacity additions is already the most cost-effective option for increasing electricity supply across most countries. This is the case even without considering climate change-related externalities or local pollution externalities tied to fossil fuel production, extraction and combustion for electricity generation.

It also shows, reinforced by more recent work, that it is cheaper in the short- and long-run to build and operate new renewable capacity than to continue operating existing fossil-fuelled capacity in a growing range of national economies (Meng, Way, Verdolini, & Anadon, 2021; Way et al., 2022). The key inflection point, financially speaking, is the point at which it becomes cheaper to build, finance and operate new renewable capacity than to continue operating legacy fossil assets, even where these assets carry outstanding debt. At this point, a profit-maximising firm would be better off committing new capital to expanding its renewable production while ceasing operation of fossil assets. If the technology cost forecast trajectories on which these models are based are correct, new investment in fossil capacity is very likely to be uncompetitive on a technology cost basis in almost every economy by 2030. The continued operation of existing fossil capacity is also very likely to become uncompetitive in a smaller, but growing, set of countries, by 2030 (Way et al., 2022). Even for highly carbon-intensive power sectors with heavy reliance on subsidised and locally available coal, such as that of China, further declines in renewable energy costs imply that a policy requiring 50% reduction in annual power sector emissions by 2030 while still meeting demand growth could in principle be cheaper than the business-as-usual alternative (He, Lin, Sifuentes, et al., 2020).

Assuming that the real LCOE of renewable technologies continues to fall more rapidly than the real operating costs of fossil generation capacity, and that increases in electricity demand can be met with renewable capacity additions, fossil fuel assets will be progressively more likely to become stranded either by foregoing generation, incurring financial losses, or both. In this framing, the value of asset stranding can be calculated on the basis of optimising for least cost across the electricity system at an assumed rate of demand growth and deriving the extent of asset value write-downs from lower utilisation or early closure of uncompetitive fossil assets.

None of these approaches or calculation methods, however, make explicit provision for the significant economic distortions and regulatory constraints characterising many of the markets in which fossil-fuelled power plants operate today, nor do they account for cases in which the primary objective of the plant owner is not solely to maximise profits – as may well be the case for SOE-owned assets. For state-owned assets where financial returns and the marginal cost of production are not the only, or necessarily the primary, determinants of whether a power plant is built or operates, respectively, any stranded asset calculations made on the basis of minimising the cost of electricity generation are likely to incorrectly predict the actual decision-making of affected SOEs and the financial and social losses that would be incurred by their government owners. Correspondingly, they might also incorrectly predict the pace at which the power system will decarbonise by omitting important constraints and incentives affecting stranding risks for existing and planned assets under government ownership. In the literature surveyed here, the monetary estimates of stranded asset values in the power sector capture financial or electricity generation losses that would be incurred by homogeneous, profit-maximising firms operating in an environment of perfect competition and merit-based dispatch. Modifications to these models can be made to alter how electricity is dispatched and the prices different firms or power plants can command, but they are not designed to properly account for cases in which SPCs and their government shareholders play a central role in resource allocation.

3. Outline of the Thesis Papers

After explaining the general approach informing the research design of the thesis papers, this section provides a summary of the motivation, methodology, and results from each of the three papers, bringing together the material presented up to this point. The full text of each paper in its published form is provided in Appendices 1-3. In each case, supplementary material available alongside the published paper immediately follows the paper itself.

A note on research design

At a high level of abstraction, SOEs may be thought of as vehicles for governments to pursue policy goals, whether these are broad (e.g., macroeconomic growth, unemployment, financial stability) or specific (e.g., enforcing plant-level pollution controls or coal consumption targets). In practice, as noted above, assessing how the range of possible policy priorities affect SOEs' operation is both empirically challenging and subject to constant change as these priorities shift.

It was clear at the outset of the research design process that any economic model designed to simulate the role of state ownership and make falsifiable predictions on SOE behaviour, would have to allow for heterogeneous agents. In early iterations of possible research designs, one option considered for Paper 1 was to develop a political economy-driven formal model of SOE decision-making, drawing on a wide range of possible data points to build and test the model. These data points could include elements such as formal mandates, managerial incentive structures, accountability and promotion mechanisms, governance structures, financial analysis, and legal status. Some of this information would be publicly available, but accessing and confirming some other data points would likely require access to institutional and/or national archives, and access to interviewees.

By using a combination of open data, archival research and interviews, I hoped to establish what the key components of the objective functions and decision-making rules of SOEs were, and how heterogeneity among them affected the relative importance of each of these components. I would then

use this information to build a bottom-up agent-based model (ABM) in which the response of heterogeneous SOEs to different policies could be simulated, starting with agents representing government, SOEs, and private firms and limited to the power sector. Although this remains the ideal outcome of my research programme in the longer term, my ability to conduct the field-based data gathering required by such a research design was foreclosed by the suspension of nearly all international travel in early 2020 due to the COVID-19 pandemic with, at the time, a highly uncertain endpoint. Prior to the start of the pandemic, there had been some prospect of gathering non-public data from SOEs and archival sources, complemented by a process-tracing analysis facilitated by interviews with key stakeholders, particularly in China. Access to interviewees would have helped to validate and enrich any empirical data gathered from archival or institutional sources. With the closure of international borders and concurrent deterioration of diplomatic relations between China and the UK, accessing offline non-public data or holding in-person interviews with SOE staff or Chinese Communist Party officials became logistically and politically impossible, and made remote access to interviewees much more challenging to arrange.³

I spent some time determining whether data available from public sources (e.g., company reports, OECD databases), and licensed platforms available through University libraries (e.g., Bloomberg and Refinitiv databases for financial data), would be sufficiently detailed to allow the original research design to proceed. It quickly became clear that the absence of sufficient comparable primary data on (i) SOEs' political, legal, economic and social characteristics and financing arrangements, and (ii) past SOE decisions, would fatally constrain the ability to build and validate decision-making rules with a usable degree of completeness, robustness and rigour. This was particularly true for the countries in which SOEs play central roles in the power sector, most of which are outside the OECD, not publicly listed at the parent company level, and not subject to many of the

³ I had expected to include an interview-based component into this research as a means of validating information obtained from public sources, and particularly for the research specific to China, to check the robustness and fairness of my underlying assumptions. In practice, this was not possible. Some support on data validation and sourcing was obtained from researchers within academia and the non-governmental sector to partially fulfil this function.

financial, governance-related, environmental, legal and other disclosure requirements associated with other jurisdictions. The deep and historically embedded heterogeneity of SOEs' circumstances and attributes presented a further difficulty, multiplying the size of the sample that would be needed in order to establish and validate, in a statistically robust manner, how SOEs' behaviour varies with their underlying characteristics.

My conclusion at this stage was that continuing to pursue the original research design would compromise both the methodological and empirical contributions of the output. This would have been true whether or not the analysis had focused exclusively on the power sector. This confluence of factors steered the development of the methodological approach away from ABMs and towards methods more appropriate to the availability of the data, and the nature of the subject matter.

In retrospect, even if the data required for the initial research design had been obtainable, attempting to identify the objective facts needed to properly understand and model the behaviour of individual agents within and outside an SOE would still have been very challenging. This would be particularly true for contexts requiring a translator (in which important subtleties in meaning could easily have been lost, especially where interviews would be conducted online), and for SOEs engaging in clientelism, corruption, or other behaviours potentially limiting the ability or willingness of interviewees or employees to provide external researchers with information. Particularly in the case of China, my position as an outsider – a Western researcher with very limited linguistic or cultural knowledge – investigating politically sensitive issues in a single-party authoritarian state, poses a more general problem for data collection and validation, especially for interview-based material. In such circumstances, distinguishing between information that is true, false, or a combination of both – in archival documents and in interviews alike – can be extremely difficult. The provision and withholding of information may also be affected by the external political environment (in this case, the most salient being the geopolitical context) and domestic policy. Add to this the heterogeneity and number of possible agents and firms, and it is clear that, in this relatively data-poor environment, methodological approaches with less need for formal model specification and less onerous data requirements can make a more constructive contribution to the early literature on this subject. Pandemic restrictions made the

initial research design a practical impossibility, but it may well not have succeeded had the pandemic not occurred, for the reasons given.

For the purposes of this research, therefore, simplifying assumptions are made at different stages to allow for government decision-making to be conceptualised and modelled in a way that, while not strictly true to reality, can yield useful theoretical and policy-relevant insights. The limitations associated with using such simplifying assumptions are acknowledged and discussed in detail in the Limitations section of each of the three paper outlines. Rather than to attempt to formally determine and model the objective functions of different SOEs and their agents, operating in constantly shifting environments, Paper 1 opts for a more qualitative case study approach as a means of establishing a framework for analysing SOEs in the power sector. Paper 2 proposes a modification and extension of a well-known theoretical framework in financial modelling to the case of state-directed investment in assets at risk of becoming stranded. Paper 3 aims to model and understand the non-financial costs associated with power sector decarbonisation in the form of employment and tax revenues, as a counterpoint to the free-market-driven, profit-maximising paradigm of firm behaviour and a recognition of the central role of SOEs in several major economies expecting to undergo this transition in the coming decades.

Paper 1: State-owned power companies and decarbonisation

Motivation and research question

The first paper is motivated by three observations. First, that rapid decarbonisation of global electricity supply is required for the objectives of the Paris Agreement and its signatory governments to be met, and correspondingly, is also a necessary condition for the same governments' national net zero targets to be met. Second, that SPCs are the dominant type of firm in the global power sector both by current capacity and future investment, but most literature on power sector decarbonisation characterises firms as private investor-owned companies subject to market-wide regulations and policy instruments. Third, that SPCs' governance structure, objectives, relationships with government, and sources of finance may be very different to those of private companies, and they should be represented accordingly in formal analysis.

The paper brings these components together in responding to a gap in the literature linking the prevalence of state-owned assets and enterprises in the power sector to the decarbonisation imperatives endorsed by many of the governments that own them. It aims to provide an entry point for understanding SOEs' role in power sector decarbonisation. Employing a comparative case-study method, the paper surveys the tools available to governments as both policymakers and shareholders of SPCs, then develops a framework for analysing how a range of endogenously generated characteristics and exogenously imposed constraints associated with different types of SPC might affect their responses to the range of market-wide and SPC-specific interventions available to government in pursuing their climate policy goals. The intention is to use this analysis to offer insights into how governments can make the most effective use of their SPCs, given the companies' characteristics.

The core research questions explored in this paper are twofold: first, how are SPCs empirically different from the idealised, largely atomistic theoretical conception of profit-maximising firms that forms the basis of most power sector models? Second, how do SPCs' characteristics affect the potential efficacy of different climate policy options available to their government shareholders?

Methods

The overarching goal of the paper is to develop a framework for analysing the extent to which common and divergent features of SPCs, and the markets in which they operate, affect their relationship to different categories of government intervention on decarbonisation. In the paper, we use ‘decarbonisation of the power sector’ as a proxy for climate policy goals, since total or near-total elimination of fossil-fuelled power sources is a necessary feature of power sector decarbonisation in most country contexts. As a first step, we review the relevant literature on understanding SPC behaviour, with a particular focus on studies that explore the differences between state-owned and private electric utilities, with regard to their investment and capital expenditure, operational efficiency, access to finance, and response to government policy.

The second step is to identify the features of SPCs that could affect how responsive they are to interventions designed to change their behaviour – in this case, to accelerate the decarbonisation of their asset base. Developing a detailed understanding of how individual SOEs (and in particular, the SPC subset) operate is not a feasible undertaking for this project, given their variety and number, with the number of SOEs globally estimated to exceed 150,000 (International Monetary Fund, 2020). Availability of structured data on most SPCs, even those that are large and at least partially publicly-traded, also remains extremely limited. A lack of organised data is an even greater problem among unlisted firms in non-OECD countries, a group that includes many of the world’s largest SPCs. As such, a comparative case study approach is used, in which a small number of representative SPCs are analysed and compared in order to (i) identify common and divergent features of the companies and the markets in which they operate, and (ii) construct theoretical conjectures on how these features interact with the different types of intervention identified in the following step, described below. Six SPCs are selected on the basis of a ‘most-different’ case selection strategy to reflect variation in the share of equity owned by the state, and the degree of concentration in their home markets, as imperfect proxies for the degree of state control over the SPC, and the SPC’s market power, respectively. The SPCs studied operate primarily (or exclusively, depending on the case) in China (SPIC), India (NTPC), Mexico (CFE), South Korea (KEPCO), South Africa (Eskom), and Indonesia (PLN).

In the third step, we develop a typology of possible actions that a government can take to leverage its SPCs in achieving climate policy goals. Our starting point here is to review the set of policy tools available to regulate activity in the power sector where they are relevant to decarbonisation (see, for instance, Peñasco, Anadón, & Verdolini, 2021). We term these tools ‘market-wide’ interventions that in principle apply to all companies equally, private and state-owned alike, that fall within the scope of a given instrument or regulation – such as sector-wide carbon taxes, carbon credit schemes, or clean energy subsidy schemes to which any qualifying firm can apply. We then expand the scope of possible government actions to what we term ‘targeted direct’ and ‘targeted indirect’ measures. ‘Targeted direct’ measures are specifically targeted at a given SPC and reflect the government exercising its prerogative as shareholder – such as changing its legal mandate, or replacing executives or board members. ‘Targeted indirect’ measures refer to the deployment of government resources in such a way as to induce or incentivize an SPC, or group of SPCs, to pursue a certain course of action (and that are not market-wide instruments). These include directing state-owned banks to provide below-market financing facilities to SPCs under certain conditions, or using governmental authority in a manner that disproportionately benefits SPCs (e.g., investment in transmission lines close to SPC power plants, accelerated permitting processes for new plants, subsidy schemes for which SPCs overwhelmingly qualify, etc.).

Finally, by combining the second and third step we generate a set of provisional, testable (in principle) conjectures linking the potential efficacy of different types of interventions, with SPCs exhibiting different sets of characteristics, which we term ‘access factors’. In the paper, we take the additional step of developing four SPC ideal types (‘archetypes’ in the text) representing variation in the combinations of relevant features that we identify in the case study analysis, and consider how a government owner of an SPC corresponding to one of these types might design its interventions accordingly. The ideal type exercise is an initial attempt to identify systematic similarities across SPCs operating in different contexts. The ideal types may help to guide further research, especially if quantitative testing for systematic differences across SPCs becomes a more realistic possibility. To the extent that further research supports the initial classifications proposed here, it may also be useful in

narrowing down the policy options (market-wide and targeted alike) available to SPCs' government shareholders.

This paper has several limitations, as explored in more detail below. However, the goal of the research was not to test empirically the existence of a relationship or set of relationships between access factors and intervention effectiveness, given the data limitations and absence of well-developed theoretical or empirical work on this subject. The paper serves instead as a largely inductive, theory-building exercise built on SPC data, and on a review of climate policy options for the power sector. We take these observations and use them to hypothesise a set of potential factors driving the responsiveness of SPCs to climate policy interventions. From these factors, we return to our data to deduce – if our hypotheses are correct – how responsive the SPCs in our case study sample might be to different types of intervention. Finally, we return to an inductive mode in order to construct a small set of representative ideal types by categorising the performance of each of the case studies against the four access factors. Given that the degrees of freedom implied by four access factors and three overarching types of policy intervention far exceed the sample size in this case, we are explicitly not attempting to make generalised empirical claims, but rather to build a theoretical basis for testing the hypothetical relationships that our analysis suggests.

Results

In the comparative case-study analysis stage, we identify the common and divergent features of six SPCs and assess their role in determining an SPC's incentive to respond to a given climate policy intervention, and its ability to do so. By collecting and analysing data on the core characteristics of these cases and their historical responses to government climate policy, we identify four access factors that affect the government's ability to access the full emission mitigation potential of an SPC. We term these 'agency' (independence of action); 'profit motivation' (in comparison to other possible objectives, such as service provision and employment); 'capacity' (ability to implement a decarbonisation strategy); and 'exposure [to market competition]' (from both private sector and state-owned peers).

By combining the access factors deduced from the comparative case study analysis, with our typology of possible interventions, our first conclusion is that under certain circumstances, SPCs can be more effective vehicles for decarbonisation policy than their private sector peers. We find this may be the case when government has a high degree of control over strategic objectives but the SPCs is able to act independently on an operational level; when SPCs are insulated from competition; and/or when SPCs have the financial and technical capacity to invest in the decarbonisation of their asset base. Further, our second conclusion is that market-wide policy interventions (such as carbon pricing mechanisms) may be less effective for SPCs than their private sector peers, especially where the SPC lacks the capacity to invest in clean technologies and implement and operate on a technical level, and where the SPC is subject to objectives other than profit-maximisation.

In policy terms SPCs can, and where they are major market players, must, be key actors in driving decarbonization. For government action to maximise its effectiveness in helping SPCs fulfil this role, the differences between state-owned and private power companies must be taken into account both through the conventional prism of market-wide interventions, and in selecting from the suite of additional targeted interventions available to government where it plays a shareholding role. Research on other and larger samples of SPCs, with the ability to test the hypothesised relationships ex-post, is needed to test and refine the conjectures developed here, to identify the conditions under which they may break down, and to explore the extent to which they can be generalised to other sectors and geographies.

Limitations

The paper's key assumption is that the government shareholder has made a commitment to decarbonisation, and that this commitment is credible, such that the government has the capacity to implement it. This does not mean that we assume a specific decarbonisation pathway to be inflexibly pursued by governments at any cost, but rather that its commitments represent an ultimately binding long-term constraint on government policy that must be achieved on a thirty to fifty year timescale

without derogating excessively from other key policy goals. Making this assumption essentially holds the role of government ‘constant’. In essence, the paper assumes that the capacities and enforcement capabilities of governments are homogenous and sufficient for achieving their goals, and that governments’ preferences on decarbonisation are static. In reality, governments are highly heterogeneous in their capabilities, and their preferences on decarbonisation can be dynamically and endogenously determined. Indeed, accounting for the degree of (mis-)alignment between SPC and government interests would be a helpful nuance to integrate into the access factor framework, as it would highlight where additional political pressure or support from governments may be needed to ensure SPCs’ cooperation in implementing decarbonisation policy.

While these may be reasonable assumptions given that all the countries studied have a net zero target either under discussion, declared, in policy, or in law, they imply an effectively unidirectional relationship, whereby SPCs are vehicles for government policy. This does not mean that SPCs are not actors in their own right, but rather that they do not have the ability to force a derogation from their government owners’ net zero commitments. In turn, this suggests that our findings are most convincing for cases in which the climate policy goals of government are fundamentally unalterable regardless of the position the SPC takes on a given policy issue. In practice, then, the assumption of fixed government preferences may be justified where there is an effectively irreversible political or legal commitment to decarbonise, even where a government has some space to manoeuvre over the specific timing and implementation modalities of this commitment (China is perhaps the best example of this within the sample examined in the paper). It is less justifiable in contexts where the level of political commitment is unstable and closely linked to electoral cycles (such as in Mexico and South Korea), and/or where an SPC is a powerful policy advocate in its own right, to the point where its lobbying efforts or leverage over sources of political or economic power can disrupt the implementation of net zero commitments by slowing down their implementation, or reduce its exposure to unfavourable policies – even if the overall commitment remains intact. Notably, this does not necessarily mean the paper’s other main conclusion is incorrect in these circumstances, as SPCs with substantial influence over policy may still be more effective vehicles for decarbonisation than their private sector peers. Indeed, even where an

SPC has the ability to disrupt or delay the introduction of market-wide measures, such as a carbon pricing regime, this does not undermine the second conclusion that such measures would be less effective for SPCs if they were introduced.

Relatedly, the paper assumes that both SPCs and governments are unitary actors. Again, this is defensible as a simplifying assumption to make for the purposes of the study, and relaxing it would not necessarily undermine the paper's key conclusions. In reality, however, governments and SPCs are complex entities in which different sets of interest groups or individuals, at different levels of organisation, may pursue divergent, mutually reinforcing, or conflicting goals. The relevance of this feature, which applies to most large and diverse organisations, depends on the extent to which the principals (the governing party, in the case of government; and the board of directors or chief executive, in the case of an SPC) are able to override these sources of divergence such that the organisation acts as a coherent whole. To illustrate, this assumption may be most consequential for contexts in which regional government leaders acting in the interest of local industries are directly opposed to national government policies threatening those interests and possess the means to halt or disrupt policy implementation (see Paper 2, Limitations). Similarly, while strategic decisions taken by SPCs' leadership at the corporate level may conflict with incentives facing the managers of individual power plants or fleets, these are only relevant to the paper's findings if the managers act to oppose company leadership. Incorporating more detailed (and most likely, ethnographic or archival) data on the structure of governments and SPCs into future work can help to assess the extent to which internal dynamics are relevant to SPCs' relative potential as agents of decarbonisation.

A potentially more significant limitation in the paper is that it does not explore interactions between the four access factors in a systematic manner, in particular how these interactions might affect the paper's central conclusions. While the four ideal types go some way to explaining how different combinations of access factors would, in aggregate, enable or constrain a given set of policy interventions, there is no detailed consideration of how performance on one access factor might be affected by another. This is partly because the main objective of the paper was to diagnose some possible parameters for the analytical challenge posed by SPCs, rather than the details of interactions

between them. Considering the hypothetical nature of the access factors, examining how they relate to each other in detail is premature without further research to support or rebut their existence and relevance in this context. Conducting a deeper analysis looking at these possible interactions would undoubtedly add to the explanatory potential of this work, but it may be more prudent to test the robustness of the existing access factor and intervention typologies against new data before doing so, and making adjustments or alterations to the initial framework presented here as required. Interactions between access factors are plausible, however. For instance, an SPC with limited agency but a clearly articulated profit motive may not be able to prevent its shareholder from requiring it to make unprofitable short-term investments, but the consequences of doing so would be determined at least partly by its capacity to access low-cost finance and the profitability of its existing portfolio. Similarly, a monopoly SPC with no real competition but ample financial and technical resources might be theoretically able to deploy and operate low-carbon technologies more rapidly and at lower cost than a competitive power sector would, but not be incentivised to do so if its mandate focuses more on national energy security than profit maximisation.

Finally, the paper limits itself to analysing SOEs in the power sector. Some or all of the primary conclusions may be applicable to SOEs in other sectors, but additional work will be needed to assess the extent of this applicability and where sector-specific factors are relevant – or not – to SOEs' role in the decarbonisation of these other non-power sectors in which state ownership is prevalent (such as oil and gas, steel, and cement).

Paper 2: Government shareholders and stranded assets

Motivation and research question

Despite its clear policy commitment to carbon neutrality, and the prospect of increasingly stringent climate policy measures needed to achieve it, China's government is continuing to build new coal-fired power plants, predominantly through its SPCs. Existing literature on the financial and economic role of coal power in China suggests not only that the majority of the existing fleet is unprofitable despite receiving direct and indirect subsidies, and that China has more than enough generation capacity to meet electricity demand, but also that further additions will reduce average profitability further and in most of China's provinces it is already cheaper to build and operate renewable capacity than to expand the coal fleet (Bodnar et al., 2020; Caldecott, Dericks, et al., 2017; Cui et al., 2021; Denjean et al., 2016; Fei, 2014; Feng, 2017; Gray & Sundaresan, 2020b). The fact that Chinese SPCs are continuing to build coal-fired power plants unlikely to generate financial returns (in part as a consequence of the central government's carbon neutrality commitments) is an apparent contradiction with profound implications for the global decarbonisation of power given the scale of China's coal-burning activities, which contribute roughly 10% of total global emissions across all sectors (International Energy Agency, 2020c). If, then, the construction of new plants by Chinese SPCs contradicts stated policy, they are not needed to meet demand, and external assessments suggest they carry a high risk of asset stranding: why are they being built at all?

Spurred by the surprising observation that coal power capacity is continuing to grow in China, the second paper attempts to answer this question. It begins by asking whether new high-carbon investments by SPCs are indeed at risk of becoming stranded assets, given that they are ultimately owned by a government shareholder. This requires moving from the general appraisal of the relationship between SPCs and climate policy in Paper 1, to a more focused investigation of whether conventional definitions of stranded assets are appropriate in cases where the assets in question are directly state-owned. Bringing together the theory and tools of project-level financial analysis, with the core tenets of

macroeconomic policy, it aims to model how state ownership of a power-generating asset affects the value it represents to its owner. As noted in Section 2, the ‘stranded assets’ terminology is widely used in literature on technology transitions, associated financial risks, and climate policy choices in the power sector, but this literature refers almost exclusively to assets’ *financial* value to a private owner, rather than their economic value to a governmental ‘societal’ owner.

Starting from first principles, this paper compares and contrasts this traditional financial analysis – which typically underpins the quantification of asset stranding projections – with a country-level economic analysis. In doing so, the paper explicitly accounts for the perspective of a government. Without making a judgement as to how companies’ self-interest and government shareholder interests are weighted when making decisions, the intention is to reconstruct what a stranded asset means for a government entity and apply this to a representative example of a power plant investment in a contemporary context. The specific context chosen for this modelling exercise is the decision to invest in a new coal-fired power plant in China, as the country with the largest existing pipeline for new coal capacity by some margin despite its policy commitment to carbon neutrality. By assessing the expected performance of this real-world example of new investments in assets at risk of stranding from a different perspective, this study aims to develop a greater understanding of the criteria, and conditions, under which a government shareholder should and should not proceed with such investments.

Theory

The starting point for this paper is the general principle that government’s goal is to maximise social welfare – in this context, represented by the economic rate of return on a proposed coal-fired power plant. This assumption is made not to the exclusion of secondary objectives for a government (including equity and fairness, self-interested behaviour by government agents, political risks, etc.), but as a reasonable approximation of what a state-backed investment primarily aims to achieve. This simplified theoretical construct for evaluating investments made by government through its SOEs is a useful contrast to the private profit-maximising model of returns (in which the expected financial net

present value, FNPV, must be greater than zero for the project to be considered viable) that is widely used in finance and that acts as the primary approach used in the existing literature on stranded assets. In the paper, these two perspectives are referred to as ‘economic’ and ‘financial’ respectively. While it is more conventional to refer to these as ‘social’ and ‘private’ costs and benefits, we use different terms here in order to make the distinction between the two frameworks clear, given that the entity making the investment is an SOE (not a private firm) and that economic returns are based on a heavily simplified, and relatively narrow model for measuring net benefits to social welfare.

In this framework, an investment by an SPC would be justifiable from an economic (as opposed to financial) perspective if two conditions are met. First, the investment generates a positive economic rate of return to the economy over which the government has jurisdiction (i.e. the economic net present value, or ENPV, is greater than zero). If this threshold is not met, the government would be better off not investing at all. If the threshold is met, the second condition would be that the economic rate of return exceeds that of alternative investments that achieve the same practical goal – that is, the project is justified on an opportunity cost basis. In practice these two conditions are often combined by choosing the discount rate used for calculating economic returns to reflect the government’s estimate of the opportunity cost of capital (i.e., the opportunity cost of the power project relative to the highest achievable return on other possible investments). We keep the two separate in order to conceptually distinguish whether or not a project delivers net benefits, from how it compares to other possible investments where the government’s estimate of the opportunity cost of capital may not accurately reflect the true cost of capital (if, for instance, the benchmark estimate for the opportunity cost of capital for power sector investments is based on coal-fired capacity additions). Modelling the decision to invest in a new coal-fired power plant in this manner can help to evaluate in detail what a stranded asset means for a government shareholder, and help to understand the motivation behind decisions to build new, apparently financially unviable infrastructure in cases like China’s coal power expansion, where the decision appears at first glance to be irrational or wasteful when run through a standard financial model. To summarise: if one assumes that a government’s objective function is maximising social welfare, a proposed power plant that appears to be at high risk of asset stranding on a financial basis may perform

better (or worse) on a welfare-maximising basis. If the government is not only the social planner, but also the beneficial owner of an SOE with some discretion over its investment decisions, the government may be incentivised to use the SOE as a vehicle for achieving its social welfare maximisation goals. This may be particularly relevant in contexts where the state is an active (rather than passive) owner and where the SOE performs a strategically important role or one that is a fundamental driver of national or local economic development, as is the case with large SPCs, especially in China. While this does not necessarily make the financial sustainability of an investment by an SPC completely irrelevant, a more comprehensive understanding of its decision-making should at a minimum reflect elements of the social planner calculus as well as a profit-maximising one. This approach can help to identify where financial and economic interests are aligned and where they are not.

Different combinations of financial and economic results yield four distinct possibilities, outlined in

Figure 1. If the model results show, for example, that the power plant investment is not justified on a financial, project-level basis, but is viable on an economic country-level basis, it would likely become a financially stranded asset that nonetheless delivers a gain in social welfare (on a net present basis) and represents a sound investment by the state. Where an investment is justified neither on a financial nor an economic basis, the government would be wasting scarce public resources by over-investing in new uneconomic power plants that would also fail to deliver a financial return.

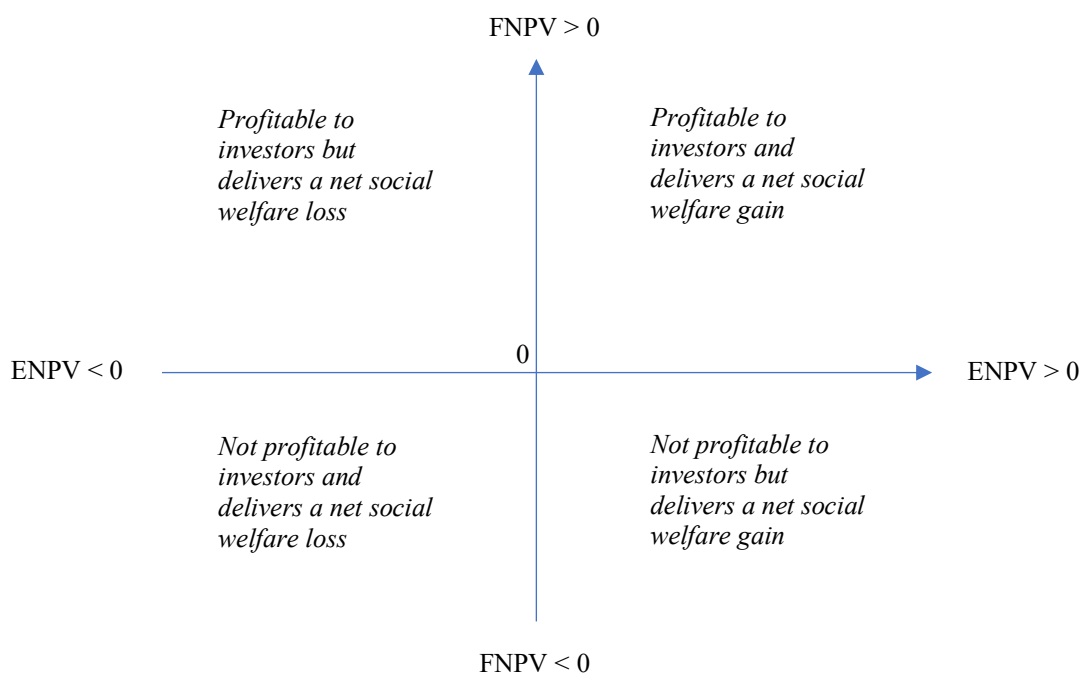


Figure 1. Possible results and interpretations of financial and economic analysis of a proposed investment. FNPV = Financial net present value. ENPV = Economic net present value.

Methods

To investigate the impact of comparing financial and economic returns, we build a standard (financial) discounted cash flow model for a *pro forma*, illustrative new coal-fired power plant project in China and complement it with a similar model that is structurally similar, but in which costs and benefits to the national economy, rather than the private costs and benefits to the investor, are captured. The models are then run in parallel to determine which of the possible results in Figure 1 apply in a business-as-usual scenario, and whether the first condition (requiring that $FNPV > 0$ and $ENPV > 0$) is satisfied. This approach is designed to capture and measure the economic rate of return on the investment from the perspective of the shareholder – in this case, the Chinese national government.

The financial model captures capital, operational, and financial expenditures and revenues at private discount rates and nominal market prices. The economic model draws on established methodologies used by multilateral lending institutions (see Belli, Anderson, Barnum, Dixon, & Tan, 1998; Meier, 2017a, 2017b; Squire & Van der Tak, 1975; World Bank, 2017) to value costs and benefits to the national economy, reflecting the government's beneficial ownership in the project, at social discount rates and real prices. Costs in the economic model exclude all internal transfers within the economy (e.g., interest payments, taxes and duties on capital and labour) and include socialised costs (e.g., pollution and climate damages). Benefits in the economic model are assessed at the point of final consumption of electricity, based on estimates of consumers' willingness-to-pay. In the financial model, benefits are the revenues accruing to the plant owner from selling electricity into wholesale markets.

The economic and financial models are then run under a range of possible alternative policy scenarios to determine where financial and economic interests would converge or diverge, and under what circumstances there may be a financial and/or economic justification for continuing to build and operate new coal-fired power plants where there is no reasonable alternative to doing so. These scenarios take two forms: either the introduction of a shadow price on carbon increasing over time as a proxy for climate policy; or restrictions on plant operating hours up to and including an eventual moratorium on coal-fired power as a proxy for direct controls on plant operations. They help to assess how sensitive the economic and financial cases are, respectively, to policies likely to affect how the plant's output is valued and controlled.

In the final stage of the analysis, we assess whether the proposed coal plant meets the second key criterion by measuring its opportunity cost against available alternatives. A similar financial and economic model is built for an illustrative alternative investment. In this case, we choose to model an illustrative solar PV array with sufficient storage capacity to have equivalent dispatchable power to the proposed coal plant, and compare the financial and economic returns to each option, under the baseline scenario and various policy scenarios. This serves to establish the circumstances under which the coal power investment should or should not proceed on financial and economic bases where alternatives are available.

Results

The results show that under a baseline scenario with no carbon pricing, the proposed coal plant delivers an FIRR (return on equity) of 8.4%, and an EIRR (economic return) of 19.1%, with the net present economic benefits of the project totalling US\$472 million in real terms. The plant breaks even on an economic basis within seven years of the plant starting operations, suggesting that if the plant were closed in 2030, it would still generate value for the Chinese economy. This suggests one possible explanation for continued investment in coal-fired power. On a financial basis, the plant takes over twenty years to realise its required return on equity and leaves investors vulnerable to adverse policy changes implemented before 2040.

If the government uses, for decision-making purposes, a modest shadow carbon price rising from US\$15/tCO₂ in 2026, to US\$30/tCO₂ in 2041, the price is sufficient to entirely eliminate the economic return such that the plant creates a net social welfare loss. Scenarios in which the load factor of the coal plant is permanently limited but no shadow carbon price is used reduce economic returns but fall short of creating welfare losses. These scenarios do, however, have a far greater impact on the project's financial performance such that the net present loss totals \$124-\$176 million, depending on the extent of load reductions applied. Without a shadow carbon price, only a full moratorium on coal-fired power in 2030 or earlier prevents the plant from realising an economic return.

Comparing these results with an alternative solar/storage investment suggests that the renewable option generates higher economic returns than the coal plant under modest shadow carbon pricing and modest declines in electricity storage costs, but does not perform as well on a financial basis. The illustrative solar/storage plant yields an 8.7% EIRR in the baseline scenario, much lower than coal in same scenario. However, since the plant produces no carbon from direct operations, it performs better than coal under modest shadow carbon pricing scenarios. A 30% decline in capital costs from 2020 values improves the solar/storage EIRR to 13.8% and generates an economic NPV of \$602 million, higher than the coal plant in the baseline scenario. If capital costs decline as they are expected to do,

new solar/storage investments should, under the model's assumptions be competitive with coal on an *economic* basis within five years, even without accounting for the social cost of carbon.

Limitations

This paper does not pretend to present a fully realistic assessment of how decisions on new coal plant investments are actually made, nor does it attempt to model the motivations of SPCs, the government, and other interest groups in a nuanced fashion reflecting political realities and the political economy of coal power investment decisions. Rather, it aims to provide a counterpoint to the financial-only analysis that dominates discussion of stranded asset risks in the literature. The results vindicate this approach by showing that, even if analysed from an economic point of view under conservative assumptions, China's new investments in coal-fired power do not appear to be viable either on a standalone basis or in comparison to renewables. Despite this, permits for new coal plants in China in 2022 were granted at the fastest rate since 2015, with half of newly announced plants located in areas where there is already excess generation capacity on the regional grids they would supply. In the same year, China began construction on six times as much new coal-fired generation capacity as the rest of the world combined (Centre for Research on Energy and Clean Air & Global Energy Monitor, 2023).

The apparent disconnect between this paper's theoretical conclusions and the reality of coal in China today suggests that the question of why coal power in China is continuing to expand is not fully resolved by the economic analysis framework applied here. Several possible alternative explanations for this inconsistency are outlined, but not systematically investigated, in the paper, and can be examined in more detail in future work (such as the role of incumbent interest groups, political bargaining, and political elites within the state bureaucracy). The Chinese government may, for instance, be operating under substantially different assumptions to those used in the paper. There may also be more than one relevant boundary condition that economic analysis should consider (e.g., the subnational level) and which could identify a conflict in the respective motivations of national and subnational governments. There could be other factors at play preventing the superior economics and

low-carbon characteristics of alternatives to coal from being properly considered in the power capacity planning process, in the form of bureaucratic or organisational limitations, or principal-agent problems arising from conflicts between government incentives and those of the various agents tasked with implementing its policy preferences.

The paper also does not account for the general equilibrium implications of investment in one additional coal-fired power plant, but rather focuses on illustrating how a national economic approach to modelling the investment decision can yield insight that a project-level financial analysis alone cannot, based on reasonable estimates of inputs, prices and other intermediate variables. A full general equilibrium analysis is beyond the scope of the paper. A comprehensive and complete general equilibrium analysis would be helpful, however, in accounting for the net impact of the investment on economic activity in other sectors, as well as the social costs and benefits associated with the plant's operation both upstream and downstream from it (known as 'multiplier effects'); and the equilibrium effects on welfare improvement (or otherwise, as deadweight loss) across the entire national economy. Upstream effects could include greater demand for construction materials, coal mining or transport, higher coal prices due to increased demand, and greater exposure of workers in the coal industry to harmful pollutants. Downstream effects could include lower electricity spot prices due to greater supply, greater economic activity resulting from lower electricity retail prices, and any substitution away from other sources of power induced by the availability of the new plant. Some aspects of these effects are included in the model in the form of local pollutant pricing and shadow carbon pricing. It would be helpful to evaluate these effects in more detail on an equilibrium basis, in order to understand whether accounting for second- and third-order impacts would change or nuance the key findings of the limited analysis conducted here.

Finally, the analysis does not account for the creation of non-domestic sources of value. In the particular case examined in the paper, the materials and labour used to build the coal plant, and the electricity it produces, are both very likely to remain largely or entirely within China's borders. Insofar as there were non-domestic benefits to building the plant (e.g. additional export of goods or services made possible with the electricity supplied by the plant), they would be indirect, small in magnitude

unlikely to be material to the analysis performed here. If the SPC was planning to build the coal plant outside China, through a Belt and Road Initiative (BRI) project for instance, accounting for non-domestic costs and benefits to the SPC (hence to the Chinese government) would be an essential component of any economic analysis. See Section 5 for further discussion on these possible extensions.

Paper 3: The effects of coal phase-out on employment and fiscal revenue in China

Motivation and research question

Coal is still a fundamental component of China's electricity generation and industrial production profiles (Energy Research Institute & China National Renewable Energy Centre, 2019). In 2019, coal combustion for electricity and heat in China was estimated to generate 4.9 GTCO_{2e}, about 10% of global emissions from all sources (International Energy Agency, 2020c). China hosts approximately 1,200 GW of coal-fired power generation capacity (Global Energy Monitor, 2020) and produced 3.69 billion tonnes of coal in 2019 (International Energy Agency, 2020a). SOEs own the majority of coal mining and power generation capacity in China (Global Energy Monitor & CREA, 2020), while state-owned banks are the main providers of financing for construction (Herve-Mignucci, Wang, Nelson, & Varadarajan, 2015). State-owned grid companies purchase and market most of the resulting electricity (Mayer et al., 2017).

The Chinese government's goal of achieving carbon neutrality by 2060 will require the coal-fired share of electricity generation in China to shrink dramatically, even if carbon capture and storage technology succeeds at scale. Recent bottom-up (i.e. asset-level) modelling efforts have analysed the financial consequences of a transition away from coal in China (Cui et al., 2021; Cui et al., 2020; Gray & Sundaresan, 2020a; Spencer, Berghmans, & Sartor, 2017), and the response of physical intra-China and international coal production and supply networks to reduced coal demand (Gosens, Turnbull, & Jotzo, 2022). Other studies have examined the political economy implications of coal phase-out at national and provincial levels (Bridle, Kitson, Duan, Sanchez, & Merrill, 2017; Caldecott, Bouveret, et al., 2017; Yuan, Guo, Zhang, Zhou, & Qin, 2019).

Still others have used macroeconomic modelling, based on input-output tables describing production-consumption networks, to capture substitution effects across industries (Mercure et al., 2018). These macroeconomic models do capture aggregate responses of a range of macroeconomic

indicators to changes in relative prices and incorporate rates of technological change, but rely to a significant degree on regional aggregation and a number of high-level assumptions for each sector. This makes it difficult to use such models to capture the dynamics of the energy transition in specific sectors and in specific geographies at a high level of granularity, and hard to validate them in data-poor contexts subject to heavily regulated markets, like China (e.g. on price elasticities, demand growth, price formation, etc.). Attempts to resolve this problem have applied network analysis to understand how labour markets adapt to changes at the micro level in the United States (del Rio-Chanona, Mealy, Pichler, Lafond, & Farmer, 2020; Mealy, 2018) – but these approaches rely on detailed, high-quality micro-level data on job vacancies, employment histories, and employee characteristics that are not available to independent researchers looking at China.

The third paper undertakes a detailed asset-level exploration of the consequences of coal phase-out in China on employment in the coal industry, and on tax revenue generated by it. The overall aim is to identify and estimate the socioeconomic implications of retiring coal-fired electricity generation assets beyond the financial losses or forgone generation that form the basis of most existing work on stranded assets in China, and their distribution across time and space. The study extends the largely theoretical and inductive work in the preceding two papers into a more empirically grounded environment, examining what the non-financial aspects of power sector decarbonisation may be – and how they might affect the actions of SPCs, and the dynamics between SPCs and government at different levels.

Methods

This study builds and runs a demand-driven plant-level model of the coal power (i.e. thermal coal) sector in China, focusing on assessing how the phase-out of coal power will affect two macroeconomic areas in which the socioeconomic impact of this decline is felt. In the paper, we construct a network of individual plants, such that changes in plant operation can propagate through the links in the network to coal mines and transport modes. Calculations for employment and tax revenue

at the power plant level are overlaid onto this network. It models the impact of a range of coal phase-out trajectories on the geographic distribution of coal demand, supply, and the associated employment and tax revenue by manipulating the activity of coal plants. Coal demand is driven by the operation of coal plants from the period 2021-2060, using province-level utilisation rates and plant-specific efficiency estimates. Since data on coal trading patterns and transportation routes is not available, plants are matched to mining regions based on location and coal type, rather than to individual mines. This methodological approach allows the model to generate results at granular levels (for individual plants, locations and SPCs), and aggregated levels (provincial and national).

Employment is estimated on the basis of (i) average labour intensity of coal mining by province, (ii) secondary survey data on the number of jobs in coal plants, and (iii) national transportation statistics. Taxes are calculated on a plant-level basis, covering taxes on labour (which are a function of jobs, wages and tax rates) and capital (which are a function of the amount or value of coal mined, how much is transported and how far, and how much coal-fired electricity is generated). Subsidies are largely estimated at an aggregate level, as very limited data availability prevents the possibility of reliable plant-level subsidy estimates. Scenarios for the phase-out of coal in the power sector are constructed by progressively shortening power plants' operating lifetimes, and observing the effects on employment and net tax revenue from the coal value chain supported by the operations of a given plant. Running the model for each scenario allows for the distributional impact of changes in employment and fiscal revenues to be observed and analysed at the national, subnational, and firm level.

Results

At the national level, under a 'baseline' (B) scenario consistent with China's carbon neutrality goal, labour productivity growth in coal mining implies that significant job losses will occur nationally in the medium term even if all coal plants continue operating as planned. Jobs supported by demand from coal power plants decline from an estimated 2.7 million in 2021, to 1.44 million in 2035 and 94,000 in 2050, with jobs losses from mining alone expected to exceed 1.1 million by 2035. Tax

revenues from thermal coal under the B scenario total approximately ¥300 billion annually from 2021-2030, peaking in 2023 at ¥340 billion. This is significantly less than estimated subsidies of at least ¥480 billion, suggesting coal is likely a net fiscal drain on China's public finances, even without accounting for the full costs of local pollution and the social cost of carbon. As coal plant retirements accelerate, from 2034 onwards, fiscal revenues begin to fall more rapidly, with annual rates of decline rising from 1% in the 2020s to over 10% by the 2040s. More aggressive climate policy and technology scenarios bring job and tax losses forward in time, while a No Transition policy, in which all currently planned coal plants are built, delays but does not ultimately prevent these losses from occurring.

Governments of coal-producing provinces like Inner Mongolia, with an industry highly dependent on exports to other provinces, are more exposed than others to declining tax revenues from coal, and more insulated from job losses, given their high current degree of labour efficiency. Although their provincial revenues are likely to remain stable until the early 2030s under the B scenario, the possibility of increasing policy stringency underlines the need for revenue and skill base diversification. At the firm level, coal plants and mines owned by China's 'Big Five' state-owned power companies are responsible for over 40% of both jobs and tax revenues in 2021. The number of jobs supported by the activities of each of the largest ten firms, with one exception, declines by 71-84% by the early 2040s, with the tax contribution of each declining by 43-69% in the same period.

Limitations

There are a number of limitations to the modelling methodology and data used in Paper 3. Several simplifying assumptions are made in constructing the model, primarily reflecting data gaps. In general, every effort has been made to find the most reliable possible data, although some of the model assumptions depend on statistical reports published by the Chinese government, the accuracy of which cannot always be independently verified.

The first and most important limitation is that there are no price dynamics, and consequently no elasticities of supply and demand, in the model. This was a conscious decision: since the various components of coal and electricity value chains are heavily regulated in China and thermal coal suppliers do not have large substitute markets to sell into when prices are low, prices are unlikely to be reliable guides to supply-demand dynamics and are of limited relevance to resource allocation. Given these distortions, price formation was considered to be too far removed from actual supply and demand to be used for model calibration. This is not to say there are no price responses at all in Chinese coal markets, but rather that structural constraints to the value chain being modelled mean that price formation is artificial enough that assuming no price movement was judged to be preferable to estimating it, and elasticity of supply is likely to be low in any case given the lack of alternative sources of demand for thermal coal. More dynamic responses to changing demand for coal from China's power plants can certainly be explored in future work (see Section 5).

Second, the rate of labour productivity growth in the coal mining sector (proxied by the number of jobs per 10,000 tonnes of coal extracted) follows the approach taken in the source from which it is taken. The source assumes productivity growth to remain constant, at 5% per year, lower than the 8% annual improvement observed from 2015-2020. The rationale for assuming a slower productivity growth rate in the future than the recent past is that at least some of the earlier, more rapid, decline was likely to have been driven by a period of rapid consolidation of the industry and closure of smaller, less efficient mines, rather than the incremental improvements to existing operations likely to play more of a role in future.

Third, the coal consumption of individual power plants is determined by age, type of coal consumed, capacity and technology type (e.g., subcritical vs. supercritical). This provides a relatively high degree of granularity, but still produces an estimate of plant efficiency conditional on basic plant characteristics, in lieu of observed data. It is also assumed that each plant consumes only the type of coal it is associated with in the dataset. For instance, a plant that normally burns anthracite is unable, in the model, to consume coal of any other type. In practice, coal plants can be technically capable of using coal within a broader range of quality and calorific content depending on availability.

This is relevant to the fourth limitation: the allocation of coal supplies to individual plants. Due to a lack of available data on transport networks, the model assumes that coal plants consume coal locally (mined in the same province as the plant) where it is available, and import coal from other provinces, with coal exports by net exporting provinces allocated *pro rata* on the basis of demand, once local supplies are exhausted. This is a relatively strong assumption, and again, may be relaxed in future work subject to improved data on transport networks becoming available. However, given strong existing incentives for provincial governments to promote local industry rather than import from other provinces, similar caveats apply as for electricity markets. Price- or distance-based optimisation of mine-plant relationships would still be likely to represent only a rough approximation of the actual structure of interprovincial coal trading for thermal power plants.

The fifth limitation is also linked to the lack of transport network data: since coal plants are linked not to specific mines but to provinces, the starting location used in calculating distances between mines and plants is the capital city of the province of origin.

Sixth, the model does adjust for coal imported from outside China, but assumes that imports are distributed *pro rata* to each province in China. In practice, imports are likely to be weighted heavily towards provinces with fewer local or regional coal resources, larger coal plant fleets, greater electricity demand, and greater access to coastal ports and international rail transport links.

Seventh, estimates of employee wages vary by province and industry, and a weighted average of public vs. private sector wages (according to the share of employment by each) is also used. This does not differentiate between employees on different salaries within a given company. In calculating income tax, it is assumed that the standard tax deduction applies, while in practice this may not be the case – or at least, would be expected to vary from one employee to another. Similarly, liabilities for corporate taxes generated in the model are assumed not to be offset by any tax credits claimed by that corporate entity. In practice, this is also unlikely to be the case, given the complexity of large corporations' tax affairs.

Finally, the scenarios against which the model is run are relatively simplistic. While they are calibrated to correspond to peer-reviewed, China-specific scenarios in He, Lin, Zhang, et al. (2020), they do so only by varying the lifetime of coal plants, rather than the average load factor, which varies by province, but is assumed to remain constant over time. In practice, as coal is steadily displaced by variable renewable energy sources and storage capacity, some coal plants may see their already-low load factors decline further.

Data constraints are also behind the paper's other major category of limitations – namely, that it does not consider the extent to which net declines in employment and tax revenue in the coal sector may be offset by substitution in labour markets away from coal towards other economic activities. It restricts itself to analysing the jobs and tax revenues lost to the coal transition, rather than the jobs created by the industries that will ultimately replace coal's role in the energy sector. The International Energy Agency (2022) finds that while 1.6 million jobs are expected to be lost in China's coal sector by 2030 under its 'Announced Pledges Scenario', 2.2 million jobs in low-carbon sectors and segments are expected to be created over the same period (across electricity generation, grid development, building retrofits, bioenergy, batteries and carbon capture and storage (CCS)). The net creation of 0.4 million jobs this implies is itself far lower than the 1.3 million net job creation expected under the 'Accelerated Transition Scenario'.

It is not, however, necessarily the case that newly unemployed coal plant workers will find re-employment in low-carbon sectors like renewable energy generation, or that coal miners and transport workers will transition into the mining and transportation of materials serving the low-carbon economy. Similarly, the locations where new jobs are created may be different from those where they are lost. Identifying the extent to which different localities and provinces can benefit from opportunities to transition workers into low-carbon industries (or simply other non-coal industries) will be crucial for national and provincial governments alike in managing the effects of the coal transition. To examine these localised, location- and industry-specific effects at the high degree of granularity permitted by the asset level approach adopted in this paper (rather than at the aggregate level of provincial statistics more common in analysing the general equilibrium effects of industrial transition), more data is needed than

is currently available. Better data on the locations of power plants and industrial facilities is becoming steadily more reliable and accessible, but data on the occupations and skills of workers across the Chinese economy – which is needed to provide a thorough assessment of opportunities to transition into other industries or roles – is still very limited.

4. Policy Implications

This dissertation takes as its starting point the necessity for SPCs in particular, and SOEs in general, to play a central role in decarbonisation. It contends that SOEs have untapped potential to play a highly effective role in supporting decarbonisation. SOEs are directly relevant to the net zero ambitions of governments across the world. The papers herein represent the beginnings of a research programme examining SOEs and decarbonisation in the power sector, developing novel theoretical and empirical approaches to understanding the role of SPCs, and the non-financial considerations of relevance to government shareholders. While research in this area is still very limited, the results discussed in the three thesis papers can nonetheless be useful to governments seeking to reconcile their dual roles as social planners and shareholders as they move to decarbonise their economies, and to SOEs faced with navigating complex and potentially contradictory social, economic and financial mandates.

Paper 1 provides governments with a framework for considering the policy options available to them beyond market-based mechanisms (e.g., carbon pricing) in pursuing decarbonisation through SPCs. Consideration of targeted interventions, channelled through SPCs, can expand the scope of action and the toolbox available to governments with direct control over SPCs and potentially allow SPCs to act as conduits for more efficient and effective outcomes than would be possible for private sector firms alone. This may be especially true for governments presiding over SPCs that are well-insulated from domestic competition, but that also have the requisite technical and financial resources to decarbonise their capital stock. Where governments directly mandate, or indirectly pressure, SPCs with these characteristics to decarbonise, the SPCs could undertake a more rapid and less costly transition than might be achieved by a privately-owned utility.

Paper 2 shows clearly that considering the economic impact of proposed carbon-intensive investments can provide government and SPC decisions with more decision-relevant information than if they were guided solely by the financial analysis informing most contemporary analysis of stranded asset risks. It suggests that new state-backed coal-fired power plant investments in China today are already likely to be wasteful on the basis of country-level economic returns under modest future climate

policy scenarios, and the opportunity cost of new coal investment will rise further as the levelised costs of dispatchable renewable alternatives fall, even without accounting for the social cost of carbon.

Paper 3 shows that while over two million jobs in China's thermal coal sector are at risk by 2050, failing to adopt decarbonisation policies will not prevent the job losses from occurring because they are driven primarily by industrial consolidation and automation. A significant increase in the rate and magnitude of job losses (most notably in the short term) would occur only in the unlikely event that China pursues decarbonisation policy with an exceptionally high level of aggression and speed. This suggests that while mass redundancies in the coal sector are important considerations for policy makers, they are not a reason to delay coal phase-out, especially considering the likelihood that some job losses will be absorbed by expanded employment in other sectors. The paper also shows that even without considering GHG emission externalities, declining tax revenues from the coal sector are probably not a reason to delay decarbonisation either, since they are likely to be offset by reduced subsidies to the same sector. Significant variations in the employment and net fiscal revenue impact on individual provinces, however, suggests there is a strong case for the Chinese national government to engage in redistributive measures to mitigate the effect on regions heavily exposed to declining coal demand, possibly funded in part or in whole by any net savings generated elsewhere, as they work to diversify regional economies. The high-resolution nature of the analysis and results can also help to anticipate and address sources of political, economic or other resistance to change, based on vulnerable locations, entrenched interests, political-economic incentives or other factors.

This dissertation demonstrates the value of explicitly accounting for SOEs and governments' role as shareholders in the formulation and evaluation of climate policy. Overall, the body of work contained herein can help governments committed to decarbonisation to understand – and take pre-emptive action to address: (i) whether and how their SPCs can help to accelerate power sector decarbonisation, (ii) the economic consequences of overinvestment in high-carbon assets, and (iii) the potential impact of decarbonisation (in this case, the employment and tax revenue effects of coal phase-out) on non-financial indicators that are of relevance to SPCs and governments alike.

5. Extensions and Future Work

This dissertation comprises three published papers that have been viewed by peer reviewers as making significant and original contributions to a nascent field, namely the study of SOEs (and SPCs as a subset) in the context of decarbonisation. There are some areas where the papers employ important simplifications or assumptions, as discussed in Section 3, and others where they deliberately confine themselves to the study of specific phenomena within the field in order to facilitate focus on tractable research questions. This section outlines a number of promising avenues for further research in this area, corresponding to a relaxation of the assumptions made in the papers, and the application of the key ideas and methodologies to new cases or contexts.

a. Improvements in data availability

Insufficiently detailed or incomplete data was the most significant challenge confronted in undertaking the research laid out in the thesis papers, constraining the scope for quantitative empirical research methods to be applied to the study of SOEs. Improvements in data availability do not necessarily mean that quantitative methods will be successful, given the heterogeneity of SPCs (and SOEs in general), but they may allow for greater use of quantitative tools in testing and building on the theoretical conjectures and hypotheses developed here. In any case, there is a clear need to develop comprehensive datasets on SOEs (or the subset with which this dissertation is primarily concerned, namely SPCs) with a sufficient amount of detail and comparability to at least partially address the heterogeneity problem and allow some form of quantitative comparison and analysis. Comprehensive public disclosure of information by the unlisted firms that comprise the bulk of the SOE universe is unlikely in the near future, but following the example set by Paper 3, efforts to refine and augment independently constructed asset-level datasets in high-carbon sectors can help to construct detailed profiles of individual SOEs, without having to rely on firm disclosures.

Open asset-level datasets linked to ownership are already available that present a detailed picture of individual physical assets owned by SOEs globally across the power, coal mining, steel and

cement sectors. In most cases, the direct owner and ultimate parent company of each asset (albeit not, typically, the intermediate companies between the direct asset owner and parent) are also recorded. This allows researchers to estimate, for SOEs specifically, decarbonisation-relevant information such as the emissions intensities, technologies, and capacity of each SOE's assets, and the geographical distribution of these assets. Where they contain geospatial coordinates, asset-level datasets can also be overlaid with other geospatial datasets. This can significantly enrich researchers' ability to associate a wide range of data points to individual assets and the SOEs that own them, and examine in more detail and with greater precision the relationships between financial ownership, socioeconomic data (e.g., employment and income statistics), and assets' physical or location-specific characteristics (e.g., water availability, ambient temperatures, irradiation, wind speeds, flood risk, exposure to environmental risks, etc.).

Assessing the exposure of SOEs' asset portfolios to the physical impact of climate change can also help to develop a deeper understanding of the challenges and opportunities faced by SOEs struggling to decarbonise. Higher average and peak temperatures can, for instance, lower the operating efficiency of existing fossil assets and strengthen the case for transition (Coffel & Mankin, 2021; Petrakopoulou, Robinson, & Olmeda-Delgado, 2020). On the other hand, unexpected changes in rainfall can prove detrimental hydroelectric generation potential (Colesanti Senni & von Jagow, 2023) and extreme weather events made more frequent and more likely by climate change can place additional financial pressure on already under-resourced SPCs forced to allocate resources to network maintenance and repair (see Handayani, Filatova, and Krozer (2019) for a case study of Indonesia's PLN).

With data made available since the study in Paper 3 was undertaken, it is now possible to extend the analysis from thermal coal alone (which accounts for approximately half of China's coal consumption) to include coal used for steel and cement manufacturing (which comprises most of the country's remaining coal consumption). The data improvements required to address the many other limitations of the model methodology may prove less forthcoming, although some – such as a coal transport network data allowing each coal plant to be linked to a specific mine – are likely to be more consequential for the results than others – such as incremental improvements in the accuracy of plant-level efficiency assumptions. Future refinements of the model should, where possible, also incorporate

better information on coal price formation; the expected rate of productivity improvement over time, sectors, and provinces; the share of coal imported from overseas by each province; and the share of employees by region and company engaged in different occupations (e.g. managerial, administrative, and operational).

More ambitious expansions of the model and associated methodology can enhance its contribution to a growing body of research on ‘just transitions’ in coal and other industries at risk (Caldecott, Clark, Koskelo, Mulholland, & Hickey, 2021; Diluiso et al., 2021; Henry, Bazilian, & Markuson, 2020; Jakob & Steckel, 2022; Sartor, 2018). Although Paper 3 already explores the socioeconomic consequences of coal phase-out for China and the options available for managing them, the incorporation of metallurgical coal, and non-coal industries, into the model could significantly expand its contribution to understanding the wider consequences of carbon neutrality for China. Specifically, as more detailed data on jobs, taxation and subsidies in industries other than thermal coal becomes available, mapping it to asset-level data on heavy industrial production facilities and non-coal installed electricity generation capacity can provide a more comprehensive picture of the impact of coal phase-out on employment and net tax revenue across multiple sectors of the Chinese economy, accounting for the effects of substitution away from coal power into other coal-using industries (e.g., cement and steel production) and into low-carbon power (e.g., nuclear, hydro, renewable). Expanding the model to incorporate asset-level data across multiple sectors would yield more complete aggregate results, but also more nuanced localised results capable of identifying where, to what extent and under what conditions job losses and tax revenue losses in the coal value chain could be dampened by substitution effects or accentuated by concurrent job losses and tax revenue losses in other sectors. This would provide useful input to the design of redistributive policies or investment programmes targeting cities, regions or industrial clusters likely to be most negatively affected by thermal coal phase-out.

Greater availability of quantitative data would also help to test the hypotheses developed in Paper 1. In the paper, the proposed access factors represent hypotheses on how different interventions by government may affect the behaviour of SPCs of different types. In turn, the ideal types provide a means of applying these hypotheses to real data with a view to generating testable potential relationships

between independent variables (in this case, government actions) and dependent variables (marginal impact on an SPC's decarbonisation as measured by, e.g., emissions intensity of existing asset stock, and capital expenditure on forward-looking assets) conditional on different SPC characteristics. Sufficiently large and granular historical datasets on SPC emissions, asset portfolios and investment decisions, for example, could make it possible to test quantitatively for differences in the size, direction and duration of the effects of past government policies on SPCs' decarbonisation trajectories, as compared to those of privately-owned comparable firms (across both listed firms and private equity). It could also be possible, depending on the number of observations for similar types of SPC, to test for differences within the sample of SPCs. However, as already noted, the many sources of heterogeneity in groups of SPCs, and the likelihood of unobserved variables explaining some sources of variation, suggest that quantitative methods in this context should be treated with caution, and as one of several tools and methodological perspectives necessary for developing a full understanding of SOEs in the decarbonisation context.

For Papers 2 and 3, data improvements would also facilitate the extension of the models in both papers, or integration of model outputs, into a more general equilibrium analysis, accounting for cross-sectoral welfare and substitution effects; the impact of the proposed investment on important macroeconomic variables such as employment and net fiscal revenue; upstream and downstream multiplier effects of government investments (via SOEs) in installed generation capacity (Paper 2); and changes in the structure of the energy sector (Paper 3). In the case of Paper 2, analysing general equilibrium effects would provide some refinement to the modelled results and indicate whether accounting they would be of sufficient magnitude to affect the central conclusions of the analysis. In Paper 3's case, equilibrium model results could serve as inputs (by projecting coal demand over time) and as a target for its outputs (by using the Paper 3 model results to calibrate external shocks to an equilibrium model capable of estimating the effects of those shocks on other real economy sectors and macroeconomic indicators).

b. Investigating the political economy of government- SPC relationships

Paper 1 explicitly holds the role of government constant and assumes all governments' political will to act on, and enforce, decarbonisation targets is homogeneous and unchanging. These assumptions are made in order to focus the analysis on how the characteristics of SPCs might affect their responses to policy measures. In practice, however, governments are heterogeneous and multi-layered organisations, with preferences and policy responses subject to constant change. Relaxing the assumption that government policy preferences are fixed would allow, in the Paper 1 framework, for preference-shaping interactions between government, SPCs and third parties to take place. This may require extending the scope of one of the four access factors – 'agency' – to include not only an SPC's control over its own behaviour, but its capacity to influence government behaviour by advocating for or obstructing climate policy measures. In the latter case, decarbonisation goals may conflict with SPCs' short-term interests or even threaten their long-term viability. The ability of an SPC to shift government preferences towards its own could, in turn, be a function of its political position, market power, financial circumstances, capital stock, and other factors. It may be useful to develop a set of 'government access factors' to parallel SPC access factors, to establish a more complete understanding of how SPCs (and other SOEs) might be able to affect governments' willingness and ability to pursue decarbonisation agendas.

Identifying sources of alignment and misalignment between governments and SOEs in other major industrial sectors is also relevant to industrial policy formation and implementation, especially where SOEs are the primary implementing entities of any transition to low-carbon technologies. Taking the framework developed in Paper 1 as a starting point, a useful avenue for further research would be to investigate the economy-wide implications of national net zero commitments for the operational and investment trajectories of specific SPCs (and SOEs in oil and gas, steel, cement, transport, chemicals, and other high-emitting sectors in which state ownership features prominently). This further work could consider how government-coordinated industrial policies would operate through SPCs, where they might encounter support or resistance, and how regulatory efforts designed primarily for private investor-owned firms would affect SPCs. The potential for SPCs to be used as direct instruments of

domestic and industrial policy was illustrated in July 2022, when the French government announcement of its intention (subject to a court ruling, at the time of writing) to increase its shareholding in its SPC *Electricité de France* (EDF) to 100%, acquire the company's long-term debt, and delist it from the stock exchange, as part of a strategic government effort to expand France's nuclear fleet in the face of energy security concerns (Electricité de France SA, 2022; Reuters, 2023).

Alongside political influence, the question of how and to what extent SPCs' and SOEs' agency is determined by their internal governance processes and structures is also worthy of further in-depth investigation. Further study of high-level and day-to-day governance structures, decision-making modalities and allocation of responsibilities for delivering on government policy priorities within and across SPCs, can help to theorise and test relationships between these components and the formulation of the companies' decarbonisation strategies. Going into greater detail in this way would also provide a natural entry point for well-developed literatures and methodological tools in management theory and science, respectively, to investigate how SOE governance affects the design and execution of their decarbonisation strategies.

A more nuanced aspect of SPC (and SOE) behaviour that also deserves integration into the theoretical framework as it evolves, is whether or not, and with what implications, variations on the 'principal-agent problem' arise with respect to governments and SPCs. The principal-agent problem refers in this context to conflicts of interest and asymmetries of information between high-level policymakers and the agents tasked with policy implementation. Principal-agent problems in government policy formulation and implementation processes are well-documented. In the context of China's climate policy, for instance, the clearest sources of conflict are divergence between the interests of central government principals, and agents in SPCs/SOEs, as well as provincial and local governments, tasked with implementing directives. The economic analysis approach developed in Paper 2 can readily be adapted for this purpose. The principles behind the analysis can be used to compare economic returns to agents (subnational governments, for instance) and principals (national economic policymakers), whereby the economic value accruing to subnational and national governments, respectively, is measured as the pertinent boundary within which economic costs and benefits accrue.

Where this additional level of analysis shows that a project is not in the national economic interest but is nonetheless be in the interest of a provincial government – or vice versa – this would suggest divergent principal-agent interests.

The just transition aspects of decarbonisation are another area in which SPCs – and SOEs more generally – may seek to influence (or be influenced by) government preferences. Much of the early literature on just transitions focuses on developed markets in which the major employers in high-carbon industries, including the power sector, are largely not state-owned (Beatty, Fothergill, & Gore, 2019; Europe Beyond Coal, 2020; International Labor Office, 2014). However, recent policy developments on financing energy transitions in major state-led economies – most notably the announcement of Just Energy Transition Partnership (JETP) programmes for SPC-dominated South Africa, Indonesia, and Vietnam, with further plans for India and Senegal under development (Kramer, 2022) – also provide a timely opportunity to ensure that research on SPCs’ behaviour, incentives and roles is integrated into the design of transition finance frameworks. Depending on the extent to which SPCs are responsible for large or dominant shares of local employment and economic activity, either they, or government actors, or both, may oppose or support efforts to integrate just transition principles into their decarbonisation strategies. For instance, SPCs might seek to limit the impact of job losses and support the creation of alternative employment opportunities, or on the contrary, seek to transfer the responsibility for managing the effects of large-scale redundancies to government. Equally, governments may wish to leverage their influence over SPCs’ social mandates to require or encourage them to take steps to absorb the short-term shocks that decarbonisation may have on employment (e.g., by retaining more employees than necessary, or offering generous redundancy or relocation packages to employees facing termination).

c. Exploring additional sectors, geographies, and scenarios

The three thesis papers have limited themselves to the power sector. They have also examined either a selection of case studies (Paper 1) or a specific country (Papers 2 and 3) in which a specific set

of policy scenarios were tested. In each case there is scope to undertake further work on additional sectors, geographies and scenarios that would prove beneficial in understanding the phenomena under study. This includes assessing the impact of sector-specific changes on the wider economy through general equilibrium or equivalent analytical approaches.

First, the case study approach in Paper 1 can be extended to SOEs in other real economy sectors (e.g., cement, steel, and oil & gas) and expanded to private and quasi-private firms in an effort to more clearly identify the sources of difference and similarity between them. Since SOEs feature more prominently in the power sector than most others, and access to electricity is both a fundamental driver of economic activity and subject to greater pressure to decarbonise in the short term, the resulting conjectures and policy prescriptions for non-power sector SOEs may prove very different. Studying SOEs in other industrial sectors can help to develop a more general understanding of their role in decarbonisation, however, and identify differences and commonalities in how governments can leverage their SOEs across multiple sectors to achieve policy goals. Similarly, while the models in Papers 2 and Paper 3 cover thermal coal use only, the data improvements discussed above mean it is now possible to adapt and expand them, respectively, to include coal use in heavy industry (primarily for steel and cement manufacturing). This would help provide a much more comprehensive picture of the role of all forms of coal in supporting employment and tax revenue in China. As already noted, the underlying approach can also, as data availability permits, be extended to non-coal sources of power generation (including gas-fired power generation). It can also be adapted to account for the introduction of emissions control technologies such as carbon capture and storage, and be applied to other components of the energy sector, such as oil and gas extraction.

Second, SOEs are also active participants in the financial economy. State-owned financial institutions can take a range of forms, including national and regional development banks, other domestic and overseas development finance institutions (DFIs), export credit agencies (ECAs), sovereign wealth funds (SWFs), public pension funds (PPFs), and international financial institutions, including the International Bank for Reconstruction and Development (World Bank). The 26 national and regional development banks comprising the International Development Finance Club (IDFC) hold

a total of over US\$ four trillion in assets and lend over US\$ 600 billion annually (International Development Finance Club, 2023). At the time of writing, the 200 largest SWFs and PPFs hold a combined total of US\$ 25 trillion in assets (Global SWF, 2023). To the extent that these institutions act as sources of equity or debt capital for SOEs, they may play an important role in guiding SOE decision-making through the provision or withholding of finance, thereby acting as a conduit for government policy preferences. The nature and extent of the current network of relationships between financial and non-financial SOEs is, however, relatively poorly understood. If the core premise of this body of work is correct – namely, that SOEs in general, and SPCs in particular, have a pivotal role to play in delivering on net zero pledges – then financial SOEs are likely to play a similar important role as capital providers throughout the transition process. Mapping and analysing financial to non-financial SOE relationships is therefore a natural, and essential, extension to this dissertation.

Third, all three papers could benefit from application to other geographies. For Paper 1, this might take the form of expanding the sample of SPCs studied to cover other countries or regions, comparing them to competing private firms in other countries, and examining the overseas activities of SPCs in the sample. In the case of Papers 2 and 3, the principles and modelling approaches are not specific to China and can in principle applied to other contexts – with appropriate modifications to account for differences in market structure, price formation, and so on – although in each case feasibility would depend on the availability of data on proposed projects (Paper 2) and on links between coal industries and employment and tax revenue generation (Paper 3). For Paper 2, understanding how financial and economic returns to new coal (or other carbon-intensive) projects differ in contexts beyond China – which is exceptional in many ways – is particularly relevant where SPCs/SOEs control substantial components of a country’s energy infrastructure (such as India, Indonesia, Mexico, Pakistan, and South Africa). In each of these cases, the application of an economic framework can complement existing (financial) stranded asset analysis and help researchers distinguish clearly between expected national- or subnational-level economic returns, and plant-level financial returns. This is true both for domestic and foreign investments. Subject to the availability of financial and operational data for coal plants, Paper 2 could be scaled up from the single pro forma plant in the paper, to analyse the economic returns

for all proposed coal plants in China and in other countries, identify the sources of differences, and calculate aggregate potential for asset stranding on an economic basis as a complement to aggregate financial stranding estimates in existing literature.

Fourth, Papers 2 and 3 could benefit from the addition of more sophistication and variety in the scenarios against which results are produced. The models in both papers are flexible enough to allow for many different types of demand- and supply- side policies to be evaluated and could be integrated into other models to translate the results of demand- or supply-side scenarios to effects on coal mining and coal power generation. This might include simulating the effect of specific provincial or national policies designed to control emissions from the coal power sector, or to limit either coal production or combustion directly.

d. Accounting for overseas assets and investments

The three thesis papers all focus on SPCs as domestic actors. However, in many cases, SPCs either control a substantial portfolio of assets overseas and/or sell electricity into overseas markets (e.g., Sweden's Vattenfall, China's SPIC, and Canada's HydroQuebec). The economic rationales for domestic and foreign activities, and government shareholders' treatment of them, can be very different. For instance, the activities of an emissions-generating asset located overseas may not fall under national net zero commitments and therefore not be subject to the same decarbonisation objectives as domestic assets. Alternatively, an overseas asset may appear to operate at a loss, but in fact be part of a wider economic relationship that is still profitable to the asset owner's national economy (e.g., a loss-making power plant in Vietnam owned by SPIC that still benefits the Chinese government because it is tied to a long-term coal supply contract from a coal mine controlled by a different Chinese SOE). Indeed, evidence from Chinese state-owned banks' lending contracts with overseas counterparties suggests that they tend to include unusually strict confidentiality clauses, requirements for priority over other creditors, and cross-default clauses more commonly found in commercial debt contracts (Gelpern et al., 2021). Differential treatment of domestic and overseas lending is consistent with the theoretical

framework adopted in Paper 2 – namely that for foreign activities in which most economic value (from electricity generation, employment, etc) is generated overseas, governments may be more concerned with maximising financial remittances from such projects than supporting economic returns to host countries unless there is a clear strategic reason to do so. In this context, it would clearly be useful to extend the analysis in Paper 2 to quantify the differences in both economic and financial returns on otherwise identical domestic and overseas projects.

Overseas lending and investment by financial SOEs generally, particularly in coordination with non-financial SOEs, also has significant implications for the geopolitics and geoeconomics of decarbonisation. This dynamic is particularly clear in the case of China and the BRI, as detailed in Clark, Jindal, Shrimali, Springer, and Rafaty (2023). Chinese financial SOEs – chiefly the China Development Bank (CDB) and Export-Import Bank of China (Exim Bank) – have provided financing for 59 GW of operating coal-fired generation capacity outside China, 39 GW of which is currently in operation. With an average age of less than ten years, these plants are concentrated in Pakistan, Indonesia and Vietnam, all of which are dominated by SPCs. These host country SPCs, as well as the Chinese financial SOEs and state-owned providers of engineering, procurement and construction (EPC) contracts responsible for the financing and construction of these plants, will all be involved in executing any decarbonisation strategy that affects these plants' operations. Exploring these cross-border interactions of state-directed capital, especially where it is bound to long-lived, high-carbon assets, present another useful direction for further research.

6. Conclusion

The introduction to this document laid out the prominence of SOEs across key high-emitting sectors of the global economy, including power, oil and gas, steel, and cement. The central role of SOEs in any transition to net zero emissions is the starting point of this dissertation. The heterogeneity, size and national economic significance of SOEs in the power sector provide ample reason for studying their characteristics more closely. This thesis has also focused on SPCs because rapidly decarbonising electricity generation – especially in China – is imperative if the global climate policy objectives articulated in the Paris Agreement are to succeed. Data on SOEs in the power sector, namely SPCs, is more detailed and widely available than it is for non-power SOEs, which carries an advantage for the formulation and investigation of tractable research questions. With the onset of the COVID-19 pandemic and ensuing travel restrictions, it became even more necessary to focus on research questions capable of being addressed with existing data and through the application of theory and modelling techniques to that data.

As such, the material in this thesis does not attempt to address the fundamental problem of insufficient data on SPCs specifically and SOEs in general. What it does do is explore how heterodox perspectives in economic theory and decision-making analysis can be applied to the question of state ownership in an economy that must be decarbonised. Focusing on state ownership in the power sector, therefore, and then on China as the largest government owner of power generation capacity, the thesis papers and the discussion presented in this document affirm the need to explicitly allow for heterogeneity, endogenous preferences, and feedback mechanisms within state-owned firms as critical to the design of effective climate policy in a world where state ownership of emitting assets is a reality.

a. Overview of main findings

Where this thesis makes its key contribution is in justifying and explaining why SPCs should be receiving distinct treatment in the literature on the economics and policy of climate change than they have to date. The starting point is necessarily to provide empirical support to this hypothesis – namely,

that SPCs are different from idealised conceptions of firms as simple profit-maximisers, and that these differences are relevant to the design and execution of climate policies aiming to accelerate the decarbonisation of SPCs' activities. Paper 1 tackles these questions and concludes not only that there are major differences between private electric utilities and SPCs, but also between SPCs themselves. It further shows that these differences have direct, often counterintuitive, implications for the effectiveness and efficiency of different climate policy instruments. Indeed, it concludes that SPCs can in some circumstances be more effective conduits for climate policy objectives than private firms, and that market-wide policies may be less effective in shaping the behaviour of SPCs than private firms. Overall, the paper makes the case that SPCs deserve different analytical treatment to private firms in the decarbonisation context. It provides a qualitative analytical framework identifying the characteristics of SPCs that are relevant to climate policy design and how they might affect the effectiveness of those policies.

Paper 1 stops short, however, of constructing a formal alternative framework. The goal of Paper 2 is consequently to make progress in this area by investigating the extent to which existing formal approaches for analysing climate policy risks facing high-carbon assets – namely, those used in the stranded assets literature – are adequate to the task of analysing state-owned assets. A narrowing of scope to address a specific empirical observation provides an appropriate test case, namely the empirical puzzle presented by Chinese SPCs' continued construction of new coal-fired power plants. Stranded asset theory would suggest that new coal plants are risky investments that also contradict clearly stated national climate policy goals.

The paper finds that stranded asset analysis based on financial metrics alone misrepresents the incentives facing SPCs and, by extension, their government shareholders by assuming costs and benefits to be borne privately. Building an alternative 'economic analysis' framework from first principles, it shows that a more complete understanding of state-owned actors' objectives can be achieved by accounting for both the financial and economic aspects of proposed new investments. It also finds that, when seen through the lens of country-level economic returns, new investments in coal-fired power generation by SPCs in China are unlikely to yield positive economic returns, and that equivalent

investments in dispatchable renewable energy will soon be competitive with coal on an economic basis without accounting for the social cost of carbon. As noted in Section 3, the analysis in Paper 2 does not constitute a complete theory of SPC decision-making and a full explanation of the behaviour observed by Chinese SPCs and their government shareholders is still lacking. Taken together with Paper 1, however, Paper 2 lends additional weight to the case for a new, or at least more comprehensive, analytical approach to SPCs and state ownership in the climate policy context.

The third and final Paper remains focused on China. This is partly for practical reasons given China's uniquely large and coal-dependent electricity sector, and partly to complement the analysis conducted in Paper 2 by taking a view of the legacy coal power industry as a whole, rather than the marginal capacity addition discussed in that paper. The work preceding Paper 3 shows that non-financial considerations are likely to play a role in SPCs' decision-making. Paper 3 attempts to build an empirical understanding of the magnitude and nature of these non-financial considerations by looking at how employment and fiscal revenue from the coal power sector in China is affected by different decarbonisation scenarios. It demonstrates that delaying the implementation of coal phase-out policies cannot prevent significant job and tax revenue losses in the state-owned Chinese thermal coal sector, concentrated in a small number of provinces and linked to demand from a handful of large state-owned firms for whom the employment and fiscal implications may well have decision-making ramifications for the reasons already discussed in the preceding two papers.

b. Looking ahead: towards including SOEs in climate policy design and analysis

Section 5 of this dissertation proposes ways in which the work contained within the thesis papers can be refined, improved and extended. It identifies a range of promising directions for further research to take, and opportunities to integrate an emerging research agenda on the decarbonisation of SOEs into other disciplines and sub-disciplines. These include – but are not limited to – industrial economics and policy, accounting and finance, and management.

Some of the possible extensions and adaptations for the work conducted in this dissertation are more ambitious than others, and some more contingent on improved data availability than others. The remaining part of this concluding section highlights those that would be of most immediate interest for further research both in the interest of scholarly understanding and for the benefit of the policy community given the importance of the subject matter.

The first is to explore the extent to which the findings in Paper 1 are generalisable to other high-emitting sectors in which SOEs have a substantial presence. Intuitively, some degree of generalisability would be expected, since a defining characteristic of a state-owned company is *de facto* or *de jure* government control, and this feature is shared with SOEs outside the power sector. The largest SOE presence outside the power sector globally, in terms of associated emissions, is oil and gas, in which national oil companies (NOCs) play a major role in shaping exploration, extraction and marketing of oil and gas resources. Of secondary but still considerable importance are the cement and steel sectors, in which SOEs also play a role, particularly in China. This natural progression from the initial study on SPCs will be an important component of any concerted effort to understand the nature of the fundamental differences between private and state-owned firms, which of these are common across multiple sectors and which are not, and the extent to which factors other than equity ownership alone dictate the scope of state influence over SOEs' activities. While the current limitations on SOEs' financial, operational and governance-related data remain, methodological constraints will exist limiting the scope for large-N, statistical studies. To address this problem, further work can certainly be undertaken to construct usable databases on SOEs, which in turn could be used for econometric or otherwise quantitative studies assessing the impact of policy interventions and other factors on behaviour. This would be a resource-intensive effort, however, and require both linguistic expertise and a robust standardisation and normalisation process for any data gathered. There is nonetheless significant untapped scope to employ comparative case study and other complementary approaches in understanding how SOEs take decisions, and what this implies for their capacity and motivation to decarbonise. This in turn can provide initial guidance to policymakers as to the factors they should consider when designing direct, indirect or market-wide policies that affect sectors featuring SOEs.

The second is to improve the policy relevance of the modelling in Paper 3 by expanding it to cover sectors within the Chinese economy that use coal to produce steel and cement, since production assets in both sectors are largely under state ownership and use coal as a source of heat for industrial processes. Doing so would help to provide a much more complete picture of the employment and fiscal consequences of coal phaseout across all industrial uses of coal, and allow for modelling of different phase-out scenarios for each sector, given the greater difficulty of finding viable substitutes for metallurgical and coking coal (used to produce steel and cement respectively). In turn, this would provide policymakers in China, as well as those outside China with an interest in its energy transition, with a more broad-based understanding of the challenges and opportunities associated with coal phase-out.

The third, and most challenging, is to build on the research conducted in Paper 1 to move towards a formalisation of the political economy of SPC-government relationships in objective functions (and, depending on the generalisability of findings, SOE-government relationships), with a view to incorporating the results into the broader modelling community. The term 'political economy' is used loosely in this context, reflecting a key conclusion of this work – namely, that the treatment of SPCs (indeed, all firms) as pure profit-maximisers in existing climate policy models is difficult to justify. As discussed in Section 1, the leading IAMs used for modelling the economic impact of climate policies do not currently allow for firms with complex behaviours that are not simply optimisation functions (whether the variable being optimised is profit, revenue or something else).

It would be highly policy-relevant to extend the research in this thesis to posit possible decision-making functions that better approximate the spectrum of SPC/SOE behaviour than optimising for a single outcome (i.e., the paradigmatic utility-maximising function). This would be useful both on a standalone basis, in the design of individual policies (e.g. carbon taxes or zero-carbon technology subsidies), and for use within larger modelling exercises and structures, including but not limited to IAMs and dynamic stochastic general equilibrium (DSGE) models, as well as those employing complexity-based methods such as ABMs in which agents can interact directly with one another,

generating emergent behaviours at the system level that may not obviously follow from those at the agent level.

To the extent that further work in this area suggests strategic behaviour by agents within SOEs, possible functional forms for SOE decision-making given a set of options may, on the basis of the work conducted in this dissertation, include elements of (i) 'minimax' behaviour (choosing to minimise loss from the worst possible outcome); (ii) 'maximin' behaviour (choosing to maximise gains from the worst possible scenario); (iii) variants of satisficing behaviour (choosing options that pass an acceptability threshold, especially in deliberative situations or those involving multi-stage games); (iv) multi-objective optimisation (choosing to achieve the best possible combination of outcomes given trade-offs between each of them). With sufficient data on historical decision-making, it may be possible to test specific functional forms. In the shorter term, however, it would be worthwhile to include the general classes of non-optimising objective functions described here as a sensitivity analysis exercise within existing climate policy models in order to better represent the role of SOEs as economic agents in the countries and sectors where they play a significant role and better anticipate how they might respond to given policy stimuli. Such an approach would be most informative, and most powerful as a modelling approach, in models resolved to the firm- or asset-level.

This would be an initial step, but an important one, to improving the realism of the models and their capacity to capture a range of decision-making heuristics that reflect the incentives that SOEs actually face. Further steps, and ones requiring much more research into the nature of SOE-government relationships, could endogenise the process of preference formation such that governments' objective functions can be influenced by firms (state-owned and private alike) and vice versa.

The key conclusions of the work presented here also provide some insights as to how SOEs should feature in the process of climate policy design and implementation. It is clear that there is much more to accomplish in enriching our understanding of SOEs' behaviour in the context of decarbonisation and what this implies for climate policy design. The work represented in this dissertation has taken some initial steps towards this ultimate objective. The findings of the studies herein may yet be

strengthened, weakened or otherwise qualified by future work, but it is nonetheless possible to draw out some early lessons for policy design and execution.

First, when dealing with more than one type of firm (approximate profit-maximisers versus SOEs that may yet be shown to have complex and heterogeneous objective functions) there is unlikely to be a single optimal set of policies for decarbonisation, in the power sector and in others where there is a heavy state presence. Indeed, the same policy may elicit a range of responses from firms with otherwise similar cost and revenue curves if some are private and others state-owned. It may be prudent for governments in which the state holds significant assets to explicitly design policies accounting not just for efficiency, but for maximising the chances of overall success and minimising the chances of failure given the range of possible responses across private and state-owned market participants.

Second, market-based mechanisms may not achieve the expected results when some or many of the participants are state-owned. They may be more or less effective than they would be for private firms. In the latter scenario, governments should consider taking targeted action to achieve the desired policy outcome, either by directly exercising shareholder power to compel or incent an SOE to take a decision or adopt a behaviour; or exercising state power to indirectly create similar conditions.

Third, where governments hold dual roles as social planners and shareholders in SOEs, it is instructive to analyse *both* the expected financial and economic net present value of major SOE investment proposals. Where the social and financial payoffs are aligned, the decision is likely to benefit both government and the SOE; where they are opposed, the proposed action may require closer evaluation. This is likely to be the case for China's state-driven investments in domestic coal-fired power generation capacity. It may also be instructive to analyse economic returns at different administrative levels, for instance, to a province or metropolitan area, as well as at the national level.

Finally, where SOEs are formally mandated to pursue objectives other than maximising shareholder returns (i.e., profits) these objectives should be explicitly accounted for when designing policies that affect them. This might include, *inter alia*, market share, employment, revenue and revenue growth, energy security, service delivery, and contribution to fiscal revenues. Taken together, the papers

in this dissertation justify the need to explicitly consider the implications of state ownership for the economic theories upon which climate policies and analysis today is still built. While the investigation and analysis is confined to the power sector, to the extent that there are systematic similarities between SPCs and SOEs in other sectors there would be reason to expect the findings to apply, to a degree, in those sectors as well. The work in this thesis also provides theoretical and empirical support to the assertion that taking a narrow view of firms' objectives, and specifically assuming financial objectives to reign supreme in firms' decision making in response to climate policy objectives, is not only incorrect but can lead to suboptimal, or even counterproductive, climate policy design. Indeed, if SPCs may respond differently – relative to private investor-owned power companies – to the market-wide incentives and regulations that remain the near-exclusive focus of contemporary discourses in climate policy, models and analytical frameworks must be adapted accordingly.

7. References

Note: Each of the thesis papers contains its own reference list. This section lists only the references featured in this synthesis document.

- Arthur, W. B. (1995). Complexity in economic and financial markets. *Complexity*, 1(1), 20-25.
- Balint, T., Lamperti, F., Mandel, A., Napoletano, M., Roventini, A., & Sapio, A. (2017). Complexity and the Economics of Climate Change: A Survey and a Look Forward. *Ecological Economics*, 138, 252-265. doi:10.1016/j.ecolecon.2017.03.032
- Beatty, C., Fothergill, S., & Gore, A. (2019). *The State of the Coalfields 2019: Economic and social conditions in the former coalfields of England, Scotland and Wales*: Sheffield Hallam University.
- Beinhocker, E. D. (2007). *The origin of wealth : evolution, complexity, and the radical remaking of economics*. London: Random House Business.
- Bellas, A. S., & Nentl, N. J. (2007). Adoption of environmental innovations at US power plants. *Journal of Business & Industrial Marketing*, 22(5), 336-341. doi:10.1108/08858620710773468
- Belli, P., Anderson, J., Barnum, H., Dixon, J., & Tan, J.-P. (1998). *Handbook on Economic Analysis of Investment Operations*. Washington, D.C.: World Bank.
- Belloc, F. (2014). Innovation in State-Owned Enterprises: Reconsidering the Conventional Wisdom. *Journal of economic issues*, 48(3), 821-848. doi:10.2753/JEI0021-3624480311
- Belsie, L. (2019). Favoritism toward China's Former State-Owned Enterprises. *The NBER Digest*.
- Benoit, P. (2019). State owned enterprises: No climate success without them. *Journal of International Affairs*, 73(1), 135-144.
- Bernier, L. (2014). Public enterprises as policy instruments: the importance of public entrepreneurship. *Journal of economic policy reform*, 17(3), 253-266. doi:10.1080/17487870.2014.909312
- Bodnar, P., Gray, M., Grbusic, T., Herz, S., Lonsdale, A., Mardell, S., . . . Varadarajan, U. (2020). *How to Retire Early: Making Accelerated Coal Phaseout Feasible and Just*. Retrieved from Boulder, CO: <https://rmi.org/how-to-retire-early-making-accelerated-coal-phaseout-feasible-and-just/>
- Boston University Global Development Policy Center. (2022). *China's Overseas Development Finance Database*.

- Boycko, M., Shleifer, A., & Vishny, R. W. (1996). A Theory of Privatisation. *The Economic Journal*, 106(435), 309-319. doi:10.2307/2235248
- Bridle, R., Kitson, L., Duan, H., Sanchez, L., & Merrill, T. (2017). *At the Crossroads: Balancing the financial and social costs of coal transition in China*: International Institute for Sustainable Development (IISD).
- Caldecott, B. (2019). *Stranded Assets : Developments in Finance and Investment* (1st ed.): Routledge.
- Caldecott, B., Bouveret, G., Dericks, G., Kruitwagen, L., Tulloch, D., & Liao, X. (2017). *Managing the political economy frictions of closing coal in China*. Retrieved from <https://www.smithschool.ox.ac.uk/sites/default/files/2022-04/Managing-the-political-economy-frictions-of-closing-coal-in-China-SFP-Working-Paper.pdf>
- Caldecott, B., Clark, A., Koskelo, K., Mulholland, E., & Hickey, C. (2021). Stranded assets: environmental drivers, societal challenges, and supervisory responses. *Annual Review of Environment and Resources*, 46, 417-447.
- Caldecott, B., Dericks, G., Tulloch, D. J., Liao, X., Kruitwagen, L., Bouveret, G., & Mitchell, J. (2017). *Stranded assets and thermal coal in China: An analysis of environment-related risk exposure*. Retrieved from <http://www.nrdc.cn/Public/uploads/2017-11-06/5a0014d70ac24.pdf>
- Caldecott, B., Howarth, N., & McSharry, P. (2013). *Stranded Assets in Agriculture: Protecting Value from Environment-Related Risks*. Retrieved from <https://www.smithschool.ox.ac.uk/publications/reports/stranded-assets-agriculture-report-final.pdf>
- Caldecott, B., Kruitwagen, L., Dericks, G. H., Tulloch, D. J., Kok, I., & Mitchell, J. (2016). *Stranded Assets and Thermal Coal: An analysis of environment-related risk exposure*. Retrieved from <https://dx.doi.org/10.2139/ssrn.2724550>
- Caldecott, B., McCarten, M., & Triantafyllidis, C. (2018). *Carbon Lock-in Curves and Southeast Asia: Implications for the Paris Agreement*. Retrieved from <https://www.smithschool.ox.ac.uk/research/sustainable-finance/publications/Carbon-Lock-in-Curves-and-Southeast-Asia.pdf>
- Centre for Research on Energy and Clean Air, & Global Energy Monitor. (2023). *China permits two new coal power plants per week in 2022*. Retrieved from https://energyandcleanair.org/wp/wp-content/uploads/2023/02/CREA_GEM_China-permits-two-new-coal-power-plants-per-week-in-2022.pdf

- Clark, A., & Benoit, P. (2022). *Greenhouse gas emissions from state-owned enterprises: A preliminary inventory*. Retrieved from https://www.energypolicy.columbia.edu/sites/default/files/file-uploads/SOE_Emissions-CGEP_Report_020322.pdf
- Clark, A., Jindal, A., Shrimali, G., Springer, C. H., & Rafaty, R. (2023). *Capitalizing on coal: early retirement options for China-financed coal plants in Southeast Asia and beyond*. Retrieved from https://www.bu.edu/gdp/files/2023/03/GCI_WP_030_CLARK_FIN.pdf
- Coffel, E. D., & Mankin, J. S. (2021). Thermal power generation is disadvantaged in a warming world. *Environmental Research Letters*, 16(2), 024043. doi:10.1088/1748-9326/abd4a8
- Colesanti Senni, C., & von Jagow, A. (2023). *Water risks for hydroelectricity generation*. Retrieved from London: <https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2023/02/working-paper-394-colesanti-senni-von-jagow.pdf>
- Cui, R., Hultman, N., Cui, D., McJeon, H., Yu, S., Edwards, M., . . . Zhu, M. (2021). A plant-by-plant strategy for high-ambition coal power phaseout in China. *Nature communications*, 12(1), 1-10. doi:10.1038/s41467-021-21786-0
- Cui, R., Hultman, N., Jiang, K., McJeon, H., Yu, S., Cui, D., . . . Zhang, W. (2020). *A High Ambition Coal Phaseout in China: Feasible Strategies through a Comprehensive Plant-by-Plant Assessment*. Retrieved from https://publicpolicy.umd.edu/sites/default/files/2020-01/1.13.2020_AHighAmbitionCoalPhaseoutInChina_EN_fullreport%20.pdf
- Cullenward, D., & Victor, D. G. (2020). *Making climate policy work*. Cambridge: Polity Press.
- Curtin, J., McNerney, C., Gallachóir, B. Ó., Hickey, C., Deane, P., & Deeney, P. (2019). Quantifying stranding risk for fossil fuel assets and implications for renewable energy investment: A review of the literature. *Renewable and Sustainable Energy Reviews*, 116, 109402.
- del Rio-Chanona, R. M., Mealy, P., Pichler, A., Lafond, F., & Farmer, D. (2020). Supply and demand shocks in the COVID-19 pandemic: An industry and occupation perspective. *Oxford Review of Economic Policy*. doi:10.1093/oxrep/graa033
- Denjean, B., Su, T., Attwood, C., Bridle, R., Duan, H., & Gerasimchuk, I. (2016). *Subsidies to coal power generation in China*: International Institute for Sustainable Development.
- Dibley, A. (2021). Engaging Asia's State-Owned Enterprises in the Climate Challenge. *Asia Society*. <https://asiasociety.org/australia/engaging-asias-state-owned-enterprises-climate-challenge>

- Diluiso, F., Walk, P., Manych, N., Cerutti, N., Chipiga, V., Workman, A., . . . Minx, J. C. (2021). Coal transitions—part 1: a systematic map and review of case study learnings from regional, national, and local coal phase-out experiences. *Environ. Res. Lett.*, *16*(11), 113003. doi:10.1088/1748-9326/ac1b58
- Electricité de France SA. (2022). 2022 Half-Year Results [Press release]. Retrieved from https://www.edf.fr/sites/groupe/files/epresspack/3495/PR_EDF-financial-Results_H1-2022.pdf
- Energy & Climate Intelligence Unit, Data Driven Envirolab, New Climate Institute, & Oxford Net Zero. (2023). Net Zero Tracker. Retrieved from <https://zerotracker.net/>
- Energy Research Institute, & China National Renewable Energy Centre. (2019). *China Renewable Energy Outlook 2019*. Retrieved from <https://www.thinkchina.ku.dk/documents/CREO-2019-EN-Final-0316.pdf>
- Europe Beyond Coal. (2020). *Just Transition in the Context of the European Power Utilities and Financial Institutions*. Retrieved from https://beyondfossilfuels.org/wp-content/uploads/2020/08/Just_Transition_European_Power_Utilities_and_Finance_Institutions-Europe-Beyond-Coal-Nov-2019.pdf
- Farmer, J. D., Hepburn, C., Ives, M. C., Hale, T., Wetzler, T., Mealy, P., . . . Way, R. (2019). Sensitive Intervention Points in the Low-Carbon Transition. *Science*, *364*(6436), 132-134. doi:10.1126/science.aaw7287
- Farmer, J. D., Hepburn, C., Mealy, P., & Teytelboym, A. (2015). A Third Wave in the Economics of Climate Change. *The Official Journal of the European Association of Environmental and Resource Economists*, *62*(2), 329-357. doi:10.1007/s10640-015-9965-2
- Fei, T. (2014). *The True Cost of Coal*. Retrieved from <http://coalcap.nrdc.cn/pdfviewer/web/?15083101061229121311.pdf>
- Feng, E. (2017). China faces glut of 'stranded coal assets' after green energy switch. In (pp. 2). London (UK).
- Florio, M., & Fecher, F. (2011). The Future of Public Enterprises - Contributions to a New Discourse. *Annals of Public and Cooperative Economics*, *82*(4), 361-373. doi:10.1111/j.1467-8292.2011.00445.x

- Fungáčová, Z., Klein, P. O., & Weill, L. (2020). Persistent and transient inefficiency: Explaining the low efficiency of Chinese big banks. *China Economic Review*, 59. doi:10.1016/j.chieco.2019.101368
- Gelpern, A., Horn, S., Morris, S., Parks, B., & Trebesch, C. (2021). How China Lends: A Rare Look Into 100 Debt Contracts With Foreign Governments. In: AidData, Kiel Institute for the World Economy, Center for Global Development.
- Gençsü, I., & Chen, H. (2019). *G20 coal subsidies: tracking government support to a fading industry - China Background Paper*. Retrieved from <https://www.odi.org/publications/11362-g20-coal-subsidies-china>
- Global Energy Monitor. (2020). Global Coal Plant Tracker. Retrieved from <https://endcoal.org/tracker/>
- Global Energy Monitor, & CREA. (2020). *A New Coal Boom in China: Country Accelerates New Coal Plant Permitting and Proposals*. Retrieved from <https://globalenergymonitor.org/wp-content/uploads/2021/01/China-coal-plant-brief-June-2020Eng.pdf>
- Global SWF. (2023). Ranking. Retrieved from <https://globalswf.com/ranking>
- Gosens, J., Turnbull, A. B. H., & Jotzo, F. (2022). China's decarbonization and energy security plans will reduce seaborne coal imports: Results from an installation-level model. *Joule*, 6(4), 782-815. doi:10.1016/j.joule.2022.03.008
- Gray, M., & Sundaresan, S. (2020a). *How to waste over half a trillion dollars: The economic implications of deflationary renewable energy for coal power investments*. Retrieved from <https://carbontracker.org/reports/how-to-waste-over-half-a-trillion-dollars/>
- Gray, M., & Sundaresan, S. (2020b). *Political decisions, economic realities: The underlying operating cashflows of coal power during COVID-19*. Retrieved from <https://carbontracker.org/reports/political-decisions-economic-realities/>
- Handayani, K., Filatova, T., & Krozer, Y. (2019). The Vulnerability of the Power Sector to Climate Variability and Change: Evidence from Indonesia. *Energies*, 12(19). doi:10.3390/en12193640
- Hans, F., Kuramochi, T., Black, R., Hale, T., & Lang, J. (2022). *Net Zero Stocktake 2022*. Retrieved from <https://ca1-nzt.edcdn.com/@storage/Net-Zero-Stocktake-Report-2022.pdf?v=1655074300>
- Hart, O., Shleifer, A., & Vishny, R. W. (1997). The proper scope of government: theory and an application to prisons. *The Quarterly Journal of Economics*, 112(4), 1127-1161.

- He, G., Lin, J., Sifuentes, F., Liu, X., Abhyankar, N., & Phadke, A. (2020). Rapid cost decrease of renewables and storage accelerates the decarbonization of China's power system. *Nature communications*, *11*(1), 1-9.
- He, G., Lin, J., Zhang, Y., Zhang, W., Larangeira, G., Zhang, C., . . . Yang, F. (2020). Enabling a rapid and just transition away from coal in China. *One Earth*, *3*(2), 187-194.
- Henry, M. S., Bazilian, M. D., & Markuson, C. (2020). Just transitions: Histories and futures in a post-COVID world. *Energy Research & Social Science*, *68*. doi:10.1016/j.erss.2020.101668
- Hertog, S. (2010). Defying the Resource Curse: Explaining Successful State-Owned Enterprises in Rentier States. *World Pol.*, *62*(2), 261-301. doi:10.1017/S0043887110000055
- Hervé-Mignucci, M., & Wang, X. (2015). *Slowing the growth of coal power outside China: The role of Chinese finance*. Retrieved from <https://www.climatepolicyinitiative.org/wp-content/uploads/2015/11/Slowing-the-Growth-of-Coal-Power-Outside-China.pdf>
- Herve-Mignucci, M., Wang, X., Nelson, D., & Varadarajan, U. (2015). *Slowing the Growth of Coal Power in China: The Role of Finance in State-Owned Enterprises*. Retrieved from <https://climatepolicyinitiative.org/wp-content/uploads/2015/12/Slowing-the-Growth-of-Coal-Power-in-China-%E2%80%93-the-Role-of-Finance-in-State-Owned-Enterprises.pdf>
- Holmstrom, B., & Milgrom, P. (1991). Multitask Principal-Agent Analyses: Incentive Contracts, Asset Ownership, and Job Design. *Journal of Law, Economics, & Organization*, *7*, 24-52.
- Hsu, P.-H., & Liang, H. (2017). Leviathan Inc. and Corporate Environmental Engagement. *SSRN Electronic Journal*. doi:10.2139/ssrn.2960832
- Inoue, C., Lazzarini, S., & Musacchio, A. (2013). Leviathan as a Minority Shareholder: Firm-level Implications of State Equity Purchases. *Academy of Management Journal*, *56*(6), 1775. doi:10.5465/amj.2012.0406
- International Development Finance Club. (2023). Mission & Vision. Retrieved from <https://www.idfc.org/mission-vision/>
- International Energy Agency. (2020a). *Coal Information 2020: Overview*. Retrieved from Paris: https://iea.blob.core.windows.net/assets/a5f208e9-f66b-4d31-b5af-87d581b70c18/Coal_Information_Overview_2020_edition.pdf

- International Energy Agency. (2020b). *Special Report on Clean Energy Innovation: Accelerating technology progress for a sustainable future*. Retrieved from Paris, France: <https://www.iea.org/reports/clean-energy-innovation>
- International Energy Agency. (2020c). *World Energy Outlook 2020*. Retrieved from Paris: <https://www.iea.org/reports/world-energy-outlook-2020>
- International Energy Agency. (2021). *Net Zero by 2050: A Roadmap for the Global Energy Sector*. Retrieved from Paris: <https://www.iea.org/reports/net-zero-by-2050>
- International Energy Agency. (2022). *Change in employment in China by scenario, 2019-2030*. Retrieved from Paris: <https://www.iea.org/data-and-statistics/charts/change-in-employment-in-china-by-scenario-2019-2030>
- International Energy Agency, & OECD. (2017). *World Energy Investment 2018*. Retrieved from Paris, France: <https://www.iea.org/reports/world-energy-investment-2018>
- International Labor Office. (2014). A just transition for all: Can the past inform the future? *International journal of labour research*, 6(2), 173.
- International Monetary Fund. (2020). State-owned Enterprises: The Other Government. In International Monetary Fund (Ed.), *Fiscal Monitor: Policies to Support People During the COVID-19 Pandemic*. Washington, D.C.
- Ives, M., Righetti, L., Schiele, J., De Meyer, K., Hubble-Rose, L., Teng, F., . . . Way, R. (2021). *A new perspective on decarbonising the global energy system*. Retrieved from <https://www.inet.ox.ac.uk/images/SSEE-New-perspective-report-summary.pdf>
- Jakob, M., & Steckel, J. (2022). *The Political Economy of Coal: Obstacles to Clean Energy Transitions* (M. Jakob & J. Steckel Eds. 1 ed. Vol. 1): Routledge.
- Kramer, K. (2022). *Making the Leap: The need for Just Energy Transition Partnerships to support leapfrogging fossil gas to a clean renewable energy future*. Retrieved from Winnipeg: <https://www.iisd.org/system/files/2022-11/just-energy-transition-partnerships.pdf>
- Leutert, W. (2016). Challenges ahead in China's reform of state-owned enterprises. *Asia policy*(21), 83-100.
- Lin, K. J., Lu, X., Zhang, J., & Zheng, Y. (2020). State-owned enterprises in China: A review of 40 years of research and practice. *China journal of accounting research*, 13(1), 31-55. doi:10.1016/j.cjar.2019.12.001

- Lu, Y., Cohen, F., Smith, S. M., & Pfeiffer, A. (2022). Plant conversions and abatement technologies cannot prevent stranding of power plant assets in 2 °C scenarios. *Nature communications*, 13(1), 806. doi:10.1038/s41467-022-28458-7
- Mattauch, L., & Hepburn, C. (2016). Climate Policy When Preferences Are Endogenous-and Sometimes They Are. *Ethics And Global Climate Change*, 40, 76-95.
- Mayer, B., & Rajavuori, M. (2017). State Ownership and Climate Change Mitigation: Overcoming the Carbon Curse? *Carbon & Climate Law Review : CCLR*, 11(3), 223-233. doi:10.21552/cclr/2017/3/15
- Mayer, B., Rajavuori, M., & Fang, M. M. (2017). The Contribution of State-Owned Enterprises to Climate Change Mitigation in China. *Climate Law*, 7(2-3), 97-124. doi:10.1163/18786561-00702002
- Mazzucato, M. (2018). *The entrepreneurial state: debunking public vs private sector myths*. London: Penguin Books.
- Mazzucato, M., & Semieniuk, G. (2017). Public financing of innovation: new questions. *Oxford Review of Economic Policy*, 33(1), 24-48. doi:10.1093/oxrep/grw036
- McGlade, C., & Ekins, P. (2015). The geographical distribution of fossil fuels unused when limiting global warming to 2 ° C. *Nature*, 517(7533), 187. doi:10.1038/nature14016
- Mealy, P. (2018). Know what? New lenses on productive knowledge shed light on long run development, structural change, job switching and the transition to the green economy. In J. D. Farmer & C. Hepburn (Eds.).
- Meggison, W. L., & Netter, J. M. (2001). From State to Market: A Survey of Empirical Studies on Privatization. *Journal of Economic Literature*, 39(2), 321-389. doi:10.1257/jel.39.2.321
- Meier, P. (2017a). *Power Sector Investment Projects: Guidelines for Economic Analysis*. World Bank.
- Meier, P. (2017b). *Power Sector Investment Projects: Guidelines for Economic Analysis: Technical Notes*. World Bank.
- Meng, J., Way, R., Verdolini, E., & Anadon, L. D. (2021). Comparing expert elicitation and model-based probabilistic technology cost forecasts for the energy transition. *Proceedings of the National Academy of Sciences - PNAS*, 118(27), 1. doi:10.1073/pnas.1917165118

- Mercure, J.-F., Pollitt, H., Viñuales, J. E., Edwards, N. R., Holden, P. B., Chewpreecha, U., . . . Knobloch, F. (2018). Macroeconomic impact of stranded fossil fuel assets. *Nature Climate Change*, 8(7), 588-593. doi:10.1038/s41558-018-0182-1
- Milhaupt, C. J. (2020). The state as owner—China's experience. *Oxford Review of Economic Policy*, 36(2), pp362-379. doi:10.1093/oxrep/graa001
- Milhaupt, C. J., & Pargendler, M. (2019). Related-Party Transactions in State-Owned Enterprises: Tunneling, Propping, and Policy Channeling. In L. Enriques & T. H. Troeger (Eds.), *The Law and Finance of Related Party Transactions*. New York: Cambridge University Press.
- Milhaupt, C. J., & Zheng, W. (2015). Beyond ownership: state capitalism and the Chinese firm. *Georgetown Law Journal*, 103(3), 665-722.
- Millward, R. (2011). Public Enterprise in the Modern Western World: An Historical Analysis. *Annals of Public and Cooperative Economics*, 82(4), 375-398. doi:10.1111/j.1467-8292.2011.00447.x
- Musacchio, A., & Lazzarini, S. G. (2014). *Reinventing state capitalism: Leviathan in business, Brazil and beyond*. Cambridge, Massachusetts: Harvard University Press.
- Musacchio, A., Lazzarini, S. G., & Aguilera, R. V. (2015). New Varieties of State Capitalism: Strategic and Governance Implications. *Academy of Management Perspectives*, 29(1), 115-131. doi:10.5465/amp.2013.0094
- OECD. (2022). *Climate change and low-carbon transition policies in state-owned enterprises*. Paris: OECD.
- Peñasco, C., Anadón, L. D., & Verdolini, E. (2021). Systematic review of the outcomes and trade-offs of ten types of decarbonization policy instruments. *Nature Climate Change*, 1-9.
- Peng, W., Iyer, G., Bosetti, V., Chaturvedi, V., Edmonds, J., Fawcett, A., . . . Weyant, J. (2021). Climate policy models need to get real about people — here's how. *Nature*, 594, 174-176. doi:10.1038/d41586-021-01500-2
- Petrakopoulou, F., Robinson, A., & Olmeda-Delgado, M. (2020). Impact of climate change on fossil fuel power-plant efficiency and water use. *Journal of Cleaner Production*, 273, 122816. doi:<https://doi.org/10.1016/j.jclepro.2020.122816>
- Pfeiffer, A. (2018). *The Decarbonization Identity and Pathways to Net-Zero: The scale and impact of committed cumulative carbon emissions and stranded assets in the electricity generation sector*

- on the decarbonisation of the economy*. (Doctor of Philosophy in Geography and the Environment), University of Oxford, Oxford.
- Pfeiffer, A., Hepburn, C., Vogt-Schilb, A., & Caldecott, B. (2018). Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement. *Environmental Research Letters*, 13. doi:10.1088/1748-9326/aabc5f
- Pfeiffer, A., Millar, R., Hepburn, C., & Beinhocker, E. (2016). The '2°C capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy. *Applied Energy*, 179(C), 1395-1408. doi:10.1016/j.apenergy.2016.02.093
- Prag, A., Röttgers, D., & Scherrer, I. (2018). State-Owned Enterprises and the Low-Carbon Transition. *IDEAS Working Paper Series from RePEc*.
- Reuters. (2023). Paris court to rule on minority shareholders' challenge to EDF buyout process by May 2 at the latest. *Reuters*. <https://www.reuters.com/article/edf-nationalisation-court-idUSP6N34B01E>
- Sartor, O. (2018). Implementing coal transitions: Insights from case studies of major coal-consuming economies. *IDDRI and Climate Strategies*.
- Shearer, C., & Myllyvirta, L. (2021). *China Dominates 2020 Coal Plant Development*. Retrieved from <https://globalenergymonitor.org/wp-content/uploads/2021/02/China-Dominates-2020-Coal-Development.pdf>
- Shleifer, A. (1998). *State Versus Private Ownership*. Cambridge, Mass: National Bureau of Economic Research.
- Shleifer, A., & Vishny, R. W. (1998). *The grabbing hand: government pathologies and their cures*. Cambridge, Mass. ; London: Harvard University Press.
- Spencer, T., Berghmans, N., & Sartor, O. (2017). *Coal Transitions in China's power sector: A plant-level assessment of stranded assets and retirement pathways*. Retrieved from Paris, France: https://www.iddri.org/sites/default/files/import/publications/st1217_china-coal.pdf
- Squire, L., & Van der Tak, H. G. (1975). *Economic analysis of projects*: World Bank Publications.
- Steffen, B., Karplus, V. J., & Schmidt, T. S. (2020). State ownership and technology adoption: The case of electric utilities and renewable energy. In: MIT Center for Energy and Environmental Policy Research.

- Sterlacchini, A. (2012). Energy R&D in private and state-owned utilities: An analysis of the major world electric companies. *Energy R&D in private and state-owned utilities: An analysis of the major world electric companies*, 41, 494-506.
- Su, K., Wan, R., & Song, V. Y. (2018). Pyramidal structure, risk-taking and firm value. *Economics of Transition and Institutional Change*, 26(3), 401-427. doi:<https://doi.org/10.1111/ecot.12156>
- Tienhaara, K., & Cotula, L. (2017). *Raising the cost of climate action? Investor-state dispute settlement and compensation for stranded fossil fuel assets*. Retrieved from <https://pubs.iied.org/sites/default/files/pdfs/migrate/17660IIED.pdf>
- Tirole, J. (1994). The Internal Organization of Government. *Oxford economic papers*, 46(1), 1-29. doi:10.1093/oxfordjournals.oep.a042114
- Tõnurist, P. (2015). Framework for analysing the role of state owned enterprises in innovation policy management: The case of energy technologies and Eesti Energia. *Technovation*, 38, 1-14. doi:10.1016/j.technovation.2014.08.001
- Tõnurist, P., & Karo, E. (2016). State owned enterprises as instruments of innovation policy. *Annals of Public and Cooperative Economics*, 87(4), 623-648. doi:10.1111/apce.12126
- UNFCCC. (2015). *Adoption of the Paris Agreement* (FCCC/CP/2015/L.9/Rev.1). Retrieved from Paris: <https://unfccc.int/resource/docs/2015/cop21/eng/109r01.pdf>
- Way, R., Ives, M. C., Mealy, P., & Farmer, J. D. (2022). Empirically grounded technology forecasts and the energy transition. *Joule*, 6(9), 2057-2082. doi:<https://doi.org/10.1016/j.joule.2022.08.009>
- Webber, M. (2012). The Political Economy of the Three Gorges Project. *Geographical Research*, 50(2), 154-165. doi:10.1111/j.1745-5871.2011.00725.x
- Wettenhall, R. (1985). Acworth, attlee and now: One hundred years of debate about public enterprise—government relations. *Political Science*, 37(2), 125-139.
- Whincop, M. J. (2016). *Corporate governance in government corporations*. London, [England] ; New York, [New York: Routledge.
- World Bank. (2017). *Shadow price of carbon in economic analysis: Guidance note*. Retrieved from <https://thedocs.worldbank.org/en/doc/911381516303509498-0020022018/original/2017ShadowPriceofCarbonGuidanceNoteFINALCLEARED.pdf>

- Yuan, J., Guo, X., Zhang, W., Zhou, J., & Qin, C. (2019). Stranded Coal Power Assets in China: A Case Study of Jilin Province. *Emerging Markets Finance and Trade*, 55(12), 2673-2688. doi:10.1080/1540496X.2018.1541134
- Zhu, M., Qi, Y., Belis, D., Lu, J., & Kerremans, B. (2019). The China wind paradox: The role of state-owned enterprises in wind power investment versus wind curtailment. *Energy Policy*, 127, 200-212. doi:10.1016/j.enpol.2018.10.059

A1. Paper 1: State-owned power companies and decarbonisation

The subsequent pages contain an offprint of the article published in the Journal of Cleaner Production.

The full citation is:

Benoit, P., Clark, A., Schwarz, M., & Dibley, A. (2022). Decarbonization in state-owned power companies: Lessons from a comparative analysis. *Journal of Cleaner Production*, 355, 131796. doi: <https://doi.org/10.1016/j.jclepro.2022.131796>.

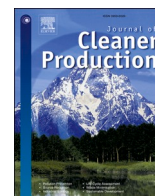
The article length is 13 pages.

The length of the Supplemental Data appendix is 25 pages.

The authors' contributions to the paper were as follows:

- **Philippe Benoit:** conceptualisation, methodology, draft manuscript preparation, review and editing, supervision, funding acquisition.
- **Alex Clark:** conceptualisation, methodology, literature review, data collection, analysis and interpretation, draft manuscript preparation, review and editing, visualisation
- **Moritz Schwarz:** conceptualisation, methodology, data collection, analysis and interpretation, draft manuscript preparation, review and editing.
- **Arjuna Dibley:** conceptualisation, methodology, literature review, draft manuscript preparation, review and editing.

All authors reviewed the results and approved the final version of the manuscript.



Decarbonization in state-owned power companies: Lessons from a comparative analysis

Philippe Benoit^a, Alex Clark^{b,c,*}, Moritz Schwarz^{b,c,d}, Arjuna Dibley^{b,e}

^a Center on Global Energy Policy, Columbia University, 420 West 118th Street, New York, NY, 10027, United States

^b Smith School of Enterprise and the Environment, University of Oxford, South Parks Road, Oxford, OX1 3QY, United Kingdom

^c Institute for New Economic Thinking at the Oxford Martin School, Manor Road Building, Manor Road Oxford, OX1 3UQ, United Kingdom

^d Climate Econometrics, Nuffield College, New Road, Oxford, OX1 1NF, United Kingdom

^e Stanford Law School, 450 Serra Mall, Palo Alto, CA, United States

ARTICLE INFO

Handling Editor: Zhifu Mi

Keywords:

State-owned enterprises
Carbon neutrality
Decarbonization
Climate policy
Electricity sector

ABSTRACT

A rapid decarbonization of the electricity system is urgently required for the Paris Agreement objectives to stand a reasonable chance of being met. While state-owned power companies (SPCs) are the dominant firm type in the global electricity sector, representing nearly two thirds of global electric power generation capacity, most climate policy literature focuses on private sector companies when analyzing decarbonization interventions. SPCs' distinct corporate governance structures, objectives, relationships with government, and sources of finance, however, can be markedly different from those of private companies. Here, we develop a framework for analyzing the extent to which common and divergent features of SPCs, and the markets in which they operate, affect their relationship to government interventions on decarbonization. We also consider the implications of these relationships for the effective implementation of sector-wide decarbonization strategies. We then apply this framework using a comparative case study analysis of six major SPCs, and highlight how differences in their agency, motivation, capacity, and market exposure may result in different potential responsiveness to government regulatory, policy and market interventions on decarbonization. We generalize these findings by developing four SPC archetypes and illustrate how they might respond differently to government interventions targeting decarbonization. Our analysis posits that SPCs can, under the guidance of governments pursuing ambitious climate policy, be more effective vehicles for decarbonization relative to private sector companies, particularly when they operate with a high degree of operational independence, are insulated from competitive pressures, and have the financial and technical capacity to invest in the decarbonization of their asset base. Similarly, market-wide policy interventions, such as carbon pricing mechanisms, could in practice be less effective interventions with respect to SPCs than their private counterparts when the SPC is ill-equipped to translate these incentives into decarbonization action because it is mandated to pursue supplementary objectives other than profit maximization alone. Ultimately, governments will need to step up their climate action to achieve carbon neutrality. SPCs can, and where they are major market players, must be key actors in driving decarbonization when the appropriate interventions are utilized and therefore deserve significantly more attention in the climate policy debate.

1. Introduction

1.1. The power sector and the Paris Agreement

Power generation makes the largest sectoral contribution to greenhouse gas emissions. Electricity and heat generation produced nearly 15.2 billion tons of carbon dioxide-equivalent (GtCO₂e) in 2017, 32.5%

of the global total (ClimateWatch, 2020). Growing numbers of national governments have either announced or legislated for economy-wide 'net zero emissions', including China (peaking before 2030, neutrality by 2060), Japan, the United States, South Africa, Brazil, Canada, South Korea, New Zealand, Chile, and the European Union (all 2050) (Energy & Climate Intelligence Unit, 2021). The International Energy Agency (2021) cautions that economy-wide decarbonization by 2050 will, on aggregate, require advanced economies to decarbonize electricity by

* Corresponding author. Smith School of Enterprise and the Environment, University of Oxford, South Parks Road, Oxford OX1 3QY, United Kingdom.

E-mail address: alex.clark@smithschool.ox.ac.uk (A. Clark).

<https://doi.org/10.1016/j.jclepro.2022.131796>

Received 30 June 2021; Received in revised form 21 January 2022; Accepted 13 April 2022

Available online 17 April 2022

0959-6526/© 2022 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Abbreviations

SPC	state-owned power company
SOE	state-owned enterprise
IPP	independent power producer
CEO	chief executive officer
ETS	emissions trading system
HHI	Herfindahl-Hirschman Index
CFE	Comisión Federal de Electricidad
KEPCO	Korea Electric Power Corporation
NTPC	NTPC Limited
PLN	Perusahaan Listrik Negara
SPIC	State Power Investment Corporation
PEMEX	Petróleos Mexicanos
R&D	research and development
T&D	transmission and distribution
1 GtCO _{2e}	one Gigatonne of carbon dioxide-equivalent
1 GW	one Gigawatt
1 TWh	one Terawatt-hour

2035, and emerging and developing economies, by 2040. This implies that fossil-fueled generation capacity built today should either find viable ways of capturing and storing its emissions or be retired within twenty years.

Recent scholarship suggests that accelerating the power sector transition through the 2020s is increasingly a cost-effective option for governments to follow independent of climate considerations (He et al., 2020; Ives et al., 2021; Way et al., 2019, 2020). Decarbonization of power is a requirement for carbon-free electrification of other high-emitting sectors, including transport and heavy industry.

The strategic direction and investment decisions of power companies with large existing fossil fuel asset bases are major drivers of power sector emissions. In high-income economies, these companies are mostly private sector investor-owned, publicly-traded utilities. They operate in largely liberalized electricity markets under regulated-return models (typically in natural monopoly contexts) or competing with other firms, subject to legal fiduciary duties towards their investors. Their responses to climate policies correspond in principle to their effect on short- and long-term profitability.

However, state-owned power companies (SPCs) are significant actors in the global electricity sector. Although global data does not exist on all SPCs, available evidence suggests that state-owned companies are the dominant firm type for the largest power generators globally, accounting for 61% of installed capacity in 2016, and 52% of capacity planned and under construction (Prag et al., 2018). While state ownership varies among different countries, SPCs still feature prominently even in countries with highly privatized electricity markets like the United States, where there are thousands of municipal, state, and federal government owned utilities (Dibley, 2021), as well as in Canada, Sweden, Japan, Italy, and France (Prag et al., 2018). This makes SPCs crucial actors in implementing national strategies for reaching carbon neutrality by mid-century. The implications of states' significant direct stakes in electricity markets for the achievement of power sector decarbonization goals has been seriously understudied. Accounting for this government presence can help better identify how SPCs might respond to climate policy tools differently to their private sector counterparts, and what tools may be available to governments in directing the incentives and behaviors of these firms.

1.2. The role of state-owned power companies

Governments are no ordinary shareholders: they also make policy and set regulatory boundaries, meaning their influence on SPCs extends

beyond equity ownership alone. As scholars of state-owned enterprise (SOE) corporate governance have noted, governments also determine the distribution of resources among SOEs and public agencies and frequently provide them with favorable financial arrangements (Milhaupt and Pargendler, 2019). Other work explores how the legal structure regulating government-firm relationships, and the market power of the firm, affects the degree of state influence over an SOE, both within and outside formal corporate governance structures (Belloc, 2014; Dibley, 2021; Su et al., 2018).

As Cullenward and Victor (2020) show, climate policy discourse tends to focus on market-based interventions (most frequently carbon pricing and regulatory standards) as potential motivators for action by firms, largely omitting consideration of mechanisms for direct state intervention. They suggest this reflects a dominant notion of the state's role being limited to setting frameworks and rules for competition among private actors, without intervening directly in firm behavior. The effects of market-based measures may, however, play out differently in markets featuring SOEs for whom financial returns can compete with other objectives.

Electricity sector decarbonization scholarship also does not generally distinguish between the behavioral characteristics and responses of private and state-owned firms, even as the broader literature on SOEs suggests they are sufficiently different from the private investor-owned archetype to merit standalone analytical treatment (Megginson and Netter, 2001; Shleifer, 1998). Such broader literature on SOEs has argued that private firms are superior in terms of productivity and with respect to the adoption of new technologies, which comprise a prerequisite for long-term productivity growth (Hart et al., 1997; Shleifer, 1998). SOEs are burdened by complex and sometimes conflicting policy goals, which, unlikely private firms, distract them and reduce their capacity to make innovative investments (Tirole, 1994). An emerging literature has started to critique the effect on innovation outcomes between this private-investor-owned firm archetype and state-owned firms (Belloc, 2014; Dibley, 2021; Steffen et al., 2020). However, the extent to which this existing literature has considered SPCs tends to be limited. It considers only a limited set of SPC characteristics, such as firm size and government equity ownership share (Bellás and Nentl, 2007; Steffen et al., 2020), or is confined to individual case studies (Tönurist, 2015).

This narrow focus matters in the electricity sector because governments in many of the world's large and emerging economies rely heavily on SPCs to deliver electricity sector decarbonization. Prag et al. (2018) estimate that SPCs controlled 62% of electricity generation capacity globally in 2016. Governments owned 60% of fossil fuel capacity, and 64% of low-carbon capacity, which includes hydro and nuclear. They also accounted for 52% of planned coal power, and 56% of planned low-carbon capacity. SPCs' role in deploying non-hydro renewables grew from 9% of capacity additions in 2000 (0.63 GW), to 23% in 2014 (34 GW).

State-owned firms exhibit wide-ranging heterogeneity. Some differences relate to corporate structure: SPCs can be vertically integrated utilities, nationally important diversified generators, or specialist firms with dominance over specific subsectors, technologies, or subnational jurisdictions. Other differences are more subtle, relating to SPCs' embeddedness in political and historical circumstances, as well as legal, institutional, and financial frameworks defining electricity sector activity. SPCs also differ in their corporate governance structures, formal and informal mandates, and the nature of political and financial relationships with government and other public institutions.

In this paper we offer an initial framework, based on existing literature and case studies (all data as of June 2021), for assessing how the unique features of SPCs can be better engaged by national governments seeking to decarbonize electricity. SPCs' central contribution to power sector emissions suggests that accounting for their presence when designing policies for decarbonization may make a substantial difference to actual national emissions pathways.

Section 2 sets out the methodological approach, briefly reviews the

relevant literature, and introduces our case study analysis. Section 3 presents a four-factor framework for analyzing SPCs in the context of decarbonization, and a typology of policy interventions applicable to SPCs. Section 4 applies the four-factor framework to six SPC case studies in as many countries. Section 5 discusses insights from the case study analysis and formulates four SPC archetypes, which we consider representative of key sources of variance in the cases examined along the four key factors. It then considers the relevance of these findings to sector-wide outcomes and the rationale for government ownership over time. Section 6 concludes.

2. Methodology and background

2.1. Summary of approach

This paper develops a framework for assessing potential SPC responses to different government interventions. The framework development is supported by a meso-level comparative case study of SPCs in China, India, Indonesia, South Africa, Mexico, and South Korea seeking to identify how common and divergent features of SPCs and the markets in which they operate might affect their relationship to government decarbonization policy. We theorize how SPCs might respond both to market-based climate policies and to the expanded suite of interventions at governments' disposal when leveraging SPCs to achieve national climate objectives. In assessing the effectiveness of these interventions, we look to the characteristics of each SPC. The analysis proceeds in five stages (see Table 1).

First, we draw on existing academic scholarship and gray literature on SPCs and policy levers, alongside initial scoping analysis of our case studies, to develop a set of four proposed 'access factors' dictating the degree of responsiveness of an SPC to a given intervention in the decarbonization context, hence also the ability of government to prompt low-carbon action through SPCs. These are *agency* (the SPC's operational autonomy and independence); *profit motivation* (pursuit of financial versus social and other non-financial objectives); *capacity* (access to resources and technical expertise, and ability to leverage them in pursuit of decarbonization); and *exposure to market competition*.

Table 1
Overview of methodological approach.

Step	Theme	Task	Details	Section
1	Framework Development	Determine Access factors influencing SPC responsiveness to decarbonization interventions	Agency Profit motivation Capacity Exposure to market competition	3
2		Policy toolbox for SPC decarbonization	Targeted (direct) Targeted (indirect) Market-wide	3
3		Associating intervention clusters with access factors		3
4	Application	Application to case studies	CFE (Mexico) Eskom (South Africa) KEPCO (Korea) NTPC (India) PLN (Indonesia) SPIC (China)	4
5	Discussion	Generate SPC archetypes and associate with intervention clusters	Competitive Contributor Grinding Behemoth Statist Caterer Depleted Provider	5

Second, we draw on the literature to assess ways in which governments may attempt to influence SPCs and assemble a non-exhaustive 'policy toolbox' of potential interventions. We cluster interventions into three types: *targeted* interventions focused specifically on the SPC, both (a) *direct* and (b) *indirect*; and (c) *market-wide, non-targeted* interventions applying to all firms. Direct interventions attempt to alter SPC behavior through the exercise of various forms of shareholder power. Indirect interventions constitute mobilizing and making available to the SPC additional resources external to its corporate structure to support decarbonization action. Market-wide interventions deploy systematic measures to which all market participants, including the SPC, are subject to.

Third, we analyze how SPC access factors and intervention clusters may interact while considering how to maximize the likelihood of success in generating favorable mitigation outcomes.

Fourth, using an interpretative case selection approach, we apply the intervention clusters to case studies of prominent SPCs in six different countries, considering how each might respond to different intervention types given their specific circumstances.

Finally, we propose a generalized set of four SPC 'archetypes', representing the spectrum of observed characteristics in the case studies. We use these to illustrate the potential effectiveness of different types of policy intervention for each archetype in achieving the ultimate 'end game' of sector-wide net zero emissions.

We are conscious that our conclusions remain empirically untested and we consider this study a guide for further investigation and testing rather than presenting a validated theory of SPC behavior and decarbonization policy. In the remainder of this section, we present background evidence on SPC-government relationships and explain our case selection strategy.

2.2. Review of mechanisms for government influence on SPCs

Late 20th century neoclassical scholarship broadly associates state ownership with chronic, structural inefficiencies generated by the distortion of market incentives by political or otherwise non-financial goals, and tendencies towards clientelism and corruption (Holmstrom and Milgrom, 1991; Shleifer, 1998; Shleifer and Vishny, 1998). More recent scholarship challenges this narrative: Chandra (2018) finds the large SOE *Coal India* to be highly adaptive to changing financial, political, and economic circumstances and capable of undergoing significant endogenous change to remain competitive as market conditions evolve. Haney and Pollitt (2013) suggest that governments looking to balance efficient market operation with the ability to pursue public policy goals (including decarbonization) can successfully combine some form of direct state ownership with meaningful private sector participation and key elements of competition.

Empirical studies associate SPCs with greater R&D spending on clean energy, facilitated by access to state capital resources on preferential terms (Mazzucato and Semieniuk, 2017, 2018; Sterlacchini, 2012). Steffen et al. (2020) present evidence showing state-owned utilities in the European Union are more likely than private firms to invest in renewables, conditional on policy incentives and enforcement capacity. Prag et al. (2018) show that SPCs with greater levels of state ownership tend to adopt renewable technologies more quickly than private firms. Beyond the electricity sector, International Energy Agency (2016) research suggests that carbon pricing measures were influential in Norwegian national oil company *Equinor*'s decision to invest heavily in carbon capture and storage, largely as a result of its commercial independence.

Studies of the Estonian SPC *Eesti Energia* (Tõnurist, 2015) and the role of SOEs in innovation policy (Tõnurist and Karo, 2016) find that SPCs have historically played roles as direct implementation vehicles for coordinated environmental and energy policy initiatives, suggesting they may play a similar role in decarbonization both sector-wide (through risk-taking and innovation capacity) and internally (by

leveraging privileged access to financial and political capital). Further, despite their major role in deploying renewable energy, the high carbon intensity of SPC generation asset portfolios suggest that innovation and risk capacity alone may be insufficient to effect transformation at the necessary scale (Prag et al., 2018).

There may be conditions on SPCs meeting even this, potentially limited, innovation potential. Asane-Otoo (2016), for instance, shows that firms innovate less in low-competition environments, which many SPCs inhabit. Studies of Eastern European SPCs suggest their environmental performance is worse than that of private peers for this and related reasons (Harrison et al., 2019; Meyer and Pac, 2013; Ordóñez et al., 2021).

From a corporate governance perspective, studies of minority government-owned *Enel* (Italy) and privately-held *Iberdrola* (Spain) find that SPCs are slower to adopt clean technologies than private firms (Nisar et al., 2013). US SPCs have historically adopted less clean technology than investor-owned counterparts (Bellas and Nentl, 2007; Rose and Joskow, 1990), although emerging evidence suggests this may be more driven by corporate governance and financial rules governing these firms than state equity ownership per se (Dibley, 2021). China's pilot emissions trading schemes (ETS) from 2011 to 2015, for instance, predominantly affected SOEs but saw weak demand nonetheless, given the much greater incentive to focus on regulatory compliance over active corporate emissions management (Yu and Lo, 2015). Bergsager and Korppoo (2013) speculate that China's state bureaucracy regards SPCs primarily as tools for the efficient direct implementation of technology and policy measures, rather than as agents responding to market-based mechanisms. Benoit (2019a, 2019b) and Mayer et al. (2017) also point to factors beyond state equity ownership as determinants of their role in decarbonization, including the SPC's commercial independence and the overarching business environment.

By examining large SPCs in diverse empirical contexts, we aim to establish a more systematic framework for analyzing and understanding tools available to government owners in using SPCs to promote power sector decarbonization, and how SPC and market characteristics may determine the interventions most likely to achieve this.

2.3. Case study selection

In this paper, we use the 'interpretative' case selection approach laid out in Lijphart (1971) and refined in King et al. (1994) and Seawright and Gerring (2008). Among the various possible case selection strategies (Bennett and Checkel, 2015; George and Bennett, 2005; Moses and Knutsen, 2012), we select 'diverse' cases, to help identify common and divergent characteristics.

The cases we selected represent variance on two criteria that previous scholarship suggests affect SPC behavior. The first is the extent of government control over the SPC. Our best available – though imperfect – measure is the share of equity ownership, as a partial proxy for alignment between SPC and government preferences and how directly the SPC can act as a policy instrument. Government control can be exerted on firms through many different avenues beyond equity ownership (Dibley, 2021). For instance, scholarship on private-investor-owned Chinese firms highlights the regulatory, political and contracting arrangements which the state uses to influence such firms (Milhaupt and Zheng, 2015). Conversely, state equity ownership of a firm does not guarantee government influence over its operations, particularly if held in minority share. Previous literature has nonetheless categorized modern SOEs into three government equity ownership structures: wholly- (100%), majority- (>50%), and minority- (<50%) owned companies (Musacchio et al., 2015; Prag et al., 2018; Ruffin et al., 2003). While we are critical of the notion of making causal claims about the impact of state equity ownership on firm control, we think that there are likely to be relevant differences between these broad categories of firms and therefore consider it useful for the purposes of case selection. That is, wholly-owned SPCs may have less autonomy than minority held

SPCs, notwithstanding the many other avenues of influence available to the state. Because our interest is on state-ownership and the role of state mechanisms and influence on SPCs, in our case selection, we focus on wholly- and majority-owned firms.

The second criterion suggested by previous scholarship as relevant to SPC behavior is the degree of market concentration. Specifically, Prag et al. (2018)'s analysis suggests that the propensity to invest in renewable energy capacity may be lower in highly concentrated markets, while Seligsohn (2018) shows that increasing competition in China's energy sector is associated with stricter and more effectively enforceable air quality standards. Our measure for competitiveness is the national Herfindahl-Hirschman market concentration index (HHI) for the power sector in each case, obtained by squaring market shares of all firms and summing the squares (Rhoades, 1993). We consider this to be an indicator of SPC autonomy, assuming that in highly concentrated markets where SPCs are present, SPCs hold greater market power. The HHI is, however, limited in that it does not capture specialization by market segment, or degree of vertical integration of power companies.

In addition, we limited our sample universe to SPCs that provide >50% of national power generation and/or operate >50 GW in generation capacity.

Our six selected cases represent diversity across both criteria (Table 2). State Power Investment Corporation (SPIC, China) and NTPC (India) operate in a relatively competitive market, with the former wholly-owned and latter majority-owned. Eskom (South Africa), Korea Electric Power Corporation (KEPCO, Korea), Perusahaan Listrik Negara (PLN, Indonesia) and Comisión Federal de Electricidad (CFE, Mexico) specialize to varying degrees in coal, oil, and gas-fired generation, and are all vertically integrated.

Importantly, the firms we selected are all large companies with prominent, in some cases dominant, roles in their respective markets. The firms are also situated in countries in different regions (Latin America, Sub-Saharan Africa, South Asia, Southeast Asia, East Asia) and at differing levels of economic development (except for low-income countries), however as noted below, the majority of the studied countries lie within the middle-income category.

Table 3 summarizes high-level characteristics of each SPC, including aspects of government ownership, key operational and corporate governance characteristics, financial and technical capacity, and the overall policy environment set by government. A more detailed version of this table is available in Appendix A. The comparison is intended to illustrate the convergence and divergence across cases on meso-level characteristics.

3. Analytical framework

3.1. Four 'access factors' for mitigation efforts

Based on the available literature, as well as the initial scoping of our case studies, we propose a set of characteristics for assessing the potential for policy interventions to encourage low-carbon action by SPCs. While individual SPCs' circumstances are highly nuanced, historically complex, and cannot be described in great depth here, meso-level comparison of the case studies demonstrates a number of convergent and divergent characteristics, each subject to specific market contexts.

We group these characteristics into four proposed access factors for understanding, and ultimately predicting, SPC responsiveness to government intervention across the direct, indirect, and market-wide intervention options (see Section 3.2). These four factors capture SPCs': (i) agency, (ii) relative importance of profit-maximization motives versus other corporate priorities, such as social and economic development, and reliable, affordable electricity supplies, (iii) capacity to act, and (iv) exposure to market forces. Each factor is explained in further detail below.

The first factor, *agency*, describes the degree of independence the SPC has over its own decision-making, and by extension – in some cases – its

Table 2
Overview over identification criteria of selected cases.

Country	World Bank income group (2021)	Electricity market concentration index (HHI) [1–100]	Company	Government equity ownership	% National Generation	Installed Capacity (GW)
Republic of Korea	High income	60	KEPCO	51.1%	92%	83.7
India	Lower- middle income	6	NTPC	51%	25%	65.8
China	Upper- middle income	8	SPIC	100%	5%	165
Mexico	Upper- middle income	52	CFE	100%	79%	56.18
Indonesia	Lower- middle income ²	50	PLN	100%	66%	41.7
South Africa	Upper- middle income	87	Eskom	100%	85%	44.2

² The World Bank downgraded Indonesia from upper-middle income status to lower middle-income in July 2021.

Sources: Electricity market concentration: [Prag et al. \(2018\)](#). Country income group data: [World Bank \(2021\)](#). Others: see [Appendix A](#) and [Appendix C](#).

Table 3
Comparative meso-level summary assessment of six major SPCs.

Characteristic	CFE	Eskom	KEPCO	NTPC	PLN	SPIC
Government Owner	Mexico	South Africa	Republic of Korea	India	Indonesia	China
Proportion of government equity ownership	100%	100%	51%	51%	100%	100%
Government control on Board composition	Full	Full	Some limitations	Some limitations	Full	Full
Company listed in a domestic stock market	No	No	Yes	Yes	No	Some subsidiaries
Vertical integrated utility	Yes	Yes	Yes	No	Yes	No
Exposed to Competition	Limited (in generation); none in T&D	Very Limited (94%)	Limited (in generation); none in T&D	Yes	Limited (in generation); none in T&D	Yes (in generation, including other SPCs); T&D controlled by other SPCs
Main generation source(s)	Fuel oil, nuclear, hydro, gas (via IPPs)	Coal	Coal, nuclear, gas	Coal, gas	Coal, diesel, gas, hydro	Coal, solar, wind, hydro, nuclear
Financial Performance	Moderate	Low	High	High	Low	High
Technical/Commercial Capacity	Moderate	Low	High	High	Moderate	High
Overall Government Climate	Low	Low	High	Moderately Low	Moderately Low	Moderate
Prioritization/National “net-zero” target	No net-zero target	No net-zero target	Net-zero by 2050	No net-zero target	Several Net-zero dates under consideration ³	Net-zero 2060

³ At the time of writing the Government of Indonesia was introducing increasingly ambitious electricity sector decarbonization goals, including for PLN’s electricity planning and the management of existing coal assets.

ability to influence government decision-making to ensure favorable treatment. Our cases differ by the degree of direct government control over firm-level decisions. In cases where government holds 100% equity, there is full control over Board composition and executive appointments; in cases where government holds less than 100% equity ownership, government priorities can compete with those of investors. In the two case studies in this category, KEPCO and NTPC, large international investors hold the majority of traded shares (albeit still less than half of the entire equity given both companies are only partially floated). In either case, government may be able to exert influence more easily where political and SPC motivations converge. Where they diverge, the degree of SPC independence (legally, politically, and operationally) can affect both the formulation of government policy and the results of its implementation through SPCs. In all our cases, SPCs are used as instruments for meeting energy policy goals, although in different ways and to a different extent. Where the SPC has limited or no independent agency, the incentives of the SPC in principle collapse to the incentives of the government directing SPC activity.

The second factor is *profit motivation*. This describes the degree to which financial considerations (such as profit, revenue or short-term equity value maximization typically driving private sector company decisions) will also drive SPC actions, as compared to non-financial elements (such as low-cost power delivery, rent seeking or political patronage) which are clearly observed in the case studies and in the literature ([Shleifer, 1998](#)). In most cases where the SPCs are vertically integrated, SPCs have dual responsibilities for generation power and ensuring service delivery, as well as supporting national economic development. Financial sustainability is desirable, but not necessarily

the sole or even primary objective. The historical foundations of each SPC are relevant here, since in most cases they were originally established for non-financial reasons, including for the provision of secure, low-cost electricity to support economic growth and development, and to give government direct control over strategically important power sector assets ([Lazzarini et al., 2020](#); [Megginson and Netter, 2001](#); [Milhaupt, 2020](#)). Ultimately, though, it is the formal and informal objectives of each SPC in the present that determine its objective function, and thus how it chooses to respond to a given set of incentives (including carbon pricing, renewable energy mandates, etc.).

Third is the *capacity* of the SPC to carry out its corporate functions. This requires access to financial resources on sufficiently favorable terms, as well as sufficient operational, technological, and commercial expertise to implement financed projects. The capacity of an SPC to act on its objectives can also depend on the sources and degree of diversification of revenues, access to subsidies, and access to physical resources (e.g., coal, gas, nuclear fuel). It is these factors that determine the extent to which the SPC can exercise its agency in the realization of its goals.

The fourth relates to the degree of SPC exposure to *market competition*. This can affect the extent to which the SPC may be susceptible to pressure from other market actors. Greater competitive pressures can make SPCs more likely to respond to, or anticipate, what their competitors are doing, including in a context where government is encouraging decarbonization (e.g., through carbon pricing systems or technological support). Conversely, where an SPC faces little or no competition (e.g., dominant vertically integrated utilities, such as Eskom, KEPCO, CFE and PLN), then its actions and choices will be relatively independent of other market actors.

Each factor may itself be determined by a number of underlying characteristics. Since these potential differences in the makeup of each factor across SPCs can make each difficult to quantify in objective terms, we opt for a relative scale along a spectrum ranging from ‘low’ to ‘high’, where the benchmark is a private sector firm scoring highly on all four. Table 4 summarizes, through illustrating expected conditions for ‘low’ and ‘high’ performance on each factor, how this relative ranking maps to access factors along the spectrum.

3.2. A toolbox of policy interventions to incentivize SPC decarbonization action

Using previous scholarship on SPCs and analysis of decarbonization efforts directed through SPCs to date as a point of departure, we propose a framework that recognizes the role of state equity ownership but considers it a part of a wider set of features that might determine SPCs’ reactions to possible interventions. These interventions are separated

Table 4
Access Factors: High and Low degree conditions.

Range	Agency	Profit Motivation	Capacity	Exposure to Market Competition
Low	Government exercises close control over management and operational decisions of the SPC. Frequent replacement of SPC Executives and/or Board members, reflecting political affiliations and other loyalties, including in single-party states.	Focus on non-financial goals, particularly on promoting national development, and/or delivering sufficient, secure, high-quality power to customers at an affordable price. May also include emphasis on employment generation, political patronage, and other similar goals.	Poor financial situation, tending towards bankruptcy in the absence of government support. Chronic dependence on government budgetary transfers. Faces regular difficulties in ensuring delivery of services. Limited or no experience in deployment of low-carbon technologies.	Faces no or very limited competition from other generators (typically IPPs). Monopoly over distribution and, by extension, power purchasing (from IPPs). Often a vertically integrated utility.
High	Exercises a high degree of autonomy and independence, including in its commercial operations and staffing and strategy decisions. Replacement of Executives and Board members is undertaken for commercial reasons and with input from advisors outside government	Focus on maximizing profits (or similar financial goals, including revenue or equity value maximization) over non-financial goals.	Strong financial resources, and ability to effectively raise funds from financial markets to finance strategic investments. Strong commercial, operational and technical competency and direct experience with deployment of low-carbon technologies.	Faces significant competition in generation markets. Not extensively involved, if at all, in distribution or transmission activities.

into *targeted* (i.e., SPC-specific) and *market-wide* actions. Targeted actions are broken down further into *direct* (exercise of shareholder power within the SPC corporate governance structure) and *indirect* (deployment of government resources outside this structure). Below we briefly consider each category.

The first cluster of policies, ‘targeted direct interventions’, rely on the government’s shareholder prerogative. These ‘targeted direct’ actions are mechanisms and policies designed to influence SPCs directly through the government exercising its ownership rights. These include formal directives and instructions, appointments and dismissals of Board members and senior executives, and informal discussions between government and SPC executives. Relative to a typical private sector firm (publicly listed or otherwise), the ability to exercise shareholder power in this way presents the clearest advantage for governments since it can simply require the SPC to take certain specific actions, change the parameters under which it operates, and hold it accountable for meeting certain objectives.

The second cluster of interventions considers ‘targeted indirect interventions’ that operate primarily through the deployment of government resources. Governments can make use of financial, administrative, and other resources outside the SPC’s corporate structure to indirectly influence its decision-making by (dis)incentivizing certain strategies, including through preferential financing, construction or subsidization of facilities relevant to its activities (such as transmission lines for low-carbon assets), coordinated SPC/public-sector R&D, and changes in prices faced by state-owned enterprises upstream (e.g., coal suppliers) or downstream (e.g., utility off-takers), thereby affecting prices faced by the SPC.

Our third collection of interventions and policies is the set of tools featured in the standard climate policy toolbox: ‘market-wide interventions’. This refers to governments taking market-wide measures that affect (or are available to) all firms active in the power market and are not specific to the SPC. These include carbon pricing mechanisms such as emissions trading systems and carbon taxes, regulations imposing portfolio renewables and technology standards, changes in dispatch regulations affecting high carbon and renewables, generalized changes to pricing regimes (e.g., subsidy policies), use of feed-in-tariffs and other price support measures, and broader funding of relevant research.

The distinctions between these three clusters of interventions can blur, particularly between targeted indirect support and market-wide actions. For example, some government preferential financing programs can be applied to all market participants in theory, but in practice disproportionately benefit a particular SPC due to its position in the market and corporate capacity. Similarly, construction of facilitative infrastructure can be directed towards all market players in principle, but mostly benefit SPCs (e.g., siting of new transmission lines close to state-owned power plants). There are also other nuances; for example, the difference between the government providing equity injections to its SPC (targeted direct) versus making low-cost financing readily available through state banks (targeted indirect). A more extensive (yet still non-exhaustive) list of such policies and mechanisms is set out in [Appendix B](#).

3.3. Mapping impact of access factors on list of selected policy interventions

This section ties the effectiveness of various climate policy interventions to the four access factors set out above. Before positing hypotheses on how the access factors may determine the optimal decarbonization policy mix, we note that in all assessments of climate policy effectiveness it is essential to consider the context in which the government itself is operating, and the robustness of the measures it has, or plans to, adopt in pursuit of decarbonization. Binding legislative and regulatory climate provisions are indicative of a government with a strong apparent commitment to pursuing an enabling environment for decarbonization. Such provisions do not necessarily indicate actual

commitment or the presence of a workable, coherent strategy, but since the degree and breadth of political commitment sincerity of government action is not easily observable or verifiable, we necessarily assume some degree of credibility in proposed government policy for the purposes of this analysis. Consistent messaging from the country’s leadership and political establishment – particularly where a stable cross-party consensus exists – is also a relevant indicator for the commitment of government climate action. The relative ease, scope and cost of access to high- and low-carbon resources (e.g., availability of domestic coal resources, and average solar irradiation) can indirectly affect the government’s position on decarbonization. Lastly, the capacity of a government to enact effective and well-designed policy, as well as its enforcement, are crucial contextual factors that matter independent of the SPC. For simplicity, we assume here that governments are both willing and able to implement stated decarbonization policies.

Table 5 hypothesizes the association between a ‘high’ rating on each of the four SPC access factors in enabling or hindering the potential impact of a specific government climate intervention. We code this assessment as high (H), moderate (M), and low (L) intervention effectiveness for the overall intervention categories, and for three illustrative interventions in each category. The scores are based on a qualitative assessment of these factors on the effect of similar interventions on SPC behavior, as observed in the case studies and literature review. As a hypothesis-generating exercise, and in the absence of sufficiently robust data, the scoring for each component and overall intervention is necessarily subjective and should be subject to targeted and rigorous testing in future work.

Based on this qualitative assessment, we note several key insights that we seek to validate below in our application of this framework with the case studies.

First, SPCs with high agency (i.e., a high degree of independence) may be considerably more difficult for government to influence through direct control measures, particularly the less coercive policy of holding informal discussions. This also applies to SPCs with a strong profit motive.

Second, a high level of capacity can also give the SPC the ability to resist government pressures; or the ability to carry out government preferences should their interests align, or agency be low. This raises the possibility of multiple configurations of performance along capacity and agency. Informal interventions are likely to be least effective for SPCs that rank relatively highly on both factors.

Where an SPC has access to ample non-government financial resources, and operates independently, even formal directives from government (even when ostensibly accompanied by sanctions for non-compliance), may not translate into effective execution by the SPC. In these cases, changing key personnel, such as the CEO or senior management, may be a more effective strategy for inducing beneficial climate action. Again, where the agency and capacity of the SPC are limited, newly appointed senior leadership might face an SPC leadership and bureaucracy reluctant to enact climate action.

Our analysis also suggests that market interventions will not always be successful in driving climate action in SPCs. Market-wide policies, such as carbon pricing, are expected to work better on companies that operate with relative commercial autonomy, are profit-oriented, and have the resources to respond to long-term market signals. As we demonstrate below using our case studies, these factors are not always present, suggesting that the efficacy of market-wide interventions in driving mitigation success is conditional on SPCs being of a particular type.

4. Application to SPC case studies

Following the development of our framework above, we apply it to each of the six case studies selected, and then proceed to developing a set of SPC archetypes derived from close examination of the cases.

Table 5

Initial mapping of ‘high’ performance on SPC access factors to potential decarbonization impact of selected climate interventions (High/Low imply high/low impact of the intervention)^a.

Selected Climate Intervention	High Agency	High Profit Motivation	High Capacity	High Exposure to Market Competition
1. Targeted Direct Actions – Shareholder Prerogatives structure)	L	L	M	L
i. Formal shareholder/board directives to SPCs	L	L	M	L
ii. Appointment/Replacement of CEO	M	M	M	M
iii. Informal engagement with SPC to influence decarbonization strategy	L	L	L	L
2. Targeted actions – indirect (deployment of government resources)	L	H	H	H
i. Targeted preferential low/zero-carbon financing through 3rd party lenders and financial institutions	M	H	H	H
ii. Investment in supporting infrastructure (transmission, storage, etc.) for zero-carbon energy assets)	L	H	H	H
iii. Mobilization of public sector agencies and other technical/administrative resources to support zero/low-carbon investments	L	M	M	H
3. Market-wide interventions	M	H	M	H
i. Carbon pricing mechanisms (ETS or carbon tax)	H	H	H	H
ii. Changes in regulated prices (e.g., removing subsidies favoring high carbon or adding subsidies/pricing favoring low/zero carbon), portfolio standards or renewables-friendly dispatch	H	H	M	H
ii. Increased R&D spending on low/zero-carbon technologies (e.g., nuclear, hydrogen, storage, renewables)	M	M	M	M

^a For each overall intervention category (numbered 1,2,3), the qualitative score is the modal qualitative score of each of its illustrative components (numbered i,ii,iii).

4.1. Access factors

While each access factor depends on multiple data points, Table 6 captures how each SPC performs against them in overall terms. We recognize that SPCs are not static entities and these assessments are

Table 6
Variation across proposed key factors.

SPC	Agency	Profit Motivation	Capacity	Exposure to Market Competition
CFE	Low. Fully state-owned. Sets retail and T&D prices subject to state approval. Management under full state control. Unlisted.	Moderate (moving to Moderately low). Affordability and reliability. Energy sovereignty. Support to national development.	Moderately high. Good access to debt markets and government support. Fuel oil asset base. Cannot meet future energy investment needs alone. Dependent on subsidies.	Moderately low (moving to Low). Near-monopsony in generation. IPP participation but is expected to fall under current policy. Proposed changes to dispatch rules benefit older CFE fuel oil assets.
Eskom	Low. Fully state-owned, Board and Executive under state control, unlisted, heavily dependent on subsidies, subject to imminent corporate restructuring	Moderately low. Focus on national and regional development, Black Economic Empowerment mandate.	Moderately low. Weak financial and operational position, access to debt markets and government support, high dependence on domestic and international coal industry, coal-heavy generation profile	Low. Integrated monopoly over T&D except for municipalities and some private PPAs, near-monopsony on generation, 8% purchased from IPPs, exports to 16-country regional grid.
KEPCO	Moderate. Majority state-owned, Board and Executive under partial state control, publicly traded.	Moderately high. Profitability, national development, technology export, greater liberalization of electricity prices from 2021.	High. Strong financial position, access to debt and equity markets, export business vulnerable to domestic nuclear policy, coal-heavy generation profile, limited domestic resources. Coal mine ownership abroad.	Low. Integrated monopoly over T&D, monopsony on generation, 30% purchased from IPPs, merit order dispatch.
NTPC	Moderately high. Majority state-owned, legal status allows independent investment decisions, Board and Executive under partial state control, publicly traded.	Moderately high. Profitability, reliable power delivery, electricity access, efficiency, innovation.	Moderately high. Strong financial position, access to debt and equity markets, strong technical performance, high dependence on coal and distribution company contracts, ongoing diversification. Coal price exposure partly hedged through mine ownership.	High. Largest national generator, approximately 20% of national generation (25% of thermal generation), with interests in distribution, transmission, ancillary services, trading, storage. Power sold mainly through bilateral PPAs. Moving towards merit order dispatch.
PLN	Moderately low. Fully state-owned, Board, Executive and strategic direction under state control, some discretion over strategy implementation, unlisted, heavily dependent on subsidies	Moderately low. Affordable power, access to power, (formally) profit generation, although chronically loss-making on operational basis.	Moderate. Weak financial position, good government-supported access to debt markets and government equity support, high dependence on direct subsidies and to domestic coal supplies, increasing exposure to IPPs, geographically challenging service area.	Moderately low Integrated monopoly over T&D, near-monopsony on generation with limited but growing IPP participation, first refusal on all projects within business areas, responsible for executing national expansion plan.
SPIC	Moderate. Fully state-owned. Control over input or wholesale prices limited to influence on policy through China Electricity Council and State-owned Assets Supervision and Administration Commission. Board and Executive under full state control. Multiple listed subsidiaries. Geographically diversified.	Moderately high. Public and social responsibility mandate. Major technology exporter. In competition with other large SPC generators. Significant nuclear and renewable energy assets.	High. Access to debt, government finance, and (through subsidiaries) equity markets. Exclusive CAP1400 nuclear technology development rights. Extensive experience in solar and wind, domestic and international. Relatively small coal asset base versus competitors. Some coal mine ownership.	Moderate. Approximately 10% of national generation. Non-nuclear generation in competition with four central SOEs and many smaller SOEs. Largest solar and wind generator. One of 4 firms licensed to operate nuclear plants. Equal shares dispatch (thermal).

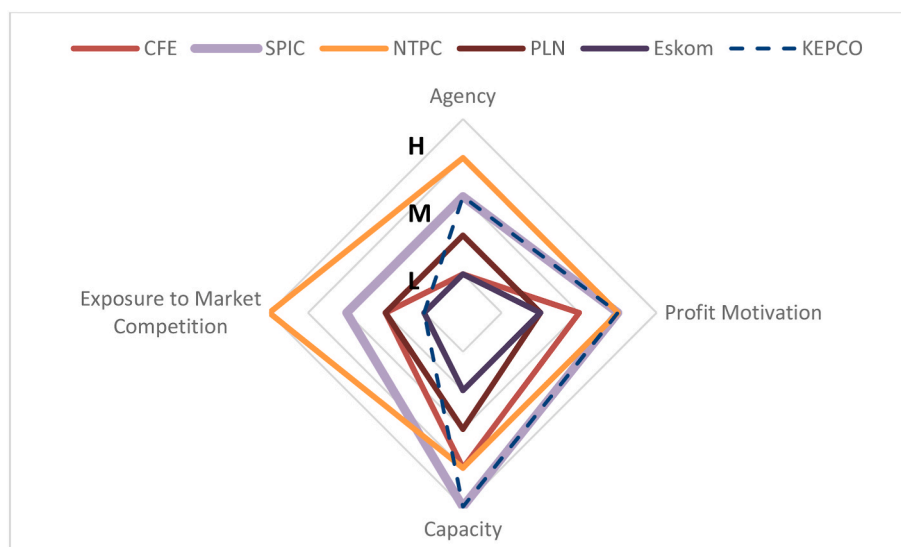


Fig. 1. Radar chart of SPCs against the four access factors (L = Low, M = Moderate, H = High).

subject to continuous change. This has occurred, for example, with the Mexican government's change of administration prompting a deprioritization of decarbonization goals for CFE and the sector in recent years. In line with the relative scale defined in Table 4, we have attempted to qualitatively rank our assessment of each case study against each factor (Fig. 1), where L (H) represents the lowest (highest) possible performance on a given factor.

None of the SPCs examined scores higher than 'moderate' on agency except NTPC, highlighting the policy relevance of the influence governments exert over SPCs. SPIC, for example, has often been used as a testing ground for new technologies and is one of a handful of licensed nuclear power companies in China, affording it a strong market position but relatively little independence from government policy, while CFE, Eskom and PLN are the central delivery mechanism for national electricity capacity plans and also have little agency in practice. Recent changes in political priorities in Mexico have started to alter this position, however, with CFE and national oil company PEMEX potentially seeing increased scope to influence significant components of Mexican energy policy (Economist, 2021). NTPC has a significant degree of independence over large investment decisions but is still subject to government directives when it is considered necessary to intervene. Similarly, KEPCO's ambitions to build up a substantial international nuclear business have been severely hampered by the political decision to phase out nuclear power domestically (Economist, 2019). Considering such factors can affect the degree to which government can impose its preferences directly on the SPC through direct intervention (whether or not these preferences are aligned). It also suggests that in cases where agency is limited, SPCs will not move to decarbonize unless prompted to by government.

We note substantial variation in our profit motivation criterion, which ranges from NTPC (as a relatively profit-oriented SPC) to the almost fully developmental-motivated PLN and Eskom. While all but Eskom are profitable on a subsidized basis, CFE and PLN (and potentially SPIC) are chronically loss-making on an unsubsidized, operational basis, suggesting government is willing to socialize some of the costs of meeting non-financial goals.

SPCs that are at least partially profit-seeking also tend to see greater availability of financial, technical, and material resources. In Eskom's case – and to an extent in PLN's case – chronic losses, limited non-coal experience, poor credit, and lack of funds for new investment, restrict the expansion and modernization of the firm's capacity mix and have led to proposals to unbundle Eskom into separate generation and T&D companies by 2022 (Makeo, 2021). SPIC, NTPC and KEPCO all own significant coal resources and SPIC has access to financing through Chinese policy banks as well as much greater experience with renewable technologies than the other cases. Many SPCs are exposed to government price-setting in power markets. CFE, for example, no longer receives direct retail subsidies but its customers do and it has the capacity to set retail and T&D rates subject to government approval. Moreover, while CFE would face pressure from independent power producers (IPPs) in a competitive market, similarly to PLN, its close ties to government and financial institutions mean it has ample financial resources at present (though still insufficient to meet demand projections) and its credit rating benefits from association with the Mexican government.

Market exposure is divided into two camps: integrated near-monopolies, and those exposed to some degree of competition in generation and lacking control over distribution. Where SPCs face competition in generation, or do not control power offtake such as in NTPC's case, the SPC does not have exclusive control over the assets in the market or the ability to invest in low carbon assets as freely should it desire to do so. This is contrary to CFE's case, where the ability to influence market composition is much greater – although its motivation to enact this change is much more reliant on political directives, due to its relatively low agency.

4.2. Implications for SPC interventions

Building on, and consistent with, the theoretical assessment of the link between access factors and policy types in Section 3.3, we associate the performance of each SPC against these factors with the potential for the three intervention clusters that we have identified – targeted direct and indirect actions as well as market-wide actions – to induce decarbonization action. The results of this application are presented in Table 7.

We find that all of our case studies display some potential to realize mitigation efforts based on targeted direct effects. Interventions such as the appointment of climate-friendly senior management, corporate restructuring towards a more renewable-focused set-up, or setting corporate climate targets all have considerable potential to boost climate action in the case studies considered. We consider informal directives to be slightly less powerful for KEPCO and NTPC due to their strong profit-making motivations and relatively high degree of agency but we rate all other SPCs highly on the decarbonization potential of direct interventions.

A similarly promising picture emerges on indirect government policy, in particular the mobilization of government resources. Examples of such policies include the provision of supporting infrastructure such as transmission lines, preferential access to financing (either directly at below-market rates, or through guarantees for SPC-issued bonds), or targeted R&D funding. We consider these types of policies to be effective for all SPCs. Capacity-constrained SPCs like PLN and Eskom, however, could face difficulties in taking advantage of such measures.

Lastly, we find that market-wide interventions, when applied to our case studies, may have limited impact on SPC climate action. Examples of such policies include carbon prices, renewable portfolio standards, and efforts to reform the electricity market in a more renewable-friendly direction. Our analysis suggests that the absence of competition, presence of non-financial objectives, and dependence on government subsidies can severely limit the effectiveness of market-wide actions. For firms operating in monopolistic and competitive environments alike, the ability to pass additional costs (such as carbon pricing) through to customers, leading to changes in the cost of electricity from the sources incurring those costs, is essential for maintaining a viable business model. If government takes steps to prevent this pass-through to protect consumers from higher electricity prices, the additional incentive for climate action will be limited. In turn capital injections, restructuring, or regulatory reforms limiting SPC exposure to stranded assets and legacy liabilities could be required to prevent a significant deterioration in the firms' finances. Similarly, the threat of stranded assets, as a potential motivator for investment in renewable assets and halting of investments in high-carbon assets, is not directly comparable to that faced by a profit-maximizing private sector firm, especially when the probability of a government bail-out is relatively high. In Eskom's and PLN's cases, the challenge of low capacity would further complicate reacting to price signals in the market. Limited competition between SPCs and independent power producers (as in KEPCO's case), as well as between firms with the same government owner (in the case of SPIC), could lead to some competition-induced decarbonization incentives. In our analysis, we posit that only NTPC would be likely to swiftly and meaningfully respond to market-wide incentive changes.

5. Discussion

5.1. Implications for decarbonization interventions towards SPCs

Decarbonization ultimately requires the net replacement or retrofitting of high-carbon electricity generation assets with low- and zero-carbon ones over time. Energy efficiency, market reform, and grid modernization measures play a role, but ultimately cannot substitute for the imperative of decarbonizing generation that is the common outcome all government interventions towards SPCs should aim to achieve. In

Table 7
Application of case studies to potential SPC interventions for inducing decarbonization action.

	Agency	Profit Motivation	Capacity	Exposure to Market Competition	Targeted Direct - Shareholder Prerogatives	Targeted Indirect – Government Resource Deployment	Market Wide
NTPC	M/H	M/H	M/H	H	M	H	L
SPIC	M	M/H	H	M	H	H	M
KEPCO	M	M/H	H	L	M	H	M
PLN	M/L	M/L	M	M/L	H	M	L
CFE	L	M	M/H	M/L	H	H	L
Eskom	L	M/L	M/L	L	H	M	L

associating the four access factors described above with government interventions, it is helpful to bear this singular ultimate objective in mind.

Our analysis of case studies in Mexico, South Africa, Korea, India, Indonesia, and China suggests that SPCs are likely to respond in different ways to decarbonization interventions according to their characteristics. Our analysis finds that even among the six SPCs studied here, there is considerable variation with respect to the four ‘access factors’ identified, implying each SPC should be dealt with differently from a government policy standpoint.

Targeted interventions that aim to influence an SPC directly are a powerful tool available to governments seeking to prompt decarbonization activity in their role as shareholder, conditional on the SPC having the technical capacity and financial resources to respond. While informal engagements may be less effective towards SPCs with high agency, such as NTPC or KEPCO, interventions such as appointing leadership personnel aligned with the government’s climate strategy, or establishing binding corporate climate targets, may be more able to catalyze change.

Similarly, indirect targeted interventions aiming to support SPC’s decarbonization efforts through the external mobilization of government resources require an SPC to have enough capacity to take advantage of these resources. Providing privileged access to financing and providing essential supporting infrastructure such as transmission lines can therefore be key tools in unleashing renewable investments where this capacity exists.

Market-based decarbonization interventions, however, may not deliver significant results in environments where SPCs are largely or completely shielded from competition, or prices are heavily regulated, such as in Eskom’s or CFE’s case. The decarbonization efforts of NTPC, which most closely resembles a private company among our case studies, may be most likely to respond favorably to market-based decarbonization interventions.

While such SPC-specific assessments could guide policy makers in these specific contexts, we now propose a more general classification of to guide decarbonization interventions towards SPCs not assessed here.

5.2. Generalizing our findings: four SPC archetypes

Based on our assessment of the six case studies of SPCs in different contexts and the four access factors, we propose a generalized typology of SPCs representing four types of company observed across the

jurisdictions examined, grouped by shared characteristics across the four access factors. Each archetype is associated with a different combination of access factors (see Table 8 for a concise representation of the archetypes’ performance against each of them, with an idealized ‘private sector’ firm as a benchmark). Based on these observations, we posit four hypothetical SPC ‘archetypes’ to guide choice of government policy interventions. We emphasize that the archetypes are flexible characterizations not intended to correspond exactly to specific case studies, and that this is an exploratory exercise for empirical (in)validation in future work. Here, we are attempting to conceptualize the relevance of variation in SPC access factors to the decarbonization context with reference to existing cases, rather than make a definite assessment holding external validity.

1. **“Competitive Contributor”**: This form of SPC is most similar to a private sector company, although it operates under majority government control. The SPC has a moderate-to-high degree of *agency* to act independently of government, a moderate-to-high profit-maximizing *motivation*, and high *capacity* to pursue its goals (with access to financial resources from capital markets, and technical and commercial expertise). It can, if it chooses to, transition relatively efficiently to a zero-carbon portfolio. The SPC faces a moderate-to-high degree of *market competition* (either from private enterprise, other SPCs, or both). Its interests are aligned with government policy in a stable configuration. If effectively motivated by government policy targeted at profit-maximizers, such an SPC can be effective at advancing climate action. NTPC and SPIC are most representative of this archetype, although SPIC has relatively less independence from government and operates in a less competitive environment.
2. **“Grinding Behemoth”**: The SPC is more *motivated* by maintaining service delivery at affordable prices than profit, limiting the effectiveness of market-based measures. It enjoys protections insulating it from *market competition* and also has a dominant role in the sector (typically as a vertically integrated utility with a monopoly on T&D and a majority market share in generation). It has access to sufficient financial resources from government and/or capital markets to sustain reliable operations and make strategic investments and has a relatively high degree of *agency* in deciding how to implement decarbonization mandates within its corporate structure. The SPC has moderate-to-high technical and financial *capacity* to pursue decarbonization, which gives it significant ability to implement a decarbonization strategy, if it were motivated to do so (as there is

Table 8
Mapping archetypes to four SPC factors and potential effectiveness of intervention clusters.

SPC Archetype	SPC factors				Intervention effectiveness		
	Agency	Profit Motivation	Capacity	Exposure to Market Competition	Targeted Direct (Shareholder Prerogative)	Targeted Indirect (Government Resource Deployment)	Market-Wide
Private Sector	H	H	H	H	N/A	M (potential spillovers)	H
Competitive Contributor	M/H	M/H	H	M/H	M	H	M/H
Grinding Behemoth	M	M	M/H	M/L	H	M	M/L
Statist Caterer	L	M/L	M	L	H	H	L
Depleted Provider	L	M/L	L	L	H	M	L

limited self-interest in changing the status quo). PLN and KEPCO are most illustrative of this type, although only KEPCO is publicly listed, with a correspondingly greater profit motivation.

3. **“Statist Caterer”**: The SPC is characterized by low *agency* and a *motivation* that de-emphasizes profitability and revenue in favor of acting as a conduit for political priorities and retaining strategic control over the electricity sector. It operates under low *competitive* conditions and ultimately, its incentives to decarbonize depend on alignment with the political interests of government and firm and leadership, which may be effectively interchangeable. It has moderate *capacity* in the form of access to sufficient financial resources to operate without service interruptions, but these resources are primarily supplied by government in the form of low-cost finance and direct equity injections from the public budget, helping to sustain a relatively high debt burden that hampers its ability to invest in low- or zero-carbon assets and limits its ability to act independent of political priorities. Under Mexico’s current administration, CFE most closely resembles this type, with policies and legislation newly re-asserting government control over strategic energy assets.
4. **“Depleted Provider”**: The SPC is either insolvent or its finances are structurally weak, such that it depends on regular subsidies to maintain operations. It is fundamentally a development-*motivated* firm with a primary objective of facilitating national economic productivity, although it may also be subject to political pressure to pursue financial sustainability. Its activities are subject to capture by powerful interests in and around government. In its weakened condition, the SPC has little *agency* over decision-making regardless of political alignment with government policy. Its asset base is carbon-intensive, and it almost completely lacks the *capacity* (technical and capital) required to undertake any long-term planning, much less implement a transition to a low-carbon portfolio. Its operations focus on maintaining existing power supplies and infrastructure. The SPC’s ability to implement a decarbonization strategy is extremely limited, even if it were motivated to do so. We consider Eskom to be illustrative of this type.

With the development of these four proposed theoretical archetypes and their classification against the four access factors, we are in a position to apply each to the intervention clusters (targeted direct, targeted indirect, market-wide) in the policy toolbox developed earlier. The results are displayed in Table 8. The assessment reflects the ability of each type of intervention to affect the SPC’s behavior; and the ability of the SPC to execute on its intentions. It builds on the association of access factors to intervention categories outlined in Table 5, and is consistent with the case study assessment in Table 7.

We find that targeted interventions by governments exercising their rights as shareholders are likely to be effective with respect to a wide spectrum of SPCs – a lever unavailable to governments dealing with private sector firms. In contrast, we posit that unless the SPC operates in a manner similar to a private sector actor, market-wide instruments are likely to be less effective than direct interventions, or indirect government resource mobilization to support SPCs, as they often lack the resources necessary to respond to market signals or are otherwise shielded from competition such that they have no need to respond. Moreover, the resulting trade-offs of such interventions between passing through higher prices and increasing dependence to government subsidies by way of lower profits could fundamentally conflict with social or development objectives imposed on the SPC. Our illustrative Depleted Provider firm in particular would struggle to respond to market incentives, in large part because of capacity constraints, and would require considerable additional government resources and access to greater technical expertise to enact effective mitigation policies. This is true to a lesser extent for the Grinding Behemoth. The Competitive Contributor is most likely to realize the decarbonization potential of market incentives, conditional on availability of resources.

Finally, we consider in Table 9 how the presence of each SPC

Table 9
Potential of SPC archetypes to advance overall sectoral decarbonization.

Company Archetype	Potential Impact	Comment
Private Sector	M/H	High capacity and profit-seeking motivation allow it to be effective and efficient in implementing decarbonization actions when it chooses to do so, but its limited role in the market limit its influence on sectoral decarbonization to its impact on other private firms’ behavior. This is particularly relevant to economies featuring vertically integrated SPCs. It is more difficult for government to influence its behavior through non-market wide mechanisms.
Competitive Contributor	M/H	High capacity and generally profit-seeking motivation allow it to be effective and efficient in implementing decarbonization actions when it chooses, but its limited role in the market limit its influence on sectoral decarbonization. Government can take direct action to influence its behavior, although it may encounter resistance from the SPC in attempting to do so and the result may not be either effective or efficient.
Grinding Behemoth	H	Dominant position in the electricity market and status as near-sole, or sole, purchaser of electricity gives it potential to contribute substantially to sectoral decarbonization, but inefficiencies, motivations beyond profit-seeking, and capacity/resource constraints, can limit this potential. Government can take direct action to alter its motivations or mobilize resources in support of the SPC to allow potential to be fulfilled.
Statist Caterer	M	Dominant position in electricity market gives it potential to contribute substantially to sectoral decarbonization, but limited agency and subservience to government means ability to do so depends on SPC’s internalization of government priorities and ability to act on them. Limited capacity to address operational inefficiencies, given its primary purpose as service provider and/or development actor, will likely increase the cost of decarbonization relative to Competitive Contributors.
Depleted Provider	L	Dominant position in electricity market gives it potential to contribute substantially to sectoral decarbonization, but potential remains largely unfulfilled due to chronic financial and operational challenges preventing realization of corporate strategy. With direct, indirect and market-wide actions unlikely to succeed, government should consider firm restructuring or unbundling, and/or market reforms to encourage entry by other players.

archetype in the market might help or hinder governments’ ability to pursue the decarbonization of the electricity sector as a whole, as climate ambition increases, particularly relative to private sector companies. To illustrate, the Grinding Behemoth, Statist Caterer, and Depleted Provider tend to be vertically integrated utilities, with dominance over the market, but also be less effective conduits for decarbonization-targeting interventions than a Competitive Contributor or a Private Sector Company. Conversely, a Grinding Behemoth may be a far more direct and effective vehicle for government decarbonization ambitions than a private sector firm under the right circumstances, and if it is targeted with the right combination of direct and indirect interventions beyond market-wide instruments.

While in this analysis we have focused on interventions that apply to a certain type of SPC, the example of CFE in recent years shows that the ideal type of intervention can change depending on the contextual factors that determine the SPC type. A government might, for example, be

determined to transform a Depleted Provider into a Competitive Contributor as part of its climate strategy.

6. Conclusions

SPCs are major drivers of carbon emissions in the electricity sector and should be considered key actors required by national governments to achieve national climate targets consistent with the goals of the Paris Agreement. Nonetheless, while the climate policy literature has produced an extensive toolbox of market-wide policies and regulatory initiatives designed to incentivize private sector companies to transition to a low carbon future, it has paid relatively little attention to SPCs and their country- and market-specific contexts.

In this initial study, we have taken some early steps towards filling this gap by analyzing SPCs in six different countries. We attempt to identify overarching characteristics and archetypes that could guide policymakers, in our case study countries and elsewhere where similar conditions exist, in their efforts to use SPCs as a key component of sectoral decarbonization strategies.

Guided by the scholarly literature, and an initial scoping exercise on our case studies, we identify a set of four access factors that we hypothesize to be relevant in determining SPC responses to an intervention targeting decarbonization. These are: the degree of agency of the SPC; whether the SPC is solely profit-motivated or also guided by other, social, or service-oriented goals; its corporate capacity and access to resources; and its exposure to competition.

Subsequently, we identified three overall types of policy intervention that may be applied to SPCs. Policies and mechanisms to decarbonize SPCs can either be targeted at the SPC or attempt to change the wider market. Targeted policy approaches can either be used directly (through a government exercising its shareholder power), and indirectly (by mobilizing additional government resources in support of an SPC).

We then applied this framework to all six of our case studies, to identify which intervention types are potentially most likely to succeed in each case, as a function of performance against the four access factors. Based on the insights gained in applying our theoretical framework, we attempt to generalize our findings by presenting a set of four representative archetypes that the SPCs we have examined fall into.

We stress that our study is inherently limited by a qualitative case study approach based on incomplete and not fully comparable data, and therefore does not lay claim to having identified causal relationships, we have identified a number of conjectures for further exploration and empirical testing in empirical work.

Firstly, we show that SPCs deserve considerably more attention in the climate policy debate given their unique features and central role in the electricity sector globally. Their size, significance to national economies, and differences in response to market-wide incentives and regulations, particularly relative to private sector investor-owned utility companies, provide ample motivation to study their dynamics further.

Secondly, our analysis suggests that for all but the most profit oriented SPCs, most of the options in the traditional, neo-classical policy toolbox such as carbon prices are unlikely to lead to efficient and effective climate mitigation outcomes.

Thirdly, our analysis suggests that even assuming government is willing and able to pursue a decarbonization agenda, private sector companies might not have the highest emission mitigation potential. Our analysis suggests that SPCs resembling our archetypes of Grinding Behemoth and Statist Caterer, both of which are insulated from competition but relatively well equipped in terms of agency and capacity, could in practice outstrip the speed and efficiency of a private utility in decarbonizing its own asset base, and contribute more forcefully to sector-wide efforts, if the right non-market interventions are leveraged.

Ultimately, our study has made a first effort to shed a light on the challenge of decarbonization in the context of SPCs in a more systemic manner than has previously been attempted, to the extent that this is

possible with available data. We acknowledge the many limitations of this early work, and a more rigorous and complete data-based assessment is needed in future research, both to test our hypotheses and finesse or rework our classifications. We do, however, anticipate this initial framework to be useful in building a much-needed understanding of SPCs' role in reaching net zero emissions in the electricity sector.

CRedit authorship contribution statement

Philippe Benoit: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Alex Clark:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Moritz Schwarz:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Arjuna Dibley:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Acknowledgements

The authors are grateful for suggestions and comments on draft material from three anonymous reviewers, Linda Bach, Ben Caldecott, Gahee Han, Sugandha Srivastav, Tim Dobermann, and Yangsiyu Lu. This research was funded in part by Columbia University's Center on Global Energy Policy.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2022.131796>.

References

- Asane-Otoo, E., 2016. Competition policies and environmental quality: empirical analysis of the electricity sector in OECD countries. *Energy Pol.* 95 (C), 212–223.
- Bellas, A.S., Nentl, N.J., 2007. Adoption of environmental innovations at US power plants. (Case study). *J. Bus. Ind. Market.* 22 (5), 336–341.
- Belloc, F., 2014. Innovation in state-owned enterprises: reconsidering the conventional wisdom. *J. Econ. Issues* 48 (3), 821–848.
- Bennett, A., Checkel, J.T., 2015. *Process Tracing: from Metaphor to Analytic Tool*. Cambridge University Press, Cambridge.
- Benoit, P., 2019a. *Engaging State-Owned Enterprises in Climate Action*. Columbia University Center on Global Energy Policy, New York.
- Benoit, P., 2019b. State-owned enterprises: No climate success without them. *J. Int. Aff.* 73 (1), 135–144.
- Bergsager, H., Korppoo, A., 2013. *China's State-Owned Enterprises as Climate Policy Actors: the Power and Steel Sectors*. Nordic Council of Ministers.
- Chandra, R., 2018. *Adaptive State Capitalism in the Indian Coal Industry*. Harvard Kennedy School, Cambridge, MA.
- ClimateWatch, 2020. *Historical GHG Emissions*. <https://www.climatewatchdata.org/ghg-emissions>.
- Cullenward, D., Victor, D.G., 2020. *Making Climate Policy Work*. Polity Press, Cambridge.
- Dibley, A.C., 2021. *Why Does Leviathan Innovate? the Law and Economics of Technological Change at State-Owned Electric Utilities*. Stanford.
- Economist, T., 2019. *South Korea's government wants greener energy*. In: *Who Will Pay for it?*, the Economist, June 15th 2019 Edition.
- Economist, T., 2021. *A Bad Energy Law Says Much about Mexico's President*, Mar 13th 2021 Edition. *The Economist*.
- Energy & Climate Intelligence Unit, 2021. *Net Zero Emissions Race: 2021 Scorecard*.
- George, A.L., Bennett, A., 2005. *Case Studies and Theory Development in the Social Sciences*. MIT Press, Cambridge, Mass. ; London.
- Haney, A.B., Pollitt, M.G., 2013. New models of public ownership in energy. *Int. Rev. Appl. Econ.* 27 (2), 174–192.
- Harrison, A., Meyer, M., Wang, P., Zhao, L., Zhao, M., 2019. *Can a Tiger Change its Stripes? Reform of Chinese State-Owned Enterprises in the Penumbra of the State*. National Bureau of Economic Research.

- Hart, O., Shleifer, A., Vishny, R.W., 1997. The proper scope of government: theory and an application to prisons. *Q. J. Econ.* 112 (4), 1127–1161.
- He, G., Lin, J., Sifuentes, F., Liu, X., Abhyankar, N., Phadke, A., 2020. Rapid cost decrease of renewables and storage accelerates the decarbonization of China's power system. *Nat. Commun.* 11 (1), 1–9.
- Holmstrom, B., Milgrom, P., 1991. Multitask principal-agent analyses: incentive contracts, asset ownership, and job design. *J. Law Econ. Organ.* 7, 24–52.
- International Energy Agency, 2016. 20 Years of Carbon Capture and Storage: Accelerating Future Deployment. IEA, Paris.
- International Energy Agency, 2021. Net Zero by 2050: A Roadmap for the Global Energy Sector. International Energy Agency, Paris.
- Ives, M., Righetti, L., Schiele, J., De Meyer, K., Hubble-Rose, L., Teng, F., Kruitwagen, L., Tillmann-Morris, L., Wang, T., Way, R., 2021. A New Perspective on Decarbonising the Global Energy System. Oxford Smith School of Enterprise and the Environment.
- King, G., Keohane, R.O., Verba, S., 1994. *Designing Social Inquiry: Scientific Inference in Qualitative Research*. Princeton University Press, Princeton, N.J.
- Lazzarini, S.G., Mesquita, L.F., Monteiro, F., Musacchio, A., 2020. Leviathan as an inventor: an extended agency model of state-owned versus private firm invention in emerging and developed economies. *J. Int. Bus. Stud.* 1–35.
- Lijphart, A., 1971. Comparative politics and the comparative method. *Am. Polit. Sci. Rev.* 65 (3), 682–693.
- Makeo, T., 2021. Eskom to Be Fully Unbundled by December 2022. TechCentral.
- Mayer, B., Rajavuori, M., Fang, M.M., 2017. The contribution of state-owned enterprises to climate change mitigation in China. *Clim. Law* 7 (2–3), 97–124.
- Mazzucato, M., Semieniuk, G., 2017. Public financing of innovation: new questions. *Oxf. Rev. Econ. Pol.* 33 (1), 24–48.
- Mazzucato, M., Semieniuk, G., 2018. Financing renewable energy: who is financing what and why it matters. *Technol. Forecast. Soc. Change* 127, 8.
- Meggison, W.L., Netter, J.M., 2001. From state to market: a survey of empirical studies on privatization. *J. Econ. Lit.* 39 (2), 321–389.
- Meyer, A., Pac, G., 2013. Environmental performance of state-owned and privatized eastern European energy utilities. *Energy Econ.* 36 (C), 205–214.
- Milhaupt, C., Pargendler, M., 2019. Related-party transactions in state-owned enterprises: tunneling, propping, and policy channeling. In: Enriques, L., Troeger, T. H. (Eds.), *The Law and Finance of Related Party Transactions*. Cambridge University Press, New York.
- Milhaupt, C.J., 2020. The state as owner—China's experience. *Oxf. Rev. Econ. Pol.* 36 (2), 362–379.
- Milhaupt, C.J., Zheng, W., 2015. Beyond ownership: state capitalism and the Chinese firm. *Georgetown Law J.* 103 (3), 665–722.
- Moses, J.W., Knutsen, T.L., 2012. *Ways of Knowing: Competing Methodologies in Social and Political Research*, second ed. Palgrave Macmillan, Basingstoke.
- Musacchio, A., Lazzarini, S.G., Aguilera, R.V., 2015. New varieties of state capitalism: strategic and governance implications. *Acad. Manag. Perspect.* 29 (1), 115–131.
- Nisar, A., Ruiz, F., Palacios, M., 2013. Organisational learning, strategic rigidity and technology adoption: implications for electric utilities and renewable energy firms. *Organ. Learn. Strat. Rigidity Technol. Adopt.: Implication electric utilities Renew. Energy firms* 22, 438–445.
- Ordóñez, J.A., Jakob, M., Steckel, J.C., Fünfgeld, A., 2021. Coal, power and coal-powered politics in Indonesia. *Environ. Sci. Pol.* 123, 44–57.
- Prag, A., Röttgers, D., Scherrer, I., 2018. State-owned enterprises and the low-carbon transition. IDEAS Work. Pap. Ser. RePEc.
- Rhoades, S.A., 1993. The herfindahl-hirschman index. *Fed. Reserv. Bull.* 79, 188.
- Rose, N.L., Joskow, P.L., 1990. The diffusion of new technologies: evidence from the electric utility industry. *Rand J. Econ.* 21 (3), 354–373.
- Rufin, C., Rangan, U.S., Kumar, R., 2003. The changing role of the state in the electricity industry in Brazil, China, and India. *Am. J. Econ. Sociol.* 62 (4), 649–675.
- Seawright, J., Gerring, J., 2008. Case selection techniques in case study research: a menu of qualitative and quantitative options. *Polit. Res. Q.* 61 (2), 294–308.
- Seligsohn, D.J., 2018. Corporate Concentration and Air Pollution Governance in China. UC San Diego.
- Shleifer, A., 1998. *State versus Private Ownership*. National Bureau of Economic Research, Cambridge, Mass.
- Shleifer, A., Vishny, R.W., 1998. *The Grabbing Hand: Government Pathologies and Their Cures*. Harvard University Press, Cambridge, Mass. ; London.
- Steffen, B., Karplus, V.J., Schmidt, T.S., 2020. State Ownership and Technology Adoption: the Case of Electric Utilities and Renewable Energy. MIT Center for Energy and Environmental Policy Research.
- Sterlacchini, A., 2012. Energy R&D in private and state-owned utilities: an analysis of the major world electric companies. *Energy R&D in private and state-owned utilities: An analysis of the major world electric companies* 41, 494–506.
- Su, K., Wan, R., Song, V.Y., 2018. Pyramidal structure, risk-taking and firm value. *Econ. Transition Innovation Change* 26 (3), 401–427.
- Tirole, J., 1994. The internal organization of government. *Oxf. Econ. Pap.* 46 (1), 1–29.
- Tönurist, P., 2015. Framework for analysing the role of state owned enterprises in innovation policy management: the case of energy technologies and Eesti Energia. *Technovation* 38, 1–14.
- Tönurist, P., Karo, E., 2016. State owned enterprises as instruments of innovation policy. *Ann. Publ. Cooper. Econ.* 87 (4), 623–648.
- Way, R., Lafond, F., Lillo, F., Panchenko, V., Farmer, J.D., 2019. Wright meets Markowitz: how standard portfolio theory changes when assets are technologies following experience curves. *J. Econ. Dynam. Control* 101.
- Way, R., Mealy, P., Farmer, J.D., 2020. Estimating the Costs of Energy Transition Scenarios Using Probabilistic Forecasting Methods.
- World Bank, 2021. *World Bank Country and Lending Groups*. <https://datahelpdesk.worldbank.org/knowledgebase/articles/906519>.
- Yu, X., Lo, A.Y., 2015. Carbon finance and the carbon market in China. *Nat. Clim. Change* 5 (1), 15–16.

Appendix

A. Summary of firm- and market-level characteristics

Table A: Meso-level comparative assessment of six major SPCs in detail

Characteristic	CFE	Eskom	KEPCO	NTPC	PLN	SPIC
a. ownership						
Government	Mexico	South Africa	Republic of Korea	India	Indonesia	China
Proportion of government equity ownership	100%	100%	51%	51%	100%	100%
Company listed in a domestic stock market	No	No	Yes	Yes	No	Some subsidiaries
Government control on Board composition	Full	Full	Some limitations	Some limitations	Full	Full
Government control over executive appointments	Full	Full	Some limitations	Full	Full	Full
b. Operations						
Vertical integrated utility	Yes	Yes	Yes	No	Yes	No
Technological diversification (generation)	Low	Very low	Moderate	Low	Very low	High
Main generation source(s)	Fuel oil, nuclear, hydro, gas (via IPPs)	Coal	Coal, nuclear, gas	Coal, gas	Coal, diesel, gas, hydro	Coal, solar, wind, hydro, nuclear
Access to fossil fuel inputs	High (including via Pemex)	Moderate (domestic coal)	High (owns coal mines)	Moderate (domestic coal)	High (domestic coal)	High (domestic coal; owns coal mines)
Technical/Commercial Capacity	Moderate	Low	High	High	Moderate	High
c. Financial						
Financial Performance	Moderate	Low	High	High	Low	High
Direct and indirect subsidies	Producer, consumer	Direct	Electric Vehicles	Consumer	Direct	Direct, producer, offtaker
Profitable (with subsidies)	Yes	No	Yes	Yes	Yes	Yes
Profitable (without subsidies)	No	No	Yes	Yes	No	Unclear
d. Market structure						
Exposure to competition in generation market	Yes (IPPs)	Limited (94%)	Yes (IPPs)	Yes	Yes (IPPs)	Yes
Substantial Private participation in generation	Yes	No (8%)	Yes (30%)	Yes	Yes (33%)	No
Competition in T&D	No	No	No	Yes	No	Yes
Prospects for unbundling	No	Planned 2022	No	Completed	No	Completed
Power dispatch	Merit order	N/A	Merit order	Bilateral	N/A	Equal

Characteristic	CFE	Eskom	KEPCO	NTPC	PLN	SPIC
	reversed in 2021, CFE prioritized in dispatch			PPAs with DISCOMs		shares (thermal)
Projected growth in electricity demand	High	Moderate	None/negative	Very high	Moderate	Moderate
Energy policy certainty	Low	Low	High	Moderate	Moderate	High
e. Climate Enabling Environment						
Overall Government Climate Prioritization (trend)	Moderate (weakening)	Moderately Low	High (rising)	Moderately Low	Moderately Low (rising)	Moderate
National “net-zero” emissions target	No	No	Net zero 2050	No	Various Net zero dates discussed	Net zero 2060
SPC-level Emissions targets	None	None	Zero 2050	None	Zero 2050	Peak 2023, 75% of its capacity to be low carbon by 2030

B. Government policy, etc. interventions to influence SPC climate action

Table B: A non-exhaustive list of possible climate policy interventions

Targeted actions		Market-wide actions
Direct - Shareholder Prerogatives	Indirect - Government Resource Mobilization	
1) Formal directives through Board resolutions and instructions	1) Improving SPC access to finance for low-carbon activity (concessional loans, guarantees, tax rebates)	1) Carbon pricing (emissions trading, taxes)
2) Senior management appointments/dismissals	2) Investment in supporting associated infrastructure (e.g., transmission lines, grid expansion, etc.)	2) Generalized portfolio or technology standards and carbon budgets or intensity targets
3) Informal discussions with senior management	3) Coordinate SPC/government agency R&D in low-carbon technologies	3) Market design reforms (e.g., dispatch reform to favor renewables)
4) Changes to budgetary support from government, including low-carbon targeted/conditional equity injections and similar funding as shareholder	4) Mobilizing agency administrative and other action to support low-carbon investments (e.g., permitting, etc.)	4) Changes to competition regulations or market structure (including greater access for low-carbon private participation)
5) Mandating/prompting adoption of renewables and other portfolio targets	5) Public procurement to favor low-carbon products and services	5) Change in regulated prices upstream or downstream
6) Corporate restructuring, consolidation, or acquisition (including unbundling)	6) Price adjustments by state-owned enterprises upstream (e.g., fuel suppliers) or downstream (e.g., off-taker) of SPC to promote low-carbon activity	6) Removal (addition) of subsidies for high-carbon (low/zero-carbon) technologies
7) Mandating/prompting changes to operations, corporate strategy, culture, or cadre evaluation to boost success in decarbonization	7) Sponsoring new market entrants in low/zero-carbon technologies	7) Non-SPC targeted access to financing support
8) Mandating/prompting introduction/improvement of training and certification for climate risk management		8) General R&D spending on low/zero-carbon technologies
9) Mandating/prompting shadow carbon pricing/carbon intensity requirements for investment decisions		9) Investments in generalized infrastructure (e.g., charging stations)
10) Mandating/prompting introduction/improvement of carbon accounting and climate risk management standards		
11) Mandating/prompting introduction of measures for retirement of high-carbon assets		

C. Case Studies: Further Background Information

Comisión Federal de Electricidad (CFE)

1. Ownership and Corporate Governance

CFE is 100% state-owned, and the dominant player in the Mexican power sector, directly generating about 79.4% of Mexico's electricity. CFE is a vertically integrated company, structured into subsidiaries for service provision, distribution, and transmission, with a further six subsidiaries for power generation.¹

The company is directly supervised by the government. The Minister of Energy is Chairman of the Board of Directors, which also includes several other Ministers and independent directors appointed by the President of Mexico {add reference}. CFE's current CEO is Manuel Bartlett, a former Secretary of the Interior well known for supporting strong state involvement in the economy and is considered a "pillar" of the governing party.^{2,3}

2. Asset and Generation Profile

As of March 2019, the majority (72.7%) of CFE's installed electricity capacity was in the form of fossil fuel-fired plants, predominantly burning natural gas, coal, diesel, and fuel oil. Expensive fuel oil and diesel generating units represent a staggering 39% of total capacity (Table C-1). Combined with natural gas, CFE's fuel oil expenses amounted to 62% of its total fuel costs in Q1 2019. In 2018, electricity generation from CFE-owned sources totaled 249 TWh - a slight decrease from the 257.5 TWh peak in 2011.

Table C-1: CFE Installed Capacity as of March 31, 2019

Plant Type	GW	Share
Fuel oil and diesel	21.9	39%
Coal-fired	5.4	10%
Nuclear power	16.1	3%
Geothermal	0.87	2%
Total thermal (excluding IPPs)	29.85	53%
Hydro	12.13	21%
Wind-driven and photovoltaic	0.09	0%
IPPs (combined-cycle and wind-driven)	14.1	25%
Total CFE (including IPPs)	56.18	100%

3. Financial Performance

CFE has been, and continues to be, a major player in Mexico's economy. Its 2019 revenues totaled US\$6.2 billion (equivalent) in 2019, and its profits were US\$723 million (Table C-2). Given the close links between CFE and the Mexican government, CFE's credit ratings by Fitch Ratings are equalized to Mexico's sovereign rating, which stands at 'BBB-' as of August 2020. In isolation, CFE's rating would be 'bb'.⁴ The rating agency asserts that the current government's inclination to preserve CFE's market share could hamper urgently needed private sector investments in transmission and distribution capacity.

Table C-2: CFE Financial Indicators

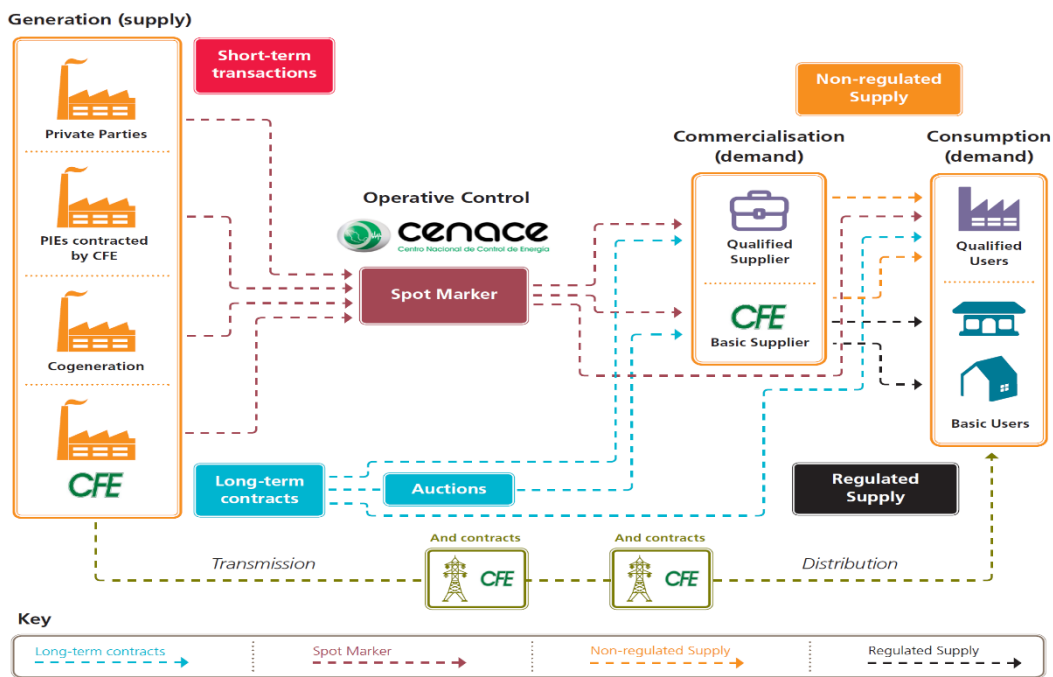
	2019	2018	2019	2018
Revenue	\$ 119,458	\$ 93,115	\$ 6,201.12	\$ 4,838.64
Profit/Loss	\$ 13,941	\$ 11,406	\$ 723.66	\$ 592.68
Total Assets	\$1,923,544	\$1,958,330	\$99,851.77	\$101,763.15
Total Equity	\$ 661,781	\$ 679,051	\$34,353.26	\$ 35,286.35
Current Liabilities	\$ 148,461	\$ 165,075	\$ 7,706.64	\$ 8,577.97
Non-Current Liabilities	\$1,113,302	\$1,114,205	\$57,791.86	\$ 57,898.82
	Mexican Pesos million		US\$ million	

Note: Financial Data to 31 March each year.
Source: CFE.⁵

4. Market and Regulatory Aspects

CFE plays an important role in Mexico’s electricity market (Figure C-1).

Figure C-1: The Mexican Electricity Market



Source: CMS Law and Tax.⁶

Besides taking major steps towards power market liberalization, the electricity reforms of 2013 increased CFE’s independence from government, drawing on corporate governance structures common in the private sector to remodel its internal decision-making processes. Prior to the reforms, CFE was subsidized directly by government to provide electricity to households at an operating loss. Following the reform, the burden to absorb the losses of the artificially low electricity prices has been transferred from CFE to the federal budget, while CFE is now required to pay the government dividends on its operating income. Since 2013, electricity prices are subsidized only for agricultural and low consumption residential customers, which amount to annual payments by the government of about MXN\$ 70bn (US\$ 3.45bn) to CFE.⁷

Government policy towards CFE changed considerably following the 2018 election of President López Obrador, widely considered an economic nationalist for whom state interventionism, and continued dominance of CFE in the Mexican power market, are attractive prospects.⁸ In this context, CFE acknowledges the fact that the government “has exercised, and continues to exercise, significant influence over the Mexican economy” as a significant risk to its future, noting that CFE’s operations are “closely linked to certain factors that are under the control of the Mexican government, such as the regulation of electricity rates throughout Mexico”.⁹ Illustrative of this is also the “wish list” of potential reforms favorable to CFE, which was sent from CFE to the Ministry of Energy and leaked in late 2019.¹⁰

In March 2021, the Mexican Congress passed a new electricity law to reverse a number of policies introduced in the past few years under President Peña Nieto. The new law hands substantial control of the Mexican electricity market back to CFE in an effort to deter increasing private sector influence on the market.¹¹ CFE is expected to play a key role as main customer of domestic fuel oil products for the Mexican State Oil company (PEMEX) as well, as President López Obrador is prioritizing energy self-sufficiency over climate ambition.

Under the new legislation, CFE generation is to be prioritized in dispatch over other market participants— largely renewable or natural gas IPPs – likely leading to an overall higher carbon intensity and higher costs. Despite the higher generation costs, electricity tariffs are not planned to be increased, indicating a higher reliance on future government subsidies.¹²

While the fate of the reform remains uncertain as legal challenges at the constitutional court and dispute-settlement mechanisms are likely and have been successful in the past,¹³ the specific consequences of the reform on CFE and existing private sectors IPPs are equally difficult to foresee, as key questions like the electricity price determination have not been clarified.¹⁴

Eskom

1. Ownership and Corporate Governance

Eskom was formally incorporated in 2002. Eskom Holdings State-owned Company (SOC) Limited is 100% owned by the South African government.

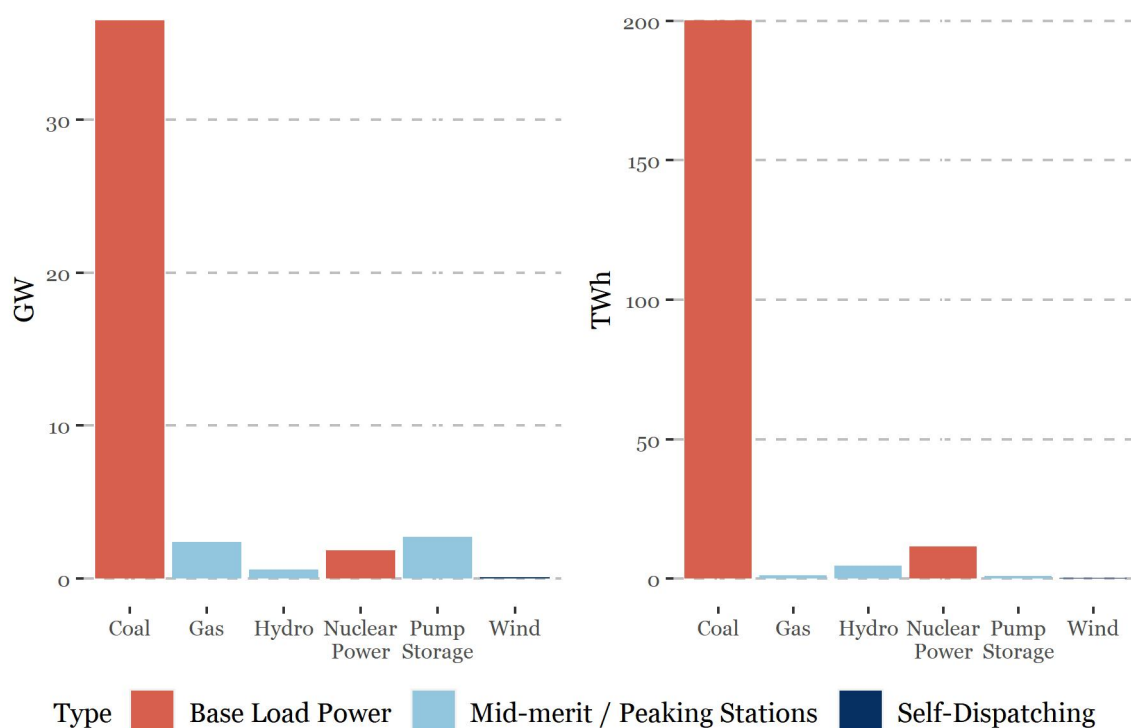
The Minister of Public Enterprises has executive authority over Eskom, while the Board sets its strategic direction and the Executive Committee implements guidance given by the Board. The current Group Chief Executive is Andre de Ruyter who has a background in the private sector fossil fuel industry.¹⁵ While the ministry formally responsible for representing the government shareholder's interests is the Department of Public Enterprises, the Department of Mineral Resources and Energy and the National Treasury are highly relevant to Eskom's strategy and operations.¹⁶

2. Asset and Generation Profile

In 2019, Eskom operated 30 power stations with a total installed capacity of 44.2 GW. It generated 218 TWh of electricity, of which 91% was from coal used for baseload power (Figure C-2). About 20 TWh of the power managed by Eskom is procured from IPPs and international suppliers. Neither Eskom nor the South African government is currently foreseeing the addition of new nuclear power stations until at least 2050.¹⁷

About 10 GW of existing capacity will need to be retired until 2030, adding further strain to an already capacity constrained system which had to shed some of its load on at least 52 days in 2020, despite the reduced demand during the COVID-19 pandemic.^{18,19}

Figure C-2: Left panel: Eskom's installed capacity (GW), 2017. Right panel: Eskom's generation in South Africa (TWh), 2017



Source: Eskom

3. Financial Performance

The Eskom Group achieved a revenue of about US\$ 12bn (equivalent) but had a net loss of US\$ 1bn in 2019. Capital expenditure amounted to about US\$ 2.1bn in the same year (Table C-3).

Table C-3: Eskom financial indicators

	2019	2018	2019	2018
Revenue	R 179,892	R 177,424	\$ 12,451	\$ 13,407
Profit/Loss	-R 20,729	-R 2,337	\$ -1,435	\$ -177
Total Assets	R 758,018	R 739,116	\$ 52,465	\$ 55,850
Total Equity	R 153,094	R 170,336	\$ 10,596	\$ 12,871
Total Liabilities	R 604,924	R 568,780	\$ 41,869	\$ 42,979
	Rand million		US\$ million	

Note: Financial Data to 31 March each year.

Source: Eskom.²⁰

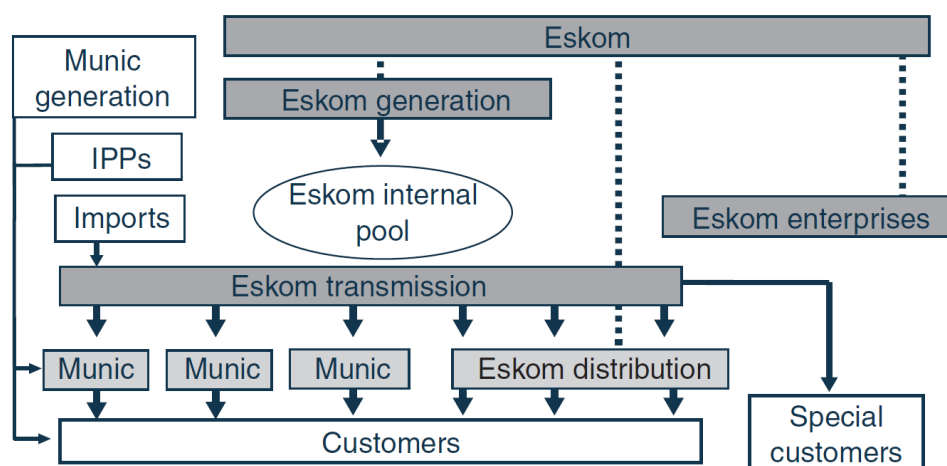
In real terms, Eskom's primary energy costs have risen by over 300% over the past two decades.²¹ The South African treasury describes Eskom's financial precarity as the "single biggest risk to the South African economy".²² Eskom is the country's largest recipient of government guarantees. Administered by the Treasury, these guarantees amounted to about R221bn (US\$ 13.4bn) in 2017 and R581bn (US\$ 40bn) by 2020.^{23,24}

As of September 2020, Fitch Ratings considers Eskom's standalone Credit Profile to be 'ccc-'. However, when considering the continued strong government support Fitch rates Eskom as 'B+' overall, albeit with a negative outlook.²⁵ By the end of the financial year 2020, Eskom constituted the lion's share of government guarantees with 77.2% of the total, amounting to about US\$ 40bn with an increase of US\$ 6.6bn in 2020.²⁶

4. Market and Regulatory Aspects

Eskom plays a central role in South Africa's electricity market (Figure C-3). Taken together with its numerous subsidiaries, Eskom resembles a vertically integrated power company. It operates primarily in South Africa and engages in some electricity trading within the 16 member states of the Southern African Development Community.

Figure C-3: Power market structure in South Africa, 2007



Source: Eberhard, 2007²⁷

The key pieces of power sector legislation in South Africa are the 2008 National Energy Act (NEA), the 2004 Energy Regulator Act (ERA) and the 2006 Regulation Act. Government-owned Eskom holds an effective monopoly over the South African electricity market, controlling over 48 GW of installed capacity and supplying around 94% of the country's power either directly or through IPPs. The remaining 6% is produced by power stations owned by municipal authorities and private companies. About 8% of total power generation is purchased by Eskom from IPPs, which focus predominantly on renewable energy.²⁸

Eskom also controls South Africa's transmission infrastructure, while municipalities are largely responsible for local distribution. The price at which municipalities can buy electricity from Eskom (or directly from IPPs) is centrally regulated, as is the margin that municipalities can make when re-selling electricity to consumers (see figure 3).

Recent reform efforts culminated in the introduction of the Independent Systems and Market Operator Act, which would have taken major steps towards more competitive power markets, including a corporate restructuring of Eskom, and providing consumers with more choice over their electricity suppliers. The bill has not yet been enacted, however, and as of 2020, has been delayed several times.²⁹ Some target the unbundling of Eskom to be completed by 2022.³⁰

Korea Electric Power Corporation (KEPCO)

1. Ownership and Corporate Governance

Korea Electric Power Company (KEPCO) was established in 1982.³¹ Through the Korea Development Bank, KDB (which merged with the Korean Finance Corporation at the end of 2014) and its direct holdings, the Korean government owns 51.1% of shares in KEPCO, with the remainder being publicly traded. As noted above, KEPCO is a vertically integrated utility active across all aspects of the Korean electricity market, including generation, transmission, distribution, and retail sales (see figure 3). KEPCO is also active in nuclear and coal fuel import markets. KEPCO's domestic thermal power generation is divided into five subsidiaries, with additional dedicated subsidiaries for its hydro and nuclear businesses. In total, KEPCO has 120 subsidiaries, 79 of which operate outside of Korea.³²

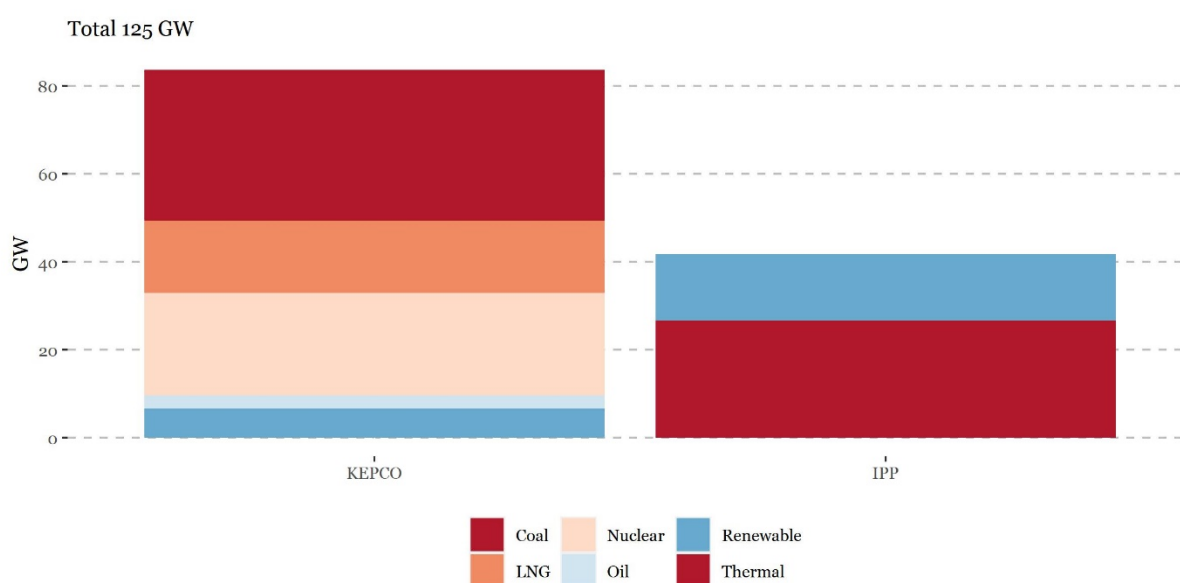
KEPCO's leadership nominations are initiated by a search committee and confirmed at the company's Annual General Meeting. The Minister of Trade, Industry and Energy recommends a CEO, which the Korean President can then choose to appoint.³³ The government is considered to have tight control over KEPCO's corporate strategy with informal directives being closely followed by the company.^{34,35}

2. Asset and Generation Profile

KEPCO's power generation mix is dominated by coal, which contributed 43.9% in Q1 2020, and nuclear generation, at 42%.³⁶ Natural gas generation (from imported LNG) provided 11.2% of power, having grown its share considerably in recent years. Renewable energy generation is very small, comprising just 2.8% in the first half of 2020.³⁷

About two thirds of KEPCO's generation is self-produced, with most of the remainder bought from IPPs. Renewable installations held directly by KEPCO make up 5% of total installed capacity, while those held by IPPs make up 12% (Figure C-4).

Figure C-4: KEPCO and IPP installed capacity (GW) Korea, 2020



Source: KEPCO³⁸

3. Financial Performance

Operationally, KEPCO generated a profit of US\$1.9 bn (equivalent) on revenues of US\$50 bn in 2019. Several key financial indicators are provided in Table C-4. Fitch Ratings equalizes KEPCO's credit rating with South Korea's 'AA-/Stable' reflecting the strong political commitment of the government to KEPCO, its strategic importance, and its prominent role in the domestic bond market.³⁹

Table C-4: KEPCO financial indicators

	2019	2018	2019	2018
Revenue	₩ 59,173	₩ 60,628	\$ 50,770	\$ 55,091
Profit/Loss	₩ 2,264	₩ 1,174	\$ 1,942	\$ 1,067
Total Assets	₩ 197,598	₩ 185,249	\$ 169,539	\$ 168,332
Total Equity	₩ 68,890	₩ 71,097	\$ 59,107	\$ 64,600
Current Liabilities	₩ 24,232	₩ 21,842	\$ 20,791	\$ 19,847
Non-Current Liabilities	₩ 104,476	₩ 92,315	\$ 89,641	\$ 83,884
	₩ billion		US\$ million	

Source: KEPCO.⁴⁰

4. Market and Regulatory Aspects

KEPCO has a central role in Korea's electricity sector (Figure C-5). KEPCO still dominates most aspects of the power market, however, with a monopoly on transmission and distribution and direct control over 66% of Korea's installed capacity. IPPs account for about 30% of generation but depend on KEPCO for transmission, distribution, and retail sale of electricity. A small share of electricity is contracted via private PPA with KEPCO. There are also a small number of captive electricity businesses which sell electricity to a specific (usually industrial) customer, but these types of transactions constitute a marginal portion of the Korean power system.

Figure C-5: The electricity market in Korea



Source: KEPCO

New coal power plants are continuously being introduced to KEPCO's grid, such as the POSCO owned 2.1 GW plant in the coastal town of Samcheok to be finished in 2024 which is being touted as "the final coal power project",⁴¹.

In 2020, KEPCO approved plans to invest in two coal plants in Indonesia and Vietnam, which triggered an international reaction by investor groups.⁴² KEPCO has since signaled it would not fund any new coal projects, in line with stated government intentions.^{43,44}

In an effort to curb carbon emissions, the government asked KEPCO in an informal request to reduce electricity output from coal-fired power stations by 18%-24% over April to November 2021, compared with the 2017 – 2019 average. Similar policies have so far only been in place over the winter months and were mainly aimed to reduce air pollution.⁴⁵

NTPC Limited (NTPC)

1. Ownership and Corporate Governance

NTPC is a “government company” under Indian law.⁴⁶ In addition to being India’s largest power company, it is the sixth largest thermal power producer in the world. As of 30 June 2020, the central government held a 51% equity stake in the company. The remaining shares are publicly traded, primarily among mutual funds and other financial institutions.⁴⁷

The Minister of Power acts as a director for the company alongside a second government director, although a number of other ministries are also relevant stakeholders.⁴⁸ Directors, including the company Chairman, are appointed by the President of India. The current Chairman and Managing Director is Shri Gurdeep Singh, a former executive at various power sector institutions. The company aligns its strategy with government priorities and agrees key performance indicators (KPIs) annually with the government through a Memorandum of Understanding.

2. Asset and Generation Profile

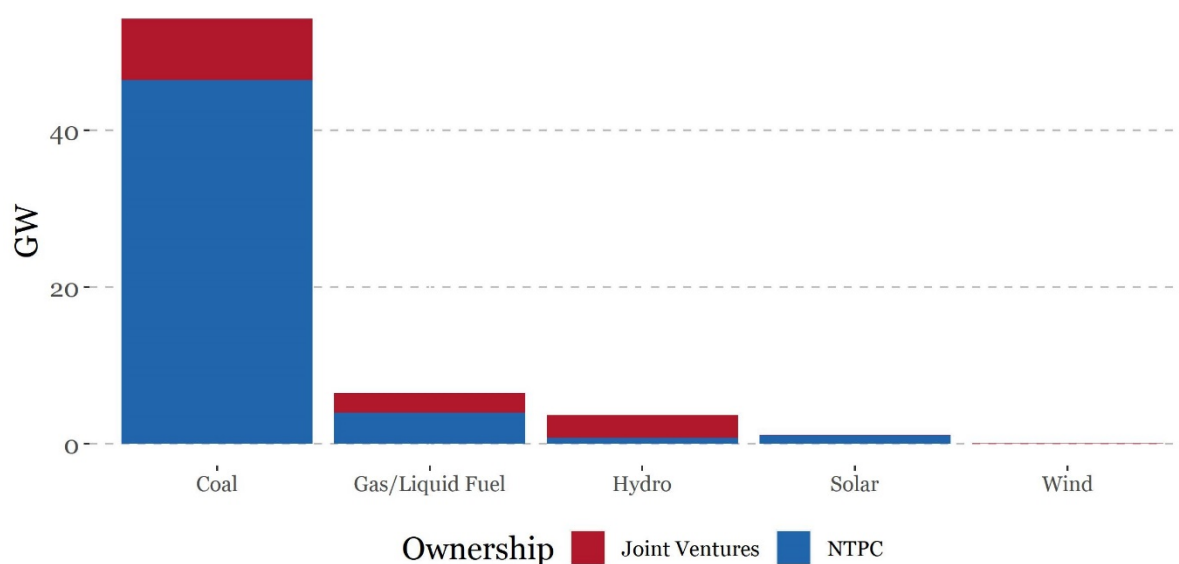
NTPC produces about a quarter of India’s electricity.⁴⁹ While the company is engaged in various electricity operations, it derives more than 90% of its revenue (94% in FY 2018-2019) from the bulk sale of power to electric utilities owned by state governments, and to a lesser extent to private distribution companies, through long-term contracts.

Including subsidiaries and joint ventures, NTPC controls 65.8 GW of generation capacity, about 82% of which is coal-fired (Figure C-6). There is currently around 20 GW of additional capacity in the pipeline, of which 18.8 GW are new coal projects, with 5.3 GW expected to become operational soon.⁵⁰ NTPC also owns some natural gas power generation assets, but very little renewable capacity; with its installed renewable energy capacity (excluding hydro) amounting to 0.93 GW (about 1.6% of total capacity), although a further 0.35 GW is under construction.

Heavy reliance on fossil fuels is a major determinant of NTPC’s business model, as fuel acquisition accounts for 81% of total operational expenditures. To hedge coal price volatility, NTPC is increasingly expanding into coal mining operations, expanding its production capacity to over 100 million metric tons per year, representing more than half of its 2018 coal consumption. Fitch Ratings also posits that in the most extreme situations, such as a default, other state-owned companies like Coal India could supply coal to NTPC as a temporary measure, exemplifying the close coordination among state-owned enterprises.⁵¹

In October 2020, NTPC announced the establishment of a new subsidiary ‘NTPC Renewable Energy Ltd’⁵² and further has announced a joint venture with the Indian Oil and Natural Gas Corp. on offshore wind.⁵³

Figure C-6: Installed capacity, NTPC (GW) in India, 2021



Source: NTPC Limited⁵⁴

3. Financial Performance

NTPC had revenues of US\$14 billion (equivalent) and profits of US\$1.4 billion (equivalent) in the fiscal year ending March 31, 2020 (Table C-5). It operates most of its generation assets directly, but also has six subsidiaries and is engaged in 17 joint-venture operations.

Table C-5: NTPC financial indicators

	2020	2019	2020	2019
Revenue	₹ 100,478	₹ 92,180	\$14,268	\$13,090
Profit/Loss	₹ 10,113	₹ 11,750	\$ 1,436	\$ 1,669
Total Assets	₹ 327,667	₹ 290,751	\$46,530	\$41,288
Total Equity	₹ 113,569	₹ 107,408	\$16,127	\$15,253
Current Liabilities	₹ 54,867	₹ 55,354	\$ 7,791	\$ 7,861
Non-Current Liabilities	₹ 155,989	₹ 125,849	\$22,151	\$17,871
	Rupee Crore		US\$ million	

Note: Financial Data to 31 March each year.

Source: NTPC.⁵⁵

Fitch Ratings rates NTPC's creditworthiness at 'bbb-' with a stable outlook. Fitch considers the link between the government and NTPC as 'Strong' and cites the strategic importance of NTPC as a key rating driver.⁵⁶ Despite the high capital expenditure that Fitch expects NTPC to invest, the company's leverage is expected to decline as past investments are due to be finalised in the coming years.⁵⁷

Compared to other state-owned utilities in India, NTPC receives fewer government subsidies due to its relatively strong financial position. NTPC's customers, mostly state-owned distribution companies, have a much weaker financial profile, although NTPC is taking steps to diversify its business model and has ambitions to become a vertically integrated energy service provider.⁵⁸

4. Market and Regulatory Aspects

NTPC is the largest producer of thermal power in India. There are other generators and other actors in the sector, including in distribution. The National Hydroelectric Power Corporation (NHPC) is India's largest hydropower producer and is also owned by the national government. Most non-hydro renewable assets in India are controlled by private companies. State-level power generators controlling a significant proportion of total coal, hydro and gas capacity.

Much of India's power activity occurs at the State level. State-level power companies in the public and private sectors play important roles across generation, transmission, and distribution. SPCs are particularly dominant in transmission and distribution.

Most States both regulate and facilitate transmission and distribution activity within their state. Transmission and distribution of electricity are liberalized to a certain degree in some states, with large private sector companies like Adani and Tata engaged in both activities in certain regions. However, the primary buyers of electricity are still State-level DISCOMs, who then sell the electricity to retail consumers.

Perusahaan Listrik Negara (PLN)

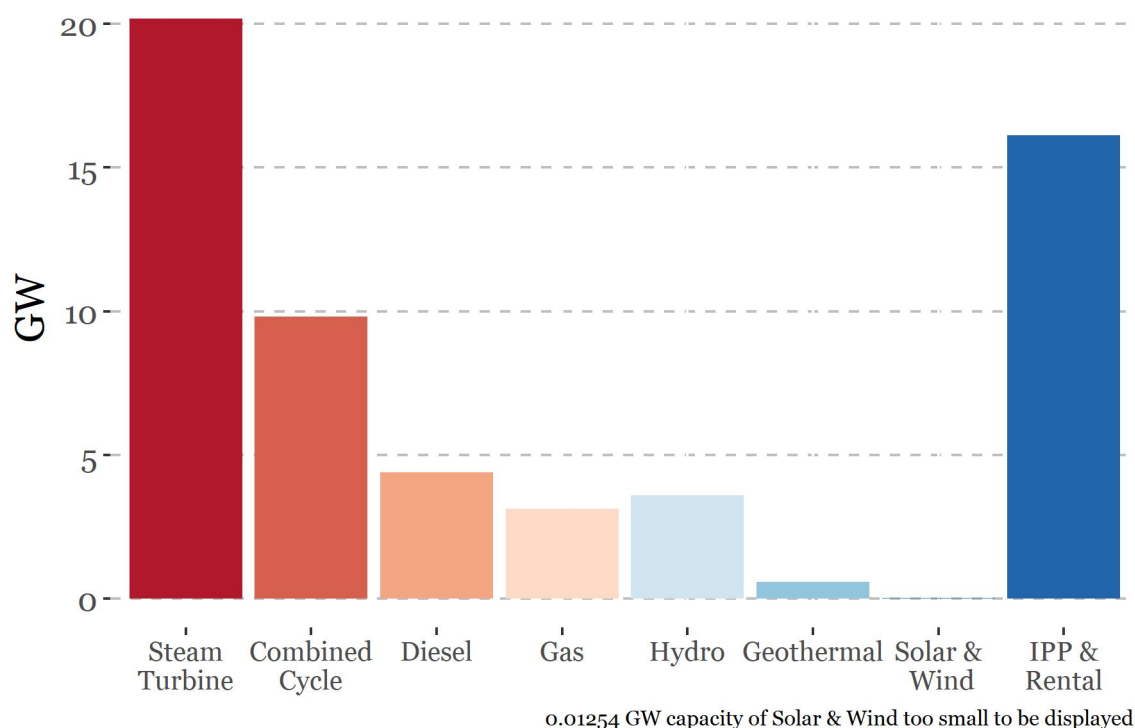
1. Ownership and Corporate Governance

As a wholly government-owned company, 100% of PLN's shares are owned by the government and administered by the Ministry of State-Owned Enterprises (BUMN). PLN's internal management structure resembles that of a private sector company, with a Board of Commissioners overseeing the Board of Directors, and the President Director. Since 2019, former banker Zulkifli Zaini has occupied the latter post⁵⁹.

2. Asset and Generation Profile

In 2018, PLN directly (or indirectly through subsidiaries) owned 41.7 GW of capacity across 6,700 individual power stations and held contractual relationships with a further 57.8 GW of generating capacity (including IPPs and rented assets). Coal-based steam turbine installations and CCNG plants represent over 30 GW of PLN's total capacity, with solar and wind installations practically inexistent. Most non-fossil-based generation comes from geothermal and hydro (Figure C-7). Of the 56 GW of additional capacity the government expects to need by 2027, PLN is tasked with constructing at least 16.6 GW.⁶⁰

Figure C-7: Installed Capacity controlled by PLN (GW), Indonesia, 2018



Source: PLN Statistics

In May 2021, PLN's President Zaini stated that electricity production is expected to increase from about 250-300 TWh today to about 1,100 TWh by 2050, which would equate to an annual growth rate of about 4.7%.

3. Financial Performance

PLN's financial performance is dominated by revenues from electric sales, which accounted for US\$ 18.6bn in 2018, or 96.55% of total operating revenue (Table C-6).⁶¹ In the same year, PLN reported

net income of US\$ 0.82bn. This figure is highly dependent on subsidies from the Ministry of Finance, however which amounted to US\$ 3.4bn in 2018, implying a substantial underlying loss once subsidies are accounted for.⁶² Operating results excluding subsidies from 2014 to 2018 suggest average annual losses of around US\$ 2.1bn.⁶³

Table C-6: PLN financial indicators

	2018	2017	2018	2017
Revenue	Rp 272,898	Rp 255,295	\$ 19,289	\$17,931
Profit/Loss	Rp 11,576	Rp 4,428	\$ 818	\$ 311
Total Assets	Rp 1,492,488	Rp 1,334,958	\$105,493	\$93,767
Total Equity	Rp 927,414	Rp 869,417	\$ 65,552	\$61,067
Current Liabilities	Rp 157,896	Rp 139,075	\$ 11,160	\$ 9,768
Non-Current Liabilities	Rp 407,178	Rp 326,466	\$ 28,780	\$22,930
	Rupiah billion		US\$ million	

Source: PLN.⁶⁴

To finance power plant construction, PLN frequently issues both domestic and international bonds. Domestic bonds are generally rated AAA, while international bonds are rated much lower, at BBB (Fitch) and Baa3 (Moody's).⁶⁵ In these ratings, agencies are equalizing the company's ratings with Indonesia's rating and cite the 'very strong' likelihood of government support for these bonds and considers the subsidy framework of PLN to be 'exceptionally strong' to meet public service obligations.⁶⁶

4. Market and Regulatory Aspects

PLN plays a dominant role in Indonesia's electricity sector. PLN oversaw the generation, distribution, transmission, and sale of electricity to 71.9 million users in 2018, either directly or through its several regional subsidiaries.

PLN enjoys a dominant position in Indonesia's power sector, accounting for about 72% of installed capacity, and 66% of electricity generated.⁶⁷ The company also has a quasi-monopoly over the transmission, distribution, and sale of electricity and right of first refusal across all its business areas under the 2009 Electricity Law. Private companies can therefore only engage in business areas not covered by PLN already, or in projects in which it chooses not to participate.⁶⁸ In theory, this allows private companies to engage in various aspects of the power market, however, "in practice, PLN remains the only party supplying electricity to end consumers in Indonesia".⁶⁹

In May 2021, PLN announced it would become carbon neutral by 2050 – significantly faster than the national target of 2070 presented by the government just a few weeks earlier.⁷⁰

State Power Investment Corporation (SPIC)

1. Ownership and Corporate Governance

The State Power Investment Corporation was formed in 2015 from the merger of China Power Investment Corporation with State Nuclear Power Technology Corporation.⁷¹ The parent company, the State-owned Assets Supervision and Administration Commission (SASAC) which owns 90% of SPIC, is owned fully by the Chinese central government. The remaining 10% are held by the National Council for Social Security Fund.⁷² SASAC, together with the Organization Department of the Communist Party of China appoint key personnel, including the current SPIC chairman Qian Zhimin and General Manager Jiang Yi.⁷³ Generally, the SPIC leadership is deeply rooted in the state-owned power industry and many executives have previously worked at other SOEs.

SPIC is majority-owned by the central government and administered by the State-owned Assets Supervision and Administration Commission (SASAC). It has established ??? subsidiaries that include some private participation and are listed on stock exchanges (e.g., Hong Kong). SPIC has a number of listed subsidiaries that include private stock ownership. SPIC has invested also in coal mining.

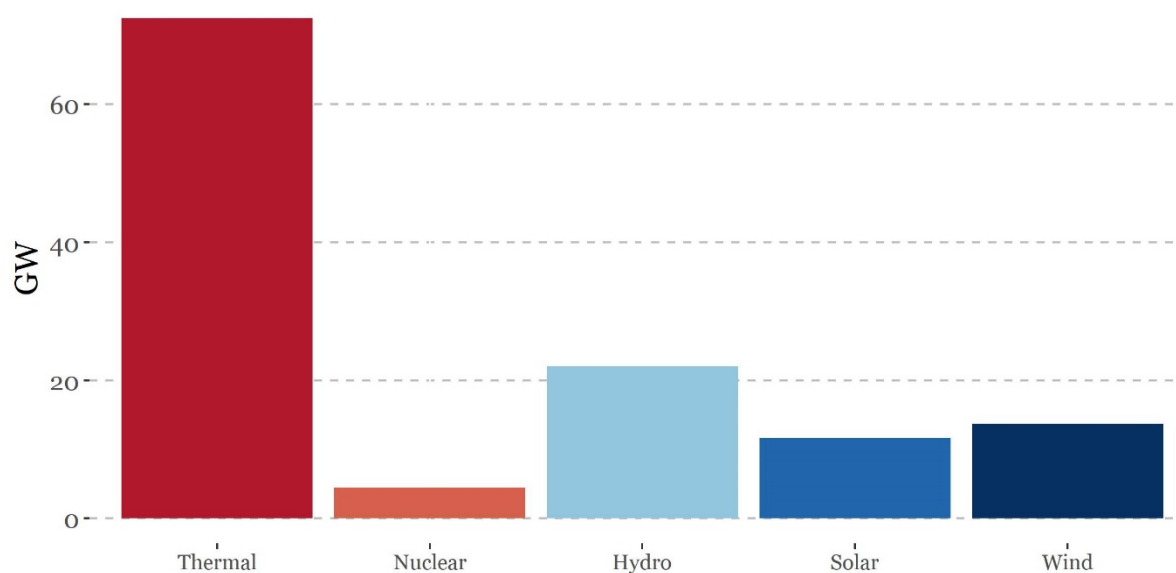
2. Asset and Generation Profile

SPIC holds the most diversified asset portfolio of all energy companies in China, spanning thermal, nuclear, hydro, and renewable assets.⁷⁴ The company is regarded as the world's largest producer of renewable power in terms of combined wind and solar capacity.⁷⁵ Overall, by 2016 SPIC controlled about 126 GW of installed capacity, 55% of which was thermal. The remaining capacity is entirely low carbon, made up of 22 GW of hydropower, 4.5 GW of nuclear power, 11.7 GW of solar power, and 13.7 GW of wind power (Figure C-8). Since then, further capacity was added so that by December 2020 SPIC operated a total of 165 GW.⁷⁶

Within its nuclear business, SPIC is playing a leading role in the development of large-scale advanced pressurized water reactors (third-generation reactors).⁷⁷

As part of its roughly RMB 1000bn (about US\$150bn; see Table C-7) in total assets, SPIC operates coal mining facilities capable of producing 78.6 million tons of coal annually.

Figure C-8: SPIC Installed Capacity (GW) in China, 2020



Source: SPIC⁷⁸

3. Financial Performance

SPIC is a Fortune Global 500 company, earning a profit of RMB 13.21bn (US\$ 1.95bn) in 2016 (Table C-7), the highest net profit among its Big Five peers.⁷⁹

Table C-7: SPIC financial indicators

	2017	2016	2017	2016
Total Assets	¥1,001	¥ 876	\$150,692	\$129,620
Revenue	¥ 201	¥ 196	\$ 30,237	\$ 28,988
Profit	¥ 9.4	¥ 13.2	\$ 1,407	\$ 1,954
Equity Return	3.18%	6.05%	-	-
Employees	127,343	127,083	-	-
	RMB bn		US\$ million	

Source: SPIC.⁸⁰

SPIC is rated 'A2' (Moody's), 'A' (Fitch; stable outlook) and 'A-' (S&P) by the three leading credit agencies, and the group issued US\$1.2bn in overseas bonds for the first time in 2017. Fitch Ratings rates SPIC one notch below China's sovereign rating ('A+/Stable') but remains confident of a strong likelihood of state support, given the company's strategic importance to the Chinese power market and its assessment that the state control over the company is 'Strong'.⁸¹

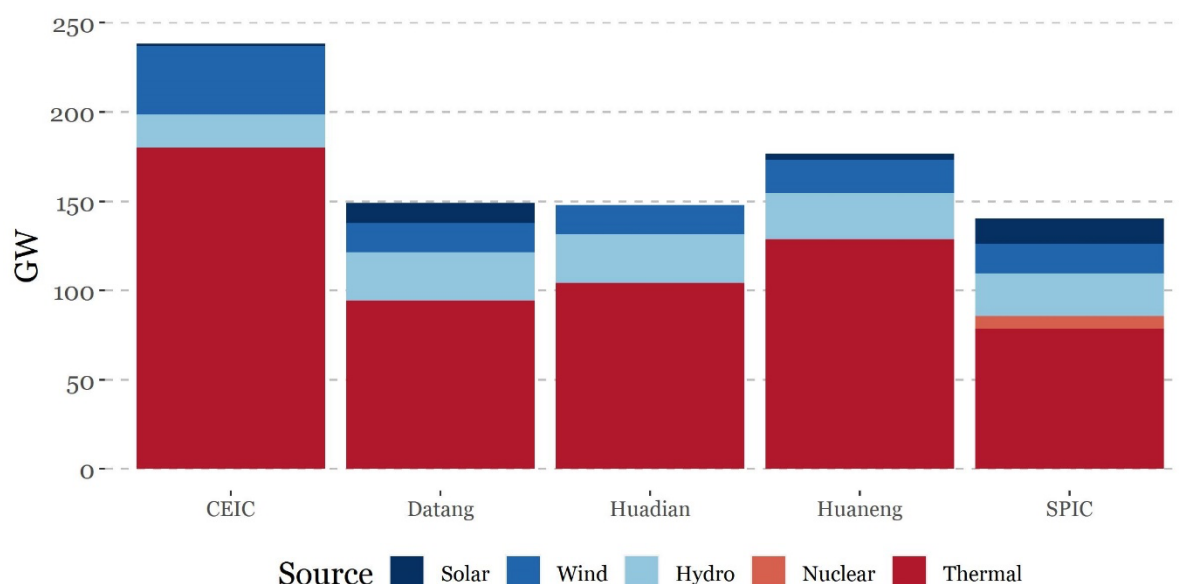
4. Market and Regulatory Aspects

In 2002, the Chinese government broke up the vertically integrated State Power Corp of China (SPCC) into the "Big Five" generation companies (including what has become State Power Investment Corporation – SPIC), two power grid companies (State Grid Corporation of China, which has over 1 billion customers, and China Southern Power Grid) and four engineering firms. These companies collectively dominate the Chinese power market.⁸²

The Big Five compete with each other in the generation market to some degree. They have been restructured a number of times, but are currently: SPIC, China Huaneng Group, China Datang Corporation, China Huadian Corporation, and China Energy Investment Corporation (CEIC or China Energy, formed in 2017 from the merger of China Guodian and Shenhua Group).

Figure C-9 sets out the size of SPIC and its generation mix relative to the other Big 5.

Figure C-9: Big Five Installed Capacity (GW) in China, 2018



Source: Energy Iceberg.⁸³

In 2015, the State Council proposed the so-called “Document 9” reform, which would abandon the equal allocation principle and the benchmark price in favor of a competitive wholesale market. To facilitate this transition, the central government has gradually reduced supply allocations to major energy generators, forcing them to directly negotiate power purchase agreements (PPAs) with large industrial customers, typically at prices lower than the benchmark. In 2018, the central government established day-ahead and real-time electricity spot auctions for the first time, in Guangdong province, as a further step towards electricity market liberalization.⁸⁴

In parallel to electricity market reforms, the central government elected to devolve decision-making on power capacity to the provincial level, leading to a coal construction boom that quickly threatened to create oversupply in electricity markets. In part to curtail coal capacity additions, a “traffic light” approval process was introduced in 2016 by the National Energy Administration, an agency of the powerful National Development and Reform Commission (NDRC). Under the system, new power plant approvals are conditional on their performance against grid capacity, resource availability (primarily water and coal), and profitability metrics. ‘Red’ or ‘orange’ performance on either of the first two criteria places a binding restriction on capacity additions. The number of provinces with red or orange ratings on both criteria has fallen from 26 in 2018 (which affects projects expected to come online in 2021) to 13 in 2020 (2023).⁸⁵

SPIC is also active internationally. It has a presence in 41 countries, including Australia, Japan, India, Turkey, South Africa, Pakistan, and Brazil, having invested into over 10 GW of power generation capacity alongside a range of other services. SPIC is also a key player in China’s Belt and Road Initiative (BRI), providing expertise and technology for renewable and nuclear power projects. Internationally SPIC is active in 46 countries with key investments in nuclear power currently undergoing in Turkey, South Africa, and Bulgaria and overall international non-fossil generation accounting for 70% of the international total.⁸⁶

-
- ¹ J.P. Morgan. Offering Memorandum. en. July 2019. url: [https://www.cfe.mx/inversionistas/Documents/emision_certificados/CFE%20Formosa%202019%20-%20Final%20OM%20\(Final\).pdf](https://www.cfe.mx/inversionistas/Documents/emision_certificados/CFE%20Formosa%202019%20-%20Final%20OM%20(Final).pdf) (visited on 07/21/2020). Cited quotes from pages p. 15 and p. 17.
- ² David Alire Garcia. "Exclusive: Renewable firms in Mexico must contribute to grid backup - CFE chief". en. In: *Reuters* (May 2020). url: <https://www.reuters.com/article/us-mexico-electricityexclusive-idUSKBN22Y2W8> (visited on 07/21/2020).
- ³ The Economist. (2021). A bad energy law says much about Mexico's president. *The Economist*. <https://www.economist.com/the-americas/2021/03/11/a-bad-energy-law-says-much-about-mexicos-president> (visited 05/05/2021).
- ⁴ Fitch Ratings (2020). Fitch Affirms Comision Federal de Electricidad's Ratings at 'BBB-'; Outlook Stable. Fitch Ratings. url: <https://www.fitchratings.com/research/corporate-finance/fitch-affirms-comision-federal-de-electricidad-ratings-at-bbb-outlook-stable-11-08-2020> (visited 05/05/2021).
- ⁵ Data from CFE Unaudited condensed consolidated financial information March 31, 2019. Annualised Exchange rates extracted from <https://data.oecd.org/conversion/exchange-rates.htm>.
- ⁶ CMS Law and Tax. A brief overview of the new Mexican Electricity Wholesale Market. url: <https://cms.law/en/content/download/300306> (visited 07/31/2020).
- ⁷ Fitch Ratings (2020). Fitch Affirms Comision Federal de Electricidad's Ratings at 'BBB-'; Outlook Stable. Fitch Ratings. url: <https://www.fitchratings.com/research/corporate-finance/fitch-affirms-comision-federal-de-electricidad-ratings-at-bbb-outlook-stable-11-08-2020> (visited 05/05/2021).
- ⁸ Veronica Irastorza and José Antonio Peñuelas. *Mexican Electricity Wholesale Market Report 2019*. en. Tech. rep. 2019, p. 10.
- ⁹ J.P. Morgan. Offering Memorandum. en. July 2019. url: [https://www.cfe.mx/inversionistas/Documents/emision_certificados/CFE%20Formosa%202019%20-%20Final%20OM%20\(Final\).pdf](https://www.cfe.mx/inversionistas/Documents/emision_certificados/CFE%20Formosa%202019%20-%20Final%20OM%20(Final).pdf) (visited on 07/21/2020). Cited quotes from pages p. 15 and p. 17.
- ¹⁰ Bierzwinsky, R., Campuzano, C. (2020). New policy in Mexico puts dagger in private sector participation in the electricity sector. Norton Rose Fulbright. url: <https://www.nortonrosefulbright.com/en/knowledge/publications/1fb1a246/new-policy-in-mexico-affects-electricity-sector> (visited 05/05/2021).
- ¹¹ The Economist. (2021). A bad energy law says much about Mexico's president. *The Economist*. <https://www.economist.com/the-americas/2021/03/11/a-bad-energy-law-says-much-about-mexicos-president> (visited 05/05/2021).
- ¹² Ibid.
- ¹³ Ibid.
- ¹⁴ Ibid.
- ¹⁵ Business Tech (2018). Eskom a risk to South Africa as finances are getting worse: report <https://businesstech.co.za/news/energy/227655/eskom-a-risk-to-south-africa-as-finances-are-getting-worse-report/> (visited 08/25/20).
- ¹⁶ Eskom (2019). Integrated Report.
- ¹⁷ Makeo, T. (2021). Eskom to be fully unbundled by December 2022. TechCentral. <https://techcentral.co.za/eskom-to-be-fully-unbundled-by-december-2022/105268/> (visited 05/04/2021).
- ¹⁸ Mhlanga, D. (2020). Unbundling of Eskom key in attracting investment into independent power grid. BizNews. url: [Unbundling of Eskom key in attracting investment into independent power grid - BizNews.com](https://www.biznews.com/unbundling-of-eskom-key-in-attracting-investment-into-independent-power-grid) (visited 05/04/2021).
- ¹⁹ Makeo, T. (2021). Eskom to be fully unbundled by December 2022. TechCentral. <https://techcentral.co.za/eskom-to-be-fully-unbundled-by-december-2022/105268/> (visited 05/04/2021).

-
- ⁴⁰ Data from KEPCO Consolidated Audit Report 2019 (2020). Annualised Exchange rates extracted from <https://data.oecd.org/conversion/exchange-rates.htm>.
- ⁴¹ Ji-hyoung, S. (2021). Korea's final coal power project faces renewed scrutiny. The Korea Herald. url: <http://www.koreaherald.com/view.php?ud=20210309000812> (visited 05/13/2021).
- ⁴² Macdonald, S. (2021). South Korea's Climate Pledges: Less Than Meets the Eye. The Diplomat. url: <https://thediplomat.com/2021/05/south-koreas-climate-pledges-less-than-meets-the-eye/> (visited 05/13/2021).
- ⁴³ Lee, H. (2021). South Korea Shuns Coal-Power Financing Amid Rising U.S. Pressure. Bloomberg. url: <https://www.bloomberg.com/news/articles/2021-04-22/south-korea-shuns-coal-power-financing-amid-rising-u-s-pressure> (visited 05/13/2021).
- ⁴⁴ Pulse (2020). KEPCO declares exit from overseas coal ventures after Vung Ang project. Pulse. url: <https://pulsenews.co.kr/view.php?year=2020&no=1110356> (visited 05/13/2021).
- ⁴⁵ Mozur, M., Brunetti, B., Lambine, A. (2021). Global thermal, coal-fired generation rebound at odds with accelerating net zero pledges. S&P Global Platts. url: <https://www.spglobal.com/platts/en/market-insights/blogs/energy-transition/051221-global-thermal-coal-generation-rebound-net-zero-climate-renewables> (visited 05/13/2021).
- ⁴⁶ Within the meaning of Section 2 (45) of the Companies Act, 2013.
- ⁴⁷ NTPC Equity Shares as of 30 June 2020. url: <https://www.ntpc.co.in/sites/default/files/downloads/NTPCSHP3062020.pdf> (visited on 07/28/2020).
- ⁴⁸ NTPC 43rd Annual Report 2018-2019. url: <https://www.ntpc.co.in/annual-reports/8863/download-complete-annual-report-2018-19-0> (visited on 07/28/2020).
- ⁴⁹ Singh, G. (2021). Power and Sustainability: The View from India's State-Owned Utility Sector. Interview at: *Columbia Global Energy Summit*. url: <https://www.energypolicy.columbia.edu/events-calendar/columbia-global-energy-summit-power-and-sustainability-view-india-s-state-owned-utility-sector> (visited 05/23/2021).
- ⁵⁰ IBEF Power Market Report 2020. url: <https://www.ibef.org/industry/power-sector-india.aspx> (visited on 07/28/2020).
- ⁵¹ Fitch Ratings (2020). Fitch Affirms India's NTPC at 'BBB-'; Outlook Stable. Fitch Ratings. url: <https://www.fitchratings.com/research/corporate-finance/fitch-affirms-india-ntpc-at-bbb-outlook-stable-12-06-2020> (visited 05/23/21).
- ⁵² Saur Energy International (2020). url: <https://www.saurenergy.com/solar-energy-news/in-ntpcs-30-gw-solar-plan-a-move-to-maintain-control-over-indias-solar-targets> (visited 05/24/2021).
- ⁵³ World Benchmarking Alliance (2021). NTPC. World Benchmarking Alliance. url: <https://www.worldbenchmarkingalliance.org/publication/electric-utilities/companies/ntpc/> (visited 05/24/2021).
- ⁵⁴ NTPC (2021). Installed Capacity. NTPC Website. url: <https://www.ntpc.co.in/en/power-generation/installed-capacity> (visited 05/24/2021).
- ⁵⁵ Data from Statement of Audited Standalone & Consolidated Results for the Quarter and Year ended 31 March 2020. Annualised Exchange rates extracted from <https://data.oecd.org/conversion/exchange-rates.htm>.
- ⁵⁶ Fitch Ratings (2020). Fitch Affirms India's NTPC at 'BBB-'; Outlook Stable. Fitch Ratings. url: <https://www.fitchratings.com/research/corporate-finance/fitch-affirms-india-ntpc-at-bbb-outlook-stable-12-06-2020> (visited 05/23/21).
- ⁵⁷ Ibid.
- ⁵⁸ Singh, G. (2021). Power and Sustainability: The View from India's State-Owned Utility Sector. Interview at: *Columbia Global Energy Summit*. url: <https://www.energypolicy.columbia.edu/events-calendar/columbia-global-energy-summit-power-and-sustainability-view-india-s-state-owned-utility-sector> (visited 05/23/2021).

Similar views were voiced at the World Economic Forum, covered here: The Economic Times (2021). NTPC aims to be integrated energy giant, not just coal-based power firm: CMD Gurdeep Singh. The Economic Times. url: <https://economictimes.indiatimes.com/industry/energy/ntpc-aims-to-be-integrated-energy-giant-not-just-coal-based-power-firm-cmd-gurdeep-singh/articleshow/80482603.cms>

⁵⁹ Jakarta Globe (2019). Former Banker Zulkifli Zaini Named as New PLN Boss.

<https://jakartaglobe.id/business/former-banker-zulkifli-zaini-named-as-new-pln-boss/>

⁶⁰ PWC (2018). Power in Indonesia Investment and Taxation Guide. November 2018, 6th Edition

⁶¹ PLN (2019). PLN Statistics 2018. url: <https://web.pln.co.id/statics/uploads/2019/07/STATISTICS-English-26.7.19.pdf>

⁶² PLN Annual Report (2018).

⁶³ IEEFA (2018). Perusahaan Listrik Negara (PLN): A Power Company Out of Step With Global Trends

<https://ieefa.org/wp-content/uploads/2018/04/PLN-A-Power-Company-out-of-Step-With-Global-Trends-April-2018.pdf> (visited 08/11/2020).

⁶⁴ Data from PLN Consolidated Financial Statements 2018. Annualised Exchange rates extracted from

<https://data.oecd.org/conversion/exchange-rates.htm>.

⁶⁵ PLN Annual Report (2018).

⁶⁶ Fitch Ratings (2020). Fitch Affirms Indonesia's PLN at 'BBB'; Outlook Stable. Fitch Ratings. url:

<https://www.fitchratings.com/research/corporate-finance/fitch-affirms-indonesia-pln-at-bbb-outlook-stable-07-09-2020> (visited 05/14/2021).

⁶⁷ Statistics PLN (2018).

⁶⁸ Thomson Reuters Pratical Law (2020). Electricity regulation in Indonesia: overview Q&A by Firmansyah and Rizki Karim, KarimSyah Law Firm.

[https://uk.practicallaw.thomsonreuters.com/w-025-0669?transitionType=Default&contextData=\(sc.Default\)&firstPage=true&bhcp=1](https://uk.practicallaw.thomsonreuters.com/w-025-0669?transitionType=Default&contextData=(sc.Default)&firstPage=true&bhcp=1) (visited 08/11/2020).

⁶⁹ Quoted from Question 23 in Thomson Reuters Pratical Law (2020). Electricity regulation in Indonesia: overview Q&A by Firmansyah and Rizki Karim, KarimSyah Law Firm.

[https://uk.practicallaw.thomsonreuters.com/w-025-0669?transitionType=Default&contextData=\(sc.Default\)&firstPage=true&bhcp=1](https://uk.practicallaw.thomsonreuters.com/w-025-0669?transitionType=Default&contextData=(sc.Default)&firstPage=true&bhcp=1) (visited 08/11/2020).

⁷⁰ The Star (2021). Indonesia's electricity body PLN pledges carbon neutrality by 2050. url:

<https://www.thestar.com.my/aseanplus/aseanplus-news/2021/05/09/indonesia039s-electricity-body-pln-pledges-carbon-neutrality-by-2050> (visited 05/17/2021).

⁷¹ SPIC (2020). Company Overview. url: <http://eng.spic.com.cn/2016SiteEn/aboutSPIC/CompanyOverview/> (visited 09/16/2020).

⁷² Fitch Ratings (2020). State Power Investment Corporation Limited. Fitch Ratings. url:

<https://www.fitchratings.com/research/corporate-finance/state-power-investment-corporation-limited-15-01-2020> (visited 05/25/2021).

⁷³ Ibid.

⁷⁴ IHA (2020). State Power Investment Company (SPIC). url: <https://www.hydropower.org/companies/state-power-investment-corporation-spic> (visited 09/16/2020).

⁷⁵ Energy Iceberg (2019). China's State-Owned Power Generation Utilities, Who Are They? url:

<https://energyiceberg.com/state-owned-power-utilities/> (visited 09/17/2020).

⁷⁶ Reuters (2020, 10 December). "China's SPIC aims to cap domestic carbon emissions by 2023". Reuters. url:

<https://www.reuters.com/article/china-spic-climatechange-idUSL4N2IQ0R4> (visited 12/20/2020).

⁷⁷ WNN (2020). China launches CAP1400 reactor design. url: <https://world-nuclear-news.org/Articles/Large-scale-Chinese-reactor-design-officially-laun> (visited 09/30/2020).

⁷⁸ SPIC (2020). Company Overview. url: <http://eng.spic.com.cn/2016SiteEn/aboutSPIC/CompanyOverview/> (visited 09/16/2020).

⁷⁹ Ibid.

⁸⁰ Data from SPIC Corporate Responsibility Report 2017 (2018). Annualised Exchange rates extracted from <https://data.oecd.org/conversion/exchange-rates.htm>.

⁸¹ Fitch Ratings (2020). State Power Investment Corporation Limited. Fitch Ratings. url: <https://www.fitchratings.com/research/corporate-finance/state-power-investment-corporation-limited-15-01-2020> (visited 05/25/2021).

⁸² Energy Iceberg (2019). China's State-Owned Power Generation Utilities, Who Are They? url: <https://energyiceberg.com/state-owned-power-utilities/> (visited 09/17/2020).

⁸³ Energy Iceberg (2020). China's Power Utilities: 2019 Results & Strategy Update. url: <https://energyiceberg.com/chinese-power-utilities-2019/> (visited 09/26/2020).

⁸⁴ Lin, J., Kahrl, F., Yuan, J., Liu, X., & Zhang, W. (2019). Challenges and strategies for electricity market transition in China. *Energy Policy*, 133, 110899.

⁸⁵ Baiyu, G. (2020). China relaxes restrictions on coal power expansion for third year running. *China Dialogue*. <https://chinadialogue.org.cn/article/show/single/en/11966-China-relaxes-restrictions-on-coal-power-expansion-for-third-year-running>.

⁸⁶ SPIC (2020). SPIC Global: Main Business Activities. url: <http://eng.spic.com.cn/2016SiteEn/SPICGlobal/activities/#section1> visited (09/30/2020). Updated 05/26/2021 based on a translated version of SPIC (2021). Transnational business development. SPIC Website. url: <http://www.spic.com.cn/2018jtcy/jw/> (visited 05/26/2021).

A2. Paper 2: Government shareholders and stranded assets

The subsequent pages contain an offprint of the article published in Climate Policy.

The full citation is:

Clark, A., Benoit, P., & Walters, J. (2022). Government shareholders, wasted resources and climate ambitions: why is China still building new coal-fired power plants? *Climate Policy*, 1-16. doi:10.1080/14693062.2022.2062285

The article length is 17 pages.

The length of the Supplemental Data appendix is 8 pages.

The authors' contributions to the paper were as follows:

- **Philippe Benoit:** conceptualisation, methodology, draft manuscript preparation, review and editing, supervision, funding acquisition.
- **Alex Clark:** conceptualisation, methodology, investigation, modelling, validation, draft manuscript preparation, review and editing, visualisation.
- **Jonathan Walters:** conceptualisation, review and editing.

All authors reviewed the results and approved the final version of the manuscript.



Government shareholders, wasted resources and climate ambitions: why is China still building new coal-fired power plants?

Alex Clark, Philippe Benoit & Jonathan Walters

To cite this article: Alex Clark, Philippe Benoit & Jonathan Walters (2023) Government shareholders, wasted resources and climate ambitions: why is China still building new coal-fired power plants?, *Climate Policy*, 23:1, 25-40, DOI: [10.1080/14693062.2022.2062285](https://doi.org/10.1080/14693062.2022.2062285)

To link to this article: <https://doi.org/10.1080/14693062.2022.2062285>



© 2022 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group



[View supplementary material](#)



Published online: 19 Apr 2022.



[Submit your article to this journal](#)



Article views: 2583



[View related articles](#)



[View Crossmark data](#)



Citing articles: 2 [View citing articles](#)

Government shareholders, wasted resources and climate ambitions: why is China still building new coal-fired power plants?

Alex Clark^a, Philippe Benoit^b and Jonathan Walters^c

^aSmith School of Enterprise and the Environment and Institute for New Economic Thinking, University of Oxford, Oxford, UK; ^bCenter on Global Energy Policy, Columbia University, New York, NY, USA; ^cOxford Institute for Energy Studies, Oxford, UK

ABSTRACT

Despite its carbon neutrality commitments and the prospect of increasingly stringent climate policy measures, China is continuing to build new coal-fired power plants. In assessing the expected performance of these investments, it is helpful to analyse them through an ‘economic’ framework measuring a broader view of the country-level economic returns on new coal power investments, as a complement to the plant-level financial analysis framework commonly used to assess stranded asset risks. This simplified economic framework, in which inputs and outputs are measured according to the costs and benefits they generate for the national economy, leads to markedly different dynamics than financial analysis alone. This framework can help China to avoid ‘wasting’ scarce public resources by over-investing in new uneconomic power plants through its state-owned enterprises. Applying this approach to a representative new coal plant in China shows that modest shadow carbon pricing (rising from US\$15/tCO₂ in 2026, to US\$30/tCO₂ in 2041) eliminates the expected value of the project to China’s economy. Caps on coal-fired electricity generation have less impact on economic returns, but severely undermine financial returns, potentially making such caps a more effective short-term policy tool to dissuade company executives from making new coal investments. Without carbon pricing, only a moratorium on coal-fired power generation in 2030 or earlier prevents new plants from realizing a positive economic return. Comparing these results with an alternative solar/storage investment suggests the renewable option generates higher economic returns than the coal plant under modest shadow carbon pricing and lower electricity storage costs.

Key policy insights:





- Economic analysis of proposed coal plants complements plant-level financial analysis and better captures governments’ interests in these projects. Both economic and financial analyses are relevant to the decision-making of government shareholders.
- State-led coal plant investments in China today is likely to be economically wasteful under modest future climate policy scenarios, particularly in light of declining levelized costs of renewable alternatives.
- This framework for combined financial and economic analysis also applies to other countries’ proposed investments in carbon-intensive power generation. The framework is particularly pertinent for countries with state-led coal power investments planned, including India, Indonesia, Pakistan, South Africa, and Vietnam.


ARTICLE HISTORY

Received 1 March 2021
Accepted 31 March 2022

KEYWORDS

China; coal power; economic analysis; financial analysis; renewable energy; stranded assets

CONTACT Alex Clark  alex.clark@smithschool.ox.ac.uk  Smith School of Enterprise and the Environment and Institute for New Economic Thinking, University of Oxford, Oxford, UK; Philippe Benoit  pb2754@columbia.edu  Center on Global Energy Policy, Columbia University, New York, NY, USA

 Supplemental data for this article can be accessed online at <https://doi.org/10.1080/14693062.2022.2062285>.

© 2022 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group
This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License (<http://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited, and is not altered, transformed, or built upon in any way.

Introduction

As of July 2021, 297 GW of new coal power generation capacity was in the planning stages worldwide, with another 185 GW under construction (Global Energy Monitor et al., 2021). Large-scale net capacity additions of unabated coal-fired power is incompatible with the emissions reductions needed to achieve the temperature goals enshrined in the Paris Agreement, given that plants built in the 2020s would normally operate well into the 2050s (International Energy Agency, 2020a, 2021). Of the currently planned new capacity, India accounts for 21 GW, Vietnam 19 GW, Indonesia 18 GW, Turkey 12 GW, and Bangladesh 10 GW. Other countries planning coal power additions in excess of 4 GW include Laos, Mongolia, Zimbabwe, and Pakistan (Global Energy Monitor et al., 2021). In many of these countries, new coal investments are likely to be carried out by power companies wholly – or majority-owned by the state rather than private investors, with the public sector thereby providing a significant portion of investment capital for coal expansion.

It is China, however, that dominates planned coal power at 163 GW; 56% of the global total. In September 2020, China announced its aim to peak carbon dioxide (CO₂) emissions ‘before 2030’ and become carbon neutral by 2060 (Normile, 2020). The International Energy Agency (2020b, p. 396) estimates that coal power contributes half of China’s energy sector CO₂ emissions, at 4.9GTCO₂ in 2019. Energy transition pathways consistent with Paris Agreement targets see China’s coal-fired electricity generation falling 25% by 2030, and 60% by 2040, relative to 2018 (International Energy Agency, 2019). J. He et al. (2020) suggest Paris compliance will require China to eliminate unabated coal power generation by 2050.

Electricity demand in China is expected to increase by 60–75% over 2018 levels by 2040, whether or not a Paris-compliant development pathway is followed (International Energy Agency, 2019). Electricity’s share of the primary energy mix is likely to rise from 45% to 75% by 2040 (He, 2020). A range of power technologies are available for meeting this demand (G. He et al., 2020), but despite China’s long-term emissions reduction targets, coal capacity is continuing to expand. Commissioning of new coal capacity in 2020 totalled 38.4 GW, and approvals for new plants reached 36.9 GW, exceeding the 28.5 GW approved in 2017–19 combined (Shearer & Myllyvirta, 2021).¹

Newly built coal plants will join a coal fleet already seeing low utilization rates (China Electric Power Statistics and Data Center, 2020). Additionally, competition from renewable alternatives is increasing. Levelized cost of electricity estimates suggest that solar and wind power generation are already competitive across most of China’s provinces (Gray & Sundaresan, 2020a). Further, G. He et al. (2020) find that under optimistic cost projections for renewables, 62% of China’s electricity could come from non-fossil sources by 2030 at 11% lower cost than business-as-usual, and power sector emissions can be reduced by 50% at 6% lower cost.

Stranded coal assets: current approaches

This paper seeks to fill an important gap in the existing literature on stranded asset risks for thermal coal power. Existing studies largely define stranded assets one of two ways. ‘Financial’ analysis defines them as expected or realized financial losses for corporate owners (Spencer et al., 2017), consistent with accepted definitions in the wider literature (Caldecott et al., 2013) and global or regional stranded asset calculation methodologies (Mercure et al., 2018). ‘Technical’ analysis identifies stranded capacity (GW) or electricity generation (TWh), using a sectoral carbon budget or policy setting as a starting point and identifying stranded assets by the extent to which the early retirement or under-utilization of power generation infrastructure occurs under various policy pathways or carbon budget constraints (Caldecott et al., 2017; Caldecott et al., 2018; Johnson et al., 2015; Pfeiffer et al., 2018).

These approaches are helpful guides, but do not consider what stranded asset risks imply for governments, which are often the ultimate arbiters of whether or not new coal power projects should proceed. This is

¹An additional 38.4 GW was commissioned and 31.5 GW resumed construction. Major coal-producing provinces Inner Mongolia and Shaanxi accounted for over half of newly permitted capacity.

particularly true in China, as well as those countries where the government is the majority or sole shareholder in most power companies and associated electricity generation projects. From a government planner's perspective, expectations of financial losses and early retirement do not necessarily imply that building a new coal plant is unjustified on an economic basis. Indeed, governments subsidize financially risky projects precisely because they consider them to be economically worthwhile. Could this be the case for coal? To the best of the authors' knowledge, project-level evaluation of expected economic returns on coal power investments at the country level (as opposed to financial returns at corporate level) is not addressed in the literature on stranded assets. Applications of an approach based on economic returns are largely confined to ex-ante project assessments by development finance institutions, who have routinely employed economic metrics to evaluate investments' value to a country, for coal and other individual projects (Asian Development Bank, 2013; Meier, 2017a; World Bank, 2011), based on a methodology elaborated at the World Bank by Squire and Van der Tak (1975).

The literature on coal asset stranding in China that does exist clearly underlines the scale of its potential financial exposure to coal power asset stranding, both in absolute terms and as a share of the global total – as much as 45% of an estimated US\$927 billion global power sector asset stranding by 2050, albeit under an accelerated renewables scenario (Saygin et al., 2019). In other studies, coal power stranding is estimated at US\$15–53 billion (CNY 100–340 billion) by 2030 under high – and low-carbon pathways, respectively (H. Zhang et al., 2020). Analyses of China's coal fleet consistently find that both current and proposed power plants face stranded asset risks under most climate policy scenarios that are amplified by weak underlying profitability and market conditions (Cui et al., 2021, 2020; Gray & Sundaresan, 2020b; Spencer et al., 2017; Yuan, Guo, Zhang, Zhou, et al., 2019; Yuan & Zhang, 2017). Ongoing reforms to liberalize power markets are likely to further depress coal plants' net revenues and impair commercial operation by exposing them to greater competition (Lin et al., 2019). The finding, based on financial analysis, in Mo et al. (2021) is therefore unsurprising: a modest US\$7.5 (50 CNY) per ton carbon dioxide price (close to China's national ETS price at the time of writing) reduces coal plant lifetimes by 5.4 years on average, with five provinces seeing retirements 12–17 years earlier than planned.

What the literature on coal stranding in China does not address is whether continuing to build coal plants is justified on an country-level economic basis. This is more representative of the government's perspective in its role as shareholder of state-owned companies and requires measuring projects' contributions to economic growth (i.e. the benefits of electricity production to the national economy after accounting for economic costs), rather than just the net private benefits to the plant's corporate owner (i.e. return on equity after interest and taxes). This article complements standard financial analysis with country-level economic analysis to assess under what conditions building a new plant today constitutes a productive – or wasteful – use of resources by the government of China, both on a standalone basis and relative to other options for meeting electricity demand.

Coal power investment and government shareholders

This country-level 'economic' framing is important for several reasons. In China, key actors across the coal power value chain are state-owned enterprises (SOEs) – including owners of coal mines and power plants (Global Energy Monitor & CREA, 2020), banks financing plant construction (Herve-Mignucci et al., 2015) and grid operators (Mayer et al., 2017). Potential financial losses from coal plant stranding represent direct liabilities for individual SOEs, and ultimately contingent liabilities for China's government in its capacity as shareholder (depending on how the stranding of each coal asset affects the government's overall portfolio). Additionally, the prevalence of SOEs in China's coal sector – an estimated 94% of coal capacity in 2015 was state-owned (Herve-Mignucci et al., 2015) – means that the financial arrangements determining stranding risk for a given coal power asset (i.e. the proportion of the original investment that is not recovered under a given scenario) are negotiated between companies with a common government shareholder, making the corresponding contracts essentially transfers between subsidiaries of the state, and raising the possibility that government ownership distorts the pricing and value of these contracts. In China, therefore, financial-only stranded asset analysis is an incomplete, and potentially misleading, representation of the value of the asset to the majority government shareholder that the SOE serves.

In this paper, we are not, however, concerned with assessing the financial risks to SOEs or the contingent liabilities these represent for the government. Rather, we propose a framework for assessing the risk of new coal power investments being economically wasteful from a government's perspective. Of course, as social planners, governments are in principle concerned with the economic rationale for all coal investments, whether or not they are state-owned. Indeed, in China, electric power – predominantly from coal – has been 'one of the main driving forces' advancing China's social and economic development (Zhang et al., 2017). However, governments that are both social planners *and* shareholders have both financial and economic interests in projects. In these cases, complementing existing financial analyses of planned coal power investments with economic analysis is particularly relevant. Governments investing through their SOEs need to consider not only whether new coal power plants will be profitable, but whether they contribute to wider economic development or produce economic returns below the social discount rate. In the latter case, they are unable to generate sufficient benefits to recover their economic costs, thereby constituting a waste of national resources relative to alternative uses: what can be termed an 'economically "stranded" asset'.

It is in this context of ubiquitous state presence in the coal sector and the centrality of coal to China's economic development that this paper situates its contribution to the literature on stranded assets and coal power. Given the dual roles of China's government as both the beneficial owner of power plants and manager of the economy, its investments in electricity generation, and the stranded asset risk associated with them, should be analyzed both in terms of their financial return to plant owners as well as their potential contribution to the country's economic growth. Here, we explicitly represent the critically important governmental perspective missing from much existing work on China's coal transition and stranded asset risk, and examine how it responds to changes in policy and technology. This framing also applies, with country-specific qualifications, to other economies planning coal power expansion in which coal SOEs feature heavily, notably India, Indonesia, Pakistan, South Africa, and Vietnam.

Economic analysis of coal capacity additions

Coal plants generate economic costs and benefits for the wider economy, notably from (i) generation and consumption of electricity generated by businesses, households and other users, and (ii) economic effects on sectors linked to plant construction and operations.² As a consequence, the scope and valuation of costs and benefits from economic and financial standpoints differs substantially (see Methods section). Comparing the financial and economic benefits from new coal projects under different climate policy scenarios for coal can help identify economic – as distinct from financial – rationales and risks for coal power investment in China, and determine where corporate and government interests may diverge.

In this paper, we consider how a new coal power investment in China looks when assessing the costs and benefits to the national economy from the perspective of a government shareholder concerned with the investment's contribution to national economic growth. This approach looks beyond plant-level financial returns to understand the rationale for new coal power investments from the government's point of view. It improves our understanding of whether and how new coal plants might be perceived by the Chinese government to generate country-level economic returns, and the conditions under which new plants risk becoming 'stranded' on an economic basis, representing a waste of public sector investments better allocated to other power sector investment options. We do this under several plausible climate policy scenarios. We then compare the results with those for a power generation investment in a hypothetical 'renewable with storage' alternative and discuss the implications for coal power investment policy in China.

Approaching the coal investment question from this perspective is not intended to promote coal as a sensible investment option, but rather to recognize the relevance of economic returns to power investments in

²Economic returns are of interest to governments whether or not they are shareholders in the company implementing the project, but tools available to government for influencing investment and operational decisions of state-owned enterprises are greater and more diverse than those it can typically apply to private sector companies (Benoit, 2019).

China and rebase the ‘stranded asset’ conversation around a more comprehensive representation of governments’ incentives.

Methods

Framework for economic analysis

We explore the rationale for coal power investments from two analytical foci. First, the standard ‘financial’ approach, measuring the net present value to equity holders (FNPV) of nominal free cash flows produced by the coal project over its lifetime (not including benefits to other businesses owned by the same company, e.g. in coal mining and transport), using a private discount rate based on the company’s weighted average cost of capital (1). Second, the country-level economic returns to China, i.e. the real-terms net present value of net economic benefits (ENPV) within China’s borders, using a social discount rate (2). See Supplementary Material (SM) for further detail.

$$FNPV = \sum_{t=0}^n \frac{\text{NetIncome}_t}{(1 + r_F)^t} \text{ where } r_F \text{ is the private discount rate} \quad (1)$$

$$ENPV = \sum_{t=0}^n \frac{\text{NetBenefits}_t}{(1 + r_E)^t} \text{ where } r_E \text{ is the social discount rate} \quad (2)$$

The economic and financial analyses share common physical and operational attributes, but the valuation and scope of costs and benefits considered differ substantially. One significant, but often overlooked, distinction between the two approaches is that the financial analysis is based on nominal contracted costs and revenues, whereas economic analysis assesses real-terms costs and benefits to the economy (Belli et al., 1998; Meier, 2017a, 2017b). In the financial analysis, for instance, construction costs reflect the face value of the engineering, procurement and construction (EPC) contract. In the economic analysis, these are adjusted to exclude domestic import duties and taxes on capital and labour (which are effectively transfers between different economic actors within China), reflecting the cost to the economy of fulfilling the contract. Similar adjustments apply to operating costs and financing costs. Environmental costs are included in the financial analysis only to the extent they are priced into the market; in the economic analysis, they are valued on the basis of the government’s estimate of the national economic costs of local and global pollution, both at the plant and upstream/downstream. Interest payments between Chinese entities are not included in economic analysis as these constitute domestic transfers. In the financial analysis, the benefits of generation correspond to revenues from the sale of electricity by the power plant operator. In economic analysis, the benefits of generation are assessed further down the value chain, at the point of actual use by consumers, based on their willingness-to-pay (WTP) for the electricity after deducting the cost of transmission and distribution (‘T&D’) incurred in delivering the power.

Comprehensive economic analysis should account for a broad array of economic and environmental effects linked to the plant’s construction and operation both upstream and downstream.

Local pollution costs have come under increased scrutiny in China in recent years.³ In addition to environmental impacts from the combustion of coal (see ‘Key model parameters’ below), there are additional costs ‘beyond the plant’, such as the environmental and health impacts of coal mining, processing, and transportation upstream. Several scholars have suggested that the combined environmental costs of coal power generation (both within and beyond coal plants), are sufficiently large to outweigh all other economic benefits, even without considering available alternatives (Fei, 2014; Selim et al., 2020; Xiang & Kuang, 2020). These broader effects are therefore clearly important, but also highly context-specific, especially when applied to a specific plant (depending on the coal mines supplying it, population density in surrounding area, etc.).

³Mitigating air, water and ground pollution is a major policy priority in China, reflected in the rapid installation of pollution control measures across the coal fleet, closure or relocation of poorly performing plants and tax reforms (see Chang et al. (2016) and Mining Technology (2017)).

Consequently, while we do not include environmental damages beyond the plant in this simplified analysis, findings from other literature placing a high cost on these damages are important to bear in mind when interpreting our results.

Additional employment, income and investment stimulated by the economic activity associated with plant construction and coal production, also generates economic benefits. Conversely, where a coal plant becomes ‘economically stranded’ as part of a sharp policy – and/or technology-induced transition away from coal, the wider social consequences of future job and tax revenue losses, and any relocation, retraining and opportunity costs associated with finding alternative employment, are also relevant to government, as are the implications for equity and fairness among those negatively affected by the transition. While not measured in this exercise, they may be of particular short – and medium-term salience for China’s government amid the economic fallout from the COVID-19 pandemic (Benoit & Tu, 2020; Tu, 2020).

Decision-making criteria

To be justified financially/economically, a project (in this case, a coal plant) should deliver a financial/economic rate of return (FIRR/EIRR) exceeding the private/social discount rate, respectively, reflecting the investor/government’s assessment of the relative benefits of future versus present financial value/ economic growth (Meier, 2017b, p. 63). The second criterion for justification is whether alternative investments would generate higher financial/economic returns than the proposed coal plant project.

Financial and economic approaches estimate the coal project’s value with respect to each corresponding stakeholder: the corporate owner and the Chinese government. In the example modelled here and as discussed above, the central government is both the indirect owner and the referent party to the economic analysis. Sub-national levels of government may also be involved in the coal project, financially or through ownership of provincially owned SOEs. In these cases, economic analysis should be conducted from the perspective of both national and provincial governments, with the cost–benefit analysis undertaken based on the appropriate sub-national boundaries in the latter case. Future work comparing economic returns at these different levels of government would be a useful expansion of this paper, given the well-documented and historically rooted differences and tensions between central and provincial government interests (Chung, 1995; Li, 1998; Zeng, 2016), particularly with respect to environmental policy (Li et al., 2019).⁴

Key model parameters

In our ‘Base Case’, with plant parameters and costs reflecting the Chinese context, we model a one gigawatt-rated (GW) ultra-supercritical coal plant with a 48% starting load factor, consistent with average national coal utilization rates and well below the plant’s technical maximum.⁵ Debt is provided by Chinese banks, meaning that interest rates and debt-equity ratios – which do affect the financial return on equity – have no impact on country-level economic results. The financial discount rate is 6%, reflecting weighted average cost of capital to the corporate owner. The social discount rate is 8%, consistent with reported practice in China for state-led infrastructure projects (World Bank, 2019, p. 18,50). Table 1 lists other key financial and economic parameters (see SM Table A3, for expanded detail and sources).

Under the national carbon emissions trading system (ETS) launched in July 2021, China allows free allocation of permits for plants operating within emissions thresholds designed to penalize older, less efficient plants rather than high-efficiency, ultra-supercritical capacity additions. The ‘Base Case’ scenario, therefore, does not include a carbon price, either financial (in the form of a price or quantity-based market instrument⁶) or economic (such as a shadow price used for government decision-making). The Base Case includes local

⁴In practice, their interests can, and often do, diverge, leading to a more complex decision-making dynamic.

⁵China operates an ‘equal shares’ system such that coal power is contractually dispatched for a fixed number of hours per year. In combination with limited inter-provincial electricity trading, this means the average load factor of China’s coal plants is just 48% (Gray & Sundaesan, 2020b), far below their technical capacity. Well-planned transmission expansions and dispatch liberalization could pre-empt any financial or economic need for new generation capacity. This would not necessarily be consistent with power sector decarbonization trajectories, particularly if the plants in which load factors increase are less efficient than the ultra-supercritical example here.

Table 1. Key data points for *pro forma* coal plant model (see SM Table A3 for expanded table and sources).

Component	Unit	Plant-level (financial)	Country-level (economic)
Capacity	MW	1,000	
Coal energy content	MWh/ton (metric)	18.84	
Plant efficiency	%	48%	
Construction period	years	3	
Capital cost	US\$ / MW	517,366	401,657
Inflation rate	%/year	2.1% (1.5% on tariff)	–
Discount rate	%/year	6%	8%
Domestic financing	% of financing	100%	
Loan tenor	years	20	–
Operating life	years	30	
Load factor	%	48%	
Coal fuel cost (delivered)	US\$ / ton	76.52	72.57
Initial operating costs	US\$ / MW-year	11,549	9,816
Weighted average T&D costs	US\$ / MWh	–	30.0
Electricity tariff received	US\$ / MWh	47.12	–
% industrial users	%	–	62%
Weighted average WTP	US\$ / MWh	–	87.9
Local pollution taxes	US\$ / MWh	0.05	0.26

pollution costs based on Environmental Pollution Tax (EPT) charges for sulfur dioxide (SO₂), nitrogen oxides (NO_x), and particulate matter (PM_{2.5}) emissions from coal plants.⁷ The financial analysis uses the median tax across all provinces. The administratively-set upper limit (applied only by Beijing, Tianjin, and Hebei) for pollution taxes is used for the economic analysis, as a conservative proxy for the lower bound on the true social cost of local pollution.⁸ Significantly higher figures are found in the literature (Biao et al., 2020; Fei, 2014), and Table 2 presents the results of using a higher social cost closer to the estimates in the broader literature. WTP for electricity is, by definition, at least as high as the electricity retail price that consumers actually pay. We assume that on average, electricity consumers will generate an economic return on electricity consumption equal to China's annual GDP growth rate and are willing to pay a corresponding premium of 6% over retail prices.

Alternatives to coal power

Available alternatives to additional coal power investments include dispatchable non-coal generation technologies, transmission infrastructure investments, increased interprovincial electricity trading, demand-side management and efficiency measures.

We assume a non-fungible need for additional generation capacity, partly reflecting a bias towards capacity additions over greater inter-provincial electricity trading as an economic stimulus strategy (Hove, 2020). The illustrative alternative modelled here is a utility-scale solar photovoltaic (PV) plant with sufficient storage to provide dispatchable power comparable to the coal plant.⁹ Illustrative technical parameters for the solar/storage model are listed in SM, Table A1. Most other parameters (e.g. financing arrangements) are the same as those for coal.

Like coal, solar/storage investments generate external economic impacts beyond the plant itself. Liu et al. (2019) find that renewable energy development in China delivers greater external economic benefits than

⁶Pilot carbon emissions trading systems (ETSs) have been operational in several provinces in China and a national scheme was launched in February 2021, but prices are low and volatile. It is not yet clear how caps and permit allocation will work, and the extent to which emitters will need to trade in permits.

⁷Local air pollution taxes range from 1.2-12 CNY/kg for regulated pollutants, depending on the province. The Base Case assumes 1.2 CNY/kg, the level set by most of the less population-dense provinces building new coal capacity.

⁸Estimates of social costs associated with coal production and combustion suggest that local pollution taxes only partially internalize these pollution costs. See Fei (2014) and Selim et al. (2020).

⁹Dispatchable renewable electricity costs are highly sensitive to the choice of generation and storage technologies. Here we set out an illustrative solar/storage alternative, but there may be configurations that ultimately are more cost-effective, especially when considering China's system-decarbonisation needs (G. He et al., 2020).

Table 2. Selected sensitivities.

Factor	Unit	Base case value	Sensitivity	EIRR	Equity FIRR
Base Case				19.1%	8.4%
Plant life	years	30	40	19.1%	8.9%
Lower off-taker tariff	US\$/MWh	47.12	−10%	"	−0.5%
Higher WTP for electricity	US\$/MWh	87.90	+10%	25.0%	"
Higher CapEx (financial)	US\$/MW	517,366	+10%	17.5%	6.8%
Higher coal price	US\$/ton	76.5	+10%	16.7%	2.4%
Higher T&D costs	US\$/MWh	30.0	+10%	16.8%	"
Higher tax on local pollution (financial)	equivalent US\$/MWh	0.05	0.47	"	7.8%
Higher social cost on local pollution (economic switching value)	US\$/MWh	0.26	13.1	8.0%	"
Lower load factor	%	48%	−20%	15.3%	3.8%
Higher load factor	%	48%	+20%	23.4%	13.3%

coal even without accounting for environmental costs, while Garrett-Peltier (2017) finds that renewable energy capital investment consistently generates more jobs than coal, and contingent valuation studies (Guo et al., 2014; Xie & Zhao, 2018; L. Zhang & Wu, 2012) find mixed evidence of greater WTP for renewable electricity in China. The negative environmental impacts upstream of the solar/storage alternative are likely much smaller (albeit non-zero) than those associated with coal plants. To maintain comparability, we have once again, as for the coal analysis, not quantified these effects, but the net benefits of beyond-plant effects for solar are likely to be significantly greater than for coal.

Policy scenarios

Increasingly stringent CO₂ reduction policies in China are inevitable if 2060 targets are to be achieved. These policies could take various forms, including progressive tightening of emissions trading markets, direct carbon taxation, obligatory shadow carbon pricing for new investments, preferential tariffs for renewables, absolute coal power generation caps, or moratoriums on the operation of coal plants failing to meet certain criteria. Electricity dispatch reforms may also expose coal power to greater competition from renewables, leading to fewer operating hours. Direct regulatory measures to close inefficient plants, or compel them to meet emissions standards, have been progressively deployed since 2007 (Tang et al., 2019; Yuan, Guo, Zhang, Chen, et al., 2019).

Table 3 describes two sets of possible policy scenarios affecting the economic analysis of coal: carbon pricing (implemented explicitly through a trading system or taxation, or implicitly through regulatory measures) and

Table 3. Summary of climate policy scenarios.

	Start year	Shadow carbon price (SCP) (US\$/tCO ₂ , \$2020)		Load factor restriction (LR) (%)	
		"Modest ambition SCP scenario"	"Higher ambition SCP scenario"	"LR stated policies scenario"	"LR below 2C scenario"
Base Case	2021	0	0	48%	48%
Five Year Plan					
15th FYP	2026	15	15	43%	41%
16th FYP	2031	20	30	36%	31%
17th FYP	2036	25	45	25%	18%
18th FYP	2041	30	60	18%	13%
World Bank					
Lower bound SCP	2020	40 (+2.25%/ year)		48%	
Upper bound SCP	2020	80 (+2.25% year)		48%	
Coal Power Moratorium					
2030 Moratorium	2030	–	–	0%	
2035 Moratorium	2035	–	–	0%	

electricity production caps (regulated or informal). These scenarios have been structured along China's Five-Year Plan (FYP) schedule, such that changes are implemented in each FYP's first year. The scenarios do not attempt to estimate the full economic cost of carbon emissions (the 'social cost of carbon') from coal power generation, but rather reflect a more conservative position for the Chinese government in setting a cost for emissions from coal generation.

In the carbon pricing scenarios, a shadow carbon price (SCP) is implemented by the government. The Modest Ambition SCP scenario (MA-SCP) starts at US\$15/tCO₂ in 2026 (the 15th FYP's first year), increasing by US\$5 every five years to reach US\$30/tCO₂ in 2041. In the Higher Ambition SCP scenario (HA-SCP), the value increases by US\$15 every five years to reach US\$60/tCO₂ in 2041. These prices are well below the range currently applied by the World Bank (2017) for project evaluation, which is explored below.¹⁰

In the production cap scenarios, load factor restrictions (LR) are imposed on the plant, consistent with projected changes in the share of coal in China's total primary energy supply¹¹ under the 'Stated Policies' (SP-LR) (falling from 43% in 2026 to 18% by 2041) and 'Below 2C' (B2C-LR) scenarios (from 41% to 13%), respectively, set out by the Energy Research Institute and China National Renewable Energy Centre (2019, p. 207). We also model the effect of moratoriums on the coal plant coming into effect in 2030 and 2035.

Results

The EIRR in the Base Case with no carbon pricing or production limits is 19.1%, with an ENPV of US\$472 m. By comparison, the FIRR (return on equity) is just 8.4%. This divergence in results is driven largely by the difference between financial and economic values for capital and fuel costs, and the different valuation points for benefits (i.e. privately contracted electricity price versus WTP of ultimate consumers). This is unsurprising: governments make investments through SOEs precisely because they generate economic benefits in addition to any financial return the plant owner – often also the government – receives. Investors require 21 years to see a positive financial return (leaving their capital highly vulnerable to climate policies implemented before 2040), but the project requires just seven years to break even economically, meaning the project could deliver net economic value even if it was forced to close before 2030, under a Base Case scenario that does not incorporate any shadow carbon pricing. This difference in the rate of recovery of the initial investment offers an explanation for continued coal plant construction by China's SOEs, even when the long-term financial case appears tenuous.

The plant's economic value is sensitive to changes in WTP for electricity, the plant's utilization rate, and the social costs of local pollution. Its financial performance is, by comparison, relatively sensitive to wholesale electricity tariffs, higher coal prices, and lower load factors. Table 2 summarizes the effects of these and other sensitivities on returns and net present value.

Carbon pricing scenarios

Shadow carbon pricing reduces economic returns by adding a cost to each kWh of electricity generated. Under the (lower) MA-SCP scenario, the plant's EIRR drops to 5.1% and the plant creates an economic loss of US\$50 m, never recovering its initial investment in economic terms (Figure 1). This suggests that if China's government expects to introduce the equivalent of even a modest SCP in subsequent FYPs, an apparently appealing coal plant investment becomes economically undesirable and should not, in principle, proceed to commissioning. The (higher) HA-SCP scenario magnifies the economic loss to US\$355 m (see SM for full details). Using the much higher shadow price ranges applied by the World Bank dramatically aggravates the economic costs induced by the plant, to between US\$1 billion and US\$2.7 billion.

The plant begins to make an economic operating loss (accounting for fixed and variable costs) at an SCP of US\$28/tCO₂ or more, a level reached in 2041 in the MA-SCP scenario, and 2031 in the HA-SCP scenario (see

¹⁰The High-Level Commission on Carbon Prices concluded that a range of US\$40-80 per ton of CO₂e in 2020, rising to US\$50-100 by 2030, is consistent with achieving the 2C Paris target, provided supportive policies are in place. The World Bank recommends these ranges for project economic analysis, with prices extrapolated from 2030 to 2050 at the same growth rate (2.25% per year).

¹¹These are probably conservative estimates of coal power's declining share in electricity generation because electricity is likely to be decarbonized more rapidly than others in which coal also features heavily, notably heavy industry and space heating.

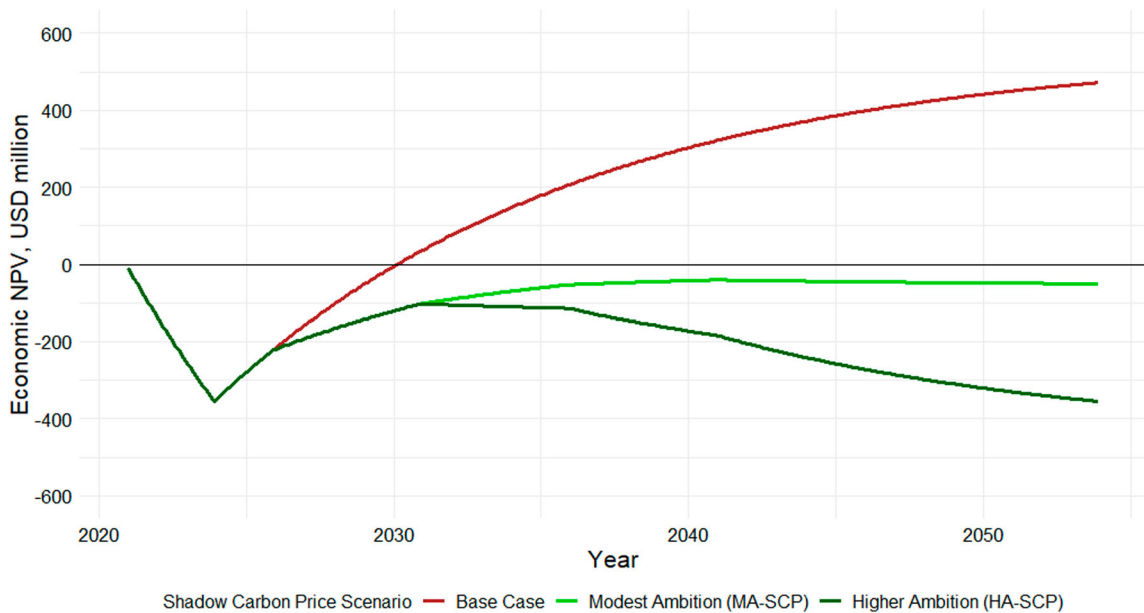


Figure 1. Economic NPV at 8% under different shadow carbon price scenarios.

Figure 1). Assuming the plant is already operating, it would be economically desirable to permanently cease operation at these inflection points in each respective scenario to prevent further economic losses in each scenario, cutting the plant's intended lifetime short by 22 and 12 years, respectively.

Shadow carbon pricing only affects plant-level financial returns if it is passed through to the generator as an actual charge (under an ETS, as a carbon tax, through a technology standard, or other measures). The carbon price required to result in a financial operating loss is lower, at US\$18/tCO₂ (2020 US\$); China's average ETS price in July 2021 was just under \$8/tCO₂. Thus, in the modelled case, even if the government's SCP exceeds US\$28/tCO₂, unless it is translated into a financial charge exceeding US\$18/tCO₂, there remains a financial incentive to operate the plant even as it destroys economic value, placing the government at odds with SOE-level financial incentives.

Production cap scenarios

Constraining production levels also affects country-level economic returns, but by less than an SCP (see Figure 2). The decline in plant utilization rate under the SP-LR scenario reduces ENPV from US\$472 m to US\$229 m, and the B2C-LR scenario results in US\$161 m. Even a moratorium on generation in 2035, consistent with coal phase-out policies in several EU states,¹² still produces a positive economic return of \$179 m. Absent any shadow carbon pricing, the plant only fails to generate a positive economic return when forced to close in 2030 or earlier. Since each marginal kWh still delivers the same economic benefit under LR scenarios, being unaffected by a shadow carbon cost, the threat of load factor restrictions may not be an effective tools for dissuading government investment in new coal power generation relative to carbon pricing.

Production caps have a much more severe effect on financial returns, generating losses (i.e. stranded asset values) of US\$124 m and US\$176 m in SP-LR and B2C-LR scenarios, respectively. The difference between economic and financial returns is so large because the marginal economic benefit of each kWh produced (the

¹²This is comparable with coal phase-out plans in numerous countries (e.g., Germany's intended phase-out by 2038, U.S. President Biden's campaign pledge to make power generation carbon-free by 2035) and is less constraining than the United Kingdom's announced ban on unabated coal power by 2025.

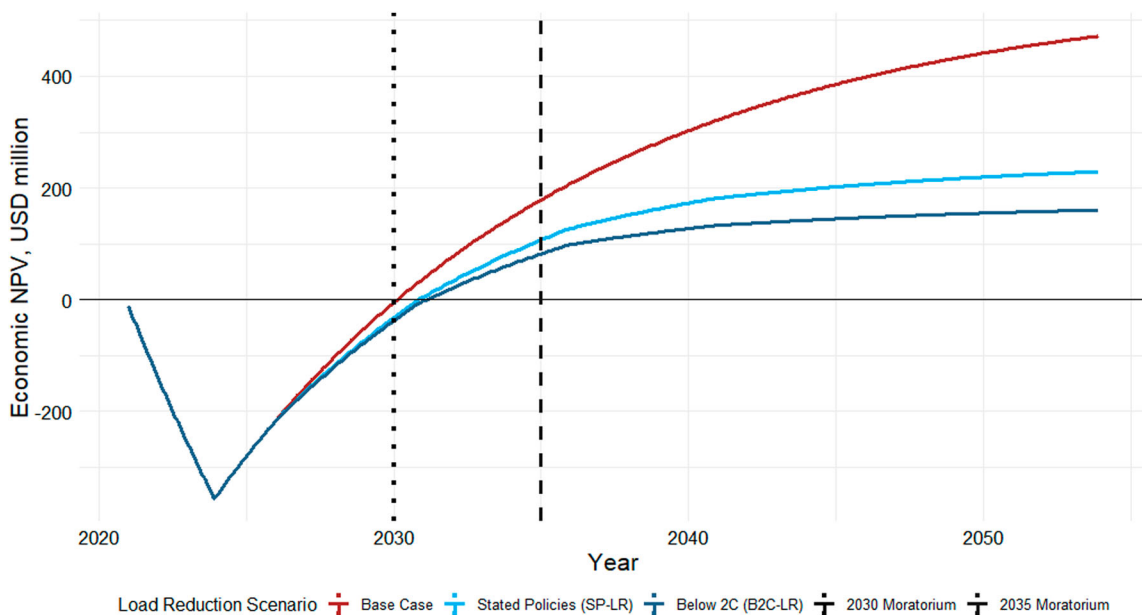


Figure 2. Economic NPV at 8% under different LR policy and moratorium scenarios.

difference between WTP and economic cost of producing and delivering electricity) in the absence of shadow carbon pricing significantly exceeds the marginal financial benefit (the difference between electricity tariff revenue and financial cost, including interest) to the plant owners. This is why the Base Case economic breakeven point required to justify the investment is reached after eight years of operation, compared to 20 for financial breakeven.

By reducing the volume of electricity sales, which does not affect the marginal benefit of production, the LR scenarios have a greater impact on financial than economic results and severely limit the project's ability to recover its initial financial investment. The same dynamics apply for an absolute moratorium on production. A moratorium starting in 2030 would generate a financial loss of US\$113 m, and a moratorium starting in 2035, a US\$72 m loss.

The renewable alternative

The solar/storage alternative yields an 8.7% EIRR, and an ENPV of US\$54 m, both substantially lower than coal in the Base Case. However, while the SCP and LR scenarios depress economic returns for coal generation, they have no effect on the renewable alternative, improving its relative appeal. Even low levels of shadow carbon pricing (i.e. the MA-SCP scenario) can make solar/storage economically preferable to coal. The renewable alternative delivers an ENPV that is US\$105 m larger than coal under the MA-SCP scenario (an advantage that increases to US\$409 m under the HA-SCP scenario). In contrast, coal remains more economically attractive than the solar/storage alternative under the two LR scenarios.¹³

While the renewable alternative does generate a positive ENPV, it requires 25 years to break even economically due to the high initial cost of storage infrastructure. However, a 15% decline in the capital costs of storage,

¹³Different generation options are often compared using a "levelized cost of electricity" (LCOE), which is calculated using financial costs. Because, in the Chinese context, these costs result in part from regulated and other government-influenced pricing (e.g., regulated coal prices, or EPC contract negotiated between state-owned power and construction companies), it might be more revealing and useful to calculate levelized cost using the methodology and values for the country-level economic analysis presented here, including shadow carbon pricing and other pertinent externalities – namely, the "levelized economic cost of electricity" (LECOE). The LECOE may better assist the government in identifying and advancing new generation choices with lower economic costs and thereby support the government's goals of keeping electricity tariffs low.

consistent with the NREL mid-case battery storage cost projection from 2020 to 2023 (Cole & Frazier, 2019), raises the EIRR to 10.9% and the ENPV to US\$328 m (US\$378 m greater than coal in the MA-SCP case), bringing breakeven forward to 14 years. A 30% decline (anticipated by NREL in 2027) produces a 13.8% EIRR and US \$602 m ENPV. This is US\$130 m greater than that of coal in the (no-climate-policy) Base Case. It achieves breakeven within ten years. These suggest dispatchable solar is likely to be competitive with coal as an economic investment before the late 2020s on current cost trends.

As noted above, the true relative benefits of the renewable alternative are likely understated in these results since the negative upstream environmental and health impacts associated with coal supply are not factored in. If these factors were included, assuming the economic stimulus benefits of either option are similar, the renewable alternative would likely be more competitive, and sooner, on economic terms.

Notwithstanding the growing competitiveness of unsubsidized solar generation both in China (Energy Monitor Worldwide, 2020; Yang et al., 2020) and elsewhere (Naschert, 2020), the dispatchable solar/storage alternative still faces financial challenges. The financial return is below 1%, weighed down by the cost of storage. Achieving a return on equity exceeding that for the coal Base Case would require raising the tariff received by solar/storage from its US\$47/MWh baseline to US\$62/MWh.¹⁴

Discussion

Climate policy tightening in China (through carbon pricing or otherwise) is increasingly likely well within the operating lifetimes of plants built today. Other scholars have shown that this, along with poor market conditions for coal power, will result in significant volumes of financially stranded coal assets. However, as continued coal plant construction in China suggests, weak or negative profitability alone may not be sufficient to dissuade new coal power investment, particularly where the government is the ultimate plant owner, more likely to be concerned with coal's contribution to economic growth as well as its financial viability. Distinguishing between financial and economic perspectives can help uncover differences between the rationales for coal plant construction at corporate and governmental level and identify the policy or technological changes required to counter the potential economic case for coal.

Economic analysis of the representative new coal plant modelled here suggests that modest shadow carbon pricing – well below the social cost of carbon recently proposed by the administration of U.S. President Biden (Chemnick, 2021) or the range required to limit global warming to under 2C derived by Stiglitz et al. (2017) – negates any expected positive economic returns. Compared to a US\$472 m present value in the Base Case, the MA-SCP scenario generates an economic loss of US\$50 m in present terms, while the HA-SCP scenario generates a loss of US\$355 m.

If China's government recognizes the negative economic impact of carbon emissions through a (implied or real) shadow carbon price, but does not fully translate it into a financial expense for plant owners, there is a potential misalignment of incentives for China's government in its dual roles as shareholder and social planner. The coal plant ceases generating marginal economic benefits for SCPs in excess of US\$28/tCO₂, but only makes operating financial losses if the SCP manifests as a cost of US\$18/tCO₂ or more. Unless the Chinese government, as part of its carbon neutrality goal, establishes credible expectations for an ETS or carbon tax exceeding this value, it may find itself at odds with its own SOEs, where the financial incentive to continue building and operating coal plants remains.

Production caps have a more limited impact on economic returns, since they do not affect the marginal economic benefits of production. This means that even under the B2C-LR Scenario, the plant breaks even economically by mid-2031 and requires a permanent moratorium in 2030 or earlier to be prevented from producing a positive economic return (with no shadow carbon pricing). However, the production cap scenarios impair financial returns much more significantly and prevent the plant from recovering its initial investment at all,

¹⁴The average tariff in China for solar PV (including rooftop) in 2018 was US\$124/MWh. The average for gas generation was US\$84.5/MWh (Lee, 2019). The \$62/MWh required for solar/storage equity returns to exceed coal is roughly 20% higher than average benchmark feed-in tariffs for coal at approximately US\$52/MWh (Guoneng Hutong Inner Mongolia Network Technology Co Ltd, 2019).

potentially discouraging company executives from making the investment in the first place. Where meaningful carbon taxes are not a short-term policy option, therefore, production caps may be effective in dissuading company executives from building new coal plants.

Overall, this analysis shows that the degree to which the *pro forma* coal plant becomes ‘stranded’ from an economic perspective depends both on the stringency and type of policy adopted. Our modelling suggests that a shadow price is a more effective tool than production caps to disincentivize government support for a new coal investment because of its stronger negative impact on economic returns, but is only effective at influencing financial decision-making to the extent it imposes costs on the company (in the form of a carbon tax, ETS, or equivalent instrument).

Comparison with an illustrative solar/storage alternative further weakens the economic case for coal under climate policy tightening scenarios. The solar/storage plant produces greater economic returns than the coal plant in both SCP scenarios (by US\$105 m and US\$409 m in MA-SCP and HA-SCP, respectively). A 15% decline in storage capital costs (expected by 2023, when currently planned coal capacity will remain under construction) widens its economic advantage to US\$378 m (MA-SCP) and US\$683 m (HA-SCP) over coal, while also outperforming coal in each LR and moratorium scenario.

With 30% lower storage costs, expected before the late 2020s, the solar/storage alternative delivers an ENPV of US\$602 m, over US\$100 m greater than the coal Base Case, with no shadow carbon pricing or load factor restrictions in place. This suggests that in circumstances where solar/storage is an option, there may be no economic case for new coal from the late 2020s irrespective of climate policy tightening. The combination of some shadow pricing (or, to a lesser extent, some production constraints on coal) and cost declines for solar/storage technologies suggests that investing in coal today is likely to prove a poor use of scarce economic resources.

Expected financial returns from solar/storage remain lower than those for coal in the short – and medium-term due to the capital intensity of storage and correspondingly high financing costs. Aligning government incentives with investors (even where state-owned) will require measures to address this, potentially including direct subsidies for storage, preferential lending criteria to reduce debt costs, and higher electricity tariffs. The latter has precedent in Chinese electricity markets, in which the regulatory framework already differentiates tariffs by generation source (Lee, 2019). As the cost of storage falls and climate policies tighten, the potential net economic benefits of solar/storage investment over coal could justify the expansion of subsidies to enhance financial returns for solar/storage and encourage investment by SOEs and private firms alike.

Conclusions

This paper has applied a framework for joint financial and economic analysis of prospective government investments. It represents a more complete approximation of a governmental perspective on coal power investment through state-owned enterprises than the financial-only analyses predominant in the existing literature. The results suggest that at least some of the new coal plants planned in China may never generate positive economic returns, especially if the government elects to implement even relatively modest market-based or control policies in pursuit of carbon neutrality and other environmental and societal goals.

Modelling of a *pro forma* coal plant representative of coal capacity additions in China suggests that modest shadow carbon pricing, rising linearly from US\$15 to 30/tCO₂ from 2026 through 2041, is sufficient to prevent the project from ever generating a positive economic return. A more ambitious shadow carbon pricing trajectory, increasing to US\$60/tCO₂ in 2041, causes the plant to generate an economic loss of US\$355 m. Production caps reduce economic returns to a lesser extent but cause the plant to generate negative financial returns, perhaps introducing a stronger deterrent to new plant construction for company-level executives than for the government as shareholder. Under any of the scenarios presented, investing in a coal plant today on an economic basis risks wasting productive resources better used elsewhere, especially given the decreasing costs of low-carbon alternatives immune to the effects of policies targeting carbon emissions, here represented by a solar/storage dispatchable generation plant. China’s government and, by extension, its SOEs as instruments of economic policy, should therefore carefully consider the economic viability of new, long-lived coal investments today in light of future climate policies and trends in competing renewable technologies.

This analysis also points to several possible directions for future research. First, plant-level economic performances under a more detailed range of climate policy scenarios. Second, a broader and deeper assessment of the relative economic costs and benefits of coal power (e.g. loss of employment, upstream environmental impact, investment multiplier effects), and of alternative power sector investment options for China. Third, application of this framework to other generation technologies (including natural gas and the deployment of carbon capture and storage) and alternative means of meeting demand without additional generation (such as energy efficiency, demand response and additional transmission capacity). Fourth, the use of this framework to assess the economic returns for all actual planned coal plants in China, scaling up from the single pro-forma plant analyzed here, to determine the aggregate potential for economically stranded coal assets if current coal expansion plans go ahead.

Moreover, while this analysis is tailored to China given its dominant contribution to coal capacity additions, over-investing in coal assets is an issue of global concern, particularly to countries with relatively new fleets and significant expansion plans. Understanding the convergences and divergences between financial and economic returns is particularly pertinent where there is a major state presence in the power sector, such as India, Indonesia, Mexico, Pakistan, South Africa and Vietnam. Despite coal project cancellations in Bangladesh, the Philippines, Vietnam, Indonesia, and Pakistan in 2020, an estimated 503 GW of capacity remains under development globally, 344 GW outside China (Global Energy Monitor et al., 2021). The application of an economic framework can complement existing (financial) stranded asset analysis by assessing the economic rationale for proposed coal power projects, thereby providing governments and their SOEs with insights into prospective economic returns at the country level, as distinct from the corporate financial risks.

Finally, both within China and other countries featuring semi-autonomous subnational governments investing in coal, the principles behind this analysis can be applied to evaluate economic and financial returns at different levels of government (e.g. for provincial jurisdictions such as Inner Mongolia, Shaanxi, Shanxi, and Xinjiang), whereby sub-national boundaries are used as the pertinent unit to which economic costs and benefits accrue. This can provide insight into the political economy of provincial governments' coal investments, particularly where the economic case for coal is significantly stronger in specific provinces than at the national level, and inform the national government of misaligned perspectives on coal investment with subnational authorities.

Acknowledgements

For their insights and helpful comments on earlier drafts, the authors wish to thank Peter Meier, Arnaud Hubert, David Sandalow, Thomas Hale, and several anonymous reviewers. The views expressed here are those of the authors alone.

References

- Asian Development Bank. (2013). *Qinghai delignha concentrated solar thermal power project - economic analysis*.
- Belli, P., Anderson, J., Barnum, H., Dixon, J., & Tan, J.-P. (1998). *Handbook on economic analysis of investment operations*. World Bank.
- Benoit, P. (2019). *Engaging state-owned enterprises in climate action*. <https://energypolicy.columbia.edu/research/report/engaging-state-owned-enterprises-climate-action>
- Benoit, P., & Tu, K. J. (2020). *Is China still a developing country, and why it matters for energy and climate*. C. University.
- Biao, H., Hongjia, D., Ping, J., & Jingan, Z. (2020). Analysis of the applicable rate of environmental tax through different tax rate scenarios in China. *Sustainability (Basel, Switzerland)*, 12(4233), 4233. <https://doi.org/10.3390/su12104233>
- Caldecott, B., Dericks, G., Tulloch, D. J., Liao, X., Kruitwagen, L., Bouveret, G., & Mitchell, J. (2017). *Stranded assets and thermal coal in China: An analysis of environment-related risk exposure*: University of Oxford, Smith School of the Environment, Sustainable Finance ...
- Caldecott, B., Howarth, N., & McSharry, P. (2013). *Stranded assets in agriculture: Protecting value from environment-related risks*. <https://www.smithschool.ox.ac.uk/publications/reports/stranded-assets-agriculture-report-final.pdf>
- Caldecott, B., McCarten, M., & Triantafyllidis, C. (2018). *Carbon lock-in curves and Southeast Asia: Implications for the Paris agreement*. <https://www.smithschool.ox.ac.uk/research/sustainable-finance/publications/Carbon-Lock-in-Curves-and-Southeast-Asia.pdf>
- Chang, S., Zhuo, J., Meng, S., Qin, S., & Yao, Q. (2016). Clean coal technologies in China: Current status and future perspectives. *Engineering (Beijing, China)*, 2(4), 447–459. <https://doi.org/10.1016/J.ENG.2016.04.015>
- Chemnick, J. (2021). Cost of carbon pollution pegged at \$51 a Ton. *Scientific American*.

- China Electric Power Statistics and Data Center. (2020). *Overview of the operation of the power industry from January to October 2020*. <https://www.cec.org.cn/detail/index.html?3-290358>
- Chung, J. H. (1995). Studies of central–provincial relations in the People’s Republic of China: A mid-term appraisal. *The China Quarterly*, 142, 487–508. <https://doi.org/10.1017/S0305741000035025>
- Cole, W., & Frazier, W. (2019). *Cost projections for utility-scale battery storage*. Golden, CO <https://www.nrel.gov/docs/fy19osti/73222.pdf>
- Cui, R., Hultman, N., Cui, D., McJeon, H., Yu, S., Edwards, M., Sen, A., Song, K., Bowman, C., Clarke, L., Kang, J., Lou, J., Yang, F., Yuan, J., Zhang, W., & Zhu, M. (2021). A plant-by-plant strategy for high-ambition coal power phaseout in China. *Nature Communications*, 12(1), 1–10. <https://doi.org/10.1038/s41467-021-21786-0>
- Cui, R., Hultman, N., Jiang, K., McJeon, H., Yu, S., Cui, D., ... Zhang, W. (2020). *A high ambition coal phaseout in China: Feasible strategies through a comprehensive plant-by-plant assessment*. Center for Global Sustainability.
- Energy Monitor Worldwide. (2020). Chinese fishery hosting 260 MW of unsubsidized solar. *Energy Monitor Worldwide*.
- Energy Research Institute, & China National Renewable Energy Centre. (2019). *China renewable energy outlook 2019*.
- Fei, T. (2014). *The true cost of coal*. <http://coalcap.nrdc.cn/pdfviewer/web/?15083101061229121311.pdf>
- Garrett-Peltier, H. (2017). Green versus brown: Comparing the employment impacts of energy efficiency, renewable energy, and fossil fuels using an input-output model. *Economic Modelling*, 61, 439–447. <https://doi.org/10.1016/j.econmod.2016.11.012>
- Global Energy Monitor, & CREA. (2020). *A new coal boom in China: Country accelerates new coal plant permitting and proposals*. Briefing Series.
- Global Energy Monitor, Sierra Club, CREA, Climate Risk Horizons, GreenID, & Ekosfer. (2021). *Boom and bust 2021: Tracking the global coal plant pipeline*. Boom and Bust. https://globalenergymonitor.org/wp-content/uploads/2021/04/BoomAndBust_2021_final.pdf
- Gray, M., & Sundaresan, S. (2020a). *How to waste over half a trillion dollars: The economic implications of deflationary renewable energy for coal power investments*. C. T. Initiative.
- Gray, M., & Sundaresan, S. (2020b). *Political decisions, economic realities: The underlying operating cashflows of coal power during COVID-19*.
- Guo, X., Liu, H., Mao, X., Jin, J., Chen, D., & Cheng, S. (2014). Willingness to pay for renewable electricity: A contingent valuation study in Beijing, China. *Energy Policy*, 68, 340–347. <https://doi.org/10.1016/j.enpol.2013.11.032>
- Guoneng Hutong Inner Mongolia Network Technology Co Ltd. (2019). National and provincial electricity coal price index 2019. From Guoneng Hutong Inner Mongolia Network Technology Co Ltd http://www.imcec.cn/zgdm_2019
- He, G., Lin, J., Sifuentes, F., Liu, X., Abhyankar, N., & Phadke, A. (2020). Rapid cost decrease of renewables and storage accelerates the decarbonization of China’s power system. *Nature Communications*, 11(1), 1–9. <https://doi.org/10.1038/s41467-019-13993-7>
- He, J. (2020). *China’s long-term low-carbon development strategy and pathway*. Climate Change Global Lectures.
- He, J., Li, Z., Zhang, X., Wang, H., Dong, W., Chang, S., Ou, X., Guo, S., Tian, Z., Gu, A., Teng, F., Yang, X., Chen, S., Yao, M., Yuan, Z., Zhou, L., & Zhao, X. (2020). Comprehensive report on China’s long-term Low-carbon development strategies and pathways. *Chinese Journal of Population, Resources and Environment*, 18(4), 263–295. <https://doi.org/10.1016/j.cjpre.2021.04.004>
- Herve-Mignucci, M., Wang, X., Nelson, D., & Varadarajan, U. (2015). *Slowing the growth of coal power in China: The Role of Finance in State-Owned Enterprises*.
- Hove, A. (2020). *Trends and contradictions in China’s renewable energy policy*.
- International Energy Agency. (2019). *World energy outlook 2019*. International Energy Agency.
- International Energy Agency. (2020a). *Energy technology perspectives 2020*. Energy technology perspectives.
- International Energy Agency. (2020b). *World energy outlook 2020*. International Energy Agency.
- International Energy Agency. (2021). *Net zero by 2050: A roadmap for the global energy sector*. International Energy Agency.
- Johnson, N., Krey, V., McCollum, D. L., Rao, S., Riahi, K., & Rogelj, J. (2015). Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants. *Technological Forecasting and Social Change*, 90, 89–102. <https://doi.org/10.1016/j.techfore.2014.02.028>
- Lee, H. M. (2019). *China’s electricity price from gas drops, but still over 30% higher than coal*. NEA. S&P Global Platts.
- Li, L. C. (1998). Loci and scope of state power: Central-provincial tensions in China. *Asian Economic and Political Issues*, 4, 117–134.
- Li, X., Yang, X., Wei, Q., & Zhang, B. (2019). Authoritarian environmentalism and environmental policy implementation in China. *Resources, Conservation and Recycling*, 145, 86–93. <https://doi.org/10.1016/j.resconrec.2019.02.011>
- Lin, J., Kahrl, F., Yuan, J., Liu, X., & Zhang, W. (2019). Challenges and strategies for electricity market transition in China. *Energy Policy*, 133. <https://doi.org/10.1016/j.enpol.2019.110899>
- Liu, J., Li, J., & Yao, X. (2019). The economic effects of the development of the renewable energy industry in China. *Energies (Basel)*, 12(9), 1808. <https://doi.org/10.3390/en12091808>
- Mayer, B., Rajavuori, M., & Fang, M. M. (2017). The contribution of state-owned enterprises to climate change mitigation in China. *Climate Law*, 7(2-3), 97–124. <https://doi.org/10.1163/18786561-00702002>
- Meier, P. (2017a). *Power sector investment projects: Guidelines for economic analysis*. World Bank.
- Meier, P. (2017b). *Power sector investment projects: Guidelines for economic analysis: Technical notes*. World Bank.
- Mercure, J. F., Pollitt, H., Viñuales, J. E., Edwards, N. R., Holden, P. B., Chewpreecha, U., Salas, P., Sognaaes, I., Lam, A., & Knobloch, F. (2018). Macroeconomic impact of stranded fossil fuel assets. *Nature Climate Change*, 8(7), 588–593. <https://doi.org/10.1038/s41558-018-0182-1>
- Mining Technology. (2017). Clean break: How China’s new environmental protection tax law could affect mining. *Mining Technology*.
- Mo, J., Zhang, W., Tu, Q., Yuan, J., Duan, H., Fan, Y., Pan, J., & Meng, Z. (2021). The role of national carbon pricing in phasing out China’s coal power. *iScience*, 24(6), 102655. <https://doi.org/10.1016/j.isci.2021.102655>

- Naschert, C. (2020). *European power outlook: Falling costs to drive more unsubsidized solar activity*. S&P Global.
- Normile, D. (2020). China's bold climate pledge earns praise-but is it feasible? *Science (New York, N.Y.)*, 370(6512), 17–18. <https://doi.org/10.1126/science.370.6512.17>
- Pfeiffer, A., Hepburn, C., Vogt-Schilb, A., & Caldecott, B. (2018). Committed emissions from existing and planned power plants and asset stranding required to meet the Paris agreement. *Environmental Research Letters*, 13(5). <https://doi.org/10.1088/1748-9326/aabc5f>
- Saygin, D., Rigter, J., Caldecott, B., Wagner, N., & Gielen, D. (2019). Power sector asset stranding effects of climate policies. *Energy Sources, Part B: Economics, Planning, and Policy*, 14(4), 99–124. <https://doi.org/10.1080/15567249.2019.1618421>
- Selim, K., Ichisugi, Y., Abeynayaka, A., & Itsubo, N. (2020). External-cost estimation of electricity generation in G20 countries: Case study using a global life-cycle impact-assessment method. *Sustainability*, 12(5), 2002. <https://doi.org/10.3390/su12052002>
- Shearer, C., & Myllyvirta, L. (2021). *China dominates 2020 coal plant development*. Global Energy Monitor Briefings.
- Spencer, T., Berghmans, N., & Sartor, O. (2017). *Coal transitions in China's power sector: A plant-level assessment of stranded assets and retirement pathways*. S. Po.
- Squire, L., & Van der Tak, H. G. (1975). *Economic analysis of projects*. World Bank Publications.
- Stiglitz, J. E., Stern, N., Duan, M., Edenhofer, O., Giraud, G., Heal, G. M., ... Pangestu, M. (2017). Report of the high-level commission on carbon prices.
- Tang, L., Qu, J., Mi, Z., Bo, X., Chang, X., Anadon, L. D., Wang, S., Xue, X., Li, S., Wang, X., & Zhao, X. (2019). Substantial emission reductions from Chinese power plants after the introduction of ultra-low emissions standards. *Nature Energy*, 4(11), 929–938. <https://doi.org/10.1038/s41560-019-0468-1>
- Tu, K. J. (2020). COVID-19 pandemic's impacts on China's energy sector: A preliminary analysis.
- World Bank. (2011). *Project appraisal document on a proposed loan in the amount of US\$330 million to the Socialist Republic of Vietnam for the Trung Son Hydropower Project*. (57910-VN). World Bank.
- World Bank. (2017). *Shadow price of carbon in economic analysis: Guidance note*. The World Bank Group.
- World Bank. (2019). *Project appraisal document: China renewable energy and battery storage promotion project*. The World Bank Group.
- Xiang, H., & Kuang, Y. (2020). Who benefits from China's coal subsidy policies? A computable partial equilibrium analysis. *Resource and Energy Economics*, 59. <https://doi.org/10.1016/j.reseneeco.2019.101124>
- Xie, B.-C., & Zhao, W. (2018). Willingness to pay for green electricity in Tianjin, China: Based on the contingent valuation method. *Energy Policy*, 114, 98–107. <https://doi.org/10.1016/j.enpol.2017.11.067>
- Yang, Y., Campana, P. E., & Yan, J. (2020). Potential of unsubsidized distributed solar PV to replace coal-fired power plants, and profits classification in Chinese cities. *Renewable and Sustainable Energy Reviews*, 131. <https://doi.org/10.1016/j.rser.2020.109967>
- Yuan, J., Guo, X., Zhang, W., Chen, S., Ai, Y., & Zhao, C. (2019). Deregulation of power generation planning and elimination of coal power subsidy in China. *Utilities Policy*, 57, 1–15. <https://doi.org/10.1016/j.jup.2019.01.007>
- Yuan, J., Guo, X., Zhang, W., Zhou, J., & Qin, C. (2019). Stranded coal power assets in China: A case study of jilin province. *Emerging Markets Finance and Trade*, 55(12), 2673–2688. <https://doi.org/10.1080/1540496X.2018.1541134>
- Yuan, J., & Zhang, W. (2017). *Power generation liberalisation, coal subsidies and stranded assets*.
- Zeng, Q. (2016). Control, discretion and bargaining: The politics of provincial leader rotation in China. *Chinese Political Science Review*, 1(4), 623–644. <https://doi.org/10.1007/s41111-016-0045-8>
- Zhang, C., Zhou, K., Yang, S., & Shao, Z. (2017). On electricity consumption and economic growth in China. *Renewable and Sustainable Energy Reviews*, 76, 353–368. <https://doi.org/10.1016/j.rser.2017.03.071>
- Zhang, H., Zhang, X., & Yuan, J. (2020). Transition of China's power sector consistent with Paris Agreement into 2050: Pathways and challenges. *Renewable and Sustainable Energy Reviews*, 132. <https://doi.org/10.1016/j.rser.2020.110102>
- Zhang, L., & Wu, Y. (2012). Market segmentation and willingness to pay for green electricity among urban residents in China: The case of Jiangsu province. *Energy Policy*, 51, 514–523. <https://doi.org/10.1016/j.enpol.2012.08.053>

Supplementary Material

Measurement of net income and net benefits

For the financial analysis, net income in period t is measured on the basis of net free cash flow in nominal terms, adjusting each component for inflation. For the economic analysis, net benefits are measured on the basis of cost-benefit analysis, in real terms.

$$NetIncome_t = \left[[p_e \times g] - [c + o_f + o_v + f] - [d + s] \right] \times (1 - ct)$$

$$NetBenefits_t = \left[[p_e^* \times g] - [c^* + o_f^* + o_v^*] - [c^{**} + o_f^{**} + o_v^{**} + f^{**}] \right] \times m$$

Where:

- p_e is the nominal electricity price paid to the generator, p_e^* is the real willingness-to-pay for electricity (CNY per MWh)
- g is electricity generated (MWh)
- c is nominal capital expenditure, c^* is real capital expenditure accrued in China not including taxes, c^{**} is real capital expenditure outside China (CNY)
- o_f is nominal fixed operating cost, o_f^* is real fixed operating costs accrued in China not including taxes, o_f^{**} is real fixed operating costs accrued outside China (CNY per MW)
- o_v is nominal variable operating cost (fuel costs + pollution taxes), o_v^* is real variable operating costs accrued in China (fuel costs not including taxes + social

cost of pollution), o_v^{**} is real fixed operating costs accrued outside China (fuel costs + pollution taxes) (CNY per MWh)

- f is financial expenditure (principal and interest payments on loans), f^{**} is financial expenditure on loans held by non-Chinese entities
- d is depreciation of capital assets (assuming 100% straight line depreciation over operating lifetime)
- s is the salvage value of the asset (assumed to be zero)
- ct is the rate of corporation tax (assuming tax liabilities not offset by other company activities)
- m is an economic stimulus multiplier capturing the economic value to China generated beyond the coal plant

Solar/storage assumptions

Table A-1. Solar/storage assumptions (comparable coal Base Case inputs in parentheses)

Component	Unit	Solar/storage (plant-level, financial)	Solar/storage (country- level, economic)
Capital cost	US\$m / MW	~ 0.8-1.1 (~ 0.5)	~ 0.65-0.85 (~ 0.4)
O&M costs	US\$ / MW- year	~ 23,000 (~ 11,500)	~ 16,000 (~ 10,000)
Fuel costs	US\$ / MWh	0 (~30.5)	0 (~ 29)
Load factor	%	48%, with 20% solar capacity factor (48%)	
Years of construction + operation	years	2 + 30 (3 + 30)	
Internal electrical system losses	%	~ 10% (~ 0%)	
Emissions from generation	tCO2/MWh	~ 0 (~ 0.75-0.80)	

Capital cost of the solar PV component is approximately the same as coal (US\$500,000/MW). Capital cost of storage depends on technology options and storage requirements, which are location-specific factors. Pumped storage (installed cost estimated at US\$75,000/MWh assuming pre-existing capacity) can be the cheapest option. China has potential to expand its pumped storage capacity from 25GW to 130GW

by 2030 (He et al., 2020). Lithium-ion batteries (US\$300,000/MWh) are convenient but expensive, though costs continue to decline rapidly. Chemical storage technologies sit between the two (US\$220,000/MWh). Overall storage costs depend on allocation across these options. A blend of all three options is used in the model, with lithium-ion batteries comprising 25% of total storage capacity, chemical storage 25%, and pumped storage 50%, reflecting the significant untapped potential of the latter in China at present. The lithium-ion batteries are fully replaced every ten years based on cost projections in Cole and Frazier (2019), and chemical storage every twenty years, based on projections in Energy Research Institute and China National Renewable Energy Centre (2019). The solar & storage plant provides the same average daily energy as the coal plant: 11,520 MWh/day (480 MWh/hour). At a 20% capacity factor, this requires a 2.67GW PV plant producing 2.4GW peak power, once accounting for losses. The PV plant is coupled with a battery system capable of storing 4.7 hours of the coal plant's peak output (four hours is typical for such a system; we have added a buffer of 17.5% for additional flexibility). Electrical system losses include inverter losses (3.5%), transformer losses (1.6%), cable and technical losses (2.8%), and downtime/soiling losses (2%). See Gensol (2016).

Table A-2. Economic NPV and IRR for all coal scenarios and solar/storage alternative (US\$m)

	Economic NPV@8%	Equity FNPV@6%
Coal		
Base Case	472	62
SCP – Modest Ambition (MA-SCP)_	-50	62
SCP – Higher Ambition (HA-SCP)	-355	62
LR – Stated Policies (SP-LR)	229	-124
LR – Below 2C (B2C-LR)	161	-176
2030 Moratorium	-6	-129
2035 Moratorium	179	-118
Solar/Storage		
Base Case	54	-362
15% Lower Capital Cost	328	-36
30% Lower Capital Cost	602	290

Table A-3. Full table of key inputs for financial and economic analysis

Component	Unit	Value for Financial Analysis	Value for Economic Analysis
US\$ to Yuan conversion rate	CNY/US\$	6.91	
Capacity	MW	1,000	
Coal energy content	MWh/ton	18.84 ¹	
Plant efficiency	%	48% ²	
Construction period	years	3	
Capital cost	US\$ / MW	517,366 ³	401,657 ⁴
Private discount rate	%/year	6% ⁵	-
Social discount rate	%/year	-	8%
Inflation rate	%/year	2.1% (1.5% for tariff)	-
Domestic financing	% of financing	100%	
Debt financing	% of total capital cost	60%	-
Cost of debt ⁶	%/year	4.35%	-
Corporate tax rate	% of profits	25%	-
Operating life	years	30	
Load factor	%	48% ⁷	
Coal fuel cost	US\$ / ton of fuel delivered	76.52 ⁸	67.64 ⁹
Operating costs	US\$ / MW-year	11,549 ¹⁰	9,816
Transmission costs ¹¹	US\$ / MWh	19	
Distribution costs	US\$ / MWh	29	
Transmission and Distribution losses	%	5% ¹²	
Electricity price received	US\$ / MWh	47.12 ¹³	-
Percentage of power used by industrial users ¹⁴	%	-	62%
Residential electricity tariff ¹⁵	US\$ / MWh	-	79.16
Commercial electricity tariff	US\$ / MWh	-	96.38
Industrial electricity tariff ¹⁶	US\$ / MWh	-	79.96
<i>Environmental</i>			
Carbon price/tax	US\$ / ton	0	-
Shadow carbon price	US\$ / ton	-	See SCP scenarios
Upstream coal production and transportation		-	<0 (not estimated)
<i>Economic</i>			
CapEx stimulus	US\$ / US\$ spent on CapEx	-	>0 (not estimated)
Employment (upstream) stimulus	US\$ / additional ton of coal extracted	-	>0 (not estimated)

References

- Asian Development Bank. (2013). *Qinghai Delignha Concentrated Solar Thermal Power Project - Economic Analysis*. Asian Development Bank.
- Cole, W., & Frazier, W. (2019). *Cost Projections for Utility-Scale Battery Storage*. Golden, CO. <https://www.nrel.gov/docs/fy19osti/73222.pdf>.
- Cornot-Gandolphe, S. (2014). *China's coal market: can Beijing tame 'King Coal'?* (Report No. 9781784670177). Oxford. Retrieved from Can Beijing tame 'King Coal?': <https://www.oxfordenergy.org/wpcms/wp-content/uploads/2014/12/CL-11.pdf>.
- Electric Power Planning & Engineering Institute. (2019). *Report on China's Electric Power Development 2018*. Beijing.
- Gensol. (2016). *Generation Assessment and Loss Justification*.
- Global Petrol Prices. (2020). China electricity prices. Retrieved 1 August 2020 https://www.globalpetrolprices.com/China/electricity_prices/
- Gray, M., & Sundaresan, S. (2020). *Political decisions, economic realities: The underlying operating cashflows of coal power during COVID-19*.
- Guoneng Hutong Inner Mongolia Network Technology Co Ltd. (2019). National and provincial electricity coal price index 2019. from Guoneng Hutong Inner Mongolia Network Technology Co Ltd http://www.imcec.cn/zgdm_2019
- He, G., Lin, J., Sifuentes, F., Liu, X., Abhyankar, N., & Phadke, A. (2020). Rapid cost decrease of renewables and storage accelerates the decarbonization of China's power system. *Nature communications*, 11(1), 1-9
- International Energy Agency. (2019). *World Energy Balances*. Paris, France.
- Lin, B., & Wu, W. (2017). Cost of long distance electricity transmission in China. *Energy Policy*, 109, 132
- National Research Council, Chinese Academy of Sciences, & Chinese Academy of Engineering. (2000). *Cooperation in the energy futures of China and the United States*. Washington, D.C.: National Academy Press.
- Patel, S. (2019). How China is Improving Coal Technology. *Power Magazine*.
- Wong, S. (2020). Electric power transmission loss in China from 2010 to 2019. Retrieved 13 August 2020, from Statista <https://www.statista.com/statistics/302292/china-electric-power-transmission-loss/>
- Zhang, D., & Paltsev, S. (2016). *The Future of Natural Gas in China: Effects of Pricing Reform and Climate Policy*. Retrieved from Tsinghua-MIT China Energy and Climate Project, MIT Joint Program on the Science and Policy of Global Change.
- Zhang, Z. Y. (2019). China Electricity Prices for Industrial Customers. *China Briefing*.
- Zhao, Z. (2019, 28 October). China Electricity Union: 2018 Net Source Project Cost Rises and Falls, *People.cn*. Retrieved from http://paper.people.com.cn/zgnyb/html/2019-10/28/content_1953235.htm

-
- ¹ Assumed low heat value of 5,000 kcal/kg (20.93 GJ/ton), adjusted to 4,500 kcal/kg to account for lower-quality coal mined in rural provinces. One tonne of coal equivalent (tce) contains 7,000 kcal/kg (29.31 GJ/ton). For calorific content of Chinese thermal (steam) coal, see Cornot-Gandolphe (2014). See also National Research Council, Chinese Academy of Sciences, and Chinese Academy of Engineering (2000, Chapter 8).
- ² Represents a highly efficient ultra-supercritical coal unit. The world's most efficient unit (as of 2019) has final efficiency of 49.6%. Plants with smaller boilers more like this example, have efficiencies closer to 48%. See Patel (2019).
- ³ Average estimate for cost of a modern ultra-supercritical coal plant with a ~600MW boiler. See Electric Power Planning & Engineering Institute (2019) and 2018 China Electricity Council report cited in Zhao (2019).
- ⁴ Differences between financial and economic capital costs reflect adjustments for domestic taxes, supplier mark-up on construction materials and import/value-added taxes.
- ⁵ Weighted average cost of capital given 60% debt, 40% equity. Cost of debt is prime lending rate (4.35% at time of writing). Cost of equity is 8%, based on rate applied by China General Nuclear Power Corporation in Asian Development Bank (2013).
- ⁶ See endnote 17.
- ⁷ Estimated average load factor of Chinese coal fleet in Gray and Sundaresan (2020).
- ⁸ Median NDRC Monitoring Centre price for 2019 of 528.74 Yuan/ton delivered coal. See Guoneng Hutong Inner Mongolia Network Technology Co Ltd (2019).
- ⁹ Difference between financial and economic fuel cost reflects adjustments for domestic taxes and duties, and supplier mark-up at the point of production.
- ¹⁰ Estimated fixed O&M costs assumed to be CNY 62,000 (2012), adjusted upwards by 20% to account for inflation 2012-20. See D. Zhang and Paltsev (2016).
- ¹¹ Based on average T&D charges for industrial, residential, and commercial customers in B. Lin and Wu (2017). Cost of local distribution inferred from difference between them. We assume no new T&D infrastructure is required, and that it would carry electricity from other sources if the coal plant were not built. Thus, T&D infrastructure costs have already been incurred, and benefits of power generation are net of these costs.
- ¹² Based on 5.9% average transmission system losses, 2010-2019 (Wong, 2020).

¹³ Mean of provincial wholesale market prices for coal power. The majority is still sold at fixed official benchmark rates, but this is being gradually replaced by market prices. See Guoneng Hutong Inner Mongolia Network Technology Co Ltd (2019).

¹⁴ We assume 62% of electricity is sent to industrial high-voltage users; 19% to residential, and 19% to commercial users. In 2017, industry represented 62% of electricity consumption (International Energy Agency, 2019). The residential and commercial share may increase as China shifts towards a more service-based economy.

¹⁵ WTP is estimated as 6% mark-up on electricity prices. Economic benefit is derived by adjusting for T&D costs. This is consistent with International Monetary Fund projections for China's annual growth in the early 2020s. Household and commercial retail prices correct as of December 2019. See Global Petrol Prices (2020).

¹⁶ Median large-scale industrial electricity prices for 220kv customers. See Z. Y. Zhang (2019).

A3. Paper 3: The effects of coal phase-out on employment and fiscal revenue in China

The subsequent pages contain an offprint of the article published in *Energies*.

The full citation is:

Clark, A., & Zhang, W. (2022). Estimating the Employment and Fiscal Consequences of Thermal Coal Phase-Out in China. *Energies (Basel)*, 15(3), 800. doi:10.3390/en15030800

The article length, including supplemental data in an appendix, is 42 pages.

The authors' contributions to the paper were as follows:

- **Alex Clark:** conceptualisation, methodology, formal analysis, investigation, draft manuscript preparation, review and editing, visualisation.
- **Weirong Zhang:** validation, investigation, review and editing.

All authors reviewed the results and approved the final version of the manuscript.

Article

Estimating the Employment and Fiscal Consequences of Thermal Coal Phase-Out in China

Alex Clark ^{1,*}  and Weirong Zhang ²¹ Smith School of Enterprise and the Environment, University of Oxford, Oxford OX1 3QY, UK² School of Economic and Management, North China Electric Power University, Beijing 102206, China; 18801379886@163.com

* Correspondence: alex.clark@smithschool.ox.ac.uk

Abstract: China hosts over half of global coal-fired power generation capacity and has the world's largest coal reserves. Its 2060 carbon neutrality goal will require coal-fired electricity generation to shrink dramatically, with or without carbon capture and storage technology. Two macroeconomic areas in which the socioeconomic impact of this decline is felt are losses in jobs and tax revenues supported by thermal coal mining, transport and power generation. At the national level, under a 'baseline' (B) scenario consistent with China's carbon neutrality goal, labour productivity growth in coal mining implies that significant job losses will occur nationally in the medium term, even if all coal plants continue operating as planned. Jobs supported by the coal power industry would decline from an estimated 2.7 million in 2021, to 1.44 million in 2035 and 94,000 in 2050, with jobs losses from mining alone expected to exceed 1.1 million by 2035. Tax revenues from thermal coal would total approximately CNY 300 billion annually from 2021–2030, peaking in 2023 at CNY 340 billion. This is significantly less than estimated subsidies of at least CNY 480 billion, suggesting coal is likely a net fiscal drain on China's public finances, even without accounting for the costs of local pollution and the social cost of carbon. As coal plant retirements accelerate, from 2034 onwards, fiscal revenues begin to fall more rapidly, with rates of decline rising from 1% in the 2020s to over 10% a year by the 2040s. More aggressive climate policy and technology scenarios bring job and tax losses forward in time, while a No Transition policy, in which all currently planned coal plants are built, delays but does not ultimately prevent these losses. At the provincial level, China's major coal-producing provinces will likely face challenges in managing the localised effects of expected job losses and finding productive alternative uses for this labour. Governments of coal-producing provinces like Inner Mongolia, with an industry highly dependent on exports to other provinces, are more exposed than others to declining tax revenues from coal, and more insulated from job losses, given their high current degree of labour efficiency. Although their provincial revenues are likely to remain stable until the early 2030s under the B scenario, the possibility of increasing policy stringency underlines the need for revenue and skill base diversification. At the firm level, China's 'Big Five' state-owned power companies were responsible for over 40% of both jobs and tax revenues in 2021. The number of jobs supported by the activities of each of the largest ten firms, with one exception, will decline by 71–84% by the early 2040s, with the tax contribution of each declining by 43–69% in the same period.

Keywords: China; coal phase-out; climate policy; just transition; tax revenue; employment

Citation: Clark, A.; Zhang, W. Estimating the Employment and Fiscal Consequences of Thermal Coal Phase-Out in China. *Energies* **2022**, *15*, 800. <https://doi.org/10.3390/en15030800>

Academic Editor: Gireesh Shrimali

Received: 5 November 2021

Accepted: 19 January 2022

Published: 22 January 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

China has been the world's largest annual emitter of greenhouse gases since 2005 [1] and hosts more than half of global coal-fired power generation (thermal coal) capacity. Coal power generation capacity in China is concentrated in the populous Eastern provinces, and increasingly in the coal-rich autonomous regions of Inner Mongolia in the North and Xinjiang in the West, as well as the Central province of Shanxi. In 2020, amid the global economic slowdown induced by the COVID-19 virus pandemic, capacity additions

accelerated, accounting for three-quarters of globally commissioned coal capacity, and 85% of capacity under development [2]. China also produced 53% of the world's crude steel in 2019 and 60% of its cement in 2017 [3,4], both of which rely heavily on coal as an energy source. Replacing unabated coal plants with net zero emissions alternatives in China is, therefore, critical to global decarbonisation.

In September 2020, President Xi Jinping announced China would set itself a target of reaching carbon neutrality by 2060, and to peak emissions “before 2030” [5]. The 14th Five Year Plan (FYP), a guide to national policy priorities from 2021–25 published after the announcement, targets 20% non-fossil energy in final consumption by 2025 and 25% by 2030. While it mentions an 18% drop in CO₂ emissions intensity by 2025, the targeted 6% annual GDP growth means total emissions may still rise by 2025 [6].

However, modelling of multi-sector development pathways led by Tsinghua University [7] projects that China's coal-fired power generation capacity will decline to 191 GW by 2050 under a 2 °C global warming scenario, with 47% electricity generated coming from carbon capture and storage (CCS)-enabled units, and coal contributing just 6.5% of total power generation. Under a 1.5 °C scenario reaching net zero sectoral emissions in 2045, coal capacity in 2050 will be just 181 GW, with 88% of generation being CCS-enabled and contributing just 6% of total electricity generation. Global assessments of cost-effective pathways for coal plant retirement find that operational lifetimes of 30 years, including plants under construction but assuming no capacity currently in the planning stages is ultimately built, are considered cost-effective for a 2 °C scenario, implying phase-out by the early 2050s. Operating lifetimes of 15 years are deemed optimal for a 1.5 °C scenario, implying phase-out by the late 2030s [8].

Thus, even if CCS technologies reach commercial scalability and see wide deployment, China's coal fleet—over 90% of which is estimated to be controlled by state-owned enterprises [9]—is expected to shrink by over 80% by 2050 under either a 2 °C or 1.5 °C scenario. If China is to meet its carbon neutrality targets, a total phase-out of unabated coal-fired electricity generation in China by 2060, across both the thermal and metallurgical coal segments, is nearly inevitable.

Prior analysis of thermal coal phase-out in China and beyond has focused on the financial implications of asset stranding for the owners of coal plants and mines [10–14], and optimises plant-level phase-out processes according to profitability, environmental impact, or both. Studies of other countries have considered the financial consequences, but also consider the impact of coal transition on some of the other priorities of government, often using the term ‘just transition’ to call for or to describe measures that protect the interests of those negatively affected. These include mitigating the short- and medium-term effects on coal industry employment and structural deindustrialisation, as well as the fiscal impact of declining coal revenue and, in some cases, higher costs for electricity consumers [15]. Strategies for managing these and other political economy frictions of phasing out coal in China have been examined qualitatively [16] and integrated assessment models (IAMs) have been used to project changes in energy sector employment across different countries, including China [17]. However, the reconstruction and quantification of employment and fiscal impacts of coal phase-out in China, in a granular, bottom-up manner and using publicly available data, has not yet been attempted. This paper, therefore, makes a first attempt to answer calls for new research [18] on the national, subnational, corporate and supply chain impacts of coal phase-out in China.

This analysis uses plant-level data and a reconstruction of the coal production-consumption network to model the impact of coal phase-out on jobs within, and tax revenues from, the thermal coal industry in China under a range of plausible climate policy scenarios. It considers the implications for the political economy of coal transition, and for the design of corresponding redistributive policies in China. Section 2 presents an overview of current literature on the socioeconomic challenges presented by coal phase-out and strategies employed for managing the impact on consumers, workers, and public sector revenues. It situates these challenges within the context of the Chinese coal industry.

Section 3 lays out a methodology for projecting the employment and fiscal impacts of coal transition in China. Section 4 presents results at national, subnational, and firm levels. Section 5 analyzes the implications of the findings for the Chinese government in managing the transition. Section 6 concludes.

2. Reviewing Experiences with Coal Transitions: China and Beyond

2.1. Coal Transitions outside China

Analyses of the drivers and effects of coal industry maturation, transition and decline outside China are dominated by studies of the United States (U.S.), United Kingdom (U.K.), and Western Europe, particularly Germany. Eastern Europe and developing economies at earlier stages of transition are systematically under-represented [19]. While coal was, until relatively recently, the main source of primary energy in most advanced economies, the energy market structures and political systems under which their coal transitions took, or are taking place, are very different to those in China. Even in Western economies still in the throes of coal transition, energy demand growth is low or negative, absolute coal consumption is far smaller, and coal now contributes a much lower proportion for primary or industrial energy supply than it once did. The relevance of this literature to China lies in the historical and contemporary experiences of structural change that coal transitions have induced in these contexts, particularly on industry and labour.

A comprehensive review of the literature on coal transitions [19] finds that loss of employment is their most frequently documented economic consequence. The U.K., Western Europe and the U.S. exhibited a sustained decline in coal industry employment in the late 20th and early 21st centuries. In the U.K., coal production declined 99% from 1962 to 2012, with coal-related employment also falling 99% in the same period, from 664,000 to 6000 [20]. In Germany, direct and indirect employment in coal power and mining declined from over 700,000 in 1985 to under 100,000 in 2015, driven by post-Soviet market liberalisation, international competition, and technical advances, among other factors [21]. Across the E.U., coal mining employment fell 50% to 130,000 between 2007–2017. Alves Dias, et al. [22] estimate coal-related employment in the E.U. at 238,000 in 2018 (less than 0.1% of total employment). About 160,000 of these remaining jobs are expected to be lost by 2030, 25% of those in Upper Silesia, a region of Poland [23]. In the U.S., coal mining supported just 40,000 jobs in 2020, down 55% from 2011 and 77% from 1985 [24]. Coal is also being outstripped by clean power generation: U.S. coal power plant-related jobs averaged 79,700 in 2019, only 22% of the jobs in wind and solar power in the same year [25].

In aggregate, coal phase-out can be associated with substantial net employment gains in the power sector as coal jobs are replaced by renewables. Net overall job gains do not, however, imply that former coal miners and plant operators will be re-employed in renewable industries, since they do not necessarily occur in the same place, and at the same time, as job losses in coal, or demand the same skills and experience. Upstream activities in coal mining that cannot easily pivot to new sources of demand and are not necessarily well-located for renewable industries are more likely to see concentrated net job losses. Theoretical work on ‘adjacent’ future career pathways in green industries for existing U.S. fossil fuel workers, matching occupational skills across time and space [26] can help to address this problem, but has yet to be applied in practice.

Loss of employment linked to coal transitions is associated with a series of other social impacts. To manage these impacts, a variety of ‘just transition’ measures have been adopted across different countries and regions. Observed negative social outcomes include declining living standards, increasing poverty, and a drop in public service provision, partially mitigated by robust social security and redistributive tax systems, but also the generation of alternative employment opportunities through economic diversification and new investment [27]. Significant negative effects on public finances are reported in some cases, linked to declining tax revenues from coal and high remediation costs for former mining areas [28,29]. Measures to dampen localised employment shocks, prevent deterioration of locally funded services and infrastructure, and divert surplus labour

supply into new markets have been deployed in several European countries. These include Germany's EUR 40 billion investment in education, innovation, and social safety nets, in collaboration with trade unions, and Spain's EUR 250 million transition support package that also requires firms to submit just transition plans before closing mining sites [30]. There is some evidence of positive social outcomes from coal industry closures, in terms of declining mortality and morbidity [31,32], particularly from cardiovascular and respiratory diseases [33].

Analysis of transition measures suggests that while support for diversification into other industries has generated new investment and jobs in former coal regions, former coal workers and their dependents have not necessarily benefited from these measures [34]. Early findings also suggest that early retirement schemes can soften the immediate impact of redundancies and reduce fiscal uncertainty for local governments, but do not help workers seeking alternative employment or retraining. Such schemes can also be very costly to maintain through to retirement age, particularly for younger workforces. In terms of fiscal impact, the coal industry in G20 countries is estimated to benefit from at least USD 63.9 billion in subsidies annually, with the majority accruing to consumers of coal-fired electricity through USD 15.4 billion in direct fiscal support, and USD 20.9 billion in capital investments by state-owned enterprises [35]. Even without considering health and climate externalities, to the extent that reduced tax revenues from coal are offset by reductions in these subsidies, coal phase-out can be revenue-neutral or even revenue-positive for governments. If true, this implies that redistribution of fiscal support, social support, and productive investment among subnational regions or groups, rather than macroeconomic stability or growth, should be the primary concern for policymakers.

2.2. Coal Transition in China

The scale of the economic transformation China must undertake in the next four decades to meet its public commitments to carbon peaking (2030) and neutrality (2060) is historically unprecedented. Previous regulatory efforts to streamline China's coal industry over the last twenty years have focused not on replacing coal itself, but on replacing old coal infrastructure with new, small thermal plants and mines with large ones, inefficient machinery with high efficiency technology, and moving polluting activities from high- to low-population density areas. These goals have been pursued through two overarching sets of national policies, as well as pilot emissions trading programmes.

The first national policy framework relates to coal mine consolidation. These began in the 1990s, and saw thousands of small mine closures, including over 40,000 mine closures in 2000 alone [36] and almost 45,000 mining company closures from 1998–2002 [37], citing illegal extraction, poor safety and environmental records, low recovery rates and suboptimal locations [38]. From 2003 onwards, central government continued its policy of closing smaller mines and plants, moving more recently towards large, centralised state-owned coal bases [39], nominally driven by safety, industrial restructuring, and environmental factors [40]. Small-scale state-owned mines accounted for 73% of mine closures from 2016–18; however, they were still larger and more labour-efficient than privately-owned mines, and more often controlled by large conglomerates able to redeploy workers elsewhere within their corporate structure and geographic reach [41]. Consolidation policies have also increased mining industry concentration: in 2018, 10 mining companies accounted for 42% of national output, and mines with over 1.2 million tonnes (Mt) of annual production capacity comprised 80% of output [41]. The China National Coal Association expects the total number of mines to decline further, from 4700 in 2020 to 4000 in 2025, even as annual production rises to 4.1 billion tonnes. By this time, 25% of mines are expected to employ labour-saving "smart production techniques" [42].

The second set of national policies reflects the government's "build big, close small" approach of removing excess capacity through supply side structural reforms and the establishment of emissions standards for coal-fired thermal power plants. The government's "developing large units, suppressing small ones" policy resulted in the closure of 77 GW of

older, mostly small-scale capacity plants during the 11th FYP period (2006–2010) and 28 GW during the 12th FYP (2011–2015) [43]. The definition of “outdated” coal-fired power was extended to all units under 300 MW in the 2013 Action Plan for Air Pollution Prevention and Control [44]. In 2014, China introduced ultra-low emission (ULE) standards, requiring coal-fired power generation units to be renovated to limit emissions of sulphur dioxide (SO₂), nitrogen oxides (NO_x) and particulate matter (PM) to 35, 50 and 10 mg/m³ concentrations in the plant exhaust stack, respectively [45]. Subsequent government subsidies enabled large swathes of remaining non-compliant capacity to improve overall plant efficiency and implement emissions control technology, at an estimated cost of CNY 130 billion in 2014–15. Pressure on municipal and regional governments to reduce coal power generation in urban areas has also contributed to an ongoing shift in generation capacity towards more rural Eastern and Northern mining regions and the export of power to demand centres through long-distance transmission lines [46]. In 2017, the Chinese government pledged to cancel or postpone construction of 150 GW of additional coal power generation capacity, and to remove a further 20 GW of technologically outdated coal-fired power stations by 2020 [47].

China’s carbon emissions trading system (ETS), formally proposed by the National Development and Reform Commission in 2011, was first implemented in six subnational “pilot” jurisdictions (Beijing, Shanghai, Tianjin, Chongqing, Hubei, and Guangdong). The pilot programmes were expected to be problematic, and indeed experienced design- and context-induced difficulties, with low prices and volumes, insufficient market supervision [48,49] and consequently weak incentives to choose emissions abatement over acquiring more permits. Evaluation of the programmes’ success suggests that, while there is evidence that the ETS pilots were associated with lower emissions [50,51], other contributing factors included levels of economic development, higher population density, greater economic openness (which could enable carbon leakage, particularly where emissions could be relocated to less population-dense parts of China), research expenditure, and strength of environmental regulations, as well as the maturity of the trading market, with the wealthier Eastern provinces seeing higher prices and greater emissions reductions relative to counterfactual baselines [52]. The national ETS was launched in July 2021, although it retains many of the design elements of the pilots and its role in slowing or accelerating the coal transition is not yet clear.

These consolidation, efficiency, and carbon trading measures have not yet achieved the absolute reduction in total national thermal coal consumption or emissions required by the government’s new commitments, but they do provide some insight as to the effects of industrial restructuring and consolidation on employment. Direct employment by coal companies peaked at 5.3 million in 2013, falling to 3.2 million in 2018 [53]. Independent forecasts made in 2017 suggest that improved technology will reduce coal sector jobs by a further 50% to 1.6 million in 2050, with further restrictions on capacity growth reducing total coal jobs in 2050 to 900,000 [16]. In a reflection of how these trends are expected to continue, the International Energy Agency (IEA) predicts a 30% drop in global coal employment from 2019–2030 in its Accelerated Policy Scenario, with the sharpest drop seen in China, resulting from a combination of increased productivity and industrial restructuring [54].

Previous experience with the depletion of specific coal mines also sheds some light on the potential consequences of large-scale disruption where cities built on coal have failed to diversify before supplies run out. Fuxin, in Liaoning province, once hosted Asia’s largest open pit mine, with 500,000 city residents either employed in, or dependent on it at peak production, and the mining bureau funding local hospitals, schools and other facilities. The mine entered bankruptcy in 2005. Some jobs for younger, stronger workers were restored following restructuring, but with lower wages [55]. While Fuxin’s economy has since partly recovered through new investment in wind and solar industries, without proactive policy, a similar trajectory may be repeated in many other locations as demand for coal declines and mining area consolidation proceeds.

China has already put some transition management measures in place. In 2016, the government itself projected 1.3 million jobs would be lost by 2020 in the coal sector as a

result of capacity reduction and consolidation policies [56], and implemented measures including a CNY 100 bn (c. \$15 bn) “Industrial Special Fund” launched by the Ministry of Finance to support worker relocation and fund welfare payments [57]. Shanxi province, the second-largest coal producer in China, is expected to draw at least CNY 3.5 billion from the fund by 2022 to support relocation, retraining, early retirement, and public sector job creation to offset the effects of coal capacity control policies. Shanxi’s investment in regeneration of depleted mining areas, energy source diversification, and other measures, remains a relative outlier, however [34].

If these projections are correct, large-scale job losses in the coal industry are likely to materialise even in the absence of punitive climate policy measures, and even new coal-fired power generation and mining capacity is added. In a scenario in which the 2030 and 2060 targets are realised, coal power generation must peak within a decade and decline thereafter, further accelerating thermal coal industry job losses. Coal phase-out will also affect the fiscal contribution of coal to national and subnational governments, with tax revenues from coal providing funding for local research facilities, hospitals, infrastructure, and public services, as well as contributing to the general public budget.

This study aims to model and test these hypotheses by charting the trajectory of jobs and tax revenues associated with the thermal coal industry under different coal phase-out scenarios. This can help to identify the scale of the changes that are likely to occur, and the policy options available to state institutions for managing and redistributing social cost and benefits.

3. Materials and Methods

Using asset-level datasets of China’s coal power plants and coal mines, supplemented by a range of independently sourced data points and assumptions on employment in coal transport, plant utilisation rates, tax rates, and productivity improvements, this study models and interprets the magnitude and distribution of jobs and tax revenues across space and time in China’s coal power sector. See Appendix D for further detail on assumptions and calculations.

The model overlays employment and tax calculations on a demand-driven coal production network constructed from plant and mine datasets, both of which also contain information on the corporate owners of each asset. It links employment in the coal power sector and coal mining industries to the building and retirement of plants from 2021 to 2060, according to five progressively stricter policy scenarios (see Appendix B). The transportation of coal from mines to the plants where it is used is also accounted for.

Coal demand is modelled on the basis of operating or planned coal-fired power plants in China, using a composite dataset updated in February 2021. The power plant dataset is hosted by the Smith School of Enterprise and the Environment at the University of Oxford. It combines coal power plant information from the S&P Global World Electric Power Plant (WEPP) Database, Global Energy Monitor’s Global Coal Plant Tracker (GCPT), and the World Resource Institute’s Global Power Plant Database. Plant-level coal consumption is estimated on the basis of 2019 province-level utilisation rates, to avoid pandemic-related distortions—i.e., markedly lower average utilisation rates—in 2020, particularly given China’s strong industrial recovery since then. The starting year of the analysis is 2021, to ensure that results reflect actual operating coal generation capacity in the middle of that year. Coal consumption rates vary depending on the size and type of plant (subcritical, supercritical, or ultra-supercritical), its operating efficiency, and the type of coal it consumes (anthracite, bituminous, sub-bituminous, or lignite), each of which has different estimated energy content. Table 1 summarises coal-fired power generation capacity (GW), estimated utilisation rates (%), corresponding electricity generation (TWh) and coal production statistics by province (million tonnes of coal equivalent, Mtce). Coal supplies are modelled based on a dataset of coal mines producing over one million tonnes annually, last updated in June 2021 [58]. The dataset represents at least 80% of total national coal output [41].

Table 1. Coal capacity, generation, and production statistics by province (B scenario, 2021).

Province	Capacity (GW) ¹	Average Capacity Factor (%) ²	Generation (TWh) ¹	Coal Production (Mtce) ²
Anhui	52.0	55.2%	251.4	70.4
Chongqing	14.0	39.4%	48.2	-
Fujian	27.1	49.1%	116.7	-
Gansu	21.6	45.2%	85.5	33.1
Guangdong	72.6	40.0%	254.5	-
Guangxi	20.5	47.4%	85.2	-
Guizhou	35.2	48.4%	149.0	8.8
Hainan	3.9	53.3%	18.0	-
Hebei	58.2	55.4%	282.3	3.0
Heilongjiang	21.1	43.7%	80.9	12.2
Henan	80.8	40.2%	284.7	19.9
Hubei	33.8	44.6%	132.2	-
Hunan	21.9	45.7%	87.5	-
Inner Mongolia	103.3	61.1%	552.7	904.0
Jiangsu	89.6	49.4%	387.7	-
Jiangxi	27.9	58.8%	143.7	-
Jilin	19.2	42.9%	72.1	-
Liaoning	38.4	45.5%	153.2	8.0
Ningxia	32.6	52.5%	150.2	101.1
Qinghai	5.7	29.2%	14.6	5.8
Shaanxi	44.2	50.0%	193.9	467.9
Shandong	110.3	50.7%	490.3	49.1
Shanghai	15.9	35.6%	49.7	-
Shanxi	73.3	50.5%	324.2	498.0
Sichuan	15.5	34.7%	47.0	1.8
Tianjin	15.3	45.0%	60.2	-
Tibet	0.0	3.3%	0.0	-
Xinjiang	65.8	57.9%	333.8	237.3
Yunnan	14.7	18.0%	23.1	24.0
Zhejiang	45.5	46.5%	185.3	-
Total	1180		5058	2444

¹ Capacity and generation figures are 2021 figures based on asset-level data. ² Capacity factors and coal production are taken from 2019 statistics.

Power generation and coal mining are distributed very differently across China. Three provinces supply 1.87 billion tonnes of thermal coal, about 75% of the 2.44 billion tonnes of total production: Inner Mongolia (IM, 904 Mt), Shaanxi (SN, 498 Mt), and Shanxi (SX, 468 Mt). Xinjiang (XJ) is the fourth-largest coal producer at 237 Mtce annually. Inner Mongolia exports most of its coal to other provinces, as shown in Figure 1. All of these four provinces are net coal exporters, while every other province is a net coal importer, from other provinces and from abroad. Comparing aggregate national supplies to demand indicates an excess of low-quality lignite, and a shortage of high-quality anthracite, with the supply gap closed with imports from outside China. Several coastal provinces—notably Guangdong (home to the Shenzhen industrial zone), Beijing and Tianjin (TJ), and Zhejiang (ZJ)—produce no coal at all, relying entirely on imports from other provinces and international markets.

Coal plants are much more dispersed. No single province hosts more than 9.4% of coal power generation capacity. While the densely populated coastal and Eastern regions host some of the largest provincial fleets at 110.3 GW (Shandong, SD), 89.6 GW (Jiangsu, JS), 80.8 GW (Henan, HN) and 73.3 GW (Shanxi, SX), the sparsely populated Northern region of Inner Mongolia is expected to become the largest by 2023 at 120 GW if plants currently under construction are completed, with Xinjiang in the Northwest also expected to reach over 70 GW in the same year. This compares to a U.S. coal fleet expected to fall below 200 GW in total by 2025 [59] and reflects an ongoing shift, at least partly induced by public health concerns, from building coal power along the densely populated Eastern coast, to locating plants closer to production sites in less population-dense mining areas and exporting the resultant electricity.

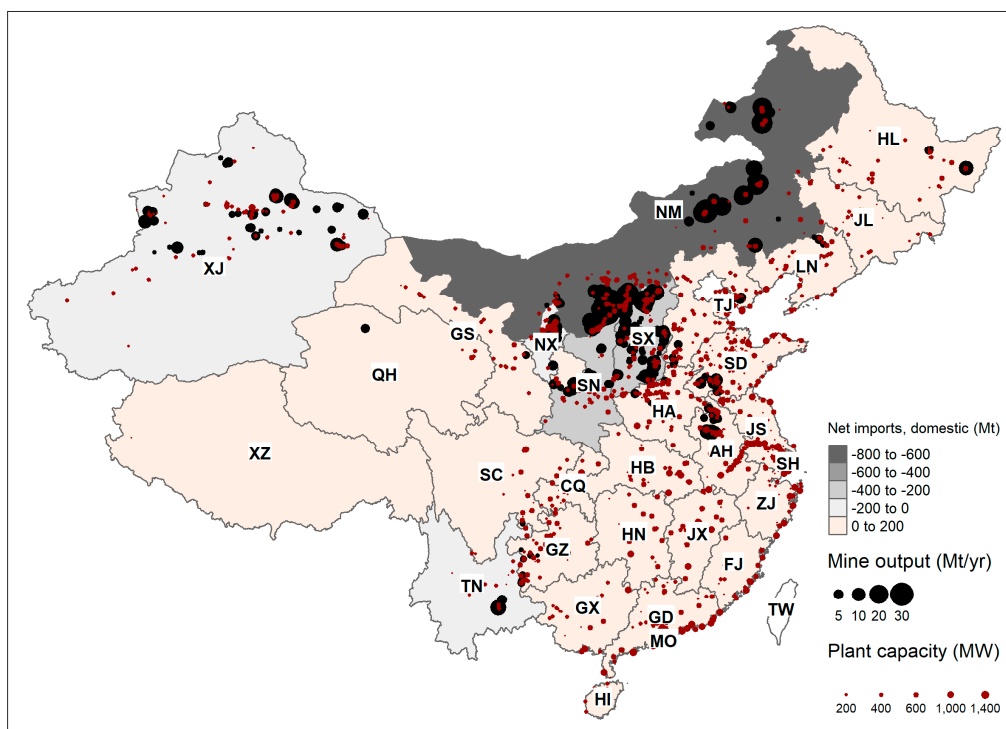


Figure 1. Estimated interprovincial trade balances for thermal coal in China by province (2021). Overlaid with coal mine output, and coal plants (operating and under construction), by capacity. See Appendix A for province codes.

Data on coal trading patterns between provinces is not available; however, plant and mine datasets alike contain information on the type of coal produced and consumed, such that anthracite mines can only supply anthracite-consuming plants, and so on. Only thermal coal-producing mines are included in the analysis, given that thermal coal dominates coal use in power generation, with metallurgical coal being used for steel production.

Matching first by coal type, coal plants consume coal from local (i.e., same province) mines where they exist first, and then import coal from other provinces on a pro-rata basis according to the distribution of supplies remaining once each province has met its own demand for coal. Although province-level average coal prices are available and average transportation costs from provincial or municipal capitals to plants can be estimated, these do not reflect actual intra-provincial coal price variations with any accuracy. Further, coal prices remain heavily regulated in China, albeit less so than electricity prices. Because of these uncertainties and distortions, price-based optimisation methods are not used to determine from which provinces plants choose to purchase their coal, as they would likely be no more accurate than the simple method employed here. In effect, this means that the three largest coal producers supply 90% of interprovincial coal trade: Inner Mongolia (an estimated 659 Mt in 2021, 40% of the total), Shanxi (426 Mt, 26%), Shaanxi (396 Mt, 24%). In the model, coal is imported from outside China only to the extent that domestic mines are unable to supply it. This results in China's imports being largely comprised of the highest-quality type of thermal coal, anthracite.

While these figures are based on a best-effort reconstruction of the coal network in China with major limitations on data availability, and subject to constant change based on market conditions, they should represent an approximation of where and in what quantities coal is produced and consumed in China. Associating coal plants with mines in this way makes it possible to link the operation (and retirement schedule) of specific plants with upstream mining jobs (both locally and externally to each province) and associated tax revenues.

3.1. Estimating Employment

Data on the number of jobs supported by coal plants themselves is not easily available. Survey information suggests that the number of jobs supported directly by a given plant can vary significantly based on the age and size of the plant (with newer, larger plants typically requiring less employees to operate) and the age stratification of employees [60]. In addition, staff may be employed in non-technical positions tied directly to the plant, including catering, accommodation, logistics, and construction [61], depending on the degree of vertical and horizontal integration of the plant or the enterprise that controls it. Accurately estimating the number of employees in each specific plant is not feasible, since this can depend on factors in addition to the plant's location, type, owner, age, and design for which data is not available. Bearing in mind these limitations, this analysis uses the best available estimates of staff numbers differentiated by plant size [60] (Table 4), resulting in estimated employment of approximately 400,000 in China's coal plants in 2021.

The number of jobs supported by the mines supplying coal plants is much larger. National statistics place the total number of jobs in coal mining and dressing at a peak of 5.3 million in 2014, falling to 4.5 million in 2015, 2.85 million in 2019 and 2.68 million in 2020 [62]. This decline, of nearly 50% in six years, reflects a combination of small mine closures and falling labour intensity, as noted above.

In some cases, the number of employees in a specific mine are available in the coal mine dataset used for this analysis. The data is incomplete, however, and biased towards large, more labour-efficient mines. Because of this, the number of employees in coal mining in each province is estimated by applying province-level estimates of labour intensity (in jobs per 10,000 tonnes of annual production) [63] (Table 4). The estimated average labour intensity of coal mining and washing diverges sharply across provinces [63]. That of the most efficient province, Inner Mongolia (1.7 jobs/10,000 additional tons of coal production in 2015) is similar to that of contemporary Germany. The least efficient is Jiangsu, at 30.8 jobs/10,000 tons on average. At a constant rate of productivity increase, this suggests that less labour-efficient provinces will see much greater job losses as a proportion of total mining employment in the short term.

These estimates, which are for the year 2015, are projected forward in the source's methodology by assuming an 8% annual increase in labour productivity consistent with historical trends each year from 2015–2020, slowing to 5% per year from 2021–2050, and 0% thereafter (i.e., assuming no potential for further improvement at that point) [63]. This assumption does not account for the actual dynamics of labour elasticity of demand in the industry, such as structural impediments to hiring and firing workers, and indispensable mining jobs unaffected by changes in output. This results in an estimate of 1.72 million thermal coal mining jobs in 2021, which accounts for 63% of total coal mining and washing jobs in reported in 2020 national statistics [64] and 59% of total estimated coal production in 2019. This suggests that the model estimates aggregate employment in coal mining reasonably well, with thermal coal demand (excluding metallurgical coal and coal for heating) accounting for approximately 60% of total coal mine output and associated jobs.

The coal industry also supports jobs in the transport sector, particularly where dedicated rail, road and port infrastructure has been put in place for specific mines, depending on the degree of automation and efficiency of the transport process. The employment elasticity of coal demand in turn depends at least partly on the substitutability of coal for other products or commodities not correlated with coal demand. In the model, it is assumed that coal transport is not substitutable, implying that coal is mostly transported along routes and using equipment dedicated to the purpose. Coal is transported by rail, road, and water (river or ocean) in different proportions. To arrive at an estimate of the employment intensity of coal transport, the number of jobs in each coal transport segment is divided by ton-kilometres of freight transported in each segment [64], then a weighted average is calculated based on the shares of each transport mode in the coal sector [65]. This results in an estimate of 433 jobs per billion ton-km of coal transported. Actual costs are calculated based on the amount of coal transported, multiplied by the distance between

each plant and the capital city of the province it imports from (as a reasonable proxy for average distance travelled).

Labour productivity improvements are likely to occur in the transport and power sectors, as well as coal mining, driven in particular by automation. The authors have been unable to locate data to substantiate any assumptions on the rate of improvement. Accounting for some further automation in both sectors would accelerate the rate of job losses observed in the results but would still have a relatively small impact in comparison to the mining sector given the dominance of the latter in coal sector employment.

3.2. Estimating Taxes and Subsidies

The coal industry raises tax and social security revenues for subnational and national governments in several ways. Income taxes to central government, and social security contributions for investment in managed public funds, are calculated on the basis of employee wages, which vary by employment type and region [66], using current tax brackets and assuming only the standard deduction is made [67,68]. Social security contributions vary across provinces and cities, but are assumed here to total 50% of base salary, with 30% employer-contributed and 20% deducted from wages [69]. Real wages, prices and tax rates are assumed to remain constant in the model.

The 2018 Environmental Pollution Tax levies charges on several pollutants, with the level generally decided by subnational governments and set at higher levels for more populous provinces (see Appendix D, Figure A1). In this study, coal plants are subject to taxes on sulphur, nitrogen, particulates, and wastewater. Coal mines are taxed on gangue, tailings, ash, and wastewater.

Coal mines also pay fees for mining rights, at 0.5–4% of sales value (of which 80% goes to subnational governments), as well as (minimal) prospecting and exploration fees based on estimated mine surface area. Resource taxes, based on the value of coal sales, accrue to subnational government and vary by province. Finally, value-added tax (VAT), reduced in 2019 to 13% for coal products, is levied cumulatively on coal and, ultimately, electricity sales, using price data that is assumed to already include VAT. VAT is collected by the national government, and 25% is then returned to the subnational government from which the revenue was raised. Surcharges for education and construction are levied as a percentage of VAT: 3% for education, and 1% (rural), 5% (county) and 7% (urban) for construction. Since construction surcharges are levied based on the location of the parent company's headquarters, we assume, for simplicity, that all construction surcharges are levied at the higher urban rate at 7% of VAT.

Total tax revenues to central government, therefore, include income taxes, prospecting, and exploration fees, 20% of mining royalties, and 75% of VAT. Total revenues to subnational governments include environmental pollution taxes, resource taxes, 80% of mining royalties, 25% of VAT, and education and construction surcharges.

Data limitations prevent estimation of subsidies at plant or mine level or distinguishing between subsidies benefiting coal power generation, versus coal use in industry and heating. Subsidies are estimated in aggregate on the basis of point-in-time studies, themselves reliant on multiple assumptions and subject to uncertainty. They include subnational fiscal support to coal mines, VAT rebates and subsidies for R&D and coalbed methane production, the aforementioned Industrial Special Fund, price subsidies to electricity and coal transport, and credit support. Electricity price subsidies can be estimated at plant level based on the difference between the administratively-set benchmark (regulated) price and spot (market) prices for electricity. Mines are assumed to take full advantage of available VAT rebates.

With the caveat that subsidy estimates are uncertain and highly aggregated, recent estimates place overall production subsidies at CNY 17–18 per tonne of coal [70], implying a CNY 350–375 billion production subsidy to the approximately 2.08 billion tonnes of coal consumed by thermal plants in 2021. Annual generation subsidies for coal power are estimated at CNY 120 billion [71] to CNY 263 billion [72] (although, in the latter case, the bulk of these subsidies were expected at the time of writing to be eliminated by 2020

amid the end of funding for pollution control upgrades and deregulation of price controls). Subsidies to rail transport add at least another CNY 10 billion, with central government subsidies estimated at CNY 2 billion [73] in 2015, and provincial subsidies from Inner Mongolia alone at CNY 7.2 billion [71]. Taking the lower ranges, this suggests an overall current subsidy level of at least CNY 480 billion annually to the thermal coal industry across plants, transport, and mines, not counting historical subsidies for plant pollution control equipment.

The negative environmental and health externalities to coal production are also not included in this figure (although they are subject to some limited taxation). Estimates of externalities per tonne of coal production (including impact on air quality, water and soil quality, global warming, prevalence of respiratory disease, and a range of other factors at various stages of production and consumption) vary. Coady, et al. [74] assess damages from all energy sources in China (to which coal is a major, if not majority contributor) at CNY 3 trillion for global warming impact, and a further CNY 12 trillion for local pollution, around 40 times higher than all other subsidies combined. Zhao, et al. [75] use revealed preference methods to estimate the environmental cost of coal-fired power plants at CNY 300 per MWh (implying a subsidy of CNY 1.52 trillion in 2021, given 5058 TWh of coal-fired generation), which is still five times all other subsidies. Annual externality subsidies to coal power generation are estimated by others at a more modest CNY 180 billion [72], around a third of all other subsidies.

4. Results

4.1. National Level Results

The model was constructed to run from 2021 to 2060 for five scenarios (see Appendix B for detail), under which the life of each plant becomes progressively shorter: 30 years under the “No Transition” (NT) and “Baseline” (B) scenarios, 25 under “Low-Cost Renewables” (R), 20 under 50% lower emissions than 2015 (C50) and 15 under “80% lower” (C80), respectively. Figure 2 shows the production-consumption relationships of thermal coal of all types between provinces in the B scenario, where each coal-consuming province (outside ring) consumes coal from local mines where it is available, and imports from other provinces where it is not (cross-circle links, where the colour of the link is that of the destination province). The prominence of Inner Mongolia (NM), Shaanxi (SN), and Shanxi (SX) as coal suppliers to many other provinces is clearly visible. All three produce a large amount of coal, consume a significant share of their own coal, and export the rest to other provinces. Inner Mongolia’s and Shanxi’s prominence as both producers and consumers will continue to grow, such that, by 2050, both provinces will dominate coal demand, obtaining the vast majority of coal from their own local mines.

Table 2 summarises the number of jobs supported by each province’s coal fleet, which are also visualised in Figure 3. This refers to jobs at coal plants in that province, as well as upstream supply chain jobs in mining and transport supported by each plant’s coal consumption. The number of support jobs is determined largely by the labour intensity of mining in the provinces from which the coal is sourced. Provinces themselves are more likely to be home to a greater number of coal jobs (both locally and nationally) when they have a combination of large coal fleets, large mining capacity, and high labour intensity. Coal plants in Shandong, for instance, support 491,200 jobs nationally, both locally and indirectly by importing coal from other provinces. Inner Mongolia’s coal fleet is of a similar size but is supplied entirely by its ultra-efficient domestic mining industry workforce and supports only 102,000 jobs, although coal exports to other provinces supports another 444,000 coal mining jobs in Inner Mongolia’s mines.

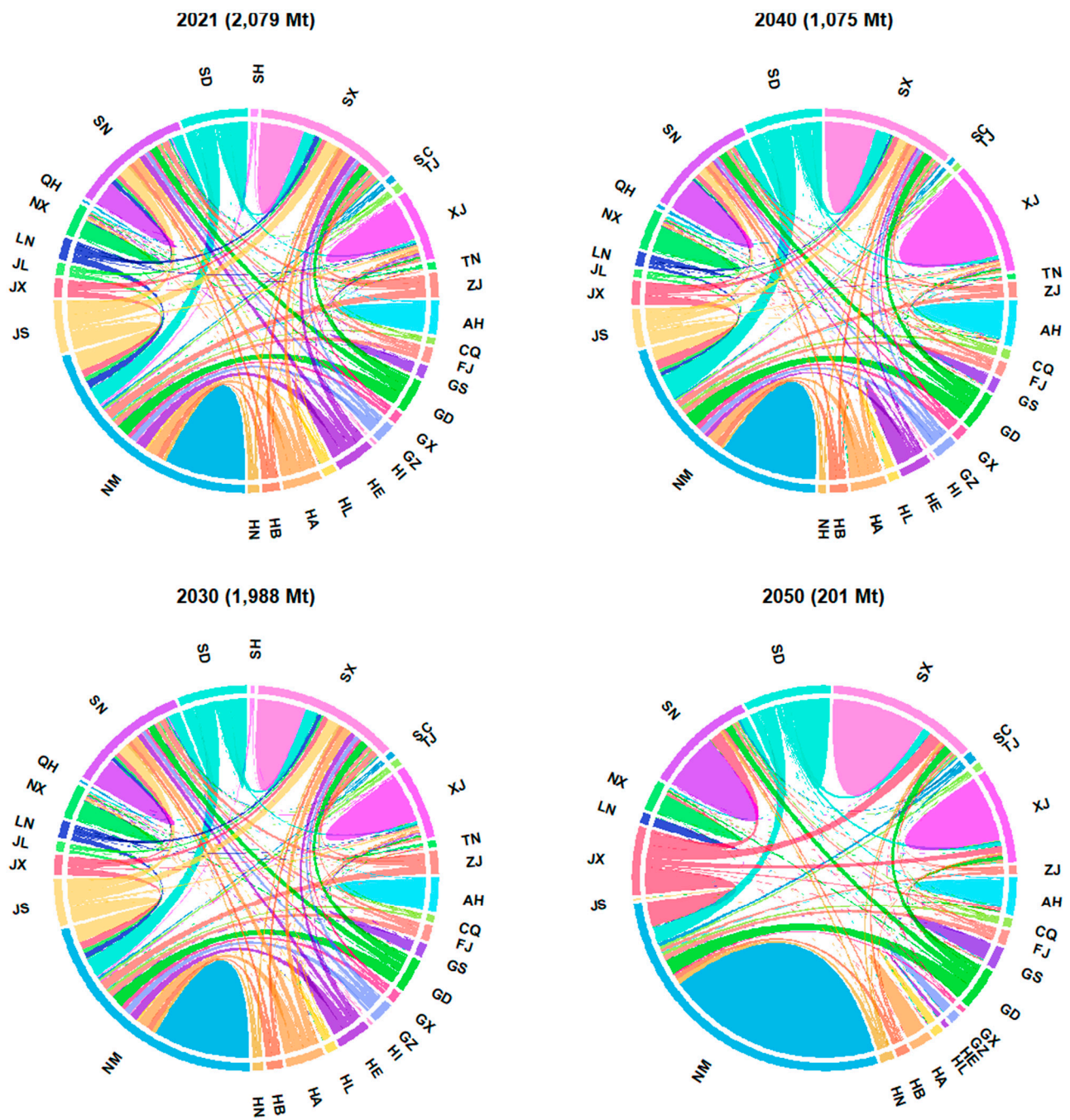


Figure 2. Coal production-consumption network by province, 2021–2050 (B scenario). For province codes, see Appendix A. For a given producer (outer ring), ‘humps’ in the same colour as the outer ring represent coal consumed in the same province in which it is produced. ‘Links’, in different colours, represent coal exported to other provinces, where the colour of the link is that of the destination province.

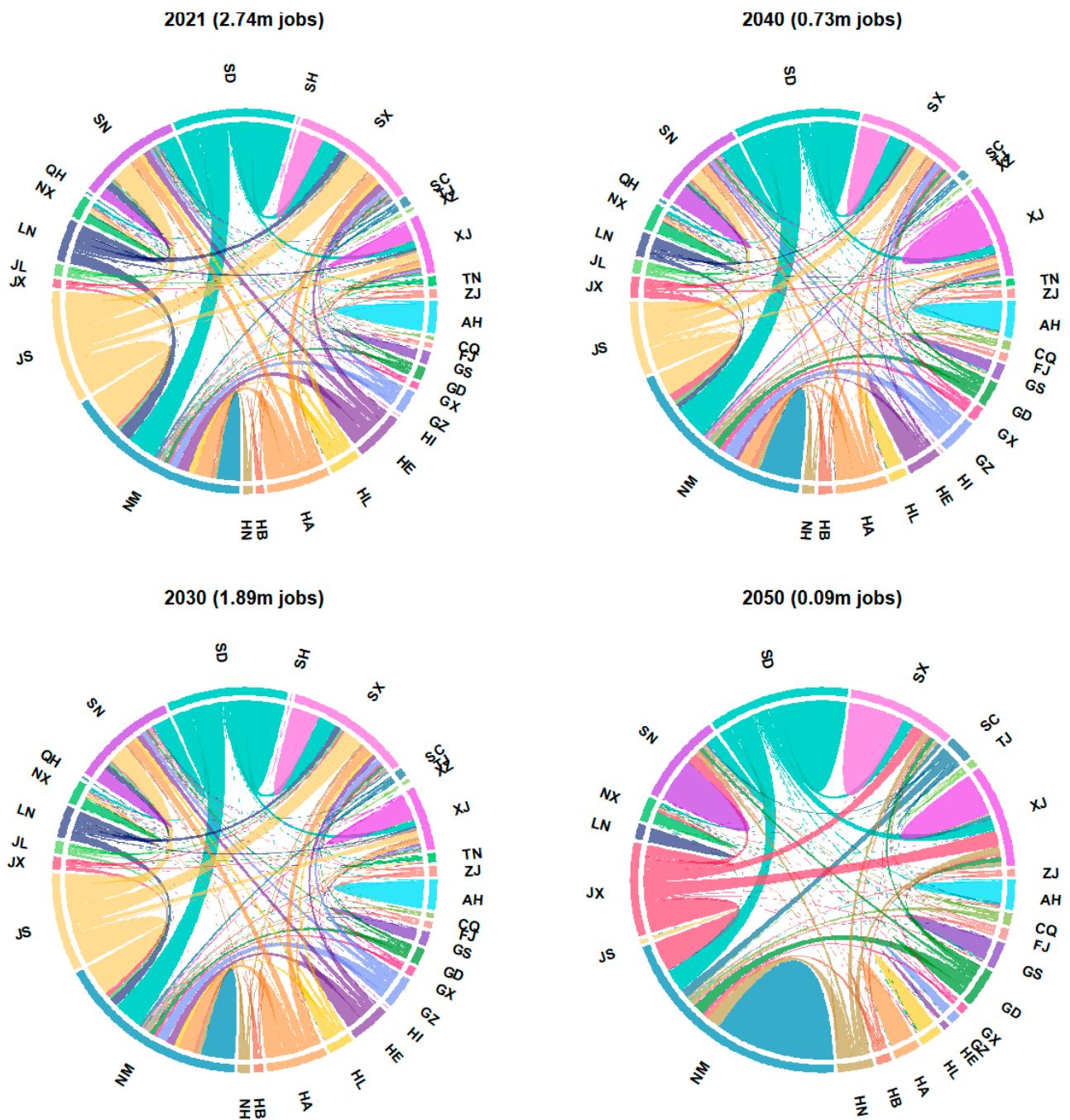


Figure 3. Coal jobs supported by each province, B scenario. Flows from province X (the colour of the outside ring) to province Y, in the same colour as province X, represent jobs in province Y supported by coal imports to fuel coal-fired power generation activity in province X.

Table 2. Summary information on estimated coal industry employment in 2021 (B scenario), in descending order of total jobs supported by coal power generation in each province.

Province	Jobs Supported by Coal Power Generation in the Province (Thousands)	Thermal Coal Consumption (Mt)	Total Jobs Supported per 10,000 Tonnes of Coal Consumed (2021)	Share of Total Jobs Supported
Shandong	491.2	198.9	24.7	17.9%
Jiangsu	451.7	154.8	29.2	16.5%
Henan	256.7	114.4	22.4	9.4%
Hebei	197.5	115.3	17.1	7.2%

Table 2. Cont.

Province	Jobs Supported by Coal Power Generation in the Province (Thousands)	Thermal Coal Consumption (Mt)	Total Jobs Supported per 10,000 Tonnes of Coal Consumed (2021)	Share of Total Jobs Supported
Liaoning	172.2	66.8	25.8	6.3%
Anhui	126.8	99.3	12.8	4.6%
Heilongjiang	122.5	36.2	33.8	4.5%
Shanxi	109.2	131.2	8.3	4.0%
Inner Mongolia	102.1	256.1	4.0	3.7%
Guizhou	95.6	58.9	16.2	3.5%
Xinjiang	86.8	136.7	6.3	3.2%
Guangdong	54.5	101.6	5.4	2.0%
Gansu	49.6	35.3	14.1	1.8%
Jilin	47.0	36.9	12.7	1.7%
Shaanxi	44.8	77.8	5.8	1.6%
Ningxia	39.8	59.8	6.7	1.5%
Hunan	39.8	32.5	12.2	1.5%
Sichuan	37.6	18.9	19.9	1.4%
Zhejiang	36.0	74.2	4.8	1.3%
Jiangxi	35.8	55.3	6.5	1.3%
Hubei	32.1	52.2	6.1	1.2%
Guangxi	27.2	33.3	8.2	1.0%
Fujian	20.5	45.8	4.5	0.7%
Yunnan	20.3	9.4	21.6	0.7%
Chongqing	13.7	18.9	7.3	0.5%
Tianjin	11.7	24.5	4.8	0.4%
Shanghai	7.0	20.9	3.4	0.3%
Qinghai	7.0	6.0	11.7	0.3%
Hainan	4.8	7.4	6.5	0.2%
Tibet	0.1	0.0	736.2	0.0%
Total	2742	2079		

Figure 4 plots baseline scenario estimates for employment in the coal power industry from 2021–2060. Employment in coal mines starts at a higher level (1.72 million) but follows a steep downward trajectory, declining by over 60% to 655,000 by 2035. Employment in plants (starting at 393,000) falls half as fast, by just under 30% to 277,000 in the same period. Transport jobs are proportional to ton-km of coal transported and again fall half as fast as plant jobs: 632,000 in 2021 falling 15% to 238,000 in 2035, reflecting a 15% drop in coal consumption over that period. The sharp fall in mining jobs reflects the extrapolation of past declines in mining labour intensity and the slow pace of plant retirements up to about 2034. From this point onwards, total job losses accelerate as the pace of plant retirements increases and coal demand falls more rapidly, slowing slightly again in the 2040s and declining to zero in 2054 as the wave of plants built in the decade to 2020 reach the end of their operating lifetimes.

Under the baseline scenario, reflecting current policies, total employment supported by the thermal coal power industry is projected to drop from 2.74 million in 2021, to below 1 million by 2038, below 500,000 by 2043, and below 250,000 by 2046 (see Figure 4). As noted in previous work [16], the net employment impact of coal closure on the whole economy is unlikely to be significantly negative as other forms of energy production and supporting industries take its place. The public policy challenge is anticipating job losses sufficiently well across space and time to take early action to redeploy workers elsewhere or offer retraining programmes to avoid the potentially very large burden of mass early retirements, or chronic unemployment, on the social security system. Methodologies have been developed to undertake this analysis by identifying green industries and skills that are ‘adjacent’ to emissions-intensive ones [76], but have not yet been applied in detail to China.

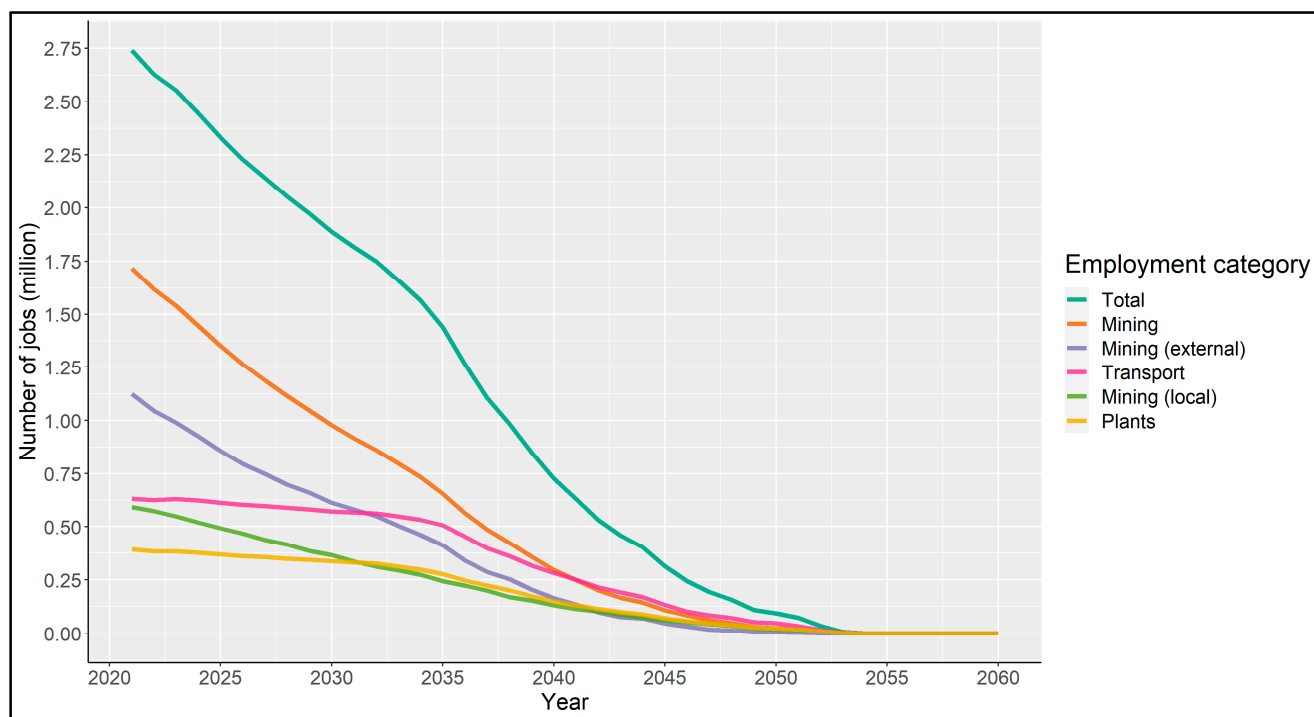


Figure 4. Employment in coal plants, transport and mines, 2021–2060, baseline scenario.

The trajectory of fiscal revenues in the B scenario does not decline as sharply and in fact rises slightly in the short term. Income taxes and social security payments fall with the decline in employment; however, total revenues rise initially from CNY 330 billion to CNY 339 billion in 2023, at which point total coal capacity peaks at 1205 GW. This reflects the tax burden on physical capital (notably resource and environmental pollution taxes, VAT, and surcharges linked to VAT) representing a much greater proportion of total revenue than taxes on labour.

In 2021, VAT contributes CNY 153.7 billion in tax revenues to the national government (95% of the total), about 2.7% of total VAT revenue in 2020 [77]. Of the remaining national government revenues, income taxes contribute CNY 5.6 billion (3.4%), and mining royalties CNY 2.6 billion (1.6%), and. For subnational governments, pollution taxes on mines generate CNY 52.7 billion (31.3%), VAT, CNY 51.2 billion (30.5%), resource taxes CNY 47.8 billion (28.4%), and pollution taxes on plants, CNY 4.7 billion (2.8%).

As Figure 5 shows, despite the difference in composition, absolute revenues flowing to national and subnational governments are very similar and follow a near-identical trajectory. Annual revenues to national/subnational/all levels of government decline slowly by 1–1.5% annually from their CNY 166/173/339 billion peaks in 2023, to CNY 151/160/311 billion in 2030. Tax revenues start to fall steeply around 2034 as plant retirements accelerate, with annual rates of decline in both cases jumping from 3% in 2034, to 5% in 2035 and 9% in 2036, continuing to fall by 9–11% per year until 2044 and significantly faster thereafter. Total tax revenues from the thermal coal industry fall below CNY 100 billion by 2045, and just over CNY 30 billion in 2050. Social security payments (not strictly a tax, but a relevant contribution to publicly managed funds) are also plotted for comparison. The trend in social security revenue, falling from CNY 112 billion in 2021 to CNY 76 billion in 2030 (a 32% decline), and CNY 3.6 billion in 2050 (a 97% decline) is based entirely on wages, and, therefore, follows a similar trajectory to total job losses (Figure 4) rather than tracking plant closures, with some variation due to differences in average wage over time.

When compared to the estimated current annual subsidy level of CNY 480 billion or more, the total of around CNY 330 billion in total tax revenue suggests that the net fiscal contribution of the coal industry to public revenues is likely to be negative, without

accounting for the cost of negative externalities. As the revenues associated with capital assets fall more sharply after 2035, it becomes increasingly likely that coal will become a net fiscal drain on China, even without accounting for the public health, productivity, and other environmental and climate externalities that coal mining and combustion generate. While subsidies to capital assets and power price subsidies for coal may fall as generation and coal consumption declines, other costs may rise to negate this, including contingent liabilities arising from state-owned power or mining company losses, defaults, or bankruptcies, restructuring efforts, and relocation/retraining costs for laid-off workers.

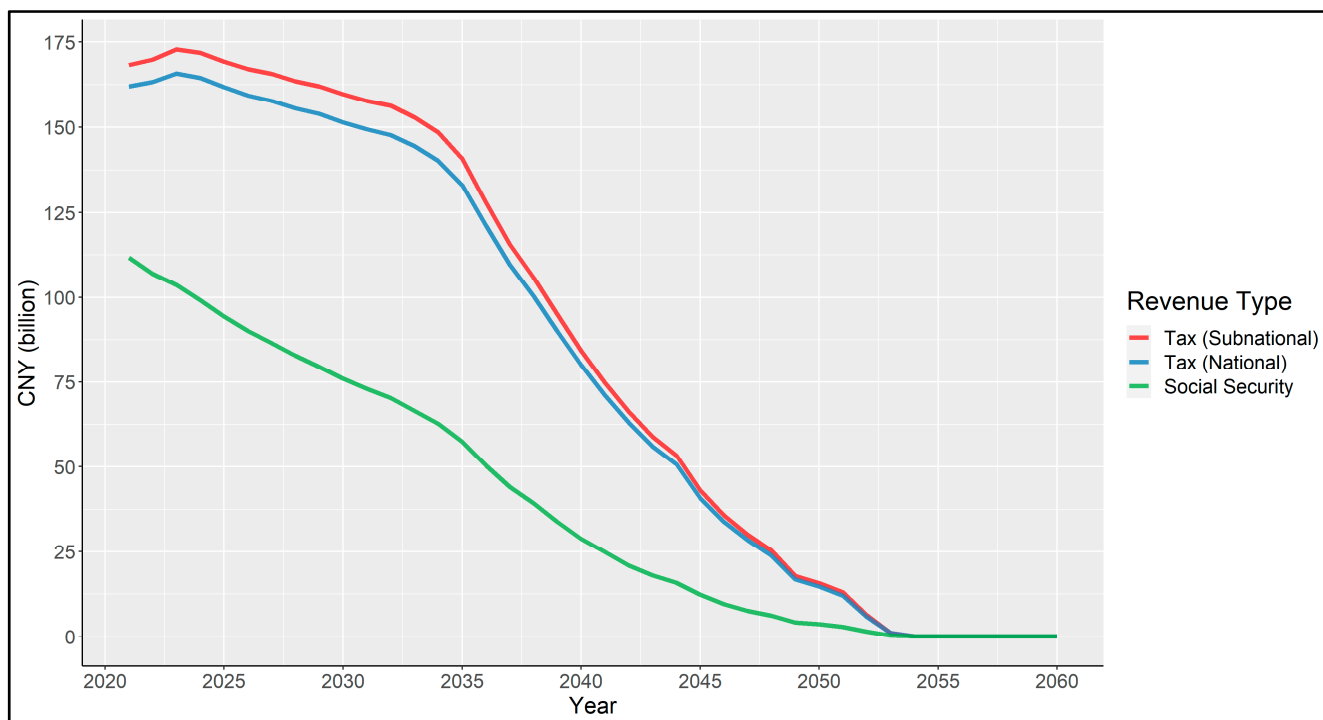


Figure 5. Breakdown of tax (national and subnational) and social security revenues, 2021–2060, B scenario.

Comparing the baseline against the R scenario, with lower expected technology costs, and the more aggressive C50 and C80 scenarios, which artificially constrain total sector emissions, helps to understand the marginal impact of climate policy on thermal coal employment and the sector’s fiscal contribution. Under progressively stricter scenarios, the short-term drop in coal capacity (reflecting the retirement of older plants) needed to meet the target requirements becomes increasingly large.

The R scenario has relatively little impact on total employment until the late 2020s, leading to about 270,000 fewer jobs in 2030 relative to the baseline (Figure 6). The differential between the two pathways widens to over 630,000 in 2035, before converging back to 214,000 by 2045. Under the C50 scenario, implying coal phase-out by 2040, over 1.1 million additional job losses compared to the baseline would be expected by 2030, while, under the C80 scenario (phase-out by 2035), almost 1.6 million additional jobs disappear by 2030—almost 40% of total thermal coal industry jobs today. Notably, even the No Transition scenario, where all planned plants are built, only protects about 500,000 employees from redundancy by 2030 compared to the baseline. Total jobs still fall 40% by 2040 and 85% by 2050, declining to zero in 2060.

The more ambitious phase-out pathways do have serious employment consequences in the short term; however, the absolute magnitude of these changes is not unprecedented in China’s coal industry. Absolute job losses by 2030, even under the C80 scenario, are still fewer than the estimated 2.7 million coal industry jobs already lost between 2014 and

2020 [62]. If 181 GW of CCS-enabled capacity were kept open in 2050 (as in the 2 °C scenario described above), even at the current rate of around 150 employees for a large (circa 1 GW) plant, this would be unlikely to support more than about 25,000–30,000 coal plant jobs at the most in the second half of the century, and fewer in mining and transport.

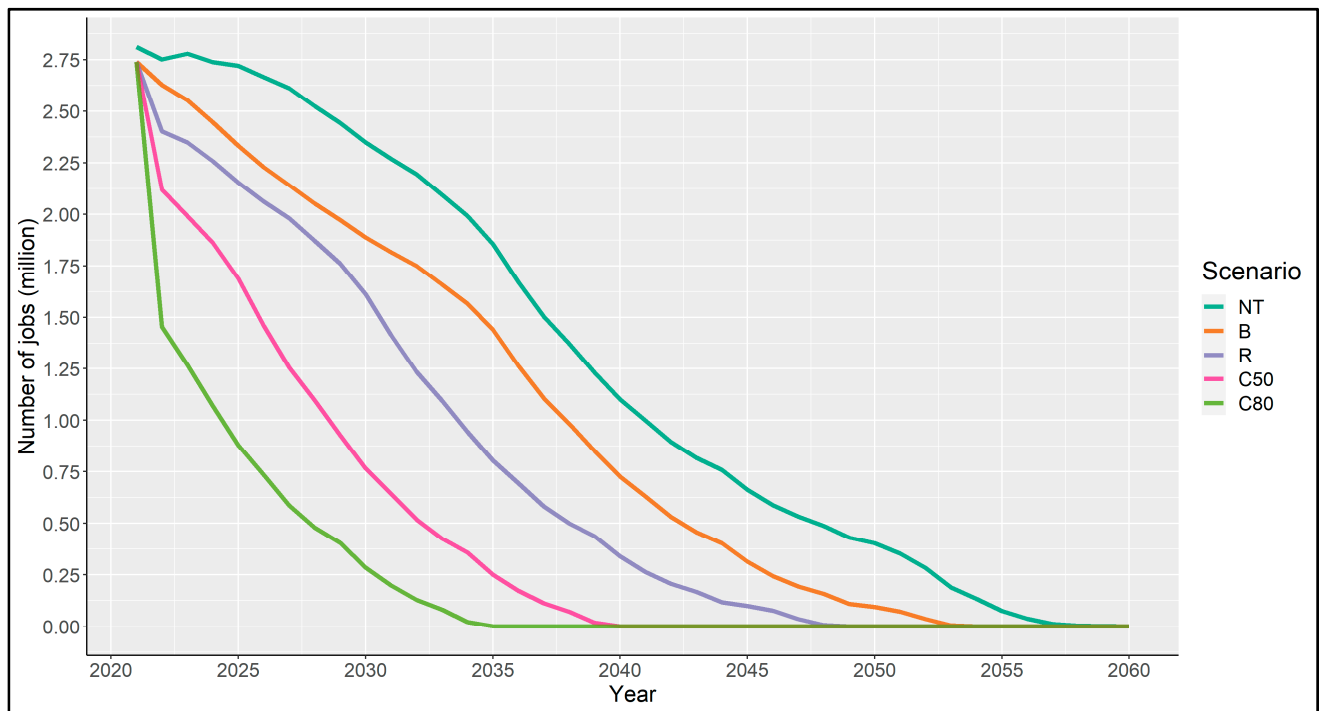


Figure 6. Employment in the thermal coal mining, power, and transport sectors under five coal phase-out scenarios, 2021–2060.

The fiscal picture (Figure 7) is somewhat different for the first three scenarios. In the Baseline and No Transition scenarios, revenues keep increasing as long as coal generation capacity, hence also coal consumption (under the model assumptions), keeps increasing. Revenues peak in 2023 (CNY 339 billion) and 2027 (CNY 399 billion) under the B and NT scenarios, respectively. Total tax revenues remain relatively stable up to 2030 under the R scenario, falling by just 17% through the 2020s. They decline rapidly thereafter, following a similar trajectory as the baseline but, five years earlier, declining to zero in the late 2040s. In the C50 and C80 scenarios, the trajectory is also similar after a sharp initial drop in revenues, with subsequent rates of decline tracking the baseline, but starting 10–11 years and 15–16 years sooner, respectively. These patterns again reflect that the tax base for coal is much more capital-intensive than labour-intensive, since initial job losses do not offset increasing tax revenues from new plants, and, in each scenario, sharp declines in tax revenues coincide with increasing rates of capacity retirement.

Overall, scenario analysis suggests that the additional job losses associated with a pre-2050 coal phase-out target are relatively minor, even without counting job creation in the renewables sector. Job losses are much faster in the C50 and C80 scenarios but still slower in absolute terms than China has seen over the past decade. The timing, rather than the rate, of tax revenue decline is most affected by more ambitious phase-out scenarios.

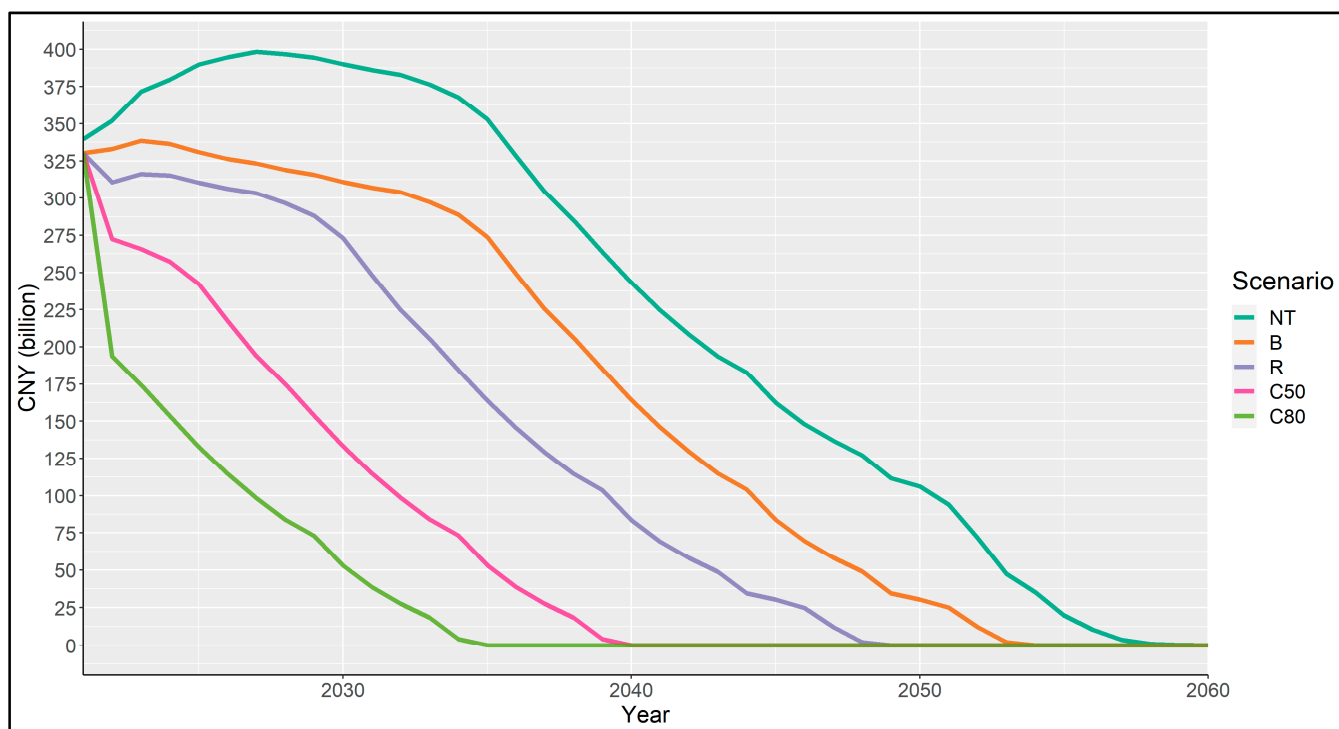


Figure 7. Total tax revenues under different coal phase-out scenarios, 2021–2060.

4.2. Province-Level Results

The impact of coal phase-out is very different across provinces, due to differential exposure to the coal industry. When ‘internal’ coal jobs in each province (jobs at coal plants, and jobs at coal mines in the same province that supply these plants), and ‘external’ ones (jobs at coal mines in other provinces supported by demand from coal plants) are overlaid on the production-consumption network in Figure 2, the results follow a markedly different pattern, due to the differences in labour intensity between coal mines in different provinces (Table 3; see Appendix C for full results for other scenarios) and how these interact with changing coal demand over space and time. Under the baseline scenario, 31% of coal industry jobs (853,000) are lost by 2030, at a similar rate to the IEA’s global predictions and consistent with its finding of a slightly higher rate of job loss in China than elsewhere. Perhaps most notably, the provinces at the root of the largest absolute jobs losses in the medium term (2021–2030) are not the large mining provinces, but those with large coal fleets that are declining in size, and moderate-to-large coal mining industries with high, but declining, labour intensity. In combination, plant closures and inefficient local mining means the number of total jobs lost for each GW of capacity closed is more than twice as high in Jiangsu (where 13.5 GW are retired from 2021–2030) as Hebei (11.5 GW).

Similarly, coal plants in Inner Mongolia, despite accounting for over 10% of China’s thermal coal demand in 2021, initially support only 3.7% of total coal jobs because the coal mines supplying most of these plants are also in (highly labour-efficient) Inner Mongolia. Similarly, plants in Shandong account for 8% of coal demand, but support 18% of coal jobs nationally because of the higher average labour intensity of the mines supplying them—some of which are in Shandong, with most of the rest sourced from Inner Mongolia, Shaanxi, and Shanxi. By 2050, differences in labour intensity have converged significantly and interprovincial trade in coal has largely disappeared, such that most remaining coal mining jobs are supported by demand from plants in the same province, with Shandong remaining the only notable exception.

Table 3. Trends in coal industry employment supported by each province, 2021–2060 and change to 2030 (B scenario).

Province in Which Coal Plants Are Located	Coal Industry Jobs Supported by Those Plants (Thousands, 2021)	2030	2040	2050	Change in Jobs Supported 2021–2030	% Change 2021–2030
Jiangsu	451,727	266,907	74,712	424	184,820	−40.9%
Shandong	491,171	329,085	127,033	16,277	162,086	−33.0%
Hebei	197,482	107,543	33,509	611	89,939	−45.5%
Henan	256,720	166,846	51,210	2995	89,874	−35.0%
Liaoning	172,183	87,222	24,526	1689	84,961	−49.3%
Heilongjiang	122,479	67,113	16,507	2150	55,366	−45.2%
Anhui	126,761	81,032	30,334	2677	45,729	−36.1%
Shanxi	109,169	81,933	32,223	6756	27,236	−24.9%
Gansu	49,634	36,818	12,692	2669	12,817	−25.8%
Sichuan	37,593	25,408	8158	2881	12,186	−32.4%
Jilin	46,989	35,728	14,085	-	11,261	−24.0%
Guizhou	95,572	85,962	36,825	1146	9610	−10.1%
Ningxia	39,826	31,067	13,857	1606	8759	−22.0%
Guangdong	54,472	46,874	25,475	4447	7598	−13.9%
Yunnan	20,310	12,799	1689	-	7510	−37.0%
Xinjiang	86,787	79,472	59,785	5234	7315	−8.4%
Hubei	32,071	26,214	14,422	1762	5857	−18.3%
Zhejiang	35,969	30,152	9245	860	5817	−16.2%
Hunan	39,824	34,893	12,819	4199	4930	−12.4%
Shaanxi	44,823	41,179	21,831	5519	3644	−8.1%
Shanghai	7050	3702	-	-	3348	−47.5%
Inner Mongolia	102,063	98,857	44,985	14,608	3206	−3.1%
Tianjin	11,705	9346	3343	867	2359	−20.2%
Qinghai	7007	4948	2679	-	2059	−29.4%
Fujian	20,519	18,849	8314	1319	1670	−8.1%
Guangxi	27,191	25,723	14,723	961	1468	−5.4%
Hainan	4827	3555	1589	-	1271	−26.3%
Chongqing	13,695	13,101	8787	1373	595	−4.3%
Jiangxi	35,765	35,581	21,651	10,801	183	−0.5%
Tibet	125	125	125	-	−0	0.1%
Total	2,741,506	1,888,033	727,133	93,832	853,473	−31.1%

For provinces that are already very labour-efficient, productivity improvements have less absolute impact over time relative to total provincial mining jobs, while, for provinces with high labour intensity, annual job losses are much greater, reflecting the active consolidation, closure of small mines and rollout of automated mining infrastructure that are a feature of current government policy. In Shanxi province, for instance, the Yangquan Coal Industry Group is using 5G technology to monitor and run mining operations remotely at its Xinyuan mine. Having employed 3000 workers in 2012, the mine expects to provide under 1000 jobs by 2025 [55]. This means that more jobs are lost to efficiency than to planned or policy-accelerated plant closures and the ensuing effects on coal demand, at least in the short term, under current policies.

The following section explores in more detail the employment and fiscal implications of coal phase-out for a major net coal-producing province (Inner Mongolia) and a net coal-consumer (Jing-Jin-Ji region), comparing the two and reflecting on the dynamics these and provinces with similar net-producer and net-consumer characteristics are likely to see if China’s coal demand falls as projected.

4.2.1. Inner Mongolia

Inner Mongolia is the largest coal-producing province in China, at over 900 million tonnes annually, 37% of national production and nearly twice that of the next-largest producers, Shanxi (20%) and Shaanxi (19%). As one of China’s most suitable locations for wind farm development [78], the province also hosts substantially more wind generation capacity than any other, at 11.4 GW, with a further 3.3 GW currently planned, although these are still dwarfed by its 103 GW of thermal coal generation capacity (as of 2021). Inner Mongolia has historically seen high curtailment rates for wind energy. These have

since declined, from an average of 15% in 2016 to 10% in 2018 [79], supported by greater long-distance transmission capacity to serve markets in Eastern provinces. Investment in additional transmission capacity appears to have grown since the onset of COVID-19, and is believed to have been supporting the transmission of locally generated coal-fired electricity to demand centres in the East for at least 7.9 GW of capacity commissioned in the first half of the year [80].

Inner Mongolia is also fast becoming China's largest consumer of coal. As of 2021, the province hosts 103 GW of capacity, nearly 9% of China's total and just shy of Shandong's 110 GW. Based on plants currently under construction, Inner Mongolia will overtake Shandong in 2023 to become host to China's largest provincial fleet, reaching peak capacity at 120 GW in 2024. This is more than the total combined fleets of Germany and Japan, and roughly half the size of the entire fleets of the U.S. and India. Its dependence on coal mining and other minerals, the use of coal for domestic heating, and the provincial government's support for coal (extending to enterprises under government control), support the continued expansion of the coal industry despite national policy.

In terms of employment, Inner Mongolia is, however, relatively well positioned to transition away from a coal-based economy, with appropriate planning. Its mining workforce is the most efficient in China, at 1.7 jobs per additional 10,000 tonnes produced (the second-least labour intensive are Shaanxi, at 3.3, and Xinjiang, at 3.5). Thus, despite massive coal mining and combustion operations, coal plants located in Inner Mongolia are estimated to support just 102,000 jobs, of which only 27,000 are in the mining industry.

However, since Inner Mongolia exports over two-thirds of its coal and meets almost 40% of total interprovincial demand, the jobs associated with meeting demand from other provinces are several times those associated with supplying just its own plants. Over 440,000 additional coal mining jobs and 39,000 coal transport jobs are associated with coal supplied by Inner Mongolia to other provinces. Once accounting for exported coal, therefore, over 500,000 jobs in Inner Mongolia depend on demand for thermal coal.

On the fiscal front, Inner Mongolia's coal industry contributes CNY 33.7 billion to central government revenues (about 15% of national revenues from coal), peaking at CNY 35.9 billion in 2024 before falling sharply after 2030 to under CNY 15 billion by 2041. Contribution to subnational tax revenues (in Inner Mongolia and the provinces it exports to) start at a higher level, peaking at CNY 44 billion in 2023 and falling below CNY 15 billion by 2043. Of these subnational tax revenues, over 40% are resource taxes and nearly 20% are VAT payments. This is as expected: the relatively low labour intensity of coal production, low environmental pollution taxes, and the fact that most of Inner Mongolia's coal is exported, means that tax revenues associated with the local coal industry are closely tied to the production and sale of coal.

Estimates of subsidies directed by the provincial government to Inner Mongolia's coal industry in the past add some context to these estimates, suggesting that the apparent net fiscal boon from coal industry operations is not as great as it first appears. While subsidies vary from year to year depending on funding priorities and are difficult to measure with any accuracy or certainty, historically, Inner Mongolia is estimated to have granted at least CNY 720 million in temporary tax relief for coal price adjustments and coal rail transport. In 2013, the cost to Inner Mongolia's provincial government of providing coal users with rail transportation below market rate was estimated at CNY 7.2 billion [73].

4.2.2. Jing-Jin-Ji

'Jing-Jin-Ji' is shorthand for the combined Beijing, Hebei and Tianjin area, a heavily urbanised region with a population of over 112 million. In Beijing's case, the municipality contains no coal mines, and recently closed its last coal-fired power plant. It imports large volumes of electricity, a majority of which is necessarily from coal plants given China's electricity mix but does not directly contribute to employment or tax revenue in the coal sector. Tianjin does not produce any coal but hosts 15 GW of coal-fired power plant capacity, while Hebei hosts 58 GW of generating capacity. The combined total of about

72 GW represents 6% of China's total operating capacity in 2021. Hebei produces about 0.1% of China's thermal coal (3 million tonnes annually). No new coal capacity is planned, and current capacity will decline as existing plants are progressively closed.

The wealth and population density of Jing-Jin-Ji relative to other provinces, and its status as political capital, have direct implications for the political economy of coal phase-out. With the effects of local air pollution affecting a very large populace, pressure to address air quality issues that have plagued the area for decades has led to the relocation of coal power serving Jing-Jin-Ji away from city areas, and the imposition of the highest environmental pollution tax rates in China. At the same time, government policy promotes the maintenance of stable, affordable electricity prices to help sustain continued high growth rates. Achieving these goals simultaneously requires importing electricity from sources cheap and flexible enough to offset transmission infrastructure costs and ensure uninterrupted power supplies, a role still played predominantly by coal.

Neither electricity prices (both benchmark and spot prices) nor coal prices in Jing-Jin-Ji are particularly high or low, hovering near the national median. This implies greater tax revenue per unit of coal mined or consumed in Jing-Jin-Ji than Inner Mongolia (through greater unit VAT and resource tax revenues, both generated *ad valorem*). Beijing, Hebei, and Tianjin all impose maximum plant-level environmental pollution taxes (CNY 12/kg for air pollutants, and CNY 14/m³ for wastewater), the only provinces currently doing so (see Appendix D, Figure A1). In Tianjin, these charges are relatively immaterial given the lack of a coal mining industry and relatively small amount of coal-fired generation. In Beijing, they are non-existent. (It should be noted that 65% of Beijing's electricity demand and 40% of Tianjin's is met through imported electricity, the bulk of which is generated in coal-fired units in Inner Mongolia, Shanxi, Shaanxi, and Hebei and exported via long-distance transmission lines [81]).

Hebei's significant coal plant and mining industry, however, faces higher charges per tonne of coal extracted or burned than other provinces. In combination, the Jing-Jin-Ji provinces collect CNY 1 billion in environmental taxes on coal plants annually (compared to CNY 0.43 billion in Inner Mongolia, which has nearly twice the generation capacity, albeit with fewer operating hours). Further, the estimated average labour intensity of coal mining in Hebei is 16.7 jobs per additional 10,000 tonnes extracted, more than five times that of Inner Mongolia (2.8). Consequently, despite having half as much coal power plant capacity, Hebei's coal plants support nearly 70% more local coal mining jobs (45,000) as Inner Mongolian plants do (27,000).

4.2.3. Province-Level Comparison

In terms of employment, the national coal industry supports ten times as many mining jobs in Inner Mongolia as Jing-Jin-Ji, and the gap will remain significant for the next two decades. Because of Inner Mongolia's superior labour efficiency and much larger scale, the absolute numbers converge sharply by 2040, not least because some coal mine employment in Inner Mongolia depends on demand from Jing-Jin-Ji, and Jing-Jin-Ji's coal demand supports Inner Mongolia jobs. The gap narrows to under 10,000 jobs by 2050. Plant jobs decline steadily in Jing-Jin-Ji as its remaining plants retire on a smooth trajectory to 2050. In Inner Mongolia, employment in plants is stable until the mid-2030s, before declining sharply to 2040 as plants built in the 2010s start to retire and reaching zero in the mid-2050s.

Where the focus for Inner Mongolia is on coal production, continued industrial development, growth in electricity generation and upgrading its position on the electricity value chain, Jing-Jin-Ji is more likely to be concerned with securing reliable, affordable power to facilitate further economic development. These contrasting potential motivations, which mirror the relationship between net coal producers and consumers across China, are not incompatible—in fact, the provinces' respective interests are well-aligned, such that an expansion of coal power in Inner Mongolia benefits both, particularly in the context of power shortages induced by a shortage of coal supplies in late 2020 [82] and autumn 2021 [83].

4.3. Firm-Level Results

Company identifiers in the source datasets allow the composition and trajectory of jobs and tax revenues supported by plants operated by individual companies to be traced. This analysis does so at the parent level, since China's power generation firms typically control many subsidiaries that ultimately share a beneficial owner—often the government. Since plants can also be owned in different shares by multiple companies, the number of jobs associated with each company is scaled by the proportion of equity ownership it has in a given plant.

Under the B scenario, the five largest sources of employment in coal power generation and the mines supplying them in 2021 are the 'Big Five' power generation companies. In descending order of coal-fired generation capacity, these are National Energy Investment Group (NEI; formerly Shenhua and also known as CHN Energy), Huaneng, Datang, Huadian, and State Power Investment Corporation (SPIC). Each of these firms also controls a considerable amount of coal production (see Table 4). NEI, created from a merger between two large generating and mining firms, is by far the largest annual producer, at 183 million tonnes.

Table 4. Largest 10 companies by capacity (in 2021, B scenario), with corresponding coal production capacity, and jobs and tax revenues supported by each company's coal plants.

Company	Capacity (GW)	Coal Production (Mt/Year)	Jobs Supported (Thousands)	Total Tax Revenue Supported (CNY bn)
NEI/CHN Energy	142.7	183.0	297.0	39.4
Huaneng	117.0	65.0	238.4	33.3
Datang	84.8	8.0	204.7	24.0
Huadian	84.3	8.8	229.4	23.5
SPIC	67.8	19.3	160.0	18.4
China Resources	44.2	8.0	124.2	12.8
Shandong Weiqiao Group	22.4	0.0	99.8	7.1
Zhejiang Provincial Energy Group	19.6	0.0	15.6	5.4
Beijing Energy Group	18.8	1.9	22.5	5.5
Jiangsu Guoxin	17.6	0.0	82.2	5.3

Between them, the 'Big Five' support 43% of the jobs in China's thermal coal industry; the top 10 support 56%. The largest single source of employment, at 297,000, is NEI (see Figure 8). The coal activities of Huaneng and Huadian support 238,400 and 229,400 jobs each, respectively, while Datang supports 204,700. SPIC supports 160,000. Beyond the 'Big Five', plants owned by China Resources (a state-owned integrated mining company) are the next largest source of employment, supporting 135,000 jobs. Among the remaining top ten firms, Shandong Weiqiao (a private sector aluminium producer), and Jiangsu Guoxin (a diversified state-owned investment company) support over 80,000 workers apiece. Looking only at these ten largest firms, it is possible to deduce that close to half of all coal jobs in China, and likely much more across all firms, are directly supported by coal plants in which state-owned enterprises have controlling or minority interests.

Mirroring the trajectory of job losses nationally, in the B scenario, 28% of the jobs currently supported by each of the Big 5 are lost by 2030, and another 50% are lost by 2040. By the 2040s, employment supported by the ten largest firms has declined by 77% in aggregate, ranging from 71–84% for individual companies. The exception is Shandong Weiqiao, where job losses are slower because of Shandong's high mining labour intensity and significant local coal resources, meaning it imports relatively less from more efficient provinces than other firms.

Unsurprisingly, the Big Five are also the largest contributors (directly and indirectly) to tax revenues nationally (see Figure 9), with the activities of the two largest, NEI and Huaneng, generating CNY 39.4 billion and CNY 33.3 billion in revenue respectively, and the 'Big Five' together, almost CNY 140 billion. The largest ten firms contribute almost CNY

175 billion between them, representing more than half of total tax revenues from thermal coal. Mirroring the national trajectory, total tax contributions from the ‘Big Five’ decline relatively slowly at first, falling just 13% to CNY 121.2 billion in 2030, then start to fall much more rapidly after 2034, falling by 60% from their 2021 levels to just CNY 55.2 billion by 2040. The tax contribution of each top ten firm falls by 43–69% by 2040, with the exception of China Resources. By 2050, revenues from the ‘Big Five’ are CNY 9.2 billion (6.6% of their starting value), and those from the top ten firms, CNY 11.1 billion (6.3%).

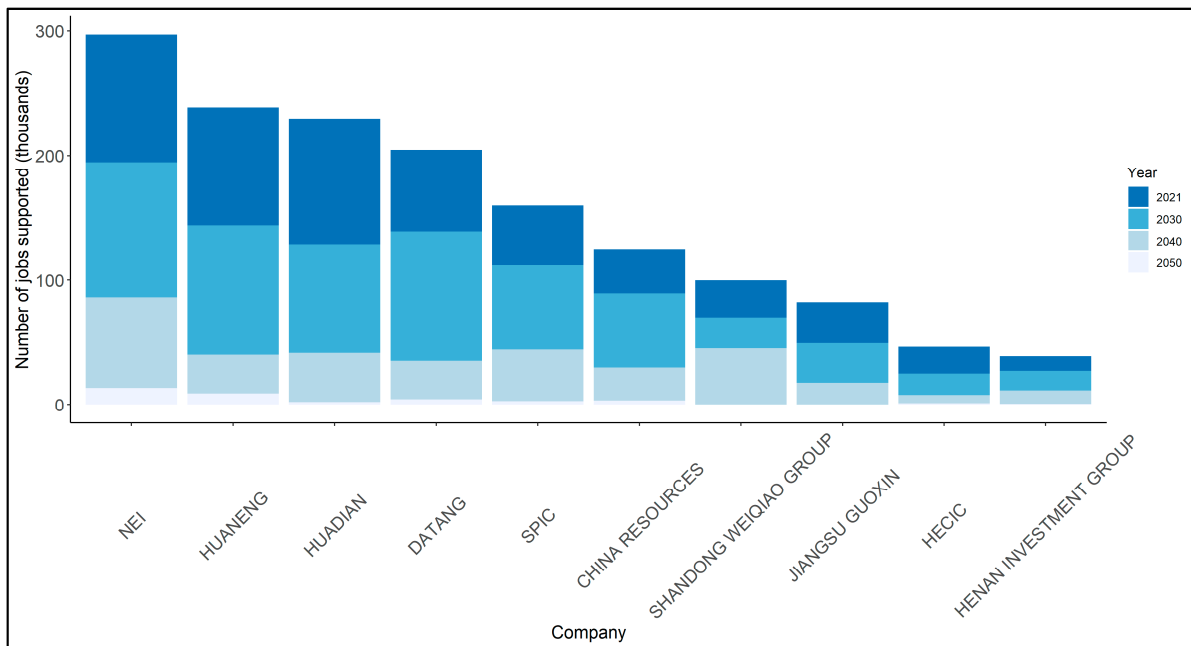


Figure 8. Largest parent companies by number of coal jobs supported, 2021–2050 (baseline scenario).

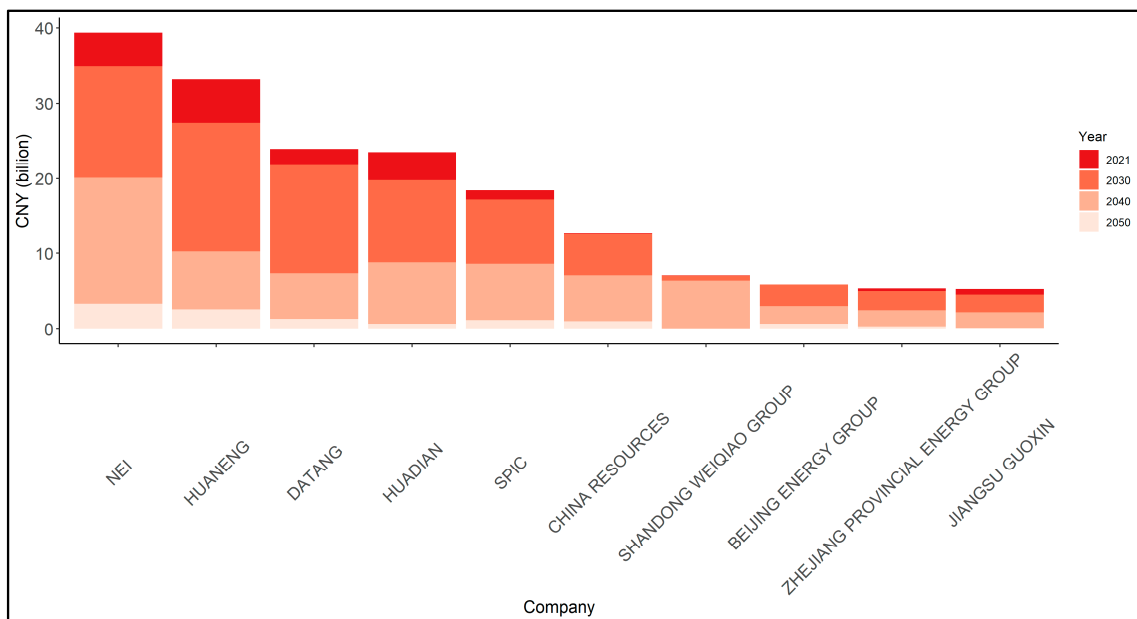


Figure 9. Largest parent companies by direct and indirect contribution to total tax revenues from coal, 2021–2050 (B scenario).

5. Discussion

Most job losses in China's coal power sector in any scenario are associated with mining, which represents over four times the employment in thermal coal plants and nearly three times that in thermal coal transport. The magnitude of expected employment decline by 2050 in coal mines is significant but is driven more by declining labour intensity than climate policy stringency.

The experiences of the E.U. and U.S., as the preeminent economies experiencing a long-term decline in the coal industry, are instructive for China. However, the scale of China's coal industry and its central role in driving economic growth and development, as well as the dominance of SOEs in the sector, imbue China's coal transition with unique political economy challenges. Existing policies have focused largely on worker relocation, an option that is more relevant for large, diversified SOEs, but does little to support workers in smaller, local mines that have fallen victim to consolidation policies. This approach is likely not viable in the longer term, since relocation will not be an option as plant retirements accelerate, and a much greater focus on retraining (where relevant) and redeployment of existing skills in clean power and industrial technologies is essential.

Managing job losses on an aggregate basis may be within reach of China's existing transition planning apparatus, given that the total expected job losses by 2030, even in the most extreme climate policy scenario, are fewer than those experienced from 2014–20, along with prospects for growth in clean technology value chains. However, at a local level, new 'green' job creation may not occur in the same place and at the same time as coal industry decline, making strategic planning at a provincial scale necessary to avoid the long-term consequences of rapid deindustrialisation observed in coal transitions outside China. State-owned and private enterprises across the country have developed, at speed and scale, remarkable capabilities in the manufacture and development of complex low-carbon products (notably solar panels, electric vehicles, and third generation nuclear reactors) that have propelled China to a global leadership position in the production of each. In anticipation of the inevitable decline in coal sector employment, China's national and subnational governments, as well as its SOEs in energy and industry, may do well to focus on identifying means for further scaling up these industries that can make use of the human capital at their disposal—including by making use of skills and expertise developed in the coal industry—and be supported by appropriate incentives for capital reallocation, including financial market design and regulation. Developing a package of mutually supportive measures for efficient labour redeployment is an important topic for further research.

The replacement of fiscal revenues tied to coal presents different challenges. In the B scenario, two-thirds of total tax revenues linked to coal power flow to the central government and remain relatively stable until the mid-2030s. For large coal producers, particularly Inner Mongolia, subnational governments receive over 50% of total tax revenues from coal. Since subnational governments and SOEs have relative fiscal independence and can generally issue their own debt, they represent a contingent liability for the central government that is realised whenever they are unable to meet financial obligations, for instance, if they borrow excessively to finance coal expansion that subsequently finds itself in insufficient demand, either as a result of government policy, sector reforms, competition from renewables, or all three. The risk of default and size of potential public sector liabilities is greater for more ambitious phase-out scenarios.

Managing these potential fiscal risks is a task falling to the central government and its agencies across multiple ministries. The National Energy Administration's role in approving coal power, for example, is already under review following a highly critical public evaluation by the influential Central Environment Inspection Team (CEIT) and will be an important instrument in preventing further investment in coal assets that may present fiscal risks to provinces either subsidising them or investing through locally owned SOEs. Similarly important is the China Banking and Insurance Regulatory Commission (CBIRC)

in crafting regulation designed to prevent provinces with an interest in growing coal from doing so where the financial (and, by implication, fiscal risks) are significant.

The national ETS—effectively an emissions standard in which the penalty for an asset not meeting the standard is for it to be included in the scheme—is unlikely to deliver significant revenues in the near term if current prices, allocations, and trading volumes persist [84]. This is not least because the trajectory for free permit allocation, versus auctioning, is not yet clear, and the exclusion of plants meeting a given emissions standard is equivalent to free permit allocations to coal power emissions. Even if provinces are allowed to retain a share of revenues from local permit trading, the incentive to keep prices low to avoid accelerating the decline of coal industries, particularly those run by SOEs, is strong.

The approximate magnitude of non-externality subsidies to the coal industry is uncertain, but likely to be significantly higher than tax revenues from it. This suggests that the net effect of coal phase-out may be revenue-neutral or positive, and further that the role of central government in managing the fiscal implications of coal-phase out in itself is likely to be largely redistributive, rather than requiring additional borrowing or monetary stimulus measures. Central fiscal support to provinces to aid their transition—funded partly through savings from reduced subsidy payments—may be essential to weakening the destructive incentives for coal expansion in mining regions, such as Inner Mongolia, that also have plentiful renewable resources able to compete on price with coal. In the longer term, ways of taxing clean technologies will be needed to replace the resource taxes and VAT receipts (tied to coal sales) that represent a significant proportion of subnational revenue. In locations where coal is unlikely to be replaced directly with renewable, investments in building up other clean industries by development finance actors including policy banks and—to an extent—state-owned commercial banks, is likely to be required. Longer-term measures are likely to require either raising revenues from clean energy without unnecessarily slowing its development, greater borrowing on the expectation of higher future growth, or reducing public spending. The latter may be unviable, not least due to the need to meet contingent liabilities in the coal industry (e.g., outstanding bonds and loans) to which government is exposed through ownership of state-owned enterprises (SOEs), pressure to meet annual GDP growth targets, clean-up costs for former mining sites, long-term health, environmental and climate costs, and the cost of relocating and retraining labour supplies.

The extent to which additional investment is needed in reorienting labour resources to clean industries is a more complicated question, and one requiring more data, to be addressed in future research. Large net fiscal outlays are likely to be necessary for China to accelerate the pace of decarbonisation, given the need for research and development spending, and infrastructure investment, in key technologies, notably hydrogen, nuclear, direct air capture, storage, and possibly CCS.

6. Conclusions

This analysis has focused on the employment implications of transitioning China's economy away from coal, as well as the fiscal ramifications for areas dependent on the tax revenues it generates. The results of the simulations constructed here show that the absolute magnitude of the labour transition challenge facing China is not unprecedented in its recent history; however, central and subnational governments will need to carefully manage the localised effects of job losses and find productive alternative uses for unemployed labour.

The majority of tax revenues from coal flow to central government and are unlikely to decline until the 2030s. Coal-producing provinces such as Inner Mongolia are more dependent on subnational tax revenues, both accentuating the need for diversification and making it more politically challenging to achieve. National-level regulation and enforcement will be essential in limiting provincial exposure to fiscal shortfalls caused by coal industry declines, although these are likely to be limited until the 2030s unless China pursues a much more aggressive phase-out strategy than currently envisaged. Almost half

of total employment is driven by coal plants owned by five large state-owned enterprises that are integral to several local economies and providers of critical physical and social infrastructure, further accentuating the difficulties of embarking on such significant structural change. China is exceptionally well-positioned to divert coal subsidies and investment to clean technologies and skills, and renewable power, both to meet domestic policy goals, and as the world's largest exporter of green products.

This initial effort to reconstruct the coal network and associated jobs and tax revenues in China has many limitations and can be extended in multiple directions. These may include the addition of unpriced subsidies, particularly those typically considered to be externalities. It is also possible to overlay other economic, environmental and financial metrics on the underlying network to consider, for example, how the marginal financial position of each plant and its owners are affected; and where and in what quantities pollutant emissions at source are “traded” across China's power system. As better data becomes available, there is also potential for examination of structural change dynamics in the labour market induced by coal phase-out. This might include examining the risk of regional economic decline when accounting for where opportunities for re-employment in a range of emerging clean industries might arise, with corresponding implications for subnational migration and reskilling needs, both for governments and for large state-owned companies with the capacity to redeploy workers across the country. Similarly, the accuracy of the reconstructed network can be improved by accounting for price dynamics and transport availability between provinces and matching specific mines to specific plants based on multiple criteria, including but not limited to coal prices. Finally, this modelling effort raises pertinent hypotheses about China's coal transition that merit further multi-method investigation, particularly to explore the political economy dynamics between agents driving, and affected by, the transition.

Author Contributions: Conceptualization, A.C.; methodology, A.C.; validation, W.Z.; formal analysis, A.C.; investigation, A.C. and W.Z.; writing—original draft preparation, A.C.; writing—review and editing, A.C. and W.Z.; visualization, A.C. All authors have read and agreed to the published version of the manuscript.

Funding: The research was initiated with funding from the Foreign, Commonwealth and Development Office (FCDO), Government of the United Kingdom, grant number FP099. The research was continued and refined with funding from the Natural Environment Research Council (NERC) in its capacity as National Member Organization for the United Kingdom to the International Institute for Applied Systems Analysis (IIASA); and the Economics of Energy Innovation and Systems Transition (EEIST) project. EEIST is jointly funded through UK Aid by the UK Government Department for Business, Energy and Industrial Strategy (BEIS), and the Children's Investment Fund Foundation (CIFF). The contents of this manuscript represent the views of the authors and should not be taken to represent the views of the UK government, CIFF or the organisations to which the authors are affiliated. Weirong Zhang is funded by the National Natural Science Foundation of China, grant number 72173043, under project leader Jiahai Yuan.

Data Availability Statement: The dataset on coal mines can be accessed upon request from Global Energy Monitor (<https://globalenergymonitor.org/projects/global-coal-mine-tracker/> (accessed on 11 July 2021)). The dataset on coal plants (accessed on 20 February 2021) combines publicly available data from Global Energy Monitor and the World Resources Institute (<https://www.wri.org/research/global-database-power-plants> with proprietary data from S&P Global Platts.

Acknowledgments: The author gratefully acknowledges data support from Durand D'Souza and Lily Chau at the Carbon Tracker Initiative, Jiahai Yuan at North China Electric Power University, and Matthew McCarten and Nataliya Tkachenko at the Oxford Sustainable Finance Programme. For valuable comments and suggestions, thanks to David Robinson, Conor Hickey, Ben Caldecott, Xin Li, and three anonymous reviewers. Thank you to Sebastian Poledna at the International Institute for Applied Systems Analysis (IIASA) for his support, encouragement, and feedback throughout the later development of this project, and to the Advancing Systems Analysis group for helpful comments.

Conflicts of Interest: The author declares no conflict of interest.

Appendix A. Province Codes

Table A1. Province codes used in the main text.

Province	Code
Anhui	AH
Beijing	BJ
Chongqing	CQ
Fujian	FJ
Guangdong	GD
Gansu	GS
Guangxi	GX
Guizhou	GZ
Henan	HA
Hubei	HB
Hebei	HE
Hainan	HI
Heilongjiang	HL
Hunan	HN
Jilin	JL
Jiangsu	JS
Jiangxi	JX
Liaoning	LN
Inner Mongolia	NM
Ningxia	NX
Qinghai	QH
Sichuan	SC
Shandong	SD
Shanghai	SH
Shaanxi	SN
Shanxi	SX
Tianjin	TJ
Tibet	XZ
Xinjiang	XJ
Yunnan	TN
Zhejiang	ZJ

Appendix B. Scenarios

This study examines the impact of coal phase-out under five scenarios. The first is a ‘no transition’ scenario (NT) assuming that the coal sector continues to develop with no constraints over and above those already in place; namely, that all plants that are either planned or under construction are built and operated as expected, while the remainder of the fleet is phased out according to its age.

The remaining four scenarios, which play out from 2021–2060, are designed to be roughly equivalent to the four scenarios developed in He, et al. [85] that describe the trajectory of coal power generation up to 2030. The standard operating lifetime of the coal plants is manipulated.

Under the ‘baseline’ scenario (B), which reflects current policies, coal power plants operate for 30 years, and no further plants are built other than those already approved. This implies that coal use in electricity generation will not quite be fully phased out by 2050. In the baseline and the ‘no transition’ scenario, currently operating plants more than 30 years old are assumed to cease operating after 35 years, plants more than 35 years old, after 40 years, and all plants more than 40 years old are assumed to retire the following year.

This implies that 108 GW of coal power (approximately 10% of the currently operating fleet) remains online in 2050, concentrated in Inner Mongolia, Shanxi, Shandong, Xinjiang, and Shaanxi. Coal is phased out entirely in the power sector by 2054. While the implications for carbon budgets are not addressed here, previous studies [86,87] suggest that committed emissions from energy infrastructure built well before 2020 significantly exceed the global

carbon budgets for both 1.5 °C and 2 °C and that compliance with these budgets will require a faster phase-out than projected here. Given China's major contribution to power sector emissions globally, the baseline scenario is unlikely to be compatible with either of the Paris Agreement targets without significant deployment of negative emissions technologies in the form of CCS (including variants such as co-firing coal with biomass) and direct air capture.

The baseline therefore represents a trajectory for China's coal power sector that reflects existing policies (including the 2060 carbon neutrality announcement) but is not necessarily in line with China's international commitments under the Paris Agreement, or with the best available science. Meeting these targets would require that CCS deployment be rapidly accelerated, and that coal with CCS remain competitive in the long term against available alternatives. Both appear unlikely at present.

Allowing plants to operate for this long reduces the financial risk of stranded or otherwise non-performing assets accumulating on coal and utility company balance sheets—although this does not eliminate them, since the economics of China's coal plants and decreasing utilization hours for coal suggest as much as half the current fleet is suffering operating financial losses [10].

The baseline is, however, consistent with China decarbonisation pathway modelling in [7], in which the unabated coal generation fleet stands at 123 GW (+68 GW CCS) in 2050 under a 2 °C scenario, and 32 GW (+149 GW CCS) under a more ambitious 1.5 °C scenario, partially reflecting the use of CCS as a means of justifying carbon budget overshoot before 2050. In the model in this study, 472 TWh of coal-fired electricity is generated in 2050 under the baseline scenario, similar to the 450 TWh (unabated; 850 TWh including CCS) in [7] for a 2 °C scenario, and much higher than the 110 TWh (unabated; 900 TWh including CCS) in the 1.5 °C scenario, in which net zero emissions are achieved in the power sector between 2045 and 2050.

CCS does feature in the 1.5 °C and 2 °C scenarios, however, since its scalability and competitiveness are not yet established, particularly when considering price trends in clean technologies, it is not considered as an option in the model. The potential for CCS to sustain existing coal sector jobs and create new ones will merit further study as its feasibility becomes clearer.

China may opt to phase out its coal plants more rapidly than in the baseline scenario, either as a matter of top-down policy (particularly if responding to new information on the climate system), or proliferation of cheaper, cleaner alternatives in the market, or both. Three alternative scenarios are modelled in which coal plants are closed more quickly than expected (i.e., an accelerated decline in capacity), assuming no additional CCS capacity. An alternative route to a similar outcome is to keep plants open as originally planned, but with much fewer generating hours. This may help to preserve jobs at the plants for longer, but with severe financial consequences for plant owners that are, in many cases, already absorbing operating losses. We assume that the closure of plants, rather than running increasing portions of the fleet at increasingly large losses, is the preferred strategy in designing these scenarios. In the first alternative scenario, 'R', the trajectory of accelerated plant closures is calibrated to correspond to match the share of coal capacity closures between 2020 and 2030 in the three scenarios presented in He, Lin, Sifuentes, Liu, Abhyankar and Phadke [85], a power system model that optimises for cost given a set of energy technology prices and carbon constraints. In the 'R' scenario, a more rapid phase-out reflects the impact of lower-than-expected renewables costs on capacity additions. In the more aggressive 'C50' and 'C80' scenarios, lower-than-expected renewables costs are combined with exogenously-imposed emissions constraints for the power sector of 50% and 80% below 2015 levels by 2030, respectively. These latter two scenarios are reflective of different levels of carbon constraints placed on the power sector as a proxy for the aggressiveness of national decarbonisation policy.

To implement the scenarios, the only variable that is changed is the operating lifetime of each coal plant, which is calibrated to reflect the approximate capacity remaining by

2030 in the scenarios constructed in [85], multiplied by a factor of 1.42 to account for the ratio between expected 2020 installed capacity in the source paper (832 GW) and actual operating capacity in 2020 (1180 GW) for scenarios B and R. The higher installed capacity in these scenarios is largely offset by lower operating hours, such that coal power generation is similar under the B scenario, and slightly higher under the R scenario. In the C50 and C80 scenarios, no multiplier is used since they are based on emissions reductions from a 2015 (not 2020) baseline. The scenarios, and how they are implemented into the model in this paper, are summarised in Table A2.

Table A2. Overview of coal phase-out scenarios employed.

Scenario	Description	Plant Operating Lifetime (Years)	Capacity in 2030 (GW)		Generation in 2030 (TWh)	
			He et al. (2020)	Model	He et al. (2020)	Model
NT	No transition: all plants planned or under construction are built and operated as intended	30 if plant age < 30; 35 if plant age > 30; 40 if plant age > 35; Age + 1 if plant age > 40	N/A	1398	N/A	6069
B	Baseline; reflects existing policy of carbon neutrality by 2060	Same as NT	$751 \times 1.42 = 1057$	1114	4915	4827
R	Low-cost renewables; reflects greater than expected declines in renewables costs	25	$707 \times 1.42 = 1003$	984	3676	4270
C50	50% decline in emissions from coal power by 2030 relative to 2015	20; cancellation of plants under construction	498	486	2371	2125
C80	80% decline in emissions from coal power by 2030 relative to 2015	15; cancellation of all plants under construction	196	195	957	867

Appendix C. Employment Trajectories for All Provinces, in All Scenarios

Table A3. Trends in coal industry employment supported by each province, 2021–2060 and change to 2030 (NT scenario).

Province in Which Coal Plants Are Located	Coal Industry Jobs Supported by Those Plants (Thousands, 2021)	Coal Industry Jobs Supported by Those Plants			Change in Jobs Supported 2021–2030	% Change in Jobs Supported 2021–2030
		2030	2040	2050		
Jiangsu	454,814	309,291	105,484	23,119	145,523	−32.0%
Shandong	498,112	369,899	155,862	39,018	128,213	−25.7%
Hebei	197,592	112,941	37,300	3230	84,651	−42.8%
Liaoning	174,692	101,769	35,186	8559	72,923	−41.7%
Henan	261,630	193,992	70,763	18,090	67,638	−25.9%
Heilongjiang	136,288	76,313	22,747	4936	59,975	−44.0%
Shanxi	111,179	94,533	41,478	13,298	16,645	−15.0%
Sichuan	37,556	29,784	12,268	6903	7772	−20.7%
Ningxia	39,855	33,594	15,492	2952	6262	−15.7%
Yunnan	20,298	14,518	3251	1456	5780	−28.5%
Zhejiang	36,564	31,332	10,646	1690	5232	−14.3%
Shanghai	7049	4094	410	426	2956	−41.9%
Tianjin	11,964	9788	3812	1426	2176	−18.2%
Hainan	4824	3537	1588	-	1286	−26.7%
Guangdong	56,109	55,114	34,164	12,473	995	−1.8%
Chongqing	15,602	15,208	11,029	3775	394	−2.5%
Jilin	49,346	49,228	27,642	14,336	118	−0.2%
Tibet	125	125	125	-	−0	0.1%
Anhui	131,335	131,347	61,094	23,470	−13	0.0%
Hubei	32,703	33,775	22,471	10,690	−1072	3.3%
Qinghai	7037	8145	4829	1769	−1108	15.7%

Table A3. Cont.

Province in Which Coal Plants Are Located	Coal Industry Jobs Supported by Those Plants (Thousands, 2021)	2030	2040	2050	Change in Jobs Supported 2021–2030	% Change in Jobs Supported 2021–2030
Fujian	21,641	24,287	13,984	6851	−2646	12.2%
Guangxi	29,432	35,313	24,697	10,223	−5881	20.0%
Shaanxi	47,039	57,887	36,137	18,439	−10,849	23.1%
Hunan	41,329	55,033	33,913	25,576	−13,703	33.2%
Jiangxi	38,186	54,671	41,601	32,527	−16,485	43.2%
Gansu	58,412	77,101	40,963	21,561	−18,689	32.0%
Inner Mongolia	104,358	125,769	70,231	38,657	−21,410	20.5%
Xinjiang	88,704	113,471	87,001	24,037	−24,767	27.9%
Guizhou	98,991	127,164	76,066	34,038	−28,173	28.5%
Total	2,812,764	2,349,021	1,102,235	403,526	463,743	−16.5%

Table A4. Trends in coal industry employment supported by each province, 2021–2060 and change to 2030 (R scenario).

Province in Which Coal Plants Are Located	Coal Industry Jobs Supported by Those Plants (Thousands, 2021)	2030	2040	2050	Change in Employment 2021–2030	% Employment Loss 2021–2030
Jiangsu	451,727	204,389	30,884	-	247,338	−54.8%
Shandong	491,171	278,881	55,747	-	212,290	−43.2%
Henan	256,720	140,251	19,213	-	116,469	−45.4%
Hebei	197,482	88,824	18,825	-	108,658	−55.0%
Liaoning	172,183	80,029	9253	-	92,153	−53.5%
Heilongjiang	122,479	57,417	8011	-	65,062	−53.1%
Anhui	126,761	76,000	12,768	-	50,762	−40.0%
Shanxi	109,169	68,753	17,948	-	40,416	−37.0%
Guizhou	95,572	69,376	15,441	-	26,196	−27.4%
Gansu	49,634	31,043	6091	-	18,591	−37.5%
Sichuan	37,593	21,373	3883	-	16,221	−43.1%
Jilin	46,989	31,572	2691	-	15,417	−32.8%
Guangdong	54,472	41,286	9748	-	13,186	−24.2%
Inner Mongolia	102,063	88,979	27,705	-	13,084	−12.8%
Zhejiang	35,969	24,336	1344	-	11,633	−32.3%
Ningxia	39,826	28,746	10,353	-	11,080	−27.8%
Yunnan	20,310	9339	-	-	10,970	−54.0%
Hunan	39,824	29,554	6581	-	10,270	−25.8%
Xinjiang	86,787	76,995	23,726	-	9792	−11.3%
Hubei	32,071	24,210	8883	-	7861	−24.5%
Shaanxi	44,823	37,658	14,121	-	7166	−16.0%
Fujian	20,519	16,098	4470	-	4421	−21.5%
Tianjin	11,705	7404	2507	-	4301	−36.7%
Shanghai	7050	2759	-	-	4291	−60.9%
Guangxi	27,191	22,962	8929	-	4229	−15.6%
Jiangxi	35,765	32,930	14,977	-	2835	−7.9%
Qinghai	7007	4649	1094	-	2358	−33.7%
Hainan	4827	3109	-	-	1717	−35.6%
Chongqing	13,695	12,577	4116	-	1118	−8.2%
Tibet	125	125	125	-	−0	0.1%
Total	2,741,506	1,611,622	339,436	-	1,129,885	−41.2%

Table A5. Trends in coal industry employment supported by each province, 2021–2060 and change to 2030 (C50 scenario).

Province in Which Coal Plants Are Located	Coal Industry Jobs Supported by Those Plants (Thousands, 2021)	2030	2040	2050	Change in Employment 2021–2030	% Employment Loss 2021–2030
Shandong	491,171	138,729	-	-	352,442	−71.8%
Jiangsu	451,727	103,992	-	-	347,735	−77.0%
Henan	256,720	63,422	-	-	193,298	−75.3%
Hebei	197,482	47,124	-	-	150,358	−76.1%
Liaoning	172,183	30,375	-	-	141,808	−82.4%

Table A5. Cont.

Province in Which Coal Plants Are Located	Coal Industry Jobs Supported by Those Plants (Thousands, 2021)	2030	2040	2050	Change in Employment 2021–2030	% Employment Loss 2021–2030
Heilongjiang	122,479	18,720	-	-	103,759	−84.7%
Anhui	126,761	39,220	-	-	87,541	−69.1%
Shanxi	109,169	31,127	-	-	78,043	−71.5%
Inner Mongolia	102,063	31,868	-	-	70,195	−68.8%
Guizhou	95,572	36,280	-	-	59,292	−62.0%
Gansu	49,634	12,444	-	-	37,191	−74.9%
Guangdong	54,472	21,005	-	-	33,467	−61.4%
Jilin	46,989	13,880	-	-	33,109	−70.5%
Sichuan	37,593	5739	-	-	31,855	−84.7%
Hunan	39,824	8790	-	-	31,033	−77.9%
Zhejiang	35,969	8345	-	-	27,624	−76.8%
Xinjiang	86,787	59,426	-	-	27,361	−31.5%
Shaanxi	44,823	17,680	-	-	27,144	−60.6%
Jiangxi	35,765	11,389	-	-	24,375	−68.2%
Ningxia	39,826	15,807	-	-	24,019	−60.3%
Hubei	32,071	12,681	-	-	19,390	−60.5%
Yunnan	20,310	2141	-	-	18,168	−89.5%
Guangxi	27,191	13,648	-	-	13,543	−49.8%
Fujian	20,519	6987	-	-	13,531	−65.9%
Tianjin	11,705	2521	-	-	9184	−78.5%
Shanghai	7050	-	-	-	7050	−100.0%
Chongqing	13,695	7442	-	-	6253	−45.7%
Qinghai	7007	3255	-	-	3752	−53.5%
Hainan	4827	1572	-	-	3254	−67.4%
Tibet	125	125	-	-	−0	0.1%
Total	2,741,506	765,732	-	-	1,975,774	−72.1%

Table A6. Trends in coal industry employment supported by each province, 2021–2060 and change to 2030 (C80 scenario).

Province in Which Coal Plants Are Located	Coal Industry Jobs Supported by Those Plants (Thousands, 2021)	2030	2040	2050	Change in Employment 2021–2030	% Employment Loss 2021–2030
Shandong	491,171	42,493	-	-	448,678	−91.3%
Jiangsu	451,727	42,550	-	-	409,176	−90.6%
Henan	256,720	19,468	-	-	237,252	−92.4%
Hebei	197,482	26,462	-	-	171,020	−86.6%
Liaoning	172,183	9815	-	-	162,368	−94.3%
Heilongjiang	122,479	7308	-	-	115,171	−94.0%
Anhui	126,761	13,136	-	-	113,625	−89.6%
Shanxi	109,169	12,279	-	-	96,890	−88.8%
Inner Mongolia	102,063	13,439	-	-	88,624	−86.8%
Guizhou	95,572	13,147	-	-	82,425	−86.2%
Xinjiang	86,787	20,095	-	-	66,692	−76.8%
Guangdong	54,472	5354	-	-	49,117	−90.2%
Gansu	49,634	3758	-	-	45,877	−92.4%
Jilin	46,989	2646	-	-	44,343	−94.4%
Hunan	39,824	2502	-	-	37,322	−93.7%
Sichuan	37,593	914	-	-	36,679	−97.6%
Shaanxi	44,823	9172	-	-	35,651	−79.5%
Zhejiang	35,969	508	-	-	35,461	−98.6%
Jiangxi	35,765	4506	-	-	31,259	−87.4%
Ningxia	39,826	11,204	-	-	28,622	−71.9%
Hubei	32,071	7086	-	-	24,985	−77.9%
Yunnan	20,310	-	-	-	20,310	−100.0%
Guangxi	27,191	7886	-	-	19,305	−71.0%
Fujian	20,519	3145	-	-	17,374	−84.7%
Chongqing	13,695	2761	-	-	10,934	−79.8%
Tianjin	11,705	1642	-	-	10,063	−86.0%
Shanghai	7050	-	-	-	7050	−100.0%

Table A6. Cont.

Province in Which Coal Plants Are Located	Coal Industry Jobs Supported by Those Plants (Thousands, 2021)	2030	2040	2050	Change in Employment 2021–2030	% Employment Loss 2021–2030
Qinghai	7007	1346	-	-	5661	−80.8%
Hainan	4827	-	-	-	4827	−100.0%
Tibet	125	125	-	-	−0	0.1%
Total	2,741,506	284,746	-	-	2,456,760	−89.6%

Appendix D. Technical Appendix

This appendix details the assumptions and calculations made in order to generate the model results reported in the paper.

Appendix D.1. Coal Plant Operations

Coal plants are deemed to be operational or non-operational based on the start year of operations (contained in the data) and end year (determined in each scenario based on the methodology in Appendix B). To estimate coal consumption per useful unit of electricity produced, information on coal energy content (*EC*) and plant efficiency is required. Coal energy content assumptions differ by the type of coal consumed (see Table A7).

Table A7. Coal energy content assumptions. Source: Carbon Tracker Initiative.

Coal Type	Energy Content (kcal per kg)
Anthracite	6066
Bituminous	5316
Sub-bituminous	4897
Lignite	3713
Average (used when coal type unknown)	4500

These figures are then converted to GJ per tonne using the conversion factor 239,005.7 GJ/kcal, and then to M/Wh per tonne using the conversion factor 3.6 GJ/MWh (A1).

$$EC \left(\frac{\text{MWh}}{\text{t}} \right) = 3.6 \times EC \left(\frac{\text{kcal}}{\text{kg}} \right) \times \left(\frac{1000}{239,005.7} \right) \quad (\text{A1})$$

Plant efficiency factors (*EF*) vary by type of plant (see Table A8) and are estimated to decay (*d*) by 0.18% per year, based on data provided by Carbon Tracker Initiative.

Table A8. Plant efficiency assumptions by technology type.

Plant Technology Type	Efficiency (%)	Source
Subcritical	39.6%	[88]
Supercritical	42%	[89]
Ultra-supercritical	44%	[89]

Estimated capacity factors (*CF*) by province are provided in Table 1 in the main text and are sourced from published statistics provided by the China Electricity Council (CEC) for the year 2019. Coal consumption (*C*) by plant *i* with capacity *CA* in year *t* that began operating in year *t** is calculated using Equations (A2) and (A3):

$$Efficiency_{it} = EF_i \times (1 - d)^{t-t^*} \quad (\text{A2})$$

$$C_{it} = \frac{CA_i \times CF_{it} \times 8766}{EC} \times Efficiency_{it} \quad (\text{A3})$$

It is assumed that each plant starts phasing down its operations two years ahead of closure, reducing its initial capacity factor by one third for the penultimate year of operation, and by two thirds for the last year of operation. This is intended to be a crude proxy for reflecting declining demand for the services of coal plants targeted for phase-out, either because they are not providing sufficient value to the market or are considered not to meet regulatory targets.

Appendix D.2. Coal Mining Operations

The coal mine dataset contains fields for each mine's opening year and remaining operational lifetime. If remaining lifetime data is not available, the mine is assumed to operate either until 2050, or for 50 years from its opening year, whichever is the longest. If the opening year is also unavailable, the mine is assumed to operate for 50 years after the base year (2021). The dataset is filtered for mines that produce thermal coal. If the mine produces both thermal and metallurgical coal, it is classed as a thermal coal mine. Thermal coal production by province and coal type is then aggregated.

Appendix D.3. Coal Production-Consumption Network

Each plant prioritises the consumption of coal mined in the province in which it is located (which must match the type of coal the plant consumes) and imports the balance from other provinces. Similarly, China prioritises the consumption of domestic coal, and is assumed to import coal only when there is an undersupply (which is the case for, e.g., anthracite). In each province p and for each coal type ct , the amount of coal demand met by local supplies (CD^{local}) is the minimum of local demand d (coal of that type consumed by plants in that province) and local supply s (coal of that type produced by mines m in the same province) (A4).

$$CD_{p,ct}^{local} = \min \left(\sum_{n=1}^i d_{i,p,ct}, \sum_{n=1}^m s_{p,ct} \right) \quad (A4)$$

The amount of each plant's total coal demand (CD^{total}) met by importing from other provinces ($CD^{external}$) or from outside China is what remains when local demand is subtracted from it. The amount of each province's coal supply exported to other provinces ($CS^{exported}$) is what remains once local demand is subtracted from total local production (A5).

$$CS_{p,ct}^{exported} = \sum_{n=1}^m s_{p,ct} - \sum_{n=1}^i CD_{i,p,ct}^{local} \quad (A5)$$

The amount of coal (by type) imported from outside China ($CD^{imported}$) is the maximum of total demand (CD^{total}), minus total domestic supply ($CD^{local} + CD^{external}$) across all provinces; and zero (A6).

$$CD_{ct}^{imported} = \max \left(0, \sum_{n=1}^p CD_{p,ct}^{total} - \sum_{n=1}^p CD_{p,ct}^{local} - \sum_{n=1}^p CD_{p,ct}^{external} \right) \quad (A6)$$

The percentage of the interprovincial coal export market (ep) held by each province is the share of coal exported by that province over total interprovincial exports, for each coal type (A7).

$$ep_{p,ct} = \frac{CS_{p,ct}^{exported}}{\sum_{n=1}^p CS_{p,ct}^{exported}} \quad (A7)$$

Each province then sources its coal externally from other provinces (where applicable) on a pro-rata basis according to each other province's share of the interprovincial market. This is recalculated for each year t in the model.

Appendix D.4. Coal Transport Operations

Since the model aggregates mines at the provincial level and does not link specific mines to specific plants, coal transportation distances are calculated on the basis of the shortest geographic distance between the capital city of each province, and the plant. See [90] for a similar approach. A calculation for the cost of transport is required in order to assess revenues from VAT levied on the transport and power generation components of the supply chain. Average coal transport prices by mode, and the share of each mode in total transport volumes, are used to estimate an overall average cost per ton-km.

Table A9. Cost and share of transport by mode.

Transport Mode	Average Cost (CNY /ton-km) [Source]	Share (Scaled to 100%) [65]	Weighted Average Cost of Transport (CNY /ton-km)
Rail	0.1 [91]	46.67%	0.2196
Road	0.55 [92]	28.57%	
Water	0.06375 [92]	24.76%	

Total transport costs (TC) for each plant in a given year are the sum, across provinces, of the product of distance $dist$ between plant i and the capital of province p , and the amount of coal demanded from each province CD^p (A8).

$$TC_i = \sum_{n=1}^p dist_{ip} \times CD^p \quad (A8)$$

Appendix D.5. Employment

The number of jobs supported by each coal plant while it is operating depends on the capacity of the plant (Table A10).

Table A10. Number of jobs in coal plants by plant capacity. Adapted from [60].

Plant Capacity (c) (MW)	Number of Jobs
$0 \leq c < 100$	60
$100 \leq c < 300$	100
$300 \leq c < 600$	110
$600 \leq c < 1000$	120
≥ 1000	150

The number of jobs (per billion ton-km) supported by the transport of coal in each province is the weighted average across modes of the total number of jobs supported by each transport mode in each province, divided by total freight volumes for each mode in each province. Table A11 summarises the data points used in constructing this measure, as well as the 2015 figures for coal mining jobs per 10,000 tons of coal production by province. This coal mining labour intensity measure, L , is projected forward based on annual rates of labour productivity growth g cited in [63] (A9). In the transport sector, jobs are assumed to be held in the province of origin of the coal being transported.

$$L_t = L_b \times (1 - g)^{t-b} \quad \text{where} \quad \begin{cases} b = 2015, g = 8\%, & 2015 \leq t \leq 2020 \\ b = 2020, g = 5\%, & 2021 \leq t \leq 2050 \\ b = 2050, g = 0\%, & 2051 \leq t \leq 2060 \end{cases} \quad (A9)$$

Table A11. Estimated jobs per billion ton-km of coal transported, and per 10,000 tons of coal produced, by province.

Province	Jobs (2020) [64]			Freight Volumes (Billion ton-km, 2020) [65]			Weighted Average Jobs per Billion ton-km	Jobs per 10,000 tons Coal Production (L), 2015 [63]
	Road	Rail	Water	Road	Rail	Water		
Anhui	47.3	132.3	8.4	75.4	326.8	622.5	183.5	17.5
Beijing	103.3	262.2	0.3	81.4	27.6	0.0	3354.8	20
Chongqing	27.2	123.7	12.1	20.8	95.3	245.3	451.0	18
Fujian	33.5	96.0	14.6	19.4	96.2	713.6	173.8	9
Gansu	64.8	44.3	0.2	151.7	98.0	0.0	438.0	16.5
Guangdong	72.1	388.3	41.4	30.1	256.4	2450.8	183.3	0
Guangxi	66.4	66.8	4.4	75.3	147.1	176.5	345.1	25.5
Guizhou	33.5	59.6	0.2	64.2	54.8	4.5	755.1	8
Hainan	6.5	19.4	6.1	1.7	4.1	159.0	194.2	0
Hebei	88.1	118.0	18.0	493.7	802.7	59.9	165.2	23
Heilongjiang	137.3	60.6	0.6	81.4	79.5	0.6	1229.5	29
Henan	110.8	229.5	2.1	214.6	530.0	121.2	395.5	28.7
Hubei	78.6	159.7	13.2	93.9	226.8	292.6	410.1	9.5
Hunan	77.8	129.5	3.2	85.5	131.7	42.2	811.9	16.5
Inner Mongolia	108.1	57.6	0.0	273.5	195.5	0.0	353.4	1.7
Jiangsu	64.0	233.6	51.7	33.3	323.5	637.9	351.1	37
Jiangxi	56.3	89.7	3.3	56.5	304.0	25.5	386.9	21
Jilin	62.6	61.9	0.0	54.0	126.3	0.0	690.5	26
Liaoning	112.6	115.6	28.4	123.2	266.3	502.7	287.6	32.5
Ningxia	19.7	11.1	0.2	21.4	43.7	0.0	473.6	7.5
Qinghai	23.3	19.6	0.0	27.2	12.6	0.0	1076.7	10.5
Shaanxi	97.4	111.0	0.0	175.0	173.1	0.1	598.6	3.3
Shandong	88.0	203.7	38.4	152.5	674.6	189.6	324.7	32.2
Shanghai	33.7	179.7	31.6	1.5	83.9	2947.1	80.8	0
Shanxi	102.6	75.8	0.0	277.5	269.2	0.0	326.4	9.5
Sichuan	70.8	166.8	0.7	87.8	152.8	30.6	879.4	12
Tianjin	28.3	58.8	10.9	51.7	59.9	154.6	367.8	0
Tibet	0.7	15.4	0.0	4.0	11.4	0.0	1041.6	0
Xinjiang	57.4	79.7	0.1	114.6	80.2	0.0	703.8	3.5
Yunnan	39.0	75.2	0.2	51.9	101.5	1.7	737.5	20
Zhejiang	4.0	202.2	29.0	23.6	208.2	1007.4	189.7	0
Total	1915.8	3647.4	319.5					

Appendix D.6. Tax Revenues and Subsidies

Estimation of tax revenues raised from employment requires estimating average wages by province for each type of employee. Data on average wages in the mining, power, and transport industries for each province is drawn from the China Statistical Yearbook 2019 [93]. In each industry, there is a substantial difference between public and private sector wages (public sector wages are typically much higher), and a weighted average is taken based on the proportion of public vs. private employees in each sector. In the mining sector, the public/private ratio (%) is 62/38; in power, it is 80/20; and in transport, 44/56 (Table A12).

Social security payments are raised from wages; they are not strictly a tax but are made up of contributions by employers and employees. All employees are assumed to contribute to social security at the rate of 20% of gross salary; all employers, 30% of gross salary.

Income taxes are levied based on each employee's taxable income. The standard deduction for income taxes in China is CNY 60,000 [68]. We assume that each employee claims the standard deduction. Taxable income is the maximum of what remains, and zero. Total tax payable by each employee is taxable income multiplied by the tax rate for the applicable tax bracket, minus an additional 'quick deduction' for that bracket reflecting the amount taxed at a lower rate (Table A13).

Table A12. Wages by sector (public sector, private sector, and weighted average) and province.

Province	Average Wage, Public Sector (Thousand CNY/Year)			Average Wage, Private Sector (Thousand CNY/Year)			Weighted Average Wage (Thousand CNY/Year)		
	Mining	Power	Transport	Mining	Power	Transport	Mining	Power	Transport
Anhui	59.0	101.9	85.5	48.5	113.1	100.3	48.9	80.9	62.9
Beijing	67.0	135.0	109.0	74.6	176.7	156.4	66.1	123.3	91.1
Chongqing	60.3	74.4	69.1	54.9	92.9	85.4	57.7	89.5	71.6
Fujian	54.3	61.3	58.6	44.7	119.7	104.8	58.0	90.1	72.0
Gansu	43.2	85.4	69.3	47.4	83.5	76.3	45.3	84.6	62.5
Guangdong	48.6	142.3	106.6	48.0	142.6	123.8	62.5	107.5	82.2
Guangxi	45.3	63.9	56.8	44.5	101.7	90.3	46.0	89.8	65.2
Guizhou	52.6	71.1	64.0	55.3	110.8	99.7	42.7	91.5	64.0
Hainan	44.7	65.6	57.6	35.4	100.8	87.7	54.3	97.6	73.2
Hebei	43.9	82.2	67.6	44.6	100.4	89.3	48.4	87.1	65.3
Heilongjiang	39.3	90.0	70.7	36.2	80.3	71.5	43.7	83.1	60.9
Henan	39.2	71.8	59.4	42.9	88.5	79.5	43.0	75.9	57.4
Hubei	43.5	82.8	67.8	39.7	103.2	90.5	42.2	86.4	61.5
Hunan	42.7	57.6	51.9	39.7	94.3	83.4	39.6	85.2	59.5
Inner Mongolia	57.1	120.1	96.1	50.5	101.4	91.3	45.1	91.5	65.4
Jiangsu	55.8	94.1	79.5	56.0	142.7	125.5	62.6	98.5	78.3
Jiangxi	47.5	60.1	55.3	45.4	85.0	77.2	47.1	87.0	64.6
Jilin	36.5	71.2	58.0	32.1	89.6	78.1	36.6	77.9	54.6
Liaoning	40.9	79.2	64.6	41.1	78.9	71.3	42.2	85.9	61.3
Ningxia	50.4	128.9	99.0	54.9	120.3	107.3	49.6	88.0	66.4
Qinghai	43.9	130.2	97.3	53.5	102.7	92.9	48.2	99.9	70.8
Shaanxi	49.3	100.6	81.0	45.8	105.7	93.8	44.2	89.9	64.2
Shandong	53.1	96.2	79.7	66.4	107.7	99.5	61.4	90.9	74.3
Shanghai	0.0	271.2	167.8	57.5	204.3	175.1	65.7	134.4	95.7
Shanxi	50.2	81.3	69.5	41.1	87.1	78.0	44.2	93.6	65.8
Sichuan	47.2	103.2	81.9	46.7	108.9	96.6	48.1	98.1	69.9
Tianjin	68.3	140.1	112.7	63.9	156.4	138.0	58.2	103.3	77.9
Tibet	0.0	105.2	65.1	0.0	104.0	83.3	0.0	108.8	47.6
Xinjiang	68.6	141.6	113.8	61.4	103.8	95.4	50.0	104.6	73.9
Yunnan	50.9	70.5	63.0	55.4	102.9	93.4	46.3	100.9	70.1
Zhejiang	61.9	87.5	77.7	58.7	129.4	115.3	60.6	97.0	76.5

Table A13. Income tax brackets, rates, and quick deductions.

Taxable Income (T, Thousand CNY)	Rate (%)	Quick Deduction (Thousand CNY)
$0 \leq T < 36$	3	0
$36 \leq T < 144$	10	2.52
$144 \leq T < 300$	20	16.92
$300 \leq T < 420$	25	31.92
$420 \leq T < 660$	30	52.92
$660 \leq T < 960$	35	85.92
$T \geq 960$	40	181.92

Data on environmental pollution taxes is available only as ranges for each province (Figure A1), with more population-dense provinces typically opting for higher tax rates across all pollutants. In each case, the average of the range for each province is used to calculate the applicable tax. Taxes are levied on plants' sulphur dioxide, nitrous oxide, particulate matter, and wastewater emissions. The first three are levied at rates ranging from CNY 1.2–10/kg; wastewater is taxed at CNY 1.4–10.5/m³. Emissions of pollutants per MWh generated vary by plant type (see Table A14).

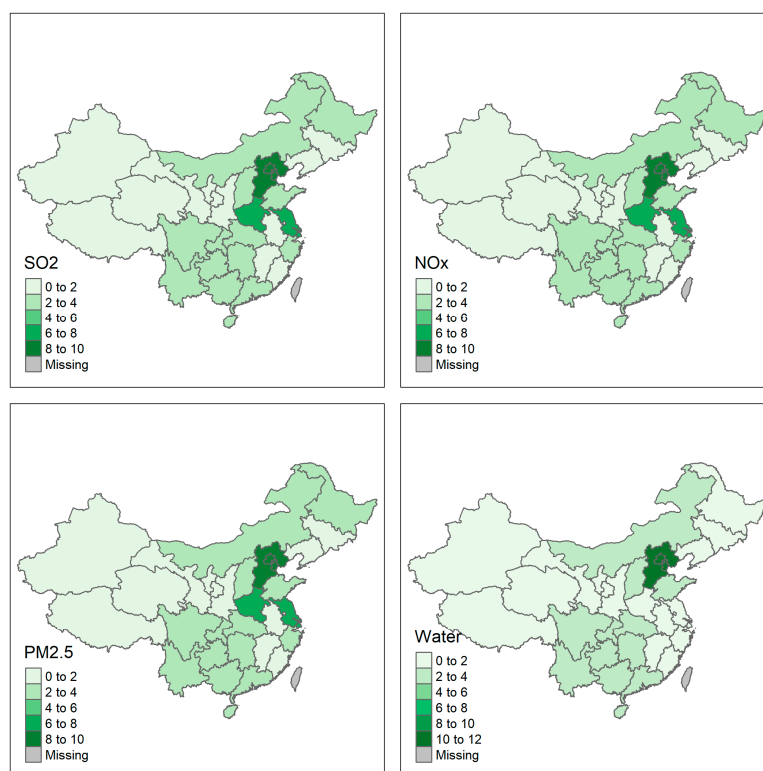


Figure A1. Environmental Pollution Tax rates for selected pollutants by province. Units: CNY/kg (CNY/m³ for wastewater).

Table A14. Coal plant local pollutant emissions by plant type.

Plant Type	SO _x (kg/MWh) [89]	NO _x (kg/MWh) [89]	PM2.5 (kg/MWh) [89]	Wastewater (m ³ /MWh) [94]
Subcritical	0.117	0.165	0.032	2.27 × 10 ⁻⁵
Supercritical	0.103	0.15	0.03	2.27 × 10 ⁻⁵
Ultra-supercritical	0.1	0.142	0.028	2.27 × 10 ⁻⁵

Further pollution taxes are levied on mining activities (and, in principle, transport activities, although these are assumed to be insignificant in this analysis and are not included). The relevant taxes and pollution rates per tonne of coal equivalent (tce; a standard measurement based on coal with 7000 kcal/kg calorific value) are detailed in Table A15.

Table A15. Coal mining pollutant tax and emissions rates [95,96].

Pollutant	Tax Rate (CNY/kg)	Emissions (kg/tce)
Coal gangue	0.005	175
Mine tailings	0.015	0.013
Coal ash	0.025	39.6
Wastewater [94]	1.4–10.5	0.3

Prospecting and exploration fees are levied on operational mines, based on the area that the mine covers: CNY 500/km²/year for the former, and CNY 1000/km²/year for the latter. Since the dataset used for this exercise contains very limited information on mine sizes, an average production density of 0.52 million tons (Mt)/km²/year is used as an approximate proxy [97]. Precision for this tax is relatively less important than for other taxes, since it represents a very small proportion of total revenues. This produces estimates of CNY 964.7/Mt in prospecting fees, and CNY 1929.4/Mt in exploration fees.

Mining royalties (of which 20% go to central government, 80% to provincial government) and resource taxes (100% provincial governments) are levied ad valorem on coal sales by value, which are derived from the amount of coal consumed by each plant from each province. Royalties range from 0.5–4% of sales; here an average figure of 1.8% of sales is used. Resource tax rates vary by province and are provided in Table A16 alongside average provincial coal and coal-fired electricity prices (weighted average of fixed (benchmark) and spot market tariffs), which are used in the calculation of VAT.

VAT (of which 75% goes to central government, 25% returned to the subnational jurisdictions in which it was generated) is levied at the rate r of 12%, cumulatively, on coal sales, transport, and electricity sales. As with other VAT systems, each buyer in the process pays the requisite VAT and reclaims it once the good in question is sold, such that total VAT paid should be 12% of the final sale price. Prices used in the data already include VAT; the formula for calculating VAT payable is found in Equation (A10). At each stage, VAT is calculated based on the price of the service or good (coal, transport, wholesale electricity), and the VAT already paid upstream is deducted. If VAT already paid exceeds VAT payable at that stage of the value chain, no VAT is paid at that stage.

$$\text{VAT} = p_{\text{VAT}} \times \frac{r}{1+r} \quad (\text{A10})$$

Table A16. Average coal [98] and electricity prices [99] (2019, incl. VAT), and resource tax rates [100], by province.

Province	Coal Price (CNY/ton)	Electricity Price (Benchmark) (CNY/MWh)	Electricity Price (Spot) (CNY/MWh)	% Electricity Sold on Spot Market	Weighted Average Electricity Price (CNY/MWh)	Resource Tax Rate (%)
Anhui	584.37	384.4	346	33.7%	371.5	2.0%
Beijing	473.11	368.2	353.3	24.0%	364.6	2.0%
Chongqing	591.97	396.4	394.6	23.9%	396.0	3.0%
Fujian	542.08	393.2	363.2	27.6%	384.9	2.0%
Gansu	468.87	297.8	190.6	22.8%	273.4	2.5%
Guangdong	571.98	453	412.8	29.2%	441.3	0.0%
Guangxi	688.14	420.7	306.6	36.2%	379.4	2.5%
Guizhou	492.4	351.5	323.6	30.0%	343.1	5.0%
Hainan	505.69	429.8	399.8	1.3%	429.4	0.0%
Hebei	473.11	368.2	353.3	24.0%	364.6	2.0%
Heilongjiang	522.7	374	362.6	15.3%	372.3	2.0%
Henan	527.87	377.9	359.4	30.8%	372.2	2.0%
Hubei	597.44	416.1	408.6	27.4%	414.0	2.0%
Hunan	633.34	450	436.5	24.8%	446.7	2.5%
Inner Mongolia	272.44	293.2	220.2	36.0%	266.9	9.0%
Jiangsu	541.3	391	360.5	49.6%	375.9	2.0%
Jiangxi	656.69	414.3	403.6	26.7%	411.4	2.0%
Jilin	540.57	373.1	250.9	24.0%	343.8	2.0%
Liaoning	540.29	375.3	360	34.9%	370.0	2.0%
Ningxia	359.74	259.5	248.4	30.5%	256.1	6.5%
Qinghai	528.74	324.7	224.7	49.0%	275.7	6.0%
Shaanxi	419.07	354.5	291.6	14.6%	345.3	6.0%
Shandong	559.98	394.9	381.1	25.3%	391.4	4.0%
Shanghai	528.7	415.5	385.5	9.7%	412.6	0.0%
Shanxi	352.17	332	310.8	43.7%	322.7	8.0%
Sichuan	589.21	401.2	298.2	22.9%	377.6	2.5%
Tianjin	491.24	365.5	306.4	13.2%	357.7	0.0%
Tibet	589.21	401.2	298.2	22.9%	377.6	0.0%
Xinjiang	253.89	260	170.2	16.7%	245.0	6.0%
Yunnan	479.79	335.8	181	57.7%	246.5	5.5%
Zhejiang	582.75	415.3	390.2	27.8%	408.3	0.0%

Only a handful of relevant subsidies can be calculated within the model. They are summarized in Table A17. The first is VAT rebates for coal mines and coalbed methane production; these are capped at a fixed level. It is assumed that they are claimed to the maximum amount as long as the total VAT liabilities generated by coal mines exceed the

subsidy cap. The general VAT rebate is applied first; if sufficient liabilities remain after that, the coalbed methane rebate is applied.

The price protection subsidy is calculated on the basis of the average difference between fixed benchmark price and spot prices for electricity by province in Table A16, multiplied by the proportion of coal-fired electricity sold. Environmental externality subsidies for coal plants are calculated on the basis of tce (converted from tonnes of coal based on the calorific content of each coal type).

Table A17. Estimated annual subsidies to the coal industry.

Subsidy	Type	Origin	Unit	Value	Source
VAT rebate (general)	Fiscal	Central	CNY bn	1.71	[73]
VAT rebate (coalbed methane)	Fiscal	Central	CNY bn	1.1	[73]
Fiscal support	Fiscal	Provincial	CNY bn	5.3	[101]
Research	Direct	Central	CNY bn	0.33	[73]
Coalbed methane production	Direct	Both	CNY bn	0.41	[73]
Transition Fund	Direct	Central	CNY bn	10.5	[35]
Rate subsidy—electricity	Rates	Central	CNY bn	146	[102]
Rate subsidy—rail	Rates	Central	CNY bn	1.9	[73]
Rate subsidy—rail	Rates	Provincial	CNY bn	7.2	[71]
Price protection—direct		Central	CNY/kWh	0.064	[72]
Price protection—spot markets		Central	CNY/kWh	0.13	[72]
Credit support		Central	CNY	35.7	[73]
Priority dispatch		Central	CNY	6.8	[71]
Environmental externalities		Central	CNY/tce	154	[72]
Total (estimated)					
Production		Both	CNY/ton	17.78	[70]
Generation		Both	CNY bn	120.8	[71]
Generation		Both	CNY bn	263	[72]
Generation—environmental		Both	CNY bn	119.3	[72]
Generation—externalities		Both	CNY bn	179	[72]
Generation—price protection		Both	CNY bn	183.3	[72]
Generation—crowding out renewables		Both	CNY bn	17.5	[72]

References

- ClimateWatch. *Historical GHG Emissions*; ClimateWatch: Washington, DC, USA, 2020.
- Shearer, C.; Myllyvirta, L. *China Dominates 2020 Coal Plant Development*; Global Energy Monitor and Centre for Research on Energy and Clean Air: San Francisco, CA, USA, 2021.
- World Steel Association. *World Crude Steel Production—Summary*; World Steel Association: Brussels, Belgium, 2020.
- Curry, K.C.; van Oss, H.G. *2017 Minerals Yearbook: Cement*; United States Geological Survey: Reston, VA, USA, 2020.
- Myers, S.L. China's pledge to be carbon neutral by 2060: What it means. *The New York Times*, 2020.
- Myllyvirta, L. *China's Five-Year Plan: Baby Steps towards Carbon Neutrality*; Centre for Research on Energy and Clean Air, 2021.
- He, J.; Xie, Z.; Li, Z.; Zhang, X.; Chang, S.; Chen, S.; Dong, W.; Guo, S.; Gu, A.; Ou, X.; et al. Comprehensive Report on China's Long-Term Low-Carbon Development Strategy and Pathways. *Chin. J. Popul. Resour. Environ.* **2021**, *18*, 263–295. [CrossRef]
- Cui, R.Y.; Hultman, N.; Edwards, M.R.; He, L.; Sen, A.; Surana, K.; McJeon, H.; Iyer, G.; Patel, P.; Yu, S.; et al. Quantifying operational lifetimes for coal power plants under the Paris goals. *Nat. Commun.* **2019**, *10*, 4759. [CrossRef] [PubMed]
- Herve-Mignucci, M.; Wang, X.; Nelson, D.; Varadarajan, U. *Slowing the Growth of Coal Power in China: The Role of Finance in State-Owned Enterprises*; Climate Policy Initiative: San Francisco, CA, USA, 2015.
- Gray, M.; Sundaresan, S. *Political Decisions, Economic Realities: The underlying Operating Cashflows of Coal Power during COVID-19*; Carbon Tracker Initiative: London, UK, 2020.
- Bodnar, P.; Gray, M.; Grbusic, T.; Herz, S.; Lonsdale, A.; Mardell, S.; Ott, C.; Sundaresan, S.; Varadarajan, U. *How to Retire Early: Making Accelerated Coal Phaseout Feasible and Just*; Rock Mountain Institute: Boulder, CO, USA, 2020.
- Yuan, J.; Zhang, W.; Zhang, K.; Meng, Z.; Zhu, Y.; Qiu, Y.; Wu, R.; Zhang, C. *The Choice for China's Power Sector Strategic Pathway in the Post-Pandemic Era: Coal Power or New Power Infrastructure?* North China Electric Power University: Beijing, China, 2020.
- Cui, R.; Hultman, N.; Jiang, K.; McJeon, H.; Yu, S.; Cui, D.; Edwards, M.; Sen, A.; Song, K.; Bowman, C.; et al. *A High Ambition Coal Phaseout in China: Feasible Strategies through a Comprehensive Plant-by-Plant Assessment*; Center for Global Sustainability, University of Maryland and Energy Research Institute: College Park, MD, USA, 2020.

14. Spencer, T.; Berghmans, N.; Sartor, O. *Coal Transitions in China's Power Sector: A Plant-Level Assessment of Stranded Assets and Retirement Pathways*; Institut du Développement Durable et des Relations Internationales: Paris, France, 2017.
15. Jakob, M.; Steckel, J.C.; Jotzo, F.; Sovacool, B.K.; Cornelisen, L.; Chandra, R.; Edenhofer, O.; Holden, C.; Löschel, A.; Nace, T.; et al. The future of coal in a carbon-constrained climate. *Nat. Clim. Chang.* **2020**, *10*, 704–707. [[CrossRef](#)]
16. Caldecott, B.; Bouveret, G.; Dericks, G.; Kruitwagen, L.; Tulloch, D.; Liao, X. *Managing the Political Economy Frictions of Closing Coal in China*; Discussion Paper; Smith School of Enterprise and the Environment, University: Oxford, UK, 2017.
17. Pai, S.; Emmerling, J.; Drouet, L.; Zerriffi, H.; Jewell, J. Meeting well-below 2 °C target would increase energy sector jobs globally. *One Earth* **2021**, *4*, 1026–1036. [[CrossRef](#)]
18. Cui, R.; Hultman, N.; Cui, D.; McJeon, H.; Yu, S.; Edwards, M.; Sen, A.; Song, K.; Bowman, C.; Clarke, L.; et al. A plant-by-plant strategy for high-ambition coal power phaseout in China. *Nat. Commun.* **2021**, *12*, 1–10. [[CrossRef](#)]
19. Diluiso, F.; Walk, P.; Manych, N.; Cerutti, N.; Chipiga, V.; Workman, A.; Ayas, C.; Cui, R.Y.; Cui, D.; Song, K.; et al. Coal transitions—part 1: A systematic map and review of case study learnings from regional, national, and local coal phase-out experiences. *Environ. Res. Lett.* **2021**, *16*, 113003. [[CrossRef](#)]
20. Department for Business Energy & Industrial Strategy. *Historical Coal Data: Coal Production, Availability and Consumption*; Department for Business Energy & Industrial Strategy: London, UK, 2020.
21. Oei, P.-Y.; Hermann, H.; Herpich, P.; Holtemöller, O.; Lünenbürger, B.; Schult, C. Coal phase-out in Germany—Implications and policies for affected regions. *Energy* **2020**, *196*, 117004. [[CrossRef](#)]
22. Alves Dias, P.; Kanellopoulos, K.; Medarac, H.; Kapetaki, Z.; Miranda-Barbosa, E.; Shortall, R.; Czako, V.; Telsnig, T.; Vazquez-Hernandez, C.; Lacal Arántegui, R. *EU Coal Regions: Opportunities and Challenges Ahead*; European Commission, Joint Research Centre: Petten, The Netherlands, 2018.
23. Galgóczi, B. *Towards a just Transition: Coal, Cars and the World of Work*; European Trade Union Institute: Brussels, Belgium, 2019.
24. U.S. Bureau of Labor Statistics. *All Employees, Coal Mining [CES1021210001]*; Federal Reserve Bank of St. Louis, Ed.; U.S. Bureau of Labor Statistics: St. Louis, MO, USA, 2021.
25. National Association of State Energy Officials; Energy Futures Initiative. *2020 U.S. Energy and Employment Report*; National Association of State Energy Officials: Arlington, VA, USA; Energy Futures Initiative: Washington, DC, USA, 2020.
26. Mealy, P.; Teytelboym, A. Economic Complexity and the Green Economy. *Research Policy* **2020**. [[CrossRef](#)]
27. Oei, P.-Y.; Brauers, H.; Herpich, P. Lessons from Germany's hard coal mining phase-out: Policies and transition from 1950 to 2018. *Clim. Policy* **2020**, *20*, 963–979. [[CrossRef](#)]
28. Andrews-Speed, P.; Ma, G.; Shao, B.; Liao, C. Economic responses to the closure of small-scale coal mines in Chongqing, China. *Resour. Policy* **2005**, *30*, 39–54. [[CrossRef](#)]
29. Mayer, A. The Fiscal Impacts of Energy: Perspectives from local governments in the Mountain West, USA. *Energy Policy* **2018**, *122*, 186–193. [[CrossRef](#)]
30. Sandbag. *Solving the Coal Puzzle: Lessons from Four Years of Coal Phase-Out Policy in Europe*; Europe Beyond Coal: Berlin, Germany, 2019.
31. Goodman, P.G.; Rich, D.Q.; Zeka, A.; Clancy, L.; Dockery, D.W. Effect of Air Pollution Controls on Black Smoke and Sulfur Dioxide Concentrations across Ireland. *J. Air Waste Manag. Assoc.* **2009**, *59*, 207–213. [[CrossRef](#)] [[PubMed](#)]
32. Office, I.L. A just transition for all: Can the past inform the future? *Int. J. Labour Res.* **2014**, *6*, 173.
33. Skorkovsky, J.; Kotesovec, F. Mortality in Northwestern Bohemia in Periods of High and Low Air Pollution. In *Environmental Health in Central and Eastern Europe*; Springer: New York, NY, USA, 2006; pp. 1–11.
34. Bridle, R.; Kitson, L.; Duan, H.; Sanchez, L.; Merrill, T. *At the Crossroads: Balancing the Financial and Social Costs of Coal Transition in China*; International Institute for Sustainable Development (IISD): Winnipeg, MB, Canada, 2017.
35. Gençsü, I.; Whitley, S.; Roberts, L.; Beaton, C.; Chen, H.; Doukas, A.; Geddes, A.; Gerasimchuk, I.; Sanchez, L.; Suharsono, A. *G20 Coal Subsidies: Tracking Government Support to a Fading Industry*; Overseas Development Institute: London, UK, 2019.
36. Sheldon, C.G.; Strongman, J.; Weber-Fahr, M. *It's Not Over When It's Over: Mine Closure Around the World*; World Bank: Washington, DC, USA; International Finance Corporation: Washington, DC, USA, 2002.
37. Rui, H. Development, Transition and Globalization in China's Coal Industry. *Dev. Chang.* **2005**, *36*, 691–710. [[CrossRef](#)]
38. Song, Z.; Kuenzer, C. Coal fires in China over the last decade: A comprehensive review. *Int. J. Coal Geol.* **2014**, *133*, 72–99. [[CrossRef](#)]
39. People's Republic of China. *Notice Regarding Completing 2016 Work on Coal Consumption Reduction and Substitution*; National Development and Reform Commission, People's Republic of China: Beijing, China, 2016.
40. Cao, X. Policy and regulatory responses to coalmine closure and coal resources consolidation for sustainability in Shanxi, China. *J. Clean. Prod.* **2017**, *145*, 199–208. [[CrossRef](#)]
41. Hao, X.; Song, M.; Feng, Y.; Zhang, W. De-Capacity Policy Effect on China's Coal Industry. *Energies* **2019**, *12*, 2331. [[CrossRef](#)]
42. Liu, Z. China caps coal output goal at 4.1b tons. *China Daily*, 2021.
43. Myllyvirta, L.; Shen, X. *Burning Money: How China Could Squander Over One Trillion Yuan on Unneeded Coal-Fired Capacity*; Greenpeace: Hong Kong, China, 2016.
44. State Council of the People's Republic of China. *国务院关于印发大气污染防治行动计划的通知 [Action Plan for Air Pollution Prevention and Control]*; State Council of the People's Republic of China: Beijing, China, 2013.

45. Tang, L.; Qu, J.; Mi, Z.; Bo, X.; Chang, X.; Anadon, L.D.; Wang, S.; Xue, X.; Li, S.; Wang, X.; et al. Substantial emission reductions from Chinese power plants after the introduction of ultra-low emissions standards. *Nat. Energy* **2019**, *4*, 929–938. [CrossRef]
46. Zhang, P.; Zhang, L.; Tian, X.; Hao, Y.; Wang, C. Urban energy transition in China: Insights from trends, socioeconomic drivers, and environmental impacts of Beijing. *Energy Policy* **2018**, *117*, 173–183. [CrossRef]
47. Tan, H.; Thurbon, E.; Kim, S.-Y.; Mathews, J.A. Overcoming incumbent resistance to the clean energy shift: How local governments act as change agents in coal power station closures in China. *Energy Policy* **2021**, *149*, 112058. [CrossRef]
48. Lo, A.Y. Carbon trading in a socialist market economy: Can China make a difference? *Ecol. Econ.* **2013**, *87*, 72–74. [CrossRef]
49. Zeng, M.; Li, J.; Tian, L.; Liu, Y.; Wang, L. *Review of Concentrating Solar Thermal Power in China: Status Quo, Problems and Countermeasures*; AIP Publishing: Melville, NY, USA, 2018.
50. Zhang, W.; Li, J.; Li, G.; Guo, S. Emission reduction effect and carbon market efficiency of carbon emissions trading policy in China. *Energy* **2020**, *196*, 117117. [CrossRef]
51. Zhang, Y.; Li, S.; Luo, T.; Gao, J. The effect of emission trading policy on carbon emission reduction: Evidence from an integrated study of pilot regions in China. *J. Clean. Prod.* **2020**, *265*, 121843. [CrossRef]
52. Aihua, L.; Miglietta, P.P.; Toma, P. Did carbon emission trading system reduce emissions in China? An integrated approach to support policy modeling and implementation. *Energy Syst.* **2021**. [CrossRef]
53. He, G.; Lin, J.; Zhang, Y.; Zhang, W.; Larangeira, G.; Zhang, C.; Peng, W.; Liu, M.; Yang, F. Enabling a rapid and just transition away from coal in China. *One Earth* **2020**, *3*, 187–194. [CrossRef] [PubMed]
54. International Energy Agency. *World Energy Outlook 2021*; International Energy Agency: Paris, France, 2020.
55. Murtagh, D.; Kan, K.; Murphy, C.; Mayger, J. China’s Coal Industry Fights for Survival in a Greener World. *Bloomberg News*, 2020.
56. Ministry of Human Resources and Social Security. *Press Conference on Employment and Social Security of the State Council Information Office*; People’s Republic of China: Beijing, China, 2016.
57. People’s Republic of China. *Notice of the Five Departments on Doing a Good Job in the Resettlement of Employees in Resolving the Overcapacity of the Steel and Coal Industry in 2017*; People’s Republic of China: Beijing, China, 2017.
58. Global Energy Monitor. *Global Coal Mine Tracker*; Global Energy Monitor: San Francisco, CA, USA, 2021.
59. Energy Information Administration. As U.S. coal-fired capacity and utilization decline, operators consider seasonal operation. In *Today in Energy*; U.S. Energy Information Administration: Washington, DC, USA, 2020.
60. Yuan, J.; Zhang, W.; Guo, X.; Ai, Y.; Zheng, R. Deepening Supply-Side Structural Reforms in Coal Power with a Power Market. *Emerg. Mark. Financ. Trade* **2021**, *57*, 773–785. [CrossRef]
61. Institute for Labor Studies. *Study on Green Employment in China*; Institute for Labor Studies: Manila, Philippines, 2010.
62. CEIC China No of Employee: Coal Mining & Dressing. Available online: <https://www.ceicdata.com/en/china/no-of-employee-by-industry-monthly/no-of-employee-coal-mining-dressing> (accessed on 7 February 2021).
63. UIBE; Chinese Academy of Sciences. *Research on Employment Issues Associated with Coal Industry Transition*; Institute of Global Value Chains, University of International Business and Economics: Beijing, China; Institute of Urban Development and Environment, Chinese Academy of Sciences: Beijing, China, 2019.
64. China Statistics Press China Statistical Yearbook 2020. Available online: www.stats.gov.cn/tjsj/ndsj/2020/indexeh.htm (accessed on 2 November 2021).
65. Pan, H.; Zheng, Y. Chapter 8—The development and status quo of freight transport in China. In *Urban Freight Transportation Systems*; Elbert, R., Friedrich, C., Boltze, M., Pfohl, H.-C., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 135–161.
66. National Bureau of Statistics of China. *Average Annual Wage of Employed Persons in Different Positions in Enterprises above Designated Size in 2019*; National Bureau of Statistics of China: Beijing, China, 2020.
67. PWC China. People’s Republic of: Individual—Taxes on Personal Income. Available online: <https://taxsummaries.pwc.com/peoples-republic-of-china/individual/taxes-on-personal-income> (accessed on 8 March 2021).
68. PWC China. People’s Republic of: Individual—Deductions. Available online: <https://taxsummaries.pwc.com/peoples-republic-of-china/individual/deductions> (accessed on 8 March 2021).
69. MS Advisory Explaining China’s Social Security System and Housing Fund Scheme for Employers. Available online: <https://www.msadvisory.com/news-updates/august-2020/china-social-security-system-and-housing-fund> (accessed on 8 March 2021).
70. Xiang, H.; Kuang, Y. Who benefits from China’s coal subsidy policies? A computable partial equilibrium analysis. *Resour. Energy Econ.* **2020**, *59*, 101124. [CrossRef]
71. Denjean, B.; Su, T.; Attwood, C.; Bridle, R.; Duan, H.; Gerasimchuk, I. *Subsidies to Coal Power Generation in China*; International Institute for Sustainable Development: Winnipeg, MB, Canada, 2016.
72. Yuan, J.; Guo, X.; Zhang, W.; Chen, S.; Ai, Y.; Zhao, C. Deregulation of power generation planning and elimination of coal power subsidy in China. *Util. Policy* **2019**, *57*, 1–15. [CrossRef]
73. Xue, H.; Wang, H.; Bridle, R.; Gerasimchuk, I.; Attwood, C. *Subsidies to Coal Production in China*; International Institute for Sustainable Development: Winnipeg, MB, Canada, 2015.
74. Coady, D.; Parry, I.; Sears, L.; Shang, B. How Large Are Global Fossil Fuel Subsidies? *World Dev.* **2017**, *91*, 11–27. [CrossRef]
75. Zhao, X.; Cai, Q.; Ma, C.; Hu, Y.; Luo, K.; Li, W. Economic evaluation of environmental externalities in China’s coal-fired power generation. *Energy Policy* **2017**, *102*, 307–317. [CrossRef]
76. Mealy, P. Know What? New Lenses on Productive Knowledge Shed Light on Long Run Development, Structural Change, Job Switching and the Transition to the Green Economy. Ph.D. Thesis, University of Oxford, Oxford, UK, 2018.

77. Statista Revenue of Value-Added Tax (VAT) in China from 2011 to 2020. Available online: <https://www.statista.com/statistics/455231/china-vat-revenue/> (accessed on 10 March 2021).
78. Gao, Y.; Ma, S.; Wang, T.; Wang, T.; Gong, Y.; Peng, F.; Tsunekawa, A. Assessing the wind energy potential of China in considering its variability/intermittency. *Energy Convers. Manag.* **2020**, *226*, 113580. [[CrossRef](#)]
79. Energy Research Institute; China National Renewable Energy Centre. *China Renewable Energy Outlook 2019*; Energy Research Institute of Academy of Macroeconomic Research: Beijing, China; NDRC: Beijing, China, 2019.
80. Global Energy Monitor; CREA. *A New Coal Boom in China: Country Accelerates New Coal Plant Permitting and Proposals*; Global Energy Monitor and Centre for Research on Energy and Clean Air: San Francisco, CA, USA, 2020.
81. Li, W.; Yang, M.; Long, R.; He, Z.; Zhang, L.; Chen, F. Assessment of greenhouse gasses and air pollutant emissions embodied in cross-province electricity trade in China. *Resour. Conserv. Recycl.* **2021**, *171*, 105623. [[CrossRef](#)]
82. New York Times. ‘The Whole City Was Dark’: China Rations Electricity for Millions. *The New York Times*, 2020.
83. Reuters. Column: China’s widening electricity crisis caused by coal shortage. *Reuters*, 2021.
84. Slater, H.; de Boer, D.; Guoqiang, Q.; Shu, W. *2020 China Carbon Pricing Survey*; China Carbon Forum: Beijing, China, 2020.
85. He, G.; Lin, J.; Sifuentes, F.; Liu, X.; Abhyankar, N.; Phadke, A. Rapid cost decrease of renewables and storage accelerates the decarbonization of China’s power system. *Nat. Commun.* **2020**, *11*, 1–9. [[CrossRef](#)]
86. Pfeiffer, A.; Hepburn, C.; Vogt-Schilb, A.; Caldecott, B. Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement. *Environ. Res. Lett.* **2018**, *13*, 054019. [[CrossRef](#)]
87. Tong, D.; Zhang, Q.; Zheng, Y.; Caldeira, K.; Shearer, C.; Hong, C.; Qin, Y.; Davis, S.J. Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. *Nature* **2019**, *572*, 373. [[CrossRef](#)]
88. Minchener, A. *Another Innovative Idea from the Waigaoqiao No.3 Coal Power Plant Engineers*; International Centre for Sustainable Carbon: London, UK, 2019.
89. Myllyvirta, L. How much do ultra-supercritical coal plants really reduce air pollution? *Renew Economy*, 2017.
90. Li, N.; Chen, W.; Zhang, Q. Development of China TIMES-30P model and its application to model China’s provincial low carbon (Pre-proof). *Energy Econ.* **2020**, *92*, 104955. [[CrossRef](#)]
91. Zhang, B.; Kang, Z. *China Railway Freight Price Reform Analysis: Based on Price Elasticity of Freight Demand*; IEIS2019; Li, M., Dresner, M., Zhang, R., Hua, G., Shang, X., Eds.; Springer: Singapore, 2020; pp. 573–585.
92. Rioux, B.; Galkin, P.; Murphy, F.; Pierru, A. Economic impacts of debottlenecking congestion in the Chinese coal supply chain. *Energy Econ.* **2016**, *60*, 387–399. [[CrossRef](#)]
93. People’s Republic of China. *China Statistical Yearbook 2019*; People’s Republic of China: Beijing, China, 2019.
94. Zhu, Y.; Jiang, S.; Zhao, Y.; Li, H.; He, G.; Li, L. Life-cycle-based water footprint assessment of coal-fired power generation in China. *J. Clean. Prod.* **2020**, *254*, 120098. [[CrossRef](#)]
95. Xu, S. The situation of generation, treatment and supervision of common industrial solid wastes in China. *IOP Conf. Ser. Earth Environ. Sci.* **2018**, *113*, 012154. [[CrossRef](#)]
96. Zhang, Y.; Ling, T.-C. Reactivity activation of waste coal gangue and its impact on the properties of cement-based materials—A review. *Constr. Build. Mater.* **2020**, *234*, 117424. [[CrossRef](#)]
97. Mining Technology. *The Ten Biggest Coal Mines in the World*; Verdict Media Limited: London, UK, 2020.
98. Guoneng Hutong Inner Mongolia Network Technology Co Ltd. National and provincial electricity coal price index 2019. In *Inner Mongolia Coal Exchange Center*; Guoneng Hutong Inner Mongolia Network Technology Co Ltd., 2019.
99. Cheng, S.; Li, K. *Electrical Equipment Securities Research Report—Industry Review*; Bank of China International Securities Co Ltd.: Hong Kong, China, 2020.
100. Qin, P.; Chen, P.; Zhang, X.-B.; Xie, L. Coal taxation reform in China and its distributional effects on residential consumers. *Energy Policy* **2020**, *139*, 111366. [[CrossRef](#)]
101. Gençsü, I.; Chen, H. *G20 Coal Subsidies: Tracking Government Support to a Fading Industry—China Background Paper*; Overseas Development Institute: London, UK, 2019.
102. International Energy Agency. Energy Subsidies: Tracking the Impact of Fossil-Fuel Subsidies. Available online: <https://www.iea.org/topics/energy-subsidies> (accessed on 9 March 2021).

A4. Additional work and related publications

The three papers submitted for consideration as part of this dissertation have emerged from, and stimulated, a wider body of work. In some cases, the additional pieces of research shaped the methodological approach and data choices in the papers. In others, the discoveries or frameworks developed in the papers motivated further work.

Early in the research design process, I convened a day-long conference on the use of asset-level data for use in decision-making related to climate and environmental risks. The conference, summarised in Clark and McNally (2020), took place while I was still aiming to make use of agent-based modelling methods in simulating the transmission of stranded asset risks across economies featuring SOEs. While the methodological approaches ultimately chosen for Papers 1 and 2 precluded the use of asset-level or geospatial data for this purpose, asset-level datasets with geospatial coordinates became a core component of Paper 3 once a key dataset on coal mining became available. I was able to apply some of the technical and subject-specific knowledge and techniques discussed from the conference and resulting dialogues to the development of the asset-level coal industry model used in the third paper.

In developing the research design for the first paper, I worked with the Center on Global Energy Policy (CGEP) at the Columbia University School of International and Public Affairs (SIPA) to host and report on a researcher-practitioner dialogue exploring the role of SOEs in the low-carbon transition. Subsequently planned workshops in India were curtailed by travel restrictions in 2020 and 2021, but the workshop report findings were published (Benoit & Clark, 2020) and influenced the development of Paper 1's methodology. After the paper's publication a second workshop focusing specifically on SPCs was convened by Agora Energiewende in Berlin, featuring representation from all six of the countries examined in the paper. A third workshop, looking more closely at the role of SOEs in China's transition, took place in February 2023 at the University of California San Diego.

The initial collaboration with CGEP progressed to the development of a database of GHG emissions associated with SOEs across multiple sectors, the most comprehensive of its kind to date and a useful exercise in validating the empirical relevance of the research questions explored in this

dissertation. The findings are summarised in Clark and Benoit (2022) and highlight the severity of data limitations in tracking SOE's emissions profiles and obtaining robust information on their activities. Even with incomplete reported emissions data, the publication accompanying the completion of the database concludes that SOEs account for at least 7.49 GtCO_{2e} in annual direct emissions. Including estimated emissions from non-reporting entities raised the total to 8.89 GtCO_{2e}.

The initial research for Papers 2 and 3 both involved a detailed review of the literature on stranded assets, particularly evidence concerning the consequences of asset stranding beyond the financial markets, and by extension on labour markets and fiscal revenue from disrupted industries. The review also examined the political economy dynamics determining how losses on stranded assets are allocated, and how the credibility of policy measures for managing stranding risks and materialised costs interacts with entrenched interest groups. This work, along with a review of the role of COVID-19 related recovery stimulus measures in reducing or increasing governments' exposure to asset stranding risks, contributed to a publication in the Annual Review of Environment and Resources (Caldecott, Clark, Koskelo, Mulholland, & Hickey, 2021),

Some of the research conducted for this dissertation was applied to a joint policy research project with a multidisciplinary group of research students associated with several European universities (Europaeum Scholars). The project, 'Lost in Transition? Charting a Course for Europe's Automotive Industry Workers' consisted of a detailed proposal for a 'just transition' mechanism for automotive sector suppliers in Europe (Renard et al., 2021). The investigation process featured workshops with actors including established academics in the field, environmental and labour law experts, and trade union representatives. The literature and policy documents reviewed for this work were informed by the research conducted as part of this dissertation.

Three other policy research publications also extended and applied parts of the material developed in the thesis papers. They investigated how governments can complement efforts to transition away from fossil fuels by promoting innovation in clean technologies. The first of these was a case study on the role of German and Chinese industrial policy in the development of the solar photovoltaic

industry, and the rationale behind it. An abridged version of the study was incorporated into a review of the role of state innovation policy in promoting technological change in the energy system, and the full case study was published as an Appendix (Grubb et al., 2021). The second included a policy-focused case study of the material in Paper 3, which appears in full within the body of the report (Barbrook-Johnson et al., 2023). Both of these were published under the Economics of Energy Innovation and Systems Transition (EEIST) project. The third was an investigation into the use of contracts-for-difference as a market-based innovation mechanism for decarbonising international shipping, drawing on its use in the power sector to design a version adapted to the maritime context (Clark et al., 2021).

The literature review and methodology development in Paper 3 also benefited directly from a wide-ranging project on the challenges and opportunities associated with phasing out coal in China commissioned by the UK's Foreign Commonwealth and Development Office. The project, delivered in collaboration with Dr David Robinson (Oxford Institute for Energy Studies), Dr Conor Hickey (Oxford University) and several researchers at Tsinghua University, was part of the China Energy and Low-Carbon Economy Programme (CELCEP) under the UK Government's Prosperity Fund. While the policy report that inspired the paper was not published because the project funding was withdrawn prior to completion, it laid the analytical groundwork for the analysis ultimately conducted in Paper 3. Tsinghua University researchers were able to conduct interviews with otherwise unreachable Chinese stakeholders across industry, government, and academia that helped to shape the research design. The data and modelling underlying the finished paper was then further developed and refined during a three-month fellowship with the International Institute for Applied Systems Analysis (IIASA) in 2021, culminating in a working paper that formed the basis for the peer-reviewed version of Paper 3. The working paper is stored in IIASA's research depository.

The research conducted in the three papers and ancillary publications, particularly the material most relevant to China, culminated in a wide-ranging policy-focused paper targeting high-level policymakers in the Chinese government. The paper lays out a detailed framework for sustainable economic and ecological development in China consistent with its carbon neutrality pledges, and identifies a set of actions and policy initiatives across every major economic sector required in order to

achieve the pledges while laying the foundation for long-term growth. A confidential version of the paper was submitted directly to the State Council of the Chinese government in December 2022. An abridged version was also published in collaboration with the London School of Economics, Columbia University, Tsinghua University, the Chinese Academy of Sciences, and the Capital University of Economics and Business in 2023 (Zhu et al., 2023). A third, abridged, version will be submitted for publication in a peer-reviewed journal later in 2023.

Finally, a collaboration with Boston University yielded a working paper examining the early retirement options for coal-fired power plants owned and financed by Chinese SOEs (both in the form of SPCs and development banks) outside China's borders (Clark, Jindal, Shrimali, Springer, & Rafaty, 2023). This explores one of the possible extensions of Paper 2 into a new context – namely, one where the economic benefits of infrastructure investments accrue to the host country, not the country where the investment originated. This will also be submitted for publication in a peer-reviewed journal later in 2023.

Appendix References

- Barbrook-Johnson, P., Pasqualino, R., Senra de Moura, F., Nijse, F., Vercoulen, P., Clark, A., . . . Lenton, T. M. (2023). *New economic models of energy innovation and transition: Addressing new questions and providing better answers*. Retrieved from <https://eeist.co.uk/download/1132/>
- Benoit, P., & Clark, A. (2020). *Engaging state-owned enterprises in climate action: Workshop report*. Retrieved from <https://www.energypolicy.columbia.edu/sites/default/files/file-uploads/SOE%20workshop%20summary,%20designed%20v3,%2011.04.20.pdf>
- Caldecott, B., Clark, A., Koskelo, K., Mulholland, E., & Hickey, C. (2021). Stranded assets: environmental drivers, societal challenges, and supervisory responses. *Annual Review of Environment and Resources*, 46, 417-447.
- Clark, A., & Benoit, P. (2022). *Greenhouse gas emissions from state-owned enterprises: A preliminary inventory*. Retrieved from https://www.energypolicy.columbia.edu/sites/default/files/file-uploads/SOE_Emissions-CGEP_Report_020322.pdf
- Clark, A., Ives, M., Fay, B., Lambe, R., Schiele, J., Larsson, L., . . . Hepburn, C. (2021). *Zero-Emissions Shipping: Contracts-for-difference as incentives for the decarbonisation of international shipping*. Retrieved from <https://www.smithschool.ox.ac.uk/publications/reports/zero-emissions-shipping.pdf>
- Clark, A., Jindal, A., Shrimali, G., Springer, C. H., & Rafaty, R. (2023). *Capitalizing on coal: early retirement options for China-financed coal plants in Southeast Asia and beyond*. Retrieved from https://www.bu.edu/gdp/files/2023/03/GCI_WP_030_CLARK_FIN.pdf
- Clark, A., & McNally, C. (2020). *Asset-Level Data Annual Meeting Event Report*. Retrieved from https://www.cgfi.ac.uk/wp-content/uploads/2021/07/Asset-Level-Data-Annual-Meeting-Report_Final.pdf
- Grubb, M., Drummond, P., Mercure, J.-F., Hepburn, C., Barbrook-Johnson, P., Ferraz, J. C., . . . Zhang, X. (2021). *The New Economics of Innovation and Transition: Evaluating Opportunities and Risks*. Retrieved from <https://eeist.co.uk/download/557/>
- Renard, N., Lovotti, C., Vihma, P., Leitão Amaro, A., Ørskov, F. F., Hill, J., . . . Clark, A. (2021). *Lost in Transition? Charting a Course for Europe's Automotive Industry Workers*. Retrieved from <https://45n1ej27ymq723ofrn2vh7nc-wpengine.netdna-ssl.com/wp-content/uploads/2021/10/ASTA-Supporting-Document.pdf>

Zhu, M., Stern, N., Stiglitz, J. E., Liu, S., Zhang, Y., Li, J., . . . Peng, D. (2023). *Embracing the new paradigm of green development: China Carbon Neutrality Policy Framework research report*. Retrieved from <https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2023/02/Embracing-the-New-Paradigm-of-Green-Development-in-China.pdf>