Technical Pathways to and Economic Issues with Decarbonizing Electricity Systems[1][2]

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[1]Based on joint work with M. Arbabzadeh, J. Barrera-Santana, L. Boffino, A.J. Conejo, P. Denholm, R. Hunter-Rinderle, J.X. Johnson, G.A. Keoleian, Y. Liu, C. Luo, G. Oggioni, and K. Yagi.

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Electricity-System Decarbonization

Challenges and Opportunities

- Electricity production is a major carbon source in many countries
- Technical solutions to decarbonize (perhaps partially) electricity production exist today
- Other carbon-intensive sectors (*e.g.*, transportation and heat) can be electrified
- Electricity-system planning and operation become more complex and are sensitive to technology development
- Policy, legal, or regulatory changes will be needed

Goals for the Next Few Minutes

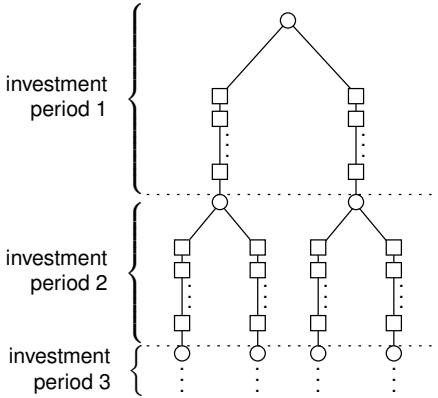
- Summarize a body of work that examines some of these challenges and questions
- Capacity-planning with decarbonization goals/targets: [Liu et al., 2018b, Liu et al., 2018a]
- Technical pathways to decarbonization: [Liu et al., 2018b, Boffino et al., 2019, Arbabzadeh et al., 2019, Barrera-Santana and Sioshansi, 2022]
- Technology development and decarbonization: [Boffino et al., 2019, Arbabzadeh et al., 2019, Yagi et al., 2019, Yagi et al., 2021]
- Decarbonization policy: [Liu et al., 2021, Yagi and Sioshansi, 2021]

Key Findings

- Technologies that are available today can achieve fairly aggressive decarbonization targets
- Getting the final 10%–20% of carbon out of electricity production is prohibitively expensive with today's technologies
- Long-duration/seasonal energy storage is a key challenge to full decarbonization
- Standard policy instruments to achieve decarbonization can have mixed effects, depending upon market assumptions and policy goals

Planning Challenges

- Technology options (*e.g.*, renewables) introduce supply uncertainty and variability, increase flexibility needs
- Significant strategic uncertainty (*e.g.*, fuel and technology costs, stranded investments, technology development, policy choices)
- Planning decisions are lumpy, long-lived, and high-cost, with long lead times
- Translation: plan investments with uncertainty about their prudence decades into the future, which depends on detailed operating decisions
- Only hope is clever (*e.g.*, multi-scale) modeling with decomposition



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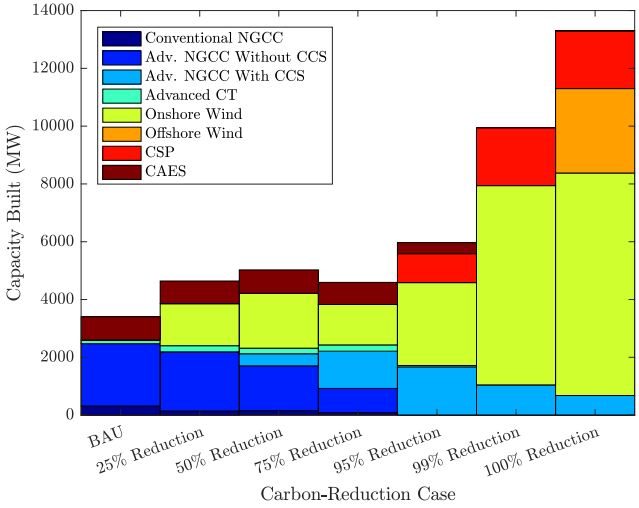
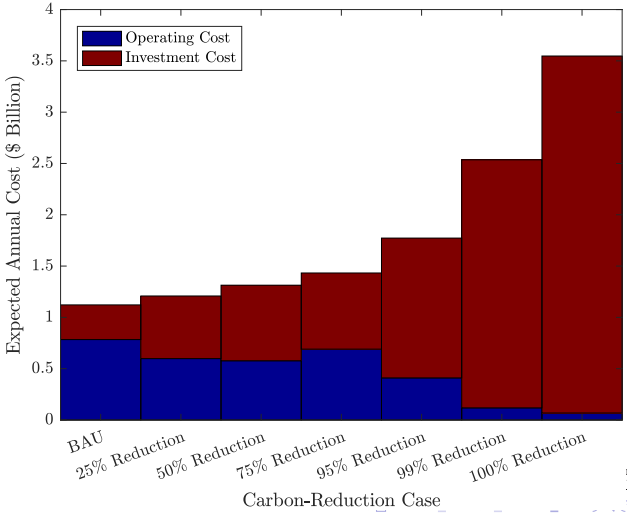
Illustrative Technology Pathway



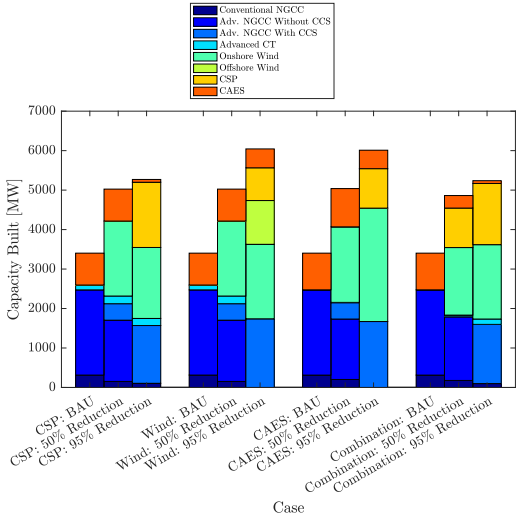
- Mild carbon reductions through renewable energy that is supplemented with short-duration energy storage and natural-gas-fired generation
- Cannot rely upon natural gas with more stringent carbon constraints, which requires significant capacity overbuild

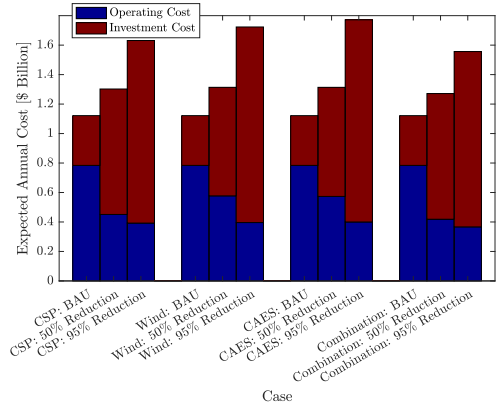
Decarbonization Cost

- Small but manageable cost increases for mild carbon reductions
- Capacity overbuild with more stringent carbon constraints is very costly
- Carbon reductions of $\approx$ 85% relative to business as usual are socially optimal with today's technologies and cost-of-carbon estimates



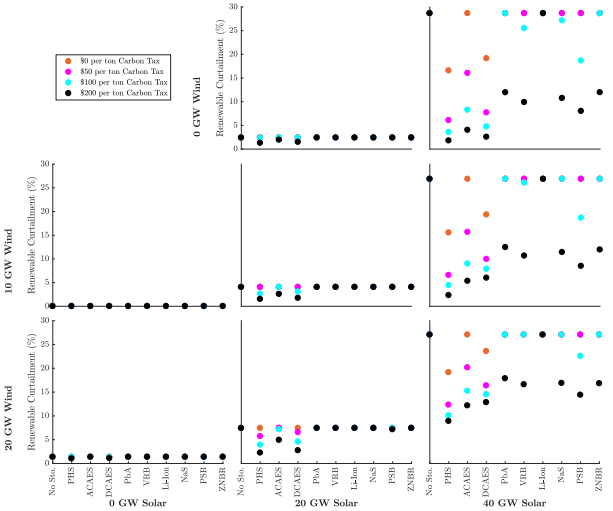
Technology Improvement





- $\approx$ 95% carbon reductions can become socially optimal

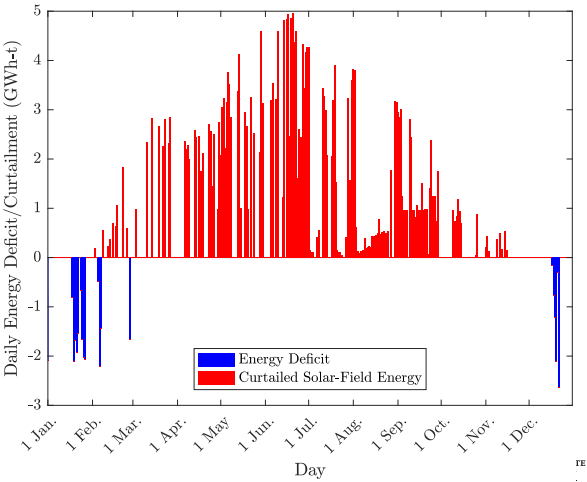
Role of Energy Storage



- Energy-storage technologies that are available today and suited to short-duration/diurnal applications (*e.g.*, mitigating curtailment)
- Major issue is long-duration/seasonal energy storage

Energy-Storage Challenges

- Long-duration/seasonal energy storage is of particular importance for electricity-system reliability and resilience



Other Considerations

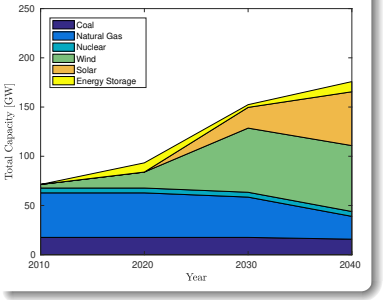
- Nuclear and modular reactors
- Bio, synthetic, or hydrogen-based fuels
- Carbon capture and sequestration
- Demand flexibility, electrification, and resilience
- Stranded investments
- Climate-change-based reliability and resilience challenges

Policy Levers

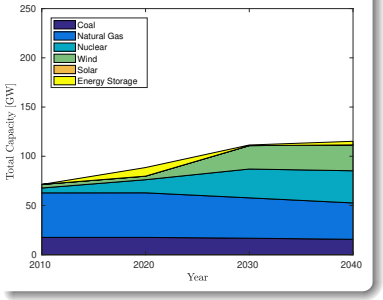
- With few exceptions, mandates and subsidies are used widely to achieve decarbonization goals [van der Linden et al., 2005]
- Economic theory suggests that carbon pricing, Pigouvian taxes, cap and trade are more efficient [Newbery, 1993, Ellerman, 2004, Metcalf, 2009]
- Market power, transmission congestion, and other market failures can yield counterintuitive outcomes wherein price-based policy mechanisms are less efficient than alternatives [Newbery, 2008, Downward, 2010]
- Another consideration is technology improvement (*e.g.*, learning by doing) through technology-push or -pull policies [van Benthem et al., 2008]

Decarbonization Pathways

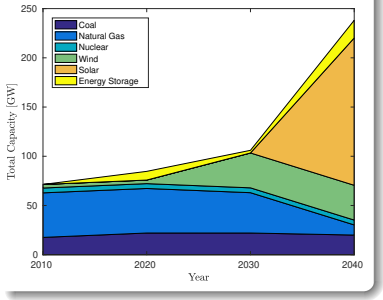
PTC



Carbon Tax



RPS



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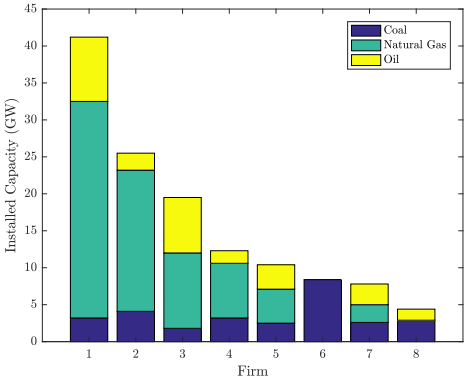
Cost Comparison

	BAU	Carbon Tax	PTC	RPS
Investment Cost [$ Billion]				
2020	69.49	95.83	99.94	58.09
2030	102.11	143.39	187.28	106.96
2040	67.65	67.27	104.66	179.45
Operating Cost [$ Billion/Year]				
2020	11.43	12.81	8.32	12.20
2030	3.87	2.64	−2.36	4.00
2040	1.60	1.24	−2.45	0.49
Total Gross Cost [$ Billion]	408.21	473.46	427.00	511.41
Policy Cost Adjust. [$ Billion]	0.00	−35.84	218.87	0.00
Net Cost				
Aggregate [$ Billion]	408.21	437.62	645.87	511.41
Per-MWh [$/MWh]	33.34	35.74	52.75	41.77

Price-Based Policies

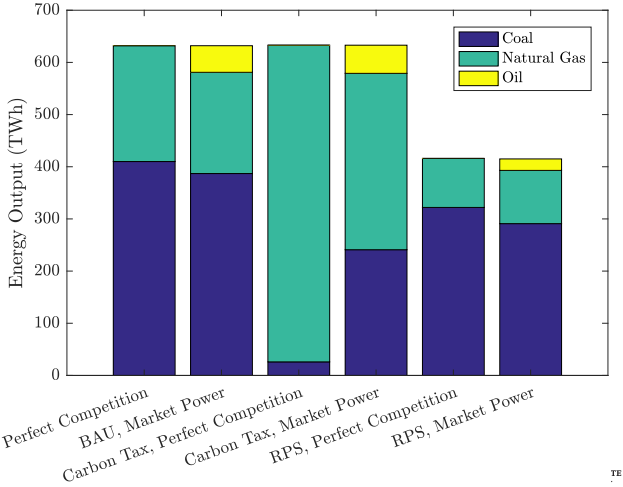
- Carbon tax appears to be *significantly* more efficient than other policy options
- *Caveat*: this assumes a central planner/perfect competition



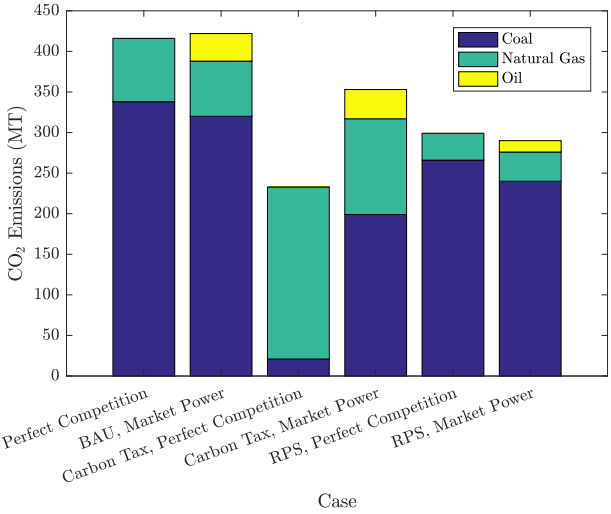
- How does the picture change with the potential exercise of market power?
- Examine a concentrated and highly asymmetric market (Japan)

Market Equilibria

- Large firms (which hold much of the natural-gas-fired capacity) exercise market power by withholding capacity from the market
- Absent policy intervention, this has little impact because natural is costly relative to coal
- Carbon tax results in relatively inexpensive natural-gas-fired generation being withheld from the market



Equilibrium Carbon Emissions



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To Conclude

- Decarbonizing electricity production requires new approaches to and ways of thinking about building and operating power systems
- Non-trivial decarbonization can be achieved with technologies that are available today
- Long-duration/seasonal energy storage or another carbon-free technology to address flexibility and dispatchability needs are required to decarbonize fully
- Policy choices need to be made to drive toward this goal
- Poor policy choices can deliver costly outcomes, and market failure can affect these trade-offs

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Thank you!