# Technology and Market-Design Challenges to Decarbonize Electricity Systems

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# Electricity Decarbonization

- Electricity is a leading carbon source in many regions
- Technical solutions to decarbonize electricity (at least partially) exist today
- Other carbon-intensive sectors (*e.g.*, transportation and heat) can be electrified

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# Many Changes

- Resource mix will change significantly, making planning and operation more complex
- Most regions of the world can achieve $\approx$ 80%–90% decarbonization (relative to business as usual) with economically justifiable incremental cost (if we believe social-cost-of-carbon estimates)
- The final $\approx$ 10%–20% of decarbonization is prohibitively expensive, due to the cost of maintaining resource/energy adequacy with carbon-free resources
- Market designs need to evolve—politics and poor policy choices exacerbate these challenges

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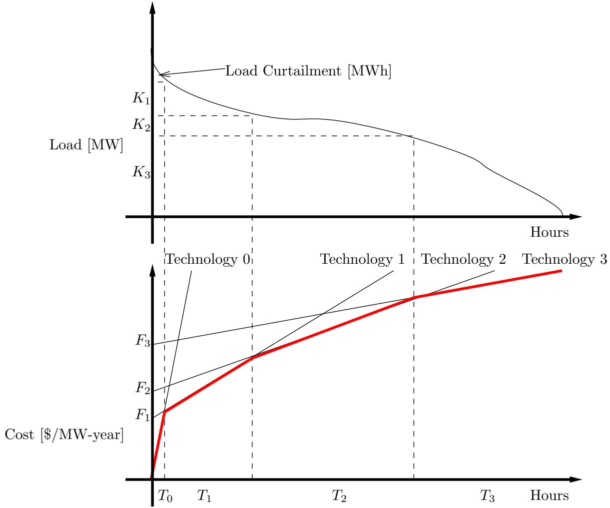
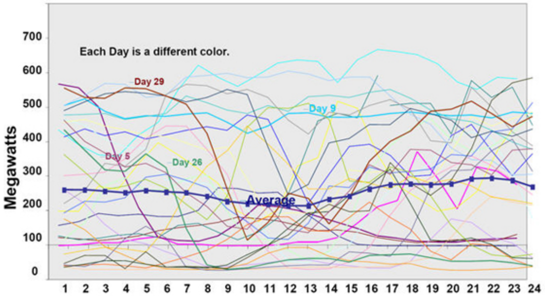
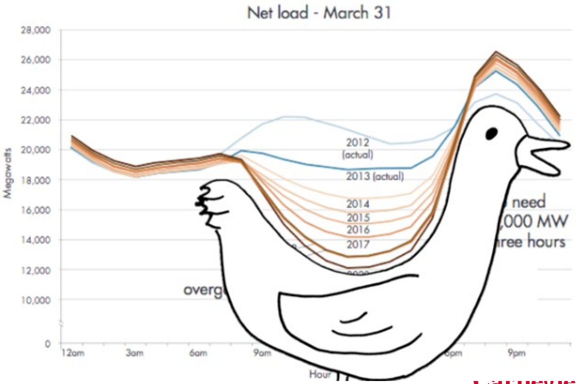
# Simple Resource Planning




- Resources were dispatchable
- Key consideration was tradeoff between fixed and variable cost
- This could be analyzed by examining the load-duration curve
- An added planning-reserve margin protects against unexpected generator failures and load

# Resource Planning with Carbon Constraints



# Multi-Horizon Optimization

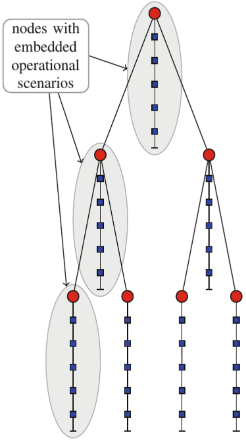



Figure: [Kaut et al., 2014]

- Multi-horizon stochastic optimization balances model tractability and solution quality
- Large-scale/strategic uncertainties represented in the scenario tree
- Small-scale/operational uncertainties represented by operating conditions
- Operating conditions between investment epochs are not linked explicitly

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- Linking operating conditions between investment epochs may be important
- Scenario-tree and problem size grow—decomposition can help

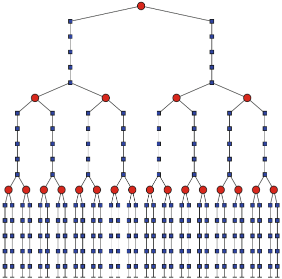


Figure: [Kaut et al., 2014]

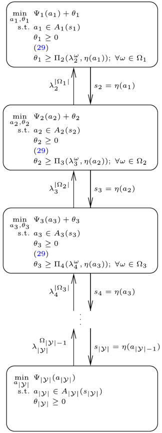
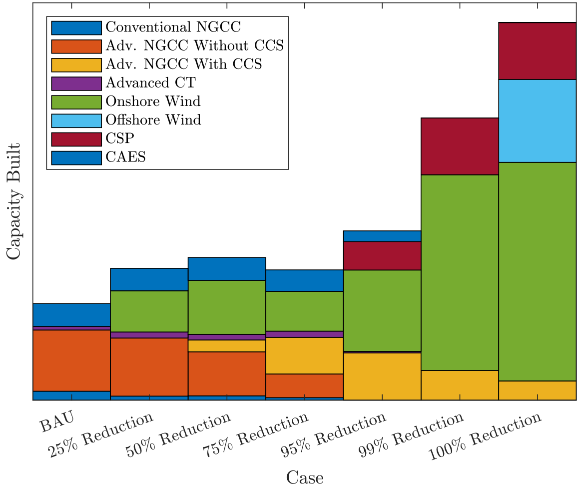



Figure: [Yagi and Sioshansi, 2024]

# Illustrative Technology Mix

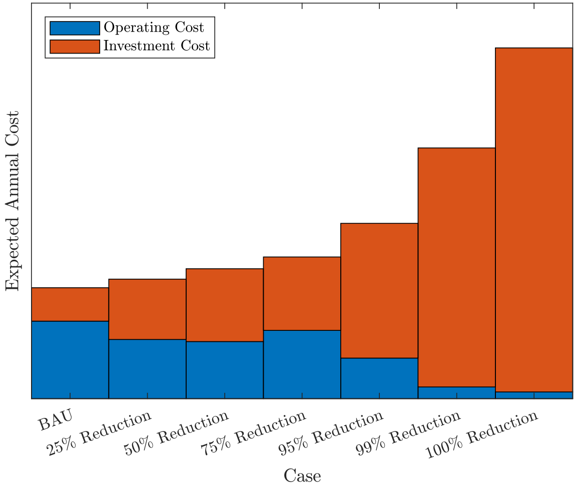
[Boffino et al., 2019, Barrera-Santana and Sioshansi, 2023]




- Mild carbon reductions can be done with lots of renewable resources that are supplemented with natural-gas-fired generation during unfavorable (weather and demand) conditions
- Cannot rely upon natural gas with more stringent carbon constraints, which requires very significant capacity overbuild

# Illustrative Decarbonization Cost

- Small but manageable cost increases for mild carbon reductions
- Capacity overbuild with more stringent carbon constraints is very costly
- ≈ 80%–90% decarbonization is justifiable based on today's technology options and social-cost-of-carbon estimates



# Why Does Decarbonization Get So Expensive?

## Seasonal Supply/Demand Mismatch

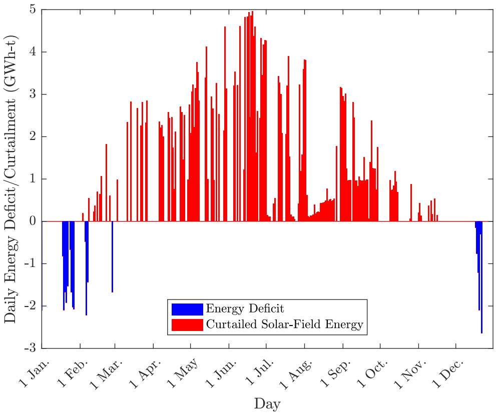



Figure: [Yagi et al., 2019, Yagi et al., 2021]

- Key challenge is resource/energy adequacy
- Need a carbon-free dispatchable resource that can fill gaps in renewable-resource availability (*e.g.*, long-duration/seasonal energy storage)
- Energy-storage technologies that are available today are suited to short-duration applications (*e.g.*, reducing renewable curtailment)

# Demand Response and Flexible Demand

- Electrification may increase scope for demand response [Chandrashekar et al., 2017, Mansouri and Sioshansi, 2023]
- Primarily for short-duration applications (*e.g.*, reducing renewable-energy curtailment or managing small-scale variability)
- Electrification will make resource/energy adequacy a more acute problem
- Winter Storm Uri was a demand-response event during which $>$ 100 people died [Hunter-Rinderle et al., 2023]
- Electrification can exacerbate the seasonal demand/supply mismatch

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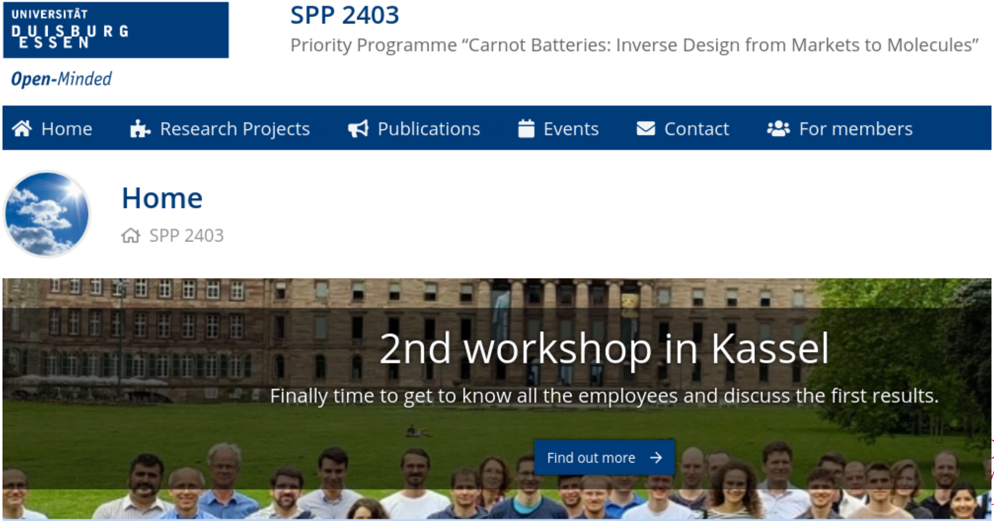
# Technology Development



# Do Market Designs Need to Change?

- A common misconception is that renewable energy ‘breaks’ electricity markets and price formation due to having (near-)zero marginal cost

### Simple Counterexample

- Single period
- Demand: $p(D) = 10 - D$
- Conventional-generation cost: $c(q) = 0.4q + 0.1q^2$
- Renewable investment cost: \$1.80/MW

### Competitive Entry

- 1.2 MW of renewable capacity built and operated
- 7 MWh of conventional output
- Market price: \$1.80/MWh
- Conventional-generator profit: \$4.90
- Renewable-generator profit: \$0

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# Policy Distortion

- Well intentioned regulator imposes a requirement that 30% of energy must be renewable
- $\approx$ 2.5 MW of renewable energy built and operated
- $\approx$ 5.9 MWh of conventional output
- Market price: $\approx$\$1.64/MWh
- Renewable generator loses $\approx$\$0.40
- Conventional-generator profit decreases to $\approx$\$3.83

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# We Can 'Price' the Policy Distortion

- Consider a simple investment model:

$$\begin{aligned}
\min \quad & \sum_{g \in \Omega^G} I_g^G(p_g^{G,\max}) + \sum_{t \in \mathcal{T}} \left[ \sum_{g \in \Omega^G} K_g^G(p_{g,t}^G) + K^D(p_t^D) \right] & \\
\text{s.t.} \quad & \sum_{g \in \Omega^G} p_{g,t}^G = P_t^{D,\max} - p_t^D; \forall t \in \mathcal{T} & (\lambda_t) \\
& 0 \le p_{g,t}^G \le f_{g,t} p_g^{G,\max}; \forall g \in \Omega^G, t \in \mathcal{T} & (\mu_{g,t}^-, \mu_{g,t}^+) \\
& 0 \le p_t^D \le P_t^{D,\max}; \forall t \in \mathcal{T} & (\gamma_t^-, \gamma_t^+)
\end{aligned}$$

- KKT conditions:

$$\nabla I_g^G(p_g^{G,\max}) - \sum_{t \in \mathcal{T}} f_{g,t} \mu_{g,t}^+ = 0; \forall g \in \Omega^G$$

$$\nabla K_g^G(p_{g,t}^G) + \lambda_t - \mu_{g,t}^- + \mu_{g,t}^+ = 0; \forall g \in \Omega^G, t \in \mathcal{T}$$

$$\nabla K^D(p_t^D) + \lambda_t - \gamma_t^- + \gamma_t^+ = 0; \forall t \in \mathcal{T}$$

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# Investment Incentives

- Under standard assumptions, setting energy prices equal to $-\lambda_t; \forall t \in \mathcal{T}$ yields the same KKT conditions/investment incentives from the market as from a central planner
- This result remains if all resources have zero marginal cost:

$$\nabla I^G_g(p^{G,\max}_g) - \sum_{t \in \mathcal{T}} f_{g,t}\mu^+_{g,t} = 0; \forall g \in \Omega^G$$

$$\nabla K^G_g(p^G_{g,t}) + \lambda_t - \mu^-_{g,t} + \mu^+_{g,t} = 0; \forall g \in \Omega^G, t \in \mathcal{T}$$

$$\nabla K^D(p^D_t) + \lambda_t - \gamma^-_t + \gamma^+_t = 0; \forall t \in \mathcal{T}$$

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$$\nabla I_g^G(p_g^{G,\max}) - \sum_{t \in \mathcal{T}} f_{g,t}\mu_{g,t}^+ = 0; \forall g \in \Omega^G$$

$$\lambda_t - \mu_{g,t}^- + \mu_{g,t}^+ = 0; \forall g \in \Omega^G, t \in \mathcal{T}$$

$$\nabla K^D(p_t^D) + \lambda_t - \gamma_t^- + \gamma_t^+ = 0; \forall t \in \mathcal{T}$$

- Key difference is that prices will be set equal to zero or cost of load curtailment, not to marginal (fuel) cost

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# Example: Renewable-Portfolio Standard

$$\min \sum_{g \in \Omega^G} I_g^G(p_g^{G,\max}) + \sum_{t \in \mathcal{T}} \left[ \sum_{g \in \Omega^G} K_g^G(p_{g,t}^G) + K^D(p_t^D) \right]$$

$$\text{s.t.} \sum_{g \in \Omega^G} p_{g,t}^G = P_t^{D,\max} - p_t^D; \forall t \in \mathcal{T} \qquad (\lambda_t)$$

$$0 \le p_{g,t}^G \le f_{g,t} p_g^{G,\max}; \forall g \in \Omega^G, t \in \mathcal{T} \qquad (\mu_{g,t}^-, \mu_{g,t}^+)$$

$$0 \le p_t^D \le P_t^{D,\max}; \forall t \in \mathcal{T} \qquad (\gamma_t^-, \gamma_t^+)$$

$$\sum_{t \in \mathcal{T}} \sum_{g \in \Omega^{G'}} p_{g,t}^G \ge \psi \sum_{t \in \mathcal{T}} \left( P_t^{D,\max} - p_t^D \right); \qquad (\eta)$$

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# Price the Policy Distortion

- KKT conditions become:

$$\nabla I_g^G(p_g^{G,\max}) - \sum_{t \in \mathcal{T}} f_{g,t}\mu_{g,t}^+ = 0; \forall g \in \Omega^G$$

$$\nabla K_g^G(p_{g,t}^G) + \lambda_t - \mu_{g,t}^- + \mu_{g,t}^+ - \eta = 0; \forall g \in \Omega^{G'}, t \in \mathcal{T}$$

$$\nabla K_g^G(p_{g,t}^G) + \lambda_t - \mu_{g,t}^- + \mu_{g,t}^+ = 0; \forall g \in \Omega^G \setminus \Omega^{G'}, t \in \mathcal{T}$$

$$\nabla K^D(p_t^D) + \lambda_t - \gamma_t^- + \gamma_t^+ - \eta = 0; \forall t \in \mathcal{T}$$

- In other words, pay $\eta$ (known also as a REC payment) to generators that meet the renewable-portfolio standard
  - ➥ In the simple example, the effective value of $\eta$ is $\approx 0.16$, which makes the renewable generator whole
- My observation: The bigger concern is having a resource mix that can meet reliability, resource-/energy-adequacy, security-of-supply considerations, but this can be priced and monetized in the same manner
- All of this follows directly from Lagrange-multiplier theory/KKT conditions

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# Technical Considerations

- What properties do prices from a stochastic-planning model have [Pritchard et al., 2010]?
- Non-convexities (*e.g.*, unit commitment and energy storage) can complicate remuneration [O'Neill et al., 2005]
- Resource-adequacy assessment with changing climate and needing to capture extreme events
- Market monitoring and mitigation with energy storage
- Unconventional resources [Sioshansi, 2017]

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# Political and Policy-Making Considerations

- Are these prices politically palatable?
- How to handle balkanized policy regimes or poor policy-mechanism choices within a market?
  - This is proving especially difficult with transmission projects
- Reliability and power-quality standards are set by engineers, should this be done by economists?
- How should we think about and describe reliability and resource/energy adequacy?
  - Solar produces zero during the night, that doesn't mean zero reliability value (the way that engineers think about reliability today)

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# Wrapping Up

- Despite efforts, we don't know how to design an economic and reliable carbon-free electricity system (or if a 100%-renewable energy mix is physically feasible)
- There are important research and policy-analysis gaps to which system scientists, operations researchers, *etc.* can contribute to move towards such systems:
  - improving planning methods
  - optimizing technology pathways
  - providing technology-characteristic benchmarks and targets
  - improved resource-/energy-adequacy assessment
  - policy analysis
  - policy- and technology-informed market design

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*Thank you!*