ELECTRICITY MARKET DESIGN:
More on the Green Agenda and Carbon Pricing

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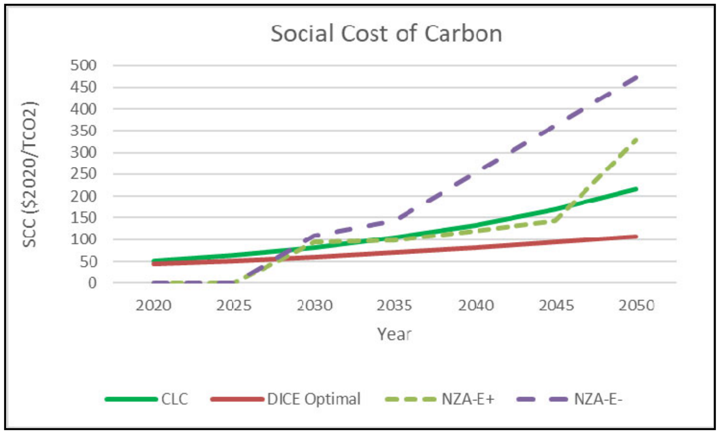
The challenges of climate change present a ‘wicked problem’ that is difficult to solve because of incomplete, contradictory, and changing requirements. The scale is global, the duration covers many generations into the future, and the uncertainties can seem overwhelming.

Overview

- **The Science helps identify the challenges and opportunities.**
- **The Science does not and cannot tell us what to do.**
- **There are tradeoffs and this points to the need for cost-benefit analysis.**
- **One guidepost is the Social Cost of Carbon that provides a standard for what to do and how much is enough.**
- **There are many critical uncertainties.**
- **A central problem is the continuing debate about discount rates.**



- **The climate policy choices will interact with everything else, including the design and operation of energy markets.**

"CLIMATE CHANGE IS ONE OF THE DEFINING ISSUES OF OUR TIME." … From Royal Society and National Academy of Sciences "Climate Change Evidence & Causes, Update 2020." (The Royal Society and National Academy of Sciences, 2020)

From the Forward: "The evidence is clear. However, due to the nature of science, not every detail is ever totally settled or certain. Nor has every pertinent question yet been answered. Scientific evidence continues to be gathered around the world. Some things have become clearer and new insights have emerged. For example, the period of slower warming during the 2000s and early 2010s has ended with a dramatic jump to warmer temperatures between 2014 and 2015. Antarctic sea ice extent, which had been increasing, began to decline in 2014, reaching a record low in 2017 that has persisted. These and other recent observations have been woven into the discussions of the questions addressed in this booklet.

Calls for action are getting louder. The 2020 Global Risks Perception Survey from the World Economic Forum ranked climate change and related environmental issues as the top five global risks likely to occur within the next ten years. Yet, the international community still has far to go in showing increased ambition on mitigation, adaptation, and other ways to tackle climate change."

From the Conclusion: "Citizens and governments can choose among several options (or a mixture of those options) in response to this information: they can change their pattern of energy production and usage in order to limit emissions of greenhouse gases and hence the magnitude of climate changes; they can wait for changes to occur and accept the losses, damage, and suffering that arise; they can adapt to actual and expected changes as much as possible; or they can seek as yet unproven "geoengineering" solutions to counteract some of the climate changes that would otherwise occur. Each of these options has risks, attractions and costs, and what is actually done may be a mixture of these different options. Different nations and communities will vary in their vulnerability and their capacity to adapt. ***There is an important debate to be had about choices among these options***, to decide what is best for each group or nation, and most importantly for the global population as a whole. The options have to be discussed at a global scale because in many cases those communities that are most vulnerable control few of the emissions, either past or future. Our description of the science of climate change, with both its facts and its uncertainties, is offered as a basis to inform that policy debate." (Emphasis added)

CLEANER ENERGY Policy Barriers

The NAS identified two main barriers and emphasized two "overarching recommendations."
(National Academy of Sciences, *The Power of Change: Innovation for Development and Deployment of Increasingly Clean Electric Power Technologies*, Washington D.C., 2016, pp.3-4.) (National Academy of Sciences, 2016)

Barriers

"The committee concluded that there are two significant barriers to accelerating greater penetration of increasingly clean electricity technologies. First, as noted above, the market prices for electricity do not include "hidden" costs from pollution, stemming mainly from negative impacts on human health, agriculture, and the environment. Levels of criteria pollutants declined over the past three decades, but still cause harms. Harms from GHGs are difficult to estimate, but if accounted for in the market, could be considered by consumers. …

The second barrier is that the scale of the climate change challenge is so large that it necessitates a significant switch to increasingly clean power sources. In most of the United States, however, even with a price on pollution, most increasingly clean technologies would lack cost and performance profiles that would result in the levels of adoption required. In most cases, their levelized costs are higher than those of dirtier technologies, and there are significant challenges and costs entailed in integrating them into the grid at high levels. This means that reducing the harmful effects of emissions due to electricity generation will require a broader range of low-cost, low- and zero-emission energy options than is currently available, as well as significant changes to the technologies and functionality of the electricity grid and the roles of utilities, regulators, and third parties. …

…even if the technological and institutional barriers to greater adoption of increasingly clean power technologies were overcome but their prices were not competitive, an adequate scale of deployment would require tremendous public outlays, and in many parts of the world would be unlikely to occur. While learning by doing can lower some costs, deployment incentives are likely to be insufficient as the primary policy mechanism for achieving timely cost and performance improvements."

The NAS identified emphasized two "overarching recommendations." (National Academy of Sciences, 2016)

Recommendations

"The U.S. federal government and state governments should significantly increase their emphasis on supporting innovation in increasingly clean electric power generation technologies.

Simply put, the best way to encourage market uptake is first to have technologies with competitive cost and performance profiles. The need for increased innovation and expanded technology options is especially important given the global picture. In many parts of the world, coal remains the cheapest fuel for electricity generation. China, India, and the nations of Southeast Asia are expected to continue rapidly adding new electricity generation facilities, most of them coal-fired and with minimal pollution controls. Thus there is a need for technological innovations that are affordable outside the United States as well. These improvements in performance and cost will be essential to achieve long-term GHG reductions, such as the reduction called for in the COP21 agreement, without significantly increasing electricity prices. …"

This addresses the usual ***Research, Development and Demonstration (RD&D)*** market failure and identifies a target for government action. The need for expanded RD&D is widely recognized, from The National Academies to Bill Gates.

The NAS offered a second recommendation which addresses the third "D" of deployment. (National Academy of Sciences, 2016)

Recommendations

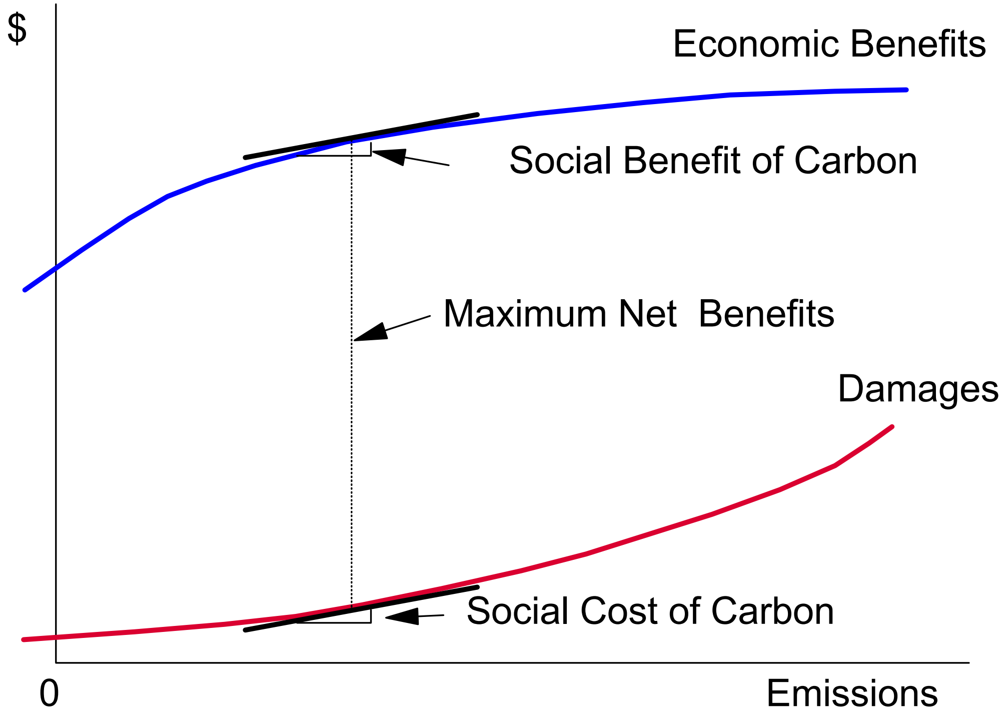
"Congress should consider an appropriate price on pollution from power production to level the playing field; create consistent market pull; and expand research, development, and commercialization of increasingly clean energy resources and technologies.

Correcting market prices will encourage more deployment of increasingly clean technologies. Where such technologies are already the lowest-price choice, they will become even more so; in other locations, a pollution price will make these technologies the most affordable option or narrow the gap. In addition to providing this market pull for the deployment of mature increasingly clean technologies, pollution pricing can be expected to spur the development of new, even more effective and competitively priced technologies."

This addresses the Research, Development, Demonstration and ***Deployment*** (RDD&D) market failure. Here the policy would recognize the need for the "appropriate price on pollution." What is the appropriate price on carbon emissions and why is this important?

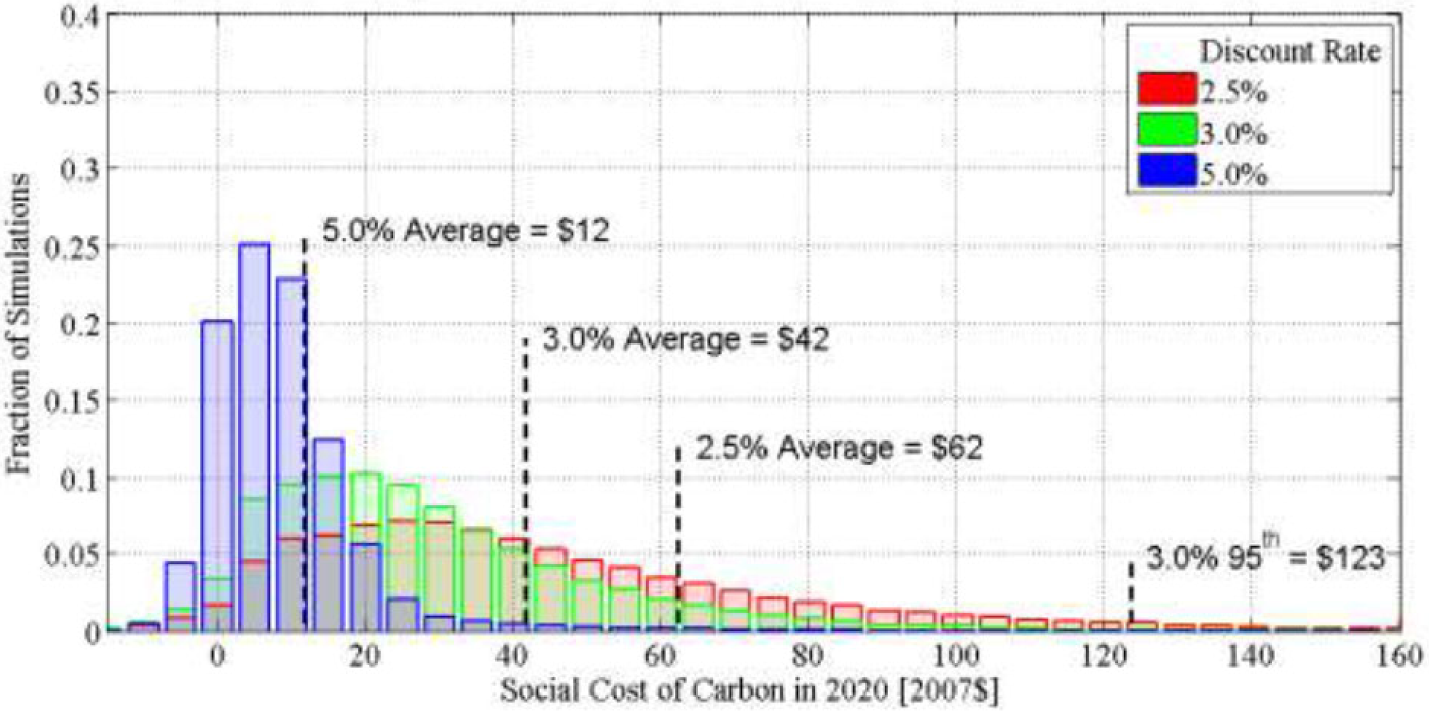
Higher carbon emissions increase conventional measures of economic benefit but create climate related damages that are not otherwise recognized in private decisions. The Social Cost of Carbon would define the "appropriate price on pollution." Too high or too low would reduce net welfare.

Benefits, Costs, Welfare Maximization and the Social Cost of Carbon



Social Cost of Carbon

The challenge of climate change and the impact of carbon dioxide and other greenhouse gas emissions is a textbook example of a market failure. The policy implication is to internalize the cost of carbon. The benchmark for the best policy is a carbon tax. Although there is significant uncertainty, the estimates from the U.S. government imply a substantial social cost of carbon dioxide ($/ton CO2) that is not internalized in the market.



Regulatory Impact Analysis - Under Executive Interagency Working Group on Social Cost of Carbon. (2013). Technical Update of the Social Cost of Carbon for Order 12866, (U. S. Government Interagency Working Group on Social Cost of Carbon, 2016)

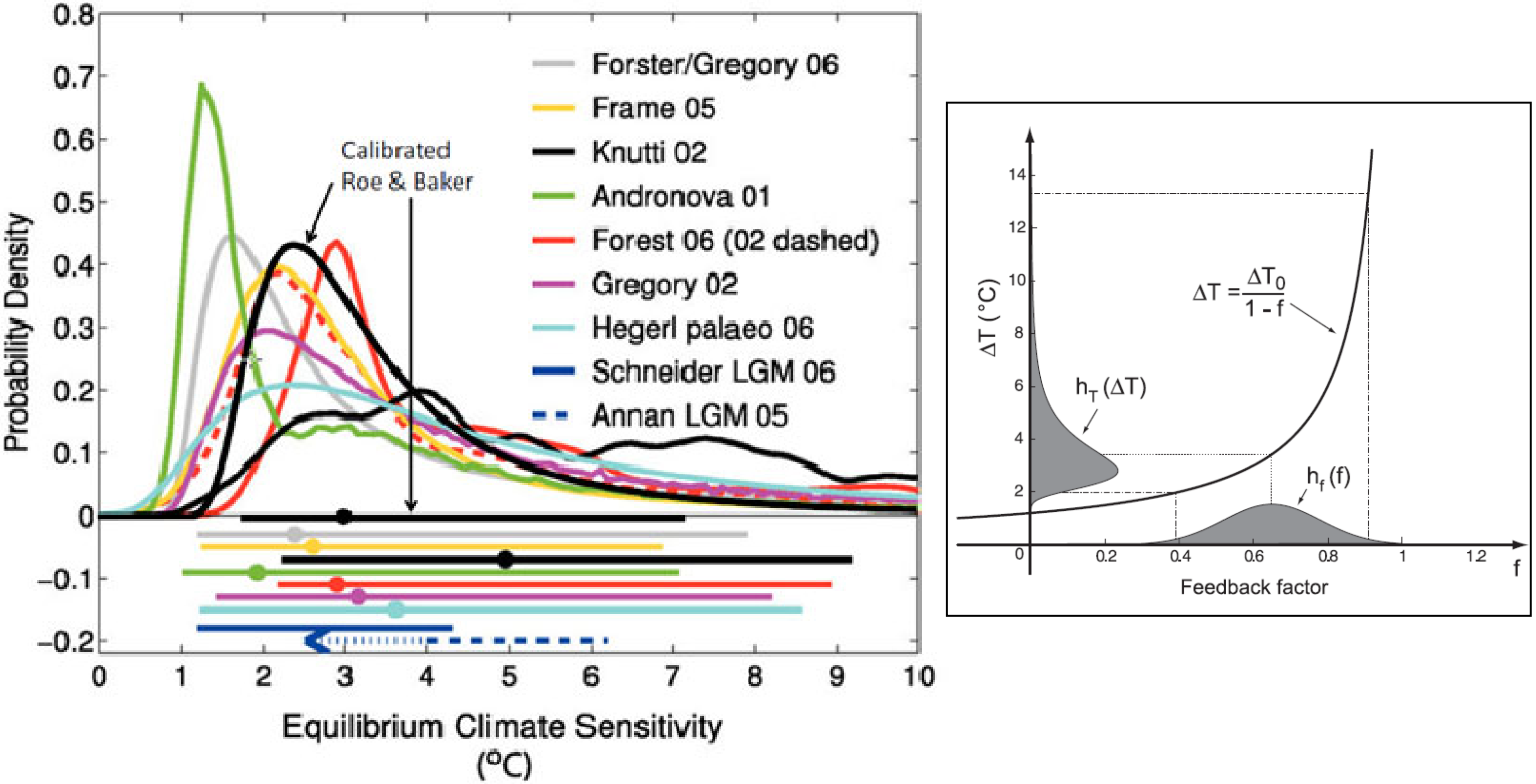
The debate over the basic elements of the social cost of carbon is mind numbing. There is a temptation to dismiss the conversations as without a possible resolution.

- **Emission benefits accrue now, and emission costs are in the future.**
- **Uncertainty affects everything.**
  - Economic and population growth are uncertain.
  - Technology change rates are uncertain.
  - ***Implied temperature levels are uncertain.***
  - Climate induced damages are uncertain.
  - ***Catastrophic climate effects could be irreversible.***
- **Seemingly small changes in discount rates have a major impact.**
  - ***Unsettled issues about discount rates for the economy.***
  - ***Discounting requires intergenerational comparisons.***

CLEAN ENERGY Uncertain Temperature Effects

The climate sensitivity measures the equilibrium change in temperature from a doubling of carbon concentrations. The reported uncertainty has not changed much in three decades.

Figure 2: Estimates of the Probability Density Function for Equilibrium Climate Sensitivity (°C)

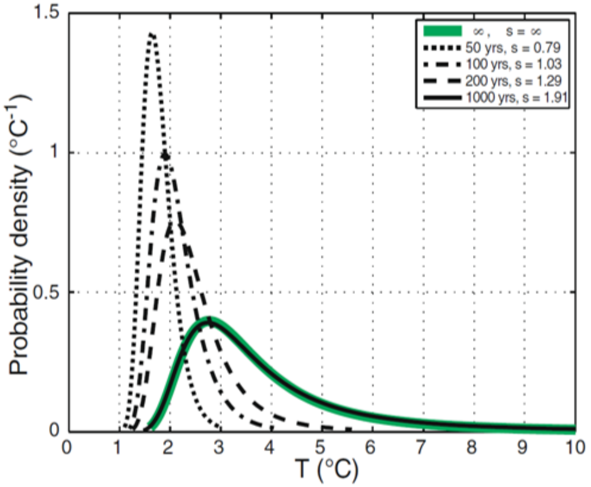


The basic equilibrium theory is found in (Roe & Baker, 2007). The various model representations found in (Meinshausen et al., 2009). The graphic is from (U. S. Government Interagency Working Group on Social Cost of Carbon, 2010)

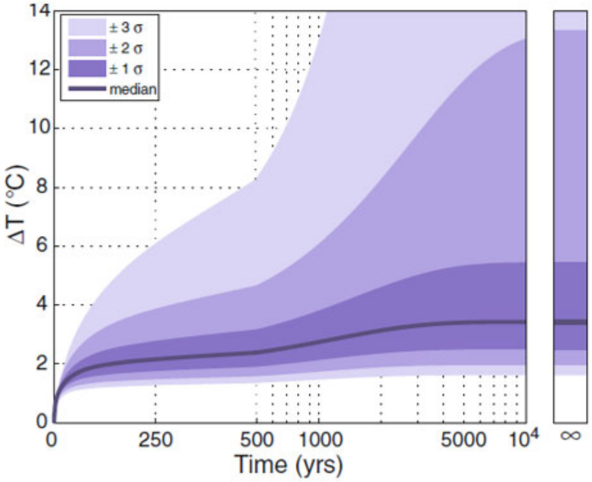
Uncertain Temperature Effects

The larger the estimated climate sensitivity, the longer it takes to arrive at the temperature change. “Should the climate tail wag the policy dog?” (Roe & Bauman, 2013) (emphasis added)

“**Fig. 2 b** The shape of the [climate sensitivity] distribution at particular times. The skewness of the distributions are also shown in the legend; as described in the text, **the upper bound on possible temperatures is finite at finite time, limiting the skewness**” (Roe & Bauman, 2013, p. 651)



“**Fig. 2** **a** The time evolution of uncertainty in global temperature in response to an instantaneous doubling of CO_2 at t = 0, and for standard parameters. The shading reflects the range of feedbacks considered (symmetric in feedbacks, but not in climate response), as explained in the text. Note the change to a logarithmic x-axis after t = 500 yr. The panel illustrates that **for high climate sensitivity it takes a very long time to come to equilibrium**.” (Roe & Bauman, 2013, p. 651)



The net effect of the timing is to substantially moderate the impact on the present social cost of carbon.

Uncertain Catastrophic Impacts

Climate catastrophic effects that might be irreversible are part of active investigation. As with the climate sensitivity, there an uncertain likelihood and the timing may be far in the future.

The Gulf Stream: “Results from the best available climate models do not predict an abrupt change in (or collapse of) the Atlantic Meridional Overturning Circulation, … . Some abrupt changes are already underway, such as the decrease in Arctic sea ice extent …, and as warming increases, the possibility of other major abrupt changes cannot be ruled out.” (The Royal Society and National Academy of Sciences, 2020)

The Greenland Ice Sheet: “Concerns about the impact on large-scale earth systems have taken center stage in the scientific and economic analysis of climate change. The present study analyzes the economic impact of a potential disintegration of the Greenland ice sheet (GIS). … The study demonstrates that social cost–benefit analysis and damage-limiting strategies can be usefully extended to illuminate issues with major long-term consequences, as well as concerns such as potential tipping points, irreversibility, and hysteresis. A key finding is that, under a wide range of assumptions, the risk of GIS disintegration makes a small contribution to the optimal stringency of current policy or to the overall social cost of climate change.”

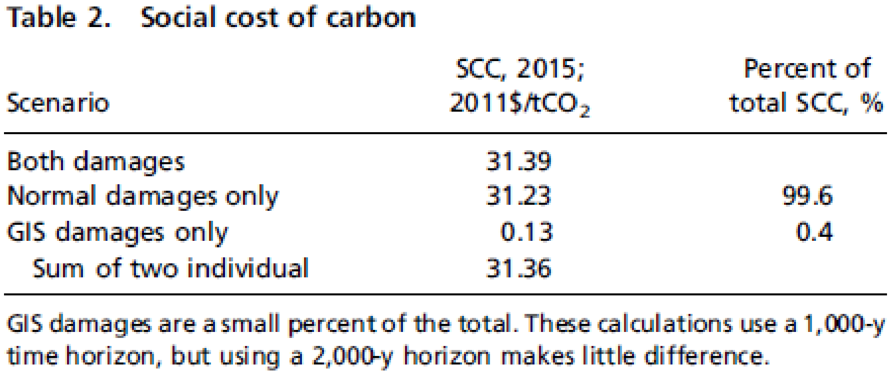


Table 2. Social cost of carbon

Scenario	SCC, 2015; 2011\$/tCO$_2$	Percent of total SCC, %
Both damages	31.39	
Normal damages only	31.23	99.6
GIS damages only	0.13	0.4
Sum of two individual	31.36	

GIS damages are a small percent of the total. These calculations use a 1,000-y time horizon, but using a 2,000-y horizon makes little difference.

(Nordhaus, 2019)

The net effect is to substantially moderate the impact on the present social cost of carbon.

Seemingly small changes in discount rates have a major impact on the estimated social cost of carbon.

Estimates for different policies and different discounting assumptions are summarized in (Nordhaus, 2017).

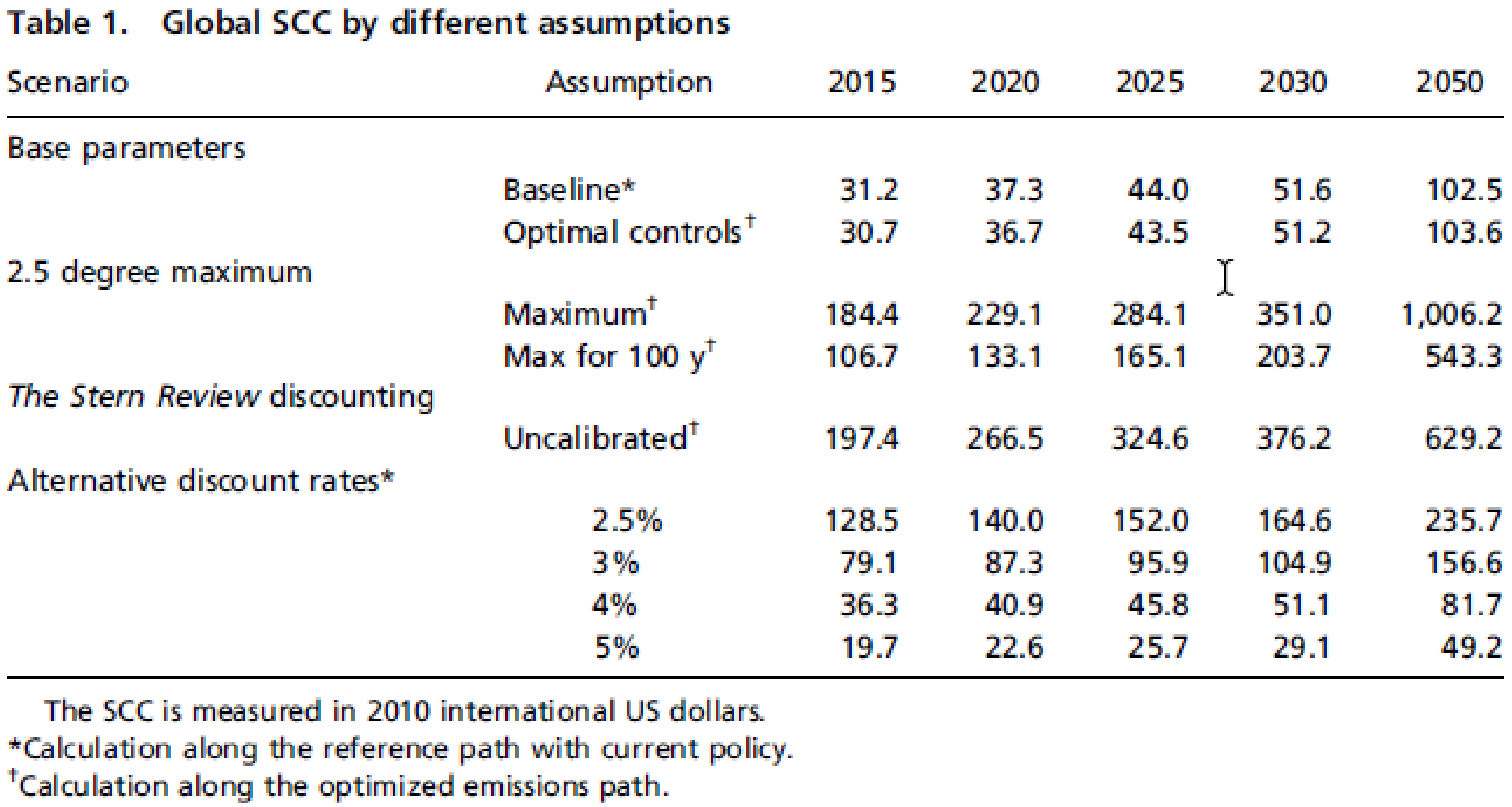


Table 1. Global SCC by different assumptions

Scenario	Assumption	2015	2020	2025	2030	2050
Base parameters						
	Baseline*	31.2	37.3	44.0	51.6	102.5
	Optimal controls†	30.7	36.7	43.5	51.2	103.6
2.5 degree maximum						
	Maximum†	184.4	229.1	284.1	351.0	1,006.2
	Max for 100 y†	106.7	133.1	165.1	203.7	543.3
The Stern Review discounting						
	Uncalibrated†	197.4	266.5	324.6	376.2	629.2
Alternative discount rates*						
	2.5%	128.5	140.0	152.0	164.6	235.7
	3%	79.1	87.3	95.9	104.9	156.6
	4%	36.3	40.9	45.8	51.1	81.7
	5%	19.7	22.6	25.7	29.1	49.2

The SCC is measured in 2010 international US dollars.

*Calculation along the reference path with current policy.

†Calculation along the optimized emissions path.

Unsettled issues arise in the analysis of markets and rates of return for the economy.

"The disagreements about the discount rate are not merely arguments about empirical matters; there are major debates about conceptual issues as well. For example, Stern (2008) and Sterner and Persson (2008) argue that the choice of consumption discount rate should be based almost entirely on ethical considerations: there is no need, for example, to ground the consumption discount rate in observed or expected interest rates or in estimates of the opportunity cost of capital. In contrast, Nordhaus maintains that it is critical to base the choice of discount rate in observed behavior — behavior that is reflected in market interest rates. Similarly, some analysts argue that the choice of discount rate is a purely prescriptive issue, while others claim it should be a descriptive question (i.e., empirically based)." (Goulder & Williams, 2012)

- Model Constructs
    - Utility Discount Rate (ρ)
    - Social Welfare Consumption Discount Rate (r_{SW})
    - Risk-Free Consumption Discount Rate (r_F)
    - Risky Consumption Discount Rate (r_C)
- Market Results across 17 countries (Barro & Jin, 2021, p. 15)
    - Market Risk-Free Return on Government Bills (r_G) (0.75%/yr.)
    - Market Return on Capital (r_M) (7.90%/yr.)

Application of the Consumption Capital Asset Pricing Model (CCAPM) yields model results that are inconsistent with market outcomes, with $r_C < r_M$ and $r_C - r_F < r_M - r_G$.

This is the unsettled equity premium puzzle (Dietz, Gollier, & Kessler, 2018) (Barro & Jin, 2021).

Discount Rates

The Nordhaus Dynamic Integrated Climate-Economy (DICE) model applies a deterministic optimal growth framework, derived from a standard expected utility objective function. (Nordhaus, 2018)

$$W = \sum_{t=1}^{T_{MAX}} \frac{1}{\left(1+\rho\right)^{t}} \frac{c\left(t\right)^{1-\alpha}}{1-\alpha} L\left(t\right)$$

where

$c\left(t\right)$	Per Capita Consumption
$L\left(t\right)$	Population
ρ	Utility Discount Rate

The parameter α is interpreted as the generational inequality aversion. For example, in the DICE model per capita consumption in 2100 is 4.4 times the 2020 level. With $\alpha = 1.45$, the undiscounted per capita tradeoff has an \$8.59 decrease in consumption in 2100 indifferent to a \$1 increase in 2020.

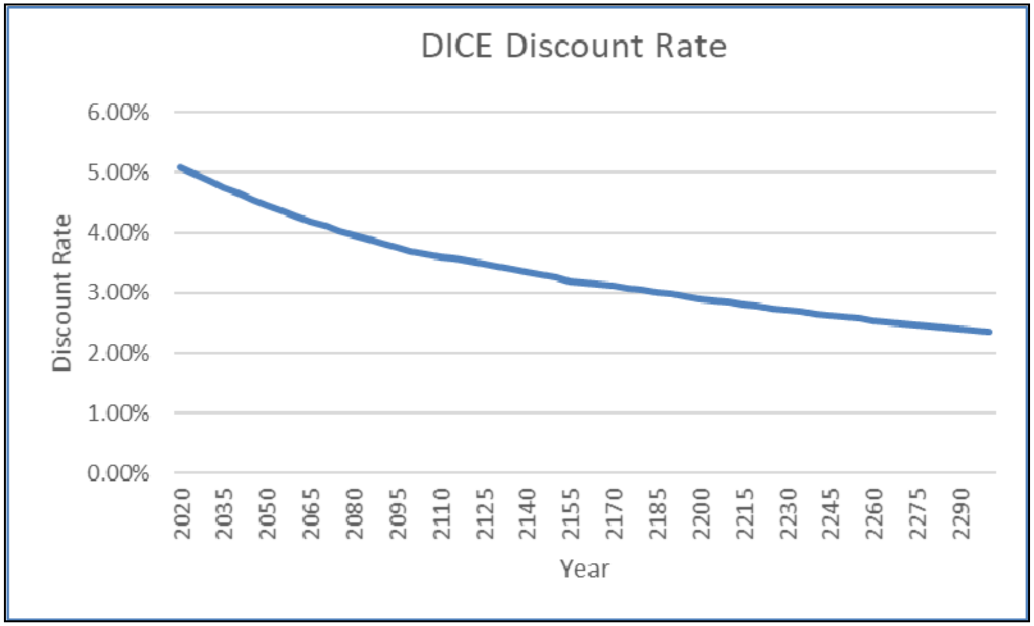
The DICE model is based on expected values (no uncertainty). Hence the discount rate on goods is same as the risk-free rate determined as a function of the utility discount rate ($\rho = 1.5\%$), inequality aversion, and the economic growth rate (g):

$$r_F = \rho + \alpha g \,.$$

The model parameters are chosen to make these endogenous discount rates in a deterministic model more consistent with the "discount rate in observed behavior." ($r_{SW} \approx r_F \approx r_C \approx r_M$)

Arguably the DICE discount rates are too low relative to the empirical observations:

$$r_M = 7.76\% \,.$$



An alternative to the additive utility model in DICE is the recursive Epstein-Zin utility function. (Kreps & Porteus, 1978) (Epstein & Zin, 1989) (Weil, 1990) **This introduces a new parameter and allows a different characterization of risk aversion and intertemporal substitution.**

The core element of the objective function is per capita utility as:

$$U_t = \left[(1-\beta) c_t^{1-\alpha} + \beta \left(E_t \left[U_{t+1}^{1-\theta} \right] \right)^{1-\alpha / 1-\theta} \right]^{1/ 1-\alpha} .$$

The discount factor is ($\beta = (1+\rho)^{-1}$) and the application has corresponding adjustments for population growth. However, a key feature is the separate treatment of relative risk aversion (θ) and intertemporal substitution parameters (α). Small values of α produce high values of the elasticity of intertemporal substitution ($\mathrm{EIS}{=}\alpha^{-1}$) and much lower discount rates.

Applications illustrate that the separate EIS assumption is critical. For example, (Ackerman, Stanton, & Bueno, 2013) address Roe-Baker ECS uncertainty and assume an EIS=1.5, which increases initial SCC by over 400%. In (Cai, Lenton, & Lontzek, 2016) Roe-Baker ECS uncertainty not addressed, but multiple tipping point analysis raises the initial SCC by over 600%. The support for EIS=1.5 cites (Pindyck & Wang, 2013). However, Pindyck and Wang emphasize the inability to separately identify the EIS and the pure rate of time preference (ρ). The utility rate of pure time preference in (Pindyck & Wang, 2013, p. 319) is 4.98%, compared to the use of the DICE value of 1.5%. By comparison, (Cai, Judd, & Lontzek, 2015) Incorporates uncertainty in economic growth, and separate analysis that includes stochastic tipping points, and finds the SCC is driven by the EIS assumption. With an EIS comparable to the DICE model ($\mathrm{EIS}{=}(1.45)^{-1} = 0.69$), the SCC results are much closer to DICE.

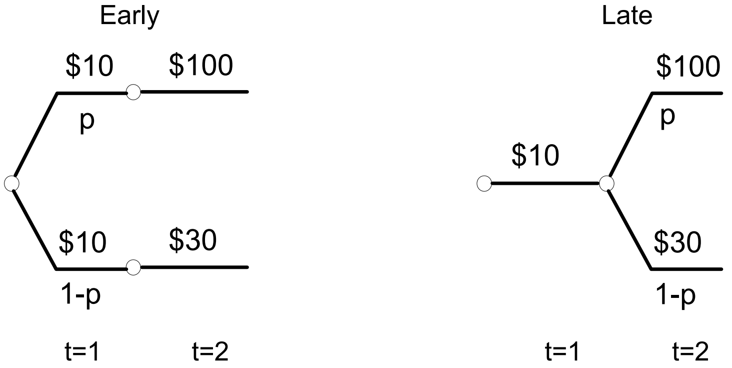
The recursive Epstein-Zin utility function provides flexibility in representing intertemporal tradeoffs. However, this comes at a cost for its use in climate integrated assessment models.

The basic structure of the EZ utility function creates a premium for early resolution of uncertainty (ERU) when $\theta \neq \alpha$. (Gollier & Kihlstrom, 2016)

For two different representations of uncertainty with identical payoffs, early resolution is preferred to later resolution. The impacts can be significant:

"Would you give up 25 or 30 percent of your lifetime consumption in order to have all risk resolved next month? … Though risk aversion and the elasticity of intertemporal substitution have been the subjects of careful scrutiny when calibrating preferences, the long-run risks literature and the broader literature using recursive utility to address asset pricing puzzles have ignored the full implications of their parameter specifications. … (this) ***inflates timing premia to levels that seem implausible***." (Epstein, Farhi, & Strzalecki, 2014) (emphasis added)

Epstein-Zin Early Resolution of Uncertainty



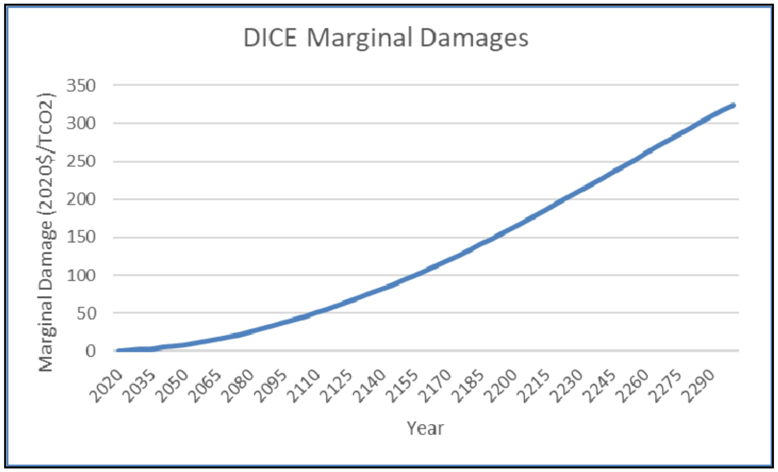
No Decisions and Same Expected Payoffs

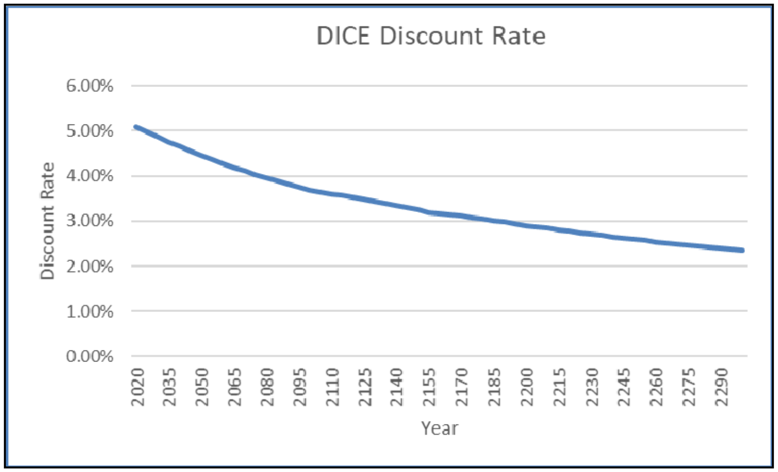
However, without the embedded timing premium, in the case with $\theta = \alpha$, or when there is independent uncertainty, or for the special case of deterministic consumption, the EZ model returns to the same structure as the utility function in DICE. (Gollier & Kihlstrom, 2016, p. 7)

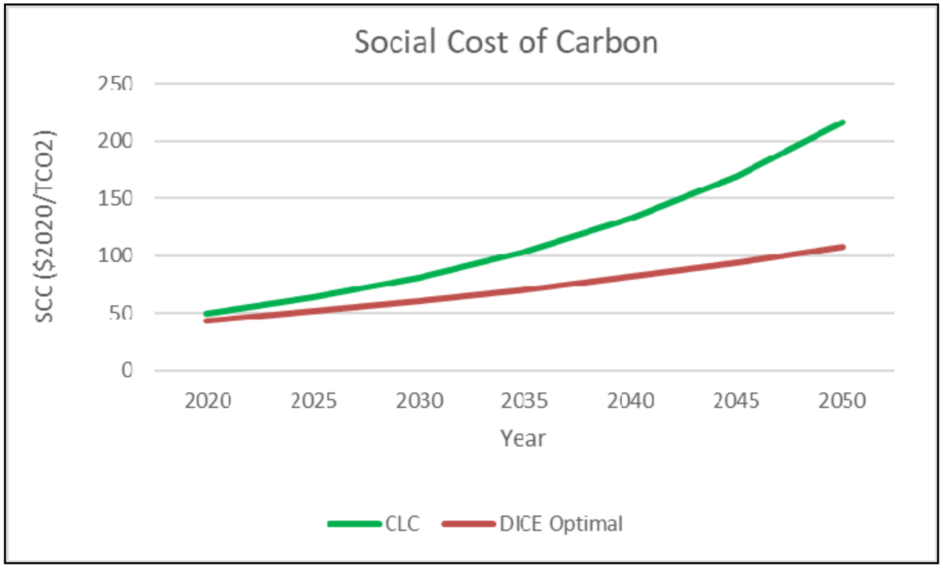
CLEAN ENERGY Social Cost of Carbon

This leads back to the DICE formulation and the calculation of the SCC.

The discount rate combines with the marginal damages from an additional CO2 emission to produce the SCC. Here the DICE optimal case is compared with the Climate Leadership Council (CLC) proposal.







Uncertainty and the Social Cost of Carbon

The DICE model is deterministic. Nordhaus examines some of the effects of uncertainty in terms of the implied SCC today by approximating the impact of uncertainty in the DICE model.

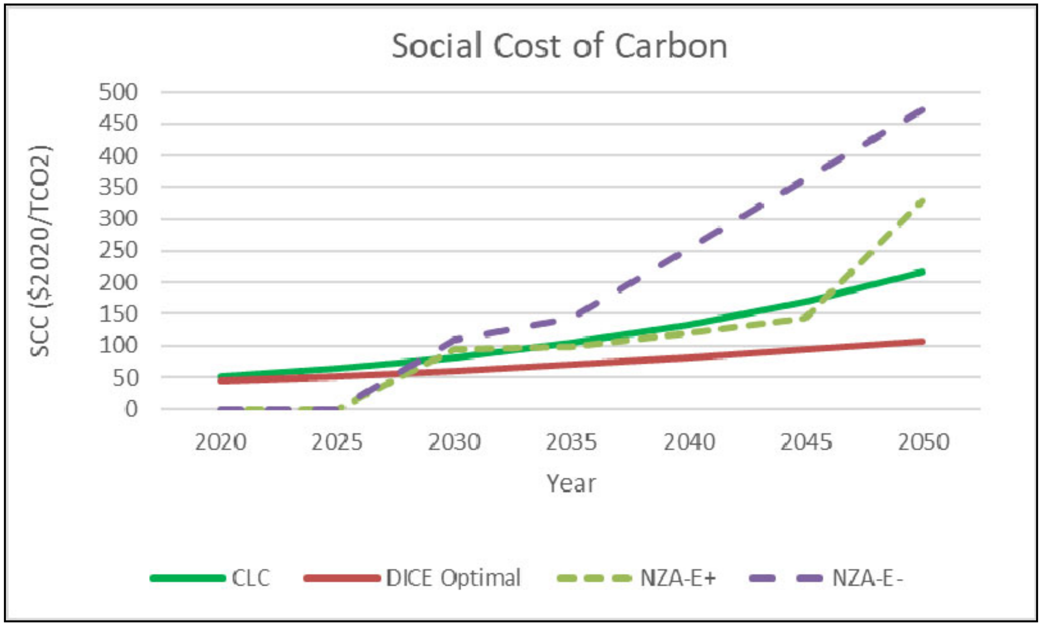
“When uncertainties are accounted for, the expected values of most of the major geophysical variables, such as temperature, are largely unchanged. However, the social cost of carbon is higher (by about 10 percent) under uncertainty than in the best-guess case because of the asymmetry in the impacts of uncertainty on the damages from climate change. … the relative uncertainty is much higher for economic variables than for geophysical variables.” (Nordhaus, 2018, p. 335)

“The ranges of uncertainty for future emissions, concentrations, temperature, and damages are extremely large. However, this does not reduce the urgency of taking strong climate change policies today. When taking uncertainties into account, the desirable strength of policy (as measured by the social cost of carbon or the optimal carbon tax) would increase, not decrease.” (Nordhaus, 2018, p. 335)

“The act-then-learn approach to decisions cannot be fully incorporated into the current DICE uncertainty structure. … I have undertaken a small test case which examines the impact of learning that is delayed until 2050. …. The results of this simplified example indicate that policies are relatively insensitive to late learning, although there is substantial value of learning. The optimal carbon price in the act-then-learn approach is about 6 percent higher than for that of learn-then-act (\$36.1/tCO2 rather than \$34.2/tCO2 in 2015.” (Nordhaus, 2018, p. 358)

The estimates for the Social Cost of Carbon from the DICE optimization, the CLC policy proposal, and the Net-Zero America cost effective trajectories diverge substantially.

The DICE model computes an optimal trajectory. The Clmate Leadership Council proposal includes a "Gradually Rising Carbon Fee … Carbon Dividends for All Americans … Significant Regulatory Simplification … Border Carbon Adjustment."[1] The Princeton Net-Zero America report sets a 2050 emissions target and estimates the implied marginal cost of emission reduction for a range of trajectories. (Larson et al., 2020, p. 204) The near term estimates are similar, but by 2050 the implied SCCs diverge from substantially from the DICE optimum. (Gollier, 2020)



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[1] https://clcouncil.org/our-plan/

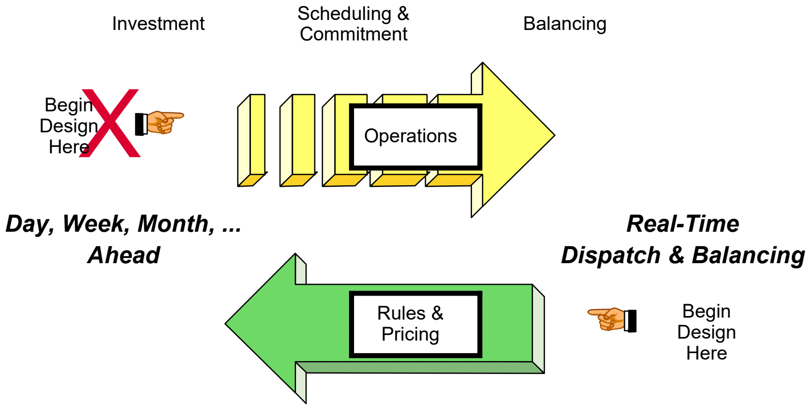
The climate challenge will stress the electricity system. The cost-benefit analysis and the Social Cost of Carbon provide guidance for what, how much and how fast a transformation is needed.

- **Clean Energy Innovation**
  - Research, Development and Demonstration RD&D.
    - Government RD&D Support to Overcome Traditional Market Failure.
    - Learning-by-Doing Subsidies of Limited Size and Duration. (National Academy of Sciences, 2016, p. 279)
  - Clean Energy Deployment Based on System Wide Carbon Pricing at the SCC.
    - Incentives for Diverse Supply Investment Decisions Operations.
    - Incentives for Diverse Demand Investment Decisions and Demand Participation.

The climate challenge will stress the electricity system. The cost-benefit analysis and the Social Cost of Carbon provide guidance for what, how much and how fast a transformation is needed.

- **Electricity Market Design**
  - Focus on Basic Principles of Electricity Systems
    - Real-Time Market Creates the Incentives.
    - Forward Markets Can Support Investment.

False Starts for the Electricity Market



Investment

Scheduling & Commitment

Balancing

~~Begin Design Here~~

Operations

Day, Week, Month, ... Ahead

Real-Time Dispatch & Balancing

Rules & Pricing

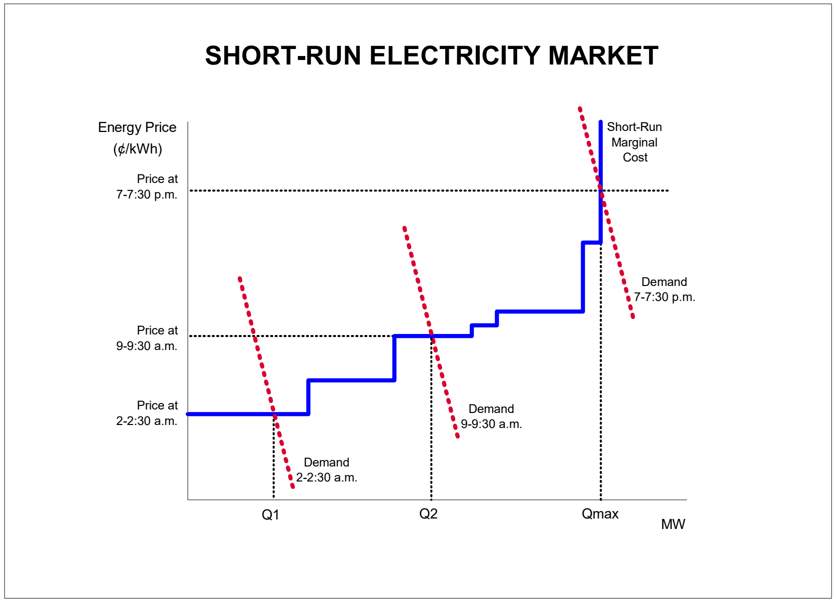
Begin Design Here

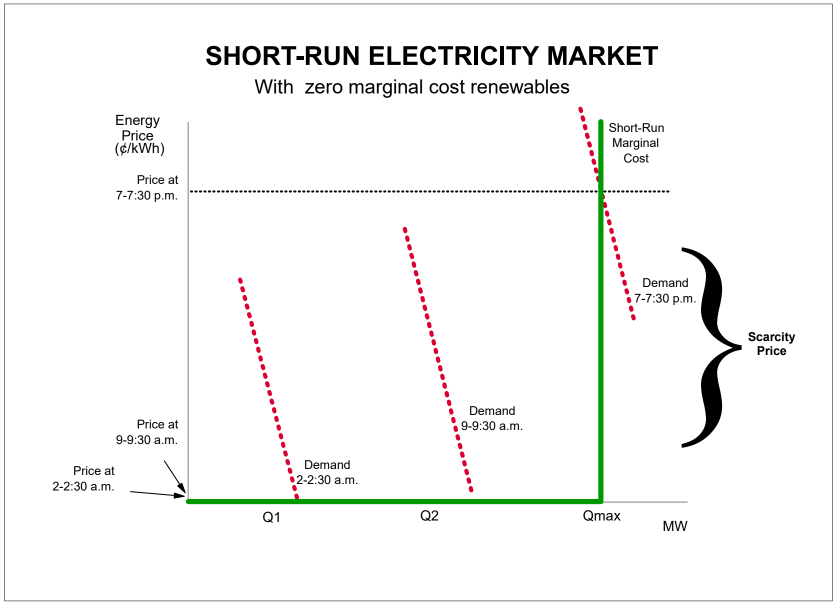
Market expectations determine incentives. Start at the end.
Work backward, not forward, in setting market design.

CLEAN ENERGY — Electricity Markets

The climate challenge will stress the electricity system. The cost-benefit analysis and the Social Cost of Carbon provide guidance for what, how much and how fast a transformation is needed.

- **Real-Time Electricity Markets.**
  - Low or Zero-Variable Cost Renewables Do Not Change the Basic Principles.
  - Wholesale Markets Following Successful Markets Design.
  - Expanded Pricing for Real-Time Ramping and Dynamic Dispatch.
  - Demand Participation and Distributed Generation Through Workable Distribution Pricing Reforms (e.g. FERC Order 2222)





CLEAN ENERGY Electricity Markets

The climate challenge will stress the electricity system. The cost-benefit analysis and the Social Cost of Carbon provide guidance for what, how much and how fast a transformation is needed.

- **Infrastructure.**
  - Completing the Smart Meter Revolution with Smart Pricing.
  - Transmission Expansion for Integrating Intermittent Renewables.
- **Avoid New Stranded Assets.**
  - Clean Energy Technologies Where the Deployment Costs Exceed the Climate Benefits.
  - Infrastructure Investments Anticipate Trajectories that Are Too Expensive.

Market Design: Expect surprises, focus on the incentives, and get the prices right.

Appendix Notes

Indifferent Transfers

Ignoring utility discounting, the equivalent tradeoff for consumption transfer between representative agents with different consumption levels with the DICE utility function satisfies

$$u'\left(c_1\right)=u'\left(c_2\right)\delta,$$

$$c_1^{-\alpha}=c_2^{-\alpha}\delta,$$

$$\delta=\left(\frac{c_2}{c_1}\right)^{\alpha}.$$

Hence, for the comparison in DICE, a reduction in 2020 consumption by one unit balanced by increase in 2100 consumption of

$$\delta=\left(\frac{c_{2100}}{c_{2020}}\right)^{1.45}=\left(4.41\right)^{1.45}=8.59\,.$$

Deterministic Consumption

With deterministic consumption, the Epstein-Zin utility model reverts to the DICE formulation. For Epstein-Zin recursive preferences,

$$U_t=\left[\left(1-\beta\right)c_t^{1-\alpha}+\beta\left(E_t\left[U_{t+1}^{1-\theta}\right]\right)^{1-\alpha/1-\theta}\right]^{1/1-\alpha}.$$

With no uncertainty, this becomes as in

$$U_t^{1-\alpha}=\left(1-\beta\right)c_t^{1-\alpha}+\beta\left(U_{t+1}^{1-\alpha}\right).$$

Use the ordinally equivalent transformation (Kasa, 2018),

$$V = \frac{1}{1-\alpha} U^{1-\alpha} .$$

We obtain the time additive preferences, as in DICE.

$$V_t = (1-\beta)\frac{c_t^{1-\alpha}}{1-\alpha} + \beta(V_{t+1}) = \frac{(1-\beta)}{\beta}\left[\sum_{t=1} \beta^t \frac{c_t^{1-\alpha}}{1-\alpha}\right].$$

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