EPA's Response to IPM v6 Peer Review Report

April 2022

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Response to the Peer Review Report

EPA Reference Case Version 6 Using IPM

U.S. EPA, Clean Air Markets Division

SECTION 1

INTRODUCTION

Background on Peer Review Process

In May 2018, the U.S. Environmental Protection Agency (EPA) released a new version of EPA's power sector modeling platform (designated Integrated Planning Model (IPM) version 6) [1] . This new EPA modeling platform incorporated important structural improvements and data updates with respect to EPA's previous version (version 5). EPA published several updates to EPA modeling platform version 6 Reference Case between May 2018 and September 2021.

IPM is a multiregional, dynamic, deterministic model of the U.S. power sector that provides projections of least-cost capacity expansion, electricity dispatch and emissions. The EPA uses the platform to project and evaluate the cost and emissions impacts of various policies to limit emissions of sulfur dioxide, nitrogen oxides, particulate matter, mercury, hydrogen chloride, and carbon dioxide.

In September 2019, EPA commissioned a peer review of EPA's v6 Reference Case using the Integrated Planning Model (IPM). Industrial Economics Inc., an independent contractor, facilitated the peer review of the EPA Version 6 Reference Case in compliance with EPA's *Peer Review Handbook* (U.S. EPA, 2006) and produced a report from that peer review.[2] Industrial Economics Inc. selected five peer reviewers (Dr. Dallas Burtraw, Dr. Seth Blumsack, Dr. James Bushnell, Dr. Frank Felder, And Frances Wood) who have extensive expertise in energy policy, power sector modeling and economics to review the EPA Version 6 Reference Case and provide feedback. The panel focused on the latest available Reference Case version and its documentation at that time (May 2019 Reference Case).

Peer review panel has been asked to:

- **Evaluate the suitability and scientific basis** of the methods (model formulation), model assumptions, model outputs, and conclusions derived from the model;

[1] EPA periodically publishes updated projections and their documentation. Documentation, input and output files for the latest EPA v6 Reference Case using IPM and links to the previous versions are located at https://www.epa.gov/airmarkets/power-sector-modeling

[2] https://www.epa.gov/airmarkets/ipm-peer-reviews-and-responses

- **Identify specific strengths, weaknesses, limitations, and errors** in the model formulation, model assumptions, model outputs, and conclusions derived;
- **Propose specific options** for correcting errors and fixing or mitigating weaknesses and limitations in the model formulation, model assumptions, model outputs, and conclusions derived;
- **Check the appropriateness of the set of model-scenarios for addressing uncertainty** in potential future power-sector trends and of particular relevance to future power sector emissions.

The peer reviewers evaluated the adequacy of the framework, assumptions, and supporting data used in the EPA Version 6 Reference Case using IPM, and they suggested potential improvements. Overall, the panel found much to commend EPA; stating that the modeling platform:

- lends itself well to EPA analyses of air policy focused on the power sector
- includes significant detail related to electricity supply and demand
- includes data-rich representation both across different geographic areas and across time
- provides a reasonable representation of power sector operations, generating technologies, emissions performance and controls, and markets for fuels used by the power sector
- is well suited to assess the costs and emissions impacts
- documentation is well written, clearly organized, and detailed in its presentation of most model characteristics

The independent peer review panel provided expert feedback on whether the analytical framework, assumptions and applications of data in the Version 6 Reference Case using IPM are sufficient for the EPA's needs in estimating the economic and emissions impacts associated with the power sector due to emissions policy alternatives. The panel made recommendations to improve the model's ability to represent the ongoing evolution of the industry; in particular:

- Continued penetration of renewables
- Increasing developments in energy storage technologies and markets
- Changes in load shapes from new forms of demand, like electric vehicles
- Evolving state and regional policies
- Evolving ISO/RTO market rules
- Increasing need for and advances in modeling capabilities of temporal resolution

Executive summary recommendations included:

1. Clarify types of **uncertainty** that the model is capable of handling

2. Reconsider **coal plant turndowns** and addition of operating reserves
3. Consider incorporating **upstream emissions**
4. Distinguish investment decisions between **utility and merchant power plants**
5. Address the **evolving gas markets** regionalization and emerging sectors
6. Consider alternatives to the current **load duration curves**
7. Improve representation of **behind-the-meter generation**
8. Increase transparency of **retail pricing** results
9. Consider improvements in the representation of various **policy mechanisms**
10. More thorough citing of sources and expanded explanations in **documentation**

Body of the Peer Review Report included over 100 recommendations (of which most of them tied back to the Executive Summary Recommendations) and about 50 edits to documentation. For quick and easy reference, all of the Peer Review Report recommendations and EPA's responses to those are tabulated in the Appendix and also referenced to the Section 2 of this document (EPA's response to Peer Review Report) for narrated responses.

Section 2 of this document provides a high-level response to the Executive Summary recommendations of the Peer Review Report, where we also grouped, incorporated and addressed many of the recommendations included elsewhere in the Peer Review Report.

Before and after Peer Review Panel completed their work, EPA published five updated v6 Reference Cases; namely May 2018, November 2018, May 2019, January 2020, and Summer 2021 Reference Cases. Vast majority of the Peer Review Panel recommendations, both in terms of capability improvements and documentation, have been addressed in the last public release with the Summer 2021 Reference Case (published in September 2021). EPA anticipates that future updates will continue to improve some existing features and will introduce new capabilities, as well as more detailed documentation as needed EPA is also working on publishing a number of side cases with alternative set of assumptions.

SECTION 2

ADDRESSING MAIN RECOMMENDATIONS

2.1 Updates to model to improve the model's ability to represent the ongoing evolution of the industry: demand/supply, new technologies, transmission, evolving state and regional policies, and ISO/RTO market rules

EPA continuously evaluates and makes updates or improvements to the model capabilities, parametrization heuristics, input data, and assumptions. Some of these are routine updates that are updated with every new reference case (such as the fleet information), some are integrated as new data becomes available (such as demand, generation cost and performance assumptions), and some categories are specifically evaluated as they become more prominent and potentially impacting projections through emerging future power sector dynamics and policy. EPA's reference case reflects on the books state and regional policies, and relevant ISO/RTO market rules. In addition, model has existing and potential capabilities for various possible policy mechanisms. Documentation of these capabilities. are usually not part of the Reference Cases but are routine part of the incremental documentation or Technical Support Documentation that accompanies policy or scenario analysis. Appendix of this document gives a detailed account of such capabilities mentioned in the Peer Review Report.

2.2 Types of uncertainty that the model handles

EPA primarily focuses on a central "reference case", which highlights conditions that can be reasonably expected. In order to evaluate how key uncertainties impact model projections, EPA has previously released (incremental to May 2018 Reference Case)[3] and plans to release (incremental to Summer 2021 Reference Case) a range of scenarios that outline a representative cone of outcomes. These scenarios will estimate the impact of changing natural gas prices, renewable technology costs, and demand.

2.3 Coal plant turndowns, operating reserves, continued penetration of renewables, dispatch

EPA models the turndown rate for coal plants at the unit level. The unit level turndown percentages for coal units were estimated based on a review of recent hourly Air Markets Program Data where most of the coal capacity has a turndown rate between 40% and 60%. EPA believes having unit-specific turndown rate is beneficial to our model projections because it accounts for the variation in performance of coal plants rather than representing it as a single value for the entire fleet, which is the approach employed by many other power sector models. EPA's turndown approach is an aspect of the model that we have revisited regularly and expect

[3] https://www.epa.gov/power-sector-modeling/results-using-epas-power-sector-modeling-platform-v6-may-2018

to continue to do so in the future, given that load following behavior has recently become more common in the coal-fired fleet.

EPA has evaluated the inclusion of operating reserve constraints in IPM through a variety of test runs and determined them to be beneficial for the projections, particularly for scenarios with a high deployment of renewable resources. At this time, EPA does not believe additional reserve products beyond operating reserve are necessary but will continue to evaluate this moving forward.

2.4 Incorporating upstream emissions

It is important for EPA to maintain the ability to show emissions from the combustion of the fuel and emissions specifically occurring at the power plant stack. This is central to both air quality modeling efforts and the majority of EPA EGU rulemakings that regulate stack emissions.

At the same time, EPA is developing approaches for quantifying upstream methane and CO2 emissions associated with the extraction, production, and distribution of coal, oil, and gas used in the power sector. EPA will include and document such data in relevant future applications.

2.5 Investment decision-making of utility and merchant power plants and capacity markets

While new build financing assumptions are not differentiated based on utility/merchant categorization, retrofits do include this differentiation. This in turn results in more realistic retrofit/retirement decisions for the existing fleet.

Within a cost minimizing framework assuming differentiated financing for new builds would result in possible over-builds and under-builds as a result of effective differences in levelized costs. Based on prior runs, these builds may be unrealistic in their concentrations. Instead, IPM assumes a weighted average financing charge for all new builds of a given technology type.

Based on prior testing we believe the current approach, i.e. differentiated financing for retrofits and weighted average financing for new builds is the most reasonable modeling convention.

2.6 Gas markets and natural gas price

Comments in this area tended to focus on two areas: 1) more transparency in documentation, 2) more definition given to under what scenarios EPA would reconstitute its natural gas supply curves.

In regard to the former, EPA has supplemented the documentation with additional language regarding the LNG export volume, non-power sector demand assumptions (particularly how it is

accounting for significant changes in the petro-chemical industry), and the relationship between GMM and IPM oil price assumptions. This is somewhat similar to the basin-specific discussion included in the coal supply section (except that gas supply curves are national in scope and the gas supply implementation is different from the coal supply implementation) where EPA provides detail on mining techniques, market conditions, and geological factors that are basin specific and experiencing change.

The appropriateness of the natural gas demand projected by IPM and the supply curves used in the model are considered throughout scenario production. In each run, EPA evaluates consistency of projected natural gas consumption and production with the basis differentials provided by GMM. EPA will continue to document information concerning the incorporation of GMM outputs in IPM analyses.

2.7 Alternative load duration curves changes in load shapes from new forms of demand (such as electric vehicles); regional and temporal resolution

As an input to the model, the impact of alternative load shapes has been tested in a number of scenarios and applications. For example, EPA is working on an analysis to support the evaluation of impacts of warming temperatures on the power sector in the USA using IPM and IPCC scenarios. This side case will demonstrate and quantify incremental impacts relative to the EPA's reference case, taking into consideration impacts on electricity demand, power plant capacity, power plant heat rates, transmission capacity and hydropower impacts, in addition to identifying additional areas and improvements needed for further study. EPA has also completed a number of internal analyses evaluating the impact of electric vehicle charging load, varying both its magnitude and timing. Since the model's input structure allows to modify load (both its shape and magnitude) as needed, we have evaluated various Energy Efficiency cases in the past and will continue to do so.

IPM can be configured with varying number of seasons. For example, in v6, a winter shoulder season was added to better capture seasonality in wind generation. The load segments can also be customized to account for time of day to better capture solar generation. The seasonal structure and segmental configuration is reviewed with each update and might need to be revised in the future to capture electric vehicle load.

2.8 Improving representation of behind-the-meter generation

To improve the representation of behind-the-meter generation, EPA has recently updated its approach so that non-dispatchable distributed generation affects the shape of the load duration curve, instead of simply reducing the net energy for demand used in the projection.

2.9 Increasing transparency of retail pricing model

EPA is improving the documentation for the Retail Price Model by providing further clarification on and discussion of key components of the model. Additional improvements to the documentation will also include an enhanced discussion of the purpose of the model, and explain how that relates to the different methodologies for estimating retail price in competitive and regulated regions.

2.10 Representation the of various policy mechanisms and publishing alternative/side cases

EPA has the capability to run a wide array of scenarios in IPM to inform and shed light on important power sector projections. Previous iterations of IPM that have been released have included alternative scenarios, for public dissemination and review. These scenarios have included alternative assumptions for electric demand (high and low), renewable energy costs (high and low), and natural gas price. EPA continues to consider, develop, and perform alternative scenarios to inform its efforts to address pollution from the power sector, and will continue such efforts. Where appropriate, EPA will release and disseminate scenarios to accompany future IPM updates. In addition, EPA will consider such scenarios in other contexts where IPM is being used, such as regulatory development.

2.11 Documentation improvements including results viewer

A number of documentation improvements were reflected in the Summer 2021 Reference Case full-fledged documentation providing additional detail and clarity. These are tracked in the Appendix table. Documentation updates will continue with each update as needed in light of both formal reviews and comments received from stakeholder and user community.

EPA has refined the Results Viewer to make it more intuitive and easier to use. The controls were modified to automatically match between primary and comparison cases to make use easier. The units displayed above charts were updated to clearly indicate the cases being compared. And finally, the “Read Me” guide was edited and updated for clarity.

Appendix: Table for Detailed Accounting of Peer Review Recommendations and Narrated Responses

Response Document Section where addressed	PR Sect. #	PR Page #	PR Para. #	PR Recommendation Section/Category	PR Recommendation Summary	Detailed Recommendation Text	Additional EPA Response Notes (detailed narratives start after Executive Summary rows) EPA's IPM Summer 2021 Reference Case Documentation is available here
2.1	ES	ii	1	Consider changes to the model formulation that would improve the model's ability to represent the ongoing evolution of the industry	represent the ongoing evolution of renewable industry	increases in the penetration of renewables	
2.1	ES	ii	1	Consider changes to the model formulation that would improve the model's ability to represent the ongoing evolution of the industry	represent the ongoing evolution of EF adoption	changes in load shapes… [from] electric vehicles	
2.1	ES	ii	1	Consider changes to the model formulation that would improve the model's ability to represent the ongoing evolution of the industry	represent the ongoing evolution of storage industry	changes in load shapes… [from] energy storage	
2.1	ES	ii	1	Consider changes to the model formulation that would improve the model's ability to represent the ongoing evolution of the industry	represent the ongoing evolution of state and regional policies	state and regional policies	

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2.1	ES	ii	1	Consider changes to the model formulation that would improve the model's ability to represent the ongoing evolution of the industry	represent the ongoing evolution of changes in LDC	revising the intra-annual load segments	
2.1	ES	ii	1	Consider changes to the model formulation that would improve the model's ability to represent the ongoing evolution of the industry	represent the ongoing evolution of modeling for the power sector	solving the model chronologically	
2.1	ES	ii	1	Consider changes to the model formulation that would improve the model's ability to represent the ongoing evolution of the industry	represent the ongoing evolution of modeling for the power sector	solving a companion model that describes chronological demand and system operation using capacity assumptions from IPM	
2.1	ES	ii	1	Consider changes to the model formulation that would improve the model's ability to represent the ongoing evolution of the industry	represent the ongoing evolution of storage industry	richer representation of energy storage	

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2.1	ES	ii	1	Consider changes to the model formulation that would improve the model's ability to represent the ongoing evolution of the industry	represent the ongoing evolution of market rules	incorporating changes in capacity market rules into the model (particularly as they relate to variable renewable energy)	
2.2	ES	ii	2	Clarify the types of uncertainty that EPA's Platform v6 is capable of handling	Clarify the types of uncertainty that are not captured by the model	documentation should provide guidance to model users that more clearly articulates the types of uncertainties captured and not captured by the model	
2.2	ES	ii	2	Clarify the types of uncertainty that EPA's Platform v6 is capable of handling	Clarify the types of uncertainty and address uncertainty in a broader manner	consider evolution in the model structure to address uncertainty in a broader manner	
2.3	ES	ii	3	Reconsider coal plant turndown constraints and possible addition of operating reserves	Reconsider coal plant turndown constraints to determine if it creates bias in coal operations	EPA examine the turndown constraints more closely to determine if they create bias in coal plant operations, especially in scenarios with low gas prices or high renewable generation	
2.3	ES	ii	3	Reconsider coal plant turndown constraints and possible addition of operating reserves	Reconsider coal plant turndown constraints and consider operating reserves as an alternative solution	consider whether adding explicit operating reserve requirements in the dispatch would provide a better representation of the impact of high levels of renewable generators on the grid	

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2.4	ES	iii	1	Consider incorporating upstream emissions in addition to source-level (power plant) emissions	consider including upstream emissions	consider including upstream emissions in its reference case as a separately-reported item (so upstream and stack emissions are not combined together)	
2.5	ES	iii	2	Distinguish between investment decision-making of utility and merchant power plants	Distinguish between investment decision-making of utility and merchant power plants	Distinguish between investment decision-making of utility and merchant power plants	
2.5	ES	iii	2	Distinguish between investment decision-making of utility and merchant power plants	Distinguish between investment decision-making of utility and merchant power plants	evaluate whether a weighted average of existing firms within a power region or some other rule is a reasonable representation of which type of firm is more likely to make an incremental investment	
2.6	ES	iii	3	Address evolving gas markets where Henry Hub is less central to pricing and where emerging petrochemical production has greater influence	Address evolving gas market by describing in the documentation the model process for using GMM	[Describe in the documentation the model process for] iterating with the Gas Market Model that generates the natural gas supply curves and basis differentials	

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2.6	ES	iii	3	Address evolving gas markets where Henry Hub is less central to pricing and where emerging petrochemical production has greater influence	Address evolving gas market by tracking emerging petrochemical sector	emerging petrochemical sector in the Appalachian production region is likely to affect regional natural gas pricing in ways that may not be well represented in the gas market model that EPA's Platform v6 relies upon	
2.7	ES	iii	4	Consider alternatives to the current load duration curves (LDCs)	Consider alternatives to the LDC to better account for inter-regional trade	[How EPA] aggregates time into LDCs in a way that... creates biases related to the opportunities for inter-regional trade	
2.7	ES	iii	4	Consider alternatives to the current load duration curves (LDCs)	Consider alternatives to the LDC	assess the trade-offs between different approaches to aggregating load into LDCs	
2.8	ES	iv	1	Improve representation of behind-the-meter generation	Improve representation of behind-the-meter generation	capture policies that encourage behind-the-meter generation… [beyond] represented as a change in demand	
2.9	ES	iv	2	Increase transparency of retail pricing results	Increase transparency of retail pricing results	When EPA uses the RPM, we recommend that the reporting of retail rates be broken into component parts so that the user can understand which elements are endogenous to the model and which are dominated by external sources and assumptions	

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2.10	ES	iv	3	Consider improvements in the representation of various policy mechanisms	Improve representation of policy mechanisms such as dynamic allocation of emission credits	dynamic allocations within various forms of emissions trading programs such as output-based allocation under cap and trade and a clean energy standard	
2.10	ES	iv	3	Consider improvements in the representation of various policy mechanisms	Improve representation of policy mechanisms such as EE expenditures and carbon pricing	expenditures on energy efficiency that are linked to revenue from carbon pricing	
2.10	ES	iv	3	Consider improvements in the representation of various policy mechanisms	Improve representation of policy mechanisms such as flexible demand	ability to represent flexible demand that may be encouraged at the retail level to promote the integration of variable renewable energy	
2.11	ES	iv	4	More thorough citing of sources and expanded explanations throughout the EPA Reference Case v6 documentation	Update the documentation to include the development of the load segments	development of load segments	
2.11	ES	iv	4	More thorough citing of sources and expanded explanations throughout the EPA Reference Case v6 documentation	Update the documentation to include treatment of interregional trade	treatment of interregional trading	

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2.11	ES	iv	4	More thorough citing of sources and expanded explanations throughout the EPA Reference Case v6 documentation	Update the documentation to include aggregation of model plants	aggregation of individual plants to model plants	
2.11	ES	iv	4	More thorough citing of sources and expanded explanations throughout the EPA Reference Case v6 documentation	Update the documentation to include more detail for the retail price model	retail pricing model	
2.1	2	2	3	Uncertainty	periodically review the model to determine whether model structure should be modified or complemented with other modeling capabilities	EPA should periodically review the model to determine whether EPA's application of IPM model structure should be modified or complemented with other modeling capabilities	This is part of routine model development process.
2.1	2	3	3	Chronological modeling	restructure IPM as a chronological model	restructuring IPM as a chronological model	Possibility of making IPM a chronological model is a significant task and may be investigated. However, there is segmental output information that can be used. In addition, a production costing model such as PROMOD can be used in conjunction with IPM when required.

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2.1	2	3	3	Chronological modeling	develop a companion short-run chronological model of system operation	develop a companion short-run chronological model of system operation that would enable comparing the outcomes of the model's load duration curves with a more realistic characterization of the temporal nature of demand	ICF has run GE MAPS for EPA, while performing analyses in support of the MATS rulemaking, for example. ICF runs PROMOD production costing model routinely and could setup such a framework if so desired by EPA. PROMOD is a chronological model that can be run annually and does not make investment decisions. ICF runs PROMOD either at the interconnect level or at a subset of an interconnect level.
2.1/2.10	2	3	4	Demand response	incorporate demand response	consider incorporating additional factors into the model's formulation of demand response [including]… changes in total electricity consumption in response to changes in price	
2.1/2.10	2	3	4	Demand response	incorporate demand alternatives/substitutions to electricity	consider incorporating additional factors into the model's formulation of demand response [including]… substitution between electricity and other forms of energy consumption	This is not done through model formulation. Gas power plants are a form of substitution between electricity and other forms of energy consumption. A similar approach can be evaluated to estimate a kWh to Btu relationship and can be used in IPM.
2.1/2.10	2	3	4	Demand response	incorporate changes in the load shapes	consider incorporating additional factors into the model's formulation of demand response [including]… changes in the load shapes that will be observed and projected under different scenarios	This is not done through model formulation but load shapes are adjusted based on scenarios evaluated.

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2.1/2.10	2	3	4	Demand response	incorporate variations in supply-side short run marginal costs (due to increased VRE)	consider incorporating additional factors into the model's formulation of demand response [including]… variations in supply-side short run marginal costs (due to increased penetration of variable renewable energy)	In addition to the battery approach, we could also utilize the DSM/EE option functionality. NREL simulates flexible demand/DR with a 100% efficient battery that is time constrained. We can adopt a similar approach in IPM to model DR impacts under changing pricing patterns.
2.1/2.10	2	3	4	Demand response	incorporate retail TOD pricing or retail pricing linked to RE/clean energy	consider incorporating additional factors into the model's formulation of demand response [including]… potentially demand side retail prices that vary by time of day or are linked to resource availability directly require cross-time-period analysis of electricity demand	The endogenous demand response capability allows us to estimate demand response by load segment. In v6, we use TOD based load segments and hence demand response can indeed be linked to TOD. Due to the TOD based load segment structure, the generation from solar units, for example, accounts for TOD. IPM is a wholesale price model, which makes linking to retail pricing very challenging. We can make a simplification and allow demand to move in response to wholesale pricing.
2.7	2	3	5	Climate change considerations	periodically evaluate the model with respect to weather normalization of key data inputs	recommend that EPA periodically evaluate the model with respect to weather normalization of key data inputs	This has been evaluated in the past and we will continue to do so.
2.7	2	3	5	Climate change considerations	represent climate change impacts in generation	consider a more explicit representation of climate change in the model's specification of generation	On-going as scenario study.

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2.7	2	3	5	Climate change considerations	represent climate change impacts in transmission	consider a more explicit representation of climate change in the model's specification of… transmission	On-going as scenario study
2.7	2	3	5	Climate change considerations	represent climate change impacts in load	consider a more explicit representation of climate change in the model's specification of… load assumptions	On-going as scenario study
2.1	2	4	1	Transmission capacity	regularly revisit implementation of transmission	regularly revisit and, as appropriate, revise EPA's implementation of transmission outcomes and the assumptions that shape anticipated future transmission siting decisions	Transmission assumptions are regularly updated in v6.
2.1	2	4	2	Storage	model energy storage, including end-use storage	rigorous treatment of energy storage within the formulation of the model, particularly with respect to the opportunity to schedule demand and achieve thermal and battery storage for end-uses	Storage assumptions and parametrization are regularly visited and updated as needed in v6.
2.1	2	4	3	Capacity markets	represent resource adequacy as they are structured	representations of resource adequacy requirements, as opposed to modeling a generation reserve requirement	We will continue to monitor relevant market developments and make appropriate changes. The introduction of the operating reserve constraint begins to approximate this constraint.
2.11	2	4	4	Additional operational constraint	include operating reserve requirements	include operating reserve requirements	This is implemented. See Section 3.7

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2.2	2	5	1	decision-maker uncertainty	evaluate model results in an option value framework	improve the way they use model results by explicitly considering them in an option value framework	EPA has previously released and plans to continue to release a range of scenarios that outline a representative cone of outcomes. These scenarios estimate the impact of changing natural gas prices, renewable technology costs, and demand.
2.11	2	5	2	runtime restrictions	publish runtime restriction requirements	any runtime restrictions required by the EPA should be made explicit and used to appropriately structure EPA's application of IPM to the task at hand	This is a pragmatic preference rather than restrictions.
2.10	3a	6	4	Demand	include electricity price response in policy and sensitivity cases where prices vary significantly	We view the use of fixed electricity demands without response to electricity prices as problematic in policy and sensitivity cases where prices vary significantly from the Reference Case. We recommend that EPA use this feature when analyzing policy scenarios that have significant price impacts (perhaps roughly greater than 20% variation in wholesale prices).	The capacity to perform demand response already exists. EPA has used IPM's demand response functionality while conducting carbon policy analyses in the past.
2.10	3a	6	4	Demand	publish in more detail how the elasticity is applied when used	recommend that the EPA Reference Case v6 documentation describe in more detail how the elasticity is applied when used	When a certain parameter/capability is used, they are always documented in the corresponding side/alternative case or policy case.

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2.1	3a	7	2	Demand	develop better load shapes over time	a more systematic way is needed to develop load shapes over time rather than just using a single metric of load factors from ES&D or the AEO to shift the curves	Usually, load factors are the only piece of data that is available from AEO and NERC projections. If future year load shapes that underlie AEO or NERC demand projections are available (for the use in side cases possibly), then we can develop a methodology to use those load shapes.
2.7	3a	7	4	Demand	evaluate using data for a single year vs. a multi-year average or weather normalization would be more appropriate	recommend that EPA consider whether using data for a single year creates any biases and whether a multi-year average or weather normalization would be more appropriate	Both approaches could have pros and cons for the various EPA applications (including AQM). Using a multi-year average could result in load shapes that are very different from the original load shapes and is not considered at this time.
2.11	3a	7	4	Overall	have consistency among AEO vintages used for data assumptions	have consistency among AEO vintages used for data assumptions	This is a goal but is hard to implement in practice as not all parameters are available or updated in any given year. AEO or other sources, we strive to incorporate most recent data available with significance with every update. Inevitably, not all data categories will reflect the same calendar year or vintage in any given IPM version.
2.3	3a	8	3	Dispatch	allow steam plants to shut down for lowest load time segments when they run at full capacity during the peak segment	it appears that steam plants would not be able to shut down for any time segments (such as segments with lowest load) if they are expected to run at full capacity during the peak segment.	Our turndown approach is an aspect of the model that we have revisited regularly and expect to continue to do so in the future. Turndown constraints can be reconfigured to allow coal plants to shut down at time of lowest load. However, this change should be considered with care as to disallow overoptimization through cycling.

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2.3	3a	8	3	Dispatch, turndown rate	publish information on dispatch by time segment	output files from EPA's Platform v6 do not include information on dispatch by time segment	Dispatch by time segment is not available to either the public or EPA
2.3	3a	8	4	Dispatch, turndown rate	develop turndown rates based on technical operational considerations rather than historical economic circumstances	the turndown constraints vary considerably by unit, and some are as high as 80% with most of them between 40% and 60%. Because these values are based on historical operations rather than current or projected engineering considerations, they may reflect historical economic circumstances that may not apply in the future	The turndown assumptions can be updated based on current data to reflect the current operating behavior of coal plants. Our turndown approach is an aspect of the model that we have revisited regularly and expect to continue to do so in the future. In addition, if the low gas price environment persists, then the assumptions could also be relaxed (turndown targets lowered) to reflect increased cycling.
2.3	3a	8	5	Dispatch, turndown rate	examine the turndown constraints for bias in coal scenarios with low gas prices or high renewables	recommend that EPA examine the turndown constraints more closely to determine if they create bias in coal plant operations, especially in scenarios with low gas prices or high renewable generation.	We are currently working on this.
2.1	3a	9	1	Dispatch	add operating reserve requirements	consider whether adding explicit operating reserve requirements in the dispatch would provide a better representation of the impact of high levels of variable renewable energy	This feature is implemented in the current platform. See Section 3.7

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2.1?	3a	9	2	Dispatch	analyze historical generation versus the model patterns by time period for hydro	consider analyzing historical generation patterns versus the model patterns by time period to assess whether EPA's application of IPM is significantly overoptimizing hydro generation	The concern about overoptimization is primarily related to run-of-river hydro units that do not have storage. In the current update, we have aggregated run-of-river hydro units separately and then model their generation through a generation profile based on recent history. See Section 3.5.2
2.1	3a	9	4	Transmission	update transmission loss assumptions	The application of a 2.4% transmission loss to each interregional transfer strikes us as high for the Eastern Interconnect, especially given the size of the model regions and hence relatively short distances for many of these transfers. For example, in NEMS a 2% loss factor is assumed for transfers between regions and there are fewer regions.	We are currently evaluating this recommendation and can easily update/implement.
2.1	3a	9	5	Transmission	perform sensitivity cases where transmission capacity is added	performing sensitivity cases in which additional transmission capacity is added exogenously	The recommendation is to perform sensitivity analyses where we exogenously add transmission capacity. We have incorporated endogenous transmission builds, this sensitivity analysis may be unnecessary.

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2.3	3a	10	3	Capacity Expansion - Setting the Capacity Targets	add reserve ramping constraint	application of IPM may need to be modified to reflect other capacity requirements beyond a simple reserve requirement and declining capacity values for variable renewable capacity. For example, it may be appropriate to add an additional reserve constraint requiring a percentage of capacity is capable of meeting a certain ramping capability	We monitor the electricity markets continuously and make updates to the model to be consistent with changes in the markets. As the resource mix changes and requirements like California's or other mechanisms become more common, the model will be updated accordingly to account for the changing dynamics. A step in the direction is the incorporation of the operating reserves constraints in v6. We do not believe additional reserve products are necessary for the scenarios we are currently pursuing but will continue to evaluate this moving forward.
2.3	3a	11	2	Capacity Expansion - Setting the Capacity Targets	modify the short-term supply cost adders for capacity expansion	The cost adders to capacity expansion costs when expansion is rapid… are quite steep with roughly a 45% cost penalty on the second step. It might be better to have smaller initial steps with smaller cost penalties for the second step.	These constraints are applied to all new plants for the 2021-2035 run years. However, they usually get activated for solar and wind builds in runs having stringent RPS/CES standards. In EPA v6, the short-term capital cost adders step widths are from AEO. However, the approaches differ from AEO in the sense that in IPM we are not updating the step widths to account for the IPM builds.
2.3	3a	12	2	Capacity Expansion - Rating the Capacity of Alternative Resources	update the solar capacity credits to latest AEO	if the solar capacity credits are still benchmarked to those of the AEO2017, as indicated in the documentation, this should be revisited because the AEO methodology and resulting credits for solar have changed considerably since the AEO2017 was published	Solar capacity credits are no longer being benchmarked with the AEO version. See Section 4.4.5

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2.5	3a	12	2	Capacity Expansion - Rating the Capacity of Alternative Resources	examine capacity market rules and consider the implications of non-performance risk	we recommend that EPA examine the capacity credit methodology as system operators change their capacity market rules and consider the implications of non-performance risk	This is standard practice, although there is a balance between chasing today's rules versus the 'true' value, as understood by the model. We will continue to monitor the changing rules.
2.5	3a	12	3	Capacity Expansion - Rating the Capacity of Alternative Resources	account for demand response and energy efficiency in capacity markets	worth noting that demand response and energy efficiency are providing non-trivial shares of total capacity and even larger shares of new capacity in many capacity markets	We are continuing to plan for how to incorporate these resources into our modeling projections.
2.1	3b	13	1	Storage	incorporate additional storage technologies into the model	recommends that EPA consider incorporating additional storage technologies into the model	Work is ongoing.
2.1	3b	13	1	Storage	regularly revisit energy storage cost, performance, and market assumptions	because the technologies, cost structure, performance, operating strategies, market rules, and regulations related to storage are rapidly changing, EPA may need to regularly revisit the model's representation of storage	Ongoing work. We routinely consider this for all technologies including storage.
2.1	3b	13	2	Storage	update energy storage technologies, costs, and operational assumptions regionally	consider regional variations in energy storage technology, costs, and operations	In the current version our implementation has regional variations of cost and capacity credit. See section 4.4.5

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2.1	3b	13	3	Nuclear	consider more flexible nuclear dispatch	consider more flexible nuclear dispatch in EPA's application of IPM	Nuclear dispatch is already flexible and is not hardwired. The reviewers appear to suggest that we model nuclear O&M costs as a function of the level of dispatch. EPA is participating in inter-agency workgroups to research and implement updates in modeling as needed.
2.1	3b	13	4	Heat Rates	vary heat rates by season and over time	recommend that the heat rates of generating units in EPA's application of IPM vary by season and perhaps over time	Heat rates are less impacted than capacity by change in temperature. This issue is less important as compared with the impact on capacity. We considered this in the past but have not found value for our applications so far. It might be interesting to consider grid reliability / reserves in light of units that might not be able to get the cooling water they need and therefore have to limit generation. But that would be either more episodic and hard to reflect in a long term capacity expansion model or would be considered as a side case evaluating warming impacts.
2.1	3b	14	2	Heat Rates	vary the available capacity of a given unit by season	recommend that EPA's application of IPM vary the generation capacity of a given unit by season, or add text to the documentation explaining why seasonal variation is not necessary	This primarily impacts CT and CC units. The primary impact is we might be underestimating generation potential in the winter season. We will evaluate the LOE required to implement this feature in IPM.
2.7	3b	14	3	Generation Assumptions	update generation over time to account for climate change	consider adjusting the EPA's Reference Case generation assumptions over time to account for climate change	This is a scenario case.

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2.1	3b	14	4	Generation Assumptions	vary generation assumptions by market/regulatory environment	consider varying some generation assumptions by market/regulatory environment	For existing units, EPA uses unit specific heat rates, emission rates, and technology assumptions. In addition, where possible, unit and state level emission regulations are also modeled in detail. Some of the other assumptions such as unit level availabilities can be used if such data is available.
2.4	3c	15	1	Assignment and Scope of Emissions Factors	document upstream air emissions in fuels prices or in generator marginal costs	consider documenting how upstream air emissions are reflected in fuels prices or in generator marginal costs within its Power Sector Modeling Platform	Upstream air emissions can be estimated through post processing. However, the challenge will be in defining the scope of what constitutes upstream and then developing the associated emission factors.
2.11	3c	15	3	Emission Control Options	periodically review the technology options for emissions control	suggest that EPA periodically review the technology options for emissions control in EPA's application of IPM to determine if this portion of the model could be made simpler with the reduction of emissions control technologies from which modeled plants can choose	This is always considered with major updates.

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2.11	3c	15	4	Emission Control Costs	publish the raw engineering data used to develop the unit cost values	Chapter 5 of the EPA platform v6 documentation includes unit cost estimates derived from the Sargent and Lundy study but does not provide a formal citation for the study or the raw engineering data used to develop the unit cost values. Publication of these data would make the cost figures used by EPA's Platform v6 more transparent than they are currently. We recommend that EPA consider the costs and benefits of this additional data transparency as weighed against the benefits of being able to access and use proprietary data, which in some cases may be more granular or up-to-date than data existing in the public domain.	As of 2022, we are working with S&L and in the process of updating reports.
2.11	3c	16	1	Emission Control Costs	periodically compare emissions control cost data with publicly available data	EPA should also periodically compare its emissions control cost data with relevant information that exists in the public domain, such as the Integrated Environmental Control Model (IECM) developed by Carnegie-Mellon University.	We will consider this.

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2.11	3c	16	2	Emission Control Costs	include natural gas combined cycle plants with carbon capture as a capacity option	the option to choose natural gas combined cycle plants with carbon capture appears to be turned off within the model… we recommend that EPA restore this technology option under relevant analyses.	These options are currently back in v6.
2.11	3c	16	3	Emission Control Costs	document interactions between IPM and GeoCAT	recommend that EPA incorporate additional specificity... in the documentation… [relating to] any interactions between IPM and GeoCAT.	IPM and GeoCAT are never iterated together, nor there are any interactions between the two tools. Updated documentation provides additional detail. Please see Section 6.2
2.11	3c	16	4	Emission Control Costs	re-evaluate the oil price assumption related to EOR and the CO2 storage cost curves	should re-evaluate the oil price assumption related to EOR… [and] re-evaluate the CO2 storage cost curves	On-going work, we update oil prices regularly.
2.11	3c	16	5	Emission Control Costs	remove CO2 transport pipeline economies of scale and document model approach	Some elements of the CO2 transport model are also not clear, particularly related to the economies of scale in pipeline transportation. The method described in Section 6.3 of the documentation appears to assume that CO2 sources that are transporting CO2 over longer distances for long-term geologic sequestration are taking advantage of some undescribed scale economies in the form of capacity sharing in CO2 pipelines.	In the latest reference case, EPA is no longer accounting for scale economies while estimating the cost of CO2 transportation. Please see Section 6.3

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2.5	3d	17	5	Power Sector Finances and Economics	add equation and reference for the capital charge rate	The description of the calculation of the capital charge rate would be made substantially more clear with an equation. In particular, whether EPA's Platform v6 uses the common "short cut" version of the capital charge rate (Stauffer, 2006) could be made more clear	The reviewers indicated a desire to have more information on the capital charge rate and to ensure that the concerns of Stauffer (2006) are not affecting the capital charge rate. Stauffer, a founder of ICF, indicates that there could be confusion between real and nominal capital charge rates and input parameters, which is not a problem. He may have indicated other concerns, but we have not reviewed his 2006 article in detail. We could review the article and determine next steps, if any.
2.5	3d	17	6	Power Sector Finances and Economics	describe the debt life versus the asset life	recommend an explicit statement in the documentation describing the debt life versus the asset life.	In general, the debt life is shorter than the book life. This is based on the tenure of debt, especially in the IPP sector. See Section 10.10.2
2.5	3d	17	7	Power Sector Finances and Economics	update assumptions on debt-to-equity ratios and the cost of merchant debt	assumptions on debt-to-equity ratios and the cost of merchant debt, which in the market environment at the time of this writing may be high. EPA's Platform v6 uses a value of 7.2%, but one of the stated data sources for debt-to-equity ratios currently suggests that the cost of debt may be substantially lower.This is a data point that we suggest be updated in future revisions of EPA's Platform	Financial assumptions are regularly updated, and D:E ratios are one of the metrics we closely track.

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2.5	3d	18	2	Power Sector Finances and Economics	use a different WACC formula with a constant leverage ratio	[Consider using a different WACC formula other than Hamada] Brealy and Myers (2011) point out that a constant leverage ratio is a more realistic assumption	The Hamada equation is used to adjust for differences in the reported debt to equity structure and the targeted structure. The reviewers point to a source that they assert favors a constant leverage assumption. In the case of IPPs, there has been very high debt shares, large amounts of financial distress, especially in some periods. Accordingly, we believe this unusual situation warranted adjustments to more sustainable debt levels.

2.5	3d	19	2	Power Sector Finances and Economics	account for differentiated risk appetite of utility versus merchant investment costs of capital	consider addressing this differentiated risk appetite [of utility versus merchant investment costs of capital] in future versions of EPA's modeling platform. One possibility would be to introduce different hurdle rates for different investor decision-makers and effectively split investment decisions within EPA's application of IPM.	While new build financing assumptions are not differentiated based on utility/merchant categorization, retrofits do include this differentiation. This in turn results in more realistic retrofit/retirement decisions for the existing fleet. Within a cost minimizing framework assuming differentiated financing for new builds would result in possible over-builds and under-builds because of effective differences in levelized costs. Based on prior runs, these builds may be unrealistic in their concentrations. Instead, IPM assumes a weighted average financing charge for all new builds of a given technology type. In the peer review, the issue that was identified as the most important is the use of a weighted average cost of capital of regulated utilities and merchant powerplants. In nominal terms, the WACCs of utilities are 4.9% versus 6.7% for IPPs; the weighted average is 5.6%. The latest modeling bases its financial assumptions on a 60:40 utility: merchant weighting. The 60:40 weighting approximately equals the 2015-2019 average for renewable and thermal additions in the US. The concern is that the use of the average may not adequately characterize the financing costs. The peer review suggests designating some regions as regulated utility and others as merchant IPP. The decision to use an average was based in part on the uncertainty about the structure in the long term. The approach

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							also reflects the concern that there could be an unrealistic skewing of regional results. Namely, low capital cost regions would disproportionately make capital investments including disproportionately investing for export to high capital cost regions.

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2.11	3d	19	4	Power Sector Finances and Economics	update documentation on tax credits for wind energy	The documentation could also explain more clearly how tax credits for wind energy are treated.	The tax credits for both PTC and ITC are modeled as a reduction in the levelized capital costs of those resources. We provided better documentation.
2.11	3e	20	7	Coal	update documentation on coal mine closures	there is not enough information provided in the documentation to discern whether coal mine closures are exogenous or endogenous within the model and the degree to which closures in the model reflect recent changes in regional fuel supplies	
2.11	3e	21	2	Coal	evaluate differences between EIA's and EPA's coal prices/supply to ensure consistence across other sector demands	Because the AEO2017 view of coal prices and supplies reflected in export and non-electric sector demand may not match EPA's view of coal prices and supply, the projections of other sector demands and exports may be inconsistent with power plant demand.	We acknowledge that there may be inconsistencies in our current approach. There will always be seams between IPM and AEO, we will continue to investigate to limit them and their impact.
2.11	3e	21	2	Coal	keep the base projections for coal up to date	consider keeping the base projections up to date (using AEO2018 (or AEO2020 if an update is done) versus AEO2017)	This is always considered and usually implemented at every update.

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2.6	3e	21	4	Natural Gas	run the GMM and IPM iteratively when necessary	One disadvantage of this static curve approach is that it treats prices in different years as independent in EPA's Platform v6 context, rather than as a function of cumulative production that may vary by EPA scenario, even though the underlying curves were developed with that consideration by GMM. This can be addressed by re-estimating the curves by running the models iteratively, as in the Reference Case set-up, when it seems necessary due to significant changes in gas demand.	While IPM's endogenous gas model can address this issue, an alternate approach is to regenerate the gas supply curves whenever there is significant divergence in the gas demand relative to that in the reference case. An initial Ref Case is set up by iterating between GMM and IPM. But we do check when/if the static curves are no longer appropriate for a given case.

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2.6	3e	21	4	Natural Gas	publish methodology for deriving gas supply curves	recommend that EPA publish more information about the methodology for deriving the curves	The slopes of the gas supply curves are derived based on ICF's assessment of change in natural gas prices historically based on several parameters like rig count, production, etc. and certain assumptions of the natural gas resource base moving forward to determine the short-term and long-term supply elasticity that feed into the supply curves. The way the supply curves are built is that they are more elastic over time compared to the short-term elasticity as the resource base can respond to price changes. In other words, the short-term elasticity is higher than the long-term elasticity. More elaborate documentation is provided. See Section 8.2.1
2.6	3e	22	1	Natural Gas	describe how LNG exports are determined	It is also not clear the degree to which LNG exports, both export capacity expansion and utilization, are determined endogenously versus predetermined.	ICF assumption of LNG exports for EPA base case is exogenous; however, GMM has the capability to change the LNG exports over time in response to change in natural gas prices. More elaborate documentation is provided. See Section 8.3.5

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2.6	3e	22	2	Natural Gas	update seasonal gas price differentials across scenarios	The GMM also serves as the basis for seasonal price differentials that capture the difference between the Henry Hub price and gas prices in model regions. While these differentials are endogenously projected by GMM with variable costs as a function of pipeline throughput and pipeline capacity expansions, they are fixed in a given scenario context.	Under scenarios with major changes in natural gas demand regionally, the change in basis can be captured by GMM based on the pipeline infrastructure build-out necessary to support the demand growth under that particular scenario. However, this requires iterations between GMM and IPM.
2.6	3e	22	3	Natural Gas	include petrochemical sector demand in the GMM	Within the GMM, econometric equations project other sectoral regional gas demands. The elasticity of these demands presumably impacts the overall supply elasticity of gas to the power sector. We note, however, that an emerging petrochemical sector in the Appalachian production region is likely to affect regional natural gas pricing in ways that may not be well represented in the gas market model.	GMM base case forecast for EPA base case projects significant growth in natural gas production from the Marcellus and Utica region from 2019 through 2050 (about 25 Billion Cubic Feet per Day) which does account for growth in NGL demand and exports from the Appalachia region exogenously.

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2.6	3e	22	5	Other Fuels	ensure consistency across oil price assumptions between IPM and GMM	oil prices are treated inconsistently across EPA's Platform v6 and ICF's GMM platforms. While oil prices for power generation are based on the AEO2017, diesel fuel prices used in developing rail rates for coal are from the AEO2016. At the same time, oil prices used in the GMM, which are used to determine fuel switching in the industrial sector, are quite different from those from the AEO that are used in the rest of EPA's Platform v6	In the future reference cases, DFO and RFO fuel prices will be made consistent with the crude oil price projections used in the GMM.
2.1	3e	23	4	Renewable Resources	apply generic transmission costs to all units including wind and solar	It would seem more consistent for the generic transmission network costs to be applied to all units rather than exempting wind and solar. Otherwise this provides a bias towards wind and solar PV development	These costs are currently applied in the v6. Documentation incorporated better explanation of distance to transmission vs. generic transmission network costs, aligning NREL and AEO approach as much as possible. Please see Section 4.4.2
2.7	3f	24	5	Regional and Temporal Resolution	evaluate differences in peak load and peak net-load	Load aggregation can dilute outcomes that are concentrated into a small number of hours… EPA's Platform v6 addresses this well by specifying a very high peak load segment, representing only 1% of all hours. However, key transient outcomes in the system may not be limited to only peak hours, particularly with extensive adoption of renewable energy resources.	We will investigate this in the near future.

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2.7	3f	24	6	Regional and Temporal Resolution	evaluate load aggregation implications regarding inter-regional trade	Load aggregation necessitates difficult modeling choices regarding inter-regional trade… diagnose the full impacts of this implementation. Our intuition is that it constitutes a hidden penalty on trade between regions; in order to export during hours in which trade is beneficial, the model may be forcing additional trade in hours in which trade is not beneficial. If true, this means the model will bias downward trade between regions.	The intuition is correct. There could be hours when power might be exported during hours when it might not be needed. Additional analysis is not required to confirm this assessment.
2.7	3f	26	4	Regional and Temporal Resolution	document interregional trade	One additional comment on this point is that the documentation does not describe this aspect of interregional trade.A description with an accompanying example would help promote understanding of this feature of the model	
2.7	3f	26	5	Regional and Temporal Resolution	evaluate aggregating load over a larger geography	Geographic aggregation involves trade-offs between accuracy over time vs. space… One way to reduce the problems identified above [related to inter-regional trade] is to aggregate over larger geography.	We will investigate this in the near future.

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2.7	3f	27	1	Regional and Temporal Resolution	evaluate the model's ability to represent regulations focused on peak or episodic emissions	Load aggregation limits modeling of inter-temporal constraints… For regulations that concern total output or emissions from a power plant during a season or year, the aggregation is likely relatively benign. However, for the purposes of assessing any environmental regulations focused on peak emissions, episodic emissions, or emissions intensity, the aggregation could be more problematic.	This will be considered in the future if such policy design is necessary.
2.7	3f	27	4	Regional and Temporal Resolution	Publish model outputs by load-segment	Publish more output details: Currently model outputs are not broken out by load-segment. This additional output detail may allow stakeholders to better judge the relative impacts of the various aggregation assumptions in a given policy context	Dispatch by time segment is not available to either the public or EPA. Duplicate with row 55
2.7	3f	27	5	Regional and Temporal Resolution	evaluate tradeoffs between regional and temporal aggregations	Investigate the Time vs. Geography Trade-off: It is possible that the goals of the model may be better implemented with more temporal resolution and that this could be aided by less geographic resolution	
2.7	3f	28	2	Regional and Temporal Resolution	evaluate grouping hours first by time of day and then by load segment	Consider grouping hours first by time of day and then by load segment, instead of the other way around.	The current approach was implemented for simplicity. The alternate approach can also be implemented. Such an approach will eliminate the possibility of load segments having zero hours.

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2.7	3f	28	3	Regional and Temporal Resolution	evaluate grouping hours first by load segment for a whole interconnection and then by region	Investigate the implications of grouping hours first by load segment for a whole interconnection and then by region... group hours by their interconnection-wide load level and then subdivide into regions. For example, the top 37 summer hours would be chosen from the hours with the highest total load across the WECC.	We will investigate this in the near future.
2.7	3f	28	4	Regional and Temporal Resolution	evaluate grouping hours into time-of-day blocks (e.g., 4 hours) and model them sequentially	Represent time as a sequence of "model hours" or "model days." ... One alternative would be to group hours into time-of-day blocks (e.g., 4 hours) and model them sequentially, allowing for better representation of some inter-temporal constraints, inter-regional trade, and probably renewable energy and storage output. One such "model week" per season could capture a peak day and other important load characteristics.	A sequential hour approach may not work in models that are based on a load duration curve. Needs further evaluation.
2.7	3f	28	5	Regional and Temporal Resolution	evaluate grouping hours into time-of-day blocks for typical weekdays and weekend days with a preservation of peak loads through a peak-day or other method	Represent time as a sequence of "model hours" or "model days." … Another alternative would be to group hours into time-of-day blocks for typical weekdays and weekend days with a preservation of peak loads through a peak-day or other method.	IPM has the capability to separate load segments based on weekday and weekend days in addition to TOD. We have performed some test runs. This functionality can double the number of load segments.
2.7	3f	28	6	Regional and Temporal Resolution	link the model results with a dispatch model	Run the output of a model scenario through a more detailed dispatch model.	

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2.7	3f	29	2	Regional and Temporal Resolution	model fewer future years to compensate for more detail within a given model year	Model fewer future years. One way to compensate for more detail within a given model year would be to run fewer model years. Seven, instead of eight, explicit model years would reduce the number of demand segments (region + hours).	Outputs serve multiple purposes of EPA applications and we do consider output years carefully. The future run years in five-year increments are also important due to significant reductions in new unit costs and the start of several state level clean energy standards.
2.5	3f	29	3	Regional and Temporal Resolution	evaluate using a higher discount rate in the objective function	Consider the impact of the discount rate in the objective function… An even higher discount rate may be appropriate to minimize the impact of out-year decision making on model outcomes	We use discount rates based on our financial analyses. Further thought needs to be given in regards to use of discount rates whose primary function is to reduce the impact of out years on model outcomes. Previously we used a post-processing tool to change policy cost NPV with different discount rate, not in the objective function, but it is a tool for evaluation.
2.10	3g	29	5	emerging policy and industry issues to consider	model dynamic allocation of emissions allowances in cap and trade programs	Although trading programs are represented well in EPA's Platform v6, the documentation indicates that the model does not include any explicit assumptions on the allocation of emission allowances among model plants under any of the programs. An element of cap and trade that may be challenging to model is dynamic allocation of emissions allowances that maintains the emissions cap.	IPM has the capability to model output-based allowance allocations methods and has performed such analyses in the past. However, there may not be an immediate need for this functionality. The cap and trade programs promulgated by EPA do not account for this policy lever; it is not one of the central policy parameters under discussion, and is not utilized anywhere at the moment (including RGGI).

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2.10	3g	30	2	emerging policy and industry issues to consider	model clean energy standards with effective emissions targets that adjust over time in response to the quantity of production	challenges arise in representing clean energy standards, which are emissions intensity standards with effective emissions targets that adjust over time in response to the quantity of production.	These constraints can be approximately modeled through a set of two constraints in IPM. Constraint 1 can model the emission intensity standards through lbs/MWh constraints and Constraint 2 can model the effective emissions targets through cap based constraints. We are currently exploring issues related to CES policy design.
2.10	3g	30	3	emerging policy and industry issues to consider	model dynamic allocation of emissions allowances in cap and trade programs	Other challenging elements in representing power sector environmental policies include dynamic adjustments to emissions budgets based on the prevailing price in an auction, as illustrated by the emissions containment reserve in the Regional Greenhouse Gas Initiative	
2.10	3g	30	5	emerging policy and industry issues to consider	document the interactions between electricity sales/transmission and renewable energy credit markets	there is an interaction between electricity sales and transmission, and renewable energy credit markets. Although we understand that this interaction is embodied in the model, we have not seen it represented in previous exercises of the model or described in the documentation	IPM solves for the power, fuels, and environmental markets simultaneously. The interaction among these markets and within these markets are modeled endogenously in an integrated manner. We provided further detail in documentation. Please see Section 2.3.10

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2.10	3g	31	1	emerging policy and industry issues to consider	evaluate leakage risk between RPS policies and carbon pricing policies	Policies such as carbon pricing that promote an increase in renewable generation in one region could precipitate a decrease in renewable generation in another region if renewable energy credits become available in the region introducing carbon pricing that can be used for compliance with renewable portfolio standards in other jurisdictions.	Such an analysis may only be relevant when EPA is designing or promulgating any of these policies. When necessary, leakage issues will be addressed in policy contexts in new analyses or rulemakings where this is relevant.
2.10	3g	31	2	emerging policy and industry issues to consider	evaluate impact of the New Source Review in constraining existing generation and limiting new investments	Some prescriptive policies such as New Source Review constrain the utilization of an existing generating unit and limit investments in new units in a geographic area. The Agency should pay special attention to this in evaluating its modeling	As part of the flat file generation process, emissions from new units are not assigned to areas which are non-compliant. This approach can work in instances where only a subset of an IPM region is affected by these requirements. However, if an entire region is affected by these restrictions, then we may need to disallow the build of such units in those regions.
2.10	3g	31	3	emerging policy and industry issues to consider	model state level policies that encourage behind-the-meter generation	The model seems to capture policies that affect the bulk power system – but does not seem to capture state level policies that encourage behind-the-meter generation except represented as a change in demand.	The model could be developed and enhanced to do this kind of analyses, however this is not our priority currently. We can address this in other ways using a more simplified approach. This is something we would model separately and provide it as an input into IPM.

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2.10	3g	31	4	emerging policy and industry issues to consider	account for MOPR rules impact on nuclear and capacity market compliance	if EPA models nuclear generation incentives from state-level zero-emission-credit (ZEC) policies, it would also need to evaluate whether those nuclear plans should count towards satisfying a regional capacity constraint. Under final MOPR rules, which are as of yet to be determined, such nuclear capacity may not be part of capacity market compliance	Once the final rules are known, such units can be provided with zero capacity credit.
2.10	3g	32	2	emerging policy and industry issues to consider	improve the representation of the CO2 emissions rate for imports to California	one last finding pertains to the representation of the CO2 emissions rate for imports to California, at 0.428 MT/MWh... A careful solution to this could be found through iteration, solving the model twice varying the level of demand in California in order to identify the marginal resource providing power to the state and region, but this may require additional Agency resources.	The approach implemented was a tradeoff to minimize complexity. Potential approaches can be investigated to better represent AB 32. One potential solution is to focus more on the recent CA clean energy and RE requirements. However, it's not clear to identify a good path towards modeling imports into CA. We will continue to work on the methods for how to improve upon our current approach.
2.9	3h	33	1	Retail price estimates	document the purpose of the NUG adder in RPM	While it is not obvious that the capital costs of a merchant NUG would be directly passed on to retail rates, we assume the NUG adder is included because these costs are captured in long-term contracts between the generator and the local load-serving entity (but this is not explained in the documentation)	We will include this in the documentation.

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2.9	3h	35	1	Retail price estimates	document the purpose of the NUG adder in RPM	The general structure of the generation pricing formulas seems appropriate, but the purpose and magnitude of elements, such as the NUG adder, should be better explained.	We will provide better documentation
2.9	3h	35	2	Retail price estimates	define the difference between competitive vs. regulated regions	The logic behind the definition of competitive vs. regulated regions is unclear. There are many possible definitions of "regulated" and "competitive" and the RPM utilizes definitions from EIA's Annual Energy Outlook for its assignments of regions to these categories. This may not be the best definition for this application.	We will provide better documentation
2.9	3h	35	4	Retail price estimates	publish more of RPM results and their components	Based on the above comments, we recommend that EPA improve transparency of the RPM results and their components... One suggestion would either be a table or stacked bar chart detailing not just the total rate (or change in rate) but also the components that make up that total. Most of these details are available but take considerable effort to put together.	We consider RPM as a first order price generation tool. It is also used more for estimating the change in prices rather the absolute level of prices. Providing retail price components might be confusing and a digression. Provided better documentation and disaggregated impacts.
2.9	3h	73	1	Retail price estimates	define the difference between competitive vs. regulated regions	EPA should evaluate and articulate the purpose of distinguishing between competitive and regulated regions	

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2.9	3h	37	2	Retail price estimates	consider regression analysis for estimating the retail rate	Consider a simpler retail price formula based upon regression analysis of the relationship between generation costs and retail rates over time.	The purpose of the RPM is to measure the impact of a policy on prices.
2.2	4	38	4	non-parametric uncertainty	show how behavior may change or may depart from expected net present value maximization in the presence of uncertainty	one limitation of the focus on parametric uncertainty is that sensitivity analysis does not show how behavior may change or may depart from expected net present value maximization in the presence of uncertainty	Investment decisions can be impacted under uncertainty. If the intent is to create a strategy that is robust across a range of futures, then we can evaluate an approach such as a stochastic LP that can generate robust results under a range of scenarios. Additionally, this does not have to be analyzed through IPM development but a conceptual or weight-of-evidence response. We have been evaluating this for retirements.
2.2	4	39	1	non-parametric uncertainty	adjust the hurdle rate for investment and retirement options to account for option theory	option theory suggests rational decision makers will delay irreversible investments (and retirements) in the face of uncertainty to gain more information about the uncertain aspects of the scenario. This behavior will not be evident in an inter-temporal optimization linear program such as IPM. However, this element of decision-making under uncertainty might be represented by adjusting the hurdle rate for investment and retirement options, perhaps implemented as a shadow cost of capital for investments that would be vulnerable to specific parametric uncertainty.	This does not have to be evaluated through IPM development but a conceptual or weight-of-evidence response.

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2.2	4	39	3	parametric uncertainty	publish which parameters or combinations of parameters most heavily influence model outputs	Beyond the scenario runs made public by EPA, it is not clear what sensitivity analyses EPA conducts to determine which parameters are the most important in determining variation in model outputs. EPA's application of IPM is so complex that it may be the case that no single parameter is driving the model outputs all by itself. Some attempt at investigating and publishing which parameters or combinations of parameters most heavily influence model outputs in the Reference Case would be very useful.	Having methodical and documented sensitivity runs when we go through the development phase would be a very costly and time-consuming undertaking. We do this on an ad-hoc basis (dozens of sensitivities are run/tested); and many times we do not obtain the full outputs of test runs (as they are not necessarily fully QA'd) but assess what the results directionally suggest. Also, not all of those sensitivities can be planned beforehand but as the need emerges (in conjunction to other updates being made). Best method would be to envisage/group these runs retrospectively after we have arrived at a reference case. This would still render significant additional effort but it would be a more concise and targeted work serving documentation purposes and justifying various assumptions/updates made. We will consider this when we have resources.
2.2	4	40	1	parametric uncertainty, loadshapes	model scenario that includes changes in the shape of the LDC from vehicle electrification	Changes in the shape of the load duration curve: (1) vehicle electrification	This is ongoing work.
2.2	4	40	1	parametric uncertainty, loadshapes	model scenario that includes changes in the shape of the LDC from TOD pricing	Changes in the shape of the load duration curve: (2) time-varying retail rates that encourage load shifting and peak-time demand response,	

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2.2	4	40	1	parametric uncertainty, loadshapes	model scenario that includes changes in the shape of the LDC from demand response	Changes in the shape of the load duration curve: (3) wholesale (aggregated or individual customer) demand response that is generally dispatched during summer peaks to ameliorate very high market clearing prices or reduce peak system loadings for reliability reasons	Ongoing work. In the past we added demand response in for meeting capacity markets.
2.2	4	40	1	parametric uncertainty, loadshapes	model scenario that includes changes in the shape of the LDC from behind-the-meter generation and energy storage	Changes in the shape of the load duration curve: (4) the penetration of behind-the-meter generation and energy storage.	We made adjustments to the LDC for distributed solar PV and implemented. When there is an EPA outlook/expectation we can consider this for other distributed technologies.
2.2	4	40	3	parametric uncertainty, loadshapes	model scenario with negative demand growth from EE	Even without changing the load duration curve, we also suggest including a scenario in EPA's Platform, along with the Reference Case, that involves negative demand growth arising through greater energy efficiency measures for buildings and appliances	We can execute a first order estimate run, assuming the load shape doesn't change over time. However, a more realistic approach would require more work.

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2.2/2.10	4	41	1	parametric uncertainty, fuel supply	model scenario involving negative shocks to fuel supplies	encourage EPA to publish scenarios alongside the Reference Case involving negative shocks to fuel supplies, particularly in the northeastern U.S. where resistance to additional fuel delivery infrastructure has been high. These negative shocks could be modeled as outages or de-rates to certain types of generating units in certain regions within EPA's application of IPM, or (perhaps preferably) using high fuel prices to indicate shortage (see an example for natural gas in Bent, et al., 2018).	These can be modelled either by changing fuel prices exogenously or through a full-scale iteration with GMM.
2.2/2.10	4	41	3	multiple parametric changes	model combo scenarios that interact shifts in LDC with existing parametric scenarios (such as low/high gas prices and renewable costs)	Scenarios that interact shifts in load duration curves with existing parametric scenarios (such as low/high gas prices and renewable energy costs)	We can do this if needed, deemed valuable and priority. LDC runs could be tested when we have resources.
2.10	4	41	4	multiple parametric changes	model combo scenarios involving very low gas prices and low renewables costs	Scenarios involving very low gas prices and rapidly declining capital costs for renewable power generation	We can do this if needed and if deemed valuable and priority. We are posting two alternative reference case runs.

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2.10	4	41	5	multiple parametric changes	model combo scenarios involving fuel supply shocks and low renewable costs	Scenarios involving fuel supply shocks and low capital costs for renewable power generation (implying a larger dependence on renewable energy during supply shocks, and the response of the system to that known dependence)	We can do this if needed, deemed valuable and priority. We are posting two alternative reference case runs.
2.10	4	41	6	parametric uncertainty, unexpected events	model parametric surprise events	we observe that EPA's Platform v6 as currently configured is ill-equipped to handle unexpected events that might arise over the multi-decadal time frame that it models… however, we do see a straightforward way for EPA to be able to model specific scenarios that involve parametric surprise events, and encourage EPA to publish the results of such scenarios alongside the Reference Case	EPA has performed such analyses in the past. We can do this if needed, deemed valuable and priority.
2.10	5	43	4	policy analysis	model policies or technologies that endogenously shift load across time	policies or technologies that endogenously shift load across time would introduce challenges and may not be achievable given the current model configuration, as we understand it, except through an iteration procedure.	

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2.10	5	44	1	policy analysis	model energy efficiency and improve demand representation	Because of the various federal proposals to promote energy efficiency, EPA may need to revisit its representation of demand in order to be useful to analysis of these policies.	Energy efficiency can be modeled explicitly in IPM and has been done in the past. The level of detail can be at the measure level.
2.10	5	44	2	policy analysis	model state policies governing retail tariffs, including payments for DG, electrification, and shifting demand to align with VREs	One of the largest challenges for EPA going forward may be the representation of policies at the state level governing retail tariffs, including payments for distributed generation, and incentives to promote electrification that may intentionally align demand growth with the availability of variable renewable energy resources	Demand side policy representation will have to follow an updated approach to representing demand that doesn't rely solely on EIA data. This would be a phase two of any demand work we would execute. We are developing in-house capabilities to run NEMS.
2.10	5	44	3	policy analysis	model retail TOD prices or retail RE prices	a possibly important policy mechanism in the next decade is the determination of retail prices that are differentiated by time or type of electricity use	

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2.10	5	44	3	policy analysis	model time varying prices applied to new sources of electrification	However, potentially more important are time varying prices applied to new sources of electricity demand such as electric vehicles, water heating, and building heating that embody technologies with inherent storage capability. These types of electricity uses do not require all the attributes of typical "instant on" electricity use. Consequently, they may not be priced at the same level and they may not be burdened with the sunk costs associated with the reliability aspects of the existing grid, and retail prices may be adjusted accordingly	Managed charging essentially addresses this as we have been working on. For a more comprehensive approach, we would need to develop an EPA approach to modeling demand before we can start modeling cases like this in IPM.
2.10	5	44	4	policy analysis	model time-varying prices including cross-time-period elasticities of electricity use and a demand side model	To represent the meaningful aspects of time-varying prices requires cross-time-period elasticities of electricity use within a fully functioning demand side model.	IPM's DSM/EE modeling capability can be exercised to model some of the demand-side optionalities available in the market. However, we do not plan to have a fully functional demand-side model in the near-term.
2.10	5	44	5	policy analysis	account for the effects of uncertainty on economic behavior	Another potentially important limitation of EPA's policy analyses (that we also raise in the context of EPA's Platform v6 representation of baseline uncertainty) is the model's ability to account for the effects of uncertainty on economic behavior	We have been doing analytical work on retirements outside of IPM to address this.

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2.11	6	46	3	model documentation	update documentation on developing load segments	Development of load segments: The process used for developing load segments as described in the documentation is unclear.	The documentation is already clear.
2.11	6	46	4	model documentation	update documentation on treatment of interregional trading	Treatment of interregional trading: The documentation's description of inter-regional trade, especially related to the load segments, is not very clear. The documentation indicates that trade is modeled on a seasonal basis, yet it is our understanding after discussions with EPA that trade is modeled by load segment.	
2.11	6	46	5	model documentation	update documentation on aggregation of model plants	Aggregation of model plants: The documentation's description of the aggregation of model plants also requires clarification… , it is our understanding that fossil units are aggregated no further than at the plant level	Section 4.2.6 documentation is already clear.
2.11	6	46	6	model documentation	improve the publication of data tables on the EPA website	Publication of data tables on the EPA website: The use of tables uploaded directly to the web is understandably necessary given the large size of many of the data inputs. However, a few improvements are suggested.	The list of tables posted separately are listed at the end of each chapter.

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2.11	6	47	2	model documentation	include in the documentation a more complete description of which AEO case for what	Guide to EPA's Platform v6 Output Files: It would be helpful to include a reference in section 2.5.2 of the documentation to the output file guide that is on EPA's website. In addition, when EIA's AEO cases are used to set up alternative sensitivity cases, a more complete description of which AEO case is being used and what inputs are being used from the case would be helpful.	So Far EPA has always used AEO reference cases. If and when a different AEO case or alternative demand cases are used, these will be appropriately documented.
2.11	6	47	5	results viewer	insert a few clarifications in the READ ME instructions for the Results Viewer	To avoid user confusion, we would recommend that EPA insert a few clarifications in the READ ME instructions.	Addressed.
2.11	6	47	6	results viewer	update Results Viewer's distinction between "plant type" and "plant category"	We found the Results Viewer's distinction between "plant type" and "plant category" confusing. For example, it is unclear what a user should choose for nuclear plant type. The readme tab indicates that plant type and plant category may be merged in the future, and we agree this would be clearer.	Revised.

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2.11	6	47	7	results viewer	update Results Viewer so that the displayed results indicate the cases being compared	The displayed results should indicate the cases being compared (i.e., the difference between what to what) and the units of measure reflected in the results. The readme tab indicates that the results represent "changes from the comparison model," but it would be helpful to include this on the graphics page accompanying the map.	Addressed.
2.11	6	47	8	results viewer	Make more intuitive the "comparison case" for other metrics, such as capacity factors and emissions rates	The use of the "comparison case" for other metrics, such as capacity factors and emissions rates, is clever but not very intuitive.	Already limited the dropdowns to be active when absolutely necessary and to automatically match the Primary Case selections where it makes sense to do so. The Results Viewer is squeezed for screen real estate, so the popup box seems like the best way to give users a handy cheat sheet (rather than permanently displaying it)
2.11	6	48	2	results viewer	allow map sheet to display two sets of absolute values	In the map sheet, the comparison functionality is confusing and only works for displaying differences, rather than two sets of absolute values.	While the display could be altered to show this, the challenge is that displaying two numbers per state would become illegible (either too small a font or overlapping values). The whisker chart is an alternate graphing method that can fill a user's need.

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2.9	6	48	4	retail price model documentation	update the discussion of utility depreciation costs	In the discussion of utility depreciation costs, the units are mills/kWh but these are not defined by year. In addition, the "directly from" is not explained sufficiently as to whether the reader can find these in a published document or table or whether this was provided by EIA	This will be addressed when an updated RPM documentation published.
2.9	6	48	5	retail price model documentation	update documentation with additional detail on the NUG adder and the regional tax rates	The documentation would benefit from additional detail for the non-utility generators (NUG) adder and the regional tax rates used in the RPM.	This will be addressed when an updated RPM documentation published.
2.9	6	48	6	retail price model documentation	define regional tax dollars	Also related to regional tax rates, it is not clear what is included in "regional tax dollars" referenced in the documentation.	This will be addressed when an updated RPM documentation published.
2.9	6	48	7	retail price model documentation	describe how the percentage of each region that is deregulated or regulated were derived	Attachment 1 of the documentation includes a table showing the percentage of each region that is deregulated or regulated. We recommend that EPA describe how the percentages were derived, rather than simply citing the AEO.	This will be addressed when an updated RPM documentation published.

Peer Review of EPA's Power Sector Modeling Platform v6 using Integrated Planning Model

Final Report

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Work performed under contract to the U.S. Environmental Protection Agency

through

Industrial Economics, Incorporated

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+ Review Panel Chair

March 2020

EXECUTIVE SUMMARY

The U.S. Environmental Protection Agency (EPA) contracted with Industrial Economics, Incorporated (IEc) to manage an expert review of the EPA's Power Sector Modeling Platform version 6 (v6) using Integrated Planning Model (IPM). IPM is a multi-regional, dynamic, deterministic linear programming model of the U.S. electric power sector developed by ICF International. It provides projections of least-cost capacity expansion, electricity dispatch, and emission control strategies while meeting energy demand and environmental, transmission, dispatch, and reliability constraints. EPA uses IPM to evaluate the cost and emissions impacts of alternative policies to limit emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon dioxide (CO_2), and air toxics such as mercury (Hg) and hydrochloric acid (HCl) from the electric power sector's operations. EPA has applied IPM in the regulatory impact assessments for several rulemakings. For example, EPA used IPM in its analysis of the costs and emissions impacts associated with the Clean Power Plan and the Affordable Clean Energy Rule.

This peer review was guided by a specific set of charge questions developed by EPA. The review presented in this document focuses on the specific issues raised by these questions. Furthermore, EPA provided the panel with detailed documentation of the EPA's Platform v6 and several supplementary documents and data files. The panel reviewed this material and also participated in two informational teleconferences and one in-person meeting (all organized by IEc) with EPA, ICF, and IEc staff during the review process to seek clarification on a variety of questions related to the model's design and functioning. The input provided by the panel in this document reflects the contents of the EPA Reference Case v6 documentation and related material provided to the panel as well as the input provided through these interactions.

Overall, we found much to commend EPA's Platform v6. The model formulation and structure lends itself well to EPA analyses of air policy focused on the electric power sector. In addition, it includes significant detail related to electricity supply and demand, with a data-rich representation both across different geographic areas and across time. Based on the current structure of the industry, EPA's application of IPM provides a reasonable representation of power sector operations, generating technologies, emissions performance and controls, and markets for fuels used by the power sector. The model is also well suited to assess the costs and emissions impacts of the types of power sector policies that EPA and other federal agencies have considered over the past several years. The panel also found the EPA Reference Case v6 documentation to be well written, clearly organized, and detailed in its presentation of most model characteristics.

We also recommend that EPA consider several improvements and refinements to EPA's application of IPM and the associated documentation. These recommendations are presented in detail in the main body of this document, but our highest priority recommendations are as follows:

- ***Consider changes to the model formulation that would improve the model's ability to represent the ongoing evolution of the industry:*** The electric power industry is undergoing fundamental changes with potentially expansive scope and at an uncertain rate of evolution. Such changes include significant increases in the penetration of renewables, significant changes in load shapes (related to the accelerated introduction of electric vehicles and energy storage), and significant changes in state and regional policies affecting the industry. In response to these changes, we recommend that EPA consider modifications to the model formulation that would enable it to better represent these changes. Such modifications could include revising the intra-annual load segments, solving the model chronologically (as opposed to by load segment), or alternatively solving a companion model that describes chronological demand and system operation using capacity assumptions from IPM. Other potential modifications include incorporating a richer representation of energy storage into the model, and incorporating changes in capacity market rules into the model (particularly as they relate to variable renewable energy).
- ***Clarify the types of uncertainty that EPA's Platform v6 is capable of handling:*** Within the current structure of EPA's Platform v6, the model is capable of capturing uncertainty related to the value of key model parameters, but the model is not capable of quantifying uncertainty in model structure, decision rules, or processes. We recommend that the documentation should provide guidance to model users that more clearly articulates the types of uncertainties captured and not captured by the model, and that EPA consider evolution in the model structure to address uncertainty in a broader manner.
- ***Reconsider coal plant turndown constraints and possible addition of operating reserves:*** To prevent the dispatch algorithm from setting capacity utilization to unrealistically low levels, especially during specific timeblocks given its utilization in other timeblocks, EPA's application of IPM assigns minimum capacity factors that vary by plant type (and by plant in some cases). While it is appropriate for EPA's Platform v6 to constrain modeled dispatch to account for the lack of chronological load segments and explicit unit ramping, we are concerned that the turndown constraints are overly restrictive in some circumstances and perhaps not quite restrictive enough in others. We recommend that EPA examine the turndown constraints more closely to determine if they create bias in coal plant operations, especially in scenarios with low gas prices or high renewable generation. EPA might also consider whether adding explicit operating reserve requirements in the dispatch would provide a better representation of the impact of high levels of renewable generators on the grid. The new constraint would require sufficient flexible capacity in each time period to supply operating reserves that can be met by holding

capacity back from generating in the time period or supplied by quick start capacity.

- ***Consider incorporating upstream emissions in addition to source-level (power plant) emissions:*** As designed, EPA's application of IPM explicitly considers only stack emissions at the point of fuel use. It does not consider the "life cycle" emissions associated with upstream fuel production, processing, and transportation. Since EPA may need to evaluate regulations related to fuels production that are relevant for the power sector, the panel recommends that EPA consider including upstream emissions in its reference case as a separately-reported item (so upstream and stack emissions are not combined together).
- ***Distinguish between investment decision-making of utility and merchant power plants:*** Because utility-owned and merchant plants face different risks and have different options at their disposal for managing risk, decision-making is likely to differ significantly between utility-owned and merchant plants. They may also behave differently with respect to specific types of investment. Further, we suggest EPA evaluate whether a weighted average of existing firms within a power region or some other rule is a reasonable representation of which type of firm is more likely to make an incremental investment.
- ***Address evolving gas markets where Henry Hub is less central to pricing and where emerging petrochemical production has greater influence:*** Natural gas pricing within EPA's Platform v6 is specified based on static differences between the Henry Hub price and the price in individual model regions. Under scenarios with different gas demand patterns (quantities and locations) than the Reference Case, these basis differentials could be quite different. It is the panel's understanding that EPA addresses this issue by iterating with the Gas Market Model that generates the natural gas supply curves and basis differentials, but this process is not described in the model documentation. Relatedly, the emerging petrochemical sector in the Appalachian production region is likely to affect regional natural gas pricing in ways that may not be well represented in the gas market model that EPA's Platform v6 relies upon. Review of the gas market model, however, was outside the panel's charge.
- ***Consider alternatives to the current load duration curves (LDCs):*** As currently designed, EPA's Platform v6 aggregates time into LDCs in a way that can assign the same calendar hour to different load segments in different regions. This creates biases related to the opportunities for inter-regional trade. It is difficult to assess the quantitative impact of these assumptions, but we recommend that EPA assess the trade-offs between different approaches to aggregating load into LDCs. Some approaches may bias inter-regional trade less, but we recognize they may provide less detailed resolution with respect to load within a given region.

- ***Improve representation of behind-the-meter generation:*** EPA's Platform v6 captures policies that affect the bulk power system but does not seem to capture policies that encourage behind-the-meter generation, except as represented as a change in demand. Because future federal policy may introduce new requirements that encourage increased generation behind-the-meter, EPA's modeling may, in the near future, need to capture these policies in greater detail than is currently possible in the model.
- ***Increase transparency of retail pricing results:*** EPA uses the Retail Price Model (RPM) as a post-processor to IPM results to estimate the change in retail electricity prices associated with a given policy scenario. Many elements of retail prices as reflected in the model remain constant across scenarios and policies. These elements rely upon external sources whose quality is difficult to assess. When EPA uses the RPM, we recommend that the reporting of retail rates be broken into component parts so that the user can understand which elements are endogenous to the model and which are dominated by external sources and assumptions.
- ***Consider improvements in the representation of various policy mechanisms***: Such improvements include dynamic allocations within various forms of emissions trading programs such as output-based allocation under cap and trade and a clean energy standard, expenditures on energy efficiency that are linked to revenue from carbon pricing, and the ability to represent flexible demand that may be encouraged at the retail level to promote the integration of variable renewable energy.
- ***More thorough citing of sources and expanded explanations throughout the EPA Reference Case v6 documentation:*** This additional detail is particularly needed in portions of EPA Reference Case v6 documentation pertaining to the development of load segments, the treatment of interregional trading, and the aggregation of individual plants to model plants, and the retail pricing model.

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I. INTRODUCTION

The U.S. Environmental Protection Agency (EPA) contracted with Industrial Economics, Incorporated (IEc) to manage an expert review of the EPA's Power Sector Modeling Platform version 6 (v6) using Integrated Planning Model (IPM), Version 6. IPM is a multi-regional, dynamic, deterministic linear programming model of the U.S. electric power sector developed by ICF International. It provides projections of least-cost capacity expansion, electricity dispatch, and emission control strategies while meeting energy demand and environmental, transmission, dispatch, and reliability constraints. EPA uses IPM to evaluate the cost and emissions impacts of alternative policies to limit emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon dioxide (CO_2), and air toxics such as mercury (Hg) and hydrochloric acid (HCl) from the electric power sector's operations. EPA has applied IPM in the regulatory impact assessments for several rulemakings. For example, EPA used IPM in its analysis of the costs and emissions impacts associated with the Clean Power Plan and the Affordable Clean Energy Rule.

This peer review was guided by a specific set of charge questions developed by EPA. The review presented in this document focuses on the specific issues raised by these questions. Furthermore, EPA provided the panel with detailed documentation of the EPA's application of the model and several supplementary documents and data files. The panel reviewed this material and also participated in two informational teleconferences and one in-person meeting (all organized by IEc) with EPA, ICF, and IEc staff during the review process to seek clarification on a variety of questions related to the model's design and functioning. The input provided by the panel in this document reflects the contents of the EPA Reference Case v6 documentation and related material provided to the panel, as well as the input provided through these interactions.

This document is largely organized according to the order of questions as they appear in the charge. The one exception is the panel's input on the EPA Reference Case v6 documentation, which is presented in the final section of this document.

II. MODEL FORMULATION

Identify strengths, weaknesses, limitations, and errors in the structure of the model formulation (e.g. objective function, constraints, and decision variables and their indices). Propose options as needed. Specifically, are all the necessary elements included in order to meet EPA's analytical needs? Are there any extraneous elements? Could simplifications be made?

The Integrated Planning Model (IPM) is a long-term capacity expansion and production-cost model of the U.S. electric power sector. It is a linear program, which enables quickly solving a large and detailed model using off-the-shelf solvers. It covers input fuels, air emission, and electricity markets and is designed to analyze the impacts of alternative regulatory policies on the power sector over the long term (i.e., investment horizon).

In considering the formulation of the model, we are cognizant of the fact that one model cannot address all questions or serve all purposes. Consequently, the structure of EPA's modeling should be linked to the modeling objective. Examination of the strengths, weaknesses, limitations, and errors in the structure of the model is constrained by our limited access to the coding of the objective function, constraints, and decision variables and their indices. We are able to focus, however, on the importance of aligning generation aggregation, temporal aggregation, regional definitions, transmission expansion, trading capabilities, and dynamic and elastic load with the objective of the particular modeling assignment at hand. In this context, we find that for long-term (20-40 years) modeling of overall trends, differences between the outputs of scenarios, and general emission levels changes, EPA's application of IPM has a great deal of appropriate structure (with caveats we address below with respect to demand price elasticity and transmission expansion) trading off computational time, assumption details, and long-range planning horizons. For shorter periods of time and where hourly dispatch is critical to assess emissions for more detailed air pollution modeling, where changes in near term wholesale and retail prices are important, or where the feasibility and reliability of large-scale renewable penetration is being considered, EPA may consider reconfiguring the model or complementing it with a chronological hour capability.

We also considered this charge question in the context of both the current state of the electric power industry and likely changes in the industry in the coming years, some of which have already started to occur. The electric power industry is undergoing fundamental changes with potentially expansive scope and at an uncertain rate of evolution (U.S. DOE, 2015). Based on this ongoing evolution, particularly industry changes related to the penetration of renewables, load shapes (including accelerated introduction of electric vehicles and energy storage), state and regional policies, etc., the model formulation may need to be adjusted according to suggestions offered here. However, as some of these uncertainties unfold, EPA should periodically review the model to determine

whether EPA's application of IPM model structure should be modified or complemented with other modeling capabilities.

The suggestions that we provide here regarding model formulation, as well as suggestions that we present in later sections of this review, are informed by uncertainty as an overarching consideration that affects the usefulness of EPA's application of IPM in projecting alternative futures for the industry. Uncertainty affects the choice of parameters in the model, structural relationships in the model, and the way that model results should be interpreted. Specifically related to the structure of the model, as the relative costs of renewable resources decline and more state and regional policies directly or indirectly support renewables and energy efficiency, we recommend that EPA consider the following to ensure that the model's formulation and structure endow it with capabilities critical to providing insights into the industry's response to changes in policy:[1]

a. ***Chronological modeling:*** We expect the role of chronological operation of the power system to become increasingly important with expanded availability of variable renewable energy, electricity demand growth, and demand flexibility. EPA may therefore consider restructuring IPM as a chronological model or develop a companion short-run chronological model of system operation that would enable comparing the outcomes of the model's load duration curves with a more realistic characterization of the temporal nature of demand with chronological load profiles, perhaps using capacity assumptions taken from the long-term model.

b. ***Demand responses:*** We recommend that EPA consider incorporating additional factors into the model's formulation of demand response. This would include changes in total electricity consumption in response to changes in price, substitution between electricity and other forms of energy consumption, and changes in the load shapes that will be observed and projected under different scenarios. In addition, variations in supply-side short run marginal costs (due to increased penetration of variable renewable energy) and potentially demand side retail prices that vary by time of day or are linked to resource availability directly require cross-time-period analysis of electricity demand.

c. ***Climate change considerations:*** We recommend that EPA periodically evaluate the model with respect to weather normalization of key data inputs and consider a more explicit representation of climate change in the model's specification of generation, transmission, and load assumptions.

[1] Some of the recommendations pertaining to the formulation of the model offered here overlap with recommendations in later sections of this review. This reflects the fact that the model formulation and structure are closely intertwined with the various issues related to IPM assumptions, inputs, calculations, and outputs identified in later sections.

d. ***Transmission capacity:*** Transmission expansion is one of the ways that increasing amounts of variable renewable energy may be integrated into the power system. Transmission system decisions, however, are tightly connected with regional and local land use decisions that cannot be precisely forecast. We therefore recommend that EPA regularly revisit and, as appropriate, revise EPA's implementation of transmission outcomes and the assumptions that shape anticipated future transmission siting decisions.

e. ***Storage:*** EPA's application of IPM would benefit from a more rigorous treatment of energy storage within the formulation of the model, particularly with respect to the opportunity to schedule demand and achieve thermal and battery storage for end-uses, and for storage technologies that enable sending power back to the to grid.

f. ***Capacity markets:*** The treatment of capacity markets and other representations of resource adequacy requirements, as opposed to modeling a generation reserve requirement, may be increasingly important going forward. In several large regions of the country (e.g., in PJM), capacity markets have started to change (PJM, 2019). Potential changes to capacity market rules include availability requirements (which may result in generation units pursuing dual fuel options, firm gas, or including a risk premium in their capacity offers) and changes in the conditions under which demand can participate in capacity markets. Such changes may have important effects on the level and technology of capacity investment and accompanying transmission investments.

g. ***Additional operational constraints:*** A more explicit representation of such constraints may be necessary in a capacity expansion model such as IPM because of the increased penetration of variable renewable energy. As the penetration of renewable resources increases, it may be necessary to also include operating reserve requirements, in addition to adjusting renewable capacity credits toward meeting capacity reserve margins, to account for the impact renewable resources have on economic dispatch.

We also highlight that projections with a deterministic model such as IPM, or even a set of projections, are not necessarily representative of the decision-making under uncertainty that the model is attempting to explore. Decision makers may hedge investments in various ways that do not align with the cost minimization outcome identified under a given scenario.[2] EPA may also improve

[2] Burtraw et al. (2010) illustrate one approach using Taylor series approximation to represent hedging behavior in the context of a deterministic and highly parameterized model..

the way they use model results by explicitly considering them in an option value framework.[3]

Finally, any runtime restrictions required by the EPA should be made explicit and used to appropriately structure EPA's application of IPM to the task at hand. There seems to be an implicit requirement that IPM run time should be "overnight" so that EPA can have scenarios turned around within a day. Whether increasing this turnaround time would enable the model to accommodate more of the complexities listed above should be investigated.

[3] Echeverri et al. (2013) use stochastic dynamic optimization in an engineering-economic model to describe technology choice in response to technology-forcing regulations in an uncertain environment.

III. MODEL ASSUMPTIONS AND OUTPUTS

Identify strengths, weaknesses, limitations, and errors in the model assumptions, model outputs, and conclusions derived. Propose options as needed. Specifically consider how well the representations of the following items suit EPA's analytical needs: power sector operations, generating technologies, emission factors and control alternatives, power sector finances and economics, fuels and renewable resources, regional and temporal resolution, power sector policies, and retail price estimates.

A. POWER SECTOR OPERATION

IPM uses a linear program inter-temporal optimization approach to power sector capacity expansion and economic dispatch in which costs are minimized over the projection period subject to multiple constraints. Major components the model's representation of power sector operation include demand and load growth, dispatch of existing assets, trade, representation of transmission constraints, and generating capacity expansion.

Demand

For most applications of EPA's Platform v6, electricity demand is exogenously specified. Projected annual demand is taken from the 2018 Annual Energy Outlook (AEO) Net Energy for Load and mapped from the National Energy Modeling System's Electricity Market Model (EMM) regions to EPA's model regions. The mapping currently uses relatively old data (2007 and 2011), but EPA has informed the panel that it is performing an update to 2016. Although IPM includes the capability of using price elasticity to impact demand, EPA generally does not use this feature. In addition, distributed generation (DG) is not explicitly included in the model's specification of electricity demand, with only own-use DG implicitly reflected within the demand projection.

EPA's application of IPM converts annual demands to demand by time segment by using seasonal load duration curves (load sorted by level) and then by time of day, as described more in Section III-F below. Based on this specification, the load segments in EPA's application of IPM are not chronological. Currently 2011 load data are used in all regions, except for ERCOT where 2016 is used, to develop the hourly load curves. Changes in load shapes over time are driven by assumption about load factors, with NERC electricity supply & demand (ES&D) load factors used to project peaks for 2021-2027 and changes in AEO2018 load factors for years post-2027.

We view the use of fixed electricity demands without response to electricity prices as problematic in policy and sensitivity cases where prices vary significantly from the Reference Case. We recommend that EPA use this feature when analyzing policy scenarios that have significant price impacts (perhaps roughly greater than 20% variation in wholesale prices). We also recommend that the EPA Reference Case v6 documentation describe in more detail how the elasticity is applied when

used. Based on input provided by EPA staff, it is our understanding that the baseline demands and prices are stored and that the elasticity is applied to the percent change in the scenario prices from the baseline set. In addition, the wholesale price is grossed up to approximate a retail price. However, a better approach for sensitivity cases, such as high/low natural gas price cases, in which electricity prices are expected to vary from the AEO Reference Case is to develop alternative baselines, which we understand is EPA's practice, rather than using elasticities for modifying demands from the Reference Case.

As described in Section V, the demand side of the power system is likely to become more important as the grid evolves with greater shares of intermittent or variable renewable energy sources and possible expanded uses of electricity, such as electric vehicles. At a minimum, a more systematic way is needed to develop load shapes over time rather than just using a single metric of load factors from ES&D or the AEO to shift the curves. While peak demand is important for reserve margin requirements and capacity needs, the shape/time of demand is also important for dispatch and use of variable renewable energy.

Although the 24 load segments per season within EPA's Platform v6 are at a fairly high level of resolution for a long-term planning model, the lack of chronology creates some challenges for representing trade among regions. As described in Section III-F, the importance of trade is greater as the number of regions increases. Section III-F provides specific suggestions regarding other segmentation methods that might be considered by EPA, recognizing that there is a trade-off between capturing correlations of load and variable renewable energy availability and trade among regions, while maintaining reasonable model run time performance.

As EPA updates load shapes to 2016 values, we would recommend that EPA consider whether using data for a single year creates any biases and whether a multi-year average or weather normalization would be more appropriate. Also, it may be useful to have consistency among AEO vintages used for data assumptions. For example, the model currently uses AEO2018 loads and peak load factors but Mexican trade from the AEO2017.

Dispatch

EPA's Platform v6 performs an optimal economic dispatch subject to several constraints. For most plant types, availability (using forced and scheduled outages based on the Generating Availability Data System) determines maximum generation; availability is defined by season where no planned maintenance is assumed to occur in peak demand season.

EPA assigns oil/gas steam units minimum annual capacity factors to avoid over optimization that might result in them not operating despite their historical use. These minimum capacity factors account for considerations that cannot

practicably be reflected in EPA's application of IPM, such as local transmission constraints or grid reliability concerns. These minimums terminate over time based on units' individual historical capacity factors (minimums for units with low historical capacity factors are removed sooner), but all minimums terminate by age 60. In addition, to prevent an unrealistic dispatch of fossil steam units (oil/gas and coal) within the existing non-chronological time segments, turndown constraints apply to all 23 non-peak time segments in a season if the plant runs at 100% in the peak load time segment. Oil/gas units are assumed to dispatch no less than 25% of the unit capacity for these segments. For coal, unit level turndown percentages apply based on historical rates that vary from 20% to 78%, with most units in the 40-60% range.

Wind and solar generation are determined by hourly generation profiles prepared by NREL. Hydropower dispatch is governed by seasonal capacity factors specified by model region based on a 9-year historical period (2007 to 2016) but otherwise is assumed to be fully dispatchable within those constraints.

While it is appropriate for EPA's application of IPM to constrain modeled dispatch to account for the lack of chronological load segments and explicit unit ramping, the model's turndown constraints strike us as overly restrictive in some circumstances and perhaps not quite restrictive enough in others. For example, it appears that steam plants would not be able to shut down for any time segments (such as segments with lowest load) if they are expected to run at full capacity during the peak segment. In practice, some plants likely can shut down at night and ramp up to full capacity by the middle of the following day. It was not as clear from the documentation what operations are allowed in other time blocks if units run at partial load on peak. This is not very likely to occur in practice, but it might occur in the model as a way around the minimum in the other load segments. Because output files from EPA's Platform v6 do not include information on dispatch by time segment, it is not possible to determine if this occurs.

To the degree that the model's turndown constraints result in unrealistic dispatch, they may introduce bias into the model. Specifically, they may impact the cost-effectiveness and retirements of steam plants and, by extension, annual emissions. The degree of flexibility of fossil plant dispatch in EPA's application of IPM can also impact the attractiveness of variable renewable energy. For coal plants, the turndown constraints vary considerably by unit, and some are as high as 80% with most of them between 40% and 60%. Because these values are based on historical operations rather than current or projected engineering considerations, they may reflect historical economic circumstances that may not apply in the future.

We recommend that EPA examine the turndown constraints more closely to determine if they create bias in coal plant operations, especially in scenarios with low gas prices or high renewable generation. EPA might also consider whether

adding explicit operating reserve requirements in the dispatch would provide a better representation of the impact of high levels of variable renewable energy on the grid. The new constraint would require sufficient flexible capacity in each time period to supply operating reserves that can be met by holding capacity back from generating in the time period or supplied by quick start capacity.

EPA's assumption that hydroelectric generation is fully dispatchable within seasonal capacity factor constraints may be too generous. Run-of-river conditions, location of multiple dams on a single river, and environmental considerations may make a portion of hydrogeneration somewhat inflexible. EPA might consider analyzing historical generation patterns versus the model patterns by time period to assess whether EPA's application of IPM is significantly overoptimizing hydro generation.

Transmission

EPA's Platform v6 defines transmission capacity limits for firm (capacity) and non-firm (energy) trading between model regions. The model also specifies joint limits between groups of regions to account for reliability considerations. Wheeling charges are assessed to move power between regions, except for trading within the same regional transmission organization (RTO) region. Line losses are assessed for inter-regional transmission at 2.8% for WECC and 2.4% for ERCOT and the Eastern Interconnect.

The application of a 2.4% transmission loss to each interregional transfer strikes us as high for the Eastern Interconnect, especially given the size of the model regions and hence relatively short distances for many of these transfers. For example, in NEMS a 2% loss factor is assumed for transfers between regions and there are fewer regions. In EPA's Platform v6, the large number of regions, especially in the Eastern Interconnect, means that the distances between them are relatively short so a smaller loss factor would be expected.

EPA's Platform v6 also includes the capability to add transmission capacity, though EPA rarely uses this feature. Not using this feature may be overly restrictive in some scenarios, especially given the large number of regions represented in the model. In general, one would expect new generation capacity to be added somewhat near growing loads and to be distributed across all regions. However, in scenarios that lead to an economic propensity for high levels of renewable capacity additions, there may be an economic rationale for transmission expansion to move power from regions with high levels of wind, and perhaps solar, resources to other regions. EPA could alleviate this concern by performing sensitivity cases in which additional transmission capacity is added exogenously by user assumption.

Capacity Expansion

Setting the Capacity Targets

EPA's Platform v6 projects capacity additions and retirements as part of the optimization of meeting future electricity demands. Total capacity requirements are determined by reserve margins and peak loads. Reserve margins are set for each model region based on the requirement of the NERC region to which it belongs.

Overall, we find the current method for setting capacity requirements using reserve margins by region to be reasonable, even though not all regions explicitly follow that model. The most significant deviation is ERCOT, which does not have a capacity market and hence has no way to enforce or incentivize achievement of a specific reserve requirement. In theory, capacity and "energy-only" markets such as ERCOT should achieve similar outcomes over the long run if held to similar standards. The biggest difference is that the ERCOT standard is based upon short-term operating reserves and relies upon higher energy and ancillary services (AS) prices when short-term reserves fall below the reliability standard. Therefore, the main modeling question is how the model's annual peak planning standard translates to an ongoing operating reserve margin. In the absence of uncertainty, the two concepts should be reconcilable.

California maintains a "flexible" capacity requirement that is intended to ensure a percentage of installed capacity is both fast ramping and not energy limited. The flexible capacity standard continues to evolve but may become a model for other States in the near future. If so, EPA's application of IPM may need to be modified to reflect other capacity requirements beyond a simple reserve requirement and declining capacity values for variable renewable capacity. For example, it may be appropriate to add an additional reserve constraint requiring a percentage of capacity is capable of meeting a certain ramping capability.

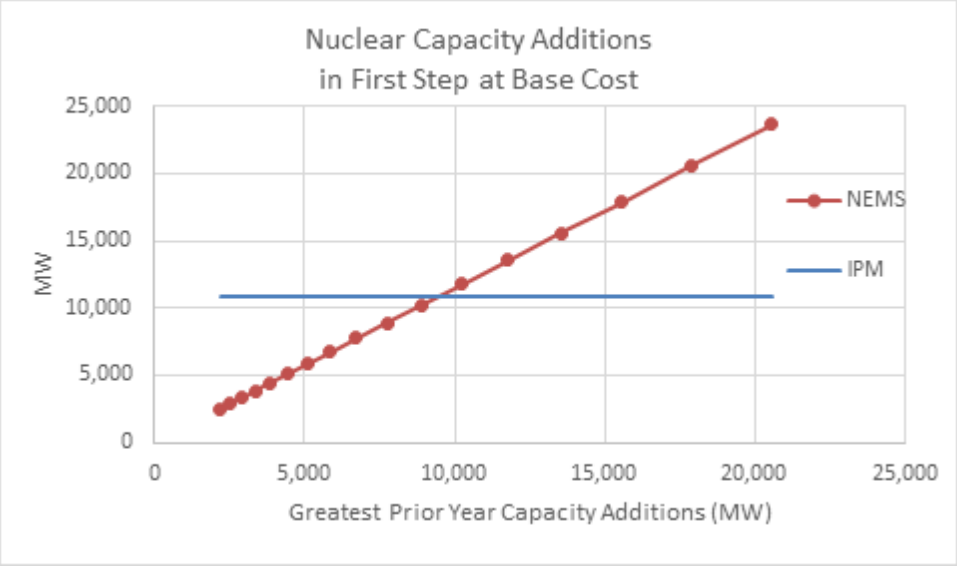
To meet capacity needs, EPA's application of IPM selects new capacity additions from a slate of multiple technology options, each with its own characteristics that vary by vintage to reflect technological improvements over time. Short-term cost adders are applied when annual capacity additions would exceed upper bounds.

We view EPA's application of cost adders to capacity expansion costs when expansion is rapid as a reasonable approach for limiting modeled deployment of a given generating technology on a large scale. We would expect that sharp increases in capacity expansion would increase the costs of a technology due to factors such as manufacturing constraints and would also expect that these increases in costs would limit deployment of the technology in question. EPA has adopted capital cost penalties like those in NEMS, although the implementation is quite different. As mentioned above, in EPA's Platform v6, the amount of capacity that can be built in a period without invoking a cost penalty is specified by time period and is currently assumed to be constant over time (same

amount per year) through 2035, after which no penalty is applied. In contrast, NEMS defines the annual capacity addition step size before a cost penalty as a function of the level of previous capacity additions. This difference is likely to accommodate the model's intertemporal optimization where the model might otherwise select a technology when not economic simply to allow lower cost future builds. However, it means that the capacity additions allowed in EPA's Platform v6 without a cost penalty are higher than in NEMS for technologies that have had low deployments, and the penalty threshold does not diminish as greater deployments occur. For example, the steps are quite large for nuclear capacity at roughly 10 GW year. Figure 1 below illustrates an example of the potential annual nuclear capacity additions that are allowed within the first step (i.e. base cost without a cost adder) where for NEMS 2200 MW are assumed to already have been recently built (planned units currently under construction). Note that 10 GW cannot be added in a single year at the base cost until many years of steady capacity additions have occurred unless a cost penalty is paid and capacity additions exceed the first step at least once. Also, after 2035, EPA's Platform v6 allows unlimited additions at the base cost which could be problematic in scenarios in which a technology cost declines over time and becomes cost-effective only late in the projection.

As in NEMS, the cost penalties are quite steep with roughly a 45% cost penalty on the second step. It might be better to have smaller initial steps with smaller cost penalties for the second step. These cost adders are not likely to be incurred in a Reference Case but could become important in scenarios with either different market conditions or technology assumptions or significant policies that impact the relative attractiveness of new capacity types.

Figure 1. Comparison of EPA's Platform v6 and NEMS AEO2020 Nuclear Capacity Additions in First Step at Base Cost



Rating the Capacity of Alternative Resources

All existing capacity in EPA's Platform v6 counts 100 percent toward planning reserve requirements except those units that depend on variable renewable energy resources. Capacity credits for wind and solar capacity are based on a supply curve approach where the credit declines as more capacity is developed.

The current method used in EPA's Platform v6 of assessing capacity credits for variable renewable energy seems to be a reasonable approximation assuming average performance. The sorting of resources in order of likely builds and assessing the renewable energy capacity contribution, taking into account generation and load profiles, is not a fully endogenous process and cannot account for the joint impact of wind and solar but is likely adequate. One caution is that if the solar capacity credits are still benchmarked to those of the AEO2017, as indicated in the documentation, this should be revisited because the AEO methodology and resulting credits for solar have changed considerably since the AEO2017 was published. In addition, we recommend that EPA examine the capacity credit methodology as system operators change their capacity market rules and consider the implications of non-performance risk. For example, the performance penalties could discourage many variable renewable energy generators from participating in capacity markets at all, due to the financial risk of the penalties. They may also result in more "dual fuel" fossil capability than would otherwise be economic.

It is also worth noting that demand response and energy efficiency are providing non-trivial shares of total capacity and even larger shares of new capacity in many capacity markets. While performance criteria are still controversial and may evolve, demand side resources are quite likely to play an increasing role in meeting reliability requirements.

B. GENERATING TECHNOLOGIES

EPA's Platform v6 models existing, planned-committed, and new generation technologies to determine the least-cost power system over the modeling horizon. Key assumptions are the types of generation units that are modeled, capital, fixed and variable costs, and performance (e.g., heat rates, capacity factors, availability, emissions, etc.). Existing and planned-committed units are based upon the National Electric Energy Data System (NEEDS) v6 database. Assumptions for new generation technologies are based upon a variety of sources.

As described below, our recommendations pertaining to generating technologies relate to energy storage, nuclear dispatch, heat rates, the specification of a unit's generating capacity, and changes in generation assumptions over time.

Storage Technologies

The panel recommends that EPA consider incorporating additional storage technologies into the model. U.S. energy storage installations are increasing significantly (EIA, 2018), and multiple states have mandates for energy storage. Currently, EPA's Platform v6 models only two types of energy storage facilities: pumped storage and lithium-ion batteries (with a four-hour charge capacity). As energy storage technologies mature and as the market responds to cost reductions, performance improvements, and regulatory changes, energy storage will likely become an increasing part of the power sector, requiring more attention and focus by the platform. In addition, because the technologies, cost structure, performance, operating strategies, market rules, and regulations related to storage are rapidly changing, EPA may need to regularly revisit the model's representation of storage.

In addition to including more storage technologies, EPA should also consider regional variations in energy storage technology, costs, and operations. These variations may include if and how energy storage counts in capacity markets. Capacity market rules may also affect the length of time energy storage facilities are discharged, which affects costs and dispatch levels. The current modeling platform does not account for these regional variations.

Nuclear Dispatch

We also suggest that EPA consider more flexible nuclear dispatch in EPA's application of IPM. As the quantities of renewables are likely to increase over time, nuclear units may be dispatched to respond to changes in net load, i.e., demand minus non-dispatchable supply. Currently, EPA's Platform v6 models nuclear units with low fuel and variable operations and maintenance costs, which results in them being run at the maximum possible available output. Although EPA's Platform v6 appropriately does not model very short-term fluctuations in net load, if in the future some nuclear units are used as flexible resources, their specific modeling assumptions may need to be revised to account for lower capacity factors of nuclear units due to increased ramping. For example, nuclear units in France dispatch at different levels based on variable changes in renewable generation.

Heat Rates

We recommend that the heat rates of generating units in EPA's application of IPM vary by season and perhaps over time. EPA's Platform v6 assumes a fixed, single heat rate for each generation unit that does not vary by season, although it does have a heat rate improvement option for coal units, which is not currently activated. Furthermore, EPA assumes that the Reference Case heat rates remain constant over time due to increased maintenance and component replacement over time. Empirical evidence suggests that such expenditures are

necessary to maintain heat rate performance, which otherwise tends to degrade over time (Linn et al., 2014).

Related to seasonal heat rates, we also recommend that EPA's application of IPM vary the generation capacity of a given unit by season, or add text to the documentation explaining why seasonal variation is not necessary. Seasonal temperature changes affect the generation capacity (MW) of many types of generation units. Currently EPA's Platform v6 uses "net summer dependable capacity".

Generation Assumptions

We also suggest that EPA consider adjusting the EPA's Reference Case generation assumptions over time to account for climate change. As average climate temperatures rise along with associated increases in cooling water, many electricity modeling assumptions, including assumptions related to generation, may need to be adjusted such as summer and winter capacity, heat rates, electrical losses, etc. (Chandramowli and Felder, 2013).

EPA may also consider varying some generation assumptions by market/regulatory environment. Currently, EPA's Platform v6 does not make different assumptions for generation units in wholesale markets versus regulated regions (except for the cost-of-capital). Generation costs (including both fixed and variable operating costs) and unit availability, however, may vary based on the market/regulatory environment in which they operate (as well as ownership) (Fabrizio, et. al, 2007). Some of these differences may be captured in the regional cost variation factors shown in Table 4-15 of the documentation (at least historically), but a clear distinction of costs between regulated and market regions is needed.

C. EMISSION FACTORS AND CONTROL ALTERNATIVES

Accounting for air emissions from electric generation units and representing the decisions to invest in air emissions control technologies are fundamentally important requirements of the model for EPA's analytical purposes. The current version of EPA's Platform v6 represents emissions rates by plant type (the "types" being aggregations of actual plants as defined in the documentation) and features a highly granular set of air emission control technologies with which plants can be outfitted. These air emissions factors and control technologies cover multiple relevant pollutants, including oxides of sulfur and nitrogen, particulate matter, mercury, and carbon dioxide.

Assignment and Scope of Emissions Factors

The method by which EPA's Platform v6 assigns emission factors to specific plant types within the model appears to be appropriate to meet EPA's analytical needs. EPA uses appropriate data sets to determine stack emissions from different power generation technology types. The model, however, explicitly

considers only stack emissions at the point of fuel use. It does not consider the "life cycle" emissions associated with upstream fuel production, processing, and transportation. There can be considerable differences between stack emissions and life-cycle emissions (Jaramillo, et al., 2007), and the life-cycle air emissions may vary considerably by location since primary energy extraction, processing, and transportation technologies (and fuels used in those phases of the life cycle) can be location-specific. In some cases, EPA may need to evaluate regulations related to fuels production that are relevant for the power sector. A recent example of this would be proposed regulations addressing fugitive methane emissions from unconventional natural gas production (Brandt, et al., 2016). Control costs to address fugitive methane emissions would add some cost to delivered natural gas (ICF, 2014; Osofsky et al., 2018), which in some cases would render natural gas a more expensive fuel than coal at the margin. EPA should consider documenting how upstream air emissions are reflected in fuels prices or in generator marginal costs within its Power Sector Modeling Platform for analysis of regulations where such upstream emissions would be relevant to power system investment and operations.

Emissions Control Options

EPA's Platform v6 contains a highly detailed representation of emissions controls options from which modeled plants can choose. The level of detail in terms of the air emissions addressed by these technologies and the different technology options for each is impressive. The extensive library of control options is a strength of EPA's Platform v6, given the analyses that EPA has needed to conduct in the past.

As the U.S. power sector continues to move away from the heavy use of coal to the heavy use of natural gas for power generation, it may be the case that some of the emissions control options currently included within EPA's Platform v6 become less relevant to the kinds of analyses that EPA is asked to perform. We suggest that EPA periodically review the technology options for emissions control in EPA's application of IPM to determine if this portion of the model could be made simpler with the reduction of emissions control technologies from which modeled plants can choose.

Emissions Control Costs

The emissions control cost data used in EPA's Platform v6 appear to come from a study by Sargent and Lundy (2017) that relies on proprietary data. Chapter 5 of the EPA platform v6 documentation includes unit cost estimates derived from the Sargent and Lundy study but does not provide a formal citation for the study or the raw engineering data used to develop the unit cost values. Publication of these data would make the cost figures used by EPA's Platform v6 more transparent than they are currently. We recommend that EPA consider the costs and benefits of this additional data transparency as weighed against the benefits of being able to access and use proprietary data, which in some cases may be

more granular or up-to-date than data existing in the public domain. EPA should also periodically compare its emissions control cost data with relevant information that exists in the public domain, such as the Integrated Environmental Control Model (IECM) developed by Carnegie-Mellon University.

For the capture of carbon dioxide specifically, we note that EPA's Platform v6 considers the costs of CO_2 capture, transport, and long-term geologic sequestration. While the model scenario runs published by EPA generally do not choose carbon capture as an emissions control option, this capability is likely to become more important in the future. In particular, the option to choose natural gas combined cycle plants with carbon capture appears to be turned off within the model in the EPA Reference Case. This technology option may become more relevant in policy scenarios where carbon capture is a more economic choice, so we recommend that EPA restore this technology option under relevant analyses.

As part of the cost estimation algorithm, EPA's application of IPM uses a proprietary model (GeoCAT) to provide information on CO_2 sequestration potential in different storage areas. While this is not described specifically in Section 6 of the documentation, it appears that IPM solves an optimization problem to find a least-cost solution for CO_2 transportation (mode and sequestration location) for each model region in which power plants are capturing CO_2. We would recommend that EPA incorporate additional specificity on this in the documentation, particularly any interactions between IPM and GeoCAT.

The CO_2 storage cost curves include opportunities for use of CO_2 for enhanced oil recovery (EOR) that yield negative storage costs assuming an oil price of $75/barrel. Given more recent developments in unconventional oil recovery, the assumed oil price may be too high. EPA should re-evaluate the oil price assumption related to EOR. Based on our reading of the documentation (Section 6.2), it appears that CO_2 sourced from industrial facilities at a positive storage cost of $50/ton could displace some CO_2 for EOR (sourced either from industrial facilities or power plants) with a negative net storage cost. Although it is necessary to consider competition between power and industrial sources, this appears to give the industrial sources preferential treatment that may not be appropriate in all scenarios, such as under power sector policies that provide an economic advantage to power compared to industrial CO_2 sources. In these circumstances or when oil prices (and hence EOR demand for CO_2) varies from the Reference Case, EPA should re-evaluate the CO_2 storage cost curves.

Some elements of the CO_2 transport model are also not clear, particularly related to the economies of scale in pipeline transportation. The method described in Section 6.3 of the documentation appears to assume that CO_2 sources that are transporting CO_2 over longer distances for long-term geologic sequestration are taking advantage of some undescribed scale economies in the form of capacity sharing in CO_2 pipelines. The documentation justifies this by saying that "the longer the distance from the source of the CO_2 to the sink for the CO_2, the greater the chance for other sources to share in transportation costs…." although there

does not appear to be any such probability calculated within EPA's application of IPM or used as an input. We interpret this statement as implying that EPA's Platform v6 assumes that CO_2 transportation over long distances will involve lower average transport costs because long-distance transportation implies multiple users sharing the cost of a larger pipeline. A CO_2 source in EPA's Platform v6 would thus face a lower cost per mile of transportation by moving captured CO_2 over longer distances. There is little real-world data to back up or refute this assumption, but if our interpretation is correct, we suspect that it may be biasing EPA's Platform v6 towards very long-distance CO_2 transportation in some cases.

D. POWER SECTOR FINANCES AND ECONOMICS

The most important economic factors governing power plant dispatch – fuel costs (where applicable) and O&M costs – are represented in EPA's Platform v6 through the use of relevant O&M cost data, fuel price data, and heat rate data where applicable. The most important economic factors governing power plant investment including new capital, retirements, and retrofits are equipment costs and the weighted average cost of capital (WACC), each of which is represented in EPA's Platform v6. The model also contains features meant to capture different investment incentives and risks in restructured versus traditionally-regulated jurisdictions.

The methods that EPA uses to determine variable dispatch cost (fuel costs plus variable O&M) seem appropriate for EPA's purposes and are based upon credible data sources.

Section 10 of the documentation has a highly detailed description for calculation of the WACC. Several elements of the determination of WACC are not clear:

- The description of the calculation of the capital charge rate would be made substantially more clear with an equation. In particular, whether EPA's Platform v6 uses the common "short cut" version of the capital charge rate (Stauffer, 2006) could be made more clear.
- The documented distinction between the book life of debt and the asset life for making investment decisions could be more clear. We recommend an explicit statement in the documentation describing the debt life versus the asset life.
- This module of EPA's Platform v6 is necessarily replete with assumptions because little financial data is in the public domain. Some of these assumptions may be questionable, although it is not clear how important they are in determining the overall WACC. Examples include the assumptions on debt-to-equity ratios and the cost of merchant debt, which in the market environment at the time of this writing may be high. EPA's Platform v6 uses a value of 7.2%, but one of the stated data sources for

debt-to-equity ratios currently suggests that the cost of debt may be substantially lower.[4] This is a data point that we suggest be updated in future revisions of EPA's Platform.

- The use of the Hamada equation (Hamada 1972) is a technical assumption that is made for convenience but the conditions under which the Hamada equation is valid include an assumption about a constant dollar value of debt. This is seldom true if firms are continuously refinancing their debts. Brealy and Myers (2011) point out that a constant leverage ratio is a more realistic assumption.

The most important issue on power sector finances that arose during our review concerned the treatment of utility versus merchant investment costs of capital in EPA's Platform v6. The documentation describes differentiated costs of capital for producers in deregulated versus traditionally-related markets, and also differentiates between capital charge rates for utility and merchant investments. This is intended to reflect differences in risk between these two types of environments (regulated/deregulated and merchant/utility) and is summarized in Table 10-2. Table 10-3 shows a single aggregate cost of capital that appears to be derived by taking the weighted average of the WACC figures for utility and merchant investment, based on the ratio of utility to merchant investment that prevailed during the period 2012-2016. This WACC is then applied to all new investments within the model. Thus, EPA's Platform v6 appears to be developing differentiated costs of capital for different market actors in the power sector, but in the model formulation is using a single cost of capital that represents a weighted average of these differentiated costs of capital.

If this is indeed how EPA's Platform v6 treats the cost of capital, we are concerned that the finance module does not sufficiently differentiate between risk attitudes by different investor types. Large integrated utilities in the U.S., for example, have had a much greater appetite for big capital projects such as nuclear power plants and carbon capture and sequestration pilot projects than merchant generators. These utilities can socialize risk across their customer base, and can also amortize costs over longer time horizons. Merchant generators cannot manage risk in this way – they may try to use financial markets to shift risk but the exposure for a merchant generator is generally higher than for a rate-regulated utility.

Additionally, the literature suggests that there are other cost differences in utility versus merchant generation firms, beyond the cost of capital. Specifically, Fabrizio, et al. (2007) suggest that independent power producers are lower-cost operators as compared to utilities. We therefore recommend that EPA consider

[4] See http://people.stern.nyu.edu/adamodar/New_Home_Page/datafile/wacc.htm.

specifying the costs of new units differently for cost-of-service regions and competitive regions.

We recommend that EPA consider addressing this differentiated risk appetite in future versions of EPA's modeling platform. One possibility would be to introduce different hurdle rates for different investor decision-makers and effectively split investment decisions within EPA's application of IPM. This would make EPA's application of IPM more complex in adding a number of new decision variables but could potentially be simplified by limiting investments of each type on a regional basis. For example, a fully "deregulated" state would have no utility investment and would have only merchant investment. The payback period for a utility (in terms of time horizon) would be much closer to life-of-plant, whereas the payback period required for new investment by a merchant generator would be shorter than the payback period for a regulated utility investment. Section 10 of the documentation refers to 10-K filings indicating long useful lifespans for generation equipment, but these are not the same as necessary payback periods for investment decisions.

It is possible that differentiating between utility and merchant investment in this way would yield model solutions where utility investors in "traditionally regulated" regions would engage in substantial new generation builds for export to "deregulated" regions. Despite this possibility, we still recommend that EPA consider separating utility versus merchant investment as separate decision variables with distinct discount rates. There are modeling steps that could be taken to mitigate the possibility of some odd simulation outcomes. Utility decision-makers within EPA's model platform, for example, could be constrained in the amount of new generation investment so that the installed capacity in those traditionally regulated regions does not exceed peak demand plus an appropriate reserve margin for that region.

The documentation could also explain more clearly how tax credits for wind energy are treated. Based on the documentation, it is not entirely clear whether wind is treated as an investment tax credit (ITC) rather than as a production tax credit (PTC). Chapter 4 of the documentation indicates that the tax credit extensions for new wind units as prescribed in H.R. 2029, the Consolidated Appropriations Act of 2016, are implemented through reductions in capital costs. As the credits are based on construction start date, the 2019 *production* tax credit (40% of initial value) is assigned to the 2021 run-year builds for wind units. The tax credit extensions for new solar units as prescribed in H.R. 2029 are implemented through reductions in capital costs. As the credits are based on construction start date, the 2020 *investment* tax credit (ITC) of 26% is assigned to the 2021 run-year builds for solar PV units. There is no discussion of why the wind tax credit is modeled as an ITC rather than a PTC – perhaps drawing parallels with other large-scale power sector planning models would be helpful in the documentation. Although the tax credit is currently set to phase out and so

may not significantly affect model results, there could be implications for modeling the credit as a PTC vs. ITC if the tax credits were extended. For example, PTCs can lead to negative prices, which has implications for the cost-effectiveness of storage.

The documentation under review did not include representation of the amended Section 45Q credit for carbon capture projects. The final version of rules implementing this tax credit appears in 2020 and thus were not included in this review.

E. FUELS AND RENEWABLE RESOURCES

Coal

EPA's application of IPM uses a set of exogenous coal supply curves for each coal grade in each supply region to solve for the price and quantities of coal used for power generation. For the purposes of modeling the coal market, EPA's Platform v6 treats each model power plant as its own demand region. These demand regions are linked through a transportation network to 36 supply regions. EPA's Platform v6 assigns coal grades to each model plant, with generally more than one coal grade per plant. Multiple transportation modes are specified based on existing infrastructure with relative competitiveness assessed for each mode. New plants use generic transport costs for different coal types.

The coal supply curves are constructed by sorting new and existing mines by cash cost per ton and plotting cumulative production. Costs include operating costs without capital for existing mines and with amortized capital for mine expansions. Considerable detail is used to build up transportation costs as well.

Projections of coal exports, imports, and non-electric sector coal demand are based on the AEO 2017 projections by region and coal grade. Because the model has more grade types and regions than the AEO, the model solves the selection of specific coal regions and grades that meet those imposed by assumption from the AEO.

Based on our review, the use of coal supply curves and a transportation network in EPA's Platform v6 appear to provide the dynamic trade-offs of coal grade selections with environmental control options that are necessary to project the effects of regulatory policy on the cost and emissions of coal generation. Consideration has been given to coal mine expansion costs and rail and other transportation costs in detail.

What is less clear is how costs and prices might change with significant reductions in coal demands that might occur under some scenarios. For example, there is not enough information provided in the documentation to discern whether coal mine closures are exogenous or endogenous within the model and the degree to which closures in the model reflect recent changes in

regional fuel supplies. The rate of mine closures and bankruptcies in the Powder River Basin (PRB) in particular seems to have been faster than expected in the past year, and at this point the only region adding coal production capacity may be Kentucky. Declining coal demand might impact unit production costs, and potentially transport costs, as volumes are reduced.

EPA's use of exogenously specified export and non-electric sector demand allows these demands to be considered in competition with electric demands, but only partially. Because the AEO2017 view of coal prices and supplies reflected in export and non-electric sector demand may not match EPA's view of coal prices and supply, the projections of other sector demands and exports may be inconsistent with power plant demand. In addition, if coal use for electricity generation varies significantly within a scenario, there will be no response in exports or other demand levels. Because these other demands are not of interest, the lack of feedback only matters if modified demands or exports would in turn impact coal prices to U.S. power generators. Overall, this is not likely to be a significant issue, but EPA should consider keeping the base projections up to date (using AEO2018 (or AEO2020 if an update is done) versus AEO2017), checking that the coal price and demand by electric sector projections between the AEO and EPA's Platform v6 are in close alignment, and assessing whether alternative projections are necessary in scenarios where electric sector coal demand varies materially from the Reference Case.

Natural Gas

EPA's Platform v6 uses natural gas supply curves derived from the proprietary ICF Gas Market Model (GMM). GMM is a gas demand and transportation network model that relies on characteristics of supply from ICF's Hydrocarbon Supply Model. To create the gas supply curves, IPM and GMM are run iteratively to find equilibrium prices and quantities. Subsequently, EPA's Platform v6 is run with the resulting set of curves that indicate how Henry Hub prices change with changes in the power sector quantity demanded, based on the supply curve for each solution year.

One disadvantage of this static curve approach is that it treats prices in different years as independent in EPA's Platform v6 context, rather than as a function of cumulative production that may vary by EPA scenario, even though the underlying curves were developed with that consideration by GMM. This can be addressed by re-estimating the curves by running the models iteratively, as in the Reference Case set-up, when it seems necessary due to significant changes in gas demand. In addition, while the slopes of the gas supply curves are clearly important to the modeling of electricity supply, it is difficult to determine how these slopes are derived based on the available documentation. Therefore, it is also difficult to assess their reasonableness. We would recommend that EPA publish more information about the methodology for deriving the curves.

It is also not clear the degree to which LNG exports, both export capacity expansion and utilization, are determined endogenously versus predetermined. If U.S. demand for natural gas changes significantly in some scenarios, one would expect that LNG exports might shift as well, which might have price implications for domestic gas buyers.

The GMM also serves as the basis for seasonal price differentials that capture the difference between the Henry Hub price and gas prices in model regions. While these differentials are endogenously projected by GMM with variable costs as a function of pipeline throughput and pipeline capacity expansions, they are fixed in a given scenario context. Under scenarios with different gas demand patterns (quantities and locations) than the Reference Case, these basis differentials could be quite different. Again, this may require additional runs iterating with GMM for some scenarios. Even now, the Appalachian trading hubs have increasingly separated from the Henry Hub in terms of pricing. Until there is significant pipeline build-out in the Appalachian region, this separation is going to be structural rather than transient (i.e. not an adjustment process to a new equilibrium).

Within the GMM, econometric equations project other sectoral regional gas demands. The elasticity of these demands presumably impacts the overall supply elasticity of gas to the power sector. We note, however, that an emerging petrochemical sector in the Appalachian production region is likely to affect regional natural gas pricing in ways that may not be well represented in the gas market model. Petrochemical facilities demand natural gas liquids (NGLs), not dry gas, and these NGLs are a co-product of natural gas production in some portions of the Marcellus and Utica deposits. Increased NGL demand from petrochemical facilities will require additional natural gas production, but without substantial regional storage or pipeline additions, there is likely to be additional stranded dry gas in Appalachia. The industry's future trajectory is uncertain, but it represents a non-power sector demand for gas that will be important for regional supply and pricing.

Other Fuels

Residual and distillate oil prices to electric generators are specified exogenously in EPA's Platform v6 and are taken from the AEO 2017. Nuclear fuel prices are from the AEO 2018.

In our view, using an exogenous oil price is appropriate because oil prices are not likely to change materially with changes in power usage. However, as a minor point, oil prices are treated inconsistently across EPA's Platform v6 and ICF's GMM platforms. While oil prices for power generation are based on the AEO2017, diesel fuel prices used in developing rail rates for coal are from the AEO2016. At the same time, oil prices used in the GMM, which are used to determine fuel switching in the industrial sector, are quite different from those

from the AEO that are used in the rest of EPA's Platform v6. In the GMM, oil prices increase and then flatten at $75/barrel. There is no indication in the documentation what oil prices are assumed in the Hydrocarbon Supply Model in developing associated oil and gas production projections, although we understand from EPA that they are the same as used in GMM.

Biomass is represented in EPA's Platform v6 by annual regional supply curves that are derived from those in the Department of Energy's 2016 Billion Ton report. The curves are built up from county level data and aggregated to each model/state region. The curves reflect transportation costs, as well as storage costs that are added to the steps of the agricultural residue supply curves. No interregional trade is allowed, which seems reasonable given the generally high cost of long-distance biomass transport.

Renewable Resources

Solar and wind resources are represented regionally in EPA application of IPM by resource class. For wind, resources are defined by techno-resource groups (TRG) as developed by NREL that are based on estimated levelized costs reflecting expected capacity factors, capital costs, and O&M costs. EPA's Platform v6 also divides resources further into 3 or 6 capital costs steps (3 for offshore wind and 6 for onshore wind and solar) that represent increasingly higher transmission costs. This is similar to the methodology used in many other capacity expansion models.

EPA's capital cost adders for wind and solar, which are based on an estimated distance to transmission infrastructure, do not appear consistent with those for non-wind and non-solar units that represent the cost of maintaining and expanding the transmission network. These latter costs are based on AEO 2017 values and are equal to 97 $/kW outside of the WECC and NY regions and 145 $/kW within those regions. The wind and solar PV adders start as low as $1/kW, with especially low values for PV even though it is assumed that these are utility scale rather than rooftop systems. It would seem more consistent for the generic transmission network costs to be applied to all units rather than exempting wind and solar. Otherwise this provides a bias towards wind and solar PV development.

F. REGIONAL AND TEMPORAL RESOLUTION

For planning models such as IPM that consider decisions related to costs and benefits over decades, a high level of aggregation is often necessary for the model to function. Consistent with this objective, EPA's application of IPM aggregates its representation of the electricity system in the three following ways.

- ***Model Run Years:*** EPA's Platform v6 contains a roughly 30-year planning horizon, compressed into eight representative model run years.

The results from a representative year are assumed to be representative of a series of years associated with the model year. Model years are more spaced further apart later in the horizon (e.g. 5 years between model years rather than 2 or 3 years as in the nearer term).

- ***Load Segments:*** The 8,760 hours in a given model year are aggregated into 72 representative hours by first dividing seasonal (3 seasons) load duration curves (LDC), in which hours are sorted by loads into 6 load levels and then dividing each of these into 4 groupings by time of day (night, morning, mid-day, and early evening). There are 72 such load segments for each model region although some may contain no load, for example the top 1% load hours in the summer may have no nighttime hours, in which case the summer/peak/nighttime segment would have no representation.

- ***Model Regions*****:** EPA's Platform v6 divides the continental U.S. and Canada into 78 modeling regions. Each region has its own load and supply characteristics, capacity requirements, and transmission capability to other regions. The model disaggregates some regions such as NYISO much more extensively than others, such as the Southeastern U.S. regions.

While in several ways, EPA's Platform v6 is "state-of-the-art" for a linear-programming model that utilizes an LDC-style aggregation of load, it is important to recognize the trade-offs inherent in aggregating space vs. time in an LDC approach, as well as in using the LDC approach at all. Key considerations related to these tradeoffs include the following:

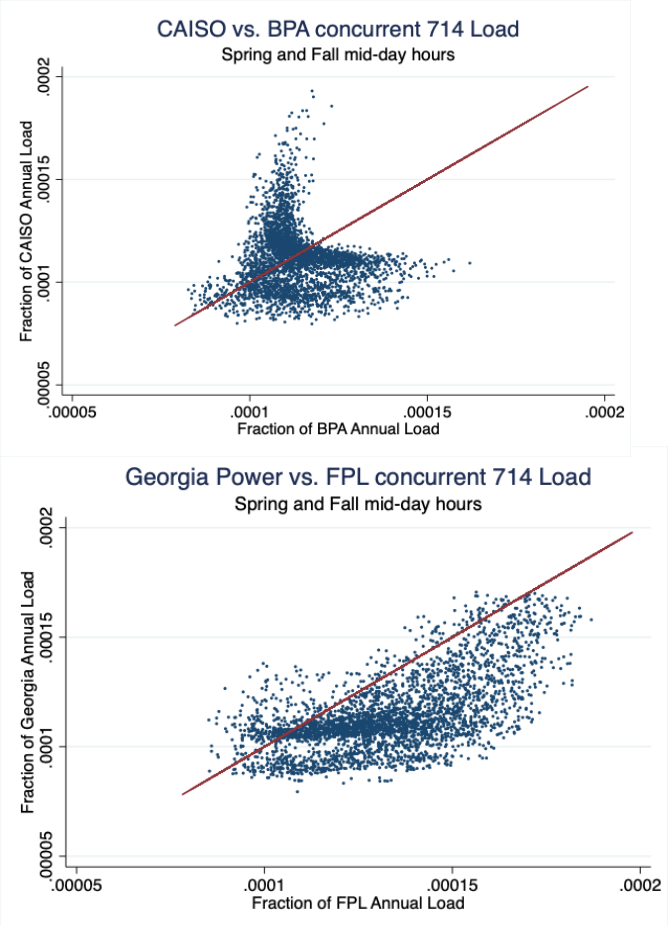
- **Load aggregation can dilute outcomes that are concentrated into a small number of hours.** If certain key outcomes, such as capacity requirements, transmission utilization, and episodic peak emissions are driven by conditions in a small set of hours, such as peak hours, then aggregation even up to 1% of all hours may average outcomes in the lower end of the load grouping with the higher end. EPA's Platform v6 addresses this well by specifying a very high peak load segment, representing only 1% of all hours. However, key transient outcomes in the system may not be limited to only peak hours, particularly with extensive adoption of renewable energy resources.

- **Load aggregation necessitates difficult modeling choices regarding inter-regional trade.** With a large number of regions aggregated up to individual load-shapes, the model must represent how exports in a given load segment (e.g. segment 1) in region A map to imports in another region's load. The standard practice for models like IPM is to simply assume that all regions are in a given segment at the same calendar time, so that trade between regions happens at the load-segment by load-

segment level. Such an assumption is problematic, as Figure 2 below illustrates.

The top panel in Figure 2 plots concurrent load in the CAISO region relative to load in the Bonneville Power Administration (BPA) region for mid-day spring and fall hours during 2014-2016. The bottom panel plots the load in Georgia Power against that in Florida Power & Light (FPL) for the same time periods. If load were perfectly correlated, all observations would fall along the 45 degree lines in each panel. The spread of observations in the top panel indicates that peak load in CAISO and BPA are very much non-concurrent. Florida and Georgia are much more correlated but there are clearly peak hours in both that fall in lower load segments in the other.

Figure 2: Load Correlations between Neighboring Control Areas



Data shown here from FERC Form No. 714 – Annual Electric Balancing Authority Area and Planning Area Report.

To its credit, EPA's Platform v6 goes beyond the simple assumption of concurrent load and requires that exports from one region's load-segment "arrive" in importing regions during the same calendar hour in which they were exported. These calendar hours likely would fall across a range of different load segments in the importing region because calendar hours are assigned to different load segments in different regions. For example, exports from the Pacific Northwest during its 1% daytime summer peak hours would be assumed to arrive in California during those same calendar hours. Some of those hours may fall within the second or third daytime summer load segment in northern California because the 1% peak demand occurs on different days or hours in the two locations.

While this is likely an improvement over the naïve assumption of perfect correlation of hours and load segments across regions, it still makes strong assumptions about the timing of trade. It is difficult to diagnose the full impacts of this implementation. Our intuition is that it constitutes a hidden penalty on trade between regions; in order to export during hours in which trade is beneficial, the model may be forcing additional trade in hours in which trade is not beneficial. If true, this means the model will bias downward trade between regions.

Again, this is in contrast to other LDC-based models that ignore these problems. Those models are not built to describe trade between identical calendar hours and allow trade between hours that do not actually coincide, simply because of their position in an LDC.

One additional comment on this point is that the documentation does not describe this aspect of interregional trade. A description with an accompanying example would help promote understanding of this feature of the model.

- **Geographic aggregation involves trade-offs between accuracy over time vs. space.** The aggregation of geographic regions implicitly assumes that all plants and loads within a region share common LDC load segments and face no transmission congestion. Our understanding is that the increase in the number of model regions in version 5 is motivated by a desire to faithfully capture important inter-regional transmission constraints. However, this benefit comes at the cost of dividing up shared calendar hours into potentially different load segments – as described above. One way to reduce the problems identified above is to aggregate over larger geography. Further, since trade between regions is subject to the distortions of which "time" the trade is occurring, the representation of transmission flows would also be skewed in the same way, limiting at least somewhat the benefits of being able to model a given transmission interface.

- **Load aggregation limits modeling of inter-temporal constraints.** While electricity markets work to operate generation units in a strict "merit-order" based upon costs, many units feature operating limits such as ramping rates, start-times, and minimum down and up times. In addition, hydro and storage units feature energy limitations or charge/discharge cycles. Fully representing these considerations requires modeling a sequencing of contiguous hours that is impossible when aggregating to an LDC. In many cases, these considerations "average out" over time. Simpler modeling understates output some hours and overstates it in other hours.

  For regulations that concern *total* output or emissions from a power plant during a season or year, the aggregation is likely relatively benign. However, for the purposes of assessing any environmental regulations focused on *peak* emissions, episodic emissions, or emissions intensity, the aggregation could be more problematic. The aggregation would likely bias downward the output of high heat-rate "peaking" plants. The *turndown* constraint could at least partially offset this bias, but it is difficult to understand what the effect of this constraint is without running the model with this constraint disabled.

Given the costs and benefits of the aggregation choices described above, we would urge EPA to consider alternatives that might be compatible with a linear-programming implementation. These are not necessarily recommendations, as it is difficult to know the magnitudes of the issues described above. We note, however, that accurately representing inter-temporal constraints and modeling the correct timing of "peak" and "off-peak" net loads could be more important in the future than is the case today due to evolving electricity supply conditions.

Publish more output details: Currently model outputs are not broken out by load-segment. This additional output detail may allow stakeholders to better judge the relative impacts of the various aggregation assumptions in a given policy context. If this information is not generally shared with the public, EPA may still consider modifying IPM to generate these outputs for purposes of model and scenario evaluation before publishing results in more aggregated form.

- **Investigate the Time vs. Geography Trade-off:** It is possible that the goals of the model may be better implemented with *more* temporal resolution and that this could be aided by *less* geographic resolution. With fewer model regions, LDCs better represent timing within a region (but could exacerbate dis-alignment between regions). There could also be some computational savings through geographic aggregation, although these may be limited by the need to model each power plant individually, no matter what region it is in. As discussed below, additional time-based modeling could take the form of additional segments or

seasons within the current framework or a more substantial reconfiguration of timing.

- **Consider grouping hours first by time of day and then by load segment, instead of the other way around.** We do not understand the motivation for dividing hours into only 3 seasonal groups before sorting into load shapes instead of grouping into 3 seasons x 4 time-of-day segments and then aggregating into 6 segments each. The latter approach would provide a more balanced number of hours in each load segment within each season/time-of-day block.
- **Investigate the implications of grouping hours first by load segment for a whole interconnection and then by region.** Another way in which the grouping order affects the trade-off between regional vs. local accuracy in load conditions is the practice of grouping load by model region first, and then sorting by load level within regions. An alternative would be to group hours by their interconnection-wide load level and then subdivide into regions. For example, the top 37 summer hours would be chosen from the hours with the highest total load across the WECC. Those hours would then be assigned to the different model regions within the WECC. This approach would more faithfully recreate the conditions available for trade between model regions, but would lose accuracy in capturing, for example, peak conditions within a given model region.
- **Represent time as a sequence of "model hours" or "model days."** Computational limits require limiting the number of demand segments (region + hours) represented in the model. LDC aggregation allows for all hours of a year to be approximately represented but at the cost of not knowing when each hour falls relative to others. One alternative would be to group hours into time-of-day blocks (e.g., 4 hours) and model them sequentially, allowing for better representation of some inter-temporal constraints, inter-regional trade, and probably renewable energy and storage output. One such "model week" per season could capture a peak day and other important load characteristics. However even this aggregation would require 126 hours of modeling, which may be infeasible.

  Another alternative would be to group hours into time-of-day blocks for typical weekdays and weekend days with a preservation of peak loads through a peak-day or other method. Once the hours are more contiguous, it may also be worth adjusting time zones across regions so that the hours represent the same actual time.
- **Run the output of a model scenario through a more detailed dispatch model.** Another way to investigate the relative importance of the inter-temporal constraints would be to take the output of a given

model scenario and run the resulting unit configurations through a different model designed to capture short-term operating constraints in more detail. This second model could be used to test for "peak" emissions impacts of intertemporal dispatch constraints, for example.

- **Model fewer future years.** One way to compensate for more detail within a given model year would be to run fewer model years. Seven, instead of eight, explicit model years would reduce the number of demand segments (region + hours). There is so much uncertainty about future conditions, particularly in the 20- to 30-year time horizon, that it is not clear how valuable more model years are that far into the future. However, care should be given to avoid "end-year" effects in years of interest.
- **Consider the impact of the discount rate in the objective function.** EPA's Platform v6 discounts model objective values by 4%, meaning that costs 20 years in the future count for roughly half of costs in the first year. Such discounting is appropriate given the high degree of uncertainty over future conditions. Important model outcomes should not hinge upon decisions the model makes 25 to 30 years in the future. An even higher discount rate may be appropriate to minimize the impact of out-year decision making on model outcomes.

G. POWER SECTOR POLICIES

Federal environmental policies aimed at the electricity sector are represented in detail in EPA's Platform v6. These policies include many prescriptive technology policies, tradable performance (emissions rate) standards, and cap and trade. In general, we find that EPA models these policies well. Power sector policies pertaining to the market structure, transmission pricing, reliability standards, and other features of economic regulation can also have an important influence on environmental outcomes; these are represented in less detail in EPA's Platform v6 than the other types of policies listed above.

Although trading programs are represented well in EPA's Platform v6, the documentation indicates that the model does not include any explicit assumptions on the allocation of emission allowances among model plants under any of the programs. An element of cap and trade that may be challenging to model is dynamic allocation of emissions allowances that maintains the emissions cap. An example of this approach appeared in Virginia's final 2019 regulation for the introduction of cap and trade for carbon emissions, in which allowances were to be distributed to generators based on their share of

generation in a recent period.[5] This approach couples a carbon price with a production incentive that stems from the ability to affect one's allocation by changing one's production. The model might represent such a policy by describing the production incentive that is embodied in this type of allocation. One difference between dynamic allocation and auctioning is the observed price of emissions allowances and the effect on the price of electricity (Rosendahl and Storrøsten (2011).

Similar challenges arise in representing clean energy standards, which are emissions intensity standards with effective emissions targets that adjust over time in response to the quantity of production. This differs from dynamic allocation of emissions allowances among facilities with a specific emissions target in place, but it is similar from an analytical perspective in that it embodies a production incentive. These issues may be challenging for EPA to represent, and may require model development. EPA's Platform v6 does not currently represent these policies, except potentially through an iteration procedure.

Other challenging elements in representing power sector environmental policies include dynamic adjustments to emissions budgets based on the prevailing price in an auction, as illustrated by the emissions containment reserve in the Regional Greenhouse Gas Initiative. Another example is program-related spending that may be tied to allowance proceeds, such as the direction of auction proceeds among states in the Regional Greenhouse Gas Initiative to investments to promote energy efficiency. In principle, these policies also can be addressed through iteration, but this may require more time and multiple runs of the model. Dynamic policy features may be increasingly relevant in the future, at both the federal and state level. The Agency needs to anticipate this in considering the evaluation of power sector environmental policies.

With the expansion of state-based environmental and clean energy policies, there is increasing interest in leakage of generation and emissions from jurisdictions introducing regulations to unregulated jurisdictions. Conversely, unregulated jurisdictions could see an increase in wholesale power prices if they increase generation to serve demand elsewhere. IPM has been used to model policies similar to these, and IPM produces projections of the implications of these market dynamics and is a useful tool for the EPA to evaluate and understand them. For example, IPM was used to assess impacts of the Clean Power Plan.

Moreover, there is an interaction between electricity sales and transmission, and renewable energy credit markets. Although we understand that this interaction is embodied in the model, we have not seen it represented in previous exercises of the model or described in the documentation. Policies such as carbon pricing that

[5] That final regulation was never implemented. Legislation in 2020 established Virginia's participation in RGGI and the allocation was replaced with a revenue-raising auction.

promote an increase in renewable generation in one region could precipitate a decrease in renewable generation in another region if renewable energy credits become available in the region introducing carbon pricing that can be used for compliance with renewable portfolio standards in other jurisdictions. These issues are the subject of an ongoing study in PJM and various types of border carbon adjustments have been proposed. These are emerging policy and industry issues that the panel wants to be sure that EPA considers in its updates to its modeling platform. EPA may want to begin to consider these issues and direct development of EPA's application of IPM to track and report the effects of policies implemented within narrow geographic regions.

Some prescriptive policies such as New Source Review constrain the utilization of an existing generating unit and limit investments in new units in a geographic area. The Agency should pay special attention to this in evaluating its modeling, because it is not obvious in the documentation that generation from units that are in nonattainment areas or subject to New Source Review are necessarily constrained from expanding generation, or may be required to introduce pollution controls that may raise their costs. Relatedly, nonattainment areas are not congruent with the power regions in EPA's Platform v6. The panel understands that no explicit generation limits are modeled; however, unit level emission rates and permit rates are explicitly modeled in the EPA Reference Case. To capture the influence of New Source Review-type regulations, the model might be adjusted to preclude increases in generation at a plant, or to condition such increases on the installation of post-combustion controls.

The model seems to capture policies that affect the bulk power system – but does not seem to capture state level policies that encourage behind-the-meter generation except represented as a change in demand. This could be increasingly important if federal policies introduce new requirements on states to achieve emissions goals, as represented for example in the recent outline of potential climate legislation developed by the House Committee on Energy and Commerce.

Several other possible energy policies may become increasingly important, such as reliability constraints defined by on-site fuel storage and the minimum offer pricing rule (MOPR). These policies may have important environmental implications. EPA's current approach to modeling capacity requirements does not fully capture the impact of any of these policies, although EPA's Platform v6 may have the capability to reflect elements of these policies. For example, if EPA models nuclear generation incentives from state-level zero-emission-credit (ZEC) policies, it would also need to evaluate whether those nuclear plans should count towards satisfying a regional capacity constraint. Under final MOPR rules, which are as of yet to be determined, such nuclear capacity may not be part of capacity market compliance. This may not require new model development, but it might

require the attention of the Agency in specifying the way policies in the model are represented.

Finally, one last finding pertains to the representation of the CO_2 emissions rate for imports to California, at 0.428 MT/MWh. This is the default rate for power that is not assigned a specific emissions rate, but the major portion of power coming into the state is assigned a specific rate. Moreover, it is unclear that the incremental unit that is affected by a policy under evaluation will have an emissions rate that is proximate to the average rate. A careful solution to this could be found through iteration, solving the model twice varying the level of demand in California in order to identify the marginal resource providing power to the state and region, but this may require additional Agency resources. With the expansion of the Western Energy Imbalance Market to reach as far as Colorado, accounting for emissions intensity of transmitted power will be increasingly important.

H. RETAIL PRICE ESTIMATES

EPA's Retail Price Model (RPM) is a post-processing model that estimates the *relative* retail electricity price impacts of different regulations or scenarios. To estimate retail price impacts, the RPM relies, in part, on scenario outputs from EPA's Platform v6 as its inputs. Retail rates in the model are comprised of three components: (1) transmission costs, (2) distribution costs, and (3) generation costs. Currently generation costs in actual rates comprise roughly 30 to 50% of the total costs included in retail rates.

As long as transmission and distribution are not modeled as endogenous choices in the model for EPA's purposes, these components should not vary between scenarios or under different regulations. Therefore, the crux of the RPM lies in its translation of wholesale energy costs into retail prices. The main challenge faced by the model in fulfilling this objective is the fact that changes to some generation costs will be transmitted into retail rates differently in fully regulated states than in states that have undergone regulatory restructuring/deregulation. The model therefore has two different generation cost pricing formulas to match the different regulatory environments. For each model region, the final retail price reflects a weighted average of the regulated and restructured generation price.

a) ***Cost of Service Generation Cost Pricing.***

$$\textit{Final Cost of Power Generation} = (\textit{Average Generation Cost} + \textit{Utility Depreciation Cost} + \textit{Return on Equity and Debt} + \textit{NUG Adder}) \times (1 + \textit{Tax Rate})$$

where the first three terms represent the variable and capital costs of a cost-of-service generator and the last term captures the cost of pre-

existing non-utility generation (NUG) present in the service territory. While it is not obvious that the capital costs of a merchant NUG would be directly passed on to retail rates, we assume the NUG adder is included because these costs are captured in long-term contracts between the generator and the local load-serving entity (but this is not explained in the documentation).

The *Average Generation Cost* represents the full average cost (including capital) of all units built or retrofit within the model run, as well as the variable cost of generation from existing units. The *Utility Depreciation Cost* represents the capital costs of existing units owned by regulated utilities. The *Return on Equity and Debt* is the return earned on those existing assets.

b) ***Deregulated Generation Cost Pricing***

Competitive Generation Cost	=	(*Marginal Energy Price + Reliability Cost + Renewable Energy Credit Cost)×(1+Tax Rate)*

Based on our review, the RPM includes much more than the rate impacts of going-forward costs (i.e., the incremental cost impacts of a policy). This is consistent with some applications of the RPM. The formulas in the RPM in theory include all components of a retail rate. A key trade-off to consider in the RPM is whether to attempt to measure the *levels* of rates or only to focus on the changes in rates going forward. For example, the formula for cost of service generation includes only one term, *Average Generation Costs,* that captures newly incurred costs. All the other elements in that formula capture components of the existing rate and should not necessarily be expected to vary by scenario going forward.

One important reason to capture the full level of rates would be to model the impact of those prices on the level and shape of demand. Currently EPA does not regularly use demand elasticity to estimate the demand response to changes in electricity prices. If that were to change and demand responses to prices became endogenously modeled, then the ability of the RPM to reflect both the changes to and levels of retail prices will influence most outputs of the model due to the feedback between wholesale outcomes and retail demand.

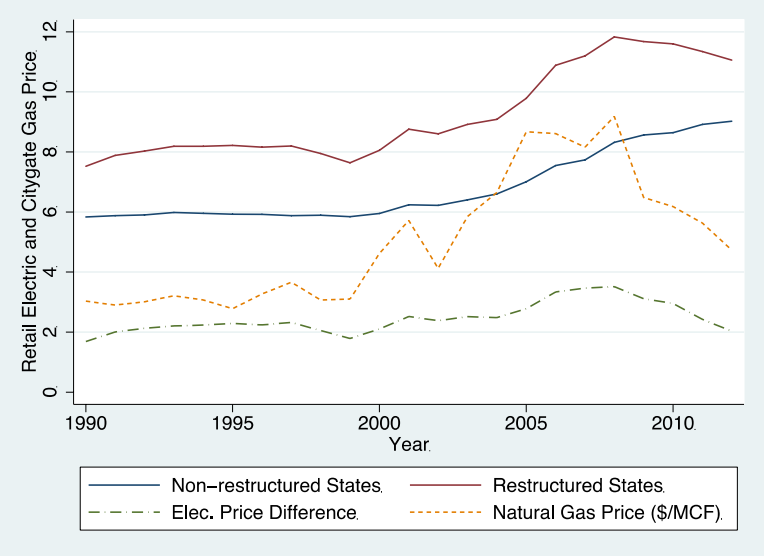
Going-forward impacts of policies can also be divided into a) impacts of policies on going forward costs and b) impacts of policies on the pass-through of existing costs to retail rates. These distinctions are important because the differences between regulated and competitive markets matter less for capturing going-forward costs than for the pass-through of existing costs. A model such as IPM effectively represents perfect competition and perfect regulation – resulting in least-cost investment and operations. In theory, both perfectly regulated and perfectly competitive markets should produce the same outcome, and total costs

going forward. Therefore, if the only purpose of the RPM were to measure the rate impacts of going-forward costs, it is not clear the model needs to make a distinction between competitive and regulated markets. However, our understanding is that EPA intends the RPM to measure rate impacts of both current and going-forward costs.

The model does attempt to capture the differential impact of policies on the pass-through of existing costs. Since the purpose of the RPM is to capture the full rate impact of policies, including their effect on the pass-through of existing capital costs, then there is justification for treating regulated and competitive markets differently. Two examples of such differences are 1) the impact of policies on marginal generation costs (energy prices) and 2) the possibility that policies might "strand" certain existing capital assets.

Given that EPA does intend the model to shed light on transitional rate impacts, such as the impact of policies on the pass-through of existing costs, then the general modeling approach taken by the RPM is appropriate. The model should capture the fact that energy prices will fluctuate more in response to certain regulations than others, and that rates in competitive states will likely reflect these fluctuations. To illustrate this point, Figure 3 shows the disparate retail rate response to natural gas price volatility since 2000. Rates in competitive states rose more rapidly when gas prices rose in the early 2000s, and fell more quickly when gas prices declined post 2008. One would expect a similar differential pattern from a regulation that effects the marginal cost of marginal generation, such as a carbon tax or the Clean Power Plan. As the figure illustrates, however, these differential effects tend to average out over long periods of time.

Figure 3. Rate Responses to Natural Gas Price Changes



Source: Borenstein and Bushnell (2015).

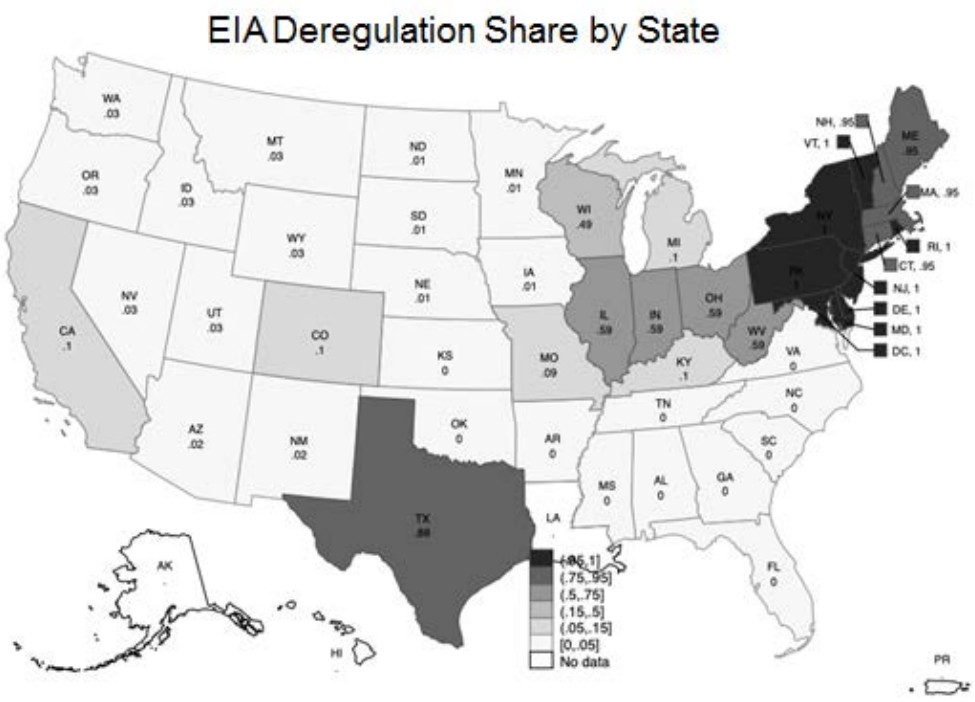
The general structure of the generation pricing formulas seems appropriate, but the purpose and magnitude of elements, such as the NUG adder, should be better explained. The formulas described above capture the key elements of pricing in regulated and competitive markets in the sense that regulated prices are based upon IPM's calculations of total average costs and competitive prices are based upon IPM's calculations of the marginal cost of serving load (including compliance with state Renewable Portfolio Standards, etc). However, there are other elements that are somewhat opaque and appear to contribute significantly to the total rate. For example, the NUG adder is substantial in many regions in early years. Our understanding is that this is meant to capture the cost of existing NUG generation in regulated states selling power through power purchase agreements (PPAs) to regulated utilities. However, even in deregulated states, there are substantial NUG transactions through PPAs, and there is no NUG adder to rates in those states.

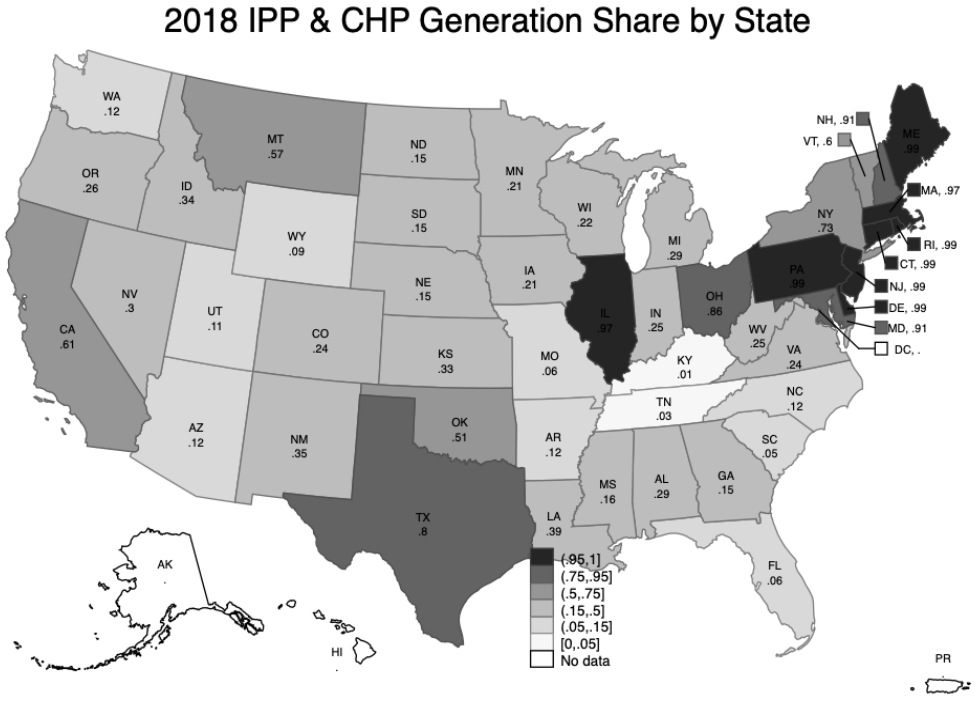
The logic behind the definition of competitive vs. regulated regions is unclear. There are many possible definitions of "regulated" and "competitive" and the RPM utilizes definitions from EIA's Annual Energy Outlook for its assignments of regions to these categories. This may not be the best definition for this application.

The RPM is ultimately trying to capture the pass-through of generation costs to retail prices, and therefore it is the regulatory treatment of the generation that is most relevant to this calculation. The weights for competitive and regulated regions in the RPM appear to be too blunt compared to generation ownership patterns defined by the EIA. Figure 4 compares the percent of generation that is regulated for each state (top panel, aggregated to states from model regions) in the RPM against the 2018 share of generation coming from non-utility (bottom panel, Independent Power Producer and Combined Heat and Power) sources according to EIA. The RPM tends to assign either a zero or 100% regulated/competitive designation in many states, while the generation shares according to EIA are much more blended. One reason for this difference is likely the NUG generation operating under power purchase agreements selling to the local utility in regulated states.

Based on the above comments, we recommend that EPA improve transparency of the RPM results and their components. The components included in the competitive and regulated pricing formulas seem appropriate, provided that exogenous components such as distribution charges and taxes are calibrated correctly. However, some components such as the NUG adder seem subjective and it would be useful for a consumer of the results to understand how important different components are to the rate impacts coming out of the RPM. One suggestion would either be a table or stacked bar chart detailing not just the total rate (or change in rate) but also the components that make up that total. Most of these details are available but take considerable effort to put together.

Figure 4. Regional Competitive Generation Shares





EPA should evaluate and articulate the purpose of distinguishing between competitive and regulated regions. The choice of whether to model competitive and regulation regions differently in the RPM depends largely upon the intended usages of the model. If it is important to capture near-term rate impacts of policies that change how existing costs are passed through to rates, then maintaining a regulation/competition distinction is important. If the model is intended more to capture the rate impacts of going forward costs created by policies, rather than the impacts of those policies on the pass through of existing costs, then there may not be much difference between the regulated/competitive results. One other point to consider is the role of PPAs and other long-term contracts with NUGs in competitive markets. Even if short-term energy prices fluctuate in response to policies, to the extent that generator payments are locked in through PPAs and other contracts, those short-term energy price changes will not all be passed through to retail prices, even in competitive markets.

Consider a simpler retail price formula based upon regression analysis of the relationship between generation costs and retail rates over time. Predicting the movements in retail prices is a difficult challenge and although the RPM captures the theoretical relationship between generation costs and retail prices, it may be more transparent (without being much less accurate) to apply a simpler formula based upon the historic relationship between costs and prices. A regression-based approach would allow for the estimation of confidence intervals or other measures capturing uncertainty as well.

IV. BASE SET OF MODEL SCENARIOS

Check the appropriateness of the base set of model-scenarios for addressing uncertainty in potential future power-sector trends, focused on answering these questions:

a. *Are the base set of model-scenarios (which include a reference case, low demand case, high demand case, low renewable cost case, high renewable cost case, and a high gas cost case) appropriately characterized? How well do these scenarios suit EPA's analytical needs?*

b. *Do the model scenarios reflect the most robust sources of uncertainty for the power sector? Are any of the model scenarios extraneous? Outside of a federal regulatory context, are there significant areas of uncertainty in the power sector that are not covered by these scenarios? How well does the range of scenarios suit EPA's analytical needs?*

EPA has made several model scenarios available in the public domain. These scenarios reflect many of the most important uncertainties driving operations and investment in the electric power sector, including the price of natural gas and the cost of renewable energy (particularly wind and solar). EPA has also made public a scenario involving changes to the U.S. tax code, which affects financial incentives for investment in the electricity sector.

NON-PARAMETRIC UNCERTAINTY

While we do not question EPA's choice of using a deterministic linear programming model, it is important to recognize that this structure limits the kinds of uncertainty that IPM can reasonably handle. The uncertainty reflected in the model run scenarios is limited to "parametric uncertainty", which can address uncertainty over the values of one or more input variables without changing the model's overall decision structure. EPA's Platform v6 as currently configured, however, cannot handle "intrinsic uncertainty", which is characterized by uncertainty over decision rules or processes. Any decision process that deviates from present discounted cost minimization, for example, cannot be captured directly by IPM.

Because EPA's Platform v6 as currently structured is limited to handling parametric type uncertainty, there may be some biases reflected in the model outputs. These biases are probably very situationally dependent. EPA's Platform v6 as currently structured, for example, may exhibit a bias towards decisions that reflect current power-sector conditions and incentives even though these conditions are rapidly changing.

Another limitation of the focus on parametric uncertainty is that sensitivity analysis does not show how behavior may change or may depart from expected net present value maximization in the presence of uncertainty. For instance, option theory suggests rational decision makers will delay irreversible

investments (and retirements) in the face of uncertainty to gain more information about the uncertain aspects of the scenario. This behavior will not be evident in an inter-temporal optimization linear program such as IPM. However, this element of decision-making under uncertainty might be represented by adjusting the hurdle rate for investment and retirement options, perhaps implemented as a shadow cost of capital for investments that would be vulnerable to specific parametric uncertainty, including those mentioned above and potential policy uncertainty.

Also of note is that EPA's Platform v6 is not currently structured to capture "deep uncertainty" (Walker et al., 2013), which reflects a situation where parties cannot agree on the nature of the uncertainties that the system faces or on how to rank or compare potential solutions.

PARAMETRIC UNCERTAINTY

The parameter uncertainty represented by the set of model run scenarios made public by EPA capture many of the most important factors that have driven power sector investment and operations over the past ten years, and are likely to continue to influence the power sector in the coming decade (at least). An important aspect of incorporating parametric uncertainty into models of this type, in which a large number of assumptions must be made due to limitations in data or model tractability, is sensitivity analyses to understand the robustness of model outputs to uncertainty in model input parameters. Beyond the scenario runs made public by EPA, it is not clear what sensitivity analyses EPA conducts to determine which parameters are the most important in determining variation in model outputs. EPA's application of IPM is so complex that it may be the case that no single parameter is driving the model outputs all by itself. Some attempt at investigating and publishing which parameters or combinations of parameters most heavily influence model outputs in the Reference Case would be very useful.

There are additional factors not represented in the set of model run scenarios published alongside the Reference Case as part of EPA's Platform v6 that are likely to be important drivers of power system operations and investment in the coming decades. We believe that model runs representing these factors are useful in understanding the influence of fundamental changes in the electricity industry on the results that EPA's Platform v6 produces, and therefore would have substantial value as additional sets of model run outputs published along with the Reference Case. EPA should therefore consider ways to represent these factors in additional sets of model runs published alongside the Reference Case in EPA's Platform. Some of these factors include the following:

Changes in the shape of the load duration curve: EPA's Platform v6 currently features low and high demand scenarios in addition to the Reference Case, that are taken from AEO projections. These low and high demand scenarios do not

explicitly modify the *shape* of the load duration curve, only the rate of overall annual growth in electricity demand. The panel understands the change in load shape can be explicitly captured in EPA's application of IPM when such information is available. Load shapes are adjusted to account for the load factor embedded in the AEO high and low demand scenarios. However, even under such scenarios, the model does not capture fundamental changes in the the way load may be shaped dynamically in the future, reflecting interactions between demand and the bulk power grid that are likely to be a defining feature of the evolving electricity system over the next two decades. Scenarios driving these changes in the nature of demand patterns (not just the amount of aggregate kilowatt hour consumption or the ex ante assignment of levels of demand over times of day) are likely to include (1) vehicle electrification, (2) time-varying retail rates that encourage load shifting and peak-time demand response, (3) wholesale (aggregated or individual customer) demand response that is generally dispatched during summer peaks to ameliorate very high market clearing prices or reduce peak system loadings for reliability reasons, and (4) the penetration of behind-the-meter generation and energy storage.

These changes in the nature of electricity demand, in isolation or taken together, can be represented in EPA's Platform v6 through adjustments to the load duration curve. In some cases, these adjustments may be fairly straightforward (for example the same solar data used to model location-specific solar production could be used to model offsets to different demand segments, by correlating time-varying solar production with the demand segments in each region and netting regional behind-the-meter solar production against regional demand segments). In others, the nature of the demand adjustment will itself be scenario-dependent. The timing and nature of electric vehicle charging, for example, will influence the impacts on diurnal load curves that may translate to changes in the demand segments used within EPA's Platform v6. Wide adoption of electric vehicles combined with primarily nighttime charging will increase the level of demand in what are currently lower-demand segments in a way that represents overall nighttime load growth, potentially without corresponding demand reduction in other load segments.

Even without changing the load duration curve, we also suggest including a scenario in EPA's Platform, along with the Reference Case, that involves negative demand growth arising through greater energy efficiency measures for buildings and appliances.

Scenarios that reflect uncertainty regarding fuel availability: Resilience of the power grid to fuel supply disruptions has gained some policy attention, particularly as power generation shifts towards the use of natural gas and away from coal. There are potential interactions between environmental policy and this kind of fuel substitution, but even cutting-edge planning models in the literature (e.g. Bent, et al., 2018) do not adequately capture the multi-decadal implications

of shortages in infrastructure to deliver fuel to power plants. We would encourage EPA to publish scenarios alongside the Reference Case involving negative shocks to fuel supplies, particularly in the northeastern U.S. where resistance to additional fuel delivery infrastructure has been high. These negative shocks could be modeled as outages or de-rates to certain types of generating units in certain regions within EPA's application of IPM, or (perhaps preferably) using high fuel prices to indicate shortage (see an example for natural gas in Bent, et al., 2018). The model scenarios should be compared to empirical experiences, of which there are some past examples due to weather events.

Scenarios that capture multiple parametric changes: We view capturing interaction effects between parametric scenarios as being valuable for EPA's purposes as well as for the broader analytical community. The number of possible combinations is large, but we would prioritize assessing and making publicly available the following model scenarios:

- Scenarios that interact shifts in load duration curves with existing parametric scenarios (such as low/high gas prices and renewable energy costs);
- Scenarios involving very low gas prices and rapidly declining capital costs for renewable power generation;
- Scenarios involving fuel supply shocks and low capital costs for renewable power generation (implying a larger dependence on renewable energy during supply shocks, and the response of the system to that known dependence).

Unexpected Events: Finally, we observe that EPA's Platform v6 as currently configured is ill-equipped to handle unexpected events that might arise over the multi-decadal time frame that it models. Yet, these kinds of surprise events can often be critical drivers of energy system change. The rise of unconventional natural gas as a major domestic fuel source is one recent example that could not have been foreseen two decades ago. IPM has difficulty handling these kinds of events because of its implicit assumption regarding perfect foresight. Without deviation from the linear programming and deterministic structure, however, we do see a straightforward way for EPA to be able to model specific scenarios that involve parametric surprise events, and encourage EPA to publish the results of such scenarios alongside the Reference Case. Such a procedure might progress as follows.

1. Define a parametric shock that would occur during a defined time interval over which IPM is run.
2. Run IPM without the parametric shock to obtain a base case of what the model's outputs would be in the absence of the shock.

3. Run IPM a second time, starting at the time of the shock and initialized with information from the base-case run just before the shock happens. The outputs from this second run (as compared to the period after the surprise in the first run) should reflect how decisions change in response to unexpected information.
4. Choose metrics to compare the base-case and second IPM runs. Aside from the metrics that EPA often uses now to describe model outputs, such as investment choices, rate outcomes, and air emissions outcomes, one particularly interesting feature of this approach could be the ability to determine which asset types in which regions would wind up "stranded" by the surprise event. Such "stranded assets" in this context would include those made under the base case model run but which would retire or be financially unviable under the scenario with the shock.

To the degree that EPA has applied this approach in past applications of its modeling platform, this is not described in the model documentation.

The potential universe of shocks that EPA might consider modeling in IPM using this framework is large, as there are a number of conditions within the power sector that could change rapidly within the time horizon considered by EPA's Platform v6. One example of potential policy importance would be a shock to natural gas supplies that arises because of policy interventions affecting the utilization of modern hydraulic fracturing techniques, stringent technology requirements to control methane emissions, or other conditions that rapidly affect the cost and availability of delivered natural gas supplies to the power generation sector.

V. IMPROVEMENTS TO SUPPORT POLICY ANALYSIS

What improvements, if any, could be made to support the analysis of the full range of policy mechanisms that may be applied to limit power sector emissions? How well does the model scenario capability of IPM version 6 suit EPA's analytical needs?

EPA's application of IPM has been developed over many years to serve as the central platform for evaluating federal environmental policies as they affect the electricity sector. The model is also used widely by state governments and non-governmental organizations. The model is dynamically consistent with perfect foresight, identifying scenario results that reflect the cost-minimizing strategies that would be expected to unfold over many years in the face of the various identified and anticipated constraints. The model embodies tradeoffs in granularity along dimensions of space and time, which is discussed elsewhere in this review.

We find EPA's Platform v6 to be versatile and capable of addressing almost any well-specified regulation including most prescriptive regulations and flexible incentive-based regulations at the federal level. Standard environmental policy mechanisms that have been built into EPA's Platform v6 include tradable emissions rate performance standards, cap and trade, inflexible emissions rate performance standards, and technology standards. Based on the evidence available for this review, the model appears to perform strongly. Nonetheless, there may be ways for EPA to more fully evaluate its performance that are discussed elsewhere in this review.

We know from the model structure that policies with a high degree of spatial or temporal resolution will not be represented perfectly in the model. An example might be the operation of resources in nonattainment areas, or the ability to site and build new resources or change the utilization of existing resources that are subject to New Source Review. Nonetheless the model makes an attempt to represent these granular constraints where it is important to do so. The panel also recognizes that the performance and capabilities of the model are co-dependent on the data configuration underlying the EPA Reference Case.

One policy area that EPA's Platform v6 may not adequately address is energy efficiency. Demand is taken as parametric in EPA's Platform v6, and demand-side policies are described as reductions in demand estimated on the basis of elasticities without changes in the load profile. Alternative load profiles can be implemented in the model. However, policies or technologies that endogenously shift load across time would introduce challenges and may not be achievable given the current model configuration, as we understand it, except through an iteration procedure. Further, investments in energy efficiency have various rates of decay, for example, due to various rates of lifetime for appliances. In addition, changes in prices trigger a partial adjustment process in which effects are

compounded as behavioral adjustments accumulate. The response to a sustained change in prices is greater than the response in the first year. Because of the various federal proposals to promote energy efficiency, EPA may need to revisit its representation of demand in order to be useful to analysis of these policies.

One of the largest challenges for EPA going forward may be the representation of policies at the state level governing retail tariffs, including payments for distributed generation, and incentives to promote electrification that may intentionally align demand growth with the availability of variable renewable energy resources. The potential expansion of flexible demand could be driven by state or federal policy to promote electrification, federal policy that gives states flexibility in how to meet emissions goals, and technological factors and may be important to the evaluation of future environmental policies.

Policies aimed at the demand side and at retail price setting are relevant to the operation of the electricity system as represented in EPA's Platform v6 because they are likely to be a key component of strategies to integrate large quantities of variable renewable energy. Specifically, a possibly important policy mechanism in the next decade is the determination of retail prices that are differentiated by time or type of electricity use. Economists have anticipated time-varying retail prices for more than four decades and although they have yet to emerge widely, in the last couple of years a number of utilities have begun to introduce time-of-day prices. If this were to expand with respect to conventional uses of electricity, it could be important for EPA's application of -IPM. However, potentially more important are time varying prices applied to new sources of electricity demand such as electric vehicles, water heating, and building heating that embody technologies with inherent storage capability. These types of electricity uses do not require all the attributes of typical "instant on" electricity use. Consequently, they may not be priced at the same level and they may not be burdened with the sunk costs associated with the reliability aspects of the existing grid, and retail prices may be adjusted accordingly.

To represent the meaningful aspects of time-varying prices requires cross-time-period elasticities of electricity use within a fully functioning demand side model. One type of modeling approach that would come close is an Almost Ideal Demand System.[6] The key feature in developing a demand side of the model is that demand should respond over time not only to changes in prices in a given time block but also to changes in relative prices in different time blocks.

Another potentially important limitation of EPA's policy analyses (that we also raise in the context of EPA's Platform v6 representation of baseline uncertainty) is the model's ability to account for the effects of uncertainty on economic

[6] An Almost Ideal Demand System (AIDS) is a relatively simple system to estimate and preserves important properties of consumer theory. See Deaton and Muellbauer (1980).

behavior. This is relevant in consideration of the analysis of the full-range of policy options because agents will view future policies and the continuation of existing policies as inherently uncertain, yet in EPA's Platform v6 the construct of perfect foresight means agents react based a known future. When using the model to anticipate the broadest possible range of future policies, the associated uncertainty of outcomes is also broad. For example, the response of investors to a new environmental policy will be shaped by legal or political challenges that might reverse it, and the public consideration of a policy in the near-term will affect behavior in the Reference Case even if such a policy is not enacted.

VI. EPA's PLATFORM V6 DOCUMENTATION

Identify strengths, weaknesses, limitations, and errors in the model documentation and the Results Viewer. Is the documentation clear and well-written? Propose options as needed. Specifically, are all the necessary elements included? Are there any extraneous elements? Could simplifications be made? How well does the Results Viewer effectively communicate model run results? What additional documentation or model results, if any, would further improve transparency?

Overall the documentation is well organized and well written. We recognize that it is a challenge to document complex models in a comprehensive way and keep the documentation up to date. EPA is commended for its achievements in both regards. However, there were several aspects of the model that we felt were not as well described as could be in the documentation. There are many instances where providing model equations would add clarity, such as previously described for the objective function and capital charge rates. In addition, there are several places where we would recommend that EPA provide more complete information about data sources. We also make some specific suggestions regarding data displays and text, as described below.

The main areas in the EPA Reference Case v6 documentation that require additional explanation include the following:

Development of load segments: The process used for developing load segments as described in the documentation is unclear. However, we found slide 30 in the briefing that EPA presented to the panel on October 16 to be quite helpful in understanding the distinction between load slices and times of day and recommend that this graphic be added to the documentation.

Treatment of interregional trading: The documentation's description of inter-regional trade, especially related to the load segments, is not very clear. The documentation indicates that trade is modeled on a seasonal basis, yet it is our understanding after discussions with EPA that trade is modeled by load segment. Because the load segments are defined uniquely for each region, a mapping of segments by hour is performed in order to capture simultaneity between regions. A description of this process with an accompanying example would help promote understanding of this model feature.

Aggregation of model plants: The documentation's description of the aggregation of model plants also requires clarification. Section 4.2.6 of the documentation describes the aggregation of model plants as occurring for plants that share several key characteristics and that are located within the same state. Based on our communication with EPA during the review, it is our understanding that fossil units are aggregated no further than at the plant level.

Publication of data tables on the EPA website: The use of tables uploaded directly to the web is understandably necessary given the large size of many of the data inputs. However, a few improvements are suggested. The first time one of these appears (Table 2-2), a footnote indicating that large tables are on the

web and that the list of these can be found at the end of each chapter would be helpful. This footnote could also provide a link to the site where the tables are posted. In addition, because some users may go directly from a search engine to the page with the complete document, it would be useful to have a link from here to the tables as well.

Guide to EPA's Platform v6 Output Files: It would be helpful to include a reference in section 2.5.2 of the documentation to the output file guide that is on EPA's website. In addition, when EIA's AEO cases are used to set up alternative sensitivity cases, a more complete description of which AEO case is being used and what inputs are being used from the case would be helpful. For example, in the AEO2018 there are no cases called High or Low Demand, but rather there are High and Low Economic Growth scenarios and two alternative efficiency cases.

Table 1 below includes specific comments and suggestions, organized by chapter of the EPA's Reference Case v6 documentation.

RESULTS VIEWER

In general, the results viewer is a great tool, as the apparent design and intent for functionality is very good. However, there are limits to it the tool in its current form that we would recommend that EPA address, because even small inconsistencies or incompleteness impart uncertainty about the use of the viewer.

To avoid user confusion, we would recommend that EPA insert a few clarifications in the READ ME instructions. The first is to define the RPE acronym at the outset of the readme tab. Second, the instructions include a reference to the "Profile worksheet" in the discussion on Workbook Navigation, but there does not seem to be such a sheet with that name in the Results Viewer. It is unclear if that reference should be changed or if a worksheet is missing from the file. Third, the description of Fuel Type is confusing because it focuses on the selection of years for displaying data rather than fuel type.

We found the Results Viewer's distinction between "plant type" and "plant category" confusing. For example, it is unclear what a user should choose for nuclear plant type. The readme tab indicates that plant type and plant category may be merged in the future, and we agree this would be clearer. For example, the merged list could include "all renewables" as well as solar, wind, etc.

The displayed results should indicate the cases being compared (i.e., the difference between what to what) and the units of measure reflected in the results. The readme tab indicates that the results represent "changes from the comparison model," but it would be helpful to include this on the graphics page accompanying the map. The names of the two scenarios should also appear in a text field. This would make the charts more useful since they cannot be edited once exported.

The use of the "comparison case" for other metrics, such as capacity factors and emissions rates, is clever but not very intuitive. The comment box that guides the

user on how to set the base and comparison cases is helpful but would perhaps be more effective as a full display (i.e. always visible). It is also a bit cumbersome that true comparisons require the user to specify twice what data to display (for the primary and comparison cases). Another approach would be to have a single place where users can select data type for comparison graphs. Only when other types of graphs are selected, such as capacity factors or emissions rates, would the user specify a second set of data types.

In the map sheet, the comparison functionality is confusing and only works for displaying differences, rather than two sets of absolute values. Additional instructions about the map feature would help users better understand this functionality.

RETAIL PRICE MODEL DOCUMENTATION

The Retail Price Model (RPM) relies heavily on assumptions from the AEO2018 and in many instances the documentation refers only generically to the AEO2018 without sufficient information about what the assumptions are and how they were derived from either published AEO2018 outputs or data provided by EIA at EPA's request. Additional specific comments on the RPM documentation include the following:

- In the discussion of utility depreciation costs, the units are mills/kWh but these are not defined by year. In addition, the "directly from" is not explained sufficiently as to whether the reader can find these in a published document or table or whether this was provided by EIA.
- The documentation would benefit from additional detail for the non-utility generators (NUG) adder and the regional tax rates used in the RPM. In both cases, the reader is referred to the EIA's AEO 2018. We recommend that the documentation present these values and describe their source (public or specially requested from EIA).
- Also related to regional tax rates, it is not clear what is included in "regional tax dollars" referenced in the documentation. Are these revenues collected only from electricity bills or do they reflect other sources of revenue? We recommend that EPA define these revenues more precisely based on input from EIA.
- Attachment 1 of the documentation includes a table showing the percentage of each region that is deregulated or regulated. We recommend that EPA describe how the percentages were derived, rather than simply citing the AEO. The version of the RPM provided to the panel includes a map of model regions that does not match the regions listed in the Attachment 1. For clarity, these should be updated to be consistent with EPA's Platform v6.

Table 1. Specific Comments and Recommendations Related to the EPA Platform v6 Documentation

Page Number	Comment/Recommendation
Chapter 1. Introduction	
Page 1-4	The technology list in Table 1-2 does not include NGCC with CCS although it is included in Chapter 6. Perhaps it would be best to include with a footnote that it is disabled in the Reference Case (see recommendation in the CCS section of the review that it be activated).
Chapter 2. Modeling Framework	
Page 2-1	"*…used IPM extensively for various ….*" For some of the IPM applications mentioned, it may have been the case that IPM provided input into those analyses (e.g., economic impact assessment) as opposed to actually conducting such an assessment. The distinction between applications that IPM can address entirely vs. ones that it provides important input to may be worth making.
Page 2-1	*". . . a globally optimal solution".* It may be possible, although highly unlikely for the LP algorithm in IPM to obtain multiple optimal solutions.
Page 2-1	*". . . reasonable solution time for LP model…"* See also p. 2-11, Section 2.4. More information on the time to run EPA's application of IPM and any formal or informal EPA requirement that it run within a particular amount of time would be helpful.
Page 2-1	*"IPM is a dynamic linear program…."* See also p. 2-6, Section 2.3.3. The use of the term "dynamic" should be clarified. It may suggest something beyond what IPM is doing. IPM can have different assumptions that vary by time, but those assumptions are not dynamic (i.e., change based upon IPM calculations). A suggested revision would

Page Number	Comment/Recommendation
	be "IPM is a linear programming model that generates optimal decisions over the projection time horizon under the assumption of perfect foresight."
Page 2-2	*"IPM provides estimates of air emission changes, …."* The documentation should clarify what EPA estimates these changes relative to (i.e., relative to different scenarios, previous year, or both).
Page 2-2	The discussion of integrated resource planning states that IPM can optimize demand-side options but a search on the documentation does not provide any further information or assumptions. Moreover, the demand side options that are available in EPA's application of IPM appear limited. For example, it is not obvious that demand could not respond to time varying prices, and demand could not shift between time blocks. It is important that the documentation not overstate the capability of the model as it is implemented by EPA so that users understand what is accomplished in the modeling, and what users must look elsewhere to address. It may be useful for the documentation to indicate where there are capabilities of the model that EPA chooses not to exercise but might find useful in future analyses.
Page 2-3	*"Many of these costs components are captured in the objective function…."* Why the use of the word "many"? Are not all costs captured as described in the sentence? If not, the documentation should explain.
Page 2-3	*"The applicable discount rates are applied to derive the net present value for the entire planning horizon…."* Rates is plural, whereas Chapter 10 indicates that a single discount rate is used for intertemporal decisions. Another sentence indicating the the EPA Reference Case uses a single discount rate would reduce confusion.
Page 2-3	In the discussion of transmission decision variables, the documentation states "…the total cost of transmission across each link." The text could be made clearer that this refers to the transmission tariff, not the capital costs.

Page Number	Comment/Recommendation
Page 2-3	As the paragraph on emission allowance decision variables reads, it sounds as though the formulation is non-linear with the multiplication of the market price of allowances times the allowance decision variables. Because this is obviously not the case, we recommend that EPA clarify.
Pages 2-5 and 2-6	Section 2.3.1 (Model Plants) should mention "planned-committed", which is one of the three categories of generation units that EPA's Platform v6 uses.
Page 2-6	The parsing discussion should provide references as well as additional documentation. The discussion identifies post-processing parsing tools to translate model plant level data into generating unit-specific results and for deriving inputs for air quality modeling. Neither references nor a detailed description are currently provided.
Page 2-6	More clarity should be provided that 2050 is both the final model run year and the last reported year. The documentation leads one to perhaps presume that the model is run farther to handle end-of-horizon end effects.
Page 2-7	The sentence of the last bullet in Section 2.3.3 reads, "*This permits the model to capture more accurately…."* This sentence and associated paragraph would benefit from more details and discussion. The reader is unable to ascertain whether this paragraph is saying that by including costs for every year, not just the individual model run years, the model is more accurate than if it only included costs in the individual model run years.
Page 2-11	Should the assumption of perfect regulation, that is regulators can determine the actual costs of the utilities that they regulate and do not allow for gold plating, be incorporated into this section? IPM seems to also be making this assumption. Also, uncertainty is not a market imperfection (and applies to regulated portions of the power system as well as to market-based portions).
Page 2-11	The discussion of hardware and programming features would benefit from several additions/clarifications including: (1) "MPS" should be spelled out or defined; (2) More information on how long it takes to run EPA's application of IPM would be helpful. Also, how quickly can performance be improved with advances in computational power? This is important in

Page Number	Comment/Recommendation
	determining potential enhancements to EPA's Platform v6. (3) The discussion related to the benchmarking tests performed by EPA's National Environmental Scientific Computing Center warrants more detail on what the unacceptable results were, why did they occur, and what are the implications for EPA's Platform v6 current and potential configurations.
Pages 2-12 and 2-13	Section 2.5 is short on detail and simply includes a high-level listing of categories of inputs and outputs. A reference to the more detailed output file guide would be helpful here. In addition, more detail, including equations or equivalent details, should be included throughout the documentation.
Page 2-13	The header *"List of tables that are uploaded …"* might be modified to include the Chapter number. For Chapter 2, this would be especially helpful because this is the first reference to these tables. Another option would be to make this a subsection of its own in each chapter.
Chapter 3. Power System Operational Assumptions	
Page 3-3	The text and Table 3-1 column heading cite different AEO vintages. Although it does not matter since the regional definitions are the same, it might be confusing to some readers.
Page 3-7	A more complete description is needed of how demand elasticities may be applied in EPA's application of IPM. For example, are the elasticities applied for annual demands or by load segment? Also, the documentation would benefit from discussion of how electricity prices are scaled up to approximate retail prices.
Page 3-14	In the section about minimum capacity factors for oil/gas plants, it might be clearer in step 3 to insert the phrase "annual historical average" to describe the capacity factor threshold for removal. It should also specify that the minimum capacity factors are applied to units as annual averages rather than by load/time segment.
Page 3-14	Incorporate more detail about how the coal turndown constraints were developed from the recent hourly Air Markets Program Data (AMPD) data. For example, how many years of data were used and what was the criteria for setting the minimums (single hour, multiple hour averages, etc.)?
Page 3-15	In Table 3-9, include a citation for the planning reserve margins listed.

Page Number	Comment/Recommendation
Page 3-26	The treatment of 316(b) costs in EPA's Reference Case is unclear. The documentation states that "EPA Platform v6 includes cost of complying with this rule" and points to another document where the cost assumptions and analysis for 316(b) can be found but does not provide any information about how these costs are incorporated. Are these investment (sunk) costs, operating costs (fixed or variable)? Do they impact plant operations (heat rates or other performance characteristics)?
Chapter 4. Generation Technologies	
Throughout	Many assumptions and associated calculations and algorithms to calculate those assumptions are not documented. For instance, the capacity parsing algorithm (p. 4-4), the level of aggregation of generation units (p. 4-6), coal switching (p. 4-6), how availability accounts for planned and unplanned maintenance (p. 4-21), the basis for the upper bound on new power plants in Table 4-14 (discussion on p. 4-22), and existing nuclear unit assumptions (Section 4.5.1, p. 4-47). All assumptions should be precisely and specifically documented (as opposed to having incomplete or only high-level names of references) including providing references for all tables.
Page 4-2	In Table 4-2, the assumptions regarding two new nuclear units to come online may need to be updated.
Page 4-5	In Section 4.2.4, a reference to the U.S. Nuclear Regulatory Commission 80-year life should be incorporated into the documentation (https://www.nrc.gov/reactors/operating/licensing/renewal/subsequent-license-renewal.html).
Page 4-5	The last sentence of Section 4.2.4 reads: "The unit, however, continues to make annualized capital cost payment on any previously incurred capital cost for model-installed retrofits projected prior to retirement." We recommend that the documentation state if, and how, regulated vs. competitive retired generation units are treated differently with respect to future annualized capital costs payments.
Page 4-7 and 4-20	The type of energy storage should be specified in Table 4-7 (p. 4-7) and Table 4-12 (p. 4-20).
Page 4-7	Add a definition clarifying what IMPORT represents in Table 4-7.

Page Number	Comment/Recommendation
Page 4-11	The discussion of the data sources for gas-turbine based prime movers references ICF's experience and expertise related to O&M costs. We recommend that documentation and clarification of the referenced ICF expertise and experience be provided.
Pages 4-11 and 4-12	Table 4-8 provides ranges of variable O&M costs for some generation technologies. We recommend that the documentation clarify how how ranges of assumptions are implemented (e.g., use of median point estimate).
Page 4-18	The basis and reference for the lifespan without life extension expenditures assumptions in Table 4-10 are not provided. In particular, the lifespan of combustion turbine of 30 years may be too long. See Newell et al. (2014), which assumes a 20-year economic life for combustion turbines.
Page 4-18	The Non-conventional and Conventional labels in Table 4-11 may be unnecessary. They could be modified to Renewable/Storage and Fossil/Nuclear.
Page 4-19	Table 4-12 should clarify that the capacity information presented represents Summer Capacity (MW).
Page 4-22	In the discussion of regional cost adjustments, the documentation should define what is meant by the term "ambient conditions." Also, this discussion indicates that regional cost multipliers from the University of Texas are applied. The documentation is unclear why those are used instead of data from EIA.
Page 4-29	The values in the second half of Table 4-16 (vintage #4 and later) appear to be shifted over a column (i.e. the PV values are in the fuel cell column etc.).
Page 4-30	A more complete definition of wind techno-resource groups (TRGs) would be useful for readers who are not familiar with the National Renewable Energy Laboratory (NREL) Annual Technology Baseline (ATB).
Page 4-30	Assumptions of wind potential by resource and cost class is shown Table 4-17 before the concept of cost classes is introduced and defined. Adding one sentence about them at the end of the paragraph before the table would be helpful.
Pages 4-34 to 4-36	The citations for wind resource, capacity factors and generation profiles from NREL should be more specific and summarize the methodology used by NREL for their derivation.

Page Number	Comment/Recommendation
Page 4-34	The documentation needs to make clear how solar and wind capacity factors are adjusted, if at all, for planned and unplanned maintenance. As written, the documentation suggests that no adjustment is made because the capacity factor is multiplied by the installed capacity to obtain the amount of energy produced for a given season.
Pages 4-35, 36, and 41	The ranges of wind and solar PV reserve margin contributions in Tables 4-21,4-23,4-25, 4-27 and 4-32 are too large to be meaningful. It would be more useful to show the initial year values by region and resource class with an indication of how they may change by 2050 in the Reference case. An alternative would be to show the stacked sequence of cumulative capacity and reserve margin contributions by region.
Page 4-36	The discussion of wind tax credits does not indicate why EPA chose to model the credit as a reduction in capital cost (investment tax credit) rather than a production tax credit (PTC). The wording suggests that this is done as a modeling convenience rather than due to an assumption that wind generators will select an ITC rather than a PTC, but it is not clear.
Page 4-40	The wind calculation example refers to Table 4-20b as the source of the reserve margin contribution, but there is no such table.
Page 4-45	The acronym IDC in Table 4-35 should be defined.
Page 4-47	Section 4.5 includes a long discussion of capacity factors by vintage for nuclear power plants, but most of the existing capacity was built before 1982 and is older than 25 years so have constant capacity factors anyway. In addition, it is not clear from the Reference Case outputs whether the new planned units exhibit a lower capacity factor at start.
Chapter 8. Development of Natural Gas Supply Curves for EPA Platform v6	
Pages 8-10 to 8-12	In section 8.3.4, more information is needed about LNG exports. It is not clear to what degree these are an exogenous assumption vs. model outcome. Particularly ambiguous is the phrase "ICF assumes." Does this mean an ICF assumption that goes into the Gas Market Model (GMM) or an outcome of GMM?

Page Number	Comment/Recommendation
Page 8-17	The discussion on this page outlines the four main drivers of natural gas demand. This seems like it would be better placed before the discussion of gas demand projections – perhaps at the start of Section 8.5.

REFERENCES

Bent, R., S. Blumsack, P. Van Hentenryck, C. Borraz-Sánchez and M. Shahriari. 2018. "Joint Electricity and Natural Gas Transmission Planning With Endogenous Market Feedbacks." *IEEE Transactions on Power Systems*, 33(6): 6397-6409.

Borenstein, Severin and James Bushnell. 2015. "The US electricity industry after 20 years of restructuring." *Annu. Rev. Econ*. 7(1): 437-463.

Brandt, A. R., Heath, G. A., & Cooley, D. 2016. "Methane leaks from natural gas systems follow extreme distributions." *Environmental Science & Technology.* 50(22): 12512-12520.

Brealy, Richard, Stewart Myers, and Franklin Allen. 2011. *Principles of Corporate Finance* (10th Ed.), McGraw Hill, New York NY.

Burtraw, Dallas, Karen Palmer, and Danny Kahn. 2010. "A symmetric safety valve." *Energy Policy.* 38:4921-4932.

Chandramowli, Shankar N. and Frank A. Felder. 2014. "Impact of climate change on electricity systems and markets–a review of models and forecasts." *Sustainable Energy Technologies and Assessments*. 5: 62-74.

Couzo, Evan, James McCann, William Vizuete, J. Jason West, and Seth Blumsack. 2016. "Modeled Response of Ozone to Electricity Generation Emissions in the Northeastern United States Using Three Sensitivity Techniques." *Journal of the Air and Waste Management Association.* 66(5): 456-469.

Deaton, Angus and John Muellbauer. 1980. "An Almost Ideal Demand System." *The American Economic Review*. 70(3): 312-326.

Echeverri, Dalia Patino, Dallas Burtraw, and Karen Palmer. 2013. "Flexible Mandates for Investment in New Technology." *Journal of Regulatory Economics.* 44 (2): 121-155.

Fabrizio, Kira R., Nancy L. Rose, and Catherine D. Wolfram. 2007. "Do markets reduce costs? Assessing the impact of regulatory restructuring on US electric generation efficiency." *American Economic Review*. 97(4): 1250-1277.

Hamada, Robert. 1972. "The effect of the firm's capital structure on the systematic risk of common stocks." *The Journal of Finance.* 27(2): 435-452.

ICF International. 2014. *Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries*. Available at:

<https://www.edf.org/sites/default/files/methane_cost_curve_report.pdf>.

Jaramillo, P., Griffin, W. M., & Matthews, H. S. 2007. "Comparative life-cycle air emissions of coal, domestic natural gas, LNG, and SNG for electricity generation." *Environmental Science & Technology.* 41(17): 6290-6296.

Linn, Joshua, Erin Mastrangelo, and Dallas Burtraw. 2014. "Regulating Greenhouse Gases from Coal Power Plants under the Clean Air Act." *Journal of the Association of Environmental and Resource Economists*. 1(1):97-134.

Newell, Samuel A., J. Michael Hagerty, Kathleen Spees, Johannes P. Pfeifenberger, Quincy Liao, Christopher D. Ungate, and John Wroble. 2014. *Cost of New Entry Estimates for Combustion Turbine and Combined Cyucle Plants in PJM*. Prepared for PJM Interconnection, LLC. Available at: <http://www.ercot.com/content/wcm/lists/114801/Cost_of_New_Entry_Estimates_for_Combustion_Turbine_and_Combined_Cycle_Plants_in_PJM.pdf>.

Organisation for Economic Cooperation and Development, Nuclear Energy Agency. 2011. *Technical and Economic Aspects of Load Following with Nuclear Power Plants.* Available at: <http://www.oecd-nea.org/ndd/reports/2011/load-following-npp.pdf>.

Osofsky, Hari M., Zachary R. Barkley, Seth Blumsack, Kenneth J. Davis, Lara B., Fowler, Thomas Lauvaux, Ross H. Pifer, Ekrem Korkut & Chloe Marie. 2018. *Regulation of Methane Emissions from Unconventional Oil and Gas: Current Approaches and Possibilities for Innovation Based on Emerging Science.* Penn State University Center for Energy Law and Policy. Available at: <https://sites.psu.edu/celp/files/2018/09/PSUCELP-Methane-Emissions-Regulation-White-Paper-164277w.pdf>.

PJM. 2019. Inside Lines, December 30. Available at: <https://insidelines.pjm.com/tag/capacity-market/>.

Rosendahl, Knut Einar and Halvor Briseid Storrøsten. 2011. "Emissions Trading with Updated Allocation: Effects on Entry/Exit and Distribution," *Environ Resource Econ.* 49: 243-261.

Sargent & Lundy. 2017. "IPM Model – Updates to Cost and Performance for APC Technologies – CO_2 Reduction Cost Development Methodology." Project 13527-001.

Stauffer, Hoff. 2006. "Beware Capital Charge Rates." *Electricity Journal* 19(3): 81-86.

U.S. Department of Energy (DOE). 2015. *Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities*.

U.S. Energy Information Administration (EIA), U.S. 2018. Battery Storage Market Trends, May 21. Available at: <https://www.eia.gov/analysis/studies/electricity/batterystorage/pdf/battery_storage.pdf>.

Walker W.E., Lempert R.J., Kwakkel J.H. 2013. "Deep Uncertainty". In: Gass S.I., Fu M.C. (eds) *Encyclopedia of Operations Research and Management Science*. Springer, Boston, MA

IEc

MEMORANDUM | FEBRUARY 7, 2020

TO Lorraine Reddick and Cara Marcy, U.S. Environmental Protection Agency

FROM Jason Price, IEc

SUBJECT Documentation of Peer Review Process for the Integrated Planning Model (IPM) Version 6

1. INTRODUCTION

Industrial Economics, Inc. (IEc) was contracted by EPA to manage the external peer review of the Integrated Planning Model (IPM), Version 6. EPA's Clean Air Markets Division (CAMD) uses IPM to evaluate the cost and emissions impacts of alternative policies to limit emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon dioxide (CO_2), and air toxics such as mercury (Hg) and hydrochloric acid (HCl) from the electric power sector's operations. This memorandum summarizes the process followed by IEc for managing the peer review. The first section provides a brief description of the process for selecting individuals to serve on the peer review panel. Following this discussion, the second section identifies the materials provided to reviewers at the outset of the review to support their activities. The third section describes the questions that the review panel posed to EPA during the course of the review, the Agency's responses to these questions, and a summary of any supplemental material provided by EPA in conjunction with its responses.

This independent, external peer review was conducted in compliance with EPA's Peer Review Handbook.[1] The peer review will assist CAMD in supporting its analytical responsibilities to assess the cost, emissions, and related impacts of policies designed to limit power sector emissions. These analyses inform the rule-making process by providing policymakers with insights into both the relative and absolute cost and emissions impacts of different policy options, and the spatial distribution of these impacts across the U.S. IPM has been used extensively by EPA in this way to inform the development of multiple rulemakings over the past several years.

The results of this peer review will be used to help CAMD evaluate the strengths and limitations of IPM Version 6. The review will also help to identify opportunities for improvements and refinements to the model and suggest research directions that strengthen the credibility of model results.

The peer review panel was asked to comment on the methods and data employed by the model. While EPA will continue to use IPM to support policy decision-making, no specific policy questions were asked of reviewers.

[1] U.S. Environmental Protection Agency, *Peer Review Handbook, 4th Edition*, EPA/100/B-15/001, October 2015.

2. PROCESS FOR SELECTING PEER REVIEW PANELISTS

The peer review process began in August 2019 and is now complete. IEc recruited five reviewers for the panel; one of these reviewers was recruited to serve as the panel chair. The panel's work began in September 2019 and ended in February 2020. The reviewers were compensated for approximately six days of effort and were provided an honorarium sufficient to attract a high-quality review panel. The panel chair, who also asked to oversee the review and engage particularly in the technical and substantive elements of the review, was compensated for approximately nine days of time.

Prior to identifying potential reviewers, IEc consulted with EPA to determine the qualifications and expertise necessary to perform the review. Based on these requirements, IEc independently identified potential reviewers, consistent with the guidelines in EPA's Peer Review Handbook.[2] IEc contacted potential reviewers to gather additional information on their qualifications and to gauge their interest and availability to serve on the review panel. IEc discussed conflict of interest and independence issues with each potential reviewer, and each empaneled reviewer signed a statement confirming that they had no financial or personal conflicts of interest (included as Attachment A). In addition, all five reviewers signed a contract with IEc that included a requirement to immediately report any potential personal or organizational conflict of interest, should one arise during the course of completing the review.

Following our initial outreach to candidates for the panel, IEc selected reviewers for independence and knowledge, expertise, and experience in the following areas:

- Capacity expansion modeling and production cost modeling
- Power system operation and generating capacity
- Environmental regulation of the power sector
- Emission control technologies and strategies
- Electric power sector financing
- Coal markets
- Natural gas markets
- Renewable energy sources
- Wholesale and retail electricity prices

Exhibit 1 below provides a brief description of the five reviewers and their relevant expertise. A full curriculum vitae (CV) for each reviewer is included in Attachment B to this memo.

[2] *Op. cit.*

EXHIBIT 1. SUMMARY OF QUALIFICATIONS FOR PEER REVIEW PANEL

PEER REVIEWER	SUMMARY OF QUALIFICATIONS
Dr. Seth Blumsack, Pennsylvania State University	Professor of Energy and Environmental Economics and International Affairs and Associate Head for Undergraduate Programs in the Department of Energy and Mineral Engineering at Penn State University. His research centers on the electricity and natural gas industries; environmental management related to energy and infrastructure; resilience of energy infrastructure; regulation and deregulation in network industries; network science; risk analysis; and managing complex infrastructure systems.
Dr. Dallas Burtraw, Resources for the Future (RFF)*	Darius Gaskins Senior Fellow at RFF. His research includes analysis of the distributional and regional consequences of climate policy, the evolution of electricity markets including renewable integration, and the interaction of climate policy with electricity markets. In addition, he currently serves as Chair of California's Independent Emissions Market Advisory Committee.
Dr. James Bushnell	Professor in the Department of Economics at the University of California, Davis, and a Research Associate of the National Bureau of Economic Research. Previously spent 15 years as the Research Director of the University of California Energy Institute in Berkeley, and two years as the Cargill Chair in Energy Economics at Iowa State University. Since 2002, he has served as a member of the Market Surveillance Committee (MSC) of the California Independent System Operator (CAISO). He has also advised the California Air Resources Board in several capacities, including as a member of the Emissions Market Advisory Committee from 2012-2014.
Dr. Frank Felder	Director of the Rutgers Energy Institute and of the Center for Energy, Economics & Environmental Policy at Rutgers University's Edward J. Bloustein School of Planning and Public Policy. Research and teaching interests include the reliability and economics of electricity markets, state energy policy, energy efficiency and renewable energy evaluation, and integrated energy modeling. He teaches undergraduate and graduate level courses in Energy Engineering, Economics and Policy; Energy Policy and Planning; and the Science, Technology and Policy of Climate Change. He has also taught short courses on electricity markets in Africa, Asia, Canada, Europe and the United States.
Frances Wood	Director at OnLocation, an energy economics consultancy located in the greater Washington, DC area. Ms. Wood has led analyses applying a variety of integrated energy models such as the Energy Information Administration's (EIA's) National Energy Modeling System (NEMS) and has analyzed the impacts of numerous policy proposals for reducing emissions from the electric power sector, as well as the industry's capability to adopt new technologies, such as wind and solar.
**Peer review panel chair*	

3. MATERIALS PROVIDED TO PEER REVIEW PANELISTS

IEc provided peer reviewers with a list of charge questions developed by the EPA sponsors in consultation IEc (included in Attachment C), as well as several materials to inform their review. These materials include the following:

1. ***IPM Version 6 Model Documentation***:[3] This document details IPM's structure, methods, assumptions, data, and overall capabilities.
2. ***Supplemental Tables to the Model Documentation***: A number of the tables listed in the IPM documentation are published separately on the EPA website.[4] IEc provided these tables directly to the panel.
3. ***Incremental Model Documentation***:[5] This short document describes a small number of additions/refinements made to IPM following publication of the IPM Version 6 model documentation.
4. ***Guide to IPM Outputs:***[6] This file describes the structure of the IPM output files and was provided as a reference to the panel to aid in navigating the IPM output files.
5. ***May 2019 Reference Case Results Data***:[7] This was the most recent set of reference case results generated by the model at the time of the review.
6. ***May 2019 Results Viewer***:[8] This Excel file shows the May 2019 reference case results in an interactive spreadsheet developed by EPA that allows the user to select specific results to view.
7. ***May 2018 Side Cases***:[9] The charge (question 4) specifically asks for the panel's input on whether the base set model scenarios adequately address uncertainty in future power sector trends. The May 2018 Side Cases include this full set of scenarios.

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[3] U.S. Environmental Protection Agency, *Documentation for EPA's Power Sector Modeling Platform v6 Using the Integrated Planning Model*, November 2018.

[4] At the time of this writing, these tables are available at https://www.epa.gov/airmarkets/documentation-epas-power-sector-modeling-platform-v6-november-2018-reference-case

[5] U.S. Environmental Protection Agency, *Updates in May 2019 Reference Case*, May 2019.

[6] U.S. Environmental Protection Agency, Guide to IPM Output Files: EPA Initial Run v.6, available at https://www.epa.gov/sites/production/files/2018-05/documents/epa_initial_run_v6_inputoutputguide_june_2018.pdf.

[7] U.S. Environmental Protection Agency, Results using EPA's Power Sector Modeling Platform v6 - May 2019 Reference Case, available at https://www.epa.gov/airmarkets/results-using-epas-power-sector-modeling-platform-v6-may-2019-reference-case.

[8] U.S. Environmental Protection Agency, Integrated Planning Model (IPM) Results Viewer, posted on June 25, 2019 at https://www.epa.gov/airmarkets/integrated-planning-model-ipm-results-viewer.

[9] U.S. Environmental Protection Agency, Results using EPA's Power Sector Modeling Platform v6, posted on June 4, 2018 at https://www.epa.gov/airmarkets/results-using-epas-power-sector-modeling-platform-v6.

8. ***Retail Price Model***:[10] The retail price model uses IPM results and other data to estimate average retail electricity prices. Though the retail price model is separate from IPM, the charge asks the panel to review it as part of this review process.
9. ***Retail Price Model documentation***:[11] The retail price model documentation describes the methods applied in the retail price model.
10. ***National Electric Energy Data System (NEEDS) database for IPM Version 6***:[12] This database contains the generation unit records used to construct the model plants that represent existing and planned/committed units in EPA modeling applications of IPM. This database was provided to the panel for reference purposes.

After IEc provided the above materials to the peer review panel, the panel and IEc convened an organizing teleconference on October 10, 2019. Exhibit 1 summarizes each of the panel's teleconferences and meetings.

In addition to the items above, which IEc circulated to the review panel with the charge, the panel was provided with a slide deck describing the model. The EPA sponsors presented these slides to the panel during a web conference facilitated by IEc on October 16, 2019. These slides are included as Attachment D to this memo.

[10] U.S. Environmental Protection Agency, Retail Price Model, posted on July 9, 2019 at https://www.epa.gov/airmarkets/retail-price-model

[11] U.S. Environmental Protection Agency, *Documentation of the Retail Price Model: Draft*, March 2019.

[12] U.S. Environmental Protection Agency, National Electric Energy Data System (NEEDS) v6, May 2019, available at https://www.epa.gov/airmarkets/national-electric-energy-data-system-needs-v6.

EXHIBIT 1. SUMMARY OF PEER REVIEW PANEL CALLS AND MEETINGS

DATE	MEETING TYPE	MEETING PURPOSE AND TOPIC(S)
October 10, 2019	Conference call	• Introductions • Develop schedule for the review • Assign a primary reviewer and secondary reviewer to each charge question. Primary reviewer has lead responsibility for drafting the charge question response; the secondary reviewer provides input during the drafting process.
October 16, 2019	Conference call	• EPA sponsors give presentation on IPM to the peer review panel during teleconference facilitated by IEc.
November 1, 2019	Conference call	• Panel members provide status update on their review and begin to identify issues to highlight in their charge question responses. • Panel members begin to compile questions for EPA based on their reading of the model documentation and related materials to date.
November 14, 2019	Conference call	• Panel members finalize questions to pose to the EPA sponsors for the November 20 call with IEc and EPA. • Panel members discuss key issues that they plan to raise in their charge question responses.
November 20, 2019	Conference call	• Obtain EPA answers to the panel's questions about IPM methods, data, and assumptions.
December 3, 2019	In-person meeting of the panel and IEc	• Discuss implications of EPA's November 20 responses to the panel's questions. • Discuss panel members' findings with respect to each charge question and key points to include in the panel's responses to the charge questions. • For a portion of the meeting, pose follow up questions to the EPA sponsors and obtain responses. This process was facilitated by IEc.

4. ADDITIONAL INFORMATION REQUESTED BY THE PANEL

During the review process, the review panel developed a compilation of clarifying questions to ask EPA regarding the data and methods applied in the model. Panel members submitted their questions to the IEc project manager, who then compiled the questions and sent them to the EPA technical point of contact. EPA addressed most of these questions during a call facilitated by IEc on November 20, 2019. Due to time constraints, it was not possible to address all of the panel's questions on the call. EPA

therefore sent written responses to IEc for some questions following the call; the IEc project manager forwarded these responses to the panel. Each of the questions and EPA's responses are included as Attachment E. In responding to the panel's questions, EPA also provided the following materials:

- Non-utility generation capital costs (NUG adders) from the Retail Price Model
- Capacity avoided costs for each IPM region and model run year
- Documentation of the approach used to generate the flat files of IPM outputs that EPA uses as inputs for air quality modeling
- The Retrofit Cost Analyzer (RCA) tool, which estimates the cost of installing and operating power plant air pollution control systems.[13] The data in the RCA inform the retrofit costs included in IPM.

During an in-person meeting of the review panel and IEc in Washington, DC on December 3, 2019, IEc invited the EPA sponsors to attend for part of the meeting and address follow-up questions from the panel. The questions posed by the panel and EPA's responses are included as Attachment F.

[13] The Retrofit Analyzer Tool is publicly available at https://www.epa.gov/airmarkets/retrofit-cost-analyzer.

ATTACHMENT A

CONFLICT OF INTEREST FORM

Conflict of Interest Analysis and Bias Disclosure Form

Instructions:

This disclosure form has been developed in accordance with EPA's Peer Review Handbook, 4th Edition (2013). The questions help identify any conflicts of interest and other concerns regarding each candidate reviewer's ability to independently evaluate Integrated Planning Model (IPM) Version 6. The Peer Review of IPM Version 6 will provide an independent evaluation of IPM and meet EPA's goals for analytical transparency. Analytical transparency is a critical component to make it possible for stakeholders and expert reviewers to examine specific estimated impacts of potential new policies, to evaluate the technical credibility of EPA's projections and to comment on the consequences of modeled policies.

Please answer Yes, No or Unsure in response to each question to the best of your knowledge and belief. If you answer Yes or Unsure to any of the questions, please provide a detailed explanation on a separate sheet of paper.

Answering Yes or Unsure to any of the questions will not result in disqualification for serving as a peer reviewer. The responses to the questionnaire will only be used to help ensure a balanced, unbiased group of peer reviewers. Responses will not be publicly released without consent of the candidate. However, if you are selected to serve on the peer review panel, EPA will include the signature page as part of the published peer review record.

It is expected that the candidate make a reasonable effort to obtain the answers to each question. For example, if you are unsure whether you or a relevant associated party (e.g., spouse, dependent, significant other) has a relevant connection to the peer review subject, a reasonable effort such as calling or emailing to obtain the necessary information should be made.

Conflict of Interest Questions

1. Have you had previous involvement with the development of IPM and related documents, which are under review? Yes/No/Unsure

2. Is there any connection between IPM and any of your and/or your spouse's (or other relevant associated party's):

    a. Compensated or non-compensated employment, including government service, during the past 24 months? Yes/No/Unsure
    b. Sources of research support and project funding, including from any government, during the past 24 months? Yes/No/Unsure
    c. Consulting activities during the past 24 months? Yes/No/Unsure
    d. Expert witness activity during the past 24 months? Yes/No/Unsure
    e. Other Financial Connections to IPM holding to be reworked as we discussed Yes/No/Unsure

3. To the best of your knowledge and belief, is there any direct or significant financial benefit that might be gained by you or your spouse (or other relevant associated party) as a result of the outcome of peer review of IPM? Yes/No/Unsure

4. Have you made any public statements (written or oral) or taken positions that would indicate to an observer that you have taken a position on IPM or a closely related topic under review? Yes/No/Unsure

5. Have you served on previous advisory panels, committees or subcommittees that have addressed IPM under review or addressed a closely related topic? Yes/No/Unsure

6. Are you a federally registered lobbyist? Yes/No/Unsure

7. Do you know of any reason that you might be unable to provide impartial advice on the matter under review or any reason that your impartiality in the matter might be questioned? Yes/No/Unsure

8. To the best of your knowledge and belief, is there any other information that might reasonably raise a question about whether you have an actual or potential personal conflict of interest or bias regarding the matter under review? Yes/No/Unsure

Conflict of Interest Analysis and Bias Disclosure Form Signature Page

Please sign below to certify that:

1. You have fully and to the best of your ability completed this disclosure form,
2. You will update your disclosure form promptly by contacting the IEc peer review facilitator if relevant circumstances change,
3. You are not currently negotiating new professional relationships with, or obtaining new financial holdings in, an entity (related to the peer review subject) which you have not reported, and
4. This signature page, based on information you have provided, and your CV may be made public for review and comment.

Signature _____

Date_____

(Print name)_____

ATTACHMENT B

CURRICULUM VITAE FOR EACH REVIEWER

Seth Blumsack

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Updated: December 2018

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Research Interests

- Energy, environmental and electric power systems
- Network science and graph theory
- Complex systems and network reliability
- Organizational decision-making for energy policy
- Energy infrastructure coordination, planning and management
- Energy efficiency
- Community-scale energy systems
- Water and energy policy
- Environmental risk and decision-making
- Antitrust, competition policy and the regulation of network industries
- Unconventional natural gas
- Congestion pricing and management
- Optimization models for energy markets

Education

Carnegie Mellon University – Ph.D., Engineering and Public Policy, May 2006. Dissertation title: *Network Topologies and Transmission Investment Under Electric Industry Restructuring.*
Carnegie Mellon University – M.S., Economics, May 2003.
Reed College – B.A., Mathematics and Economics, May 1998.

Professional History

The Pennsylvania State University – Assistant Professor, John and Willie Leone Family Department of Energy and Mineral Engineering (EME), June 2007 – April 2013; Associate Professor, April 2013 – 2018; Professor, July 2018 - present; Chair of Energy Business and Finance, July 2015 – 2018; Associate Head, July 2016 – present. Teaching has focused on developing interdisciplinary and problem-focused approaches to educating graduate and undergraduate students in energy business and energy systems engineering. Within EME, I teach undergraduate courses related to the electric utility industry; decision-making; environmental risk; and energy policy, as well as cross-cutting graduate courses in energy

policy; electric power systems; and engineering design to students in all of EME's graduate options. I have also developed resident and online delivery courses for Geosciences, Aerospace Engineering and Architectural Engineering at Penn State. Online course activity has included one of Penn State's first MOOCs (co-authored with Richard Alley), focused on energy and climate change. Research focuses on coupled physical, engineered and social systems, with a focus on energy, the environment and electric power. Research projects have included building planning and operational models for coupled electricity and natural gas infrastructure; governance of Regional Transmission Organizations; modeling the evolution of regional electric power grids; analysis of pricing and technology for electricity consumers in Vermont; utilization of unconventional and "stranded" natural gas; electric transmission planning, investment and optimization; predictive control of large-scale power grids to promote localized air quality improvements; project evaluation for sequestration of industrial carbon in shales; the market for combined heat and power systems; studying design and construction of energy-efficient buildings; analysis of the performance of large-scale academic research projects; design and management of electric power micro-grids; environmental risk and economic impacts of unconventional natural gas development; identification of "critical infrastructure" for electric-network reliability; building-integrated and small-scale energy systems; risk and economic assessments of geologic carbon sequestration; and transitioning to low-emissions power and transportation systems.

Santa Fe Institute – Sabbatical visitor, academic year 2014/15; External faculty member, 2016 – present.

Boise State University – Collaborating faculty and external advisor, Energy Policy Institute and Center for Advanced Energy Studies, August 2011 – present.

The Pennsylvania State University – Faculty member, Operations Research dual-degree graduate program, January 2010 – present.

Technical University of Curtin (Australia) – Collaborator, Centre for Research in Energy and Mineral Economics, September 2009 – present.

Carnegie Mellon University – Adjunct Research Professor, Carnegie Mellon Electricity Industry Center, September 2007 - present.

Carnegie Mellon University – Postdoctoral Research Fellow, Carnegie Mellon Electricity Industry Center, Tepper School of Business, May 2006 – 2007.

Carnegie Mellon University – Ph.D. Candidate, Department of Engineering and Public Policy, August 2003 – May 2006. Graduate research position with the Carnegie Mellon Electricity Industry Center.

Economic Insight, Inc. – Economist, writer, and editor, June 1998 – June 2001. Performed economic analysis to support the firm's senior consultants for a variety of public and private clients in the energy and electric power sectors. Contributing editor for the *Energy Market Report*, a daily newsletter covering North American wholesale electricity markets. Editor of *Pacific West Oil Data*, a monthly compendium of data and information concerning the crude-oil and petroleum products industry in the Western U.S. and Pacific Rim.

Oregon Department of Fish and Wildlife – Summer intern, May – August 1997. Researched social, economic, and climactic determinants of the demand for coastal salmon fishing.

Research Publications

Peer-Reviewed Journals

Student co-authors are marked with an asterisk (*)

1. Yoo, Kyungjin* and Seth Blumsack, 2018. "The Political Complexity of Regional Electricity Policy Formation" *Complexity* 3493942, 18 pp.

2. Blumsack, Seth, 2018. "Impacts of the retirement of the Beaver Valley and Three Mile Island Nuclear Power Plants on Capacity and Energy Prices in Pennsylvania, *Electricity Journal* 31:6, pp. 57-64.

3. Yoo, Kyungjin* and Seth Blumsack, 2018. "Can Capacity Markets be Designed by Democracy?" *Journal of Regulatory Economics* 53:2, pp. 127-151.

4. Tayari, Farid, Seth Blumsack, Russell T. Johns, Suli Tham, Soumyadeep Ghosh, 2018. "Techno-economic assessment of reservoir heterogeneity and permeability variation on economic value of enhanced oil recovery by gas and foam flooding," *Journal of Petroleum Science and Engineering* 166, pp. 913-923.

5. Bent, Russell, Seth Blumsack Pascal Van Hentenryck, Conrado Borraz-Sánchez and Mehdi Shahriari*, 2018. "Joint Electricity and Natural Gas Transmission Planning With Endogenous Market Feedbacks," *IEEE Transactions on Power Systems*, 33:6, pp. 6397-6409.

6. Shahriari, Mehdi* and Seth Blumsack, 2018. "The Capacity Value of Optimal Wind and Solar Portfolios," *Energy* 148, pp. 992-1005.

7. Kleit, Andrew, Chiara Lo Prete, Seth Blumsack and Nongchao Guo*, 2018. "Weather or Not: Modeling the Welfare Effects of Natural Gas Pipeline Expansion," *Energy Systems*, forthcoming.

8. Cahoy, Dan, Zhen Lei, Yuxi Meng* and Seth Blumsack, 2017. "Global Patent Chokepoints," *Stanford Technology Law Review* 20:1, pp. 213-244.

9. Shahriari, Mehdi* and Seth Blumsack, 2017. "Scaling of Wind Energy Variability Over Space and Time," *Applied Energy* 195:1, pp. 572-585.

10. Couzo, Evan, James McCann, William Vizuete, J. Jason West and Seth Blumsack, 2016. "Modeled Response of Ozone to Electricity Generation Emissions in the Northeastern United States Using Three Sensitivity Techniques," *Journal of the Air and Waste Management Association* 66:5, pp. 456-469.

11. Sahraei-Ardakani, Mostafa and Seth Blumsack, 2016. "Transfer Capability Improvement through Market-Based Operation of Series FACTS Devices," *IEEE Transactions on Power Systems* 31:5, pp. 3702-3714.

12. Sabharwall, Piyush, Shannon Bragg-Sitton, Lauren Boldon and Seth Blumsack, 2015. "Nuclear renewable energy integration: An economic case study," *Electricity Journal* 28:8, pp. 85-96.

13. Tayari, Farid, Seth Blumsack, Bob Dilmore, Shahab Mohaghegh, 2015. "Techno-Economic Assessment of Industrial CO2 Storage in Depleted Shale Gas Reservoirs," *Journal of Unconventional Oil and Gas Resources* 11, pp. 82-94.

14. Kumpf, Katrina*, Seth Blumsack, George Young and Jeffrey Brownson, 2015. "Portfolio analysis of solar photovoltaics: Quantifying the contributions of locational marginal pricing and power on revenue variability," *Solar Energy* 119, pp. 277-285.

15. Sahraei-Ardakani, Mostafa*, Seth Blumsack and Andrew Kleit, 2015. "Estimating Zonal Supply Curves in Transmission-Constrained Electricity Markets," *Energy* 80:1, pp. 10-19.

16. Govindarajan, Anand* and Seth Blumsack, 2015. "Equilibrium Deployment of Combined Heat and Power," *Journal of Energy Engineering* 04015045, doi: 10.1061/(ASCE)EY.1943-7897.0000306

17. Blumsack, Seth, 2014, "Dash for Gas, 21st Century Style," *Elements* 10:4, pp. 265-270.

18. Shcherbakova, Anastasia, Andrew Kleit, Seth Blumsack, Joohyun Cho* and Woonam Lee, 2014. "Effect of Increased Wind Penetration on System Prices in Korea's Electricity Markets," *Wind Energy* 17:10, pp. 1469-1482.

19. Fernandez, Alisha*, Seth Blumsack and Patrick Reed, 2013. "Operational Constraints and Hydrologic Variability Can Limit Hydropower in Supporting Wind Integration," *Environmental Research Letters* 8 024037; doi: 10.1088/1748-9326/8/2/024037.

20. Shcherbakova, Anastasia, Andrew Kleit, Seth Blumsack, Joohyun Cho* and Woonam Lee, "Effect of Wind Energy on Electricity Market Prices in South Korea," forthcoming, *Wind Energy*, accepted May 2013.

21. Cotilla Sanchez, Eduardo, Paul Hines, Clayton Barrows* and Seth Blumsack, 2013. "Multi-Attribute Partitioning of Power Networks Using Electrical Distance," *IEEE Transactions on Power Systems* 28:4, pp. 4979-4987.

22. Ayala, Luis and Seth Blumsack, 2013. "The Braess Paradox and its Impacts on Natural Gas Network Performance," *Oil and Gas Facilities* 2:3.

23. Dowds, Jonathan*, Paul Hines and Seth Blumsack, 2013. "Estimating the impact of fuel-switching between liquid fuels and electricity under electricity-sector carbon-pricing schemes, *Socio-Economic Planning Sciences* 47:2, pp. 76-88; DOI: 10.1016/j.seps.2012.09.004.

24. Blumsack, Seth, David Yoxtheimer, and Tom Murphy, 2012. "The Decision to Utilize Acidic Mine Discharge in Hydraulic Fracturing Applications," *Environmental Practice* 14:4, pp. 301-307.

25. Kern, Jordan*, Greg Characklis, Martin Doyle, Seth Blumsack and Richard Wishunt, 2012. "The Influence of De-Regulated Electricity Markets on Hydropower Generation

and Downstream Flow Regime," *Journal of Water Resources Planning and Mangement* 138:4, pp. 342-355. DOI: 10.1061/(ASCE)WR.1943-5452.0000183

26. Blumsack, Seth and Kelsey Richardson*, 2012. "Cost and Emissions Implications of Coupling Wind and Solar Power," *Smart Grids and Renewable Energy*, 3:4, pp. 308-315.

27. Sahraei-Ardakani, Mostafa*, Seth Blumsack and Andrew Kleit, 2012. "Distributional Impacts of State-Level Energy Efficiency Policies," *Energy Policy* 49, pp. 365-372. DOI: 10.1016/j.enpol.2012.06.034

28. Li Li, Evan Frye* and Seth Blumsack, 2012. "Environmental Controls of Cadmium Desorption During CO_2 Leakage," *Environmental Science and Technology* 46, pp. 4388-4395. DOI: 10.1021/es3005199.

29. Barrows, Clayton* and Seth Blumsack, 2012. "Transmission Switching in the IEEE RTS-96 Test System," *IEEE Transactions on Power Systems* 27:2, pp. 1134-1135. DOI: 10.1109/TPWRS.2011.2170771.

30. Hines, Paul, Seth Blumsack, Eduardo Cotilla-Sanchez* and Clayton Barrrows*. "Comparing the Topological and Electrical Structure of the North American Electric Power Infrastructure," in press, *IEEE Systems Journal*, accepted February 2012. DOI: 10.1109/JSYST.2012.2183033.

31. Blumsack, Seth, and Alisha Fernandez,* 2012. "Ready or Not, Here Comes the Smart Grid," *Energy* 37:1, pp. 61-68. DOI: 10.1016/j.energy.2011.07.054

32. Fernandez, Alisha*, Seth Blumsack and Patrick Reed, 2012. "Evaluating Wind-Following and Ecosystem Services for Hydroelectric Dams," *Journal of Regulatory Economics* 41:1, pp. 139-154. DOI: 10.1007/s11149-011-9177-9.

33. Seth Blumsack, Andrew Kleit and Stephon Smith*, 2012. "Evaluation of State and Federal Subsidies for Ground-Source Heat Pumps," *Energy Efficiency* 5:3, pp. 321-334. DOI: 10.1007/s12053-012-9144-z.

34. Blumsack, Seth and Jianhua Xu, 2011. "Spatial Variation of Emissions Impacts due to Renewable Energy Siting Decisions in the Western U.S. Under High-Renewable Penetration Scenarios" *Energy Policy* 39:11, pp. 6962-6971. DOI: 10.1016/j.enpol.2010.11.047.

35. Blumsack, Seth, 2010. "How Free Markets Rocked the Grid," *IEEE Spectrum* 47:12, 5 pages.

36. Iulo, Lisa, Seth Blumsack, Jeffrey Brownson and R. Allen Kimel, 2010. "Renewable Energy in the Planned World," *Interdisciplinary Themes Journal* 2:1, pp. 54-69.

37. Hines, Paul, Eduardo Cotilla-Sanchez* and Seth Blumsack, 2010. "Comparing Three Models of Attack and Failure Tolerance in Electric Power Networks," *Chaos: An Interdisciplinary Journal of Nonlinear Science* 20:3. DOI: 10.1063/1.3489887.

38. Walawalkar, Rahul*, Seth Blumsack, Jay Apt and Stephen Fernands, 2008. "Analyzing PJM's Economic Demand Response Program," *Energy Policy*, 36, pp. 3692-3702. DOI: 10.1016/j.enpol.2008.06.036.

39. Blumsack, Seth, Lester B. Lave and Marija Ilic, 2008. "The Real Problem with Merchant Transmission," *Electricity Journal* 21:2, pp. 9 – 19.

40. Newcomer, Adam*, Seth Blumsack, Jay Apt, Lester B. Lave and M. Granger Morgan, 2008. "Short Run Effects of a Price on Carbon Dioxide Emissions from U.S. Electric Generators," *Environmental Science and Technology* 42:9, pp. 3139 – 3144. DOI: 10.1021/es071749d.

41. Lave, Lester B., Jay Apt and Seth Blumsack, 2007. "Deregulation/Restructuring, Part I: Re-regulation Will Not Fix the Problems," *Electricity Journal* 20:8, pp. 9 – 22.

42. Lave, Lester B., Jay Apt and Seth Blumsack, 2007. "Deregulation/Restructuring, Part II: Where Do We Go From Here?" *Electricity Journal* 20:9, pp. 10 – 23.

43. Blumsack, Seth, Lester B. Lave, and Marija Ilic, 2007. "A Quantitative Analysis of the Relationship Between Congestion and Reliability in Electric Power Networks," *Energy Journal* 28:4, pp. 73 – 100.

44. Blumsack, Seth, 2007. "Measuring the Benefits and Costs of Regional Electric Grid Integration," *Energy Law Journal* 28:1, pp. 147 – 184.

45. Blumsack, Seth, Jay Apt, and Lester Lave, 2006: "Lessons From the Failure of U.S. Electricity Restructuring," *The Electricity Journal*, 19:2, pp. 15 – 32. Also translated into Japanese by the Japan Electric Power Information Center.

46. Blumsack, Seth, Jay Apt, and Lester Lave, 2005: "A Cautionary Tale: U.S. Electric Sector Reform," *Economic and Political Weekly*, 40:50, pp. 5279 – 5301.

47. Lave, Lester B., Jay Apt and Seth Blumsack, 2004: "Rethinking Electricity Deregulation", *The Electricity Journal*, Vol. 17, No. 8, pp 11 – 26.

48. Blumsack, Seth, Dmitri Perekhodtsev and Lester Lave, 2002: "Market Power in Deregulated Wholesale Electricity Markets: Issues in Measurement and the Cost of Mitigation", *The Electricity Journal*, Vol. 15, No.9, pp 1-24.

Refereed Conference Papers

Student co-authors are marked with an asterisk (*)

1. Seth Blumsack, 2018. "The Expensive Narrative of Fuel Security," *Association for Public Policy Analysis and Management*, Washington, DC, November 2018.

2. Yogarathinam, Amirthagunaraj,* Nilanjan Chaudhuri, Chiara Lo Prete, Seth Blumsack, 2018. "Towards an Economic Mechanism for Providing Inertial Support Through DFIG-based Wind Farms," *IEEE Power and Energy Society General Meeting*, Portland, OR, July 2018.

3. Seth Blumsack, 2018. "The Expensive Narrative of Fuel Security," *Energy Policy Research Conference*, Boise ID, September 2018.

4. Bent, Russell, Seth Blumsack, Pascal van Hentenryck, Scott Backhaus, Conrado Borraz Sanchez and Mehdi Shariari*, 2018. "Joint Expansion Planning for Natural Gas and Electric Power Transmission with Endogenous Price Feedbacks," *Proceedings of the 51st Hawaii International Conference on System Sciences*, Waikoloa, HI, January 2018.

5. Shahriari, Mehdi*, Guido Cervone and Seth Blumsack, 2017 (forthcoming). "Forecast-Driven Portfolio Evaluation of Renewable Energy Siting," *WindTech*, Boulder CO, November 2017.

6. Blumsack, Seth, 2017. "Modeling Coordination Between Natural Gas and Electric Power Transmission," *Energy Policy Research Conference*, Park City UT, September 2017.

7. Blumsack, Seth, 2017. "The Capacity Value of Retail Demand Response," *CRRI Workshop on Regulation and Competition*, Annapolis MD, June 2017.

8. Blumsack, Seth and Kyungjin Yoo*, 2017. "Can Electricity Markets Be Designed by Democracy?" *Proceedings of the 50th Hawaii International Conference on System Sciences*, Waikoloa, HI, January 2017.

9. Blumsack, Seth and Kyungjin Yoo*, 2017. "Political Power in the Design of Capacity Markets" *Energy Policy Research Conference*, Santa Fe, NM, September 2016.

10. Johnson, Nicholas* and Seth Blumsack, 2016. "Coalition Identification in Electricity Industry Voting Networks," *Industry Studies Association Annual Meeting*, Minneapolis MN, May 2016.

11. Blumsack, Seth and Kyungjin Yoo*, 2016. "Voting Behavior in the PJM Regional Transmission Organization," *CRRI Workshop on Regulation and Competition*, Shawnee PA, May 2016.

12. Borraz-Sanchez, Conrado, Russell Bent, Scott Backhaus, Seth Blumsack and Pascal van Hentenryck, 2016. "Convex Optimization of Joint Natural Gas and Electric Power Planning," *Proceedings of the 49th Hawaii International Conference on System Sciences*, Poipu, HI, January 2016.

13. Blumsack, Seth, 2015. "Portfolio Analysis of Variable Renewable Power Generation," *INFORMS Annual Meeting*, Philadelphia PA, November 2015.

14. Shahriari, Mehdi* and Seth Blumsack, 2015. "Portfolio Analysis of Renewable Energies," *US Association of Energy Economics Annual Conference,* Pittsburgh PA, October 2015.

15. Blumsack, Seth, 2015. "The Energy Business and Finance Program at Penn State," *US Association of Energy Economics Annual Conference,* Pittsburgh PA, October 2015.

16. Blumsack, Seth and Anand Govindarajan,* 2015. "Blackout Risk Reduction Using Combined Heat and Power," *US Association of Energy Economics Annual Conference,* Pittsburgh PA, October 2015.

17. Blumsack, Seth and Anand Govindarajan,* 2015. "Private and Social Costs of Blackout Risk Reduction Using Combined Heat and Power," *Energy Policy Research Conference,* Denver CO, September 2015.

18. Ositelu, Oladipu* and Seth Blumsack, 2015. "The Response of Investors to Blackouts," *Proceedings of the 48th Hawaii International Conference on System Sciences*, Poipu, HI, January 2015.

19. Blumsack, Seth and Nicholas Johnson,* 2014. "Formal and Informal Decision Mechanisms in Regional Transmission Organizations, *Assoc. Public Policy and Management Annual Research Conference*, Albuquerque NM, November 2014.

20. Stafford, Benjamin, Elizabeth Wilson and Seth Blumsack 2014. "The Social Side of Electrons," *Assoc. Public Policy and Management Annual Research Conference*,, Albuquerque NM, November 2014.

21. Couzo, Evan, Jason West, William Vizuete, Nicholas Johnson, Seth Blumsack, and Clayton Barrows, 2014. "Dynamically controlling daily power plant emissions to avoid ozone exceedances by coordinating air quality forecasts with electricity dispatch models," *Community Modeling and Analysis Systems*, Boston MA, July 2014.

22. Gautam, Suman* and Seth Blumsack, 2014, "Consumer Response to Peak Electricity Pricing in Vermont: The Green Mountain Power Experience," *IAEE Annual Meeting*, New York NY, June 2014.

23. Blumsack, Seth and Nicholas Johnson,* 2014, "Why Transmission Planning Reform Failed in the Mid-Atlantic but Succeeded in the Midwest," *Industry Studies Association Annual Meeting*, Portland OR, May 2014.

24. Seth Blumsack, 2014. "Smart Grid Technology Development and Workforce Training," *IEEE Transmission and Distribution Conference*, Chicago IL, April 2014.

25. Gautam, Suman* and Seth Blumsack, 2014, "Consumer Response to Critical Peak Electricity Pricing," *American Economic Association Annual Meeting*, Boston MA, January 2014.

26. Govindarajan, Anand* and Seth Blumsack, 2013, "Equilibrium Deployment of Combined Heat and Power," *USAEE North American Meeting*, Anchorage AK, July 2013.

27. Tayari, Farid*, Seth Blumsack and R.J. Briggs, 2013, "Sequestration of Industrial Carbon in Shales," *USAEE North American Meeting*, Anchorage AK, July 2013.

28. Sahraei-Ardakani, Mostafa and Seth Blumsack, 2013, "Market Design for Dispatchable Electric Transmission," *IEEE Power and Energy Society General Meeting,* Vancouver, BC (Canada), July 2013.

29. Blumsack, Seth and Mostafa Sahraei-Ardakani*, 2013. "Estimating Supply Curves in Transmission Constrained Electricity Markets" *CRRI Eastern Conference on Regulation and Competition*, May 2013, Shawnee PA.

30. Tayari, Farid*, Seth Blumsack and R.J. Briggs, 2013, "Economic Analysis of Industrial Carbon Sequestration in Shales," *Pittsburgh Conference on Carbon Capture, Sequestration and Utilization*, Pittsburgh PA, May 2013.

31. Fernandez, Alisha*, Seth Blumsack and Patrick Reed, 2013, "Hydropower Assets Must Overcome Severe Hurdles to Flexibly Support Wind Integration," *Environmental and Water Resources Institute (EWRI) Conference*, Cincinnati OH, May 2013.

32. Barrows, Clayton,* Seth Blumsack and Russell Bent, 2013. "Graph-Based Heuristics for Adaptive Electrical Networks," *Proceedings of the 46th Hawaii International Conference on System Sciences*, Wailea, HI.

33. Blumsack, Seth, Eduardo Cotilla-Sanchez, Paul Hines and Clayton Barrows*, 2012. "Multi-Objective Partitioning for Electrical Networks," *INFORMS Annual Meeting*, Phoenix AZ, October 2012.

34. Blumsack, Seth and Nicholas Johnson*, 2012. "Transmission Cost Allocation for Renewable Energy Projects," *Western Energy Policy Conference*, Boise ID, August 2012.

35. Blumsack, Seth and David Yoxtheimer, 2012. "The Utilization of Coal Mine Drainage in Hydraulic Fracturing," *Western Energy Policy Conference*, Boise ID, August 2012.

36. Ayala, Luis and Seth Blumsack, 2012. "Examining Braess' Paradox in Natural Gas Network Optimization," *Proceedings of the SPE Annual Meeting*, San Antonio TX, October 2012.

37. Barrows, Clayton* and Seth Blumsack, 2012. "Efficient Transmission Switching via Solution Space Reduction," *Proceedings of the IEEE Power and Energy Society Annual Meeting,* San Diego CA, July 2012.

38. Sahraei-Ardakani, Mostafa* and Seth Blumsack, 2012. "Strategic Dispatch of Flexible Transmission Assets in Complete Electricity Markets," *Proceedings of the IEEE Power and Energy Society Annual Meeting,* San Diego CA, July 2012.

39. Blumsack, Seth, Paul Hines and Jonathan Dowds*, 2012. "Fuel Switching Under Carbon Constraints," *International Association of Energy Economics Annual Meeting*, Perth, Australia, June 2012.

40. Blumsack, Seth, 2012. "Ready of Not, Here Comes the Smart Grid," *International Association of Energy Economics Annual Meeting*, Perth, Australia, June 2012.

41. Blumsack, Seth and Mostafa Sahraei-Ardakani*, 2012. "When is Transmission Not Transmission?" *CRRI Eastern Conference on Regulation and Competition*, Shawnee PA.

42. Blumsack, Seth and Clayton Barrows*, 2011. "Rules Versus Optimization in Adaptive Electrical Networks," *SIAM Dynamical Systems Conference*, Snowbird UT.

43. Blumsack, Seth, Alisha Fernandez* and Patrick Reed, 2011. "The Opportunity Cost of Backing up Wind Energy," *CRRI Eastern Conference on Regulation and Competition*, Skytop PA.

44. Iulo, Lisa, Rohan Haksar*, and Seth Blumsack, 2011. "Design Strategies for Community-Scale Renewable Energy Solutions," *Proceedings of the 27th International Conference on Passive and Low Energy Architecture PLEA 2011, Volume 1*, edited by Magali Bodart, Arnaud Evrard, Louvain-la-Neuve: Presses Universitaires de Louvain, pp. 621-626.

45. Hines, Paul, Eduardo Cotilla-Sanchez* and Seth Blumsack, 2010. "Two Methods of Vulnerability Assessment for Electric Power Systems," *Proceedings of the 44th Hawaii International Conference on System Sciences*, Kauai, HI.

46. Choudhary, Paras*, Seth Blumsack and George Young, 2010. "Variance Minimizing Site Selection for Interconnected Wind Farms," *Proceedings of the 44th Hawaii International Conference on System Sciences*, Kauai, HI.

47. Sahraei-Ardakani, Mostafa*, Seth Blumsack and Andrew Kleit, 2010. "Supply Curve Estimation for Congested Electric Transmission Grids," *Proceedings of the IEEE Power Engineering Society*, Minneapolis MN.

48. Hines, Paul, Seth Blumsack, Eduardo Cotilla-Sanchez* and Clayton Barrrows*, 2010 "The Topological and Electrical Structure of Power Networks, *Proc. 43rd Hawaii Int. Conf. Sys. Sci.*, Kauai, HI.

49. Blumsack, Seth, Jeffrey R. S. Brownson and Jeff Rayl*, 2010. "Matching Photovoltaic Orientation to Energy Loads, *Proc. 43rd Hawaii Int. Conf. Sys. Sci.*, Kauai, HI.

50. Hines, Paul, Seth Blumsack, Eduardo Cotilla Sanchez* and Clayton Barrows*, 2010. "The Topological and Electrical Structure of Power Transmission Networks," *Proceedings of the 43rd Hawaii International Conference on System Sciences*, Kauai HI.

51. Blumsack, Seth, 2009. "Electric Rate Design and Emissions Reductions," *Papers and Proceedings* of the IEEE Power Engineering Society, Calgary AB, July.

52. Brownson, Jeffrey, Seth Blumsack and Jeff Rayl*, 2009. "Matching Photovoltaic Orientation to Energy Loads," *Proceedings of the ASES National Solar Conference*, Buffalo NY, May.

53. Blumsack, Seth, Jeffrey Brownson and Lucas Witmer*, 2009. "Economic and Environmental Performance of Ground-Source Heat Pumps in Central Pennsylvania," *Proceedings of the 42nd Hawaii International Conference on System Sciences*, Waikoloa HI, January.

54. Blumsack, Seth, Constantine Samaras and Paul Hines, 2008. "Long-Run Electric System Investments to Support Low-Emissions Plug-in Electric Hybrid Vehicles," *Papers and Proceedings* of the IEEE Power Engineering Society, Pittsburgh PA, July.

55. Hines, Paul and Seth Blumsack, 2008. "A Centrality Measure for Electrical Networks," *Proceedings of the 41st Hawaii International Conference on System Sciences*, Waikoloa HI, January.

56. Blumsack, Seth, Lester B. Lave, and Marija Ilic, 2006. "Assessing the Tradeoffs Between Congestion and Reliability in Electric Power Networks," *Papers and Proceedings of the 26th North American Conference, U.S. Association for Energy Economics*, September, Ypsilanti, MI.

57. Blumsack, Seth (2005): "Some Implications of the Braess Paradox for Pricing and Investment in Electric Power Systems", *Proceedings of the MIT Technology, Policy, and Management Consortium*, Cambridge MA, June.

58. Blumsack, Seth and Lester B. Lave, 2004: "Mitigating Market Power in Restructured U.S. Electricity Markets", *Papers and Proceedings of the 24th North American Conference, U.S. Association for Energy Economics*, July, Washington, D.C.

Book Chapters

59. Blumsack, Seth and Dmitri Perehkodtsev, 2009. "Retail Competition in Electricity," in the *International Handbook of Energy Economics*, L. Hunt and J. Evans, eds., Edward Elgar Publishing, London.

60. Perekhodtsev, Dmitri and Seth Blumsack, 2009. "International Wholesale Markets for Electricity," in the *International Handbook of Energy Economics*, L. Hunt and J. Evans, eds., Edward Elgar Publishing, London.

61. Lave, Lester B., Seth Blumsack, Dalia Patiño-Echeverri, Eric Hseih and Marija Ilic, 2007. "Regulators as Decision Makers," *Engineering Electricity Services of the Future*, Kluwer Academic Publishing (forthcoming).

62. Ilic, Marija, Seth Blumsack, Slobodan Pajic, Le Xie, Yong Tae Yoon and Chien-Ning Yu, 2007. "Regional Transmission Organizations as Decision Makers," *Engineering Electricity Services of the Future*, Kluwer Academic Publishing (forthcoming).

63. Blumsack, Seth, Damien Ernst, Edo Macan, Anna Minoia, Jean-Pierre Leotard, Anupam Thatte, Yong Tae Yoon, Chien-Ning Yu and Marija Ilic, 2007. "Transmission Owners as Decision Makers," *Engineering Electricity Services of the Future*, Kluwer Academic Publishing (forthcoming).

64. Van Vactor, Samuel and Seth Blumsack, 2002: "How to Make Power Markets Competitive," in *Electricity Pricing in Transition*, Ahmad Faruqui and Kelly Eakin, eds., Kluwer Academic Publishing.

White Papers, Expert Testimony and Technical Reports

1. Blumsack, Seth, Chiara Lo Prete, Uday Shanbhag and Mort Webster, 2018. "State Policy Interactions with Electricity Markets," report to PJM Interconnection, LLC.

2. Blumsack, Seth, 2018. "Economic Impact Results for a Coal to Liquids Facility in Pennsylvania," report to Somerset Coal Company.

3. Seth Blumsack, October 2016. "Workshop Report: The Nature of Technological Transition and Innovation in Electric Power," report to the Alfred P. Sloan Foundation.

4. Blumsack, Seth and Kyungjin Yoo, 2015. "Economic Impacts of the Atlantic Sunrise Pipeline Expansion," report to Williams Companies.

5. Shortle, James, Dave Abler, Seth Blumsack, Rob Crane, Karen Fisher-Vanden, Marc McDill, Ray Najjar, Rich Ready and Thorsten Wagner, 2014. "Climate Impact Assessment for Pennsylvania: 2014 update," report for the Pennsylvania Department of Environmental Protection and the Governor's Climate Action Committee.

6. Blumsack, Seth, Michael Arthur and Thomas Murphy, 2013. "Water Management in the Shale Energy Sector," report for the U.S. Congressional Research Service.

7. Blumsack, Seth and Luis Ayala, 2012. "Design and Analysis of a Natural Gas Micro-Grid," report for Ben Franklin Technology Partners of Central Pennsylvania.

8. Shortle, James, Dave Abler, Seth Blumsack, Rob Crane, Karen Fisher-Vanden, Marc McDill, Ray Najjar, Rich Ready and Thorsten Wagner, 2012. "Climate Impact Assessment for Pennsylvania: 2011 update," report for the Pennsylvania Department of Environmental Protection and the Governor's Climate Action Committee.

9. Considine, Timothy, Robert Watson and Seth Blumsack, 2011. "The Pennsylvania Marcellus Natural Gas Industry: Economic Impacts and Prospects," report prepared for the Marcellus Shale Coalition.

10. Blumsack, Seth, "Economics of Wind Energy," invited expert testimony before the Pennsylvania Senate Committee on Economic and Recreational Development, March 14, 2011.

11. Blumsack, Seth, 2010. Affidavit submitted on behalf of the Connecticut Department of Public Utility Control in FERC Docket ER10-787-000, concerning the use of market power screens in the ISO New England Forward Capacity Market.

12. Considine, Timothy, Robert Watson and Seth Blumsack, 2010. "The Economic Impacts of the Marcellus Shale Natural Gas Formation: An Update," report prepared for the Marcellus Shale Coalition.

13. Kleit, Andrew, Seth Blumsack, Zhen Lei, Mostafa Sahraei-Ardakani, Lora Hutelmyer and Stephon Smith, 2010. "Electricity Prices in Rural Pennsylvania in the Post-Restructuring Era," report to the Center for Rural Pennsylvania.

14. Shortle, James, Dave Abler, Seth Blumsack, Rob Crane, Karen Fisher-Vanden, Marc McDill, Ray Najjar, Rich Ready and Thorsten Wagner, 2009. "Climate Impact Assessment for Pennsylvania," report for the Pennsylvania Department of Environmental Protection and the Governor's Climate Action Committee.

15. Blumsack, Seth, 2009. Affidavit submitted on behalf of the Connecticut Department of Public Utility Control in FERC Docket ER09-1144-000, concerning the use of market power screens in the ISO New England Forward Capacity Market.

16. Blumsack, Seth, Paul Hines, Clayton Barrows and Eduardo Cotilla Sanchez, 2008. "Network Clustering for Load Deliverability Assessments in PJM," for the PJM Interconnection, LLC.

17. Blumsack, Seth, 2008. Affidavit submitted on behalf of the Maryland Public Service Commission in FERC Docket EL08-47-000, concerning PJM's Three Pivotal Supplier Test for market power.

18. Blumsack, Seth, 2007. "Transmission Modeling in WinDS," NREL Report number AEU-7-77273-01.

19. Apt, Jay, Seth Blumsack and Lester B. Lave, 2007. *Competitive Energy Options for Pennsylvania*, report prepared for the Team Pennsylvania Foundation. Available online at: http://wpweb2.tepper.cmu.edu/ceic/papers/Competitive_Energy_Options_for_Pennsylvania.htm

20. Morgan, G., J.Apt. L. Lave, J. Bergerson, S. Blumsack, J. DeCarolis, P. Hines, D. King, D. Patiño-Echeverri, and H. Zerriffi, 2005. "The U.S. Electric Power Sector and Climate Change Mitigation," for the Pew Center on Global Climate Change.

21. Blumsack, S., S. van Vactor, and P. Stiffler, 2000. "Outlook for Gasoline and Distillates," report prepared for the Oregon Department of Energy.

Unpublished and Archived Working Papers

22. Blumsack, Seth, Lester B. Lave and Jay Apt, 2008. "Prices and Costs for Electric Utilities Under Regulation and Restructuring," CEIC Working Paper 08-03.

23. Blumsack, Seth and Marija Ilic, 2006. "Some Implications of Braess' Paradox for Electric Power Systems."

24. Blumsack, Seth, Marija Ilic, and Lester B. Lave, 2006. "Decomposing Congestion and Reliability."

25. Blumsack, Seth, 2006. "Network Decomposition via Graph Theory and Watts-Strogatz Clustering."

26. Blumsack, Seth, Lester B. Lave, and Marija Ilic, 2006. "Topological Elements of Transmission Pricing and Planning," CEIC Working Paper 06-08.

27. Blumsack, Seth, Lester B. Lave, and Marija Ilic, 2006. "A Quantitative Analysis of the Relationship Between Congestion and Reliability in Electric Power Networks," CEIC Working Paper 06-09.

28. Blumsack, Seth, 2006: "Network Topologies and Transmission Investment Under Electric Industry Restructuring," Ph.D. dissertation, Carnegie Mellon University. The dissertation committee consisted of Lester Lave (chair), Marija Ilic, Sarosh Talukdar, and Jay Apt.

29. Blumsack, Seth, 2006: "The Economic Efficiency of Point-to-Point Financial Transmission Rights is Limited by the Network Topology."

30. Perekhodtsev, Dmitri, Lester Lave, and Seth Blumsack (2002): "A Model of Pivotal Oligopoly for Electricity Markets."

Invited Lectures, Conference Papers and Presentations

31. Blumsack, Seth, 2018. "Modeling Joint Gas and Electric Transmission Planning," George Mason University, December 2018.

32. Blumsack, Seth, 2018. "Alleviating Energy Poverty: Fast Lanes and Speed Bumps," *Society for Exploration Geophysics Annual Meeting*, October 2018.

33. Blumsack, Seth, 2018. "Valuing Blackout Risk Reduction," Sandia National Laboratory, August 2018.

34. Blumsack, Seth, 2018. "Five Myths About Renewable Energy," The Village at Penn State, July 2018.

35. Blumsack, Seth, 2018. "Systems Research in Gas and Electric Transmission," Idaho National Laboratory, January 2018.

36. Blumsack, Seth, 2017. "Carrots, Sticks and Smart Grid Tricks," University of Michigan, December 2017.

37. Blumsack, Seth, 2017. "Convex Methods for Joint Gas Grid Planning Problems," ETH Zurich, October 2017.

38. Blumsack, Seth, 2017. "The Value of Joint Planning for Gas and Electric Transmission," University of Utah, September 2017.

39. Blumsack, Seth, 2017. "Joint Modeling of Gas and Electric Transmission Planning," PJM Interconnect, August 2017.

40. Blumsack, Seth, 2017. "Economic Issues in Methane Regulation from Unconventional Oil and Gas Operations," Penn State Center for Energy Law and Policy, May 2017.

41. Blumsack, Seth, 2017. "Joint Optimization of Natural Gas and Electric Power Transmission," Carnegie-Mellon University, Pittsburgh PA, May 2017.

42. Blumsack, Seth, 2017. "Coordination Problems Between Natural Gas and Electric Power Transmission and Implications for the Environment," Environmental Defense Fund, New York NY, May 2017.

43. Blumsack, Seth, 2017. "Powering the Planet," Earth Talks Series, Penn State University, February 2017.

44. Blumsack, Seth, 2016. "Voting Networks in Regional Electricity Organizations," Santa Fe Institute, Santa Fe NM, September 2016.

45. Blumsack, Seth, 2016. "Building Markets by Democracy," Carnegie-Mellon University, Pittsburgh PA, May 2016.

46. J. Jason West and Seth Blumsack, 2016. "Dynamic Electricity Generation for Addressing Daily Ozone Exceedances," EPA STAR workshop, Raleigh NC, March 2016.

47. Blumsack, Seth, 2016. "Understanding RTO Decision-Making," PJM Interconnect, Valley Forge PA, March 2016.

48. Blumsack, Seth, 2015. "Planning for an Appalachian Natural Gas Value Chain," *Natural Gas Utilization Conference*, Pittsburgh, PA, October 2015.

49. Blumsack, Seth, 2015. "Climate Change and Pennsylvania's Energy Sector," American Institute of Chemical Engineering, Hershey PA, October 2015.

50. Blumsack, Seth, 2015. "Are Power Grids Complex or Just Complicated," George Mason University, May 2015.

51. Blumsack, Seth, 2015. "Asian Carp Invade the Power Grid," Santa Fe Institute, February 2015.

52. Seth Blumsack, 2014. "Controllability of Electrical Networks," *Workshop on Dynamics of and on Networks*, Santa Fe, NM, December 2014.

53. Blumsack, Seth, 2015. "Carrots, Sticks and Electricity Consumption," Santa Fe Institute, October 2014.

54. Blumsack, Seth, 2014. "Energy Land Management Education at Penn State," *PIOGA Annual Conference,* Pittsburgh PA, May 2014.

55. Blumsack, Seth, 2013. "Energy in Pennsylvania: Past, Present and Future," invited address, Leadership Centre County, April 2013.

56. Blumsack, Seth, 2013. "Water Management in Shale Gas Operations," invited seminar speaker, University of Calgary, April 2013.

57. Blumsack, Seth, 2013. "Enabling Adaptive Electrical Networks," invited seminar speaker, University of Vermont, February 2013.

58. Blumsack, Seth, Eduardo Cotilla Sanchez, Paul Hines and Clayton Barrows, 2012, "Multi-Objective Partitioning of Electrical Networks," INFORMS, Phoenix AZ, October 2012.

59. Blumsack, Seth, 2012. "Carrots, Sticks and Other Smart Tricks: Reducing Household Electricity Demand," Penn State Behavioral Science seminar, October 2012.

60. Blumsack, Seth and Mostafa Sahraei-Ardakani, "Market-Based Control of Flexible Transmission Architectures," Center for Nonlinear Studies, Los Alamos National Laboratory, Santa Fe NM, May 2012.

61. Barrows, Clayton and Seth Blumsack, "Computationally Efficient Transmission Switching," Center for Nonlinear Studies, Los Alamos National Laboratory, Santa Fe NM, May 2012.

62. Blumsack, Seth, "Diminishing Returns to Network Flexibility," Skolkovo Foundation, Moscow, Russia, November 2011.

63. Blumsack Seth, Alisha Fernandez and Patrick Reed, "Policy Conflicts in the Utilization of Hydroelectric Dams for Eastern Wind Integration," Western Energy Policy Conference, Boise ID, August 2011.

64. Fernandez, Alisha, Seth Blumsack and Patrick Reed, "Evaluating the Costs of Alternative Wind Integration Policies," International Green Energy Economy Conference, Washington DC, July 2011.

65. Blumsack, Seth, "Natural Gas Pricing Dynamics," Workshop on Industrial Natural Gas Utilization, University Park PA, June 2011.

66. Blumsack, Seth, "The Future of U.S. Natural Gas," presentation before Credit Suisse, State College PA, April 2011.

67. Blumsack, Seth, "Economics of Marcellus Shale Natural Gas," Bayer Public Policy Forum, April 2011.

68. Blumsack, Seth, "Marcellus Shale Development and Mid-Atlantic Natural Gas Markets," GlobalCon Exposition, Philadelphia, March 2011.

69. Blumsack, Seth, "The New Age of Electric Power Systems," presentation to Penn State IEEE Power and Energy Society Student Chapter, March 2011.

70. Blumsack, Seth, "Energy Systems Economics Research at Penn State," presentation to the Office of Fossil Energy, U.S. Department of Energy, March 2011, Washington D.C.

71. Blumsack, Seth, "U.S. Natural Gas Markets," Marcellus Center for Outreach and Research brown bag lunch seminar, February 2011.

72. Blumsack, Seth, "The New Age of U.S. Electricity," presentation at Penn State Energy Day, Washington DC, November 2010.

73. "The Smart Grid," invited speaker, Universidad Autonoma de Barcelona, October 2010.

74. "The Informational Value of Topological Models in Vulnerability Assessments for Electrical Networks," invited seminar, Los Alamos National Laboratory, August 2010.

75. "Living with Sustainable Energy in a Global Society," invited presentation, Best of Greenbuild, Philadelphia PA, May 2010.

76. "The Future of U.S. Natural Gas," invited presentation, Bayer Materials, Pittsburgh PA, May 2010.

77. "Risk-Informed Site Selection for Long-Term Geological CO2 Sequestration," invited presentation, National Energy Technology Laboratory, Pittsburgh PA, May 2010.

78. Blumsack, Seth, "Pennsylvania's Energy Challenges," presentation to the Penn State Alumni Association, Harrisburg PA, March 2010.

79. "The Short-run Emissions Impacts of a Price on Carbon Dioxide Emissions from U.S. Electric Generators," invited seminar speaker, Nicholas School of the Environment, Duke University, November 2009.

80. "Carbon Taxes, Retail Electric Tariffs and Emissions Reductions," invited seminar speaker, Department of Environmental Sciences and Engineering, University of North Carolina-Chapel Hill, November 2009.

81. "Partitioning of Electrical Networks," invited seminar speaker, Los Alamos National Laboratory, March 2009.

82. "The Economics of Nuclear Power," presentation to the student-sponsored Know Nukes Forum, Penn State University, February 2009.

83. "Everything You Never Wanted to Know About Electricity Deregulation," presentation to the Penns Valley Conservation Association, November 2008.

84. "The Real Problem with Merchant Transmission," invited seminar speaker, Department of Economics, West Virginia University, Morgantown WV, November 2008.

85. "Electric Rate Tariffs Under Deregulation in Pennsylvania," invited presentation to Pennsylvania Local Development Districts, Penn State University, October 2008.

86. "Electricity Markets and Carbon Markets," invited briefing before U.S. House and Senate staffers, Washington DC, October 2008 (one briefing was given to House staffers, and one to Senate staffers).

87. "Electricity Prices Under Emissions Constraints," panelist presentation for "Electricity Markets in a Carbon-Constrained World," organized by *Energy Daily* and the Community Power Alliance, Washington DC July 2008.

88. "Prices and Costs for Electric Utilities Under Regulation and Restructuring," invited speaker, Sloan Foundation Industry Studies Program Annual Meeting, Boston MA, May 2008.

89. "Electricity Restructuring: Where Do We Go From Here," invited presentation before the Connecticut State Legislature Energy Committee, Hartford CT, April 2008.

Teaching

Courses Developed and Taught at Penn State University

1. Introduction to Energy and Earth Sciences Economics (ENNEC 100/EBF 200): Introductory course in environmental and natural resource economics. Topics covered include competitive markets; market failures in the presence of public goods and externalities; rent-seeking and problems with regulation; life-cycle environmental impact analysis; non-renewable resources; climate change policy.

2. Environmental Management, Risk and Decision-Making (EMSC 304/EBF 304W): How do companies make decisions when faced with environmental problems? This course introduces business and economics students to basic concepts in decision-making under uncertainty and the evaluation of technological and environmental risk. Students work on analyzing realistic decision problems in areas related to energy, the environment, and human health and safety. Dr. Blumsack is developing an honors-level version of this course that will be taught beginning in Fall 2012.

3. Energy and Modern Society (EM SC 420): Discussion-based course focused on the sustainable energy transition. Course focus is on the technical, social and regulatory challenges associated with the large-scale transition away from a fossil fuel based energy system.

4. Introduction to the Electric Utility Industry (EBF 483/ENNEC 597): Introduction to the industrial structure of the electricity sector. The course includes in-depth discussion of regulated and de-regulated electricity systems; current and future environmental

regulations affecting the electricity industry; the challenge of integrating renewable energy sources into electric grids; and the emerging "smart grid." An online version of this course was developed in Spring 2017.

5. Engineering Project Design (EGEE 494): Independent project work by students in the Energy Engineering major at Penn State. Capstone projects supervised by Blumsack include: analyzing the technical feasibility, economic and environmental benefits associated with lowering the moisture content of Powder River Basin coals before shipment to Eastern coal-fired power plants; a design project focused on small-scale solar photovoltaic production for a school district in Pennsylvania; the direct control of residential hot-water heaters to facilitate wind energy integration; and the air quality implications of increased cogeneration utilization in Philadelphia.

6. Integrated Design of Energy Systems (EME 580): Students in the Energy and Mineral Engineering graduate program work in interdisciplinary teams to define, scope and perform design studies that incorporate engineering, environmental, economic and policy dimensions of system design decisions.

7. Theory and Practice of Science and Technology Policy Analysis (EME 525): Graduate-level introduction to the primary tools used in science and technology policy analysis. Topics covered include the micro-economic foundations of cost-benefit analysis; probabilistic risk assessment; basic epidemiology; probabilistic decision-making; risk perception; and an overview of the U.S. federal regulatory process.

8. Distributed Energy Management (A E 597): Team-taught with several instructors for resident and online delivery. Graduate-level introduction to distributed energy systems, with a focus on the local production and delivery of renewable electric energy. Dr. Blumsack developed course material on the economics of small-scale energy systems; energy policy; and markets for electric power.

9. Solar Energy Project Development (A E 597): Team-taught with several instructors for resident and online delivery. Graduate-level introduction to the design, financing and implementation of solar energy projects. Dr. Blumsack developed course material on the economics of renewable energy, project finance and project decision-making.

10. Energy Markets and Energy Policy (EME 801): Graduate-level introduction to markets for crude-oil, petroleum products, natural gas, renewable energy and electric energy. The course provides students with a quantitatively-oriented foundation for how project decision-making is structured in the energy industries; market institutions that influence project development; and regulatory forces that constrain or encourage energy projects.

11. Demand-Side Energy Management (EGEE 497H): Honors-level undergraduate course focused on integrating the demand side into modern electricity markets through energy-efficiency and demand response. In addition to classroom lectures, students work on multi-week projects in residence at the Philadelphia Navy Yard micro-grid, implementing energy management strategies in conjunction with energy customers and energy management firms.

12. Modeling Electric Power Systems (EME 596): Graduate-level introduction to methods and tools for steady-state modeling of power systems and electricity markets. Topics included

basic circuit theory and power flow modeling; optimal power flow with and without unit commitment and security constraints; derivation of locational marginal pricing; and linear complementarity models for analyzing power market designs.

13. Energy, the Environment and Our Future (MOOC, co-authored with Richard Alley): One of the first MOOCs offered at Penn State, this 12-week course focuses on the basic science of climate change; the impacts of fossil fuel use on the environment and climate; and technological options for transitioning to a low-carbon energy future. Approximately 40,000 students are participating in the course.

14. Economic Analysis of Energy Markets (ENNEC 540): Graduate-level course first taught in Spring 2017 covering the theory and practice of modeling interconnected markets for energy commodities and environmental regulation. The course focused on the use of complementarity models, mathematical programs with equilibrium constraints, variational inequalities and optimization problems constrained by other optimization problems. Students were exposed to techniques of problem formulation and solution in commonly-used software programs for energy market simulation.

Courses Developed and Taught at Colorado School of Mines

Competition Analysis for the Electric Power Sector: Two-day module for a summer school on electric power grids at Colorado School of Mines, focused on the industrial organization of firms in the electric power industry.

Courses Developed and Taught at Vermont Law School

Energy Business Fundamentals: One-week summer term short-course, aimed at law students, on markets, regulatory institutions and decision-making in the energy and electric utility sectors.

Power Systems Engineering Fundamentals: One-week summer term short-course, aimed at law students, on engineering principles for the operation and planning of electric power grids.

Courses Developed and Taught at Carnegie-Mellon University

The Transformation of Energy Markets (Spring 2005): Introduction to the transition from regulation to competition and markets in the oil, natural gas, and electric utility industries. Emphasis in the course was placed on understanding the role of technology in facilitating or impeding the transition to competitive markets. Cross-listed in engineering and economics.

University and Professional Service Activities

University Service, Penn State University

Associate Head, Energy and Mineral Engineering, July 2016 – present

Chair, Energy Business and Finance, July 2015 – present

Co-Director, Penn State Initiative for Energy and Environmental Economics and Policy, 2011-present.

Promotion and Tenure Committee, Department of Energy and Mineral Engineering, 2013 – 2015

Reviewer of applications to the Schreyer Honors College

Advisory Committee, Earth and Environmental Systems Institute

Advisory Committee, Online Bachelor of Arts Program in Energy and Sustainability Policy

Committee Member, Penn State University Network Science Initiative
Graduate Admissions Committee, Department of Energy and Mineral Engineering
Computing Resources Committee, Department of Energy and Mineral Engineering
Service on thirteen Faculty Search Committees (between 2007 and present), Department of Energy and Mineral Engineering; Department of Agricultural Economics, Sociology and Education; Department of Architectural Engineering; School of International Affairs; and Penn State Institutes for Energy and the Environment. I chaired two of the eleven search committees, both within the Department of Energy and Mineral Engineering.
Search Committee, Earth and Mineral Sciences Associate Dean for Undergraduate Education, Spring 2016.
Search Committee, Dean of the College of Earth and Mineral Sciences, Spring 2017.

Professional Service Activities

Vice President, U.S. Association for Energy Economics (USAEE). Dr. Blumsack is the faculty advisor for the Penn State Student Chapter of the USAEE, chairs its Communications Committee and has served on conference program committees, sponsorship committees and awards nomination committees for USAEE.
Member, Society for Risk Analysis
Member, Power Engineering Society (PES) of the IEEE. Dr. Blumsack has been active in four PES technical committees: Power Systems Analysis, Computing and Economics; Subcommittee on Systems Economics; Subcommittee on FACTS; Committee on Test Systems Development.
Member, American Geophysical Union
Member, American Economic Association
Serve as Mini-Track Chair for the Electric Power Engineering and Economics track, Hawaii International Conference on System Sciences
Associate editor, *Journal of Unconventional Oil and Gas Resources, Journal of Energy Engineering* and *Journal of Regulatory Economics*
Peer reviewer for the following journals: *IEEE Transactions on Power Systems, IEEE Transactions on Power Delivery, Energy Journal, Environmental Science and Technology, Journal of Regulatory Economics, Fuel Processing Technology, Operations Research*
Review panel member for the National Academies of Science, "Analytic Foundations for the Next Generation Electrical Grid"
Peer reviewer of proposals for the U.S. Department of Energy, Environmental Protection Agency, Idaho National Laboratory, National Science Foundation, New Mexico EPSCoR Office, Oak Ridge National Laboratory, the Alfred P. Sloan Foundation and the MIT-Skolkovo Initiative
Energy Intensity Metrics review panel member for the U.S. Environmental Protection Agency
External review board member, Energy Policy Institute, Boise State University and Idaho National Laboratory
Advisory Board member, University of Wyoming EPSCoR: "Atmosphere to Grid"

Awards and Honors

Hess Energy Faculty Fellow in Energy and Mineral Engineering

Thomas P. Ryan, Jr. Faculty Fellow in the College of Earth and Mineral Sciences, July 2011 – July 2017.

Scholar-in-Residence, Penn State Earth and Environmental Systems Institute, 2011.

Best Paper Awards, Hawaii International Conference on Systems Sciences, 2011, 2016 and 2017.

Wilson Research Initiation Award, College of Earth and Mineral Sciences, Pennsylvania State University

William W. Cooper Doctoral Dissertation Award for "Outstanding Doctoral Dissertation in Management or the Management Sciences," Tepper School of Business, Carnegie Mellon University, May 2006.

Best Poster Award for "Some Implications of Braess's Paradox for Electric Power Networks," Technology, Policy and Management Consortium, Cambridge MA, May 2005.

Herbert L. Toor Award for "Outstanding Research Paper Submitted in the Qualifying Examinations of the Department of Engineering and Public Policy," Carnegie Mellon University, February 2004.

DEED Technical Grant for "Reducing Peak Demand in Public Power Systems," American Public Power Association, December 2001.

William Larimer Mellon Scholarship, Graduate School of Industrial Administration, Carnegie Mellon University, Academic years 2001 through 2003.

Consulting and Advisory Activities

Alfred P. Sloan Foundation
American Public Power Association
Bayer Materials
Congressional Research Service
Consortium for Risk Evaluation with Stakeholder Participation
Connecticut Department of Public Utility Control
Green Mountain Power
Gum & Pickett, LLC
Los Alamos National Laboratory
Maryland Public Service Commission
Minnesota Attorney General's Office
National Renewable Energy Laboratory
New Mexico EPSCoR Office
New York State Energy Research and Development Agency
Praxair Corporation
RAND Corporation
U.S. Department of Energy
U.S. Environmental Protection Agency

Vermont Electric Cooperative
Vermont Energy Investment Corporation

Graduate Student and Post-doctoral Research Mentoring

Dr. Blumsack is the primary advisor for 8 M.S. and Ph.D. students in the Department of Energy and Mineral Engineering, and has served as external advisor for 8 students outside of Energy and Mineral Engineering. Dr. Blumsack also advises Undergraduate Honors Theses in the Energy and Mineral Engineering Department.

Post-doctoral Mentoring

1. Farid Tayari (Ph.D., Penn State), 2014-2016. Funded by NETL contracts on carbon sequestration and enhanced oil recovery.

2. Daniel Xu (Ph.D., New Mexico State University), 2013. Funded by NETL Grid Technologies Initiative.

Current M.S. and Ph.D. Advising in the Energy and Mineral Engineering Department

3. Anand Govindarajan, Ph.D. Candidate, Energy Management and Policy (ABD, currently at National Renewable Energy Laboratory)

4. Nicholas Johnson, Ph.D. Candidate, Energy Management and Policy (ABD, currently at Principia College)

5. Haoming Ma, M.S. Student, Energy and Mineral Engineering

6. Roger Mina, Ph.D. Candidate, Energy Management and Policy (ABD, currently with the Columbia Energy Ministry)

7. Oladipu Ositelu, Ph.D. Candidate, Energy and Mineral Engineering

8. Mehdi Shariari, Ph.D. Candidate, Energy Management and Policy

9. Kyungjin Yoo, Ph.D. Candidate, Energy Management and Policy

10. Yucheng Wu, Ph.D. Student, Energy and Mineral Engineering

Past M.S. and Ph.D. Advising in the Energy and Mineral Engineering Department (students listed in alphabetical order – 12 M.S., 8 Ph.D., with current affiliations if known)

11. Clayton Barrows, Energy Management and Policy (Ph.D. 2012), National Renewable Energy Laboratory

12. Mesude Bayracki, Energy and Mineral Engineering (M.S. 2011), Ph.D. candidate, Penn State

13. Allison Boehm, M.S. Student, Energy and Mineral Engineering (M.S. 2013), St. Francis University

14. Mercedes Cortes, Energy and Mineral Engineering (M.S. 2012), Johnson Controls
15. Suman Gautam, Energy Management and Policy (Ph.D., 2015), Daymark Energy Advisors
16. Alisha Fernandez (NSF Graduate Fellow, M.S. 2011, Ph.D., 2014), Oak Ridge National Laboratory
17. Evan Frye, M.S. Student, Energy and Mineral Engineering (M.S. 2011), Energy Information Administration
18. Anand Govindarajan, Energy and Mineral Engineering (M.S. 2012), National Renewable Energy Laboratory
19. Babatunde Idrisu, Energy Management and Policy (M.S. 2012), Ph.D. student, University of Delaware
20. Katrina Kumpf, Energy Management and Policy (M.S. 2014), Everpower Wind
21. Zhi Li, Ph. Energy Management and Policy (Ph.D. 2015)
22. Yuxi Meng, Energy Management and Policy (Ph.D., 2014), Price Waterhouse Coopers
23. Akil Mesiwala, Energy Management and Policy (M.S., 2014)
24. Temitope Phillips, Energy and Mineral Engineering (Ph.D. 2012), Chevron
25. Stefan Nagy, Combined B.S./M.S., Energy Business and Finance (2012), National Grid
26. Mostafa Sahraei-Ardakani, Energy Management and Policy (Ph.D. 2012), University of Utah
27. Farid Tayari, Energy Management and Policy (Ph.D. 2014), Penn State
28. Egdabon Udegbe, Energy Management and Policy (M.S., 2014), Ph.D. candidate, Penn State
29. Lucas Witmer, Energy and Mineral Engineering (M.S. 2011)

External M.S. and Ph.D. Advising

30. Hanyan Shen, M.S. Student, Architectural Engineering, Penn State University
31. Guillermo Orellana, M.S. Student, Architectural Engineering, Penn State University
32. Mohammad Heidarinejad, Ph.D. Candidiate, Mechanical Engineering, Penn State University.
33. Marc McNeill, M.S. Candidate, Industrial and Manufacturing Engineering, Penn State University.
34. David Beevers, Ph.D. Candidate, Mechanical Engineering, Penn State University.
35. Pedro Neto, Ph.D. Candidate, Industrial Engineering, Penn State University (ABD 2013).

36. Tabitha Coulter, Ph.D. Candidate, Architectural Engineering, Penn State University (ABD 2012).

37. Eric Hittinger, Ph.D., Engineering and Public Policy, Carnegie-Mellon University. Date of Graduation: August 2012.

38. Steven McGuenegle, M.S., Geography, Penn State University. Date of Graduation: May 2009.

39. Steven McLaughlin, Ph.D Candidate, Computer Science and Engineering, Penn State University (ABD 2011).

40. Adam Newcomer, Ph.D., Engineering and Public Policy, Carnegie-Mellon University. Date of Graduation: May 2008.

41. Kathleen Spees, Ph.D., Engineering and Public Policy, Carnegie-Mellon University. Date of Graduation: May 2008.

42. Jason Wiegle, Ph.D., Rural Sociology, Penn State University. Date of Graduation: May 2010.

Undergraduate Honors Advising

43. Emily Shutt, Energy Business and Finance. Date of Graduation: May 2009.

44. Stephon Smith, Economics (Co-Advise with Andrew Kleit). Date of Graduation: August 2010.

45. Kelsey Richardson, Energy Business and Finance. Date of Graduation: May 2011.

46. Megan Carbine, Energy Business and Finance. Date of graduation: May 2012.

47. Drew Miller, Energy Business and Finance. Date of graduation: 2013.

48. Bridget Dougherty, Energy Business and Finance. Date of graduation: 2014.

49. Connor Brady, Energy Business and Finance. Date of graduation: 2014.

50. Josh Clothiaux, Engineering Science and Mechanics. Date of graduation: May 2016.

Grant and Contract Funding

Since July 2007, Dr. Blumsack has been Principal Investigator on 23 funded grants and contracts, with a combined value of over $2,500,000.

Dr. Blumsack has also been Co-Principal Investigator on 15 funded grants and contracts, with a combined value of over $9,500,000; and has been Senior Investigator on 5 funded grants and contracts, with a combined value of over $730,000.

Current Grant and Contract Funding

"CRISP: Computable Market and System Equilibrium Models for Coupled Infrastructures"
Funding Agency: National Science Foundation

Amount: $350,000
PI: Seth Blumsack
Period: 9/1/16 – 8/31/19
Annual Support: 0.75 person-month

"Cyber-SEES: Climate-Aware Renewable Hydropower Generation and Disaster Avoidance"
Funding Agency: National Science Foundation
Amount: $227,980
PI: Seth Blumsack
Period: 9/15/13 – 8/31/17
Annual Support: 0.5 person-month

"Collaborative Research: Transforming Power: Regional Transmission Organizations Managing Tension and Networking Innovation"
Funding Agency: National Science Foundation
Amount: $144,470
PI: Seth Blumsack
Period: 9/1/13 – 8/31/17
Annual Support: 0.5 person-month

Past Grant and Contract Funding

"Workshop Grant: The Nature of Technological Innovation in Power Generation and Delivery"
Funding Agency: Alfred P. Sloan Foundation, National Science Foundation, Santa Fe Institute
Amount: $25,000
PI: Seth Blumsack
Period: 12/1/15 – 6/1/16
Annual Support: NA (workshop grant – all funds went to support participant travel and costs to run the workshop)

"Climate Change Impacts in Pennsylvania: 2014 Update"
Funding Agency: Pennsylvania Department of Environmental Protection
Amount: $100,000
PI: James Shortle
Period: 7/1/2014 – 5/31/2015
Annual Support: 0.2 person-month

"Estimating the Impacts of the Transco Pipeline Expansion"
Funding Agency: Williams Energy
Amount: $91,044
PI: Andrew Kleit
Period: 5/1/2014 – 10/31/2014

Annual Support: 1 person-month

"Impacts of Energy Efficient Building Innovation in Greater Philadelphia: Year 3"
Funding Agency: Energy Efficient Buildings Energy Innovation HUB (DOE Prime)
Amount: $126,971
PI: Seth Blumsack
Period: 2/1/13 – 1/31/14
Annual Support: 1.2 person-month

"The Next Generation Power Converter"
Funding Agency: National Energy Technology Laboratory
Amount: $50,000
PI: Seth Blumsack
Period: 2/1/13 – 11/30/13
Annual Support: 0.2 person-month

"Dynamic Air Quality Management"
Funding Agency: U.S. Environmental Protection Agency
Amount: $250,000
PI: J. Jason West (Blumsack Co-PI)
Period: 6/1/12 – 5/31/14
Annual Support: 1 person-month

"Portfolio Approach to Demand Response and Energy Storage in the Smart Grid"
Funding Agency: Korean Electric Power (Korean Ministry of Knowledge prime)
Amount: 255,000,000 Korean won (approximately $250,000)
PI: Anastasia Shcherbakova (Blumsack Investigator)
Period: 12/1/11 – 11/30/13
Annual Support: 1 person-month

"Incorporating Environmental Risk into Business Decision-Making Education"
Funding Agency: Hess Energy
Amount: $40,000
PI: Seth Blumsack
Period: 10/1/11 – 12/31/13

"Marcellus Matters: Education for Adults in Science and Engineering"
Funding Agency: National Science Foundation
Amount: $2,541,418
PI: Michael Arthur (Blumsack Co-PI)
Period: 9/1/11 – 8/31/14

Annual Support: 0.5 person-month

"Problem-Focused Honors Education in Environmental Risk and Decision-Making"
Funding Agency: Schreyer Honors College, Penn State University
Amount: $2,000
PI: Seth Blumsack
Period: 10/1/11 – 12/31/12

"Industrial Carbon Management"
Funding Agency: NETL
Amount: $285,259
PI: Seth Blumsack
Period: 11/1/10 – 11/30/13
Annual Support: 0.5 person-month

"GridSTAR Smart Grid Training Center"
Funding Agency: U.S. Department of Energy
Amount: $5,000,000
PI: David Riley (Blumsack Co-PI)
Period: 9/1/10 – 8/31/13
Annual Support: 1 person-month

"ARRA: The eEnergy Vermont Consumer Feedback Behavior Study"
Funding Agency: Vermont Electric Company, Inc. (U.S. Department of Energy prime)
Amount: $247,599
PI: Seth Blumsack
Period: 5/31/10 – 8/31/14
Support: 1 person-month

"Penn State Electricity Markets Initiative,"
Funding Agency: Consortium of Electric Utilities
Amount: $240,000
PI: Andrew Kleit (Blumsack Co-PI)
Period: 1/1/10 – 12/31/13
Annual Support: 0.5 person-month

"Cyber-Security in the Smart Grid,"
Funding Agency: Penn State Institutes of Energy and the Environment
Amount: $50,000
PI: Seth Blumsack

Period: 1/1/10 – 12/31/13
Annual Support: 0.5 person-month

"Mid-Atlantic Clean Energy Application Center"
Funding Agency: U.S. Department of Energy
Amount: $497,375
PI: James Freihaut (Blumsack Co-PI)
Period: 10/1/09 – 9/30/13
Annual Support: 0.5 person-month

"Impacts of Energy Efficient Building Innovation in Greater Philadelphia: Year 2"
Funding Agency: Energy Efficient Buildings Energy Innovation HUB (DOE Prime)
Amount: $313,189
PI: Seth Blumsack
Period: 2/1/12 – 1/31/13
Annual Support: 1 person-month

"Philadelphia Navy Yard Network Operations Center"
Funding Agency: Energy Efficient Buildings Energy Innovation HUB (DOE Prime)
Amount: $169,836
PI: Williams Agate (Blumsack Co-PI)
Period: 2/1/12 – 1/31/13
Annual Support: 1.2 person-month

"Wind Energy Workforce Development: Science, Engineering and Technology,"
Funding Agency: U.S. Department of Energy
Amount: $398,456
PI: George Lesieutre (Blumsack Co-PI)
Period: 10/1/09 – 12/31/12
Annual Support: 0.5 person-month

"Pennsylvania Wind for Schools Program"
Funding Agency: U.S. Department of Energy
Amount: $180,000
PI: Susan W. Stewart (Blumsack Investigator)
Period: 7/1/09 – 12/31/12
Annual Support: 0.5 person-month

"The Next Generation Power Converter: Demonstration Site Plan and Development"
Funding Agency: National Energy Technology Laboratory
Amount: $50,000

PI: Gregory Dobbs (Blumsack Co-PI)
Period: 7/1/12 – 11/30/12
Annual Support: 0.2 person-month

"Design and Evaluation of a Natural Gas Micro-Grid"
Funding Agency: Little Pine Resources and Ben Franklin Technology Partners
Amount: $75,000
PI: Seth Blumsack
Period: 6/1/11 – 5/31/12
Annual Support: 0.5 person-month

"Regulating the Smart Grid"
Funding Agency: KeyLogic Corporation (NETL Prime)
Amount: $33,000
PI: Seth Blumsack
Period: 2/1/12 – 9/30/12
Annual Support: 0.75 person-month

"Economic Impacts of Climate Change in Pennsylvania: 2011 Update"
Funding Agency: Pennsylvania Department of Environmental Protection
Amount: $100,000
PI: James Shortle (Blumsack Senior Investigator)
Period: 9/1/11 – 3/31/12
Annual Support: 0.5 person-month

"Demand Response at the Philadelphia Navy Yard"
Funding Agency: Energy Efficient Buildings Energy Innovation HUB (DOE Prime)
Amount: $125,000
PI: Andrew Kleit (Blumsack Co-PI)
Period: 2/1/11 – 1/31/13
Annual Support: 0.5 person-month

"Risk-Informed Site Selection for the Long-Term Geologic Sequestration of Carbon Dioxide"
Funding Agency: NETL
Amount: $73,000
PI: Seth Blumsack
Period: 11/1/10 – 1/31/12
Annual Support: 0.5 person-month

"Impacts of Energy Efficient Building Innovation in Greater Philadelphia: Year 1"
Funding Agency: Energy Efficient Buildings Energy Innovation HUB (DOE Prime)

Amount: $125,000
PI: Seth Blumsack
Period: 2/1/11 – 1/31/12
Annual Support: 1.5 person-month

"Update of the Economic Impacts of Marcellus Shale Natural Gas Development,"
Funding Agency: Marcellus Shale Commission
Amount: $100,000
PI: Seth Blumsack
Period: 2/1/11 – 8/31/11
Support: 1 person-month

"The Impacts of Chinese Production of Rare Earth Elements on U.S. Sustainability Policy"
Funding Agency: Penn State Institutes of Energy and the Environment
Amount: $45,000
PI: Andrew Kleit (Blumsack Co-PI)
Period: 6/1/10 – 5/31/11
Support: 0.05 person-month

"Load Deliverability Assessment Support for PJM Using Tools from Complex Networks"
Funding Agency: PJM Interconnect
Amount: $67,885
PI: Seth Blumsack
Period: 1/1/09 – 12/31/10
Support: 0.05 person-month

"The Economic Impacts of Marcellus Shale Natural Gas Development,"
Funding Agency: Marcellus Shale Commission
Amount: $100,000
PI: Seth Blumsack
Period: 2/1/10 – 12/31/10
Support: 1.08 person-month

"Wilson Research Initiation Grant: Measuring the Impact of Utility-Scale Wind Integration,"
Funding Agency: College of Earth and Mineral Sciences, Penn State University
Amount: $10,000
PI: Seth A. Blumsack
Period: 7/1/09 – 6/30/10

"Impacts of Electricity Restructuring on Rural Pennsylvania,"
Funding Agency: Center for Rural Pennsylvania

Amount: $100,000
PI: Andrew Kleit (Blumsack Co-PI)
Period: 1/1/08 – 5/31/10

"Greenhouse Gas Inventory for Pennsylvania's Electricity Generation Sector"
Funding Agency: Pennsylvania Department of Environmental Protection
Amount: $100,000
PI: Seth Blumsack
Period: 12/1/08 – 9/1/09

"Economic Impacts of Climate Change in Pennsylvania"
Funding Agency: Pennsylvania Department of Environmental Protection
Amount: $193,954
PI: James Shortle (Blumsack Senior Investigator)
Period: 12/1/08 – 9/1/09

"Regulatory and Institutional Barriers to Micro-Grid Deployment"
Funding Agency: Ford Foundation
Amount: $10,000
PI: Amy Glasmeier (Blumsack Senior Investigator)
Period: 10/1/08 – 8/31/09

"Small Grant for Exploratory Research: Characterizing Power Networks with Tools from Complex Networks"
Funding Agency: National Science Foundation
Amount: $84,438
PI: Paul Hines (Blumsack Co-PI)
Period: 8/31/08 – 9/1/09

"Identifying and Mitigating Risk in PJM with Tools from Complex Networks"
Funding Agency: PJM Interconnection, LLC
Amount: $69,365
PI: Paul Hines (Blumsack Co-PI)
Period: 8/31/08 – 9/1/09

"Integrated Reservoir/Surface Analysis of Natural Gas Systems"
Funding Agency: NCL Natural Resources
Amount: $24,609
PI: Luis Ayala (Blumsack Co-PI)
Period: 6/1/08 – 12/1/08

"Engineering Analysis of a Natural Gas Gathering System and the Determination of its Optimum Operating Condition"
Funding Agency: NCL Natural Resources
Amount: $24,609
PI: Luis Ayala (Blumsack Co-PI)
Period: 1/1/08 – 5/1/08

January 2019

Resume of: **Dallas Burtraw**

Education:

Ph.D., Economics, University of Michigan, 1989.

M.P.P., Public Policy, University of Michigan, 1986.

B.S., Community Economic Development, University of California, Davis, 1980.

Areas of Specialization:

Environmental Policy, Public Finance, Industrial Organization, Applied Game Theory.

Professional Activities:

Darius Gaskins Senior Fellow, Resources for the Future, 2010-.

Senior Fellow, Resources for the Future, Quality of the Environment Division, 1998-present.

Fellow, Resources for the Future, Quality of the Environment Division, 1989-1998.

Consultant to state and federal agencies, electricity companies, environmental organizations and international lending and economic assistance institutions.

Previous Experience:

Professional Lecturer in International Relations, Energy, Environment, Science and Technology. Johns Hopkins SAIS University. (1993-1999).

Adjunct Professor, Department of Economics, Georgetown University. (1998).

Instructor, University of Michigan: Introductory Microeconomics.
Teaching Assistant, University of Michigan: Operations Research.
Teaching Assistant, University of Michigan: Law and Economics. (1984-1989).

Economic Analyst, Pacific Gas and Electric Company. (1984)

Program Manager, SolarCal Local Government Commission on Conservation and Renewable Resources, State of California. (1981-1982).

PUBLICATIONS

"The Affordable Clean Energy Rule and the Impact of Emissions Rebound on Carbon Dioxide and Criteria Air Pollutant Emissions," 2019. Amelia Trafton Keyes, Kathleen Fallon Lambert, Dallas Burtraw, Jonathan J. Buonocore, Jonathan I Levy and Charles T Driscoll. *Environmental Research Letters,* https://doi.org/10.1088/1748-9326/aafe25.

"Sequencing to Ratchet Up Climate Policy Stringency," 2018. Michael Pahle, Dallas Burtraw, Christian Flachsland, Nina Kelsey, Eric Biber, Jonas Meckling, Ottmar Edenhofer, and John Zysman. *Nature Climate Change,* 8 (October): 861-867, https://rdcu.be/70ix.

"Distribution of Allowance Asset Values and the Use of Auction Revenues in the EU Emissions Trading System," 2018 (with Åsa Löfgren, Markus Wråke, and Anna Malinovskaya), *Review of Environmental Economics and Policy,* 12(2): 284-303, doi: 10.1093/reep/rey012.

"Recognizing Gravity as a Strong Force in Atmosphere Emissions Markets," 2018 (with Amelia Keyes), *Agricultural and Resource Economics Review,* 47(2): 201-219, https://doi.org/10.1017/age.2018.12; see also RFF WP 18-16.

"Emissions Trading in North America," 2018 (with Lars Zetterberg and Amelia Keyes), in *Emissions Trading: Fighting Climate Change with the Market,"* Ed: Hanna Stenegren, Stockholm: Fores and European Liberal Forum.

"European Union Reforms Its Carbon Emissions Market," 2018 (with Amelia Keyes), *Resources,* 198 (Summer).

"Companion Policies under Capped Systems and Implications for Efficiency: The North American Experience and Lessons in the EU Context," 2018 (with Amelia Keyes and Lars Zetterberg), Report Number C 312, Stockholm: IVL Swedish Environmental Research Institute; see also RFF Report (June 2018). .

"Air pollution success stories in the United States: The value of long-term observations," 2018 (with Timothy J. Sullivan, Charles T. Driscoll, Colin M. Beier, Ivan J. Fernandez, James N. Galloway, David A. Gay, Christine L. Goodale, Gene E. Likens, Gary M. Lovett, Shaun A. Watmough), *Environmental Science and Policy*, 84: 69-73.

"Stepping Up: As the Feds walk away, states hustle to reduce greenhouse gas emissions," 2018 (with Amelia Keyes), *The Milken Institute Review,* 20(2):50-61.

"Using Production Incentives to Avoid Emissions Leakage," 2017 (with Karen Palmer, Anthony Paul and Hang Yin), *Energy Economics,* 68: 45-56.

"Consignment Auctions of Free Emissions Allowances," 2017 (with Kristen McCormack), *Energy Policy,* 107: 337-344.

"The Supreme Court's Stay of the Clean Power Plan: Economic Assessment and Implications for the Future," 2016 (with Joshua Linn and Kristen McCormack), *Environmental Law Reporter,* 46 ELR: 10859-10872 (October).

"An Analysis of Costs and Health Co-Benefits for a U.S. Power Plant Carbon Standard," 2016 (with Jonathan J. Buonaocore, Kathleen F. Lambert, Dallas Burtraw, Samantha Sekar, and Charles T. Driscoll), *PLoS ONE,* 11(6): e0156308. DOI: 10.1371/journal.pone.0156308 (June 7).

"Policy Analysis: Valuation of Ecosystem Services in the Southern Appalachian Mountains," 2016 (with H. Spencer Banzhaf, Susie Chung Criscimagna, Bernard J. Cosby, David A. Evans, Alan J. Krupnick, and Juha V. Siikamäki), *Environmental Science & Technology,* DOI: 10.1021/acs.est.5b03829.

"The economics of the EU ETS market stability reserve," 2016 (with Cameron Hepburn, Karsten Neuhoff, William Acworth and Frank Jotzo), *Journal of Environmental Economics and Management*, 80: 1-5.

"The regulatory approach in U.S. Climate Mitigation Policy," 2015, in ***Towards a Workable and Effective Climate Regime,*** Scott BARRETT, Carlo CARRARO, Jaime de MELO (editors), published in French and English, CEPR Press and FERDI, ISBN: 978-1-907142-95-6.

"A Proximate Mirror: Greenhouse Gas Rules and Strategic Behavior under the US Clean Air Act," 2015 (with Karen Palmer, Anthony Paul and Sophie Pan), *Environment and Resource Economics*, 62 (2): 217-241. 10.1007/s10640-015-9963-4.

"Flexibility and Stringency in Greenhouse Gas Regulations," 2015 (with Matt Woerman and Alan Krupnick), *Environment and Resource Economics,* 63:225-248. online: DOI 10.1007/s10640-015-9951-8.

"U.S. Power Plant Carbon Standards and Clean Air Co-Benefits," 2015 (with Charles T. Driscoll, Jonathan Buonocore, Jonathan I. Levy, Kathleen F. Lambert, Stephen B. Reid, Habibollah Fakhraei, Joel Schwartz), *Nature Climate Change,* 5: 535-540.

"The Initial Incidence of a Carbon Tax Across Income Groups," 2015 (with Roberton C. Williams III, Hal Gordon, Jared C. Carbone, and Richard D. Morgenstern), *National Tax Journal,* March, 68(1): 195-214.

"Mixing It Up: Power Sector Energy and Regional and Regulatory Climate Policies in the Presence of a Carbon Tax," 2015 (with Karen L. Palmer), in *Implementing a US Carbon Tax: Challenges and Debates,* eds: Ian Parry, Adele Morris and Roberton C. Williams III, New York: Routledge.

"The Initial Incidence of a Carbon Tax Across U.S. States," 2014 (with Roberton C. Williams III, Hal Gordon, Jared C. Carbone, and Richard D. Morgenstern), *National Tax Journal,* December, 67 (4): 807–830.

"Chapter 15: National and Sub-National Policies and Institutions," 2014 (contributing author), Climate Change 2014 Mitigation of Climate Change, Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

"Regulating Greenhouse Gases from Coal Power Plants under the Clean Air Act," 2014 (with Joshua Linn and Erin Mastrangelo), *Journal of the Association of Environmental and Resource Economists,* 1(1):97-134.*

> * The Ralph C. d'Arge and Allen V. Kneese Award for Outstanding Publication in the *Journal of the Association of Environmental and Resource Economists,* 2014.

"The Costs and Consequences of Greenhouse Gas Regulation under the Clean Air Act," 2014 (with Josh Linn, Karen Palmer and Anthony Paul), *American Economic Review: Papers & Proceedings,* 104(5): 557-562.

"Two World Views on Carbon Revenues," 2014 (with Samantha Sekar), *Journal of Environmental Studies and Sciences*, 4:110-120.

"Economic Ideas for a Complex Climate Policy Regime," 2013 (with Matt Woerman), *Energy Economics,* 40: S24-S31 (Fifth Atlantic Workshop in Energy and Environmental Economics. Guest editors: Carlos de Miguel, Alberto Gago, Xavier Labandeira and Baltasar Manzano).

"Reliability in the Electricity Industry under New Environmental Regulations," 2013, (with Karen L. Palmer, Anthony Paul, Blair Beasley, and Matthew Woerman), *Energy Policy* 62: 1078-1091.

"Flexible Mandates for Investment in New Technology," 2013 (with Dalia Patino Echeverri and Karen Palmer), *Journal of Regulatory Economics,* 44 (2): 121-155.w

"The Institutional Blind Spot in Environmental Economics," 2013, *Daedalus,* 142(1):110-118.

"Soft and Hard Price Collars in a Cap-and-Trade System: A Comparative Analysis," 2012 (with Harrison Fell, Richard D. Morgenstern and Karen L. Palmer), *Journal of Environmental Economics and Management,* 64(2): 183-198.

"Rethinking Environmental Federalism in a Warming World," 2012 (with William M. Shobe), *Climate Change Economics,* 3(4): 1-33.

"Climate Policy Design with Correlated Uncertainties in Offset Supply and Abatement Cost," 2012 (with Harrison Fell, Richard D. Morgenstern and Karen L. Palmer), *Land Economics* 88(3):589-611.

"Secular Trends, Environmental Regulations and Electricity Markets," 2012 (with Karen Palmer, Anthony Paul and Matt Woerman), *The Electricity Journal,* 25 (6): 35-47.

"Introduction to California's Cap-and-Trade Program", 2012 (with David McLaughlin and Sarah Jo Szambelan), *American Bar Association: Climate Change, Sustainable Development, and Ecosystems Committee Newsletter*, 15(3): 14-18.

"Tradable Standards for Clean Air Act Carbon Policy," 2012 (with Art Fraas and Nathan Richardson), *Environmental Law Reporter,* 42 (4):10338-10345.

"What Have We Learnt from the European Union's Emissions Trading System?" 2012 (with Markus Wråke, Åsa Löfgren and Lars Zetterberg), *Ambio,* 41 (Supplement 1):12-22.

"Short-Run Allocation of Emissions Allowances and Long-Term Goals for Climate Policy," 2012 (with Lars Zetterberg, Markus Wråke, Thomas Sterner and Carolyn Fischer), *Ambio*, 41 (Supplement 1):23-32.

"Social Safety Nets and US Climate Policy Costs," 2012 (with Joshua Blonz and Margaret Walls), *Climate Policy,* 12:1-17.

"Retail Electricity Price Savings from Compliance Flexibility in GHG Standards for Stationary Sources," 2012 (with Matt Woerman and Anthony Paul), *Energy Policy,* 42:67-77.

"Greenhouse Gas Regulation under the Clean Air Act: A Guide for Economists," 2011 (with Art Fraas and Nathan Richardson), *Review of Environmental Economics and Policy*, 5 (2) 293-313.

"Greenhouse Gas Regulation Under the Clean Air Act: Structure, Effects, and Implications of a Knowable Pathway," 2011 (with Nathan Richardson and Art Fraas), *Environmental Law Reporter* 41:10098-10120.

"Price Discovery in Emissions Permit Auctions," 2011, (with Jacob Goeree, Charles Holt, Erica Myers, Karen Palmer and William Shobe), in *Experiments on Energy, the Environment, and Sustainability,* ed: R. Mark Isaac and Douglas A. Norton, in Series: *Research in Experimental Economics,* 14: 11-36, Bingley, United Kingdom: Emerald Group Publishing Limited.

"How Do the Costs of Climate Cap and Trade Affect Households?," 2011, (with Josh Blonz and Margaret Walls), *Proceedings of the 103rd Annual Conference on Taxation,* Washington DC: National Tax Association.

"U.S. Emissions Trading Markets for SO2 and NOx," 2010, (with Sarah Jo Szambelan). In *Permit Trading in Different Applications*, Bernd Hansjürgens (ed.), New York: Routledge. See also RFF Discussion Paper 09-40.

"Climate Policy's Uncertain Outcomes for Households: The Role of Complex Allocation Schemes in Cap-and-Trade," 2010, *B. E. Journal of Economic Analysis and Policy*, (with Joshua Blonz and Margaret Walls), 10:2 (Article 5). Available at: http://www.bepress.com/bejeap/vol10/iss2/art5.

"A Symmetric Safety Valve," 2010, *Energy Policy,* (with Karen Palmer and Danny Kahn), 38(9): 4921-4932.

"An Experimental Study of Auctions versus Grandfathering to Assign Pollution Permits," 2010. *Journal of the European Economics Association*, (with Jacob Goeree, Charles Holt, Karen Palmer, William Shobe), 8(2-3):514-525.

"Distributional Impacts of Carbon Pricing Policies in the Electricity Sector," 2010. (with Margaret Walls and Joshua Blonz). In *U.S. Energy Tax Policy,* Gilbert E. Metcalf (ed.). Cambridge University Press.

"Opportunity Cost for Free Allocations of Emissions Permits: An Experimental Analysis," 2010. *Environmental and Resource Economics*, (with Markus Wråke, Erica Myers, Svante Mandell, Charles Holt) 46(3): 331-336.

"An Experimental Analysis of Auctioning Emissions Allowances under a Loose Cap," 2010. *Agriculture and Resource Economics Review*, (with William Shobe, Karen Palmer, Erica Myers, Charles Holt, Jacob Goeree), 39(2): 162-175.

"Compensation for Electricity Consumers Under a US CO_2 Emissions Cap," 2010, in *Reforming Rules and Regulations: Laws, Institutions and Implementation* (with Anthony Paul and Karen Palmer), Vivek Ghosal (ed.), Cambridge MA: MIT Press.

"Teaching Opportunity Cost in an Emissions Permit Experiment," 2010. (with Charles Holt, Erica Myers, Markus Wråke and Svante Mandell), *International Review of Economics Education*, 9(2):34-41.

"From Regions to Stacks: Spatial and Temporal Downscaling of Power Pollution Scenarios," 2010. *IEEE Transactions on Power Systems,*(with Benjamin F. Hobbs, Ming-Che Hu, Yihsu Chen, J. Hugh Ellis, Anthony Paul and Karen L. Palmer), 25 (2): 1179-1189.

"The Incidence of U.S. Climate Policy: Alternative Uses of Revenues from a Cap-and-Trade Auction," 2009. *National Tax Journal*, (with Richard Sweeney and Margaret Walls), LXII(3):497-518.

"Collusion in Auctions for Emissions Permits: An Experimental Analysis, 2009. *Journal of Public Policy Analysis and Management,* (with Jacob Goeree, Charles A Holt, Erica Myers, Karen Palmer and William Shobe), 28(4):672-691.

"Air Emissions of Ammonia and Methane from Livestock Operations: Valuation and Policy Options," 2008. *Journal of the Air and Waste Management Association,* (with Jhih-Shyang Shih, Karen Palmer and Juha Siikamaki) 58: 1117-1129.

"Compensation Rules for Climate Policy in the Electricity Sector," 2008. *Journal of Policy Analysis and Management,* (with Karen Palmer), 27 (4):819-847. See also Related RFF Future Discussion Paper 07-41.

"Tradable Permit Markets and Experimental Economics: Discussion," 2008, in *Environmental Economics, Experimental Methods,* Todd Cherry, Steven Kroll and Jason F. Shogren eds, New York: Routledge.

"Valuing Benefits from Ecosystem Improvements using Stated Preference Methods: An Example from Reducing Acidification in the Adirondacks Park," 2008. (with David A. Evans, H. Spencer Banzhaf, Alan J. Krupnick and Juha Siikamaki), in *Saving Biological Diversity,* Robert A. Askins, Glenn D. Dreyer, Gerald R. Visgilio, Diana M. Whitelaw eds., New York: Springer.

"Climate Change Primer: Cap and Trade," 2008, *Energy Law Journal,* (with Bill Westerfield, Brian McLean, Franz Litz and Jeff King). 29(1): 173-193.

"Tradable Rights to Emit Air Pollution" 2008, *Australian Journal of Agricultural and Resource Economics,* (with David Evans). 53:59-84. See also Related RFF Discussion Paper 08-08.

"Property Rights Created under a Federalist Approach to Tradable Emissions Policy," 2009, (with Richard Sweeney), in *Property Rights and Land Policies,* Ed: Gregory Ingram and Yu-Hung Hong, Cambridge: Lincoln Institute of Land Policy.

"Crafting a Fair and Equitable Climate Policy: A Closer Look at the Options," 2008, *Resources*, (with Richard Sweeney and Margaret A. Walls), 170 (Fall).

"Regulating CO_2 in Electricity Markets: Sources or Consumers?" 2008. *Climate Policy,* 8: 588–606. See Related RFF Discussion Paper 07-49.

"Auctions and Revenue Recycling Under Carbon Cap-and-Trade," 2008. *Resources,* 168 (Spring).

"Local Options on Global Stocks: How the States are affecting the U.S. Debate on Climate Policy," 2007, (with Bill Shobe) in *States and Climate Change,* Policy Research Institute for the Region at Princeton University, Conference Proceedings.

"Cap and Trade Policy to Achieve Greenhouse Gas Emission Targets," 2007, In *Growing the Economy Through Global Warming Solutions*, Newton, MA: Civil Society Institute.

"Economic and Energy Impacts from Participation in the Regional Greenhouse Gas Initiative: A Case Study of the State of Maryland," 2008 *Energy Policy* (with Matthias Ruth, Steven Gabriel, Karen Palmer, Anthony Paul, Yihsu Chen, Benjamin Hobbs, Daraius Irani, Jeffrey Michael, Kim Ross, Russell Conklin, Julia Miller), vol. 36: 2279-2289.

"Simple Rules for Targeting CO_2 Allowance Allocations to Compensate Firms," 2007, *Climate Policy,* (with Karen Palmer and Danny Kahn). 6:477-493. See also RFF Discussion Paper 06-27 (May).

"A Ten-Year Rule to Guide the Allocation of EU Emission Allowances," 2007, *Energy Policy,* (with Markus Åhman, Joseph Kruger, and Lars Zetterberg). 35 (3):1718-1730.

"Modeling Economy-wide vs. Sectoral Climate Policies Using Combined Aggregate-Sectoral Models," 2006, *The Energy Journal,* (with William Pizer, Winston Harrington, Richard Newell, and James Sanchirico). 27(3), 135-168. See also: RFF Discussion Paper 05-08 (April).

"The Benefits and Costs of Reducing Emissions from the Electricity Sector," 2007, *Journal of Environmental Management,* (with Karen Palmer and Jhih-Shyang Shih) 83:115-130.

"Valuation of Natural Resource Improvements in the Adirondacks," 2006, *Land Economics,* (with Spencer Banzhaf, David Evans, and Alan Krupnick). Vol. 82, No. 3, 445-464 (August). See also RFF Report, September 2004.

"CO_2 Allowance Allocation in the Regional Greenhouse Gas Initiative and the Effect on Electricity Investors," 2006, *The Electricity Journal,* (with Danny Kahn and Karen Palmer). 19 (2): 79-90 (March). See also RFF Discussion Paper 05-55.

"Forever Wild, But Do We Care? How New Yorkers Value Natural Resource Improvement," 2005, (H. Spencer Banzhaf, David Evans, and Alan J. Krupnick), *Resources* Issue 158.

"Cost-Effectiveness of Renewable Electricity Policies," 2005, *Energy Economics,* (with Karen Palmer). 27: 873-894. See also RFF Report 2004.

"The Environmental Impacts of Electricity Restructuring: Looking Back and Looking Forward," 2005, *Environment & Energy Law & Policy Journal,* (with Karen Palmer). 1(1): 171-219. See also RFF Discussion Paper 05-07.

"Economics of Pollution Trading for SO_2 and NO_x," 2005, *Annual Review of Environment and Resources*, (with David A. Evans, Alan Krupnick, Karen Palmer, and Russell Toth). Vol. 30, 352-290. See also RFF Discussion Paper 05-05 (January).

"A Carbon Tax to Reduce the Deficit," 2004, in *New Approaches on Energy and the Environment: Policy Advice for the President*, (with Paul R. Portney). Richard D. Morgenstern and Paul R. Portney, eds., RFF Press., Chapter 3

"Cleaning Up Power Plant Emissions," 2004, in *New Approaches on Energy and the Environment: Policy Advice for the President,* (with Karen L. Palmer). Richard D. Morgenstern and Paul R. Portney, eds., RFF Press., Chapter 8

"Efficient Emission Fees in the U.S. Electricity Sector," 2004, *Resource and Energy Economics,* (with Spencer Banzhaf and Karen Palmer). Vol. 26, No. 3 (September) 317-341. See also: RFF Discussion Paper 02-45.

Air Quality Management in the United States, National Research Council, 2004. Washington DC: The National Academies Press, (January). Significant writing and editing role.

"NO_x Emissions in the United States: A Potpourri of Policies," 2004, *Choosing Environmental Policy,* (with David A. Evans). W. Harrington, R. D. Morgenstern and T. Sterner (eds.) Washington DC: Resources for the Future.

"The SO_2 Cap-and-Trade Program in the United States: A "Living Legend" of Market Effectiveness," 2004, in *Choosing Environmental Policy.* (with Karen Palmer). W. Harrington, R. D. Morgenstern and T. Sterner (eds.) Washington DC: Resources for the Future.

"Emission Trading and Allowance Distribution," 2003, *Second Generation Issues Committee Newsletter,* American Bar Association, Vol. 3, No. 2.

"Economic Benefits of Controls," 2003, in *Acid Rain: Are the Problems Solved?* Ed: James C. White. Bethesda, MD: American Fisheries Society (February).

"Trading Cases: Is Trading Credits in Created Markets a Better Way to Reduce Pollution and Protect Natural Resources?" 2003, *Environmental Science and Technology*, (with James Boyd, Alan Krupnick, Virginia McConnell, Richard G. Newell, Karen Palmer, James N. Sanchirico and Margaret Walls). Vol. 37, No. 11 (June 1) pp. 216-223.

"Uncertainty and the Net Benefits of NO_X Emissions Reductions from Electricity Generation," 2003, *Land Economics,* (with Ranjit Bharvirkar and Meghan McGuinness). Vol. 79, No. 3, 382-401. See also: Resources for the Future Discussion Paper 02-01 (January).

"Ancillary Benefits of Reduced Air Pollution in the United States from Moderate Greenhouse Gas Mitigation Policies in the Electricity Sector," 2003, *Journal of Environmental Economics and Management,* (with Alan Krupnick, Karen Palmer, Anthony Paul, Mike Toman and Cary Bloyd). Vol. 45, No. 3 (May) 650-673. See also: Resources for the Future Discussion Paper 01-61 (December); replaces Resources for the Future Discussion Paper 99-51.

"Clean Air for Less: Exploiting Tradeoffs Between Different Air Pollutants," 2002, *Fordham Environmental Law Journal,* (with Randall Lutter). Vol. 13, 555-582. See also: AEI-Brookings Joint Center for Regulatory Studies, Regulatory Analysis 03-4 (March 2003).

"Capping Emissions: How Low Should We Go?" 2002, *Public Utilities Fortnightly,* (with Karen Palmer and Spencer Banzhaf). Vol. 140, No. 22 (December) pp. 28-36.

"Proposed Regulation of Multiple Pollutants in Electricity Sector is Historic: But Is It Sensible?" 2002, *Resources,* Vol. 148, (Summer) 2-5.

"Designing the Right Multi-Pollutant Plan," 2002, *The Environmental Forum*, Vol. 19, No. 3 (May/June) pp. 52-53.

"The Effect on Asset Values of the Allocation of Carbon Dioxide Emission Allowances," 2002, *The Electricity Journal,* (with Karen Palmer, Anthony Paul and Ranjit Bharvirkar). Vol. 15, No. 5, 51-62. See also: RFF Discussion Paper 02-15 (March).

"Three Pollutants and An Emission: A Playbill for the Multipollutant Legislative Debate," 2002, *Brookings Review,* Vol. 20, No. 2 (Spring) 14-17, 48.

"Cost-Effective Reduction of NO_X Emissions from Electricity Generation," 2001, *Journal of Air & Waste Management,* (with Karen Palmer, Ranjit Bharvirkar, and Anthony Paul). Vol. 51, 1476-1489. See also: Resources for the Future Discussion Paper 00–55 (December).

"Carbon Emission Trading Costs and Allowance Allocations: Evaluating the Options," 2001, *Resources*, Issue 145 (Fall) pp. 13-16.

"'Ancillary Benefits' of Greenhouse Gas Mitigation Policies," (with Michael A. Toman) 2001, in *Climate Change Economics and Policy,* ed: Michael A. Toman, Resources for the Future.

"Electricity Restructuring: Consequences and Opportunities for the Environment," 2001, *International Yearbook of Environmental and Resource Economics*, (with Karen Palmer and Martin Heintzelman). Volume V, pp. 40-89. H. Folmer and T. Tietenberg (eds.) Northampton, Mass: Edward Elgar. See also: Resources for the Future Discussion Paper 00-39 (September).

"SO_2 Control by Electric Utilities: What are the Gains from Trade?" 2000, *Journal of Political Economy,* (with Curtis Carlson, Maureen Cropper and Karen Palmer). Vol. 108, No. 6, 1292-1326. See also: Resources for the Future Discussion Paper 98-44-REV (July).

"The Ancillary Benefits and Costs of Climate Change Mitigation: A Conceptual Framework,") 2000, Ancillary *Benefits and Costs of Greenhouse Gas Mitigation,* (with Alan Krupnick and Anil Markandya). Organization for Economic Cooperation and Development, Conference Proceedings, March 27-29, Washington DC.

"Estimating the Ancillary Benefits of Greenhouse Gas Mitigation Policies in the US," 2000, *Ancillary Benefits and Costs of Greenhouse Gas Mitigation,* (with Michael A Toman). Organization for Economic Cooperation and Development, Conference Proceedings, March 27-29, Washington DC.

"Innovation Under the Tradable Sulfur Dioxide Emission Permits Programme in the U.S. Electricity Sector," 2000, *Innovation and the Environment,* Proceedings from OECD Workshop, June 19, 2000. See also: Resources for the Future Discussion Paper 00–38 (September).

"Appraisal of the SO2 Cap-and-Trade Market," 2000, in *Emissions Trading: Environmental Policy's New Approach*, (Richard F. Kosobud, ed.). New York: John Wiley & Sons.

"Renewables from Another Angle," 2000, *Electric Perspectives,* (with James McVeigh, Joel Darmstadter, and Karen Palmer). Vol. 25, No. 2, 10-20. See: "Winner, Loser, or Innocent Victim: Has Renewable Energy Performed As Expected?"

"Winner, Loser, or Innocent Victim: Has Renewable Energy Performed As Expected?" 2000, *Solar Energy,* (with James McVeigh, Joel Darmstadter, and Karen Palmer). Vol. 68, No. 3, 237-255. Published also as Renewable Energy Policy Project Research Report No. 7, and Resources for the Future Discussion Paper 99-28 (March 1999).

"Green Taxes and Administrative Costs: Comment." 2001, *Behavioral and Distributional Effects of Environmental Policy*, (eds: Carlo Carraro and Gilbert E. Metcalf). University of Chicago Press.

"The Environmental Effects of SO_2 Trading and Banking," 1999, *Environmental Science and Technology,* (with Erin Mansur). Vol. 33, No. 20, (October 15) pp. 3489-3494.

"The Cost-Effectiveness of Alternative Instruments For Environmental Protection in a Second-Best Setting," 1999, *Journal of Public Economics,* (with Lawrence H. Goulder, Ian W. H. Parry, and Roberton C. Williams III). Vol. 72, No. 3 (June) pp. 329-360.

"Cost Savings, Market Performance and Economic Benefits of the U.S. Acid Rain Program," 1999, in *Pollution for Sale: Emissions Trading and Joint Implementation,* Steve Sorrell and Jim Skea (eds.) Edward Elgar Publishing.

"Renewable Energy: Winner, Loser, or Innocent Victim?" 1999, (with Joel Darmstadter, Karen L. Palmer, and James McVeigh). *Resources* Issue 135.

"Measuring the Value of Health Improvements from Clean-up in the Great Lakes Region," 2001, in *Great Lakes Economic Valuation Guidebook,* (with Alan J. Krupnick). Allegra Cangelosi (ed.) National Oceanic and Atmospheric Administration and Northeast-Midwest Institute.

"Assessing the Impact of Electricity Restructuring on the Environment in Maryland," 1998, *EM,* (with Diane Brown, Matt Kahal, Dallas Burtraw, Julie Ross and Mark Garrison). (August).

"The Costs and Benefits of Reducing Air Pollutants Related to Acid Rain," 1998, *Contemporary Economic Policy,* (with Alan J. Krupnick, Erin Mansur, David Austin and Deirdre Farrell). Vol. 16 (October) pp. 379-400.

"Improving Efficiency in Bilateral Emission Trading," 1998, *Environmental and Resource Economics,* (with Ken Harrison and Paul Turner). Vol. 11, No. 1, pp. 19-33.

"Revenue-Raising vs. Other Approaches to Environmental Protection: The Critical Significance of Pre-Existing Tax Distortions," 1997, *RAND Journal of Economics*, (With Lawrence H. Goulder and Ian W. H. Parry). Vol. 28, No. 4, (Winter) pp. 708-731.

"The Social Costs of Electricity: Do the Numbers Add Up?" 1997, *Resources and Energy,* (with Alan J. Krupnick). Vol. 18, No. 4 (December) pp. 423-466.

"The Second-Best Use of Social Cost Estimates," 1997, *Resources and Energy,* (with Alan J. Krupnick). Vol. 18, No. 4 (December) pp. 467-490.

"SO_2 Allowance Trading: How Do Expectations and Experience Measure Up?" 1997, *The Electricity Journal,* (with Douglas R. Bohi). Vol. 10, No. 7 (August/September) pp. 67-75.

'Second-Best' Adjustments to Externality Estimates in Electricity Planning with Competition," 1997, *Land Economics*, (with Karen L. Palmer and Alan J. Krupnick). Vol. 73, No. 2, (May) pp. 224-239.

"Electricity Restructuring and Regional Air Pollution" 1997, *Resources and Energy*, (with Karen L. Palmer). Vol 19, Nos.1-2, (March) pp. 139-174.

"Evaluation of Sulfur Dioxide Emission Allowance Trading," 1997, in *Market Tools for Green Goals,* (with Douglas R. Bohi). Peter Alonzi and Richard F. Kosobud (eds.) Conference Proceedings, Sponsored by Chicago Board of Trade.

"Economic Benefits of Emissions Reductions," (with David Austin and Alan J. Krupnick) 1997, in *NAPAP's 1996 Integrated Assessment — Report to Congress*.

"Design and Performance of Pollution Trading Programs," (with Brian Kropp) 1997, in *NAPAP's 1996 Integrated Assessment — Report to Congress*.

"Experience with Allowance Trading: Performance to Date and Lessons for Regulatory Policy," (with Douglas R. Bohi) 1997, Proceedings of the Specialty Conference of the Air & Waste Management Association, *Acid Rain & Electric Utilities II,* January 21, 1997.

Tracking and Analysis Framework (TAF) Model Documentation and User's Guide, (with Cary Bloyd *et al.*) 1996, Published by Argonne National Laboratory, ANL/DIS/TM-36 (December).

A New Standard of Performance: An Analysis of the Clean Air Act's Acid Rain Program," 1996, *Environmental Law Reporter*, (with Byron Swift). 26 (8) (August) 10411-10423.

"The Acid Rain Success Story," 1996, *The Environmental Forum*, Vol. 13, No. 3 (May/June) pp. 31-32.

"The Environmental Effects of Restructuring" 1996, in *A Shock to the System: Restructuring America's Electricity Industry*, (with Alan J. Krupnick). Resources for the Future, Washington, DC

Review of: *Sustaining Coastal Resources: Economics and the Natural Sciences*, Charles S. Colgan, ed. (1995) in *Coastal Management* 24 (3) (July-September, 1996) pp. 271-276.

"Air Quality and Electricity" 1996, (with Alan J. Krupnick and Karen L. Palmer). *Resources* 123 (Spring) 6-8.

"The SO_2 Emissions Trading Program: Cost Savings Without Allowance Trades," 1996, *Contemporary Economic Policy,* Vol. XIV (April) pp. 79-94.

"Call It 'Pollution Rights,' But It Works," 1996, *The Washington Post*, March 31.

"Trading Emissions to Clean the Air: Exchanges Few but Savings Many," 1996, *Resources* 122 (Winter) 3-6. Reprinted with revisions in: *UK CEED Bulletin,* UK Centre for Economic and Environmental Development, No. 48 (Autumn, 1996) pp. 24-26.

"Optimal Adders for Environmental Damage by Public Utilities" (with Winston Harrington, A. Myrick Freeman III, and Alan J. Krupnick) *Journal of Environmental Economics and Management,* Vol. 29, No. 2, S1-S19, 1995.

Estimating Externalities of Electricity Fuel Cycles (with Alan J. Krupnick, Russell Lee, et al.; Oak Ridge National Laboratories/Resources for the Future) 1994-1996, seven volumes, McGraw-Hill/Utility Data Institute, Washington, DC.

"Agency in International Permit Trading," 1994, in F. Førsund and G. Klaassen, eds., *Economic Instruments For Air Pollution Control,* Kluwer Academic Publishers.

"Tradable Sulfur Dioxide Emission Permits and European Economic Integration," in Michael A. Toman, ed., *Pollution Abatement Strategies in Central and Eastern Europe*, Resources for the Future, Washington, DC, 1994, pp. 49-59.

"Economic Conservation," in R. Eblen and W. Eblen, eds., *The Encyclopedia of the Environment*, Houghton Mifflin Company, Boston, MA, 1994.

"The Social Costing Debate: Issues and Resolutions" (with Alan J. Krupnick, A. Myrick Freeman III, and Winston Harrington) in O. Hohmeyer and R. Ottinger, eds., *Social Costs of Energy*, Springer-Verlag, Berlin, 1994.

"Bargaining with Noisy Delegation," *RAND Journal of Economics*, Vol. 24, No. 2 (Spring 1993) pp. 40-57.

"Weighing Environmental Externalities: How to Do It Right" (with A Myrick Freeman III, Winston Harrington and Alan J. Krupnick) *The Electricity Journal*, August/September 1992, pp. 22-29.

"Equity and International Agreements For CO_2 Containment" (with Michael A. Toman) *Journal of Energy Engineering*, Vol. 118, No. 2 (August 1992) pp. 122-135.

"The Social Costs of Electricity: How Much of The Camel To Let Into the Tent?" (with Alan J. Krupnick) *Regulatory Responses to Continuously Changing Industry Structures*, Proceedings of The Institute of Public Utilities Twenty-Third Annual Conference, Charles G. Stalon, ed., East Lansing, Mich., Institute of Public Utilities, Michigan State University, 1992. Also presented at the 85th Annual Meeting and Exhibition of the Air and Waste Management Association, Kansas City, KS, June 21-26, 1992, 92-135.03. (Resources for the Future Discussion Paper QE92-15, April 1992.)

"Utility Investment Behavior and the Emission Trading Market" (with Douglas R. Bohi) *Resources and Energy*, Vol. 14, Nos. 1/2 (April 1992) pp. 129-156.

"Strategic Delegation in Bargaining," *Economic Letters*, Vol. 38, No. 2 (February 1992) pp. 181-185.

"The Social Costs of Electricity" (with Alan J. Krupnick) *Public Power*, Vol. 50, No. 3 (May-June 1992) p. 56.

"Avoiding Regulatory Gridlock in the Acid Rain Program" (with Douglas R. Bohi) *Journal of Policy Analysis and Management*, Vol. 10, No. 4 (Fall 1991) pp. 676-684.

"Compensating Losers When Cost-Effective Environmental Policies Are Adopted," *Resources*, No. 104 (Summer 1991) Resources for the Future, Washington, DC, pp. 1-5.

"Resolving Equity Issues in Greenhouse Gas Negotiations" (with Michael A. Toman) *Resources*, No. 103 (Spring 1991) Resources for the Future, Washington, DC, pp. 10-13.

"Compensation Issues for Incentive-Based Regulation" (with Paul R. Portney) in Robert N. Stavins, ed., *Project 88-Round II - Incentives for Action: Implementing Market-Based Environmental Policies*, May 1991.

"Environmental Policy In The United States" (with Paul R. Portney) in Dieter Helm, ed., *Economic Policy Towards the Environment*, Oxford, Eng., Blackwell Publishers, 1991.

"Regulatory Aspects of Emissions Trading: Conflicts Between Economic and Environmental Goals" (with Douglas R. Bohi) *The Electricity Journal*, December 1990, pp. 47-55.

"Emissions Trading in the Electric Utility Industry" (with Douglas R. Bohi and Alan J. Krupnick) *Resources*, No. 100 (Summer 1990) Resources for the Future, Washington, DC, pp. 10-13.

"Evaluation of Inclusionary Housing Programs: Four Case Studies" (with S. Schwartz and R. Johnston) *Public Affairs Report*, Vol. 23, No. 3 (June 1982) Institute of Governmental Studies, University of California, Berkeley.

TESTIMONY and *COMMENT*

Comments to US EPA on the Proposed Affordable Clean Energy Rule. Krupnick, A. J., et al., Resources for the Future, October 31, 2018.

Testimony before the California Senate Select Committee on the Environment, the Economy and Climate Change, "Update on the Implementation of AB 32: Cap and Trade in Focus," March 27, 2012.

Testimony before the California Senate Select Committee on Climate Change and AB 32 Implementation, "*Greenhouse Gas Emissions Cap-and-Trade,"* January 7, 2010.

Testimony before the U.S. Senate Committee on Finance, "Climate Change Legislation: Allowance and Revenue Distribution," August 4, 2009.

Testimony before the U.S. House of Representatives Committee on Ways and Means, "Addressing Price Volatility in Climate Change Legislation," March 26, 2009.

Testimony before the U.S. House of Representatives Committee on Ways and Means Subcommittee on Income Security and Family Support, "Protecting Lower Income Families While Fighting Global Warming, March 12, 2009.

Testimony before the U.S. House of Representatives Committee on Ways and Means, "Preventing Climate Change: Second in a Series of Hearings, September 18, 2008.

Testimony before the U.S. House of Representatives Select Committee on Energy Independence and Global Warming, "Cap, Auction, and Trade: Auctions and Revenue Recycling under Carbon Cap and Trade," January 23, 2008.

Testimony before the U.S. House of Representatives Committee on Energy and Commerce Subcommittee on Energy and Air Quality, "Climate Change: Lessons Learned from Existing Cap and Trade Programs," March 29, 2007.

Testimony before the Senate Energy and Water Development Appropriations Subcommittee on "The Performance of Renewables," September 14, 1999.

BOOK REVIEWS and *LETTERS*

Burtraw, Dallas. 2016. To Lead on Climate, California Needs Its Whole Arsenal. *The Sacramento Bee*, op-ed. Dallas Burtraw, July 3.

Burtraw, Dallas. 2016. Forget Cap and Trade's Detractors, California's Carbon-Pricing Works. *Los Angeles Times*, June 23.

"Overcoming Political Barriers," (commentary), *The Environmental Forum* 28(2): 27, March/April 2011.

Review of: *The Economics of Energy Efficiency,* Steve Sorrell et al. (2004) in *Journal of Economics Literature,* 2006, 44(1): 190-191 (March).

Review of: *Markets for Clean Air,* A. Denny Ellerman et al. (2000) in *Regional Science and Urban Economics,* 2001. Vol. 32, Issue 1 (January) pp. 139-144.

Review of: *Acid Rain and Environmental Degradation,* Ger Klaassen (1996) in *Journal of Economic Literature,* 1998.

"A Poor Measure of Success: Reply," (with Douglas R. Bohi) Letter to the Editor, *The Electricity Journal,* 1997 (Vol. 10, No. 9) reply to Elizabeth M. Bailey, pp. 6-7.

Review of: *Sustaining Coastal Resources: Economics and the Natural Sciences*, Charles S. Colgan, ed. (1995) in *Coastal Management* 24 (3) (July-September, 1996) pp. 271-276.

"Rumors of the Demise of RECLAIM 'Greatly Exaggerated'," (with Alan J. Krupnick) Letter to the Editor, *Regulation,* 1994 (No. 4); Comment on "Pollution Trading in La La Land," by James L. Johnston, 1994 (No. 3).

REPORTS

Five Myths About an EU ETS Carbon Price Floor 2018(with Christian Flachlsand, Michael Pahle, Ottmar Edenhoffer, Milan Elkerbout, Carolyn Fischer, Oliver Tietjen and Lars Zetterberg), Brussels: Center for European Policy Studies.w

Does Integrated Resources Planning Effectively Integrate Demand-Side Resources? 2018 (with Jake Duncan), RFF Report.

Companion Policies under Capped Systems and Implications for Efficiency – The North American Experience and Lessons in the EU Context, 2018 (Dallas Burtraw, Amelia Keyes, Lars Zetterberg), RFF Report.

Expanding the Toolkit: The Potential Role for an Emissions Containment Reserve in RGGI, 2017, (Dallas Burtraw, Charles Holt, Karen Palmer, Anthony Paul, and William Shobe), RFF Report in support of the Regional Greenhouse Gas Initiative.

What Stands in the Way Becomes the Way: Sequencing in Climate Policy to Ratchet Up Stringency Over Time, 2017, (Michael Pahle, Dallas Burtraw, Christian Flachsland, Nina Kelsey, Eric Biber, Jonas Meckling, Ottmar Edenhofer, John Zysman), RFF Report.

Transportation Electrification Policy in California and Germany, 2016. (with Joanna Gubman, Michael Pahle, and Karoline Steinbacher), Potsdam Institute for Climate Impact Research (PIK) Report.

Europe's Choice – Facts and Function of the EU Emissions Trading System, 2014 (with Lars Zetterberg, Daniel Engström Stenson, Carl Paulie and Susanna Roth), Mistra Indigo Report.

For the Benefit of California Electricity Ratepayers, 2012 (with Sarah Jo Szambelan), Next10 Report. See also RFF Discussion Paper 12-24.

A Primer on the Use of Allowance Value Created under California's CO2 Cap-and-Trade Program, 2012 (with Sarah Jo Szambelan), Next10 Report. See also RFF Discussion Paper 12-23.

Summary for Policymakers The True Cost of Electric Power: An Inventory of Methodologies to Support Future Decisionmaking in Comparing the Cost and Competitiveness of Electric Generation Technologies, 2012, (with Alan Krupnick), Ren21.

The True Cost of Electric Power: An Inventory of Methodologies to Support Future Decisionmaking in Comparing the Cost and Competitiveness of Electric Generation Technologies, 2012, (with Alan Krupnick and Gabriel Sampson), Resources for the Future Report.

US Climate Change Policy Efforts, Center for European Policy Studies, Policy Brief No. 255, September 2011.

Allocating Emissions Allowances under California's Cap-and-Trade Program: Recommendations to the California Air Resources Board, 2010, Recommendations of the Economic and Allocation Advisory Committee to the California Air Resources Board, (March), Contributing Author.

Haiku Documentation: RFF's Electricity Market Model version 2.0, 2009. (with Anthony Paul and Karen L. Palmer), RFF Report, (January).

"Managing Cost Variability in Emission Allowance Markets," 2008, (with Karen Palmer and Markus Wråke), Stockholm: Elforsk report 08:56.

"Options to Alleviate the Impact of Greenhouse Gas Control Policies on Low-Income Households," (with James Neumann, Jason Price, Richard Sweeney and Margaret Walls) 2008, Industrial Economics Inc. (August).

Auction Design for Selling CO_2 Emission Allowances under the Regional Greenhouse Gas Initiative – Addendum, 2008, (with Charles Holt, William Shobe, Karen L. Palmer, Jacob Goeree, and Erica Myers), Resources for the Future Report (April).

Auction Design for Selling CO_2 Emission Allowances under the Regional Greenhouse Gas Initiative, 2007, *(with* Jacob Goeree, Charles Holt, Karen L. Palmer, and William Shobe), Resources for the Future Report, (October); Report to the New York State Energy Research and Development Authority.

Assessing U.S. Climate Policy Options, 2007, (with Raymond J. Kopp, William A. Pizer, Daniel Hall, Richard D. Morgenstern, Juha V. Siikamäki, Joseph E. Aldy, Ian W.H. Parry, Karen L. Palmer, Mun Ho, Evan M Herrnstadt, and Joseph Maher). Resources for the Future Report (November).

Recommendations for Designing a Greenhouse Gas Cap-and-Trade System for California, 2007, Recommendations of the Market Advisory Committee to the California Air Resources Board, (June 20), Contributing Author.

Not a Sure Thing: Making Regulatory Choices Under Uncertainty, 2006, (with Alan Krupnick, Richard Morgenstern, Michael Batz, Peter Nelson, Jhih-Shyang Shih, and Michael McWilliams). Resources for the Future Report (February).

"Recommendations for the Design of Modeling and Analysis of the Electricity Sector to Guide Options for Climate Policy in California," 2006, in *Managing Greenhouse Gas Emissions In California,* (Chapter 9 with Matthias Fripp, Steve Moss and Richard McCann). W. Michael Hanemann and Alexander E. Farrell, eds. U.C. Berkeley: The California Climate Change Center (January).

"Lessons for a cap-and-trade program," 2006, in *Managing Greenhouse Gas Emissions In California,* (Chapter 5, with Alexander E. Farrell, Lawrence H. Goulder and Carla Peterman). W. Michael Hanemann and Alexander E. Farrell, eds. U.C. Berkeley: The California Climate Change Center (January).

"Summary Communication: Reducing Emissions from the Electricity Sector: The Costs and Benefits Nationwide and in the Empire State," 2005, (with Karen Palmer and Jhih-Shyang Shih). New York State Energy Research and Development Authority (October).

"A Comparison of the Effects of the Distribution of Emission Allowances for Sulfur Dioxide, Nitrogen Oxides and Carbon Dioxide," 2003, (with Karen Palmer). Research Report to the EPA National Center for Environmental Research (May 2).

"NO_x Emissions Trading and Episodic Air Quality Violations In Maryland," 2003, (with Ranjit Bharvirkar and Alan J. Krupnick). Final Report Prepared for the Power Plant Research Program, State of Maryland (May).

"The RFF Haiku Electricity Market Model," 2002, (with Anthony Paul) .RFF Report (May 22).

"Electricity Restructuring, Environmental Policy and Emissions: Insights from a Policy Analysis," 2002, (with Karen Palmer, Anthony Paul and Ranjit Bharvirkar). Annapolis: Maryland Department of Natural Resources, Power Plant Research Program. Also see RFF Reports, December 2002.

Valuation of Natural Resource Improvements in the Adirondacks, 2004, (with Spencer Banzhaf, David Evans, and Alan Krupnick). RFF Report (September).

"Electricity, Renewables and Climate Change: Searching for an Efficient Policy," 2004, (with Karen Palmer). RFF Report.

"Regional Impacts of Electricity Restructuring on Emissions of NO_x and CO_2," 2000, (with Karen Palmer and Anthony Paul). Annapolis: Maryland Department of Natural Resources, Power Plant Research Program, PPRP-123 (June).

WORKING PAPERS

"Carbon Standards Examined: A Comparison of At-the-Source and Beyond-the-Source Power Plant Carbon Standards," 2018. (with Amelia T. Keyes, Kathleen F. Lambert, Jonathan J. Buonocore, Jonathan I. Levy, and Charles T. Driscoll). RFF Working Paper 18-20.

"Quantities with Prices," 2018. (with Charles Holt, Karen Palmer, Anthony Paul, and William Shobe). RFF Working Paper 18-08.

"An Economic Assessment of the Supreme Court's Stay of the Clean Power Plan and Implications for the Future," 2016 (Joshua Linn, Dallas Burtraw and Kristen McCormack), Washington DC: RFF Discussion Paper 16-21.

"Consignment Auctions of Free Emissions Allowances under EPA's Clean Power Plan," 2016 (Dallas Burtraw and Kristen McCormack), Washington DC: RFF Discussion Paper 16-20.

"A Microsimulation Model of the Distributional Impacts of Climate Policies," 2015 (with Hal G. Gordon and Roberton C. Williams III), Resources for the Future Discussion Paper 14-40.

"Linking by Degrees: Incremental Alignment of Cap-and-Trade Markets," 2013 (with Karen Palmer, Clayton Munnings, Paige Weber and Matt Woerman). RFF Discussion Paper 13-04.

"Technology Flexibility and Stringency for Greenhouse Gas Regulations," 2013 (with Matt Woerman). RFF Discussion Paper 13-24.

"Flexible Mandates for Investment in New Technology," 2012 (with Dalia Patino Echeverri and Karen L. Palmer), RFF Discussion Paper 12-14.

"Regulating Greenhouse Gases from Coal Power Plants under the Clean Air Act," 2012 (with Joshua Linn and Erin Mastrangelo), RFF Discussion Paper 11-43.

Rethinking Environmental Federalism in a Warming World," 2012 (with William M. Shobe), RFF Discussion Paper 12-04.

"Retail Electricity Price Savings from Compliance Flexibility in GHG Standards for Stationary Sources," 2011 (with Anthony Paul and Matt Woerman), RFF Discussion Paper 11-30.

"Prevailing Academic View on Compliance Flexibility under Section 111 of the Clean Air Act," 2011 (with Gregory E. Wannier , Jason A. Schwartz , Nathan Richardson, Michael A. Livermore, Michael B. Gerrard), RFF Discussion Paper 11-29.

"Options for Returning the Value of CO_2 Emissions Allowances to Households," 2011 (with Ian W. H. Parry), RFF Discussion Paper 11-03.

"How Do the Costs of Climate Policy Affect Households? The Distribution of Impacts by Age, Income, and Region," 2010 (with Joshua Blonz and Margaret A. Walls), RFF Discussion Paper 10-55.

"Greenhouse Gas Regulation under the Clean Air Act," 2010 (with Nathan Richardson and Art Fraas), RFF Discussion Paper 10-23.

"State and Local Climate Policy under a National Emissions Floor," 2009 (with William Shobe), RFF Discussion Paper 09-54.

"U.S. Emissions Trading Markets for SO_2 and NO_x" 2009 (with Sarah Jo F Szambelan), RFF Discussion Paper 09-40 (October).

"Allowance Allocation in a CO_2 Emissions Cap-and-Trade Program for the Electricity Sector in California," 2009 (with Karen L. Palmer and Anthony Paul), RFF Discussion Paper 09-41 (October).

"Pricing Strategies under Emissions Trading: An Experimental Analysis," 2008, (with Markus Wråke, Erica Myers, Svante Mandell and Charles Holt), RFF Discussion Paper 08-49 (December).

"The Incidence of U.S. Climate Policy: Where You Stand Depends on Where You Sit," 2008, (with Richard Sweeney and Margaret A. Walls), RFF Discussion Paper 08-28 (September).

"Free Allocation to Electricity Consumers Under a US CO_2 Emissions Cap," 2008, (with Anthony Paul and Karen Palmer), RFF Discussion Paper 08-25 (July).

"An Update on the Science of Acidification in the Adirondack Park," 2008, (with Anna Mische John, David A. Evans, H. Spencer Banzhaf, Alan J. Krupnick, and Juha V. Siikamäki), RFF Discussion Paper 08-11 (May).

"The Architecture of Emission Allowance Markets and Incentives for Investment in Electricity," 2007, (with Karen Palmer, Dallas Burtraw). Incentives to Build New Generation on Competitive Electricity Markets: Market Design Elforsk. See www.marketdesign.se.

"U.S. Climate Policy Developments," 2007, *Resources,* (with Toshi Arimura, Alan J. Krupnick and Karen L. Palmer), Resources for the Future Discussion Paper 07-45 (October).

"Dynamic Adjustments to Incentive Regulation to Improve Efficiency and Performance," 2007. (with Karen Palmer and Danny Kahn). Resources for the Future Discussion Paper; Presented at Market Mechanisms and Incentives: Applications to Environmental Policy | EPA | Washington DC | October 17, 2006

"U.S. Climate Policies", 2007, (with Toshi Arimura, Karen Palmer, and Alan Krupnick), Mizuho Bank Group for METI, Japan (March 15).

Economic and Energy Impacts from Maryland's Potential Participation in the Regional Greenhouse Gas Initiative, 2007, (with Anthony Paul, Mathius Ruth, Steve Gabriel, Kim Ross, Ben Hobbs, Yihsu Chen, Daraius Irani, Jeffrey Michael). Maryland Department of Environment (January 31).

"Simple Rules for Targeting CO_2 Allowance Allocations to Compensate Firms," 2006 (with Karen Palmer and Danny Kahn). RFF Discussion Paper 06-28 (May).

"Summary of the Workshop to Support Implementing the Minimum 25% Public Benefit Allocation in the Regional Greenhouse Gas Initiative," 2006 (with Karen L. Palmer), Resources for the Future Discussion Ppaer 06-45 (September).

"Valuation of Air Emissions from Livestock Operations and Options for Policy" 2006, (with Shih, Jhih-Shyang, Karen Palmer and Juha Siikamaki). Proceedings of Workshop on Agricultural Air Quality: State of the Science, June 5-8. Potomac, Maryland. Ed. Viney P. Aneja, William H. Schlesinger, Raymond Knighton, Greg Jennings, Dev Niyogi, Wendell Gilliam, and Clifford S. Duke. Raleigh: North Carolina State University.

"Air Emissions of Ammonia and Methane from Livestock Operations: Valuation and Policy Options," 2006, (with Karen Palmer, Jhih-Shyang Shih, Juha Siikamäki). Proceedings, *Workshop on Agricultural Air Quality,* Ecological Society, Washington DC (June 8). RFF Discussion Paper 06-11.

"The Impact of Long-Term Generation Contracts on Valuation of Electricity Generating Assets Under the Regional Greenhouse Gas Initiative" 2005, (with Nathan Wilson and Karen Palmer). RFF Discussion Paper 05–37 (August).

"Allocation of CO_2 Emission Allowances in the Regional Greenhouse Gas Cap-and-Trade Program," 2005, (with Karen Palmer and Danny Kahn). RFF Discussion Paper 05-25 (June).

"Economics of Pollution Trading for SO_2 and NOx," 2005, (with David A. Evans, Alan J. Krupnick, Karen L. Palmer, and Russell Toth). RFF Discussion Paper 05-05 (March).

"Reducing Emissions from the Electricity Sector: The Costs and Benefits Nationwide and in the Empire State," 2005, (with Karen Palmer and Jhih-Shyang Shih). RFF Discussion Paper 05-23 (May). Also published by the New York State Energy Research and Development Authority, Report 05-02.

"Economic Efficiency and Distributional Consequences of Different Approaches to NO_x and SO_2 Allowance Allocation," 2003, (with Karen Palmer) Prepared for the U.S. Environmental Protection Agency (October 2). http://www.epa.gov/air/clearskies/econ.html (accessed December 2, 2003).

"The Paparazzi Take a Look at a Living Legend: The SO2 Cap-and-Trade Program for Power Plants in the United States," 2003, (with Karen L. Palmer). RFF Discussion Paper 03-15, (April).

"The Evolution of NOx Control Policy for Coal-Fired Power Plants in the United States," 2003, (with David A. Evans). RFF Discussion Paper 03-23, (December).

"The Distributional Impacts of Carbon Mitigation Policies," 2002, (with Richard D. Morgenstern, Lawrence H. Goulder, Mun Ho, Karen L. Palmer, William A. Pizer, James N. Sanchirico, and Jhih-Shyang Shih). Resources for the Future Issue Brief 02-03 (March).

"Investment in Electricity Transmission and Ancillary Environmental Benefits," 2002, (with Cary Bloyd and Ranjit Bharvirkar). Discussion Paper 02-14 (March) Resources for the Future. Also see: conference proceedings, *5th Electric Utilities Environmental Conference*, Tucson, AZ, January 22-25, 2002.

"The Effect of Allowance Allocation on the Cost of Carbon Emission Trading," 2001, (with Karen Palmer, Ranjit Bharvirkar and Anthony Paul). Resources for the Future Discussion Paper 01-30 (August).

"Restructuring and the Cost of Reducing NOx Emissions in Electricity Generation," 2001, (with Karen Palmer, Ranjit Bharvirkar, and Anthony Paul). Resources for the Future Discussion Paper 01–10REV (July).

"Workshop Report: Pollution Abatement Costs and Expenditures (PACE) Survey Design for 2000 and Beyond," 2001, (with Alan Krupnick, Richard Morgenstern, William Pizer, and Jhih-Shyang Shih). Resources for the Future Discussion Paper 01–09 (March).

"The 'Ancillary Benefits' of Greenhouse Gas Mitigation Policies," 2000, (with Michael A. Toman), Resources for the Future Climate Issue Brief #7 (August)

"Summary of the Science of Acidification in the Adirondack Park," 2000, (with Alan J. Krupnick, Joe Cook, Anthony Paul, and Terrell Stoessell).

"Heterogeneity in Costs and Second-Best Policies for Environmental Protection," 2000, (with Matt Cannon). Prepared for presentation at the Association of Agricultural and Resource Economists *Workshop on Market-Based Instruments for Environmental Protection,* Kennedy School of Government, 18-20 July 1999. Resources for the Future Discussion Paper 00–20 (April).

"RAINS-ASIA: A Critique and Guide to Future Research," 1999, (with Alan J. Krupnick). Technical Paper, Resources for the Future (November 3).

"Measuring the Value of Health Improvements from Great Lakes Cleanup," 1999, (with Alan J. Krupnick), RFF Discussion Paper 99-34 (April).

"The Opportunity for Short Run Carbon Mitigation in the Electricity Sector," 1999, (with Karen Palmer and Anthony Paul). Presented at the Air & Waste Management Association Conference in Tucson, AZ in January.

"Lessons from the Integrated Assessment of Acid Deposition for Assessing Greenhouse Gas Emissions and Climate Change," 1999, (with Cary N. Bloyd and Richard Sonnenblick). Presented at the Air & Waste Management Association Conference in Tucson, AZ in January.

"State-Level Policies and Regulatory Guidance for Compliance in the Early Years of the SO2 Emission Allowance Trading Program," 1998, (with Ron Lile). RFF Discussion Paper 98-35, (May).

"The Benefits of Air Pollutant Emissions Reductions in Maryland: Results from the Maryland Externalities Screening and Valuation Model," 1998, (with David Austin, Alan Krupnick, and Terrell Stoessell). Resources for the Future Discussion Paper 99-05 (October).

"Assessing the Impact of Electricity Restructuring on the Environment in Maryland," 1998, (with Diane Brown, Matthew Kahal, Karen Palmer, Julie Ross and Mark Garrison). Presented at the Air & Waste Management Association Conference in San Diego, CA in June, (98-MP21.02(A483)).

"The Benefits of Reduced Air Pollutants in the U.S. from Greenhouse Gas Mitigation Policies," 1997, (with Michael A. Toman). Resources for the Future Discussion Paper 98-01REV.

"An Assessment of the EPA's SO_2 Emission Allowance Tracking System," 1996, (with Ronald D. Lile and Douglas R. Bohi). Resources for the Future Discussion Paper 97-21, (November).

"The Ancillary Benefits of Avoiding Climate Change" 1996, (with several co-authors). *Conference Proceedings*, Climate Change Analysis Workshop, U.S. Environmental Protection Agency, Washington, DC, June 6.

"The *Water Resource Evaluation Framework:* A Software Tool for Collaboration Among Stakeholders in Hydroelectric Facility Relicensing," 1996, (with Ken Frederick and Kris Wernstedt). Prepared for the Electric Power Research Institute (January).

"The Fiscal Effects of Electricity Generation Technology Choice: A Full Fuel Cycle Analysis" (with Pallavi R. Shah) Resources for the Future Discussion Paper 95-16, Washington, DC (March).

"The Social Benefits of Social Costing Research" 1995, (with Alan Krupnick and Karen Palmer). Resources for the Future, mimeo, Prepared for the European Commission, International Energy Agency and Organization for Economic Cooperation and Development Workshop on *The External Costs of Energy*, Brussels (January 30-31).

"Recommendations to NAPAP Regarding SO_2 Emission Projections" 1994, (with Douglas R. Bohi and John Reid) Resources for the Future, mimeo (June 15).

"Cost-Benefit Analysis and International Environmental Policy Decision Making: Problems of Income Disparity" 1994, (with Raymond J. Kopp). Discussion Paper 94-15, Resources for the Future, Washington, DC (February).

"'Easy-Riding' in Community Provision of Nonexcludable Public Goods" 1993, (with Winston Harrington and Carter Hood) Discussion Paper QE93-25, Resources for the Future, Washington, DC (September).

"The Promise and Prospect for SO_2 Emissions Trading in Europe," 1993, Discussion Paper QE93-22, Resources for the Future, Washington, DC (September).

"Bridging the Gap Between State and Federal Social Costing" 1993, (with Alan J. Krupnick). Discussion Paper QE93-19, Resources for the Future, Washington, DC (September).

"Compensation Principles for the Idaho Drawdown Plan" 1993, (with Kenneth D. Frederick) Discussion Paper ENR93-17, Resources for the Future, Washington, DC.

"Accounting for Environmental Costs in Electric Utility Resource Supply Planning" 1992, (with A. Myrick Freeman III, Winston Harrington, and Alan J. Krupnick) Discussion Paper QE92-14, Resources for the Future, Washington, DC, (April).

“Implementing Market-Based Environmental Policies: The Role of Compensation,” 1991, (with Paul R. Portney). *Project 88/Round II Series: Designing Market-Based Strategies for Environmental Protection* (April).

"The Incentive Contract for Strategic Delegation in Bargaining," 1990, Discussion Paper QE90-18, Resources for the Future, Washington, DC, (May).

"Emissions Trading in the Electric Utility Industry" 1990, (with Douglas R. Bohi, Alan J. Krupnick, and Charles G. Stalon). Discussion Paper QE90-15, Resources for the Future, Washington, DC, (March).

"Local Government Initiatives for Affordable Housing" 1981, (with S. Schwartz and R. Johnston) Institute of Governmental Affairs, University of California, Davis, EQS No. 35, (December).

AWARDS

The Northeastern Agricultural and Resource Economics Association Award for Outstanding Public Service through Economics, 2017.

The Ralph C. d’Arge and Allen V. Kneese Award for Outstanding Publication in the *Journal of the Association of Environmental and Resource Economists,* 2014.

MacArthur Scholar, University of Michigan Program in International Peace and Security Studies, 1985-1989.

Institute of Public Policy Studies Fellowship, 1983-1984.

OTHER SERVICE

Chair, California Independent Emissions Market Advisory Committee, 2018-

Treasurer, Association of Environmental and Resource Economists, 2014-2018.

Member, Princeton Carbon Mitigation Initiative Advisory Council, 2010-2016.

Member, Bard Center for Environmental Policy Advisory Committee, 2010-2013.

Member, National Academy of Sciences, Board on Environmental Studies and Toxicology, 2005-2011.

Member, Environmental Protection Agency Advisory Council on Clean Air Compliance Analysis, 2004-2010.

Member, State of California Economic and Allocation Advisory Committee, 2009-2010.

Member, State of California Market Advisory Committee for Greenhouse Gas Policy, 2006-2007.

Member, Environmental Protection Agency Science Advisory Board Second Generation Model Advisory Panel, 2004-2005.

Member, Environmental Protection Agency, Scientific Advisory Board, Environmental Economics Advisory Committee, 1998-2004.

Member, Environmental Protection Agency, Scientific Advisory Board, Committee on Illegal Competitive Advantage, 2004.

Member, National Research Council, Committee on Air Quality Management in the United States, 2001-2004.

Reviewer, National Energy Modeling System, Energy Information Administration, 1992-1999.

Reviewer of proposals for Environmental Protection Agency, National Science Foundation, Department of Energy.

Member, Environmental Protection Agency, Effluent Guidelines Task Force, 1996-1998.

Member, National Oceanic and Atmospheric Administration Blue Ribbon Panel on Valuation of Environmental Benefits in the Great Lakes Region, 1997-1998.

Member, Environmental Protection Agency, Scientific Advisory Board, Mercury Subcommittee, 1997.

Member, Management Board, New York State Environmental Externality Cost Study, 1993-1995.

Reviewer for:
American Economic Review
Climatic Change
Climate Policy
Ecological Economics
Economica
Energy Policy
Environmental and Resource Economics
The Electricity Journal
The Energy Journal
Journal of the Association of Environmental and Resource Economists
Journal of Economic Literature
Journal of Environmental Economics and Management
Journal of Environmental Planning and Management
Journal of Law and Economics
Journal of Operations Research
Policy Analysis and Management
Journal of Public Economics
Journal of Public Economic Theory

Journal of Industrial Economics
Journal of Regulatory Economics
Land Economics
Resource and Energy Economics
and various state, federal and international research agencies.

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Education

1989-1993 **University of California at Berkeley**
Ph. D. Industrial Engineering and Operations Research, December 1993
M.S. Operations Research, May 1990

1984-1989 **University of Wisconsin - Madison**
B.S. Economics and Industrial Engineering (Double Major), May 1989

Research Interests

- Industrial Organization and Regulation
- Energy Economics and Policy
- Environmental Economics

Academic Appointments

2011-present **University of California, Davis (Davis, CA)**
Associate Professor, Dept. of Economics, 2011-2015
Professor, Dept. of Economics, 2015-

2009-2011 **Iowa State University (Ames, IA)**
Associate Professor, Dept. of Economics, 2009 -
Cargill Chair in Energy Economics

Director, Biobased Industry Center, 2009 -

1993-2009 **University of California Energy Institute (Berkeley, CA)**
Assistant Research Scientist, 1993-1998
Associate Research Scientist, 1999-2002
Research Scientist, 2003-
Director of Research, 1998 -

Other Professional and Public Appointments

2007 - **National Bureau of Economic Research**
Faculty Research Fellow (2007-2009), *Research Associate* (2009-Present)

2013 **Victoria University (Wellington, New Zealand)**
S.T. Lee Fellow in Competition and Regulation.

2002 - **California Independent System Operator (Folsom, CA)**
Member, Market Surveillance Committee

1999- 2001 **California Power Exchange (Pasadena, CA)**
Member, Market Monitoring Committee

2009-2014 **California Air Resources Board (Sacramento, CA)**
Member, Economic Assessment and Allocation Committee (2009-2010),
Member Emissions Market Assessment Committee (2012-2014)

James Bushnell

Teaching Experience

2011- **Dept. of Economics, University of California, Davis (Davis, CA)**

Econ 100 – Intermediate Microeconmics, Winter 2012, 2013, 2014, 2015, 2016
Econ 125 – Energy Economics, Fall 2014, Winter 2015, Fall 2016
Econ 221 - Graduate Industrial Organization, Fall 2013.

2010 **Dept. of Economics. Iowa State University.**

Econ 301 – Intermediate Microeconomics, Fall 2010

1999-2009 **Haas School of Business, University of California (Berkeley, CA)**

BA212 –Energy and Environmental Markets, Spring 99, 01, 02, 04, 07, 08, 09
MBA201a – Economic Analysis for Business Decisions, Fall 02

Research Funding

Sloan Foundation. Research on Energy Infrastructure, with a focus on hydrocarbon transport and local energy distribution.(with Erin Mansur and Ryan Kellog) *$588,800.*

California Air Resources Board. 2015-2017. Proposal to establish the ARB Economic Fellowship Program. $350,000.

UC Energy and Envrionmental Economics Program. The costs of supply volatility in the integration of renewable electricity generation. (with Kevin Novan). $17,000.

UC-Davis Research Investments in the Sciences and Engineering. Cyber Security for Critical Infrastructures. (with Karl Levitt, Ho-Chen, George Barnett, Anna Scaglione, and Nicole Woolsey-Biggert). $840,000.

NSF 2012-2014. Towards Securing Coupled Financial and Power Systems in the Next Generation Smart Grid. (with Karl Levitt, Anna Scaglione, and Jeff Rowe and George Kasntenitas). $240,000 (Bushnell Share)

California Air Resources Board. 2012-2013. Emissions Market Assessment Committee for the California GHG Cap and Trade Market. (with Severin Borenstein and Frank Wolak). $300,000.

California Air Resources Board. 2012-2013. Market Simulation of the California Greenhouse Gas Emissions Allowance Market. (with Severin Borenstein and Frank Wolak). $300,000.

DOE/NSF, 2011-2013. Development of a Graduate Course in Energy Economics and Policy. $144,000. (Bushnell Share)

USDA-NIFA, 2011-2014. Implications of U.S. Climate Policy Choices for Agricultural Input Competitiveness, Costs, and Usage. (with Dermot Hayes). $295,000.

USDA-NNF, 2011-2014. A Proposal to Train Doctoral Students in the Economics and Management of Bio-renewable Energy (with John Beghin and Giancarlo Moschini).

California Air Resources Board. 2010-2011. Implementation of Carbon Emissions Trading in Regional Electrcicity Markets. (with Yihsu Chen). $83,000.

Power Systems Engineering Research Center. 2010-2011. "Interactions of Multiple Market-based Energy and Environmental Policies in a Transmission-Constrained Competitive National Electricity Market." (with William Schulze, Danial Tyvlasky, Ward Jewell, Shmuel Oren, Yishu Chen, and Siny Joseph). $60,000 (Bushnell Share)

California Energy Commission, 2002-2009. Grant to establish the Center for the Study of Energy Markets (with Severin Borentstein), $1,450,000. (over 2 grants)

Sloan Foundation - NBER program on International Productivity Comparisons; 2003 2007Analysis of Human - Technology Variation on the Productivity of Electricity Generation

(with Catherine Wolfram),
California Energy Commission, 2003-2005 "Analysis of the impact of environmental regulations on gasoline production in California (with Severin Borenstein)

Other Professional and Academic Activities:

Editorial Board *Economics of Energy and Environmental Policy. 2013- present.*

Associate Editor (for Energy and Resources), *Operations Research,* 2006-2011.

Associate Editor, *Utilities Policy*, 1998-2001.

Referee for: *American Economic Review*, *Annals of Operations Research, Canadian Journal of Economics, Climate Policy, The Energy Journal, Energy Policy, European Economic Review, International Journal of Industrial Organization, Journal of Economics and Management Strategy, Journal of Environmental Economics and Management, Journal of Industrial Economics, Journal of Regulatory Economics, Journal of Political Economy, Management Science, Networks, Operations Research, Rand Journal of Economics, Resource & Energy Economics, Review of Economics and Statistics, Review of Industrial Organization*

Journal Publications

"Reforming the US Coal Leasing Program.," with Kenneth Gillingham (lead author); Meredith Fowlie, Michael Greenstone, Alan Krupnick, Charles Kolstad, Adele Morris, Richard Schmalensee, James Stock. *Science,* 2016, Vol. 354 (December): 1096-1098.

"State-level Strategic Policy Choice: The EPA's Clean Power Plan." (with Stephen Holland, Jon Hughes, and Chris Knittel.) *American Economic Journal: Economic Policy.* Forthcoming.

"The US Electricity Industry after 20 Years of Restructuring." (with Severin Borenstein). *Annual Review of Economics.* Vol 7, No. 1: 437-463. 2015.

"An Economic Perspective on the EPA's Clean Power Plan," with Meredith Fowlie, Lawrence Goulder and Matthew Kotchen, (lead authors); Severin Borenstein, Lucas Davis, Michael Greenstone, Charles Kolstad, Christopher Knittel, Robert Stavins, Michael Wara, and Frank Wolak. *Science*, 2014, Vol. 346 (November): 815-816.

"Downstream Regulation of CO2 Emissions in California's Electricity Sector.'' (with Matthew Zaragoza and Yishu Chen). *Energy Policy*. Vol. 64: 313-323. January 2014.

"Profiting from Regulation: An Event Study of the EU Carbon Market." *American Economic Journal: Economic Policy.* (with Howard Chong and Erin Mansur) Vol 5, No. 4. November, 2013.

"Nation-wide Transmission Overlay Design and Benefits Assessment for the U.S." Energy Policy. (with Venkat Krishnan, James D McCalley, and Santiago Lemos) Vol 56: 221-232. May 2013.

"The Economic Effects of Vintage Differentiated Regulations: The Case of New Source Review." (with Catherine Wolfram). *Journal of Environmental Economics and Management.* Vol. 64, No. 1. September 2012.

"Regulation, Allocation and Leakage in Cap-and-Trade Markets for CO2." (with Yishu Chen) *Resources and Energy Economics*. Vol. 34, No. 4. September 2012.

"Vertical Targeting and Leakage in Carbon Policy," (with Erin Mansur), *American Economic Review Papers and Proceedings*, Volume 101, Issue 2, May 2011.

"Upstream vs. Downstream CO2 Trading: A Comparison for the Electricity Context," *Energy Policy*. 38(7), pages 3632-3643, July. 2010. (With Ben Hobbs and Frank Wolak).

"Local Solutions to Global Problems: Climate Change Policy Choice and Regulatory Jurisdiction." *Review of Environmental Economics and Policy*. Vol 2, pp. 175-193. 2008. (with Carla Peterman and Catherine Wolfram)

"Implementation of California AB 32 and its Impact on Electricity Markets." *Climate Policy*. Vol. 8, pp. 277-292. December, 2008.

"Vertical Arrangements, Market Structure and Competition: An analysis of Restructured U.S. Electricity Markets." *American Economic Review*. Vol 98, No. 1. March 2008. (with Erin Mansur and Celeste Saravia)

"Inefficiencies and Market Power in Financial Arbitrage: A Study of California's Electricity Markets," *Journal of Industrial Economics.* Vol 56, No. 2, June 2008. (with Severin Borenstein, Chris Knittel, and Catherine Wolfram).

"Oligopoly Equilibria in Electricity Contract Markets,"*Journal of Regulatory Economics.* Vol. 32: 225-245. 2007.

"Consumption under noisy price signals: a study of electricity retail rate deregulation in San Diego." *Journal of Industrial Economics.* Vol. 53, No. 4, December, 2005. (with Erin Mansur).

"California's Electricity Crisis: A Market Apart? " *Energy Policy.* Vol. 32, No. 9, June 2004.

"A Mixed Complementarity Model of Hydro-Thermal Competition in the Western U.S." *Operations Research.* Vol. 51, No. 1, January-February 2003.

"Measuring Market Inefficiencies in California's Deregulated Electricity Industry." *American Economic Review.* Vo. 92, No. 5, December 2002. (with Severin Borenstein and Frank Wolak).

"The Competitive Effects of Transmission Capacity in a Deregulated Electricity Industry." *Rand Journal of Economics*. Vol. 31, No. 2, Summer 2000. (with Severin Borenstein and Steven Stoft).

"Market Power in Electricity Markets: Beyond Concentration Measures." *The Energy Journal*. Vol. 20, No. 4, October, 1999. (with Severin Borenstein and Chris Knittel).

"An Empirical Analysis of the Potential for Market Power in a deregulated California Electricity Industry*." Journal of Industrial Economics*. Vol. 47, No. 3, September, 1999. (with Severin Borenstein).

"Transmission Pricing in California's Proposed Electricity Market." *Utilities Policy*, Vol 6, No. 3,

September, 1997. (with Shmuel Oren).

"Improving Private Incentives for Electric Grid Investment." *Resource & Energy Economics.* Vol. 19, No. 1-2, March, 1997. (with Steve Stoft).

"Market Power in California Electricity Markets." *Utilities Policy*, Vol 5, No. 3-4, October, 1996. (with Severin Borenstein, Edward Kahn, and Steven Stoft).

"Electric Grid Investment Under a Contract Network Regime." *Journal of Regulatory Economics*, Vol. 10, No.1, July, 1996. (with Steven Stoft).

"Internal Auctions for the Efficient Sourcing of Intermediate Products." *Journal of Operations Management*, Vol. 12, April 1995. (with Shmuel Oren).

"Incentive Effects of Environmental Adders in Electric Power Auctions." *The Energy Journal*, Vol. 15, No. 3, September, 1994. (with Shmuel Oren).

"Bidder Cost Revelation in Electric Power Auctions." *Journal of Regulatory Economics*, Vol. 6, No. 1, February, 1994. (with Shmuel Oren).

Other Publications

James Bushnell. "The Economics of Carbon Offsets." In *The Design and Implementation of U.S. Climate Policy*. Chapter 12 in Don Fullerton and Catherine Wolfram. Eds. University of Chicago Press. September, 2012.

James Bushnell. "Comment on `Schlenker and Roberts, Is Agricultural Production Becoming More or Less Sensitive to Extreme Heat? Evidence from US Corn and Soybean Yields'." In *The Design and Implementation of U.S. Climate Policy*. Chapter 17 in Don Fullerton and Catherine Wolfram. Eds. University of Chicago Press. September, 2012.

In James Bushnell. "Building Blocks: Investment in Renewable and Non-Renewable Resources." In *Harnessing Renewable Energy in Electric Power Systems.* Boaz Moselle, Jorge Padilla, and Richard Schmalansee, Eds. Resources for the Future Press. Washington, DC. 2010.

James Bushnell, Benjamin Hobbs, and Frank Wolak. "When it comes to demand response, is FERC its own worst enemy?" *The Electricity Journal.* November, 2009.

James Bushnell and Catherine Wolfram, "The Guy at the Controls: Labor Quality and Power Plant Efficiency." In *International Differences in the Business Practices and Productivity of Firms*. Richard Freeman and Kathryn Shaw, Eds. University of Chicago Press. 2009.

James Bushnell and Catherine Wolfram. "Electricity Markets," *New Palgrave Dictionary of Economics and the Law.* Steven N. Durlauf and Lawrence E. Blume, eds. Palgrave Macmillion. 2008**.**

James Bushnell "Electricity Resource Adequacy: Matching Policies and Goals**,**" *The Electricity Journal.* September, 2005.

James Bushnell "Looking for Trouble: Competition Policy in the U.S. Electricity Industry," Chapter 6 in *Electricity Restructuring: Choices and Challanges*. Puller and Griffen, Eds. University of Chicago Press. 2005.

James Bushnell "West Coast Power Blues." *New York Newsday* Op-ed Section. January 7, 2001.

Severin Borenstein and James Bushnell. "California consumers haven't seen the benefits of deregulating the electricity industry yet – what went wrong?" *San Jose Mercury News* Op-ed Section. August 27, 2000.

Severin Borenstein and James Bushnell, "Electricity Restructuring: Deregulation or Reregulation?" *Regulation*. Vol. 23, No. 2.

James Bushnell, "Transmission Rights and Market Power," *The Electricity Journal*, Vol. 12, No. 9, October, 1999.

James Bushnell and Steven Stoft. "Grid Investment: Can a Market do the Job?" *The Electricity Journal*, Vol. 9, No. 1, January, 1996.

Carl Blumstein and James Bushnell. "A Guide to the Blue Book: Issues in California's Electric Industry restructuring and Regulatory Reform." *The Electricity Journal*, Vol. 7, No. 7, September, 1994.

Working Papers

James Bushnell and Jacob Humber "Rethinking Trade Exposure: The Incidence of Environmental Charges in the Nitrogenous Fertilizer Industry." (with Jacob Humber). *Journal of the Association of Environmental and Resource Economists.* In 2nd Revision.

Severin Borenstein, James Bushnell, Frank Wolak, and Matthew Zaragoza-Watkins. "Expecting the Unexpected: Environmental Policy Choice and Emissions Market Design." NBER Working Paper No. 20999, March 2015. *Under submission.*

James Bushnell. "Adverse Selection and Emissions Offsets." Energy Institute at Haas Working Paper 222. September 2011.

James Bushnell, Carla Peterman, Catherine Wolfram, "California's Greenhouse Gas Policies: How do they add up?" CSEM-166. University of California Energy Institute. April 2007.

James Bushnell and Jun Ishii. "A Dynamic Model of Investment in a Restructured Electricity Industry." CSEM-164. University of California Energy Institute. January, 2007.

James Bushnell and Catherine Wolfram, "Ownership Change, Incentives and Plant Efficiency: The Divestiture of U.S. Electric Generation Plants." Report CSEM-140 University of California Energy Insitute, March 2005.

Severin Borenstein and James Bushnell, "Retail Policies and Competition in the Gasoline Industry," CSEM-144, University of California Energy Institute, May 2005.

Severin Borenstein, James Bushnell and Matthew Lewis, "Market Power in California's Gasoline Market." Report CSEM-132, University of California Energy Institute, May 2004.

James Bushnell and Celeste Saravia. "An Empirical Assessment of the Competitiveness of the ISO New England's Electricity Market," Report CSEM-101, University of California Energy Institute, December 2001.

Regulatory Filings or Reports

Opinions of the Market Surveillance Committee of the California ISO. (with Benjamin Hobbs, Scott Harvey, and Shmuel Oren (2011-2015) , Frank Wolak and Benjamin Hobbs (2005-2008) and Brad Barber (2002-2005). Numerous opinions available at http://www.caiso.com/docs/2000/09/14/20000914161002571 4.html.

Severin Borenstein, James Bushnell, Frank Wolak, and Matthew Zaragoza-Watkins. "Report of the Market Simulation Group on Competitive Supply/Demand Balance in the California Allowance Market and the Potential for Market Manipulation." California Air Resources Board. June 2014.

Ross Baldick, James Bushnell, Ben Hobbs, and Frank Wolak. "Optimal Charging Arrangements for Energy Transmission." Report prepared for Ofgem Project TransmiT, Great Britain Office of Gas & Electricity Markets. May, 2011.

Bushnell, J, L. Goulder, C.R. Knittel, S. Levy, N.E. Ryan, N. Sidhu, J. Sweeney. "EAAC Economic Impacts Subcommittee Report on Air Resources Board's Updated AB 32 Scoping Plan Analysis.", March 2010.

Goulder, L., J. Adams, V. Arroyo, M. Barger, J.K. Boyce, D. Burtraw, J. Bushnell, R. Fisher, R. Frank, R. Frank, D. Kamman, C.R. Knittel, S. Levy, J. Nation, N.E. Ryan, N Sidhu, J.L. Sweeney. "Allocating Emissions Allowances Under a California Cap-and-Trade Program: Recommendations to the California Air Resources Board and California Environmental Protection Agency from the Economic and Allocation Advisory Committee", March 2010.

Ross Baldick, Ashley Brown, James Bushnell, Sue Tierney, and Terry Winter. "A National Perspective on Allocating the Costs of New Transmission Investment: Practice and Principles." White Paper prepared by the Blue Ribbon Panel on Transmission Cost Allocation for WIRES. October, 2007.

James Bushnell. "Comments on Horizontal Market Power Screens and Market-Based Rates for Public Utilities. Federal Energy Regulatory Commission. Docket No. RM04-7-000. June 30, 2004.

James Bushnell and Robert Wilmouth. "Comments of the Market Monitoring Committee of the California Power Exchange on the Federal Energy Regulatory Commission order of Nov. 1 proposing remedies for the California wholesale electricity market. Nov. 22, 2000.

James Bushnell, Alvin Klevorick, and Robert Wilmouth. "The impact of reliability must-run contract reform and ancillary-services market redesign on the performance of California's energy market." 3rd report to FERC of the Market Monitoring Committee of the California Power Exchange. June 6, 2000.

Severin Borenstein, James Bushnell, and Chris Knittel, "Comments on the use of computer models for merger analysis in the electricity industry," Federal Energy Regulatory Commission. Docket No. PL98-6-000. June, 1998.

Severin Borenstein, James Bushnell, and Chris Knittel, "A Cournot-Nash Equilibrium Analysis of the New Jersey Electricity Market." Appendix A of Review of General Public Utilities' Restructuring Petition, Final Report. New Jersey Board of Public Utilities. Docket No. EA97060396. January, 1998.

Work in Progress

Commodity price impacts of oil-by-rail (with Aaron Smith and Jon Hughes)

Economics of the future grid: the future of electricity distribution (with Severin Borenstein, Dave Rapson, and Kevin Novan)

Vertical Position in Merger Analysis (with Erin Mansur and Frank Wolak)

Selected Presentations

"State Level Strategic Policy Choice: The US EPA's Clean Power Plan."
Colorado School of Mines (February 2016), Carnegie Mellon University (April 2015), UC Berkeley POWER conference (March 2015).

*"Expecting the Unexpected: Emissions Market Uncertainty and Environmental Market Design."*National University of Singapore (August 2015), Toulouse Conference on Energy, Toulouse, France. (June 2014). University of Illinois, Heartland Environmental and Resource Economics Workshop (October, 2013).

"The US Electricity Industry after 20 years of restructuring"
World Bank, Washington DC (November 2015), University of Melbourne (August 2015), University of Auckland (August 2015), Carnegie Mellon University (May 2015), University of Guelph, Dept. of Economics (September 2014), American Bar Association Anti-trust Symposium (May, 2009), Energy Information Administration Energy Conference (May, 2008), Harvard Electricity Policy Group (December 2007).

*"Vertical Forward Commitments."*Toulouse Conference on Energy, Toulouse, France (2014), IESE Busiiness School. Barcelona. (June 2014). UC Davis Game Theory Workshop (April 2014). University of Auckland CMSS Summer Workshop (December 2013).

"Profiting from Regulation: An event study of the EU carbon market." Rice University (March 2011), University of Michigan (October, 2010), UC Santa Barbara Occasional Workhshop on Environmental and Resource Economics (October 2009), UC Energy Institute (October 2009), UC Davis, Dept. of Economics (October, 2009), University of Illinois, Heartland Environmental and Resource Economics Workshop (November, 2009), University of Minnesota, Dept. of Applied Economics (November, 2009).

"Regulation, Allocation, & Leakage in Cap-and-Trade Markets for CO2." Rice University (December, 2008), UC Energy Institute POWER research conference (March, 2009). NBER winter institute (March, 2009), Johns Hopkins SAIS (April 2009), Iowa State University, May 2009.

"Local Solutions to Global Problems: Climate Change Policy Choice and Regulatory Jurisdiction." Gulf Coast Power Association (May, 2010), University of East Anglia, Center for Competition Policy (June, 2008), London Energy Forum (October 2007), UC Energy Institute POWER research conference (March, 2007), Western Power Trading Forum (New York, February 2007).

"The Economic Effects of Vintage Differentiated Regulations: The Case of New Source Review." Yale University Environmental Economics Seminar (October, 2006), Tufts University, Dept. of Economics (October 2006), Johns Hopkins University (October 2006), UC Berkeley, Dept. of Ag. and Resource Econ (December 2005), University of Toulouse, IDEA, Economics of the Electricity Industry Conference (June 2005).

"Vertical Arrangements, Market Structure and Competition: An analysis of Restructured U.S. Electricity Markets." Association of Competition Economists, Best paper of 2008 Award Ceremony, Berlin. (November, 2009), Nordic Energy Research Program, Iceland (September, 2006), Australian Competition and Consumer Commission Regulatory Conference (July, 2006), UC Irvine, Dept. of Economics (May, 2005), Universite Catolica de Louvain, Belgium (January 2004), Econometric Society Meetings, Northwestern University (June 2003), University of Wyoming, Dept. of Economics (April, 2003),.

"Diagnosing Market Power in California's Restructured Wholesale Electricity Market," UC Davis (Spring 2001), Dept. of Ag. & Applied Economics. University of Wisconsin, Madison. (February, 2001).

"California's Electricity Restructuring: A Market Apart?" Australian Economic Society, Sydney MIT, Center for Environmental and Energy Policy Research (December 2001), University of Arizona. (April 2001), Public Utilities Research Center, University of Florida, Gainesville (February, 2001), Presentation to the Wisconsin Congressional Delegation. Washington, D.C. (January, 2001), National Association of Business Economists. Federal Reserve Bank of San Francisco (October 2000).

Other Consulting Projects

TrustPower (New Zealand), 2014.
Ofgem (UK), 2010-2011.
Korean Power Exchange, 2008.
Korean Electric Power Company, 2007.
WIRES, 2007.
Energy Information Administration, 2006
Wisconsin Public Power Inc., 2001
ISO – New England, Massachusetts Attorney General, 2001
U.S. Dept. of Justice, 2001
Customers First! Coalition of Wisconsin, 2000
The World Bank, 1999-2000
New Jersey Board of Public Utilities, 1997

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ACADEMIC EXPERIENCE

Director, Rutgers Energy Institute, July 2018 to present

Director, Center for Energy, Economics & Environmental Policy, Edward J. Bloustein School of Planning and Public Policy, Rutgers, The State University of New Jersey, October 2006 to present, *Acting Director*, February 2006 to September 2006

Research Professor, July 2018 to present*, Associate Research Professor*, September 2007 to June 2018, *Assistant Research Professor*, September 2004 to August 2007

> Conduct research and teach on topics related to energy and environmental policies including climate change, renewable portfolio standards, energy infrastructure, cost-benefit analysis of energy efficiency, and electricity markets.

Program Director, Public Informatics, Bloustein School of Planning and Public Policy, July 2018 to present

Manhattan College, School of Business, New York City, NY, *Assistant Professor of Management,* Tenure-track Appointment, August 2002 to August 2004

> Conducted research in the reliability, operations, and management of restructured electric power systems and the application of risk analysis to management problems. Taught undergraduate classes (Operations and Management; Decision Analysis, Introduction to Management) and MBA classes (Quantitative Methods, Operations and Management, and Entrepreneurship to International MBA students).

Massachusetts Institute of Technology, Cambridge, MA

> Ph.D. in Technology, Management and Policy (Engineering Systems Division), September 2001
>
> Dissertation topic: Probabilistic Risk Analysis of Restructured Electric Power Systems: Implications for Reliability Analysis and Policies
> Dissertation Committee: Professor Michael W. Golay, Professor William W. Hogan, and Dr. Richard D. Tabors

Research Assistant: January 1998 to May 2001 for two research projects in applying probabilistic risk analysis to the regulation of nuclear facilities (Professor Golay) and for one project on the sale of commercial nuclear power plants as part of electric utility industry restructuring (Professor Hansen).
Teaching Assistant: Fall semester 1997 for a graduate seminar in Technology and Policy (Dr. Tabors).

M.S. in Technology and Policy, 1994

Columbia University, New York, NY
B.S. Applied Mathematics, 1987; B.A. in Mathematics, 1987

PUBLICATIONS AND RESEARCH (*indicates student or post-doctoral advisee)

Peer Reviewed Publications

Rodgers*, M., Coit, D., Felder, F., Carlton, A. (2018), Generation Expansion Planning Considering Health and Societal Damages - A Simulation-Based Optimization Approach, *Energy*, in press.

Rodgers*, M., Coit, D., and Felder, F. (2018). Assessing the Effects of Power Grid Expansion on Human Health Externalities, *Socio-Economic Planning Sciences*, in press.

Song*, S., Qing, L., Felder, F., Wang, H., and Coit, D. (2018). Integrated optimization of offshore wind farm layout design and turbine opportunistic condition-based maintenance, *Computers & Industrial Engineering*, 120, 288-297.

Figueroa-Candia*, M., Felder, F. and Coit, D. (2018). Resiliency-Based Optimization of Restoration Policies for Electric Power Distribution Systems, *Electric Power Systems Research*, 161, 188-198.

Zhou*, J., Huang, N., Coit, D. W., & Felder, F. A. (2018). Combined effects of load dynamics and dependence clusters on cascading failures in network systems. *Reliability Engineering & System Safety*, 170, 116-126.

Felder, F. and Athawale, R. (2018). "PACT-a-Mole": the case against using the Program Administrator Test for energy efficiency programs. *Energy Efficiency*, 11(1), 1-11.

Shan*, X., Felder, F., & Coit, D. (2017). Game-theoretic Models for Electric Distribution Resiliency/Reliability from a Multiple Stakeholder Perspective. *IIE Transactions*, 49(2), 159-177.

Felder, F., & R. Athawale. (2016). Optimizing New York's Reforming the Energy Vision. *Utilities Policy*, 41C, 160-162.

Farkas*, C. M., Moeller*, M. D., Felder, F. A., Henderson, B. H., Carlton, A. G. (2016). High Electricity Demand in the Northeast U.S.: PJM Reliability Network and Peaking Unit Impacts on Air Quality. *Environmental Science & Technology*, 50 (15), 8375-8384.

Athawale, R., Felder, F., & Goldman*, L. (2016). Do CHPs Perform? Case Study of NYSERDA Funded Projects. *Energy Policy*, 97, 618-627.

Felder, F. (2016). Why Can't We All Get Along? A Conceptual Analysis Combined with a Case Study. *Energy Policy*, 96, 711-716.
Li*, S., Coit, D., & Felder, F. (2016). Stochastic optimization of electric power generation expansion planning with discrete climate change scenarios. *Electric Power Systems Research*. 140, 401-412.

Chandramowli*, S., Felder, F., Mantell, N., Irving, W., & Seneca, J. (2016). LP-CEM: A modeling tool for power systems planning incorporating climate change effects and macro-economic trends. *Energy Strategy Review*, 11, 1-18.

Tekiner-Mogulkoc*, H., Coit, D., & Felder, F. (2015). Mean-Risk Stochastic Electricity Generation Expansion Planning Problems with Demand Uncertainties Considering Conditional-Value-at-Risk and Maximum Regret as Risk Measures. *International Journal of Electrical Power and Energy Systems*, 73, 309-317.

Farkas*, C., Moeller*, M., Felder, F., Baker, K.R., Rodgers, M., & Carlton, A. G. (2015). Temporalization of Peak Electric Generation PM Emissions during High Energy Demand Days. *Environmental Science & Technology*, 49(7), 4696-4704.

Bridges*, A., Felder, F., McKelvey*, K. & Niyogi*, I. (2015). Screening for Health Effects in Energy Planning. *Energy Research and Social Science*, 6, 74-77.

Athawale, R., & Felder, F. (2014). Incentives for Combined Heat and Power Plants: How to increase society benefits. *Utilities Policy*, 31, 121-132.

Chandramowli*, S., & Felder, F. (2014). Impact of Climate Change on Electricity Systems - A Review of Models and Forecasts. *Sustainable Energy Technologies and Assessments*, 5, 62-74.

Tekiner-Mogulkoc*, H., Coit, D., & Felder, F. (2012). Electric Power System Generation Expansion Plans Considering the Impact of Smart Grid Technologies. *International Journal of Electrical Power and Energy Systems*, 42(1), 229–239.

Chandramowli*, S., Transue*, M., & Felder, F. (2011). Analysis of Barriers to Development in Landfill Communities Using Interpretive Structural Modeling. *Habitat International*, 35, 246-253.

Tekiner*, H., Coit, D., & Felder, F. (2010). Multi-period Multi-objective Electricity Generation Expansion Planning Problem with Monte-Carlo Simulation. *Electric Power Systems Research*, 80(12), 1394-1405.

Transue*, M., & Felder, F. (2010). Comparison of Energy Efficiency Incentive Programs: Rebates and White Certificates. *Utilities Policy*, 18(2), 103-111.

Felder, F. (2009). A Critical Assessment of Energy Accident Studies. *Energy Policy*, 37, 5744-5751.

Felder, F., & Haut, R*. (2008). Balancing Alternatives and Avoiding False Dichotomies to Make Informed U.S. Electricity Policy. *Policy Sciences*, 41, 165-180.

Greenberg, M., Mantell, N., Lahr, M., Felder, F., & Zimmerman, R. (2007). Short and Intermediate Economic Impacts of a Terrorist-Initiated Loss of Electric Power: Case Study of New Jersey. *Energy Policy*, 35, 722-733.

Felder, F., & Hajos*, A. (2006). Using Restructured Electricity Markets in the Hydrogen Transition: The PJM Case. *Proceedings of the IEEE* (special issue), 94(10), 1864-1879.

Guirguis, H., & Felder, F. (2005). Accounting for Extreme Values in GARCH Forecasts of Day-Ahead Electricity Prices. *KIEE International Transactions on Power Engineering*, 5-A(3), 300-302.

Felder, F. (2005). Top-Down Composite Modeling of Bulk Power Systems. *IEEE Transactions on Power Systems*, 20(3), 1655-1656.

Guirguis, H., & Felder, F. (2004). Further Advances in Forecasting Day-Ahead Electricity Prices Using Time Series Models. *KIEE International Transactions on Power Engineering*, 4A(3), 159-166.

Felder, F. (2004). Incorporating Resource Dynamics to Determine Generation Adequacy Levels in Restructured Bulk Power Systems. *KIEE International Transactions on Power Engineering*, 4A(2), 100-105.

Yoon, Y., & Felder, F. (2003). A Critique of Designing Resource Adequacy Markets to Meet Loss of Load Probability Criterion. *KIEE International Transactions on Power Engineering*, 3A(1), 35-41.

Farr, J., & Felder, F. (2003). An Introduction to Electricity Market Auctions Using a Spreadsheet. *INFORMS Transactions on Education*, 4(1), 11-22.

Felder, F. (1996). Integrating Financial Theory and Methods in Electricity Resource Planning. *Energy Policy*, 24(2), 149-154.

U.S. National Science Foundation Grants (Peer Reviewed)

Collaborative Research Modeling Strategic Regulators in Network Infrastructure Planning, $399,002, Senior Investigator (PI for Rutgers University grant of $85,890), 1825225, CMMI September 1, 2018 through August 31, 2021.

Electrochemical Approaches to Sustainable Dinitrogen Fixation, $300,000, Senior Investigator, CHE 1665146, September 1, 2017 through August 31, 2020.

EAGER: Smart & Connected Communities, National Science Foundation, $250,000, Senior Investigator, AGS1645786, August 1, 2016 through July 31, 2018.

EaSM-3: Regional decadal predictions of coupled climate-human systems, National Science Foundation, OCE1419584, $1,200,000, co-PI, June 1, 2014 through August 31, 2017. Designated Bloustein PI for $414,615.

Green Energy Technology for Undergraduates Program (GET UP!), National Science Foundation, EEC1263250, $367,890, Senior Personnel, March 15, 2013 through February 29, 2016. Presented to high school teachers and undergraduate students on July 9, 2014.

Climate to Humans: A Study of Urbanized Coastal Environments, Their Economics and Vulnerability to Climate Change, National Science Foundation, OCE1049088, $3,853,332, co-PI, March 1, 2010 through February 28, 2016. Designated Bloustein PI for $525,448. Additional $225,000 assigned Bloustein.

IGERT: Solutions for Renewable and Sustainable Fuels in the 21st Century, National Science Foundation OCE1049088, $3,197,329, co-PI and Lead on Policy and Infrastructure Logistics for Efficient Fuel Technology Deployment, September 1, 2009 through August 30, 2014. Funded 24 doctoral students (including 2 Bloustein students) and 4 master students. Served on Leadership, Committee and Admission Committee. Developed and taught two new graduate seminars.

Nanotechnology for Clean Energy, National Science Foundation, 0903661, Faculty, $1,218,737, 2008-2013. Developed graduate course given to Rutgers and Princeton Universities.

The Electricity Journal

Freed, M. & Felder, F. (2017). Non-energy benefits: Workhorse or unicorn of energy efficiency programs? *The Electricity Journal*, 30(1), 43-46.

Felder, F. (2015). Should Relief be Granted From the Clean Power Plan for Reliability Reasons? *The Electricity Journal,* 28(6), 5-11.

Felder, F., & Athawale, R. (2014). The Life and Death of the Utility Death Spiral. *The Electricity Journal*, 27(6), 9-16.

Chandramowli*, S., & Felder, F. (2014). Climate Change and Power Systems Planning – Opportunities and Challenges. *The Electricity Journal*, 27(4), 40-50.

Felder, F. (2013). Nuclear Power in the Second Obama Administration. *The Electricity Journal*, 26(2), 25-31.

Felder, F. (2012). Watching the ISO Watchman? *The Electricity Journal*, 25(10), 24-37.

Felder, F. (2011). Examining Electricity Price Suppression Due to Renewable Resources and Other Grid Investments. *The Electricity Journal*, 24(4), 34-46.

Felder, F. (2010). The Practical Equity Implications of Advanced Metering Infrastructure. *The Electricity Journal*, 23(6), 56-64.

Farr, J. and Felder, F. (2005). Competitive Electricity Markets and System Reliability: The Case for New England's Proposed Locational Capacity Market. *The Electricity Journal*, 18(8), 22-33.

Felder, F. (2004). Shining Light, Not Shedding Light. *The Electricity Journal*, 17(7), 51-54.

Farr, J., & Felder, F. (2002). A Critique of Existing Market-based Market Performance Monitoring and Mitigation Policies. *The Electricity Journal*, 15(6), 10-18.

Felder, F. (2002). The Need for Governance of Restructured Electric Power Systems and Some Policy Implications. *The Electricity Journal*, 15(1), 36-43.

Rotger, J., & Felder, F. (2001). Reconciling Market-Based Transmission and Transmission Planning. *The Electricity Journal*, 14(9), 31-43.

Felder, F. (2001). An Island of Technicality in a Sea of Discretion': A Critique of Existing Electric Power Systems Reliability Analysis and Policy. *The Electricity Journal,* 14(3), 21-31.

Felder, F., Hopper, G., & Lukens, J. (1998). The Benefits of Retail Electricity Competition in Low-Cost States: Expectations for an Evolving Industry, *The Electricity Journal*, 11(7), 75-81.

Felder, F., & Peterson, S. (1997). Market Power Analysis in a Dynamic Electric Power Industry. *The Electricity Journal*, Volume # needed, 10(3), 12-19.

Jaffe, A., & Felder, F. (1996). Should Electricity Markets Have A Capacity Requirement: If So, How Should It Be Priced? *The Electricity Journal*, 9(10), 52-60.

Felder, F. (1996). Integrating Financial Thinking with Strategic Planning to Achieve Competitive Success. *The Electricity Journal*, 9(4), 62-67.

Felder, F. (1995) Modeling Natural Gas Prices as a Random Walk: The Advantages for Generation Planning. *The Electricity Journal*, 8(9), 61-67.

Law Review Journals

Tortta, J., Dressel, A., Agbre, S., Benevento, D., Butrus, G., Chambers, T., …Spina, S. (2014). Report of the System Reliability & Planning Committee. *Energy Law Journal*, 35(2), 1-21.

Felder, F. (2014). Climate Change Mitigation and the Global Energy System**.** *Villanova Environmental Law Journal*, 25(1), 89-106.

Book Chapters

Athawale, R., & Felder, F. (2016). Residential Rate Design and Death Spiral for Electric Utilities: Efficiency and Equity Considerations. In F. Sioshansi (Ed.), *Future of Utilities - Utilities of the Future: How technological innovations in distributed energy resources will reshape the electric power system* (pp. 193-209). Amsterdam: Elsevier Press, 2016.

Felder, F. & Chandramowli*, S (2016). Impact of Extreme Events on the Electric Power Sector: Challenges, Vulnerabilities, Institutional Responses, and Planning Implications from Hurricane Sandy. In K. M. O'Neill, & D. J. Van Abs, (Eds.), *Taking Chances on the Coast After Hurricane Sandy* (pp. 242-257). New Brunswick, NJ: Rutgers University Press.

Felder, F. (2014). What Future for the Grid Operator? In F. Sioshansi (Ed.), *Distributed Generation and its Implications for the Utility Industry* (pp. 399-415). Amsterdam: Elsevier Press.

Felder, F. (2013). The evolution of demand side management in the United States. In F. Sioshansi

(Ed.), *End of Electricity Demand Growth: How energy efficiently can put an end to the need for more power plants (*pp. 179-200). Amsterdam: Elsevier Press.

Felder, F. (2012). The Equity Implications of Smart Grid: Questioning the Size and Distribution of Smart Grid Costs and Benefits. In F. Sioshansi (Ed.). *Smart Grid: Integrating Renewable, Distributed & Efficient Energy* (pp. 85-100). Amsterdam: Elsevier Press.

Felder, F., Andrews, C., & Hulkower, S. (2011). Which Energy Future. In F. Sioshansi (Ed.), *Energy Sustainability and the Environment: Technology, incentives, behavior* (pp. 30-61). Amsterdam: Elsevier Press.

Felder, F., Mantell, N., Lovrien, N., Buehler, & Cottrell, A. (2009). Energy Master Planning: The Case of New Jersey. In E. Kahraman & A. Baig (Eds), *Environmentalism: Environmental Strategies and Environmental Sustainability* (pp. 41-72). Hauppauge, New York: Nova Science Publishers.

Working Papers

Froio, Z., Kumar, P. and Felder, F., Not Adding Up: Free Ridership and Spillover Calculations in Energy Efficiency Evaluations, January 2018.

Rodgers, M., Coit, D., Felder, F., Carlton, A. Generation Expansion Planning Considering Health Damages – A Simulation-Based Optimization Approach, November 2017.

Selcuklu, S., Coit D., Felder, F. Pareto Uncertainty Index for Stochastic Multi-objective Problems, April 2017.

Rodgers, M., Coit, D., Felder, F., Carlton, A. Assessing the Effects of Power Grid Expansion on Human Health Externalities, January 2017.

Song, S., Felder, F., Bowers, L., Miles, T., Sekora, G., Dunk, R., and Coit, D. Two-Stage Wind Farm Optimization and Application to Offshore Wind Given Installation and Maintenance Policies, February 2016.

Conference Papers and Presentations

Felder, F., "Aligning Research and Government Policies to Advance Science in the Food, Energy, Water Nexus" Oct. 25, 2018 Yixing Jiangsu, China.

Felder, F., "Advancing Offshore Wind in New Jersey", Time for Turbines: What a Difference a Year Makes, Atlantic City, August 20, 2018.

Zhou, J., Coit, D., & Felder, F., "Optimal Restoration for Resilience of Dependency Systems Against Cascading Failures", Proceedings of the 2018 IISE Annual Conference, 2018.

Felder, F., "Climate Change and New Jersey Energy Policy", New Jersey Office of Legislative Services, Trenton, NJ, April 10, 2018.

Felder, F., "Energy Economics", Mandela Washington Fellows Program, July 20, 2017, Rutgers

University.

Song, S., Q. Li, Felder, F., H. Wang, & D. Coit, "Integrated Optimization of Offshore Wind Farm Layout Design and Turbine Opportunistic Condition-Based Maintenance," INFORMS, Nashville, TN, Nov. 16, 2016.

Moeller, M., Felder, F., K. Baker, A. Carlton, "Air Pollution Externalities and Energy Choices: Linking Electricity Dispatch, Air Quality and Health Impact Models," CMAS: Community Modeling and Analysis System Conference, University of North Carolina, Oct. 24, 2016.

Felder, F., "Analysis of United States Policies to Promote CHP," The 15th International Symposium on District Heating and Cooling, September 15, 2016, Seoul, Korea.

Felder, F., "Energy Economics", Mandela Washington Fellows Program, July 15, 2016, Rutgers University.

Felder, F., "Understanding Electricity, Emission and Renewable Resource Markets," New Jersey Department of Environmental Protection Clean Air Council, May 11, 2016.

Shankar N. Chandramowli, Frank A. Felder, Xiazojun G. Shan, "Assessing the Policy Interaction Effect of Renewable Portfolio Standards (RPS) and Clean Power Plan (CPP) Emissions Goals for States in the U.S. Northeast," Proceedings of the ASME 2016 Power and Energy Conference, PowerEnergy2016, Charlotte, North Carolina, June 26-30, 2016 (paper and presentation).

Felder, F., "Energy Security and Resiliency," Institute of Public Utilities Grid School 2015, Michigan State University, Charleston, SC, March 9, 2016.

Felder, F., U.S. Northeastern Electricity Markets, Renewable and Electricity Transition to the 21st Century, International Workshop, Hong Kong, Feb. 21-23, 2016 (paper and presentation).

Felder, F., "International Experiences in Power Market Development and Cross Border Electricity Trade: Lessons Learned from Emerging and Developed Markets," USAID South Asia Regional Initiative for Energy Integration, Conference on Sustainable Development of Power Sector and Enhancement of Electricity Trade in the South Asia Region: Policy, Regulatory Issues, Challenges and Way Forward, January 15, 2016, New Delhi, India.

Felder, F., "U.S. Electricity Market Trends and the PJM Energy Market," Konkuk University, December 17, 2015.

Felder, F., "U.S. Electricity Market Trends," Konkuk University, December 15, 2015.

Felder, F., "U.S. Electricity Markets and Demand Response," Korea University, December 14, 2015.

Song, S, Felder, F., Bowers, L., Seroka, G., Dunk, R., Miles, T. and Coit, D.
"Wind Farm Design and Application to Offshore Wind in New Jersey Given Installation and Maintenance Policies," FERC Workshop/9th Annual Trans-Atlantic Infraday electricity markets and Planning, Energy Infrastructure and Systems, October 30, 2015.

Felder, F., *Capacity Building Program for Designing, Managing and Operating a Power Trading Entity in Nepal*, Workshop Facilitator, US Energy Association on behalf of USAID, September 14-18, 2015.

Park, J., Park, Y., Felder, F. and Athawale, R., "Calculating the Energy Cost Savings of Battery Energy Storage System for Frequency Control of Bulk Power Systems", International Conference on Electrical Engineering (ICEE 2015), Hong Kong, China, 5-9 July, 2015. (Paper No. ICEE15A-016-FP).

Felder, F., "Optimizing Reliability and Resiliency of Electric Distribution Systems," Center for Research in Regulated Industries, 28th Annual Western Conference, Monterey, CA, June 24-26, 2015.

Selcuklu, S, Coit, D. and Felder, F., "Aleatory and Epistemic Uncertainty Classification of the GEP Problem," ISERC, Nashville, TN, 2015.

Felder, F., "An Update on the American society of Civil Engineers' Infrastructure Report Card," Panel Participant, New Jersey Utilities Association 100th Annual Conference, Atlantic City, June 3-5, 2015.

Felder, F., "Optimizing Reliability and Resiliency of Electric Distribution Systems," Center for Research in Regulated Industries, 34th Annual Eastern Conference, Shawnee on Delaware, PA, May 13-15, 2015.

Felder, F & Athawale, R., "Efficiency and Equity Considerations in Designing Rates in the Context of the Death Spiral for Electric Utilities," 34th Annual Eastern Conference, Shawnee on Delaware, PA, May 13-15, 2015.

Felder, F., "Energy Security and Resiliency," Institute of Public Utilities Grid School 2015, Michigan State University, Chicago, IL, March 12, 2015.

Felder, F., "Transformative Technologies," Institute of Public Utilities Grid School 2015, Michigan State University, Chicago, IL, March 11, 2015.

Felder, F., Athawale, R., Chanrdramowli, S. "Planning for the Future Electric Grid," New Jersey American Planning Association, New Brunswick, NJ, January 29, 2015.

Selcuklu, S., Coit, D. and Felder, F. "Aleatory and Epistemic Uncertainty Classification of the GenerationvExpansion Problem," Industrial and Systems Engineering Research Sessions (ISERC) 2015, May 30-June 2, 2015, Nashville, TN.

Felder, F., *Expert Topic Briefing: Negotiating a Universal Agreement on Climate Change*, World Affairs Council of Philadelphia, Philadelphia, PA, Dec. 10, 2014.

Felder, F., "Framework for Assessing Reliability," Center for Research in Regulated Industries, Rutgers University, Nov. 21, 2014 (presentation).

Chandramowli, S. and Felder, F., "LP-CEM: A modeling tool for power systems planning Incorporating climate change effects and macro-economic trends". Mid-Atlantic Regional Climate Symposium, Rutgers University, New Brunswick, NJ, November 20, 2014.

Shan, X., Felder, F., and Coit, D. "Game-theoretic Model for Electric Distribution Reliability from a Multiple Stakeholder Perspective," INFORMS, San Francisco, CA, Nov. 12, 2014 (presentation).

Shan, X., Felder, F., and Coit, D. "Game-theoretic Model for Electric Distribution Reliability from a Multiple Stakeholder Perspective," FERC Workshop/Trans-Atlantic Infraday, Washington, DC, November 7, 2014 (presentation).

Felder, F., Shan, X. and Coit, D. "Multi-Objective Framework for Evaluating Resiliency Measures for Electric Power Systems," FERC Workshop/Trans-Atlantic Infraday, Washington, DC, November 7, 2014 (presentation by Felder).

Chandramowli, S. and Felder, F., "LP-CEM: A Modeling Tool for Power Systems Planning Incorporating Climate Change Effects," Energy Policy Research Conference, San Francisco, Sept. 4, 2014 (paper and presentation by Felder).

Felder, F., "Energy Policy and Ethics," Rutgers University Research for Teachers in Engineering for Green Energy Technology and the Green Energy Technology for Undergraduates Program, New Brunswick, NJ, July 9, 2014.

Felder, F., "Combined Heat and Power & Resiliency: Case Study for Post-Sandy New Jersey," 2014 Louisiana Public Service Commission Combined Heat and Power Training Workshop, Louisiana State University, Baton Rouge, LA, June 25, 2014.

Felder, F., "How the Grid Works?" New Jersey Educational Foundation, Inc., *Energy 101*, New Brunswick, NJ, June 17, 2014 (presentation).

Shan, X., Felder, F., and D. Coit, "Game-theoretic Model for Electric Distribution Reliability with Government Intervention," CESUN 2014, June 8-11, 2014 (paper and presentation).

Chandramowli, S. and Felder, F., "Integrating Power System and Macroeconomic Modeling to Project the Impacts of Climate Change in New Jersey," CESUN 2014, June 8-11, 2014 (poster).

Li, S., Coit, D., Selcuklu, S., and Felder, F., "Electric Power Generation Expansion Planning Robust Optimization Considering Climate Change," Proceedings of the 2014 Industrial and Systems Engineering Research Conference, Y. Guan and H. Liao (eds), 2014.

Athawale, R. and Felder, F., "Incentivizing Combined Heat and Power Plants – How to Maximize Society Benefits?" 33rd Annual Eastern Conference, May 14-16, 2014 (paper and presentation).

Felder, F., "ISO Governance, ISO Principal-Agent Problem and Social Welfare," Center for Research in Regulated Industries, 33rd Annual Eastern Conference, May 14-16, 2014 (paper and presentation).

Felder, F., "Will the Potential for a Death Spiral in Electricity Rates Hinder Transformation of the Electric Power System?" Rutgers Energy Institute Ninth Annual Energy Symposium, May 6, 2014.

Curchitser, E. and Felder, F., "Climate-to-humans: A study of urbanized coastal environments, their economics and vulnerability to climate change," Decadal and Regional Climate Prediction using Earth

System Models (EaSM) PI Meeting, NSF, January 27-29, 2014 (presentation by both).

S. Selcuklu, D. Coit, Felder, F., M. Rodgers, and N. Wattanapongsakorn, "A New Methodology for Solving Multi-Objective Stochastic Optimization Problems with Independent Objective Functions," IEEE International Conference on Industrial Engineering and Engineering Management (IEEM2013), Bangkok, Thailand, December 10-13, 2013 (paper and presentation by Coit).

Felder, F., "Case Study of the New York Independent System Operator's Governance," FERC Workshop/Trans-Atlantic Infraday (TAI), November 7-8, 2013 (presentation).

Felder, F., "RTO Governance Best Practices and Needed Improvements," APPA's Roundtable Discussion of the Current State of the RTO-Operated Electricity Market, Washington, DC, October 17, 2013, (presentation).

Chandramowli, S. and Felder, F., "Impact of Climate Change on Electricity Systems and Markets," INFORMS, Minneapolis, MN, Oct. 8, 2013 (interactive session, presented by Chandramowli).

Selcuklu, S., Felder, F., D. Coit, and M. Rodgers, "Pareto Uncertainty Index in Multi-Objective Genetic Algorithm: An Application to GEP," INFORMS, Minneapolis, MN, Oct. 8, 2013 (presentation by Selcuklu).

Felder, F., "Analyzing the Reliability and Resiliency of New Jersey's Urban Energy Systems in Response to Climate Change," DIMACS/CCICADA Workshop on Urban Planning for Climate Events, Rutgers University, Sept. 23, 2013 (presentation).

Felder, F., "EaSM Electricity Model Update," Regional Economists Network, Bloustein School, June 7th, 2013 (presentation).

Felder, F., "J.D. Power 2013 Hurricane Sandy Responsiveness Survey," New Jersey Utilities Association 98th Annual Conference, Galloway, NJ, June 6, 2013 (panel).

Felder, F., "Costs and Benefits of Combined Heat and Power," NJ Spotlight Webinar: Combined Heat and Power New Jersey, May 7, 2013 (presentation).

Felder, F., "Integrating New Jersey Renewable Energy Policies into Energy Markets," New York City, New York, May 1, 2013 (presentation and panel).

Felder, F., "Climate Change Mitigation and the Global Energy System," Villanova Environmental Law Journal, Villanova, Pennsylvania, April 13, 2013 (presentation).

Felder, F., "Climate Change Mitigation and the Global Energy System," Rutgers Law School Environmental Law Society, Newark, New Jersey, February 27, 2013 (presentation and panel).

Felder, F., "The NJ Spotlight Roundtable Series: Can the Energy Sector Drive New Jersey's Economy?" Ewing, New Jersey, January 28, 2013 (panel).

Farkas., C., Carlton, A., Felder, F., K Baker., and M. Rodgers., "Coupled Energy Market Trading and Air Quality models for improved simulation of peak AQ episodes," *Community Modeling and Analysis*

System Conference, Durham, North Carolina, October 15-17, 2012 (presentation).

Selcuklu., S., Coit, D., Felder, F. and Rodgers, M., "Multi-Objective Generation Expansion Planning (GEP) Problem Optimization Using Pareto Uncertainty Index," INFORMS, Phoenix, Arizona, October 12-15, 2012 (presentation).

Rodgers, M., Coit, D., Felder, F. and Selcuklu, S., "A Roadmap for Formulating the Generation Expansion Planning Model to Include Societal Health Costs," INFORMS, Phoenix, Arizona, October 12-15, 2012 (presentation).

Felder, F., Ohio Clean Energy Transmission Conference, "What Drives Electricity Prices," Panel Discussion, Ohio State University, August 6, 2012 (presentation).

Felder, F., "Social and Economic Dimensions of Energy Choices," *Third Annual International Summer Symposium,* Rutgers University, June 4-6, 2012 (presentation).

Felder, F., "Design and Governance of Market-Based Electric Power Systems," *Third International Engineering Systems Symposium,* Council of Engineering Systems Universities, Amsterdam, Netherlands, June 18-20, 2012 (presentation).

Felder F. and C. Loxley, "The Implications of a Vertical Demand Curve in Solar Renewable Portfolio Standards," 31st Annual Eastern Conference, Advanced Workshop in Regulation and Competition, Center for Research in Regulated Industries, Rutgers University, June 16-18, 2012 (paper and presentation).

Tekiner, H., Coit, D. and Felder, F., "Generation Expansion Planning (GEP) Problems Considering Uncertainty and Risk," INFORMS, Austin, TX, Nov. 10, 2010 (presentation by D. Coit).

Felder, F., "Electricity Markets Workshop", co-course developer and trainer for USAID Contract for South African Power Pool, January 31 through February 4, 2010, Kenya (presentations).

Tekiner, H., Coit, D. and Felder, F., "Effects of Smart Grid Technologies on Generation Expansion Plans," Conference on Applied Infrastructure Modeling and Policy Analysis, Washington, DC, Nov. 13, 2009 (paper and presentation).

Tekiner, H., Coit, D. and Felder, F., "Solving the Single-period Multi-objective Power Generation Expansion Planning Problem," *Proceedings of the Industrial Engineering Research Conference (IERC)*, Miami, FL, June 2009.

Coit, D., Felder, F., and Tekiner, H. "Modeling Trade-offs between Costs, Reliability, and Air Emissions for Computer Data Centers," CCC Workshop on Green Computing, May, 2009.

Felder, F., "Electricity Markets Workshop", co-course developer and trainer for USAID Contract for Central African Power Pool, January 25 through January 30, 2009, Gabon (presentations).

Felder, F., "A Framework for Evaluation of Energy Policy Proposals," IEEE Energy2030, Atlanta, GA, Nov. 17-18, 2008 (presentation and paper in the conference proceedings).

Tekiner, H., Coit, D. and Felder, F. Multi-objective Power Generation Expansion Planning Problem with Monte Carlo Simulation, *INFORMS,* Washington DC, October 2008, pp. 1394-1405.

Felder, F., "Electricity Markets Workshop", co-course developer and trainer for USAID Contract for Bangladesh, August 10 through 14, 2008, (presentations).

Felder, F., "Electricity Markets Workshop", co-course developer and trainer for USAID Contract for Sri Lanka, August 16 through 20, 2008, (presentations).

Felder, F., "Electricity Markets Workshop", co-course developer and trainer for USAID Contract for Eastern African Power Pool, June 15 through June 20, 2008, Senegal (presentations).

Coit, D., Felder, F., and Tekiner, H. Distributed vs. Centralized Planning and Trade-Off Analyses for Electric Power Systems in a Carbon Constrained World, *REI Third Annual Research Symposium*, April 2008.

Felder, F., "Opportunities For and Benefits of Greater Regional Collaboration on Energy Efficiency," Regional Strategies for Advancing Energy Efficiency in the Northeast, Boston, MA, NESCAUM, Boston, MA, March 27, 2008.

Felder, F., "Evaluation of an Appliance Cycling Load Management Program," INFORMS Annual Meeting, Denver, CO, October 24-27, 2004.

Felder, F., "Different Formulations of the Reliability Problem of Restructured Power Systems," CORS/INFORMS International, Banff, Alberta Canada, May 16-19, 2004.

Felder, F., "Advances in Probabilistic Risk Assessment Applied to Management Issues with an Application to the Reliability of a Check Processing Facility," *Trust, Responsibility, and Business*, Society for the Advancement of Management Conference Proceedings 2003.

Felder, F., "Modeling Improvements to Evaluate the Reliability of Restructured Electric Power Systems," presentation, INFORMS Annual Conference, Atlanta, Oct. 19-22, 2003.

Felder, F., "Extension of Probabilistic Risk Assessment Methodology to Management Decisions with an Application to Restructured Electric Power Systems," presentation, INFORMS Annual Conference, San Jose, Nov. 17-20, 2002.

Yoon, Y. and Felder, F., "Study of Loss of Load Probability in Designing Installed Capacity Market," IEEE Conference Proceedings, Chicago, IL, July 2002, pp. 830-835.

Felder, F. and Golay, M., "Risk Analysis in Support of Improved Safety at US Dept. of Energy Facilities," PSAM-5 Conference, Osaka, Japan, 2000, pp. 753-758.

Felder, F., Peterson, S., Tobiason, S., "Testing the Merits of Providing Customized Risk Management," USAEE/IAEE 17th Annual North American Conference, Oct. 27-30, 1996.

Felder, F., "The Application of Financial Option Theory to Electric Utility Decision Making in Integrated Resource Planning and Maintenance Shutdowns," *American Power Conference*

Proceedings, April 18-20, 1995.

Felder, F., "Price Forecasting and Risk Management: An Application of a Random Walk Model to Fuel Choice in Generation Planning," *USAEE Proceeding*, November 1994.

Other Publications

Felder, F. If We Want Clean energy, We Must Get Energy Prices Right, *NJ Spotlight,* April 18, 2017.

Athawale, R., & Felder, F. (2016, December 28). Economic Forecasts New. *New Jersey Business*.

Athawale, R., & Felder, F. (2015, December). Economic Forecasts New. *New Jersey Business*, 46-47.

Bogomolny, D., Felder, F., and Weiner, S. (2005, April). Untangling Environmental Markets. *Environmental Finance*, 27.

Felder, F. (2004). New U.S. Generation Market Power Analysis and Mitigation Procedures: What is the Federal Regulatory Commission Up To? *IPPSO FACTO*, 32-33.

Felder, F. (2003). Lessons Learned from Restructuring the United States Electric Power Industry. *IPPSO FACTO*, 17(4), 38-41.

Felder, F. (2003). The Other Side of Story Telling. *SAM Management in Practice*, No. 3, 1-4.

Felder, F. (1997). Untangling the Reliability Issue. *Electric Perspectives*, 42-48.

Kalt, J., Jaffe, A., Jones, S., and Felder, F. (1996). Regulatory Reform and the Economics of Contract Confidentiality: The Example of Natural Gas Pipelines. *Regulation*, 1, 60-65.

Jorgensen, G., and Felder, F. (1995). New England Power Pool: A Bridge to Competition. *Public Utilities Fortnightly*, 133(13).

Jones, S. and Felder, F. (1995). Natural Gas Pipelines: Roadmap to Reform. *Public Utilities Fortnightly*, 11-13.

Felder, F. (1995, January). Focusing In On Futures and Options. *Electric Perspectives*, 20(1), 47-54.

Jones, S. and Felder, F. (1994). Using Derivatives in Real Decision Making. *Public Utilities Fortnightly*, 132(19).

Book Reviews

Felder, F. (forthcoming). Review of the book *Competition and Regulation in Electricity Markets*, Sebastian Eyre and Michael G. Pollitt (eds.). *The Energy Journal*.

Felder, F. (2017). Review of the book The Economics of Electricity Markets by Darryl R. Biggar and Mohammad Reza Hesamzadeh. *The Energy Journal*, 38(1), 294-296.

Felder, F. (2016). Review of the book *Electricity Restructuring in the United States: Markets and Policy from the 1978 Energy Policy Act to the Present*, by S. Isser. *The Energy Journal*, 37(3), 294 296.

Felder, F. (2016). Review of the book *Electricity Markets and Power System Economics*, by D. Gan, D. Feng, & J. Xie. *The Energy Journal*, 37(2), 289-290.

Felder, F. (2014). Review of the book *Transforming the Grid: Electricity System Governance and Network Integration of Distributed Generation*, by D. Bauknecht. *The Energy Journal*, 35(3), 184 186.

Felder, F. (2013). Review of the book *Carbon Capture and Storage: Technologies, Policies, Economics and Implementation Strategies*, by S. M. Al-Fattah, M. F. Barghouty, & B. O. Dabbouti. *The Energy Journal*, 34(4).

Felder, F. (2011). Review of the book *Electricity Restructuring: The Texas Story*, by L. L. Kiesling and A. N. Kleit. *The Energy Journal*, 32(3), 239-241.

Felder, F. (2009). Review of the book *Deregulation, Innovation and Market Liberalization*, by L. L. Kiesling. *The Energy Journal*, 30(4), 192-195.

Felder, F. (2008). Review of the book *Competitive Electricity Markets and Sustainability*, by F. Lévêque. *The Energy Journal*, 29(3), 177-180.

Felder, F. (2008). Review of the book *Electric Choices: Deregulation and the Future of Electric Power*, by A. N. Kleit. *The Energy Journal*, 29(1), 175-178.

Felder, F. (2007). Review of the book *Electricity Market Reform: An International Perspective*, by F. P. Sioshansi & W. Pfaffenberger. *The Energy Journal*, 28(1), 173-174.

Felder, F. (2006). Review of the book *Electricity Deregulation: Choices and Challenges*, by J. M. Griffin & S. L. Puller. *The Energy Journal*, 27(4), 181-183.

Felder, F. (2006). Review of the book *Risk Assessment of Power Systems: Models, Methods and Applications*, by W. Wi. *Interfaces*, 36(2), 179-180.

Felder, F. (2005). Review of the book *Optimization Principles: Practical Applications to the Operation and Markets of the Electric Power Industry*, by N. Rau. *Interface*, 35(5), 440-441.

Felder, F. (2005). Review of the book *The Next Generation of Electric Power Unit Commitment Models*, by B. Hobbs, M. Rothkopf, R. O'Neill, & H.P. Chao. *Interfaces*, 35(2), 181-182.

Felder, F. (2005). Review of the book *Risk Modeling, Assessment, and Management*, *2nd Edition*, by Y. Y. Haimes. *IIE Transactions*, 37(6), 586.

Felder, F. (2004). Review of the book *The End of a Natural Monopoly: Deregulation and Competition in the Electric Power Industry*, by P. Z. Grossman & D. H. Cole. *The Energy Journal*, 25(4), 135-138.

Felder, F. (2004). Review of the book *Electricity Pricing in Transition*, by A. Faruqui & K. Eakin. *The Energy Journal*, 25(2), 143-144.

Felder, F. (2004). Review of the book *Efficiency Versus Sustainability in Dynamic Decision Making: Advances in Intertemporal Compromising*, by B. Blaser. *Interfaces*, 34(2), 162-163.

Felder, F. (2004). Review of the book *Stochastic Models in Reliability and Maintenance*, by S. Osaki. *Interfaces*, 34(1), 74-75.

Felder, F. (2003). Review of the book *Electricity Economics: Regulation and Deregulation*, by G. S. Rothwell & T. Gómez. *The Energy Journal*, 24(3), 151-152.

Felder, F. (2003). Review of the book *Power System Operations and Electricity Markets*, by F. I. Denny & D. E. Dismukes. *The Energy Journal*, 24(3), 153.

Felder, F. (2002). Review of the book *Power System Economics: Designing Markets for Electricity*, by Steven Stoft. *The Energy Journal*, 23(4), 112-114.

Felder, F. (2001). Review of the book *Pricing in Competitive Electricity Markets*, by A. Faruqufsi & K. Eakin. *The Energy Journal*, 22(4), 112-114.

Felder, F. (1999). Review of the book *Deregulation of Electric Utilities*, by G. Zaccour. *The Energy Journal*, 20(3), 160-162.

Felder, F. (1998). Review of the book *Electric Utility Restructuring: A Guide to the Competitive Era*, by P. Fox-Penner. *The Energy Journal*, 19(3), 133-135.

Felder, F. (1998). Review of the book *International Comparisons of Electricity Regulation*, R. J. Gilbert & E. P. Kahn. *The Energy Journal*, 19(1).

Felder, F. (1997). Review of the book *A Shock to the System: Restructuring America's Electricity Industry*, by T. J. Brennan. *The Energy Journal*, 18(3), 140-142.

Felder, F. (1996). Review of the book *The Privatization of Public Utilities*, by L. S. Hyman. *The Energy Journal*, 17(4), 163-165.

Felder, F. (1994). Review of the book *Electric Utility Mergers: Principles of Antitrust Analysis*, by M. W. Frankena & B.M. Owen. *The Energy Journal*, 15(4), 233-234.

Reports

Cottrell, A., Nielsen, V., Cassidy, B., O'Rourke, K., Felder, F., Freed, M., Jafari, M., Mahani, K., Hunter, S. and Walker, T. *CHP and Fuel Cell Evaluation Study for New Jersey*, November 3, 2016.

Bank, J., Cheng, D., Costyk, D., Leyo, M., Seguin, R., Woyak, J., Acharay-Menon, A., Steffel, S., Athawale, R., and Felder, F., *Model-Based Integrated High Penetration Renewables Planning and Control Analysis*, Final Report, DOE SUNSHOT, DOE Award Number: DE-EE0006328, September 30, 2015.

Center for Energy, Economic and Environmental Policy, *Analyzing the Costs and Benefits of Electric Utility Hardening Efforts in Response to Severe Weathe*r, Final Report to the New Jersey Board of Public Utilities, November 30, 2014.

Consumer Advisory Council to the New York Independent System Operator, *Recommendations of the NYISO Consumer Advisory Council to the NYISO Board of Directors*, November 11, 2013.

Center for Energy, Economic & Environmental Policy, *EDC Solar Long-term Contracting Program Analysis*, August 15, 2012.

Seneca, J., Mantell, N., Lahr, M., Felder, F., Zobian, A., Irving, W., *Economic Impacts of PSE&G's Burlington-Camden Transmission Network Upgrade,* Submitted to PSE&G, December 2011.

Center for Energy, Economic & Environmental Policy, *A Review of Connecticut's Renewable Portfolio Standards,* July 2011.

Center for Energy, Economic & Environmental Policy, *Analysis for the 2011 Draft New Jersey Energy Master Plan Update*, March 2011.

Lathrop, R., Clough, B., Cottrell, A., Ehrenfeld, J., Felder, F., Green, E., Specca, D., Vodax, M., Xu, M., Zhang, Y. and Vail, C., *Assessing the Potential for New Jersey Forests to Sequester Carbon and Contribute to Greenhouse Gas Emission Avoidance*, prepared for the New Department of Environmental Protection, March 2011.

Center for Energy, Economic & Environmental Policy, *PSE&G Energy Technology Demonstration Grant Program – Final Report*, March 2011.

Lahr, M., Coughlin, E. and Felder, F., *Economic Impacts of Energy Infrastructure Investments,* October 2010.

Seneca, J., Mantell, N., Lahr, M., Hughes, J., Felder, F., Cottrell, A., Irving, W. and Knox, P. "Economic Impact Analysis: Proposed Upgrades to PSE&G's Branchburg-Roseland-Hudson Transmission Lines," Edward J. Bloustein School of Planning and Public Policy, Rutgers University, September 2010.

Seneca, J., Mantell, N., Felder, F., Lahr, M., Cottrell, A. and W. Irving, "Economic Impacts of the Proposed BlueOcean Energy Offshore Liquid Natural Gas Terminal on New Jersey: Update and Expansion of the 2007 Study," Edward J. Bloustein School of Planning and Public Policy, Rutgers University, July 2010.

Bloustein School, Modeling Report of the Energy Master Plan, April 17, 2008.

Felder, F., "New Performance-Based Standards for Standby Power: Reexamining Policies to Address Changing Power Needs," Clean Energy Group Report, December 2007.

Seneca, J., Mantell, N., Lahr, M., Felder, F., Irving, W. and Davy, J. "Economic Impacts of the Proposed BlueOcean Energy Offshore Liquid Natural Gas Terminal on New Jersey", Edward J. Bloustein School of Planning and Public Policy, Rutgers University, July 2007.

Seneca, J., Hughes, J., Felder, F., Lahr, M., Mantell, N., Lovrien, N. and Irving, W. "Economic Impact of BP's Proposed Crown Landing LNG Terminal", Edward J. Bloustein School of Planning and Public Policy, Rutgers University, February 2007.

Center for Energy, Economic & Environmental Policy, *New Jersey Meadowlands Commission Renewable Energy Task Force: Background Report on New Jersey's Energy & Policy Landscape*, August 2006.

Center for Energy, Economic & Environmental Policy, *New Jersey's Energy Infrastructure: Investing in our Future*, March 2006.

Center for Energy, Economic & Environmental Policy, *Northeast RPS Compliance Markets: An Examination of Opportunities to Advance REC Trading,* October 12, 2005.

Center for Energy, Economic & Environmental Policy, *Appliance Cycling Evaluation*, September 2, 2005.

Center for Energy, Economic & Environmental Policy, *Assessment of Customer Response to Real Time Pricing Report: RESA Final Report for Task 1*, June 30, 2005.

Center for Energy, Economic & Environmental Policy, *Evaluation of CO2 Emission Allocation as part of the Regional Greenhouse Gas Initiative (RGGI)*, June 30, 2005.

Center for Energy, Economic & Environmental Policy, *Economic Impact Analysis of a 20% New Jersey Renewable Portfolio Standard*, December 1, 2004.

Center for Energy, Economic & Environmental Policy, *New Jersey and the Hydrogen Economy*, July 21, 2004.

Felder, F. and Hansen, K., The U.S. Nuclear Power Industry and Electric Industry Restructuring, Center for Advanced Nuclear Energy Systems, Massachusetts Institute of Technology, MIT-NFC-TR-032, July 2001.

Apostolakis, G., Golay, M., Chaniotakis, E., Borgonova, E., Felder, F., Ghosk, T., Sui, Y., Rempe, J., Leahy, T. and Knudson, D. "Review of Applicable U.S. Department of Energy and U.S. Nuclear Regulatory Commission Activities (Project Task 1)," MITNE-316, Department of Nuclear Engineering, M.I.T., Cambridge, MA, June 1999.

Golay, M., Dulik, J., Felder, F., and Utton, S. "Project on Integrated Models, Data Bases and Practices for Risk-Informed, Performance-Based Regulation of Nuclear Power: Final Report", MIT-ANP-TR-060, Program for Advanced Nuclear Power Studies, M.I.T., Cambridge, MA, December 1998.

Sponsored Research

New Jersey Offshore Wind Strategic Plan, New Jersey Board of Public Utilities, $259,590, Principal Investigator, July 2018 through June 2019.

Clean Energy Evaluation and Market Assessments, New Jersey Board of Public Utilities, $926,284, Principal Investigator, July 2016 through October 2017.

Clean Energy Evaluation and Market Assessments, New Jersey Board of Public Utilities, $926,284, Principal Investigator, September 2015 through June 2016.

Clean Energy Evaluation and Market Assessments, New Jersey Board of Public Utilities, $908,231, Principal Investigator, June 24, 2014 through November 6, 2015.

New Jersey Energy Resilience Bank, New Jersey Board of Public Utilities (funded by U.S. Department of Housing and Urban Development), $230,000, Principal Investigator, October 17, 2014 to March 31, 2017.

Solar Utility Networks: Replicable Innovations in Solar Energy (SUNRISE), U.S. Department of Energy (Subcontractor to PHI Services Company), $30,000, Principal Investigator, September 1, 2014 to August 31, 2016.

Clean Energy Evaluation and Market Assessments, New Jersey Board of Public Utilities, $1,356,553, Principal Investigator, June 2013 through November 2014.

Review of Impact Evaluation Contractors and Work Product, PSE&G, $113,479, Principal Investigator, January 15, 2012 to December 30, 2015.

Electricity Demand and the Impacts on Air Quality, Rutgers University Faculty Grant Proposal, $10,261, Principal Investigator, December 6, 2011 to December 30, 2012.

Evaluation of Reports re: Proposed Atlantic Wind Connection Backbone Transmission Project, Atlantic Wind Connection, $13,860, co-Principal Investigator, September 1, 2011 to October 31, 2011.

Review of Connecticut Renewable Portfolio Standards, Connecticut Energy Advisory Board, $58,963, Principal Investigator, February 18, 2011 to December 31, 2011.

Collection of Wind Resource Data, New Jersey Board of Public Utilities, $4,889, Principal Investigator, January 1, 2011 to September 30, 2011.

Economic Impacts of Water Main Infrastructure Investments, Winning Strategies, $40,782, Principal Investigator, December 20, 2010 to June 1, 2011.

Economic Impact of Accelerated Infrastructure Improvement Projects, New Jersey Natural Gas Company, $13,436, Principal Investigator, November 8, 2010 to January 14, 2011.

Economic Impacts of Water Main Infrastructure Investments, Aqua America, Inc., $17,702, Principal Investigator, November 15, 2010 to March 31, 2011.

Energy Technology Grants, PSEG Services Corporation, $236,000, Principal Investigator, December 1, 2009 to December 31, 2011.

Impacts of Energy Infrastructure, New Jersey Natural Gas, $13,587, June 17, 2010 to August 3, 2010.

Describe and Quantify the Economic Benefits of the NJ DEP Action Plan for the NJ Global Warming Response Act, New Jersey Department of Environmental Protection, $15,630, Principal Investigator, July 14, 2009 to October 14, 2009.

MOA between Rutgers' Center for Energy, Economic and Environmental Policy (CEEEP) and the New Jersey BPU/Clean Energy Program, New Jersey Board of Public Utilities, $1,830,281, Principal Investigator, June 1, 2009 through May 31, 2013 (covering four contracts).

Innovative Partnership Institute, New Jersey Department of Environmental Protection, $6,000, co-Principal Investigator, April 2009.

New Jersey Department of Environmental Protection: Assessing the Potential for New Jersey Forests to Sequester Carbon and Contribute to Greenhouse Gas Emission Avoidance, $7,000, co-Principal Investigator, May 2009.

New Jersey Office of Clean Energy Program: Research and Related Activities Regarding the Energy Efficiency Program, Principal Investigator, $244,367, September 1, 2008, to April 30, 2009.

Comprehensive Assessment of the PA Technical Reference Manual, Clean Power Markets, $187,950, Principal Investigator, October 1, 2008 to December 31, 2012.

New Jersey Hydrogen Learning Center, New Jersey Board of Public Utilities, Principal Investigator, $73,928, May 1, 2008 to June 20, 2009.

New Jersey State Energy Master Plan (Part 3), New Jersey Board of Public Utilities, Principal Investigator, $200,127, November 1, 2007 to October 31, 2008.

New Jersey State Energy Data Center (Part 2), New Jersey Board of Public Utilities, $175,989, Principal Investigator, Nov. 14, 2006 through December 31, 2007.

New Jersey State Energy Master Plan (Part 2), $216,570, New Jersey Board of Public Utilities, Principal Investigator, October 1, 2006 to June 30, 2008.

Diesel Generator and Performance Standard Abstract, Clean Energy Group, $10,000, Principal Investigator, April 30, 2007 to December 31, 2007.

Rutgers Energy Institute, The Future Electric Power System in a Carbon Constrained World, $30,000, co-Principal Investigator, 2007-2008.

New Jersey Meadowlands Renewable Energy Task Force, New Jersey Meadowlands, $100, 000, Principal Investigator, May 15, 2006 to October 31, 2008.

Natural Resources Defense Council, Energy Efficiency, $15,000, Principal Investigator as of Oct. 30, 2006 (co-Principal Investigator prior), July 26, 2005 through Dec. 31, 2006.

New Jersey Board of Public Utilities, New Jersey State Energy Data Center, $99,965, Principal Investigator as of Oct. 30, 2006 (co-Principal Investigator prior), Dec. 1, 2005 through Dec. 31, 2006.

New Jersey Board of Public Utilities, New Jersey State Energy Master Plan, $140,747, co-Principal Investigator, Feb. 1, 2005 through May 24, 2006.

New Jersey Board of Public Utilities, New Jersey Hydrogen Learning Center, $200,000, Principal Investigator as of Oct. 30, 2006, Feb. 1, 2005 through Aug. 31, 2007.

New Jersey Board of Public Utilities, New Jersey Energy Efficiency Evaluation, $523,837, Principal Investigator as of Oct. 30, 2006, (investigator prior), Jan. 1, 2005 through Dec., 31, 2006.

New Jersey Board of Public Utilities, State Technologies Advancement Collaborative, $43,881, co-Principal Investigator, May 11, 2005 through August 31, 2006.

New Jersey Board of Public Utilities, Evaluation of CO_2 Emission Allocation as part of the Regional Greenhouse Gas Initiative, $15,000, co-Principal Investigator, April 15, 2005 through June 30, 2005.

Retail Electricity Supply Association, Assessment of Customer Response to Real Time Pricing, $41,000, co-Principal Investigator, Jan. 1, 2005 through Oct. 31, 2005.

New Jersey Board of Public Utilities, Economic Impact Analysis of a 20% New Jersey Renewable Portfolio Standard, *2004,* $204,247, Senior Investigator*,* Nov 1, 2003 through Jan. 31, 2005.

New Jersey Board of Public Utilities, New Jersey Electric Distribution Reliability Standards, $33,999, Investigator, Feb. 1, 2004 through Dec. 31, 2004.

Rutgers University Teaching

Climate Change, Public Health and Policy (undergraduate)
Sustainable Energy Policy and Planning (graduate)
Introduction to Statistics (undergraduate and graduate)
The Science, Technology and Policy of Global Climate Change (undergraduate Byrne seminar, honors undergraduate seminar, undergraduate seminar at University of Konstanz)
Energy Engineering, Economics and Policy (graduate seminar; joint course with Princeton University)
Integrated Energy Challenges and Opportunities I and II (year-long graduate seminar)
Energy Planning for Communities Living in Landfills (Planning Studio)
Directed Studies: Victoria Nielsen (Fall 2013); Allison Bridges, Kathryn McKelvey, and Ishanie Niyogi (Spring 2013); Shankar Chandramowli (Summer 2012, Fall 2012, Fall, 2013), Zachary Froio (Fall 2017), Pratyusha Kiran (Fall 2017), Pranay Kumar (Fall 2017), Ashley Scull (Fall 2017)
In-depth Introduction to Electricity Markets (two-day professional short course)
Cost Benefit Analysis of Energy Efficiency and Renewable Energy Projects (one-day professional short course)
Environmental Management (four-day professional short course)

Rutgers University Service

Post-doctoral, Dissertation, Master Thesis, and Undergraduate Advisor/Committees:

- Jose Espiritu Nolasco, System Reliability Estimation and Component Replacement Analysis for Electricity Transmission and Distribution Systems, Oct. 2007 (external department doctoral committee member)
- Hatice Tekiner, Multi-Objective Power Generation Expansion Planning Considering Environmental Impacts and Smart Grid Technologies, Jan. 2008 to May 2010 (external department doctoral committee member)
- Ariel Martin, Development of a Decision Support System to Operate the Supplemental Lighting System in a Tomato Greenhouse Equipped with an On-site Power Generator, October 2013 (external department doctoral committee member)
- Bernhard Brauß, The Issue-Attention Cycle in Energy Policy, Bachelor Thesis, University of Konstanz, Department of Politics & Public Administration, March 2012 (Appraiser)
- Shuya Li, Robust Optimization of Generation Expansion Planning Problems Considering Climate Change's Uncertain Impact, September 2012 to May 2014 (external department masters committee member)
- Caroline Farkas, Impact and Sensitivity Analyses of Energy Sector Emissions: Air Quality Modeling of the PJM Region, Dec. 21, 2015, (external department doctoral committee member)
- Saltuk Bugra Selcuklu, Multi-objective Generation Expansion Planning Considering Uncertainty and Modeling with the Pareto Uncertainty Index, October 2015 (external department doctoral committee member)
- Shankar Chandramowli, Impact of Climate Change on Electricity Systems and Markets, January 2015 (doctoral committee chair)
- Xiaojun (Gene) Shan, Ph.D., Improving the Modeling of Offshore Wind and Electric Distribution Reliability for Public Policy Formulation, post-doc advisor, Jan. 2014-Dec. 2014
- Rebeca Meier, "Feed-in Tariff or Renewable Portfolio Standard – A Quantitative Analysis of the Impact of current Energy Policies on the Provision of Renewable Energy," Joint Masters Thesis with University of Konstanz and Rutgers University, Spring 2016
- Shane Patel, Fall 2014, "Characteristic Problems of Government-Supported Demonstration Scale Energy Innovation: Establishing A Framework for the Evaluation of Energy Innovation Government Programs, undergraduate research paper
- Chhayang Patel, 2014-2015 academic year, undergraduate Arresty Research Program Adviser
- Rutgers Energy Institute Summer Intern co-Adviser (Kaila Roffman, Summer 2015; Christopher Cohane, Summer 2014)
- Allison Bridges, Leveraging Amenity-Led Growth and Collective Action For Sustainable Development In Florianópolis, 1965-2016, April 2016
- Eric Zimmermann, Internship Supervisor, Summer 2016
- Brian Kemp, Internship Supervisor, Summer 2016
- Mark Rodgers, Simulation-based Optimization Models for Electricity Generation Expansion Planning Problems Considering Human Health Externalities, August 2016 (co-chair, doctoral committee)
- Sanling Song, Improving the Modeling of Offshore Wind and Electric Distribution Reliability for Public Policy Formulation, Feb. 2016 to Mar. 2017

- Carla Corona, Understanding Transitions to Sustainability in Developing Countries: The Chilean Energy Transition, May 2016
- Jacob Yu, Solar Market Analysis, Rutgers Energy Institute Summer Internship, 2017

Bloustein Faculty Search Committee (Fall 2018 to Spring 2019)
Bloustein Teaching and Advising Committee (Spring 2018)
Bloustein School Non-tenure Track Appointment and Promotion Committee (April 2018 to present)
Bloustein School Strategic Planning Committee for Research, Practice and Service (March-April 2018)
Hult Prize Challenge, Judge (December 2017)
Bloustein School Search Committee, Research Professor/Director of Research and Evaluation, Heldrich Center for Workforce Development (2017 to 2018)
Bloustein School Liaison with School of Engineering regarding Masters of Energy Systems (Spring 2015)
Board of Advisors, Rutgers EcoComplex Advisory Board, Member, May 6, 2014 to present
Bloustein Faculty Council: Non-tenure Track Committee, May 2014
Lead Instructor for a class on "Sustainable Energy" for New Jersey Governor's School in Engineering & Technology (Summer 2012); Lecturer Summer 2018
Steering Committee, Edward J. Bloustein School of Planning and Public Policy, September 2006 to August 2008
Associate Director, Rutgers Energy Institute, May 2007 to April 2009
New Jersey State Sustainability Institute, Expert Advisory Board (July 2006 to Dec. 2007)

Other Academic Activities

Editorial Boards
Member of Editorial Board, *Utilities Policy* (September 2016 to present)
Member of Editorial Board, *The Electricity Journal* (January 2013 to date)
Book Review Editor, *The Energy Journal* (January 2012 to date)
Member of Editorial Board, *KIEE International Transactions on Power Engineering* (2005 to 2006)
Member of Editorial Board, *SAM Advanced Management Journal*, (December 2002 to August 2004)

Reviewer
*Applied Energy (*June 2018*), WIREs Energy and Environment* (December 2017), *Journal of Planning Education and Research* (June 2017; July 2018), *Energy Research and Social Science* (January 2017), *Energy Efficiency Journal* (February 2018, October 2016), The *Energy Journal* (August 2016; March 2017), *Netherlands Foundation for Fundamental Research on Matter, FOM* (May 2016); *International Political Science Review* (April 2016), *MIT Press* (January 2016), *CSEE Journal of Power and Energy* Systems (November 2015), *Sustainable Cities and* Society (August 2015), *IBM Journal of Research and* Development (May 2015), *Nature Climate Change* (Apr. 2015), *Utilities Policy* (December 2018, June 2018, March 2018, Jan. 2017, Oct. 2016, Jan. 2015, June 2015, July 2015, August 2015, Oct. 2015, April 2016; July 2016), PNAS (Dec. 2014), *Environmental Science & Technology* (Nov. 2014, March 2016; April 2018), *European Journal of Transport and Infrastructure Research* (Sept. 2014, Nov. 2017), *Climatic Change* (Sept. 2014)*, Transportation Research Part D: Transport and Environment* (June 2014, March 2018), *Electric Power Systems Research* (Mar. 2014), *International Journal of Management Science and Engineering Management* (August 2013), *Policy Sciences* (June 2013), *Environmental Science and Technology* (August 2013), Academy of Finland (April 2013),

Nazarbayev University (Winter 2013; Fall 2013; Winter 2017), *Journal of Regulatory Economics* (January 2013), New Jersey Department of Environmental Protection (May 2013)

Invited Academic Activities

Geographical Sciences Committee, National Academies of Sciences, Engineering and Medicine, "Climate Change, Coastal Flooding, and the Electric Power Grid," December 6, 2018.
China-US 2018 Joint Eco-environmental Symposium: Advances in Critical Needs for the Nexus of Food, Energy, and Water Systems, Invited Keynote Speaker, October 24-28, 2018
Symposium on Realizing the Value of Nuclear Engineering – A Celebration of Michael Golay's Career, Cambridge, MA, March 26-27, 2018
Peer Reviewer, US Department of Energy, International Electricity Market Model (Nov. 2016)
University of Texas Interdisciplinary Electricity Conference, "The Nexus of Markets and the Environment," Austin, TX, April 21-22, 2016
Initiative for Sustainable Electric Power Systems Workshop, Penn State University, November 19-20, 2015, invited speaker
INFORMS 2015, organized session on Optimizing Reliability and Resiliency of Electric Power Systems, November 2015
University of Texas Interdisciplinary Electricity Conference, "The Nexus of Markets and the Environment," Austin, TX, April 9-10, 2015
Organizing Committee, Center for Research in Regulated Industries, Rutgers Business School, 34th Annual Eastern Conference
Session Chair, FERC Workshop/Trans-Atlantic Infraday, Electricity Markets Restructuring, Nov. 7, 2014
Invited Lecturer, Center for Sustainable Electric Power Systems Seminar, Penn State University, October 14, 2014
Rutgers Energy Institute, 9th Annual Symposium, "Will the Potential for a Death Spiral in Electricity Rates Hinder Transformation of the Electric Power System?", May 6, 2014
Invited Panelist, 2014 Biennial Workshop in Service Engineering (BeWiSE), Penn State University, September 16-17, 2014
Technical Program Committee, Council of Engineering Systems Universities (June 8-11, 2014)
Invited Participant, KAPSRC, Workshop on Energy Systems Modeling (October 3, 2013)
Invited Participant, MIT Conference on Modeling Social, Technical and Natural Systems for Policy (September 25-27, 2013)
Discussant, Center for Research in Regulated Industries (May 16 & 17, 2013)
Expert participant in *Gathering Global Intelligence to Accelerate Development—Foreign Experts Traveling in Anhui Specialized in New Energy*, (September 24-27, 2012)
Participant, Council of Engineering Systems Universities Conference, Delft, (June 18-20, 2012)

INDUSTRY EXPERIENCE

The Economics Resource Group, Inc., Cambridge, MA, *Senior Consultant* (title upon departure from firm), June 1994 to May 1998

> Lead consultant and case manager for a variety of projects in the electric power industry. Responsibilities included advising clients on wholesale market and power pool restructuring; providing testimony; evaluating regulatory policy proposals; and conducting antitrust, price forecast, and financial analyses.

U.S. Navy, *Lieutenant* (rank upon completion of service), 1987 to1992

Performed the duties of Department Head, Assistant Project Manager, Quality Assurance Manager, and Power Plant Supervisor for a naval nuclear propulsion plant. Planned and scheduled divisional maintenance and supervised and trained shifts of nuclear power plant personnel in power plant operations and maintenance.

OTHER PROFESSIONAL ACTIVITIES

Consumer Advisory Council, New York Independent System Operator, March 18, 2011 to December 1, 2013, Co-Chair.

Energy Services Providers, Troy, NY, Director, March 2005 to July 2006
Member of the Board of Directors of a retail electricity supplier.

Validigm Corporation, New York, NY, *Director*, June 2000 to December 2000
Member of the Board of Directors of a high-tech, computer network evaluation and applications company.

HONORS AND AWARDS

Associate Member, Sigma Xi, Scientific Research Honor Society of North America
Member, Tau Beta Pi, National Engineering Honor Society
Member, Alpha Sigma Nu, American Nuclear Society Honor Society
Twice awarded the Navy Achievement Medal

FRANCES P. WOOD
Director

EDUCATION

1989	Stanford University, Stanford, California – M.S., Engineering Economic Systems
1981	Dartmouth College, Hanover, New Hampshire – A.B., Geography/Engineering Science

EMPLOYMENT HISTORY

1997–Present	OnLocation, Inc., Director, Vienna, Virginia
1981–1996	AES Corporation, Director of Consulting, Arlington, Virginia

SELECTED PROJECT EXPERIENCE

Experience Summary

Ms. Wood has over 35 years of experience in energy and environmental policy analysis. She has managed numerous projects concerning national energy and environmental policy for DOE and other clients. Her specialty areas include integrated energy modeling, transportation energy modeling, building energy modeling, renewable energy, and electricity. She has over 20 years of experience using the National Energy Modeling System (NEMS) for forecasting and policy analysis.

Project Summaries

Climate Change Policy Analysis and Integrated Energy Modeling

Ms. Wood has led multiple analyses of GHG emission reduction policies using the National Energy Modeling System (NEMS). These studies have been conducted for the government, on-governmental organizations, and corporations interested in assessing potential impacts of a variety of policies.

Ms. Wood is currently supporting the Transportation and Climate Initiative (TCI) and the Georgetown Climate Center with modeling and analysis using the NEMS framework. The focus is on reducing carbon emissions from the transportation sector. Because transport electrification is one strategy, the interaction with the electricity markets is also being assessed. Ms. Wood assisted with the modifications to the transportation model of NEMS to better reflect the geographic scope of the TCI participants and improve the model's regional response capabilities. She has interacted with the TCI analysis working group and presented at public webinars in which TCI solicits input from stakeholders.

Ms. Wood managed modeling and analysis support for DOE's Office of Energy Policy and Systems Analysis (EPSA) that included energy supply and demand issues, technologies and policies in addition to climate change. The use of NEMS in many of these analyses allowed the examination of the interaction of different forms of energy and their prices. In support of EPSA, Ms. Wood has conducted numerous studies analyzing CO_2 mitigation strategies. Most recently this work was used in the report "United States Mid-Century Strategy for Deep Decarbonization" published by the Obama Administration, as well as in 2016 Second Biennial Report of the United States of America and the Quadrennial Energy Review. The modeling and analysis was also used in internal briefings and policy discussions. These studies illustrated the effects of the timing and severity of carbon emission reductions on the deployment of technologies and costs for energy. The role of R&D and technology improvements in reducing emissions has also been studied.

She conducted an analysis of the impact of the expansion and extension of the 45Q sequestration tax credits. An integrated approach is important because tax credits are differentiated between CO_2 storage for enhanced oil recovery (EOR) distinct from geologic storage. Thus the economic attractiveness of carbon capture is determined not just electricity revenues and competition in the power market, but also opportunities for EOR. Ms. Wood also managed a project to expand the model's representation of carbon capture at ethanol, hydrogen, and natural gas processing plants.

For over a decade, she managed annual NEMS integrated modeling efforts analyzing the energy savings and environmental benefits of R&D and deployment programs conducted by DOE's Office of Energy Efficiency and Renewable Energy (EERE) including supervisory responsibility for the OnLocation team and preparation of documentation. Key results include the interaction of efficiency gains and deployment of renewable technologies.

As a Director of Consulting at AES, Ms. Wood managed a large modeling support project for the Office of Policy, Planning and Analysis at the DOE, which primarily involved maintaining and operating an integrated energy model of the U.S. energy system called the IDEAS model (8 years). She was responsible for coordinating AES and subcontractor tasks, managing IDEAS model development activities, and assisting DOE with using the model for policy analysis. Ms. Wood coordinated AES's integrated modeling of the Clinton Administration's Climate Change Action, participating in interagency meetings to develop inputs assumptions for the actions and to report modeling results.

Electric Sector and Utility Analysis

For a number of clients, Ms. Wood has led projects that analyze policies to decarbonize electricity generation in the U.S. Policies include R&D efforts to reduce the cost of new low carbon technologies, tax incentives to accelerate the deployment of such technologies, as well as regulatory policies such as clean energy standards.

For EIA, Ms. Wood developed recommendations for NEMS modeling of renewable energy, storage and distributed generation to reflect the potential effects of grid modernization. She recommended modifications to the representation of electricity capacity markets in NEMS and managed their implementation, as well as tested and performed analysis of added representation of operating reserves. She performed analyses of high levels of PV adoption and the implication for the power system that led to enhancements to NEMS to economically account for potential PV curtailments. She also assisted in the addition of solar resource curves and the state level RPS carve outs.

Ms. Wood supported the EPSA at DOE with analyses of alternative clean energy policies in the power sector that have ranged from clean energy standards to emission intensity standards. She managed a model development effort for EPSA to add water considerations to the NEMS electricity model to allow the analysis of energy and water interactions and performed subsequent analyses of impacts of water scarcity on the power sector.

Ms. Wood assisted in the preparation of the several analyses related to electricity restructuring: Comprehensive Electricity Competition Act Supporting Analysis report, a DOE report on Market Power, transmission congestion analysis for the National Transmission Grid Study, and an analysis of FERC's proposed Standard Market Design.

At AES, Ms. Wood conducted a study of the impact that widespread adoption of environmental eternality costs in utility planning would have on the U.S. electric system, including future technology supply mix, utility demand-side program investments, utility emissions, and electricity rates. She

managed a project for the Gas Research Institute examining the investment criteria used by non-utility generators (NUGs) and projecting future NUG capacity. Ms. Wood assisted in an analysis of non-utility generation performed for the Bonneville Power Administration. She managed a Least-Cost Planning project for a New England electric utility client that included assisting in the construction of a computer model to analyze costs of various resource options, such as electricity conservation and non-utility generation, as well as to traditional supply technologies.

Transportation Vehicles and Fuels Analysis

Ms. Wood has managed several analyses of alternative transportation policies using NEMS, including fuel taxes, vehicle mandates and subsidies, CAFE standards, fuel economy feebates, biofuels mandates, and tax policies for highway use of natural gas. She worked closely with several clients on these projects to convey the capabilities of NEMS and assist in the design of scenarios as well as analysis of the results. Most recently there has been a keen interest in electric vehicles and their potential adoption rates and resulting impacts on fossil and electricity consumption. She has worked with others at OnLocation to modify the structure as needed in order to accurately represent the desired policies, an example of which is described above for TCI.

Ms. Wood assisted in the design and implementation of a new transportation model (ITEDD) for EIA's World Energy Projection System Plus (WEPS+). She developed key algorithms regarding travel demands, car ownership, vehicle market shares, and compliance with fuel economy standards. For each of these elements, illustrative examples were developed and shared with EIA before moving to full implementation. Once the initial version of ITEDD was completed, she provided support with further enhancements and analyses conducted with the model. She wrote significant portions of the model documentation. She is currently working on updating to the freight model of ITEDD.

Ms. Wood managed a model development activity to add representation of hydrogen production and delivery to NEMS, including an extension of the model to 2050. She used the model to analyze alternative policy and technology scenarios to illustrate the conditions in which a transition to hydrogen fuel cell vehicles might occur. The model was also used to estimate DOE R&D benefits.

Ms. Wood performed integrated modeling of alternative scenarios of advanced vehicles and fuels for the DOE Multi-Path Transportation Futures Study. She supported the EPA Office of Transportation and Air Quality with analysis of proposed legislation of a transportation low carbon fuel standard.

Buildings Energy Demand Analysis

Ms. Wood has conduct in-depth analysis of residential and commercial energy demand responses to targeted efficiency policies as well as carbon pricing. In one project, she managed an analysis representing the Building Technologies Office (BTO) programmatic activities within the NEMS model. In addition to measuring the program's potential impact on projected energy use in residential and commercial buildings, she helped NREL and BTO gain a deeper understanding of NEMS as part of a longer-term effort to build up a portfolio of tools to support BTO strategic planning and analysis. After successful completion of a set of sensitivity tests and two integrated scenarios, OnLocation was awarded further work to pursue model enhancements. Ms. Wood is managing those efforts regarding representation of building energy management systems and an enhancement of commercial building shell improvements.

Integrated Planning Model (IPM) Version 6:
Charge to the Peer Reviewers

Background

The U.S. Environmental Protection Agency (EPA) uses the Integrated Planning Model (IPM) developed by ICF International (ICF) to project the impacts of potential emissions policies on the U.S. electric power sector in the 48 contiguous states and the District of Columbia over the 2019-2050 time-horizon. IPM is a multi-regional, dynamic, deterministic linear programming model of the U.S. electric power sector. It provides forecasts of least-cost capacity expansion, electricity dispatch, and emission control strategies while meeting energy demand and environmental, transmission, dispatch, and reliability constraints. EPA uses IPM to evaluate the cost and emissions impacts of alternative policies to limit emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon dioxide (CO_2), and air toxics including mercury (Hg) and hydrochloric acid (HCl) from the electric power sector's operations. IPM's deterministic, linear programming formulation not only supports a large-scale model with the required level of detail, but it also allows model runs to be performed, quality assured, and delivered within turnaround times (2-3 days) required by EPA and the many decision makers who use IPM results for policy analysis.

IPM outputs at the state-, regional-, and national-levels add transparency to EPA technical analyses by making it easy for stakeholders and expert reviewers to examine the specific estimated impacts of potential new policies, to evaluate the technical credibility of EPA's projections, and to comment on the consequences of modeled policies.

EPA's Needs for a Power Sector Model

To support periodic policy and regulatory analyses of the electric power sector, EPA needs to routinely access a model of the electric power sector capable of analyzing the projected impact of environmental policies in the 48 contiguous states and the District of Columbia. The model must be able to evaluate the costs and impacts of proposed environmental programs affecting the power sector, such as programs limiting emissions of sulfur dioxide (SO_2), nitrogen oxides (NOx), carbon dioxide (CO_2), mercury (Hg), and hydrogen chloride (HCl). The model must be able to provide forecasts of the future impacts of a wide variety of potential environmental policies affecting generation capacity expansion and retirements, electricity dispatch, fuel use, and emission control strategies expected to be adopted in order to meet potential changes in energy demand and environmental, transmission, dispatch, and reliability constraints.

The model must incorporate sufficient engineering, financial, and geographical detail, as well as both the current and possible status of the power sector, in order to provide EPA with the ability to analyze emission control options encompassing a broad array of emission control technologies along with emission reductions through fuel switching, changes in capacity mix, and electricity dispatch strategies. The model must also be able to capture the complex interactions among the electric power, fuel, and environmental markets.

The power sector model that EPA uses should meet EPA's goals for transparency, scientific integrity, technical accuracy, peer review, and public participation in regulatory development proceedings. One critical component of achieving all these goals is periodic peer review of the power sector model used by EPA. The peer review of the model must follow the procedures and standards of EPA's current policies and guidance on peer review, as described in *EPA's Peer Review Handbook, 4th Edition* (2015).[1]

[1] Available at https://www.epa.gov/osa/peer-review-handbook-4th-edition-2015.

Purpose of Peer Review

In 2018 EPA released a new version of IPM (designated IPM Version 6). This new EPA model platform incorporates important structural improvements and data updates with respect to EPA's previous version (version 5).

This peer review will focus on EPA's IPM Version 6 with the intent of obtaining expert feedback on the adequacy of using IPM to meet EPA's needs for estimating the economic and operational behavior of the power sector under alternative emissions policies over a modeling time horizon of 2019-2050.

Given the scope and intended purposes of IPM Version 6, the goals of the peer review are to:

(a) evaluate the suitability and scientific basis of the methods (model formulation), model assumptions, model outputs, and conclusions derived from the model;
(b) identify specific strengths, weaknesses, limitations, and errors in the model formulation, model assumptions, model outputs, and conclusions derived;
(c) propose specific options for correcting errors and fixing or mitigating weaknesses and limitations in the model formulation, model assumptions, model outputs, and conclusions derived;
(d) check the appropriateness of the set of model-scenarios for addressing uncertainty in potential future power-sector trends and of particular relevance to future power sector emissions.

In addition to reviewing the items listed above, peer reviewers are asked to specifically evaluate the effectiveness of the incremental improvements and updates made in response to the peer review of IPM version 5.[2] Key model enhancements between version 5 and version 6 include increased temporal resolution, improved representation of wind and solar technologies and resources, inclusion of energy storage, updated financial assumptions, and improved model documentation.

Topics to Address

1. Identify strengths, weaknesses, limitations, and errors in the **model documentation and the *Results Viewer***. Is the documentation clear and well-written? Propose options as needed. Specifically, are all the necessary elements included? Are there any extraneous elements? Could simplifications be made? How well does the *Results Viewer* effectively communicate model run results? What additional documentation or model results, if any, would further improve transparency?

2. Identify strengths, weaknesses, limitations, and errors in the structure of the **model formulation (e.g. objective function, constraints, and decision variables and their indices)**. Propose options as needed. Specifically, are all the necessary elements included in order to meet EPA's analytical needs? Are there any extraneous elements? Could simplifications be made?

3. Identify strengths, weaknesses, limitations, and errors in the **model assumptions, model outputs, and conclusions derived**. Propose options as needed. Specifically consider how well the representations of the following items suit EPA's analytical needs:
   a. *Power-sector operation*, including electricity demand and growth, electricity peak demand, transmission, generation, dispatch, capacity additions, capacity factors, and reserve margins;
   b. *Generating technologies*, including existing generating units and new capacity projected to be built by the model, the classification by plant types, and the locational variations;

[2] Available at https://www.epa.gov/airmarkets/response-and-peer-review-report-epa-base-case-version-513-using-ipm.

c. *Emission factors and control alternatives*, including emission factors, existing controls, and available control alternatives within the model;
d. *Power-sector finances and economics*, including costs affecting dispatch, capacity additions, capacity retirements, retrofits, repowerings, and investment risks;
e. *Fuels and renewable resources*, including fuel costs, fuel supply and demand, competing fuel demand from non-electricity sectors, fuel transportation, and renewable resource representation;
f. R*egional and temporal resolution*, including regional representation, selected model run years, selected time segments within a given model year;
g. *Power sector policies*, including representation of current power sector policies that are differentiated by region, by policy mechanism, by nature and treatment of the regulatory instrument (e.g., allowance allocation or rate-based averaging), and by pollutant.
h. *Retail price estimates,* including transmission and distribution prices components, regional variations in prices, and variations in prices across scenarios.

4. Check the appropriateness of the **base set of model-scenarios** for addressing uncertainty in potential future power-sector trends, focused on answering these questions:
    a. Are the base set of model-scenarios (which include a reference case, low demand case, high demand case, low renewable cost case, high renewable cost case, and a high gas cost case) appropriately characterized? How well do these scenarios suit EPA's analytical needs?
    b. Do the model scenarios reflect the most robust sources of uncertainty for the power sector? Are any of the model scenarios extraneous? Outside of a federal regulatory context, are there significant areas of uncertainty in the power sector that are not covered by these scenarios? How well does the range of scenarios suit EPA's analytical needs?

5. What improvements, if any, could be made to support the **analysis of the full range of policy mechanisms** that may be applied to limit power sector emissions? How well does the model scenario capability of IPM version 6 suit EPA's analytical needs?

<u>Topics Not to Be Addressed</u>

1. Peer reviewers are asked to provide expert input on the strengths and weaknesses of the modeling platform, given EPA's choice of a deterministic, least-cost linear programming model. This peer review is not intended to obtain comments or recommendations on other models or modeling approaches for representing the power sector.

2. This peer review is not intended to be an exercise in model validation. The peer review should focus on process and techniques for model evaluation rather than model validation.

3. Peer review is not a mechanism to comment on previous regulatory decisions or policies that were informed by prior versions of IPM. This peer review is intended to focus on current and future applications of IPM Version 6.