The role of natural gas in the domestic energy economy: a story of land-use conflict and non-stationarity

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1/21/2016

Motivation

- The electricity generation mix is undergoing dramatic changes such as an increasing reliance upon variable generation sources (i.e., renewables) and an increasing role for gas fired generators in producing electricity.
- These changes are not only the result of market forces: cheaper natural gas (given shale development) but also environmental regulations like the Clean Power Plan (CPP). The plan establishes state level CO2 emission reduction targets but offers a flexible means of attaining them (i.e., energy efficiency, renewables, nuclear power, retiring coal, etc.).
- The plan has measures in place to prevent a rush to natural gas-fired plants, due to the health, price volatility, and climate risks, such as: allowing a greater role for renewables, phasing the coal to gas switch through delaying the compliance start date (has the added benefit of more planning time for the necessary pipeline and transmission infrastructure), **limiting the allowable rate of combined cycle gas turbines (CCGT) expansion**, etc.
- However, while the CPP limits the transition to natural gas, the domestic generation resource mix will still come to rely on natural gas and renewables more than at present rates and further, we will operate these plants in ways that we haven't in the past, using much of the same infrastructure that is currently in place.
- In this context, how is the electricity production industry responding to changing regulatory, infrastructure, and market conditions? And what do these changes, as well as existing constraints and limitations mean for the reliability of the electricity system in the near-term (i.e., next 10-20 years)?

Research questions:

- **Essay 1:** Are we overestimating recoverable shale gas reserves using traditional resource measures (economically recoverable (ERR) and technically recoverable (TRR) resource)(Published: Blohm et al., 2012)?
- **Essay 2:** What does uncertainty and nonstationarity in gas-fired generator reliability mean for the long-term reliability of our electricity system (and its optimal design)(In progress)?
- **Essay 3:** What is a range of plausible values for the reliability of gas-fired generators given trends in outage rates and uncertainty in parameter estimation (In Progress)?

Contribution to the literature:

- **Essay 1: Shale gas resource estimates**
  - Existing resource estimation techniques (i.e., TRR and ERR) do not consider present land-use or regulations.
  - Given the location of the Marcellus Shale Play in the more densely populated Northeast region of the United States, we expect conflicts between the extraction industry and present land-uses that will limit the total extractable resource to less than the total available resource.

Contribution to the literature:

- **Essay 2: Long-term planning of the electricity production mix**
  - In this paper, we show that the uncertainty and nonstationarity in the forced outage rate parameter can have a significant effect on the design of the future optimal generation mix (i.e., optimal investment decisions made by market participants).
  - We compare the composition, costs, and reliability of our method with existing methods, which rely on single point parameter estimates, in order to highlight the effect on system level reliability.
  - We anticipate that traditional methods significantly underestimate the riskiness of investment decisions and thus, overestimate system reliability, which potentially exposes consumers, generators, and system operators to greater risks of unmet demand.

Essay 3: Contribution to the literature

- **Essay 3: Uncertainty around the outage rate parameter**
  - Power plant reliability estimates are generally incorporated in long-term generation expansion planning models (GEP) via a single point estimate of the outage rate (i.e., FOR, EFOR, etc.).
  - Given ongoing changes in the domestic energy economy, assumptions of stationarity in the reliability parameter are no longer valid. As a result, there is a disconnect between parameter estimates using historical data and future reliability.
  - In this paper, we capture these influences in our estimation of a posterior distribution of the outage rate parameter, which not only captures the inherent uncertainty in the measure but also ongoing trends.
  - The results of our model include the ability to project these trends forward to better understand the impacts of changes in reliability over time.

Why the regulatory concern with supply security?

- Characteristics of natural gas, natural gas demand, and gas-fired plants make the interdependence of the two industry potentially problematic.
  1. Natural gas is not easily stored on-site, which requires the real time delivery of gas for continued plant operation (NERC 2013).
  2. Gas-fired plants are typically served by a single gas pipeline and thus, any issues with the pipeline can prevent the delivery of gas. (NERC 2013).
  3. Present and future natural gas pipeline capacity is based on the peak day firmly contracted capacity, which is pr… s (NERC 20… emand, ma… ccess to pi…
  4. Cl… ransportation, ex…
  5. Na… rces. Large an… equent ra… and forced ou… reserves (NERC 2014a). These types of fluctuations can be hard for pipeline operators to manage. Given the uncertainty of renewable resources the dispatch of gas-fired generation might be larger and less predictable in the future (NERC 2013).
  6. Natural gas demand from the electricity sector is more difficult for the pipeline to meet because of its high point loads, high pressure loads (i.e., higher pressure increases efficiency), large variation in loads, and non-ratable takes (NERC 2011a). In Figure below, we show a figure from NERC 2011a, which illustrates the scale of gas loads in electricity generation, in comparison to other point loads that pipeline operators are more familiar with (NERC 2011a). The takeaway from the figure is that large generator loads can be higher than an entire local distribution company (LDC) and are often served at a single point (as compared to an LDC, which typically has more than one city gate) (NERC 2011a).

Seven reasons to believe that past reliability (i.e., outage rates) doesn't necessarily inform estimates of future reliability (i.e., end of stationarity).

Why the regulatory concern with supply security?

1. Natural gas is not easily stored on-site (for most sites) and thus, requires the real time delivery of gas for continued plant operation (NERC 2013).

Why the regulatory concern with supply security?

2. Gas-fired plants are typically served by a single gas pipeline and thus, any technical issues with the pipeline can prevent the delivery of gas. (NERC 2013).

Why the regulatory concern with supply security?

3. Gas-fired generators prefer interruptible service contracts with pipeline operators. The advantage of interruptible service is that unlike firm service it is priced only on a volumetric basis (no reservation fee) (NERC 2013). Interruptible, as the name suggests, is also the lowest ranking service, which means it is the first to be restricted or reduced during periods of high use, force majeure or maintenance (NERC 2013).

Why the regulatory concern with supply security?

4. Present and future natural gas pipeline capacity is based on the peak day firmly contracted capacity, which is problematic given that gas-fired plants have a preference for interruptible pipeline capacity contracts (NERC 2013).

Why the regulatory concern with supply security?

5. Cheap natural gas prices are increasing demand for gas across industries, in particular in power generation (US EIA 2013).

Why the regulatory concern with supply security?

6. Natural gas-fired generation is increasingly being used to balance the variability of renewable resources.
   - Large amounts of renewables in the generation mix require reactive support and ramping capability.
   - More frequent ramping of conventional generation technology is having unknown effects on maintenance projections and forced outage rates (both of which could be higher) and thus would create a follow on effect requiring more installed reserves (NERC 2014a).
   - Ramping can be hard for pipeline operators to manage. Given the uncertainty of renewable resources the dispatch of gas-fired generation might be larger and less predictable in the future (NERC 2013).

Why the regulatory concern with supply security?

7. Natural gas demand from the electricity sector is more difficult for the pipeline to meet because of its high point loads, high pressure loads (i.e., higher pressure increases efficiency), large variation in loads, and non-ratable takes (NERC 2011a).

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Is this actually an issue: Polar Vortex 2014

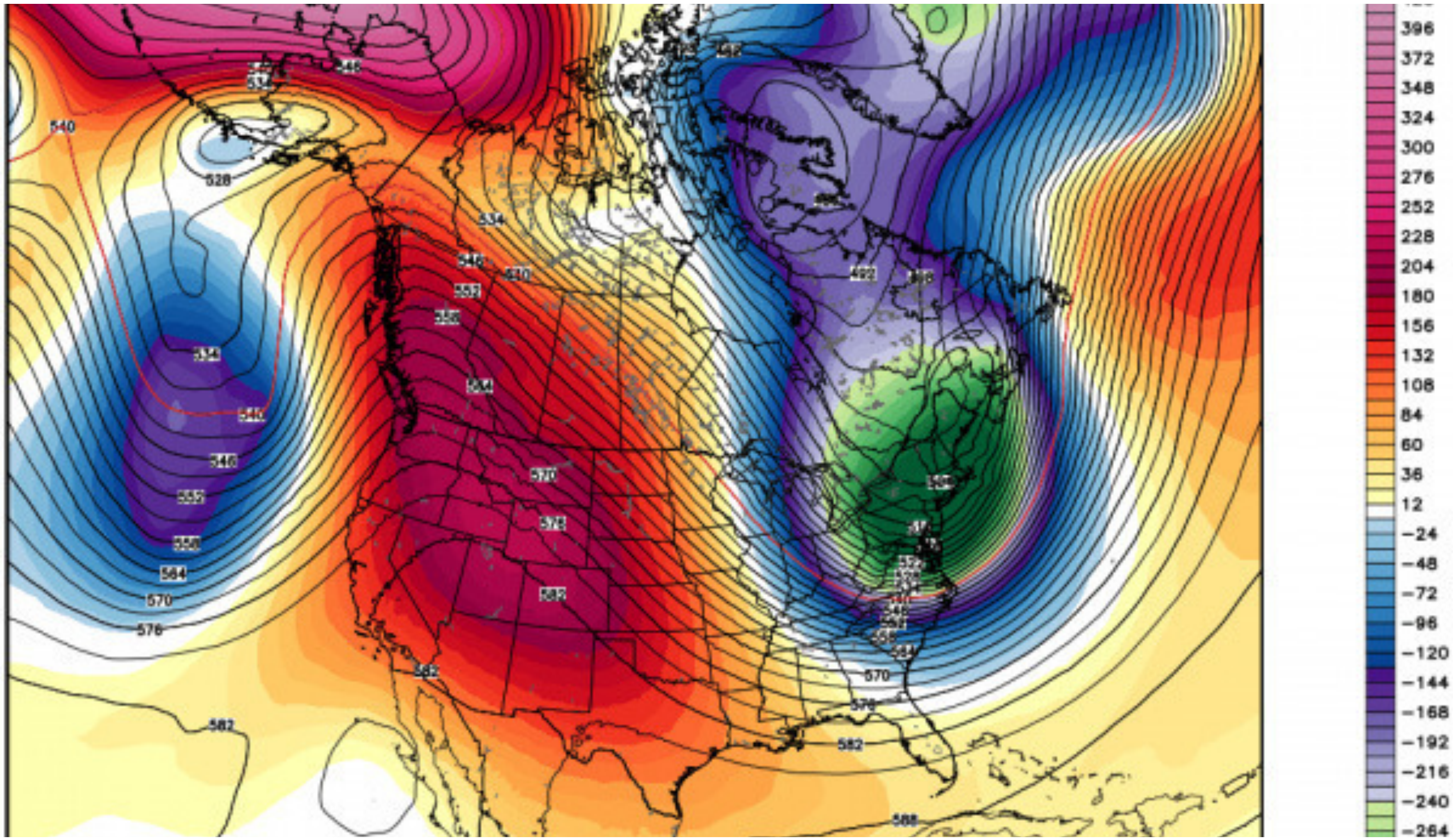


IMAGE: GEOPOTENTIAL HEIGHT ANOMALIES FORECAST FOR JAN. 8, 2015 SHOWS THE AREA OF EXTREMELY COLD TEMPERATURES IN BLUE-GREEN OVER THE EAST, AND AN AREA OF MILDER THAN AVERAGE AIR ACROSS THE MIDWEST AND ALASKA. (Source: WEATHERBELL ANALYTICS)

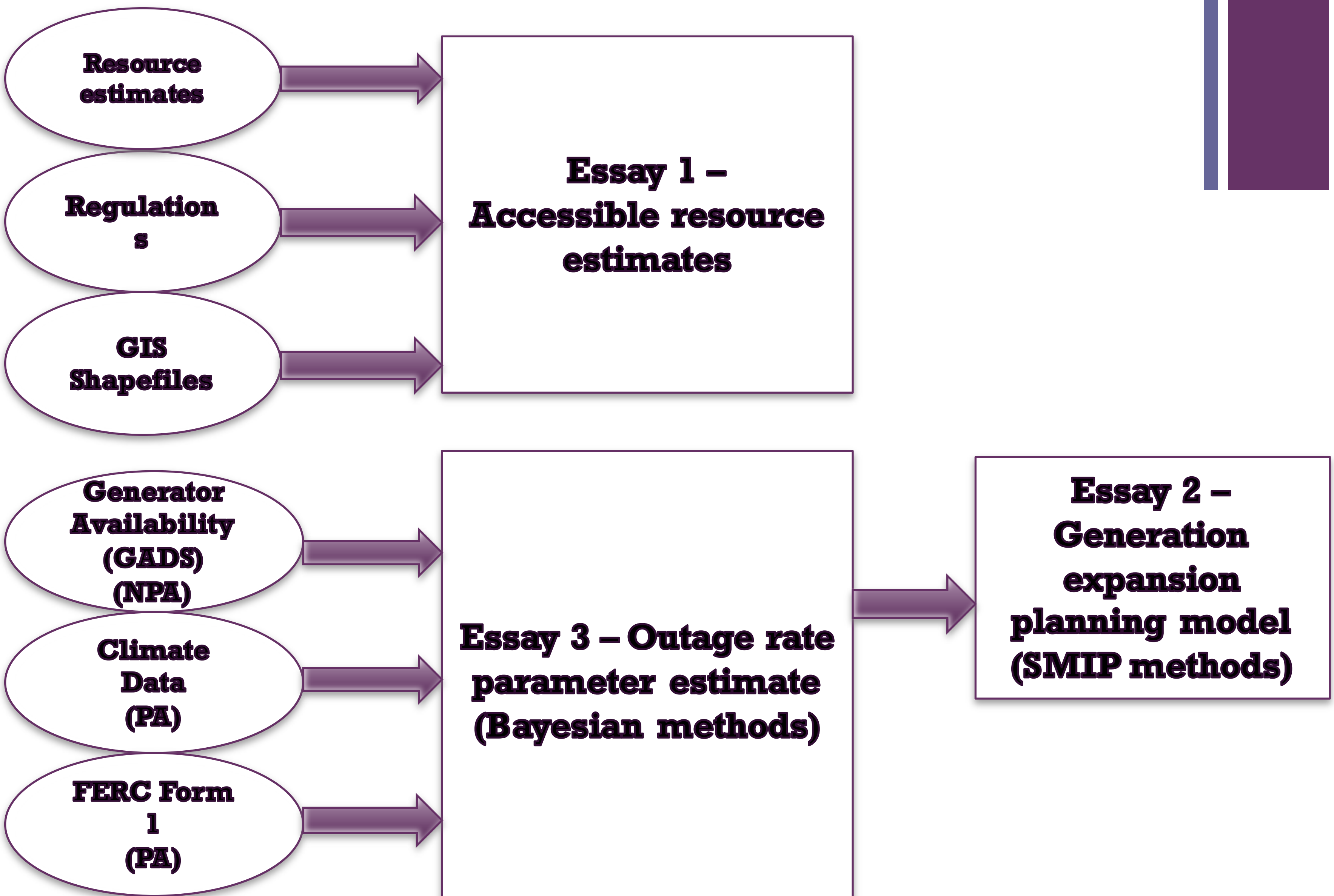
Recap: Energy security concerns

- Much of the capacity additions to the resource mix are anticipated to be natural gas-fired with the bulk of the remainder being renewable sources.
- Pipeline infrastructure is having difficulty adjusting to the increasing quantity of gas-fired generation (as shown by the Polar Vortex event).
- Further, because of the improving efficiency of gas-fired technology and the increasing penetration of variable energy sources, we are using gas-fired resources in different ways than in the past (i.e., more reactive support and ramping) (so the past is probably not the best predictor of future reliability).
- For the reasons we addressed, we believe that using historical outage rates in long-term resource planning would result in overestimating plant level reliability and thus, underestimate system level risk of unmet demand.

Essays

- The following three essays investigate two aspects of the increasing role of natural gas in the US energy economy.
- We first investigate natural gas resource estimates, as the assumptions of natural gas availability necessarily feed into production, consumption, and price estimates. In this essay, we propose the accessible recoverable resource (ARR), which overlays the policy environment (i.e., land use regulations) on top of estimates of the economically and technically recoverable resource (Blohm et al. 2012).
- Next, we investigate the energy security implications of an increasing reliance upon natural gas in the electricity production sector. In this set of essays, we first identify an estimate of the outage rate parameter that incorporates trends and uncertainty before then using that parameter estimate to determine the optimal generation mix in a long-term planning framework.

+ Dissertation structure



Essay 1: Natural gas resource estimation

Blohm, Peichel, Smith and Kougentakis. 2012. The significance of regulation and land use patterns on natural gas resource estimates in the Marcellus shale, Energy Policy, 50:358-69.

Essay 1: Research questions

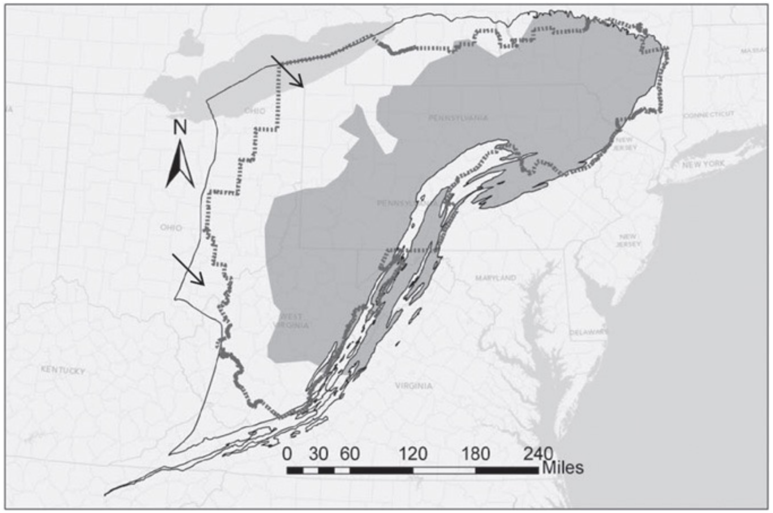
- Are we overestimating the recoverable shale gas reserves using traditional resource measures (ERR and TRR), which by definition do not incorporate existing drilling practices, policies and regulations, or land-use?

Shale gas: Public and policy concerns

Policy concerns with hydraulic fracturing

- Uncertainty of chemicals used in the process
- Potential for ground and surface water contamination
- Difficulty in ensuring proper disposal of flowback
- Lifetime emissions of shale gas development
- Impacts on local infrastructure
- Water use during the drilling process

Marcellus boundaries (Source: Blohm et al., 2012)



Marcellus shale play in New York and Pennsylvania

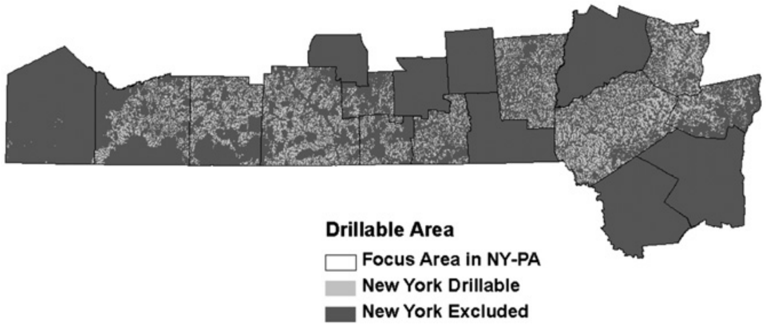
Methods

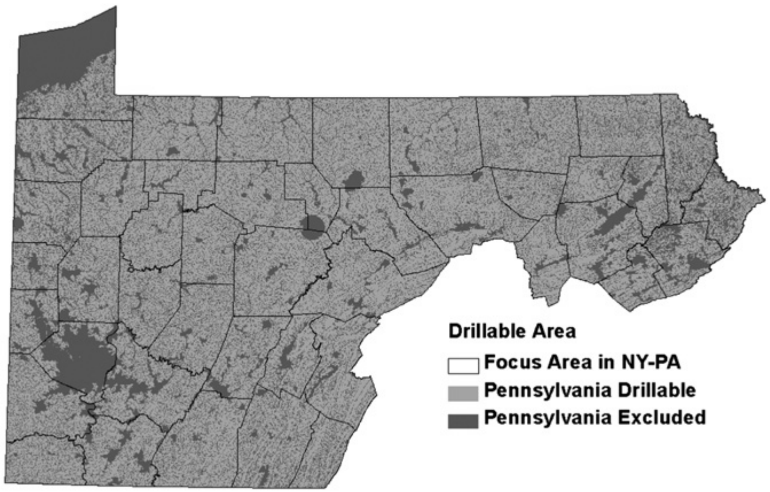
- Identify and review policies for all federal, regional, state, and local level government agencies capable of regulating any aspect of shale gas extraction.
- Using the policies and publically available shapefiles, map the public policy environment to the physical space.
- Intersect the resulting exclusion area masks (i.e., areas off-limits for shale gas drilling in the region) with county level resource estimates to determine the overall effect of policy on the available resource.

Study area (Source: Blohm et al., 2012)

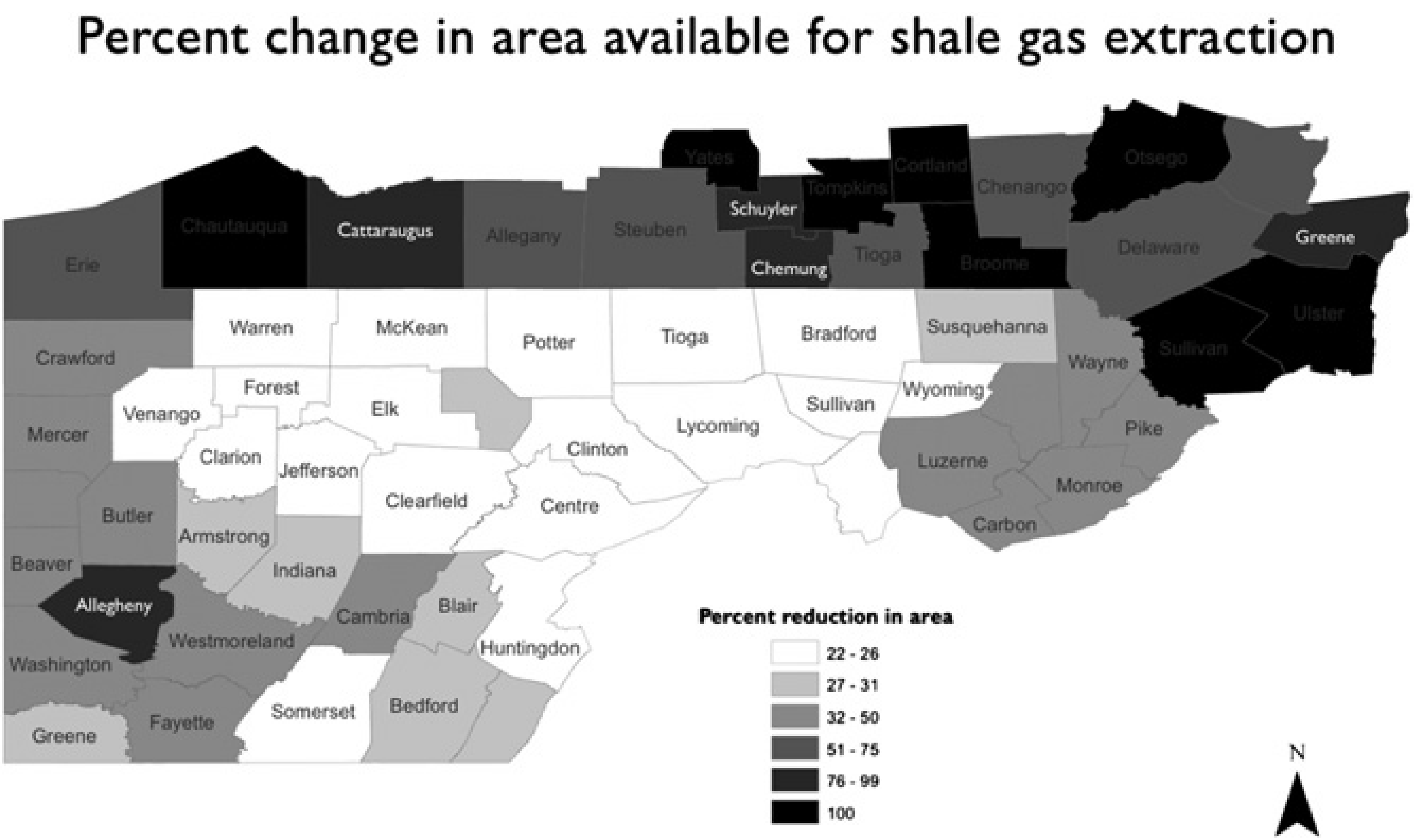
Mapping the shale gas policy environment to the physical space

New York	Pennsylvania





Change in shale gas resource



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Conclusions

- The technically recoverable resource does not take into account existing policies or conflicting land use, which in the crowded Northeastern United States means that traditional measures potentially overestimate the recoverable resource.
- Using our methodology we arrive at the following range of estimates for shale gas in the Marcellus, listing the EIA (2012) first, followed by estimates from Engelder (2011).
- Resource expectations for the New York portion of the Marcellus range between 20–69 TCF. Once we consider the exclusion areas, reserve estimates decline to between 4.2 and 14.4 TCF, a reduction of approximately 79% (Blohm et al., 2012).
- Resource expectations for the Pennsylvania portion of the Marcellus range between 87–300 TCF. In Pennsylvania the reserve estimates, once we consider the exclusion zones, declines to between 60 and 207.9 TCF; a reduction of approximately 31%.
- The total shale gas resource potential for the New York and Pennsylvania portion of the Marcellus ranges between 106 and 369 TCF. In total, given existing and/or proposed policies and regulations approximately 40% of the shale gas resource may be inaccessible in the New York and Pennsylvania portion of the Marcellus (Blohm et al., 2012).

Essay 2: Long-term power planning under uncertainty and nonstationarity

Essay 2: Research questions

- **Essay 2:** What does uncertainty and nonstationarity in the outage rate parameter mean for the long-term generation expansion planning models (i.e., generation mix, risk, etc.)?

Long-term planning: Electricity generation expansion

- Generation expansion planning model can be described as the determination of siting, timing, sizing, and technology choice of new capacity additions in order to meet forecasted demand over a planning horizon that is usually between 10-30 years (Ehrenmann and Smeers 2011; Bakirtzis, Biskas, and Chatziathanasiou 2012).

- There is an extensive literature surrounding the development and application of the generation expansion planning problem (GEP) including the use of mixed integer programming and stochastic mixed integer programming methods.

- We are in the process of building a stochastic mixed integer program model based on existing optimization theory.

- The contribution of our model to the literature is in the assessment of uncertainty and nonstationarity of the outage rate parameter on the optimal resource mix (as compared to existing methods).

GEP: Reliability incorporation

- Reliability is incorporated through deterministic or probabilistic methods (Aghaei 2013a):
  - Deterministic criteria include planning reserve margin (can be set to the largest generation unit capacity in the system). But this does not account for the stochastic nature of unit behavior (i.e. cannot incorporate forced outage rate) OR the size of different types of generating units (Aghaei 2013a).
  - Potentially leads to over investment or insufficient system adequacy in GEP problems (Aghaei 2013a).

- Three stochastic methods are most often used to ensure power system reliability: LOLP, LOLE, and EENS.
  - Loss of load expectation (LOLE) – The number of hours in which demand is not satisfied. And LOLE max ``represents the maximum number of hours along a year during which it is admitted that load is not served due to outages in the generation system'' (Pereira, 2010, p781). More often used than LOLP but related by the equation (Phoon, 2006, p25).
  - Loss of load probability (LOLP) – the probability, over the long-run, of the power system demand exceeding the capacity available (Endrenyi, 1978 from (Phoon, 2006, p23). It can be calculated using daily peak load (i.e. hour demand for a 24-hour period) or using daily peak loads for a 1-year duration using a load duration curve (Phoon, 2006, p23).
  - Expected energy not served (EENS) – reflects the amount of the energy deficit

Literature review

Reference	Model Approach	Transmission constraints	Stochasticity	Uncertainties modeled
Bakirtzis et al. (2012)	MILP	No	Scenario based	Demand, investment budget, CO2 price, RES target, fuel price
Dehghan et al. (2013)	MILP	No	Robust optimization	Load demand, investment and operation costs
Tekiner et al., (2010)	Multi-objective	No	Monte-Carlo	Demand
Gandulfo and Gil (2014)	2-stage SMIP	Yes	Yes (scenario reduction)	Demand
Hemmati et al. (2016)	NL MIP	Yes	Particle swarm methods	Wind production
You et al. (2015)	SMIP		Yes	Demand, wind production
Gil et al., 2015	2-stage SMIP	Yes	Yes (scenario reduction)	Hydro power
Wu (2014)	2-stage SMIP	Yes	Yes (scenario tree with scenario reduction)	Demand, fuel cost

Generator problem

h power production technology
l load segment
i node
ξ scenario

3.2. Generator Problem

$$\max_{x_{hli}(\xi), y_{hi}} \quad \mathbb{E}_\xi \left(\sum_l T(l) \cdot \sum_i \left(\sum_h \pi_{li} \cdot x_{hli}(\xi) - \sum_h C_h \cdot x_{hli}(\xi)\right) - \sum_i \sum_h I_h \cdot y_{hi}\right)$$

$$\begin{aligned} \text{s.t.} \quad x_{hli}(\xi) - y_{hi} \leq 0 & \quad \forall\, h, l, i, \xi \quad (\rho_{hli}(\xi)) \\ -x_{hli}(\xi) \leq 0 & \quad \forall\, h, l, i, \xi \quad (\beta_{hli}(\xi)) \\ -y_{hi} \leq 0 & \quad \forall\, h, i \quad (\lambda_{hi}) \end{aligned}$$

Capacity constraints

Non-negativity constraints

where:

y_{hi}	is the installed capacity for each technology h in MW at each node i
$x_{hli}(\xi)$	is electricity production for scenario ξ at time segment l at node i in MWh using production technology h
C_h	is the marginal cost of production technology h in USD per MWh
π_{li}	is the price of electricity during time segment l at node i
I_h	is the annual investment and maintenance cost in \$ per MW

Transmission system operator

3.3. Transmission System Operator

$$\max_{o_{li}(\xi)} \quad \sum_{\xi} \Pr(\xi) \cdot \sum_{l} T_l \cdot \sum_{i} \pi_{li}(\xi) \cdot o_{li}(\xi)$$

$$\begin{aligned}
\text{s.t.} \qquad \sum_i o_{li}(\xi) &= 0 && \forall\, l, \xi && (\nu_l(\xi)) \\
\sum_i PTDF_{ik} \cdot o_{li}(\xi) - T_{k.up} &\le 0 && \forall\, l, k, \xi && (\gamma_{lk}(\xi)) \\
-\sum_i PTDF_{ik} \cdot o_{li}(\xi) - T_{k.low} &\le 0 && \forall\, l, k, \xi && (\theta_{lk}(\xi)) \\
o_{li}(\xi) \ u.r.s.
\end{aligned}$$

Transmission constraints

where:

$o_{li}(\xi)$	is the transmission services provided by the TSO for scenario ξ
$\pi_{li}(\xi)$	is the market price for electricity received by the TSO in scenario ξ

Market clearing conditions

3.4. Market Clearing Conditions

$$\pi_{li}(\xi) - PC \leq 0 \qquad \forall\, l, i, \xi \quad (z_{li}(\xi))$$

$$q_{li}(\xi) - \left(\sum_h x_{hli}(\xi) + z_{li}(\xi) + o_{li}(\xi) \right) = 0 \qquad \forall\, l, i, \xi \quad (\pi_{li}(\xi)\ free)$$

PC is the price cap in \$ per MWh

$q_{li}(\xi)$ is the demand at node i during load segment l of scenario ξ

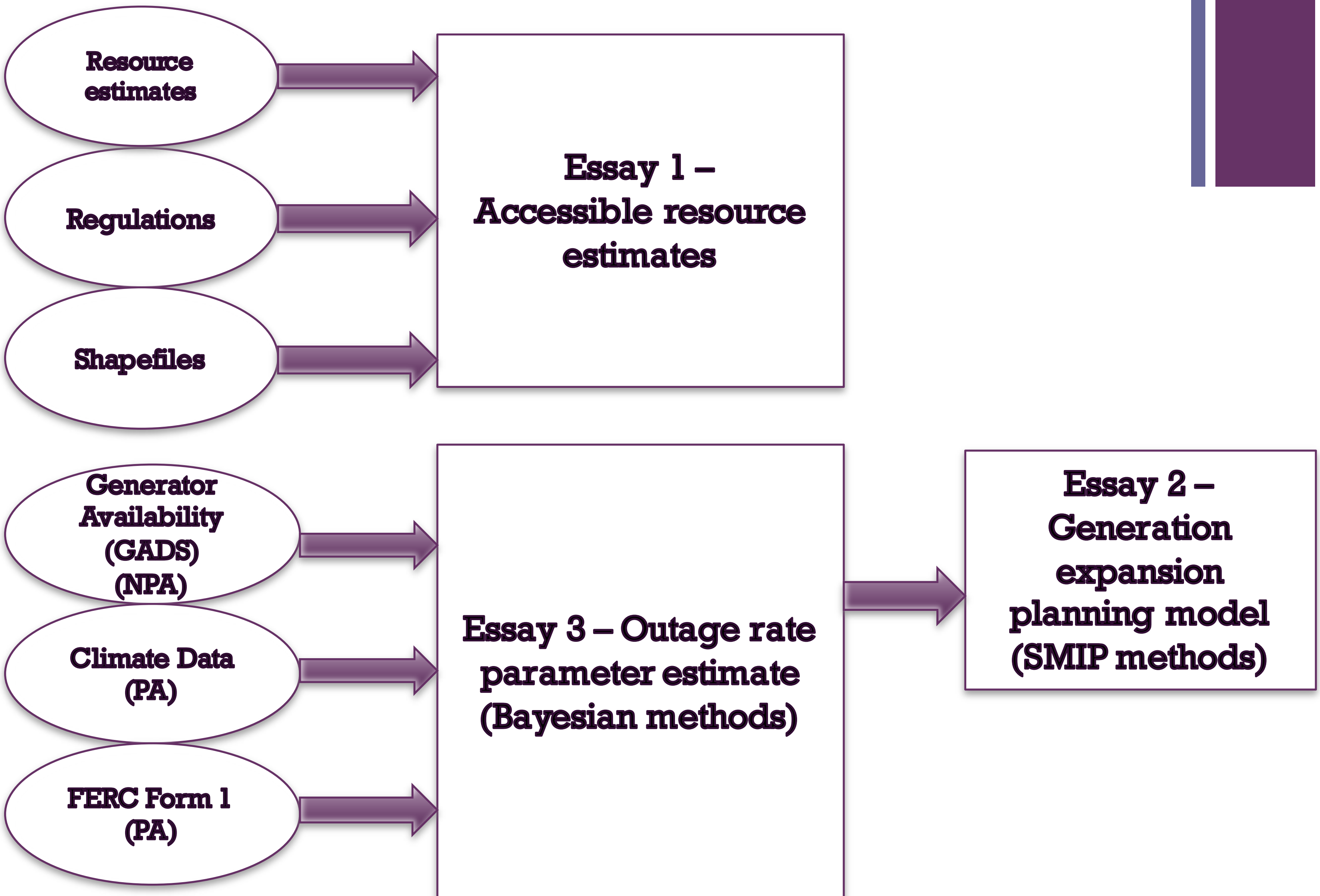
z_{li} is the shortage in MWh

Essay 2: Research design

- Model development is in progress and proceeding as follows:
  1. M1: Price taking/Single firm/single node/multiple production technologies/multiple time periods/demand known
  2. M2: Price taking/Single firm/three nodes/multiple production technologies/multiple time periods/demand known/TSO as profit maximizer/Transmission constraints
  3. M3: …/Stochastic demand
  4. M4: …/Stochastic demand, multi-period (i.e., scenario tree)
  5. …
  6. M?: Stochastic MILP
- Work remains to be done both in model development and parameterization, and solution algorithm implementation.

Essay 3: Uncertainty and nonstationarity in power plant outage rates

+ Dissertation structure



Essay 3: Research questions

- **Essay 3:** What is a range of plausible values for the reliability of gas-fired generators given uncertainty in parameter estimates while controlling for nonstationarity in historical outage rates?

Literature review: A synthesis

- Uncertainty analysis of the outage rate parameter is a well studied problem.
- A significant literature exists that continues to evolve and incorporate advancements in outside methodological techniques.
  - Late 1970's to early 1980's: Recognized need to include uncertainty in the parameter estimates through sensitivity analyses. Methods include treatment of parameter as a random variable, Fourier analysis and basic statistical methods.
  - 1990's saw the introduction of fuzzy set theory, neural networks, and Monte Carlo methods into EFOR parameter estimation.
  - There was continued development of these methods through the 2000s, which also saw evolution in the treatment of uncertainty by the division of it into random and systemic error.
- A small set of literature modeling power plant reliability (nuclear power plants) using Bayesian regression methods:
  - Grant et al. (1999) use a logistic regression model to examine the reliability of commercial nuclear power plants in the US.
  - Poloski and Sullivan (1980) use a logistic regression model to examine backup power at nuclear power plants.
- Given the state of the literature, what is the anticipated contribution of our work?

Contribution to the literature

- The literature cited establishes uncertainty bounds around the outage rate parameter using historical data.
- But we've shown that gas-fired generators are being used differently in the production mix and that existing pipeline infrastructure is having difficulty meeting demand during peak periods.
- Previous techniques are akin to looking backwards to look forwards, which is fine for a stationary world (or with methods that control for trends).
- While the existing literature controls for uncertainty it fails to control for nonstationarity.
- We propose to model outage rates as a function of unit and operation characteristics while controlling for trends in the data and accounting for uncertainty in our methods.

Research design: Bayesian regression estimation

- Problem naturally lends itself to regression techniques
  - Uncertainty characterization in MLE estimation
- We propose to estimate the posterior distribution around the outage rate parameter using the historical reliability data in Bayesian regression framework.
- Bayesian regression techniques:
  - naturally incorporate the uncertainty around the parameter estimate through the generated posterior distribution
  - allow for controlling trends in data and covariates
  - allow for incorporation of data from a variety of data sources through the specification of the prior distribution (i.e., expert elicitation, existing literature, etc.)

Model data

- Generating Availability Data System (GADS) –
  - NERC tracks reliability, availability, and maintainability for each power plant. Of particular interest to this project is the event data that describes equipment failures including the type of outage (i.e. forced, planned, etc.).
  - Publically available (aggregated data): dataset includes unit types, size, number of units, total installed capacity, outage rates, etc.
  - Proprietary dataset (unit level data): plant level data (i.e., outage event information)
- FERC Form 1
  - Contains information on the operational and maintenance cost patterns of power generators
  - All information publically available

Bayesian framework

- Dependent variable - outage rate (i.e., 2-state model):
  - $Y \sim \text{Binomial}[n, \pi(x)]$
  - Where the probability of success/failure ($\pi(x)$) is dependent upon a set of covariates *x* which are linked through the logit-link function
  - $\text{logit}(\pi) = \log[\pi / (1-\pi)] = x^T\beta$
- Covariates predicting unit reliability are known to be a function of:
  - unit design characteristics (i.e., size, type, region, etc.)
  - operational factors (i.e., capacity factor, climate, etc.)
  - maintenance and plant betterment activities (i.e., nonfuel operational and maintenance expenditures per kw) (NERC, 1995, p3).
- We will use Markov Chain Monte Carlo (MCMC) method to estimate the posterior distribution.

Anticipated conclusions: Essays 2 and 3

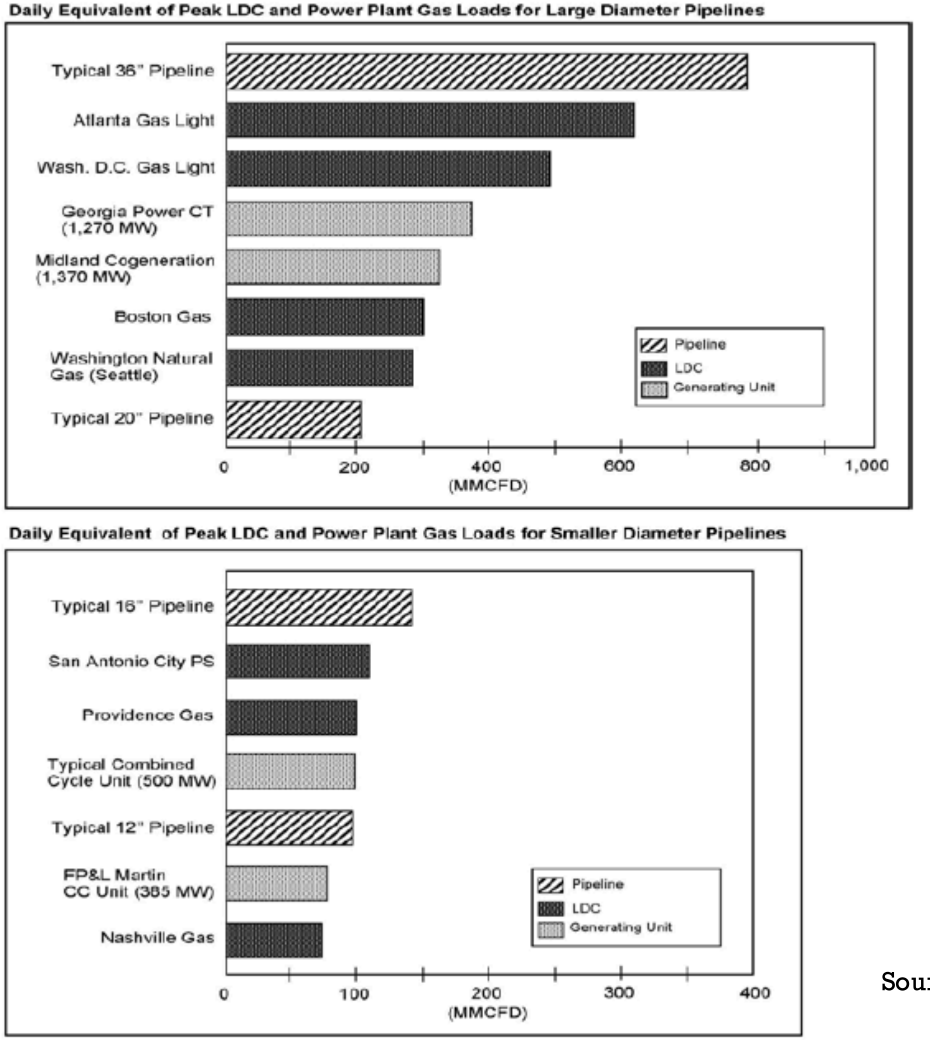
- Given ongoing changes in the domestic energy economy, assumptions of stationarity in the reliability parameter are no longer valid. As a result, there is a disconnect between parameter estimates using historical data and future reliability.
- We show that the uncertainty and nonstationarity in the forced outage rate parameter can have a significant effect on the design of the optimal generation mix.
- Further, we show that existing methods fail to internalize the true risk of unmet demand through their use of a single point estimate of the outage rate parameter.
- As a result, traditional methods significantly underestimate the riskiness of investment decisions and thus, overestimate system reliability, which potentially exposes consumers, generators, and system operators to greater risks of unmet demand.

Proposed timeline

Backup slides

Why the regulatory concern?

FIGURE 7-1: COMPARISON OF LDC, POWER PLANT LOADS AND PIPELINE CAPABILITIES



Source: NERC 2011

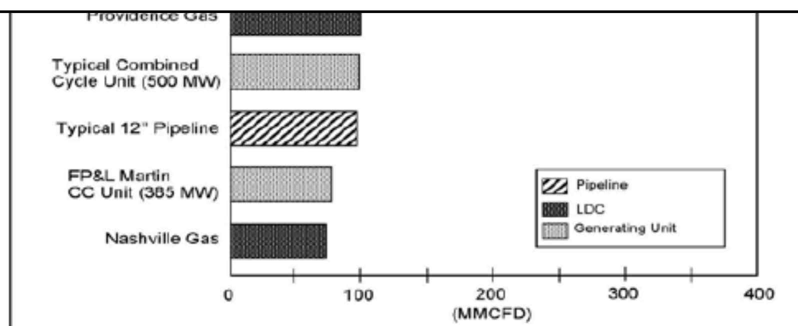
Source: EPRI, Natural Gas for Electric Generation: The Challenge of Gas and Electric Industry Coordination (TR-101239), September 1992.

Why the regulatory concern?

FIGURE 7-1: COMPARISON OF LDC, POWER PLANT LOADS AND PIPELINE CAPABILITIES

Daily Equivalent of Peak LDC and Power Plant Gas Loads for Large Diameter Pipelines

1. Typically, pipeline operators pack the pipelines in the evenings, which increases pressure, to serve the load the next day. As customers withdraw the gas the pressure necessarily declines (NERC 2011a).
2. Problems occur when unexpected events occur that result in higher than anticipated demand and subsequently, reduced system pressure (exacerbated by the slow speed of gas).
3. Historically, this hasn't been a problem but new gas turbines can exhaust the line pack quickly and reduce pressure below generator operational needs (NERC 2011a).



Source: NERC 2011

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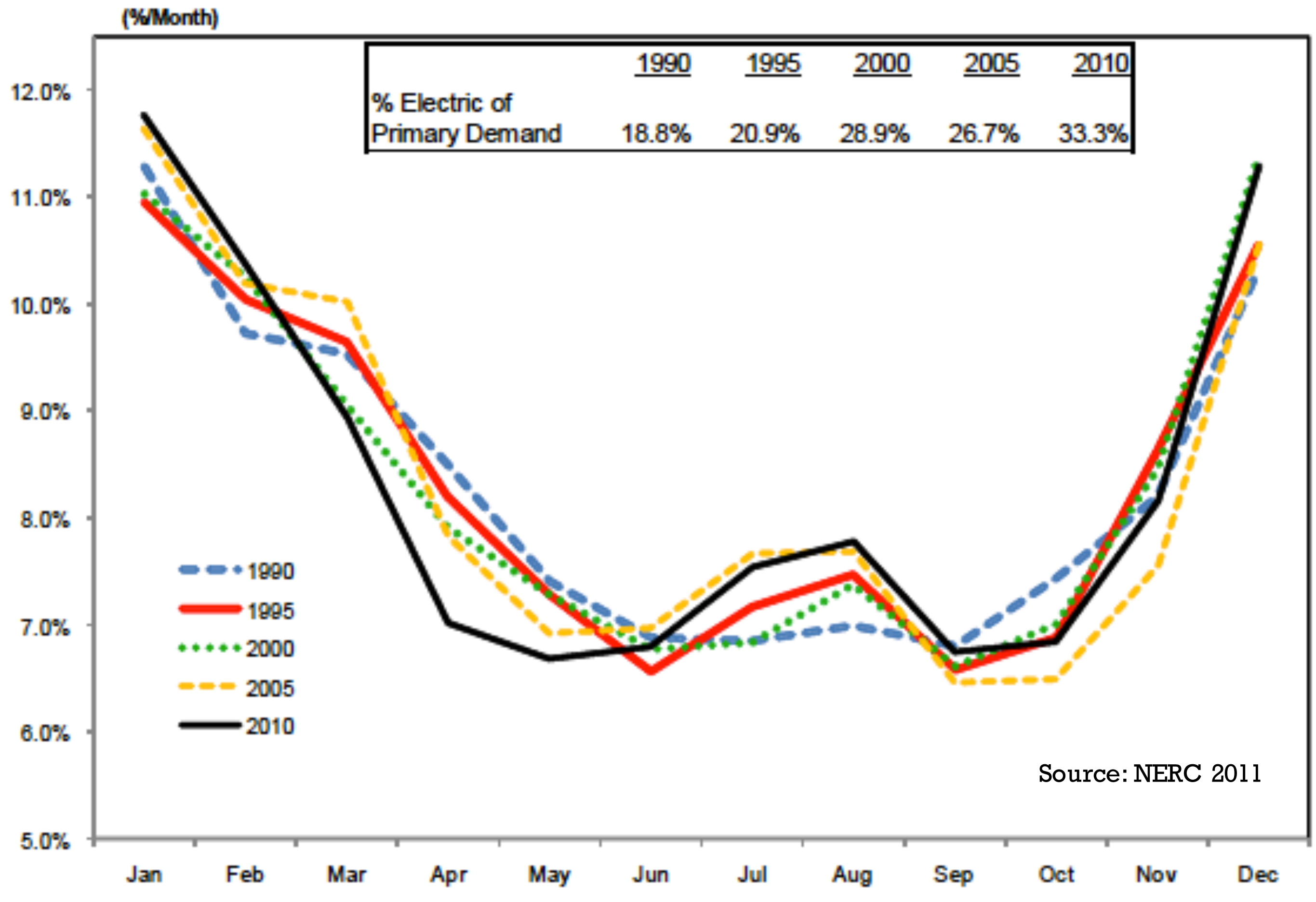
+ Why the regulatory concern?

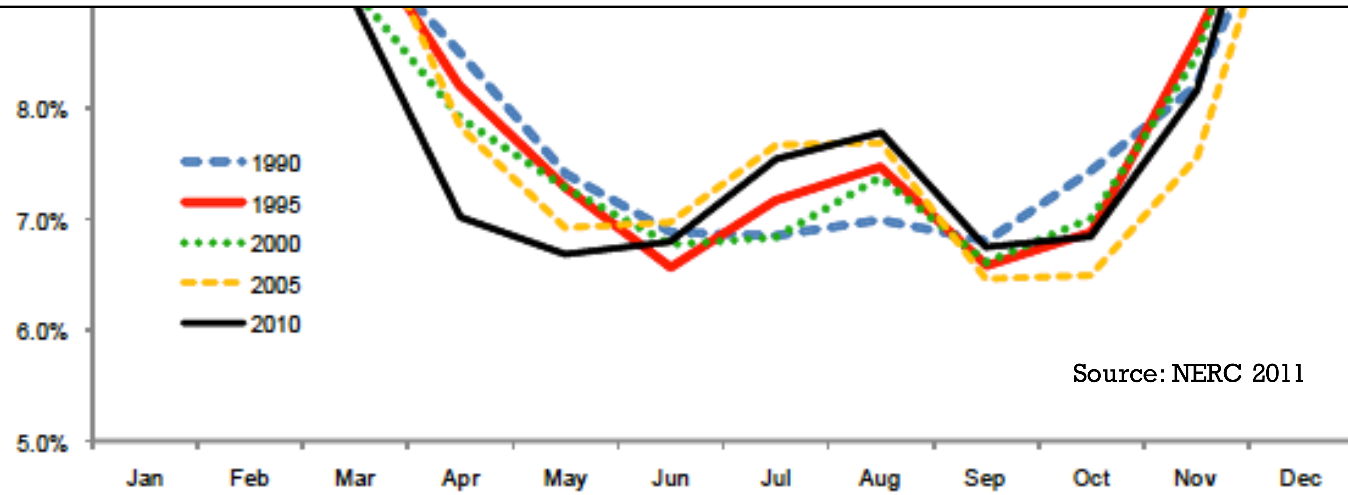
FIGURE 4-13: SEASONALITY OF NATURAL GAS DEMAND



Why the regulatory concern?

FIGURE 4-13: SEASONALITY OF NATURAL GAS DEMAND

1. Growth in gas-fired production is creating a new mid-summer peak in natural gas demand; significant, because this is typically when gas storage facilities are recharged (NERC 2011a).
2. However, it is proving more difficult for pipeline operators to address the changes in the weekly and intraday natural gas demand than the seasonal changes (NERC 2011a).



Risk reduction strategies

- Strategies to minimize the supply risk from natural gas include local gas storage, firm contracts, additional pipelines, power plants with dual fuel capabilities, redundant connections to multiple gas basins, other local plants using other fuels, or additional transmission lines from other areas (NERC 2011a).
- Firm services, while potentially a preferred option from a risk management perspective, necessarily increases cost. It is economically infeasible for a peaking generator to make capacity reservation payments for firm service, which don't vary based on volume of gas purchased or time of day, that it cannot recover in electricity sales (NERC 2011a; NERC 2013).
- The advantage of interruptible service is that unlike firm service it is priced only on a volumetric basis (no reservation fee) (NERC 2013). Interruptible, as the name suggests, is also the lowest ranking service, which means it is the first to be restricted or reduced during periods of high use, force majeure or maintenance (NERC 2013).
- In many cases dual fuel plants can switch to a backup fuel in a short amount of time (i.e., minutes) but the backup fuel is often distillate fuel oil, which can be limited to emergency situations by environmental restrictions (i.e., air pollution permits) (i.e., dirty fuel).

Table 3
Linking administrative authority and associated regulations with land availability for shale gas extraction.

Federal agency	*Regulations*	*GIS files and source*
Department of Defense (Energy Policy Act, 2005a)	No specific bans for extraction on DOD lands except for no oil or gas exploration within the Great Lakes.	Federal lands shapefile (USGS, 2003)
Bureau of Indian Affairs		
Allegany Indian Reservation (D. John, email to author, November 1, 2011) *Cattaraugus Indian Reservation (D. John, email to author, November 1, 2011)* *Oil Springs Indian Reservation (D. John, email to author, November 1, 2011)*	The Seneca Nation does not allow drilling on their lands at this time	Federal lands shapefile (USGS, 2003)
Onondaga Indian Reservation (Onondaga Nation, 2009)	The Onondaga Nation has banned hydraulic fracturing on or near their territory.	Federal lands shapefile (USGS, 2003)
US Forest Service		
Allegheny National Forest[a] (USDA, 2007)	The Forest Service provided information on the leasable and non-leasable areas within the Allegheny National Forest.[b]	ANFS shapefile (USFS, 2011)
Finger Lakes National Forest (Energy Policy Act, 2005b)	The Finger Lakes National Forest was withdrawn from oil and gas development as a part of the Energy Policy Act of 2005.	Federal lands shapefile (USGS, 2003)
Roadless rule area (USFS, 2000)	The areas impacted by the Roadless rule are located in the Allegheny National Forest.	ANFS shapefile (USFS, 2011)
US Fish and Wildlife Service	At this time the USFWS does not have regulations that would prevent the development of shale gas resources on refuge lands.	
National Park Service	We assume that shale gas extraction is possible on all National Park Service lands for the following reasons. 1. According to the National Park Service shale gas extraction is allowable but regulated. 2. A comprehensive database detailing the ownership of mineral rights on National Park Service lands does not exist. 3. In cases where the mineral rights are privately owned, the National Park must approve activity and may not prohibit it.	
Fort Necessity National Battlefield	See National Park Service above	Federal lands shapefile (USGS, 2003)
Allegheny Portage Railroad National Historic Park		Federal lands shapefile (USGS, 2003)
Friendship Hill National Historic Site		Federal lands shapefile (USGS, 2003)
Delaware Water Gap National Recreation Area		Federal lands shapefile (USGS, 2003)

Regional administrative body	*Regulations*	*GIS files and source*
Delaware River Basin Commission (DRBC, 2011a)	Prior to November 2011 the DRBC had established a moratorium within its boundaries on hydraulic fracturing. However, the DRBC has since proposed the following regulations. 1. Well pads, compressor stations, impoundments, and other non-linear infrastructure related to natural gas development may NOT be located in the floodway of any waterway within the Delaware River Basin. 2. Natural gas development is prohibited in the Upper Delaware River Corridor unless a variance is issued. 3. All well pads and other non-linear infrastructure must conform to either state setbacks or the below proposed setbacks, whichever are stricter a. Stream, water body or wetland–the greater of 300 ft. from the wellbore or 100 ft. from the nearest disturbance b. Surface water supply intake–1000 ft. from nearest disturbance c. Water supply reservoir – 1000 ft. from nearest disturbance d. Public water systems – 1000 ft. from nearest disturbance e. Private water supply well – 500 ft. from nearest	1. Flood basin data (100 year flood plains); however, this data is outside the scale of our analysis as it is at too fine a scale. 2. Upper Delaware River Corridor (Pennsylvania Natural Heritage Program, 2008) 3. Applied to relevant features where specified, see Pennsylvania and New York

Essay 3: Context

- The GEP problem determines how best to meet expected future demand through the selection of plant size, type, and location, as well as timing over a planning horizon, usually between 10 - 30 years (Hemmati, Hooshmand, and Khodabakhshian 2013).

- To ensure that adequacy requirements (i.e., minimum level of service) are maintained the GEP problem formulation typically includes reliability constraints. Reliability and adequacy are considered before stability and fault analysis and are a necessary component of any long-term planning process; otherwise, there is no guarantee of having adequate supply to meet system demand.

- Reliability is usually incorporated into GEP models using either probabilistic or deterministic methods (Aghaei et al. 2013). Probabilistic measures include: Loss of Load Expected (LOLE), Loss of Load Probability (LOLP), and Expected energy not served (EENS).

Essay 3: Context

- Recent history suggests we are overestimating reliability:
  - In 2014, the Polar Vortex exposed previously unknown or underestimated energy security issues in the Northeastern United States.
  - Shutdowns were related to two factors: energy supply curtailment and ambient conditions resulting in forced outages or deratings (in particular during startup) (Gugel et al. 2015).
  - Natural gas power plants were forced to shut down as a result of insufficient fuel supplies after there pipeline capacity was curtailed.
  - During the worst of the polar vortex more than 35,000 MW of outages existed in the Eastern and Texas Interconnections (Gugel et al. 2015).
- The role of natural gas-fired generators is changing in the production mix (i.e., higher capacity factors) and more frequent ramping as a result of more renewables with unknown consequences on maintenance schedules and reliability [add citation].
  - Generators are experiencing increasing O&M costs as a result of increasing power plant cycling given larger deployments of variable generation, especially for plants designed as baseload units (nrel:2012aa).
  - Cycling means operating the plant in response to system load requirements (i.e., load following, varying load levels, etc.); as opposed to operating it as a baseload resource (nerc:2012aa).
  - Each cycling exposes equipment to pressure and thermal stresses that can damage equipment and subsequently, lead to shorter component life expectancies, higher equivalent forced outage rates (EFOR), and shorter life expectancies (nerc:2012aa).

Essay 2: Literature review

- The GEP literature is quite large but a typology exists according to: the structure of the model used to investigate it (i.e. optimization models, equilibrium models, and simulation models); open- versus closed-loop (i.e. inter-period links); degree of competition (i.e. perfect competition, oligopoly, or monopoly) and market representation; uncertainty modeling (i.e. sensitivity analysis, stochastic programming, Monte Carlo techniques); price sensitivity of demand (i.e. load duration curve); centralized or decentralized; time scope and length of time-step; inclusion of transmission constraints; and the degree of abstraction of the underlying physics (i.e. AC vs DC load flow) (Ventosa et al. 2005).

- The choice of modeling structure necessarily depends on the research question and application posed. The choices we make are guided by the research questions, which are to better understand the effect of fuel input variability and forced outage rate (i.e. issues of energy security) on the optimal generation mix given an environment of increasing renewable energy deployment as a result of environmental and health regulation, and market forces.

Long-term generation planning: An introduction

- Three types of models are typically used in long-term electricity planning: optimization models, simulation models, and equilibrium models.
  - Optimization models are used to investigate the actions of a single firm and single objective (e.g. profit maximization) in response to some specified market parameters (e.g. exogenously determined market price) subject to technical and economic constraints (Ventosa et al. 2005).
  - Simulation models and equilibrium models represent market behavior given individual firm behavior and the type of competition amongst market participants (Ventosa et al. 2005). Equilibrium models have taken a variety of forms varying along the market mechanisms modeled, computational methods employed, types of strategic interactions allowed, and the level of realism of physical processes modeled (Gholami 2013). Equilibrium models are more commonly used in electricty modeling to model long-term planning and issues of market power with the most common configuration utilizing Cournot competition (Ventosa et al. 2005).
  - As can be imagined equilibrium models can become quite complicated and in cases where tractability is an issue researchers use simulation models. Simulation models usually use a set of rules to represent each agents strategic behavior (Ventosa et al. 2005). Simulation models are often used for medium to long-term models that have exceeded the abilities of the equilibrium framework, however, as might be expected the computational load can be challenging (Ventosa et al. 2005). Simulation models are used in a wide variety of circumstances but some disagreement exists concerning the use of agent-based models (Ventosa et al. 2005).

GEP: Literature Review

- Bakirtzis et al. (2012) uses a single-stage MILP to study optimal generation investment; major contribution is inclusion of unit maintenance schedules through binary variables and a monthly time-step [reliability measure: LNS valued at VLL, scenario-based sensitivity analysis (treatment of stochastic variables), emission allowances and RPS]
- Dehghan et al. (2013) uses robust optimization methods to solve a multiyear mixed integer linear program generation expansion planning model with uncertain load demand, investment and operation costs.
- Tekiner et al., 2010 uses a multi-objective, multi-period, mixed integer two-stage stochastic program to solve the GEP problem while accounting for unit availability using Monte Carlo methods to create scenarios [unmet demand as reliability metric].
- Shirvani, 2012 looked at the sensitivity of EENS to the Forced Outage Rate through the COPT table and showed that it has a direct effect on the reliability of the system.
- Gandulfo and Gil (2014) uses a two-stage SMIP to model future generation investment considering demand uncertainty [scenario reduction, 14-year planning horizon].

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GEP: Literature Review

- Hemmati et al. (2016) uses a nonlinear mixed-integer GEP and TEP model solved using particle swarm methods [model accounts for uncertainty in wind farm production].
- You et al. (2015) uses a stochastic mixed integer program to study the GEP and TEP co-optimization problem under load and wind uncertainties.
- Gil et al., 2015 uses a two-stage stochastic mixed-integer program to account for the uncertainty in hydro power in the optimal generation expansion plan [select a subset of scenarios].
- Wu (2014) uses a two-stage mixed-integer program with a scenario tree (and scenario reduction algorithm) to identify the optimal capacity and transmission expansion plan

Outage rate uncertainty: Literature Review

- F. Barbosa (1977); Mohanta et al. (2007); Silva et al. (1988); Suhartono, Zika, and Sasaki (2000) treats the forced outage rates as a random variable with a certain mean and variance to approximate confidence limits around the LOLP.
- Patton and Tram (1978) investigate sensitivities of reliability indices to variations in particular parameters in order to help planners identify the most important parameters and generators on the reliability indices.
- Hamoud and Billinton (1981) use Fourier Transform methods to incorporate the uncertainty of parameters into the calculation of the LOLE index for a single area system.
- Sahinoglu et al. (1983) derived probability density functions for the loss of load and unserved energy reliability indices using classical and Bayesian statistical inference.
- Singh and Kim (1992) use a weighted composite of three gamma distributions (i.e., six parameter estimates) to generate a reliability probability distribution.
- Billinton (1993) compares the accuracy and computing requirements of three analytical methods for computing reliability: load modification technique, cumulant method, and the segmentation procedure.
- Noor and McDonald (1996) used expert elicitation and fuzzy set theory to estimate the forced outage rates of generating plants.

Outage rate uncertainty: Literature Review

- Oliveira, Melo and Pinto use Monte Carlo simulation methods to determine the effect of uncertainty in equipment reliability on composite reliability at the bus level.
- Amjady and Ehsan (1999) use artificial neural networks in the estimation of forced outage rates.
- Kim and Singh (2002) use fuzzy set theory to calculate the 'possibilistic' reliability indices based upon the uncertainty in the underlying data using the probability-possibility consistency principle algorithm.
- Wu (2004) establishes a procedure for estimating Bayesian reliability in fuzzy environments (but doesn't apply it to FOR).
- Mohanta, Sadhu, and Chakrabarti (2005) uses a probabilistic Markov model in conjunction with fuzzy set theory to incorporate maintenance scheduling, failure-repair cycle, and aging of generating units in the generation of state probabilities.
- Billinton and Li (2007) compare the EFOR (i.e., two state outage model) to a multi-state generator outage model in a composite system adequacy assessment. Previous work has shown that the EFOR model can be overly pessimistic.

Outage rate uncertainty: Literature review

- Chowdhury et al. (2007) incorporated uncertainty in the forced outage rate parameter of the generation adequacy assessment through a sensitivity analysis (varying the parameter 25% from the expected value).

- Bhatkar et al. (2008) use fuzzy sets to incorporate data uncertainty into the calculation of the forced outage rate (and the well-being of the generating system).

- Chowdhury and Koval (2009) showed that the relationship between the Forced outage rate and the EENS is virtually linear (in the variation of the parameter for a single, small plant)(i.e., as the FOR increased so to did EENS).

- Abdelfatah et al. (2011) determine trends in the hazard function while assessing the reliability of transformers in the Egyptian Electricity Transmission Company.

- Dent and Bialek (2011) model both random and systematic error in unit availability probabilities, which allows them to specify error bars around the reliability index produced. The authors show that small changes in the unit availability can lead to large changes in the reliability index.

- Awadallah and Milanovic (2013) divide the uncertainty into aleatory (i.e., related to a random process) and epistemic (i.e., related to a lack of information) to quantify uncertainty representation (also have a good lit review). They use second order probability and evidence theory to quantify the uncertainty.

Exclusion area: Literature review

- **Regulatory Exclusion:** The literature surrounding the creation of exclusions areas, which incorporate policies, hazards, and resource potential is limited.
  - Prest et al. (2007) created regulatory exclusion zones on total resource potential (e.g., both existing regulations and physical hazards) in delineating the areas available for wave energy technology.
- **Operations Research:** A separate but related problem is selecting an optimal site given a set of constraints. Methods developed for this problem are used extensively by the extraction, transportation, and processing industries (Baban and Parry, 2001).
  - Baban and Parry (2001) use a combination of GIS and multi-criteria decision analysis (MCDA) in the selection of optimal wind turbine sites.
  - Hobbs (1980) used the suite of methods in the selection of an optimal site for locating power plants.
  - Baban and Flannagan (1998) used the methods to determine the optimal site for a landfill.