PJM Concept Design

A quantitative comparison of alternative reliable electric power system architecture as greenhouse gas emissions approach zero.

11/6/2019

Civilization is in the early stages of a long-term transition to a post fossil-fuel economy; the inevitable result of finite fossil-fuel resources. This transition is secular, huge and risky, one of mankind's great challenges. While the transition might take a century or more, it can be accelerated by stakeholder concerns over climate, the environment and health.

The quickest way to zero GHG emission systems is to avoid big mistakes. The low risk method is rational planning, how societies traditionally build things with clear and stable goals: bridges, skyscrapers, put a man on the moon. Electric power systems are ultimately constrained by math, physics, and economics. Stakeholders should understand these hard constraints before making large long term commitments.

The objective of this Concept Definition study is to quantify and compare whole power system choices: renewables vs nuclear vs sequestration vs mix. Everyone sees the technologies. The question is how do these technologies fit together to deliver reliable power as emissions approach zero? While stakeholders have the right to choose whatever they want (e.g. renewables or nuclear) that choice should be based on trusted fact. The purpose of a Concept Definition Study is to provide that factual comparison.



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GLOSSARY

AEO – Annual Energy Outlook published by the Department of Energy's Energy Information Agency.

Capacity factor – Average annual energy production divided by potential production assuming that the generator was operating continuously at full nameplate capacity.

Capacity credit – The amount of additional load that can be serviced by adding a particular generator type with no change in system reliability.

CASIO – California's ISO

CC – A *Combined Cycle* generator is a high efficiency generator that consists of a high temperature gas turbine in series with a lower temperature steam turbine.

CT – *Combustion turbine*. A simple single stage low capital cost, lower efficiency, turbine generator.

Dispatchable generators – Power level can be adjusted or turned on/off by command of the grid operator.

Engineering – The application of science to the efficient development of useful products.

FERC – *Federal Energy Regulatory Commission*: an independent agency that regulates the interstate transmission of natural gas, oil, and electricity.¹

FNR – A *Fast Neutron Reactor* is a type of fission reactor that can be fueled by Uranium, Thorium, or "spent fuel" from conventional light water nuclear reactors. FNRs are proven technology but not yet commercially licensed. FNRs are sustainable on civilization time scales in that earth has enough fuel to power all of man's energy needs for 2,000 years. FNRs produce much less waste than conventional nuclear reactors.

ERCOT – Electric reliability Council of Texas (an ISO)

GDP – Gross Domestic Product

GW - Giga-Watts; a billion watts.

IESO – Independent Electrical System Operator (Ontario Canada)

ISO – An *Independent System Operator* was established by FERC order #888 to "…operate the transmission systems of public utilities in a manner that is independent of any business interest in sales or purchases of electric power by those utilities."²

Microgrids — Regions of the grid that can be separated and managed to provide more reliable power under emergency conditions, and to insure rapid recovery after blackouts.

MISO – Midwest Independent System Operator

Nameplate – Factory rated maximum continuous electricity production from a particular generator.

NASEM – The *National Academy of Science, Engineering and Medicine*; more specifically, the Bureau of Energy and Environmental Engineering³ a subset of the National Research Council, the operating arm of the National Academies.

NERC – *North American Electric Reliability Corporation*. Mission is to assure the effective and efficient reduction of risks to the reliability and security of the grid.⁴

NREL – National Renewable Energy Laboratory

NSRDB – National Solar Radiation Database.

PJM - *PJM Interconnection, LLC,* is an ISO/RTO that organizes a wholesale electricity market and is responsible for balancing supply and demand in all or parts of 13 Northeastern states plus DC.⁵

PV – Photovoltaic

RPS – Renewable Portfolio Standard, incentivizes the development or renewable generators.

RTO - *Regional Transmission Organization*: Established by FERC Order No. 2000 as a voluntary Regional Transmission Organizations to administer the transmission grid on a regional basis.

TWh – Terra Watt-hour, 1,000,000,000,000 Watt-hours

VRE – Variable Renewable Generators, most notably wind and solar.

Waterfall Development - An engineering development method that proceeds through a sequence of steps; like a river flowing through a sequence of waterfalls. Between each step there is a major milestone where progress is evaluated and the project re-directed if necessary.

1.0 EXECUTIVE SUMMARY

A professional planning process by which engineers develop options for unprecedented systems consists of three sequential steps:

- 1. Executives clarify the goal (§2.0). Maryland now has a sound functional goal: 100% clean electric power by 2040.
- 2. Engineers conduct a Concept Design Study to develop options (§ 5.0). Using today's knowledge, they provide a relative comparison of the cost, performance and risk of the complete full range of system options as emissions approach zero.
- 3. Stakeholders choose a development path and a pace based on trusted fact (§7.2). This choice involves management processes similar to those used to select a public works project.

This efficient low risk process minimizes the risk of stranded hardware; it's how modern society builds things with stable goals: bridges, skyscrapers, put a man on the moon.

A Concept Design Study is feasible because the ultimate goal is certain. A post fossil fuel PJM system is inevitable. Feasible systems are fundamentally constrained by math, physics, economics and physical relationships.

The Concept Design Study defines end-states (§4.0); it provides focus; stakeholders can avoid development that conflicts with the science and math. The Study starts with a blank sheet of paper constrained by existing load centers, transmission corridors, historical load, and resource data. Development time is a variable; the pace depends on the level of stakeholder investment. Transition could be rapid (it took France 12 years to transition to 80% nuclear power); or, it could take a century or more at low cost by replacing ageing assets with new alternatives. An example of partial results for PJM is Fig. 7 in §9.0.

The proposed primary sponsor is a partnership of the PJM coastal States as these political entities are motivated by climate change induced sea level rise. Since PJM coastal States are already committing their residents to large investments in clean electric power generators, they have the responsibility to assure that the commitment is compatible with the goal. Other PJM member States have an interest in an efficient transition to avoid mistakes and increased costs (e.g. low capacity transmission, idle backup generation) resulting from decisions by coastal States. PJM finds guidance for transmission planning; a baseline enabling States to coordinate programs; definition of reliability concerns; system implications of intermittent generators; clarification of configuration conflicts and the cost basis for wholesale market reform. State Public Service Commissions find the cost basis for retail market reform. The Concept Design Study provides policymakers with a rational basis for balancing transition pace with cost and risks (both environmental and transition risks).

While markets can find the lowest cost method for reducing emissions today, markets have no information about ultimate goals, indirect costs, feasible technologies, whole system integration or reliability constraints. With expensive components and long product cycles, the risk of a market-only approach is similar to that of mandated solutions. The transition risk is that system development stalls before emission goal are achieved when ratepayers balk at additional investments. Market based development may eventually achieve large overall emission reduction, but without clear target constraints, market methods could take centuries at substantially higher cost.



2.0 THE STUDY GOAL

Based on what is known today, define the cost, performance and risk of alternative electric power system concepts as fossil-fuel consumption approaches zero - including 100% clean by 2040.

PJM member states are incentivizing the installation of intermittent generators which, in large quantities, will change the PJM system architecture. Also, the transition from fossil fuel generators to clean generators brings with it a transition from generators with high variable cost to high capital cost. This will transform market design. It is important to understand the fundamental new relationships to avoid serious and costly mistakes.

Low fossil fuel consumption is inevitable as fossil fuel resources are finite and have much higher value in applications such as aircraft fuel and chemical feedstocks. Climate change concerns might accelerate the pace of the transition. NASEM advises us that "Emission reductions larger than about 80% (overall)... are required to approximately stabilize (atmospheric) CO_2 concentrations..."⁶ A very low emission requirement for electric power enables many applications, such as electric vehicles, to decarbonize through electrification.

While the goal is inevitable, pace is a variable. A faster pace entails higher costs and higher risks than a slower pace. Whether the goal is to be achieved in 20 or 120 years it is a value choice that balances the cost and development risks of different concepts against environmental and societal risks. By illuminating fundamental relationships, the concept design study provides a rational basis for stakeholder choice of transition pace.

The Study will rank, score and provide recommendations. Its primary purpose is not to propose specific PJM "solutions" but to compare the cost, performance and risks of concepts in preparation for subsequent political value choices. These concepts should be comprehensive clean generation options, spanning the gamut between intermittent renewables and baseload nuclear power. The study should also clarify the need for better data, engineering development, critical item testing, prototype testing and implementation pathways.

3.0 BACKGROUND AND WHY THIS STUDY IS NEEDED

3.1 Roles and responsibilities

In *Systems Architecting*⁷, Rechtin teaches that there are three roles that characterize a "governance model" for successful system architecture. Society's responsibility is to choose a solution. The *executive* role is managing the execution of the process. The *technician* role is the agnostic assessment of feasible alternatives. These three roles have equal importance. No one should dominate. They should be separate and distinct, and a healthy tension should exist among them. Distortion of these roles leads to conflict of interest and dysfunction.



A good example in the public arena is architecture selection for public works projects. In the mid 1990's Maryland and Virginia decided to replace the bridge taking 195 across



the Potomac River. The executives were the governors of MD and VA. The technicians were the highway departments from both states. The society was represented by a group of key stakeholders including local community leaders. The experts explored the cost/performance/risk of a high bridge, low bridge, drawbridge and tunnel and recommended a tunnel. Society chose a drawbridge. \$2.5 billion later we have a drawbridge that is working well.

3.2 Limitations of the existing management structure

Worldwide deregulation of the electric power industries began with the Public Utility Regulatory Policies Act of 1978 (PURPA).⁸ Deregulation resulted in a decentralized market-based management structure with a dozen different Federal, State and utility agencies, each responsible for a different pieces of the electric power system. This market-based structure worked well during a period of little change. However, the existing fragmented structure interferes with the integrated system design that is now necessary. Today there is no vertically integrated organization responsible for the whole system. The proposed management plan (§7.0) compensates for this by suggesting a teaming relationship among key players.

3.3 Why the States need to lead

State Governments should be driving the Concept Design Study because State Governments are committing their residents to huge investments. In response to popular demand, some State Legislatures are committing their ratepayers to policy concepts like renewable portfolio standards. This investment is piecemeal, plug-it-in-and-hope-it-works. As yet there is no goal or comprehensive system analysis. Responsible State Governments should:

- Articulate a technology neutral performance goal, as in §2.0.
- Task technology agnostic engineering contractors to define choices and clarify cost, performance and risks.
- Partner with other PJM States to choose a technology path and a suitable pace that balances systems cost, performance and risk.
- Teach the world how to rationally design clean electric power systems.

3.4 Prior investigations

The Concept Design Study goal is to: *Quantify reliable alternative electric power system concepts as greenhouse gas (GHG) emissions approach zero.* There is no direct prior art with this goal. There is related prior art that provides useful tools, models, methods and perspectives:

- Integration studies The goal is to understand the operational implications of incorporating a modest numbers of intermittent generators. This "bottoms up" perspective generally provides no estimates of emissions or any assurance that initial achievements (particularly with intermittent generators) can be built upon to approach zero GHG emissions.
- Renewable penetration studies Generally the goal is to show that reliable systems can be built without nuclear generators. Often these are advocacy studies that rely upon something (e.g. natural gas, hydro, biomass, PEV batteries) to provide a large amount of on demand variable backup power for a limited period of time.

The following highlights those studies that are directly related to the Future of Energy Initiative (FOEI) recommended Concept Design Study.



3.4.1 Jenkins' system surveys

In a 2017 paper ⁹ Jenkins reviewed 30 system studies (published since 2014) on the "deep decarbonization" of the electric power sector. That report provides a good bibliography and offers several conclusions:

- 1. Low-cost dispatchable resources are an indispensable part of any low-cost pathway
- 2. Relying on intermittent sources alone significantly increases cost and technical challenges
- 3. Stranded assets can be avoided by focusing on long term goals

In a more recent 2018 paper¹⁰ Jenkins expanded the survey to 40 system studies published since 2014 and found "...strong agreement in the literature that reaching near-zero emissions is much more challenging – and requires a different set of resources – than comparatively modest emission reductions (e.g. CO2 reductions of 50-70%)". What this means is that the lowest cost zero GHG solution may be to discard the technologies that were chosen to get the first 30% or add additional technologies like carbon sequestration.

3.4.2 The PJM Renewable Integration Study (PRIS)

PJM commissioned a study in May 2011 to understand the impacts of State renewable goals on grid operations¹¹. Variable generation (wind and solar) was assumed to be forced onto the system by the States. The study team, led by GE Energy, evaluated 10 scenarios ranging from 2011 wind and solar levels to 30% (by energy) wind and solar. The study was directed at PJM operations and excluded generation costs, emission impact, distribution system impact, voltage and frequency controls and reserves cost. The following conclusions were relevant to this study:

- With adequate transmission expansion (\$13.7 billion) and an additional 1,500 MW of regulation reserves, PJM could reliably operate with 30% of its energy from wind and solar.
- For the 14% RPS scenario, 85% of the wind was located in Ohio, Indiana and Illinois.¹²
- Every scenario resulted in lower fuel, lower variable cost and lower revenue for conventional generation.
- All plants need improved flexibility.
- PJM needs to reconfigure the wholesale market design.
- The study focused on operations and ignored cost, emissions benefit analysis.

The following distinctions between PRIS and the FOEI-CD Study are noted.

- PRIS focused on operations of the existing system with 30% renewables, FOEI-CD will focus on comparing alternative whole system costs as GHG emissions approach zero.
- PRIS is constrained by existing systems; FOEI-CD is legacy free.
- PRIS models existing generators and transmission, the FOEI-CD study models historical loads and weather with generic components.
- PRIS employed the EWITS wind models which can now be better validated (see §5.1.2).

3.4.3 Eastern renewable generation integration study (ERGIS)

ERGIS¹³ is similar to PRIS except the study area is much larger, including 5 Canadian Provinces and 35 States. The report concludes that integrating 30% wind and solar is technically feasible. There is no cost estimate or emission impact. More important, no comment is made about the feasibility of building on this accomplishment to achieve zero GHG emissions. The ERGIS study was preceded the Eastern Wind and Transmission Study (EWITS)¹⁴

3.4.4 Renewable Electricity Futures Study (RE Futures)

The <u>Renewable Electricity Futures Study</u>¹⁵ was a large (110 author, 35 organizations, 900 pages) US Department of Energy study published in 2012. Its purpose was to maximize renewables nationwide, to

assess the technical feasibility of "high" levels of integration of commercially available renewable technology including biomass, geothermal, hydropower, solar, and wind. The study focused on electricity generation levels from 30% up to 90% focusing on 80% with nearly 50% from intermittent wind and solar PV. The key result was:

Renewable energy resources, accessed with commercially available renewable generation technologies, could adequately supply 80% of total U.S. electricity generation in 2050 while balancing supply and demand at the hourly level.

RE Futures was neither an integration study nor a concept design study. The purpose was to maximize renewables, not to compare different system configurations with an emission goal. The study was conducted at the conceptual level, minimizing some but not all of legacy complications. While this study is a better example of a concept level study it suffers from several difficulties:

- A broad national scope assumes transmission does not drive system configuration. A simpler approach is to start regionally, then expand.
- Starting with a legacy configuration mix and assuming load growth adds complications that are unnecessary for a concept design study.
- Generator performance was simulated using NRELs ReEDS model. No reference could be found to validation of intermittent generators with physical data.
- Biomass burning generators (wood, organic material) constituted 15% of electric power under the high demand scenario. Biomass may be classified as renewable because it emits non fossil carbon. However it has adverse health and environmental impacts and black carbon (soot) may have significant climate impacts.¹⁶
- Relative cost is not an explicit product of the study.
- There is no assessment of GHG emission performance.

3.4.5 The Real Cost of Energy

An example of a study similar to the proposed system level concept design study that includes both nuclear power and intermittent renewables is "<u>The Real Cost of Energy</u>" by The Ontario Society of Professional Engineers (OSPE).¹⁷ Ontario's IESO is the only grid that has successfully decarbonized. Over

the past decade, $Ontario^{18}$ reduced grid emissions by 80% to 44 g(CO₂)/kWh (grams of CO₂ per kilowatt hour of electricity). By comparison, PJM emissions are 425 g(CO₂)/kWh (2017) and the Midwest Independent System Operator (MISO) has emissions of 684 g(CO₂)/kWh¹⁹. Only the all-hydro grids like Scandinavia's and Quebec's have lower CO₂ emissions. Ontario's success offers several important lessons.

Nuclear	63%	
Hydro	26%	
Gas	4%	
Renewables	7%	
Table 1 IESO 2017		

- The key to very large emission reductions is zero-fossil-fuel base load, for Ontario this was nuclear and hydro. Ontario already had 23% hydro; they achieved an 80% reduction primarily by replacing coal with nuclear and natural gas.
- Solar has useful capacity value to the extent that it levels load.
- Too much solar and wind have little value on a zero-carbon system without seasonal storage amounting to months of total system load.
- Ontario's achievement is not cheap, electricity rates have increased by 70% over the decade.
- Ontario's dispatch is based on lowest system cost. Today approximately 2/3 of wind turbine production is curtailed (wasted) or exported at wholesale market prices. 1/3 is consumed in Ontario at retail market prices (~ 10x wholesale).

3.4.6 The 99.9% paper

A University of Delaware group published a study titled: <u>Cost-minimized combinations of wind power</u>, <u>solar power and electrochemical storage</u>, <u>powering the grid up to 99.9%of the time</u>.²⁰ This study is remarkable in that it showed that it is technically feasible for a high percentage (>90%) of PJM system electricity to originate from wind and solar. But since storage costs are so high, the authors minimize total system cost by over-building wind and generating 3x the amount of electrical energy that is actually consumed; 2/3rds of the produced electric power is discarded. While theoretically feasible, the study cost estimates and assumptions (especially reliability) would benefit from a critical review.

3.4.7 The Jacobson PNAS paper

In the Proceedings of the National Academy of Sciences, a Stanford University group claims a "<u>Low cost</u> solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for <u>all purposes</u>."²¹ This study speculates on how intermittent renewable technologies might fit together for a zero-carbon grid. This conclusions have been challenged in the literature as optimistic, the result of inadequate model validation and unrealistic assumptions particularly with regard to hydro.^{22, 23}

3.4.8 OECD Costs of Decarbonization

The Nuclear Energy Agency component of the Organization for Economic Co-operation and Development has recently (2019) published a European assessment of the electric power sector titled <u>The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables.</u>²⁴ The goal, "to reduce the carbon intensity of the electric power sector by as much as a factor of 10 (to 50 g(CO₂/kWh)" is sound. The analysis includes both Variable Renewable Generators and nuclear. The analysis is a system level legacy free (greenfield) assessment and provides useful guidance for the statement of work for recommended PJM Concept Design Study. Of the various reports cited in this § 3.4, this OECD report comes closest to the proposed PJM concept design study

The purpose of the OECD report is to provide general policy recommendations to OECD countries¹. However the wind range of countries with diverse resources (hydro, wind, solar) makes it possible to draw only very broad and general conclusions for a "representative" country. There will be considerable variation from one region to the next. The availability of dispatchable hydro is significant. The OECD report is too general to be considered a system level concept design.

The main criticism of the OECD report is that it is not possible to judge the validity or accuracy of the models used to predict production from variable generators. It is unclear that the models have been validated against empirical data. This is a core issue. The cost of systems with high levels of variable generation are driven by the requirement to reliably manage peak loads, those few hours every 5 years when wind generation is nearly zero during peak loads, or when PV production is limited by sequential cloudy days. Indeed the study appears to use only one typical year,²⁵ and load-duration-curves which assume load is independent of variable generation.



¹ OECD COUNTRIES: AUSTRALIA, AUSTRIA, BELGIUM, CANADA, CHILE, CZECH REPUBLIC, DENMARK, ESTONIA, FINLAND, FRANCE, GERMANY, GREECE, HUNGARY, ICELAND, IRELAND, ISRAEL, ITALY, JAPAN, KOREA, LATVIA, LITHUANIA, LUXEMBOURG, MEXICO, NETHERLANDS, NEW ZEALAND, NORWAY, POLAND, PORTUGAL, SLOVAK REPUBLIC, SLOVENIA, SPAIN, SWEDEN, SWITZERLAND, TURKEY, UNITED KINGDOM, UNITED STATES

3.5 The Apollo Project example of rational planning

After President Kennedy set the goal to put a man on the moon, NASA had the discipline to spend one year up front to get the concept right before they committed to a direction. There were three candidates (Fig. 2): Flash Gordon, direct surface of the earth to surface of the moon and return; low earth orbit assembly, travel from earth orbit to the surface of the moon and return to the surface of the earth; and lunar orbit rendezvous, travel from the surface of the earth to orbit the moon, drop a guy down, pick him up and return to surface of the earth. The discipline to spend one year up front and the insight to choose the correct concept (a lunar orbit rendezvous) are the main reasons why America won the space race. The Apollo Project is an excellent example of the rational planning method.



Figure 2 Apollo options

3.6 Risk & agile development

An alternative development method, common in Silicon Valley today, is agile development: evolving product design and usage based on market feedback. Agile methods are useful when the goal is unclear as is the case with consumer products, and human interface software. Recovery from mistakes is easy with short cheap product cycles. In contrast agile development is particularly risky when product cycles are as long and expensive as electric power systems. The risk is that development stalls for decades, until the next product cycle.

The risk of evolving major systems forward, ignoring the distant goal and making decisions based just on the lowest cost incremental step is that investments will likely be made in solutions that conflict with the distant goal. The existence of a clear and stable distant goal (100% clean) means we can avoid investing unknowingly in things that ultimately interfere with our ability to achieve that goal.

Electricity ratepayers have a finite price tolerance. At some point they will refuse additional investments and development will stall. This has already happened in Germany. Since 2002, Germany has spent ~\$220 billion²⁶ and has halted additional subsidies because residential electricity rates have reached 36 cts(US)/kWh. While Germany gets 35% of its electricity from renewables today, they have not reduced emissions since 2009. It will be a long time, perhaps a century, before Germany works their way to a clean power grid.

The cautious, low-risk developer, focused on the goal (§2.0), defines the cost/performance/risk of all options, including nuclear and carbon sequestration before choosing a direction. This strategy is likely to be the first to reach nearly zero emission electric power and with minimum investment.



3.7 Classical waterfall

This rational planning method is called a waterfall because it proceeds through a sequence of phases separated by major milestones (Fig. 3). These milestones consist of a management review of progress to decide whether to proceed as planned, change direction, or to repeat the earlier stage.



Figure 3 Classic Waterfall development

Clean energy today is at Milestone A, the decision to conduct a concept design study. Phase 1, concept design, systematically explores alternatives, feasible ways to achieve the goal. Concept Design concludes with Milestone B where Stakeholders choose which concepts to develop. The result of Concept Design would be one or more concept to further develop.

Phase 2, Engineering Development, (beyond the scope of this Concept Design Study) consists of component design and testing to reduce risks identified during Phase 1. For example, a Concept Design phase conclusion might be that seasonal storage is necessary for intermittent generators to economically contribute to a reliable zero carbon system. In that event, a priority Engineering Development task would be to clarify the feasibility and cost of seasonal storage technologies. Milestone C is a normally a decision point to build full-scale system prototypes and map out a plan for migrating from the existing system to the goal system. Value choices are made at all major milestones; program efforts can be continued, terminated or re-directed at major milestones. Iteration and overlap occurs mainly between the major milestones, to accommodate new information.

Clean electric power system development is difficult because the system is unprecedented and technically complex. An integrated management structure with roles and responsibilities aligned with the system does not exist. And there are many stakeholders with conflicting interests. The importance of the classic waterfall development model is that it identifies the development structure: phases and major decisions. Committing large resources to full-scale production (Milestone D) without first having a clear idea of ultimate goals (Milestone A); or a comprehensive analysis and comparison of alternatives (Milestones B); or evidence of proven technology (Milestone C); or evidence of cost-effective systems (Milestone D); entails the risk of serious investment mistakes which may be economically unrecoverable.

3.8 Let the markets decide?

Choosing technologies based solely on lowest price per kWh today will not result in efficient systems. Intermittent generators are not interchangeable with dispatchable (nuclear or fossil-fuel) generators. Intermittency changes the cost basis of the whole electric power grid. It imposes additional system costs (idle backup, transmission, storage) which can be much larger than generator cost especially at higher penetration. A rational design method is to compare whole system concepts as fossil fuel consumption approaches zero. Whole system cost is one basis for stakeholder choice of technology and pace. The stakeholder chosen concept will define a new cost structure for the power grid. Markets can then be designed to align price with cost and provide efficient incentives.

The cost/performance/risk of system concepts is relatively immutable, defined by physics and economics. Markets are a human construct and will change. Clean generators have high fixed cost and low variable cost whereas the existing system has high variable and mostly sunk fixed cost. The principle of aligning price with cost will likely cause electricity markets to evolve from energy markets (Watthours), to capacity markets (Watts). As the technology shifts to clean energy, capacity markets will become increasingly important.

3.9 Engineers use validated models

Engineering is about building systems that work. Engineering quality models are rigorously anchored on empirical data. If there is uncertainty, the assumptions should be conservative. Today, the lack of validation is a particular problem today with wind production. For example, NREL published a report titled "Validation of Power Output for the Wind Toolkit.²⁷ That report does a decent job of validating the ability to interpolate wind velocity at a historical location and time based on historical weather station records. However validation of average wind farm production was off by 25% without reconciling causes and no effort was made to validate variability which drives system capacity requirements.

3.9.1 ERCOT's phantom wind reserves

The consequence of the lack of validation is having real system consequences. In August 2019 ERCOT had two emergencies driven by low reserves. Part of the reason for this is that estimated wind reserves do not exist. The methodology ERCOT uses to calculate capacity value is flawed.

ERCOT estimates wind capacity value as the average of hourly wind capacity during the top 20 annual peak load hours. The Fig. 4 histogram shows a 4 year average of 29% or 6,450 MW based on current installed





capacity. Focusing on what happens during the top 20 peak load hours is sound. However the correct method would be to identify the worst case, not the average. The reserves shortfall is a problem during the worst case, in Fig. 4 the four hours with capacity in the 10-15% range. Based on this data a sound engineering assumption would be 10% or 2,240 MW. The reserve shortfall due to inaccurate wind reserve estimates is 4,210 MW.

It should be noted that Additional data may show 10% to be optimistic; total wind dropped below 3% for 45 hours during 2018. 2014 had one 2.7% peak load event.



3.9.2 Wind Capacity Value (aka Capacity Credit)

Wind capacity value has been defined as "... the amount of additional load that can be served due to the addition of the generator, while maintaining the existing levels of reliability"²⁸. Different grids use different methods. The traditional approach "is based on the Loss of Load Expectancy (LOLE) of 0.1 days/year as the reliability target. ... <u>the LOLE metric does not indicate the duration of the potential insufficiency, nor does it indicate the potential energy shortfall.</u>" ²⁹ LOLE becomes a problem with large wind penetration because the magnitude of the loss can be large compared to average load.



The literature presents significant levels of capacity credit for wind penetration <50%.³⁰ The curves in Fig. 5³¹ show wind capacity credit declining towards zero at high penetration.



Every regional combination of wind turbines (seen as a standalone system) loses >98% of wind production for a dozen hours per year. Another analysis^{32,33} of 12 systems and 67 years of data from around the world indicates that wind capacity credit is a low single digits percentage of wind nameplate <2% for standalone wind. A wind capacity credit in the low single digits, if not zero, is therefore a sound approximation for systems dominated by wind.

3.9.3 Intermittent generator model validation and calibration

Engineering models must be firmly anchored to empirical data. There are two metrics of interest: average power (first order statistics); and variability (second order statistics). PJM has multiple years of historical metered load; cumulative wind data for the years 2012-present; NREL has NSRDB solar data; and historical meteorological wind data exists at weather station sites. Models need to be calibrated against this data and account for technology and operational facts.

Known methods to calibrate models for first order statistics need to be rigorously applied to the PJM datasets. NREL's WIMD Toolkit validation³⁴ compared model simulations with historical windfarm data and found that the model over predicted capacity factors by ~25%. The report listed those factors that may explain the difference but did not parse them into those factors that will improve with more modern technology and those factors that are the result of real-world operations and which would be common to any practical wind farm. It is also necessary to validate wind variability, the second order statistics. Fig. 9 in § 9.0 shows that variability, wind curtailment, the amount by which wind generation exceeds load, is the primary factor limiting wind penetration.

Fig. 6 presents curtailment curves for PJM for years with available wind data. A single annual curve is based solely on the published wind and load hourly profiles. Wind is scaled, that is it is assumed that additional wind turbines are located at the same sites as old wind turbines.

For a given hour, if system wind power exceeds system load, it is assumed that the entire load can be displaced by wind and the excess wind is curtailed. For a given year, the % of load displaced by wind is calculated by summing the hourly load displaced by wind over the course of the year and dividing by total annual load. Likewise,



Figure 6 PJM 2012 Curtailment curves

for a given year, the % of wind that is curtailed is calculated by summing hourly curtailment over the course of the year and dividing by total wind for that year. This results in one data point (x,y) for one year on Fig 6.

For a given year a whole curtailment curve in Fig. 6 is calculated by scaling the wind. That is, the published PJM annual hourly wind profile is multiplied by an arbitrary scaling factor. Comparing that scaled wind with load results in one data point on the curve. Another scaling factor gives another data point. Scaling correctly preserves all of the many correlations associated with wind generation. The constraint is the assumption that all of the new wind is added using the same technology and at the same physical location as the old wind turbines.

Load-duration curves may be a useful diagnostic, to help figure out how to best calibrate the model.

Wind models should be validated by showing that they can reproduce the capacity factors and curtailment curves for the specific conditions that generated those data. It may be necessary to calibrate the models using modest adjustment factors or by injecting modest wind volatility to produce a better fit. Once the model has been calibrated against specific historical conditions, the contractor needs to explain why their modeling approach can then be generalized to simulate wind system performance for the same load profiles and meteorological conditions but with new turbine technology at new locations.

4.0 SCOPE OF THE PROPOSED CONCEPT DESIGN

An important aspect of the art of Concept Design is the appropriate level of detail. The purpose is to distinguish between concepts, so the analysis needs enough detail to clarify and distinguish structure and to provide a factual basis for making value choices. Concept design excludes detail which obscures fundamental relationships. Concept design provides a snapshot of a future zero emission systems that ignores existing infrastructure and focuses on long term goals. It establishes objectives for the later development of a detailed plan for how to get there from what exists today.

4.1 Relative comparisons, not absolute prediction

The Concept Design objective is to compare the relative cost, performance and risk of different concepts, of different system architectures. It is most difficult to make absolute cost predictions on decadal or century time scales since new technologies and social priorities may change. However, the laws of physics, mathematics and economics are not going to change; and the ultimate goal of (nearly) zero emission electric power is inevitable. These certainties make possible a meaningful relative comparison of system fundamentals. A sound comparison can be made between architecture A vs B; that system A has certain features, while system B has different features. When no system is perfect, policymakers need to see this relative comparison of different system configurations to make sound system decisions.

4.2 The distinction between a Concept Design Study and a Power Plan

20-year power plans are common tool used by utilities to guide long term investments. 20-year power plans start with existing demand profiles, markets and trends and project them forward in time. In contrast the Concept Design Study characterizes relative cost, performance and risk of different *end-state system configurations*. It does not matter when; time is a variable, a subsequent policy choice. The end state can be achieved sooner or later depending on the policy choices related to cost and risk. For example, in the 1970s France transitioned from zero to 80% nuclear in 12-15 years at high cost. 80% nuclear could have been achieved at lower total cost and risk by taking more time.

4.3 No change in demand profile, lifestyle

PJM has decent wind data since 2012 so system comparisons can be made over the period 2012present. The demand profile in future years is assumed to be defined by the demand profile over past 6 years. Likewise, major lifestyle changes to accommodate new energy concepts are not assumed; but may be found to be opportunities or risks for later detailed planning. The main purpose of a concept design study is the relative comparison of different energy system concepts. While it may be necessary to look at absolute sizes to assess the magnitude of wind turbine field areas, or the limitation of specific storage and transmission concepts, this relative comparison is rather insensitive to absolute load levels.

This concept design study therefore focuses mainly on the transition to post fossil-fuel electric power. Aside from identifying constraining factors for the various concepts, the feasibility of scaling up the system to electrify other energy sectors like transportation is beyond the scope of this study.



4.4 Known technology and proven concepts

Energy technology is mature. Technologies visible today were visible back during the last alternate energy boom in the 1970's. Advances in battery technology for example are likely to be incremental, 20-100% cost/performance improvement rather than revolutionary, 1,000-10,000%. All the battery chemistries are known and well researched. There simply is little opportunity for revolutionary new technology driven concepts. In contrast, there is opportunity for new system risk management concepts like microgrids and dispatchable generator designs that can rapidly follow variable net loads.

Rational planning is based on what is known and can be estimated with confidence today. It includes technologies and systems that have been prototyped sufficiently well to have high feasibility confidence and to be able to project volume production costs at scale. This would include technologies like certain nuclear reactors, wind turbines, solar PV and pumped hydro storage.

Other technologies and systems are potentially feasible but have specific questions that need to be demonstrated by further development. Examples are fast neutron reactors and compressed air storage. These concepts can be included in concept design options with the risks noted and recommendations made for engineering development. The same is true for new system concepts requiring lifestyle changes, such as using plugin electric vehicles for reliable grid scale storage.

Concept design would exclude technologies which do not have full scale prototypes or where serious feasibility questions exist. An example here is nuclear fusion, hot or cold.

4.6 Boundary condition

Concept modeling is simplified by the assumption of a closed boundary condition. The smallest transmission entity for which a closed boundary is a reasonable approximation is the Balancing Area defined by NERC by the requirement to match generation with load to within a certain tolerance. The PJM system is a balancing area.

NERC requires that any power interchange necessary to maintain reliability be supported by firm agreements.³⁵ Fig. 5 (next page) illustrates the 11 major interconnections to the contiguous PJM system. At the time this screenshot was taken, the net transfer through these external interconnections was only 0.24% of load suggesting that closed boundaries are a reasonable approximation at this concept design stage.

The primary set of scenarios assumes that adjacent RTOs are doing the same thing and that there is a hard boundary around the PJM system. Two exceptions are a limited set of scenarios based on a Midwest wind generation concept to access the impact of long distance transmission costs. The second exception under reimagining the RTO is a limited set of scenarios based on a closed boundary for the State of Maryland.

4.7 Excluded from the study

Excluded from the Study is a transition plan, how to evolve the existing system into a zero emission system. The study is strictly focused on the end state options. The pace of transition impacts affordability. Balancing the pace of transition against climate change consequences is a stakeholder

choice. The transition plan is a separate study defined after stakeholders choose a system architecture. Complexity is added step by step to elucidate fundamental relationships that underlie the operation of the full complex systems.

The Study excludes concepts for the overall reduction of fossil fuel in other energy sectors such as plugin electric vehicles. Electrification of other sectors often has less stringent reliability requirements and may be more tolerant of low cost intermittent generators. There is weak linkage between overall reduction and electric power such as using waste heat from nuclear plants for district heating. An overall emission reduction concept study should be conducted separately.

Likewise the Study excludes consideration of market reform. The sequential logic is to first choose the system which defines a cost structure, then design a market to provide appropriate incentives.



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5.0 RECOMMENDED STATEMENT OF WORK

The art of a Concept Design Study is to choose the appropriate level of detail. The study needs enough detail to clarify fundamental relationships and provide stakeholders with clear competent choices. Too much detail confuses and obscures these relationships.

The goal is a PJM system that is both reliable and affordable with little or no fossil fuel. A Concept Design Study compares simple systems of different technologies. It is a technology agnostic definition of the cost, performance and risks of alternative concepts subject to PJM system constraints. While somewhat idealized, the comparison must be firmly grounded by empirical data.

The recommended program consists of four phases:

- 1. Preparatory tasks The most important of which is calibration of intermittent generator models
- 2. Generator comparisons Compares the full range of generator types, locations, storage and combinations using the copper plate transmission assumption.
- 3. Transmission comparisons Uses a reduced subset of generator combinations to explore the cost implications of transmission. This subset includes as least one nuclear concept, one non-nuclear concept plus a couple of combinations, one requiring transmission from Midwest wind.
- 4. Concluding tasks Compiles all of the information necessary for stakeholder choices.

5.1 Preparatory tasks

5.1.1 Choice of Model methodologies

NREL's WIND Toolkit³⁶ appears to have the necessary capability. However NREL's published validation report³⁷ is inadequate. That validation report finds that the model over predicts historical capacity factors by about 35% and lists possible causes but does not parse the causes into factors that would be improved with better technology (such as greater hub height) and those factors that would exist for future installations (wakes; poor siting, maintenance calibration, age ...). The technology improvements can be estimated by comparing power curves. The remainders are the practical consequences of real-world operations. The validation report does not mention calibration of second order statistics.

Stochastic models are popular today. However these models generally assume that wind farm production is independent. That is, a wind farm in Baltimore could be experiencing high wind condition while at the same time a wind farm in Annapolis experiences calm conditions. Stochastic modelers would need to show that their methods correctly reproduce measured data.

As part of the proposal, contractors need to provide evidence that their chosen model can replicate curtailment and show that the model has sufficient phenomenological fidelity to be generalized.

5.1.3 GE PJM Renewable Integration Study³⁸ comparison

General Electric International, LLC led a team that investigated the integration of up to 30% renewables onto the PJ system. While the goal is different than this study, the tools and methods were similar. This task chooses one of the 30% GE scenarios and compares the results using the calibrated models from § 5.1.2 to understand the similarities and the differences between GE and the contractor's models.



5.1.4 Storage technologies and strategies

There are 3 strategies by which storage could impact clean electric power system design:

- In principle, annual or multiyear storage could make intermittent generators an effective base load generator.
- Diurnal storage could level daily load variation and reduce the cost of base load systems.
- Short term (minutes-hour) storage could regulate load and provide a patch for operational problems, this is beyond the scope of this concept design study.

While considerable effort has been directed at developing grid scale storage concepts, technologies are seriously constrained by chemical and physical realities. ARPA-E has funded a grid scale storage program for a number of years.³⁹ That program seems to have reverted to short term storage (hours). Storage will inevitably play an important role in clean energy development. This task should focus on electric power system development where feasible seasonal storage appears necessary for wind and solar to compete as a base load generator subsystem.

Generic unspecified technology storage (§ 9.3 \$200/MWh, 80% efficiency) is used for the basic system comparisons. Then PJM specific storage, estimates consistent with PJM geographic constraints. What are the costs of technically feasible storage solutions including:

- 1) Use the Great Lakes for pumped hydro storage.⁴⁰
- 2) Compressed Air Energy Storage.
- 3) Fuel production and chemical storage followed by combustion. This approach has merit both for a highly volatile net load from intermittent systems, and seasonal surplus on a system with base load generators.
- 4) Hot rock
- 5) Molten salt.

5.1.5 Nuclear power forecast

Generation III technology in both large and small modular formats is sufficient for the concept design assessments.

A critical review of nuclear fission development potential is necessary to characterize sustainability, cost, safety and waste disposal. Planet earth has enough uranium and thorium to provide all of civilization's energy needs for >2,000 years. There is enough uranium in seawater for 100,000 years.⁴¹ From a practical perspective, this is sustainable if toxic buildup is strictly controlled. Assume a public mandate to build out nuclear; what are the intermediate term technologies and cost after first-of-a-kind inefficiencies are overcome? (Note: China is currently purchasing nuclear power plants for a price that is 5x cheaper than the US.⁴² While labor rates and regulation are factors, much of the difference can be explained by multiple unit procurements of standard designs vs. custom designs.)

What are the nuclear fission technologies and viable long-term whole-system nuclear development paths? Assuming active development by DoE, which technologies (including fast neutron reactors) are appropriate for deployment in the study period of 20-100 years and suitable for cost estimating? What risks need to be resolved by Engineering Development and full-scale prototypes? What is the longer term (>100 year) potential of nuclear fission? How will radioactive waste disposal eventually be managed? What new concepts are emerging?⁴³ What is the risk?

5.1.6 Renewables forecast

Critical review of renewables technologies, performance and life-cycle costs. This review is based on what is known today and what can be projected with confidence, i.e. data supported learning curves.



5.1.7 Cost estimating

The main purpose of the Study is to compare concepts. Hence the relative consistency of cost estimates is more important than absolute accuracy. To this end, estimates should assume the same cost of capital, consistent tax structures, no subsidies, realistic equipment longevity, consistent learning curve methodology, and the same degree of conservatism.

One source of direct cost is the US Energy Information Administration⁴⁴ which provides periodic updates of generation cost. One criticism of the EIA numbers is that they seem to use equal life expectancy for all hardware; longevity should vary based on data. Another frequently cited data source for new generation is Lazard.⁴⁵ The peer reviewed literature should not be taken at face value for storage estimates, a critical review of published storage cost estimates is necessary.

Another data source is the OECD report on The Full Costs of Electricity Provision.⁴⁶ While EIA and Lazard provide estimates of direct cost, the OECD report is broader, including indirect costs such as pollution and accidents. Both direct and indirect costs are important but should not be intermingled. Policymakers need to decide how to present the results for stakeholder choice.

5.2 Basic System comparisons

Compare the full suite of candidate new construction generator types and storage assuming no loss, no cost transmission. For Basic System Comparisons, reliability can be modeled by assuming reserves of 10% of peak load; satisfied with natural gas combustion turbines. Preserving the many correlations associated with intermittent generators is essential. Models are validated and calibrated against PJM data. To do this it is necessary to locate the power plants for the purpose of performance modeling.

5.2.1 Copper-plate transmission approximation

The Basic System Comparisons assume copper-plate transmission; zero cost, zero loss and zero capacity constraints. Transmission constraints are addressed in § 5.3.

5.2.2 A reference year

A single year (more specifically a contiguous 12 month period) is selected for broad component comparisons. (In a later phase a reduced set of system options is configured as a single system for multiple years.) The reference year would be the most recent year for which a full set of load, wind, and solar data is available without substantial disruption from new additions.

5.2.3 Natural gas reference

The reference system is 100% natural gas. Using the most current EIA data the lowest cost combination of combustion + combined cycle turbines is configured to satisfy the reference year load plus 15% reserves. The reference system has a single levelized cost (cts/kWh) and CO_2 emissions.

5.2.4 Nuclear baseline

This system starts with the natural gas reference and adds Generation III nuclear plants at EIA cost for advanced nuclear. As nuclear plants displace base load natural gas plants while reducing emissions, system costs can be tracked as discussed in § 10.0. System costs begin to increase more rapidly when nuclear capacity exceeds average load.

1. The idealized zero-emission nuclear system has nuclear capacity equal to reference year peak load plus 15% combustion turbine reserves. What is the levelized cost?



- Assuming annual maintenance can be scheduled for low load periods and modest load following is by existing technology, how much baseload can be satisfied by nuclear before it needs to be curtailed.
- 3. Load leveling 1, load following Develop a load following requirement that would allow nuclear to be cycled to satisfy full peak load by itself.
- 4. Load leveling 2, storage France uses oversized domestic hot water heaters to levelize load. If the US adopts this approach what are the limits. Is the nuclear load following requirement sufficient to manage the residual?
- 5. Load leveling 3, solar PV What is the system cost impact of managing diurnal load variations with solar PV plus behind the meter battery storage? (see §5.6.7). Is there a system cost minimum? What is the nuclear load following requirement to manage the residual?

5.2.5 Onshore wind baseline

This system starts with the natural gas reference and adds onshore wind turbines. As discussed in § 3.9 it is assumed for simplicity that wind turbines provide the system with no capacity credit and do not displace natural gas generators. Added wind turbines will consist of the best visible technology

- 1. Turbines are added at the best performance wind sites (no political constraints) within the PJM system with 2 km spacing up to 75% curtailment.
- 2. Midwest turbines outside of the PJM system.
- 3. Investigate generic storage options varying storage cost. At what system cost is fossil fuel eliminated for the referenced year?
- 4. Generic storage is replaced by PJM specific storage at specific locations. Characterize the limits to which wind plus storage is a practical solution.

5.2.6 Offshore wind baseline

Adds offshore wind turbines to the natural gas reference. The contractor will explain how they will validate and calibrate the wind models employing all available data.

- 1. Best performance sites, no political constraints
- 2. Storage Generic, PJM specific, what are costs as a function of emissions
- 3. Reliability How much OSW can the system tolerate from a reliability perspective?

5.2.7 Solar PV baseline

This system assessment also starts with the natural gas reference and keeps adding solar PV.

1. Cost breakpoints – A little solar

PV has higher value because it provides the system with some capacity credit. But once the residual load curve duck-backs, additional solar does not add capacity and costs escalate. This effect is apparent in Fig. 8 from California а ISO simulation. As PV is added to the system it initially reduces bevond peak. But 5% penetration PV no longer reduces residual peak (at least for the CA system). Where is



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the knee of the curve? At what level of solar PV penetration do system costs begin escalate rapidly?

- PJM rooftop limits NREL developed methodology for estimating solar PV rooftop potential⁴⁷. How much rooftop storage is available within PJM? What are these limits when this methodology is applied to PJM?
- 3. Rooftop PV plus storage Projecting costs for behind the meter battery storage, what are total system costs and what are penetration level cost breaks?

Grid scale solar PV + storage – Distributed ground systems with generic storage and with PJM specific storage. What are the sizes and the limitations for the PJM system?

5.2.8 Grid scale storage feasibility

Storage is central to the question of whether or not intermittent renewables are a practical solution for PJM. This task is a feasibility assessment. Using generic storage assumptions (\$200/kWh, 80% round trip efficiency) and the baseline year, how much storage is required for 100% renewables. Is seasonal storage necessary? What is storage/cost/efficiency sensitivity? Run the simulation for the full 6 years of available data. To what extent does the "worst year" change the storage requirement?

Academics have proposed that PEV batteries already financed and plugged into the grid, can be used for frequency regulation.⁴⁸ All it would take would be a mod to the charging station. Pilot trials are underway in Europe.⁴⁹ A critical review is necessary to assess the impact of this concept on grid operations: What kind of mod to the charging station is necessary? Could it be completely passive or does the utility need control? How much stress is placed on the PEV battery? Does it shorten battery life? How much value is provided to the utility? Can PEVs reliably regulate frequency or does the utility still need assets?

5.2.9 Carbon Capture and Storage (CCS)

While sequestering carbon from fossil fuel production is not sustainable, it has been proposed as a way to reduce CO_2 emissions. EIA and others project costs. The Concept Definition Study needs to determine if carbon sequestration is a practical interim solution.

- 1. Add carbon sequestration to the all-natural gas system to project and compare costs as a function of CO_2 emissions.
- 2. What are practical geophysical constraints within the PJM region? How much capacity is available? What is the practical system cost of CCS as an interim solution?

5.2.10 Combinations and permutations

Engineering design gradually adds complexity to the system. This task develops and characterizes a set of generator plus storage combinations.

- 1. A key result will be a comparison between systems dominated by intermittent generators (wind and solar) vs systems containing only clean base load generators (hydro, geothermal-electric, nuclear). Do mixing clean intermittent generators with clean base load generators offer any advantage?
- 2. To what extent does combining onshore and offshore wind offer an advantage?
- 3. What is the best non-nuclear solution (in the event that stakeholders choose to reject nuclear)
- 4. Which scenarios should be forwarded for more thorough transmission analysis?



5.2.11 Parameter sensitivity variation

Cost estimates have error bars. To what extent does the range of cost (e.g. High for technology x, low for technology y) change the relative comparison of system alternatives? Does the increasing cost of fossil fuel change the relative comparison?

5.2.12 Reduced Set Systems

Choose a reduced set of system configurations for transmission analysis. As a minimum this includes a nuclear dominant scenario, a renewables dominated scenario.

5.3 Transmission comparisons

Power transmission is an important architectural discriminator because transmission costs will exceed generation costs for certain concepts and new transmission corridors can take considerable time to develop. Transmission studies are to clearly compare system concepts for the purpose of aiding stakeholder choice. The transmission studies are subject to the following constraints:

- Existing load, specifically the same load profile and load centers that existed over the study years 2012-2017.
- Coincident wind and solar for those years

5.3.1 Multiple year resizing

The basic generator comparisons in §5.2 are mainly based on a single reference year load profile. In fact, a single system must satisfy multiple years. Based on historical load profiles, this task sizes the reduced set generators so that one system reliably satisfies multiple years.

5.3.2 Optimal storage location

Choose specific grid scale storage technologies, costs and efficiencies that are compatible with the PJM system. For the high wind scenario, physically locate power plants and storage facilities and estimate transmission impact. While the location of new power plants is normally a very political process, these conceptual locations are optimal in that the location is based primarily on system cost.

5.3.3 Reliability

The basic system comparisons can be conducted using zero capacity credit for intermittent generators plus 10% system reserves. These transmission comparisons will use the more accurate statistical methods recommended by NERC⁵⁰ as appropriate.

5.3.4 Grid stability and operations cost⁵¹

Legacy grids and nuclear power concepts use synchronous generators. Legacy power management systems, fault isolation and black start recovery strategies are all designed to exploit the electro mechanical properties of large synchronous generators. In contrast, wind turbines, photovoltaic collectors and batteries must be connected to the grid with power inverters (solid-state switches). With a large number of solid-state interfaces there is concern over system Synchronous Inertial Response.⁵² When renewables penetration is low, the system is still dominated by synchronous generators and relatively simple and inexpensive grid following inverters can be used for renewables connection. But as penetration increases, more sophisticated grid forming inverters will be necessary to avoid stability issues and difficulty with black restart. One solution is to replace low cost inverters with higher cost voltage source inverters.⁵³ What are costs and risks? To what extent have voltage source inverters been validated?



5.3.5 Transmission upgrades cost

This is the cost of modernizing the transmission infrastructure to meet existing load centers for each of the resized reduced set of generators at optimal locations. There have been several studies of PJM transmission upgrades.^{54,55,56} This is not a detailed analysis but rather a conceptual adaptation of past studies to the reduced set of system concepts. Should the transmission analysis prove to be dominant, a more detailed analysis should be recommended for a later date. The tradeoff here is the capacity utilization and cost of transmission assets vs the capital cost of distributed intermittent generators.

5.3.6 Midwest wind potential

This task is a deviation from the PJM closed boundary assumption.

- A significant question is the extent to which long distance transmission (e.g. connecting PJM and MISO) may improve wind capacity credit and possibly reduce the need for seasonal storage. (There is some evidence that the contribution to capacity credit is small.⁵⁷)
- 2. What is the transmission requirement (# lines, distance and cost) to send Midwest wind to East Coast load centers
- 3. What is the cost of feasible storage required for a reliable system? There is a tradeoff here between storage located at the load centers, which requires transmission to be sized for wind generation peaks vs. storage located at generation facilities which requires transmission to be sized for average generation.

6.0 PRODUCTS OF THE STUDY

6.1 Concept comparisons

§9.0 provides examples of generators concept comparisons: all natural gas vs. wind + natural gas vs. nuclear + natural gas. In general one system is established as a baseline, then other system concepts are compared to the baseline in two A vs. B system comparisons. In §9.0 the baseline is nuclear + natural gas. This is then compared to wind + natural gas then to wind + natural gas + storage.

After the gamut of simple-system concepts comparisons has been explored, the analysis is expanded to complex-system comparisons. This expansion needs to include:

- Solar PV combination scenarios with emphasis on quantifying optimal levels.
- Offshore wind combination scenarios.
- Carbon sequestration scenarios
- Transmission options

Once the overall dataset is developed, the more promising concepts are developed in more detail to facilitate stakeholder choice.

6.2 Environmental constraints

The PJM Concept Definition Study is sized by existing load profiles. Environmental constraints are availability of suitable rooftops for behind-the-meter solar PV, land for utility scale PV and wind farms, water for cooling nuclear plants and rights-of-way for transmission improvements.

6.3 Electricity market reform requirements

Wholesale markets will need to be rethought when the system becomes dominated by generators with low variable cost and high fixed cost; and/or if intermittent generators impose substantial indirect costs on the whole system.

Today's markets are designed for systems with generator technology dominated by variable cost (fuel). The markets compete the cost of energy (\$ per kilowatt-hour). With a wholesale market that competes variable cost there is little incentive for capital investment which means no new generation. PJM has added a capacity market to the existing energy market to account for this, but more changes may be needed.

Clean generators have high fixed cost, low variable cost. This means that markets will have to be designed to encourage dispatchable capacity, the ability to satisfy peak loads whenever and wherever they occur. Once the system has enough capacity to reliably satisfy peak load, off-peak electricity is low cost. Aligning price with cost will require a substantial redesign of both the wholesale and retail electricity marketplace.



6.4 Engineering Development requirements

Concept definition produces a list of technology options and requirements for Engineering Development. The purpose of Engineering Development is to reduce risk and sharpen cost estimates through further analysis, component development and testing, and laboratory scale prototypes to resolve questions that were raised during Concept Definition. What are storage requirements for different system needs? How important are load following nuclear reactors? Air cooled nuclear reactors? DC transmission?

While Engineering Development is beyond the scope of this proposal, equipment manufacturers and the US Department of Energy should be interested in those development needs.

6.5 Risk

The main risk of the transition to clean energy is that development stalls because stakeholders reject high prices. Pace of the transition is an important value choice. Fast transition is high cost high risk; slow transition is lower cost. The relationship between pace and cost needs to be clearly defined to facilitate stakeholder choice.

Another serious risk is that stakeholders make long term commitments to technologies that interfere with the ability to reach zero-emission electric power systems. For example, intermittent wind on a zero-emission electric power system seems to have little value. Since all wind electricity production on the system goes to zero (<2%) multiple times per year, the system must have sufficient reliable seasonal storage capacity to reliably satisfy load without wind. So why have wind? Why should another clean generator start and stop to compensate for variable wind output?

All the various technologies have problems; there is no perfect solution. Offshore wind (OSW) has the systemic risk of storm damage which is likely to limit the size of OSW farms. What is the probability of multiple sequential years with low rainfall or low sunlight or low wind? Substantially scaling up nuclear power will increase background levels of ionizing radiation. By how much will background levels rise and are there health consequences? To what extent is waste heat an environmental factor.⁵⁸

The various risk elements for each solution need to be summarized for informed stakeholder choice.



7.0 GOVERNENCE FOR PJM CONCEPT DEFINITION STUDY

The Public Utilities Regulatory Policy Act of 1978 created a fragmented management structure for electric power systems. An integrated re-design of electric power systems therefore requires coordination and cooperation among many players.

Player	Role	Motivation
State of Maryland	Initiator, coordinates stakeholder value choices, decision management methodology, State co-sponsor	Clean energy leader, sea level rise vulnerability, understanding constraints and practical choices, minimize risk
Coastal PJM States	Value choices, co-sponsor	Vulnerable to sea level rise; to understand constraints and practical choices; minimize risk and cost.
Non-coastal PJM States	Value choices, co-sponsor	Understanding constraints and practical choices; minimize risk.
Future of Energy Initiative	Individual consultants as needed	Lessons for guiding other systems;
PJM Interconnection	Transmission modeling and analysis	To understand conservative integrated development.
Energy information agency (EIA)	Provides technology cost projections	A primary challenge is volume production estimates for nuclear power.
Office of Nuclear Energy (DoE)	Observer/reviewer	Nuclear reactor requirements for zero- emission system scenarios.
North American Electric Reliability Corp (NERC)	Reliability simulations	Understand reliability drivers for low- emission systems.
Federal Energy Regulatory Commission (FERC)	Observer/reviewer	Understand how markets shift as costs drivers change from variable to fixed.

Table 2

7.1 Public trust

The popular clean energy debate today is both highly politicized and ignorant of the realities of practical engineering and electric power system design and operation. The necessary authority and skill sets are analogous to the strong power planning groups of the vertically integrated utilities of the first half of the 20th century. These authorities and skill sets do not reside in any one organization today. The study contractor and its management processes also need to be regarded by the public as neutral, objective and transparent in developing and presenting the results of its analysis. Public trust is essential for the acceptance of PJM Concept Definition Study results.



7.2 Stakeholder management group

States make value choices. Stakeholders are strong participants in the major program reviews (milestones) in Waterfall development (Fig. 3). They may consist of members of different State agencies. The stakeholder team reaffirms the Goal and during milestone B decides whether the concept definition effort is complete and recommends or affirms recommendations for next steps.

The stakeholder team is the public face of the program. They communicate with various stakeholders and the public through meetings, press releases and town hall meetings much like stakeholder management teams in public works projects.

7.3 Red team

The role of red teams is an independent critical review of progress, identifying strengths, weaknesses, and next steps from the perspective of technology, architecture and the view of various stakeholders. Any sponsor can voice concerns to be investigated by appropriate red teams

8.0 SUMMARY

This Concept Definition Study compares the cost, performance and risk of alternative zero-emission system architectures for the PJM system. The study starts with a blank sheet of paper constrained only by historical load centers, transmission corridors, and historical data on load, wind and solar resources. The results are practical system options reliable feasible alternatives for stakeholder choice and policymaking.

The Study product is a definition of the cost, performance and risk of practical PJM system alternatives as greenhouse gas emissions approach zero. The target is a realistic system state, a configuration. Time is a variable, it may be 30 years, it may be 130 years. Pace, fast or slow, is a subsequent political choice that involves balancing transition cost, and risk; including both development risk and climate change risk. This is not a 20-year power plan (which has the purpose of projecting forward existing trends for 20 years).

It is expected that the PJM Concept Definition Study will be followed by other studies such as:

- Concepts for reducing non-electric power emissions by using clean electric power.
- Selecting and timing Engineering Development plans.
- Defining and planning transition options.
- Designing and planning market reform.
- Prioritizing overall emission reductions.

The following Appendix (§ 9.0 - § 11.0) illustrates a conceptual tradeoff of the type that may be expected from the study. The illustration suggests that stakeholders need to judge the risk that intermittent renewables may fail to reach zero emissions on the PJM system. § 12.0 contains the references cited in the text.



APPENDIX

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9.0 TWO-COMPONENT PJM SYSTEM CONCEPT COMPARISON

Fig. 9 illustrates a system level cost vs emission performance comparison for different 2-component system concepts using PJM 2018 wind and load profiles. Its purpose is to illustrate the level of detail

expected from a concept definition study. Specifically: How much detail is necessary for policymakers to understand the important relationships and architectures so they can make policy choices?

This §9.0 describes the Fig. 9 chart. §10.0 "The Computation basis..." explains the method. "Example §11.0 Scenario" presented the numbers behind the chart. Costs are based on the US Energy Information Agency's Annual Energy Outlook for 2018. 59 As a reference point, the orange triangle presents emission performance and average PJM wholesale market clearing price for 2018. This section is a refinement of a couple of ASME conference papers. 60, 61



Figure 9 Generation cost/performance comparison

9.1 100% natural gas reference system

Imagine a new PJM system consisting of 100% natural gas installed using AEO2015 cost estimates. This is modeled as combined cycle generators with peak load capacity (CC in the figure), plus 15% reserves consisting of combustion turbines (CT). Such a 100% natural gas system would have emissions of about 500 g(CO₂)/kWh and the levelized cost of a new installation (developed in Table 3) would be about 8.5 cts/kWh. This system is represented by the red square in Fig. 9.

9.2 Wind + natural gas systems

Now gradually add wind turbines to the all-natural gas reference system. The cost/performance of the combined wind plus natural gas systems at various levels of wind penetration is represented by the solid blue curve. The more wind that is added the lower the emissions but higher the cost.

At low wind penetration (0 to 25% clean, from 500 to 350 $g(CO_2)/kWh$), the solid blue curve is almost a straight line sloping up to the right. The reason the cost increases is because, for the EIA cost numbers



used, the discounted capital cost of the wind turbines (without subsidy) is greater than the natural gas savings. For scenarios with higher gas prices, the curve could slope down to the right.

There are certain hours (middle of the night, low load, high wind) when electricity from wind generation by itself is greater than the load and some turbines need to be shut down (curtailed). On the PJM system, curtailment begins at about 25% wind penetration (375 g/kWh). Beyond this point, the more wind turbines that are added to the system, the more wind turbines need to be shut down. Curtailment is the main reason wind system costs increase rapidly as more wind is added to the system.

The Fig. 9 PJM wind profile explains why wind by itself cannot reach zero emissions. There are 23 hours during the year when there is no wind (<1% of nameplate, red bars). When there is no wind it does not matter how many turbines the system has, there is no wind power.

In Fig. 9, the wind system indicated by the blue diamond on the blue-solid curve is for wind scale up of 50x (50 times the 2012 PJM wind penetration) and is calculated in detail as an example in §11.4.

9.3 Wind + natural gas + one-day storage systems

To illustrate the effect of system storage, consider adding one-day average-load generic storage to the wind system. The red-dot curve in Fig.9 is based on storage cost (\$200/MWh) and efficiency (80%) that is representative of pumped hydro⁶² assuming the geography exists. Storage is either charged or discharged by wind depending on the availability of excess wind. For each hour natural gas is used to the extent that wind and/or storage are insufficient.

With no curtailment (0 to 25% clean) storage does not reduce system cost and the storage system curve tracks the wind system curve but at a higher level. Storage reduces system cost when electricity that is otherwise curtailed can be used at a later time. At wind penetration beyond 25% penetration the spread between the storage and no-storage systems is reduced and the red-dot and blue-solid curves come closer together. The crossover point, where 1 day storage is cheaper than a no-storage all wind is at 80% wind penetration or 100 g/kWh. At higher wind penetration beyond 80% the storage system is cheaper than wind though at a high cost.

9.4 Nuclear + natural gas systems

Start with the same all-natural-gas system illustrated by the Fig. 9 red square. Recall system costs of 8.5 ¢/kWh was derived by assuming that this system consists of combined cycle natural gas turbines with peak system capacity plus 15% reserves consisting of simple combustion turbines.

Keep the reserves and add nuclear plants displacing the combined cycle plants. Unlike wind, nuclear power plant capacity replaces natural gas power plant capacity. The addition of nuclear increases the system cost above that of all natural gas because the levelized cost of nuclear (9.5 ¢/kWh, column f Table 3) is greater than the EIA estimate (AEO2015) levelized cost of combined cycle natural gas (7.3 ¢/kWh). This means the green dash curve slopes up to the right.

For PJM2012 average load was 58% of peak load. If nuclear displaces all natural gas below average load, the remaining emissions above average load is 36 g/kWh (black X on green-dash curve, Fig. 9). For nuclear to provide 100% of peak load, capacity has to increase from 58% to 100%, a factor of 1.72. This

capacity increase explains the sharp spike of the right of the green-dash nuclear system curve and indicates that 100% base load nuclear is not the best technology for powering diurnal load variation. A more complex system including some other technology such as diurnal storage or solar may reduce overall system cost.

9.5 PJM 2016 reference point

The yellow triangle on Fig.9 is a reference point representing the actual CO_2 emissions (454 g(CO_2)/kWh for PJM and the average wholesale clearing price (3.4 ¢/kWh) for PJM in 2016. The wholesale price does not reflect levelized cost because the fixed generator cost is often subsidized by the States and shows up on the retail cost side of the ledger.

9.6 What is missing?

Fig. 9 shows fundamental relationships and several tentative conclusions can be drawn:

- 1. Wind curtailment on PJM could be a serious cost factor at high wind penetration or in transmission congested regions. While more evidence is needed, this seems to be a general fundamental conclusion.
- 2. Storage using visible technologies is not a game changer.
- 3. Base load nuclear is important for achieving high emission reduction; this is the same conclusion as Ontario Canada.

A thorough Concept Definition Study would also include the following:

- 1. Explore the combination of wind and solar. Solar disrupts the wind-load correlation by shifting the net load peak to the evening.
- 2. There is likely to be an optimum level for solar penetration which needs to be estimated;
- 3. Transmission upgrade costs which can increase costs for all system types;
- 4. Annual variation, one system must be sized to reliably service multiple years.
- 5. Grid scale storage requirements: what performance characteristics (cost, efficiency, size) would make a difference.
- 6. Offshore wind has higher cost and different production profiles;
- 7. Combinations and permutations of different generator types;
- 8. Parameter variation, what happens as fossil fuel costs and component costs change.



10.0 COMPUTATION BASIS FOR PJM EXAMPLE

10.1 Load and wind data

The basis of the Fig. 9 PJM2012 example is hourly load data⁶³ and hourly wind data⁶⁴ published by PJM. Load data for calendar year 2012 is graphed in Fig. 8 along with the relevant design levels. Hourly wind production data is graphed in Fig. 9. Note the red bars along the axis of Fig. 9; total wind goes to zero (more accurately <2% of nameplate) for a couple of dozen hours during the year.

To conduct the analysis for various wind penetration levels wind is scaled, multiplied by a constant. Scaling assumes that additional wind turbines



have the same footprint (location) as existing wind turbines. This approach correctly preserves the many wind and wind-load correlations for that specific configuration.



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10.2 Cost data

Costs for the PJM example were published as the levelized cost reference case in the EIA Annual Energy Outlook for 2015⁶⁵ (Table 3). These numbers are from the EIA baseline national average. The reason for choosing the EIA dataset was that the EIA provides a consistent comparison with no subsidies, that is, common discount rates, and tax policies. There are other sources such as Lazard.⁶⁶ For each technology we need to know fixed costs and variable costs. In Table 3, columns a-f are EIA data (converted from \$/MWh to c/kWh). Column g was calculated for this report.

Fixed cost (column b, c, e) is the annual cost that needs to be paid regardless of how much energy is or is not produced. Think of this as a mortgage payment. The main components are the "principle payment,"

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the interest, depreciation on capital equipment investments, and taxes. The resulting cash flow is converted to an annual payment using a common discount rate. This annual fixed investment needs to be converted to an energy cost so the EIA divides the annual fixed investment by the annual energy produced [the technology capacity factor (CF), the EIA estimate of the fraction of the year that the technology is producing electricity]. For modeling, the EIA's CF assumption is backed out of the calculation by multiplying the EIA fixed cost by the EIA assumed CF to produce column g, levelized capital cost assuming the technology is sized for 100% of average power.

Variable cost (column d, var O&M, variable Operation and Maintenance) is that cost which is proportional to produced power. For wind, EIA assumed it is zero, for the other technologies variable cost is dominated by fuel cost.

	а	b	С	d	е	f b+c+d+e	g a/100*(b+c+e)
Technology		levelized				Total lev	100% fixed
	Cf	capital cost	fix O&M	var O&M	xmisson	cost	cost
Advanced nuclear	90	7.01	1.18	1.22	.11	9.52	7.47
Natural gas adv cc	87	1.59	0.20	5.36	.12	7.27	1.66
Natural gas adv ct	30	2.78	0.27	7.96	.35	11.36	1.02
Wind	36	5.77	1.28	0.0	.31	7.36	2.65

EIA (AEO2015) levelized cost estimates for 2020 installations ($\ensuremath{\textit{¢/kiloWatt-hour}}\)$ Table 3

10.3 System cost construction rules

System costs are constructed using the variable and fixed costs in the purple shaded columns of table 3.

- Fixed cost is the cost of Installed capacity on the system. Since column g is fixed cost for 100% level load, fixed cost for a new system is the amount in column g, times a factor that indicates how much the installed capacity of that technology in the new system is greater or less than average power. For example a 100% natural gas system needs to cover peak load so from Fig. 5 the factor is 154/89=1.73 and the fixed cost for cc natural gas becomes \$1.66 ¢/kWh *1.73=2.87 ¢/kWh.
- Variable cost is the cost of producing power from installed capacity. It is the amount in column d, times a factor that is the fraction that that generation technology contributes to annual demand.



11.0 SCENARIO DETAILS

Based on PJM2012 wind and load data as well as AEO2015 cost data, this section derives the numbers for the scenarios presented in Fig. 9.

11.1 All-natural gas combined cycle system cost construction

If the load were level, the all-natural gas combined cycle system would have a cost structure as illustrated in Table 4. The fixed cost and variable cost (including fuel) is obvious from Table 3. The reserve cost is 15% of the 100% capital cost (0.15*1.02=0.15).

	Level Load	factor	Real Load
Component	¢/kWh		¢/kWh
CC Fixed	1.66	1.73	2.87
CC Variable	5.36		5.36
CT Reserve	0.15	1.73	0.26
TOTAL	7.17		8.49

Table 4 All natural gas scenario

But the real load is not level. From Fig. 8 the ratio of peak load to average load is 1.73. (154/89=1.73). Therefore the fixed cost is increased by a factor of 1.73 which is reflected in

the Real Load column in Table 4. Since the reserve is 15% of the peak, the reserve capital cost is increased by the same factor of 1.73. The corresponding emission is 500 g/kWh. This data point is the red square in Fig. 9.

11.2 All-nuclear system cost construction

In a similar fashion the cost of an all-nuclear system with sufficient capacity to manage peak load is modeled in Table 5. Both the 100% capital cost number (7.47 ¢/kWh) and the reserve (1.02 ¢/kWh * 0.15) is increased by a factor of 1.73. The corresponding emissions are 0 g/kWh.

Component	Base	factor	¢/kWh
	(¢/kWh)		
Fixed	7.47	1.73	12.87
Variable	1.22		1.22
Reserve	1.02	0.15*1.73	0.26
ΤΟΤΑΙ			14.35

Table 5 All nuclear scenario

11.3 Base load nuclear + natural gas system

The nuclear + natural gas curve presented in Fig. 9 is based on four data points: all natural gas; all nuclear; nuclear providing continuous base load power at the annual load minimum load of 57 GW (Fig. 8); and nuclear providing average load power at 89 GW. This section details the calculation of nuclear providing 57 GW continuous baseload with CC natural gas the remainder.

The nuclear fixed factor is min/avg=57/89=0.64. Additionally nuclear requires down time for maintenance. When nuclear power plant capacity is less than minimum load (>180 g/kWh for PJM2012) it is assumed that nuclear has a capacity factor of 0.9 to account for scheduled maintenance. This increases the capacity factor by dividing by 0.9. (Note that forced outages are accounted for by assuming 15% reserves.)⁶⁷

At minimum load nuclear provides 57MW*8760h= 499 TWh per year so the nuclear variable cost factor is 499/781=0.64. From Fig. 8 the fixed cost of combined cycle natural gas is (max-min)/avg so the fixed factor is (154-57)/89=1.09. The energy provided by natural gas is the annual total (781 TWh) minus that



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provided by nuclear (499 TWh) or 282 TWh. So the CC variable cost factor is 282/781=0.36. As before, the reserve factor is 1.73*0.15=0.26.

Table 6 summarizes the system cost results. Since natural gas provides 36% of annual load, system emissions are $500*0.36=180 \text{ g}(\text{CO}_2)/\text{kWh}$.

11.4 Wind + natural gas system scenarios

Component	Base	factor	¢/kWh
	(¢/kWh)		
N fixed	7.47	0.64/0.9	5.31
N variable	1.22	0.64	0.78
CC fixed	1.66	1.09	1.81
CC variable	5.36	0.36	1.93
Reserve	1.02	0.26	0.26
TOTAL			10.09

Table 6 Nuclear + natural gas

Wind system scenario analysis begins with a reliable all natural gas system which has cost components presented in Table 3; emissions are $500 \text{ g}(\text{CO}_2)/\text{kWh}$.

The blue-solid curve in Fig. 7 is developed by a series of data points, each data point representing the cost-emissions of a different system, each system with a different amount of installed wind.

The amount of wind is determined by scaling the hourly wind profile (Fig. 9). An arbitrary scaling factor is chosen (say 50x). Then hour by hour, wind production data in Fig. 9 is scaled up by multiplying by 50. Scaled wind is then subtracted from corresponding hour load to determine the residual load, how much of the load must be satisfied by natural gas for that hour. If the wind exceeds the load for that hour, the difference is discarded (curtailed).

The annual sum of hourly residual loads must be satisfied by natural gas. The ratio of residual load to annual load times $500 \text{ gCO}_2/\text{kWh}$ is the specific emissions corresponding to the scaling factor chosen for that data point. For PJM2012 profiles and a scaling factor of 50, emissions are found to be 183 g(CO₂)/kWh, 37%.

The cost side of the cost-emission data point has three parts:

- Wind fixed cost The rule is that fixed cost is the amount in Table 2 column g, times a factor that indicates how much the installed (nameplate) capacity of that technology is greater or less than average power. For a scaling factor of 50, average wind production for 2012 would be 71.4 GW. Average load was 88.9 GW. So the ratio of wind production (including discard) to average load was 0.803. This is divided by the empirical capacity factor (0.247)⁶⁸ to get the ratio of installed capacity to average load.
- CC fixed cost This is the same as the first row of table 3. Wind capacity credit, the amount by which natural gas generator capacity can be reduced by the addition of wind while maintaining system reliability is small, assumed to be zero.
- 3) CC variable cost The base variable cost is reduced by the same amount as the emissions, 37%.
- 4) Reserve cost Same as table 4.

Table 7 presents the cost summary for 50x scale up, presented as the blue diamond in Fig. 7.

Component	Base (¢/kWh)	factor	¢/kWh
Wind fixed	2.65	0.80/0.25	8.48
Wind var			0.0
CC fixed			2.87
CC variable	5.36	0.37	1.96
Reserve			0.26
TOTAL			13.57

Table 7 Wind + natural gas



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 67 For the remainder of the green-dash curve, when nuclear capacity is between minimum load and average load (<180, >40 g/kWh) the maintenance capacity factor is assumed to be 0.95. When nuclear capacity is greater than average load (<40 g/kWh) there is lots of spare capacity and the maintenance capacity factor is assumed to be 1.0. 68 This is the empirical (not theoretical) wind capacity factor. It is the RGGI consolidated metered wind production divided by reported installed capacity.