

Relative Comparison of the Rate of Convergence of Collaborative Systems of Systems: A Quantified Case Study

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Relative Comparison of the Rate of Convergence of Collaborative Systems of Systems

- Abstract
- Collaborative System of System
- Modelling Approach
 - Causal Map and Dynamic Bayesian Network
- U.S. Smart Grid as a System of Systems
 - Factors which influence convergence of functionality
 - Constituent systems and Metric for Functionality
 - Representative model of the System of Systems
- Expected Results
- Initiatives to Counter Improvised Explosive Devices as a System of Systems
 - Factors which influence convergence of functionality
 - Constituent systems and Metrics of functionality

Abstract

- A System of Systems provides functionality beyond that possible from its constituent systems. The functionality emerges over time; there is a need to **predict the system's rate of convergence**.
- Convergence can be seen as a measure of technical progress towards a desired business capability. The rate of convergence is dependent on **Political, Economic, Societal and Technological (PEST) factors**.
 - For example, the United States Smart Grid, a collaborative System of Systems, is converging at various yearly rates in each of the fifty states and consequentially by a quantifiable yearly rate in the United States. In each state, the rate depends on policies, roadmaps, grants, cost recovery, consumer support and sufficiency of technological solutions.
- We constructed a **Dynamic Bayesian Network to model the rate of convergence of the Smart Grid**. The convergence model was trained using historical data representing the PEST factors and may be used to predict the future rate of convergence.
- The predictions of the convergence model may be **used to communicate technical progress to stakeholders and to make comparative assessments among the PEST factors** influencing the convergence of Systems of Systems.

Collaborative System of Systems

- Three characteristics distinguish types of SoS: Objective, Governance, Inter-relationship (of the constituent systems to the aggregated system)
- The PEST factors have differing degrees of influence for each of the SoS types

SoS Objective: Emergent					SoS Objective: Recognized
SoS Governance: Community	VIRTUAL	COLLABORATIVE	ACKNOWLEDGED	DIRECTED	SoS Governance: Centrally Managed
Inter-relationship: Independent					Inter-relationship: Subordinate

Derived from:

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- Systems of Systems (SoS). (2016, March 25). in BKCASE Editorial Board, Guide to the Systems Engineering Body of Knowledge (SEBoK), version 1.6, R.D. Adcock (EIC), Hoboken, NJ: The Trustees of the Stevens Institute of Technology ©2016. Retrieved 23 Apr 2016 14:46:14 UTC from [http://sebokwiki.org/w/index.php?title=Systems_of_Systems_\(SoS\)&oldid=51079](http://sebokwiki.org/w/index.php?title=Systems_of_Systems_(SoS)&oldid=51079).

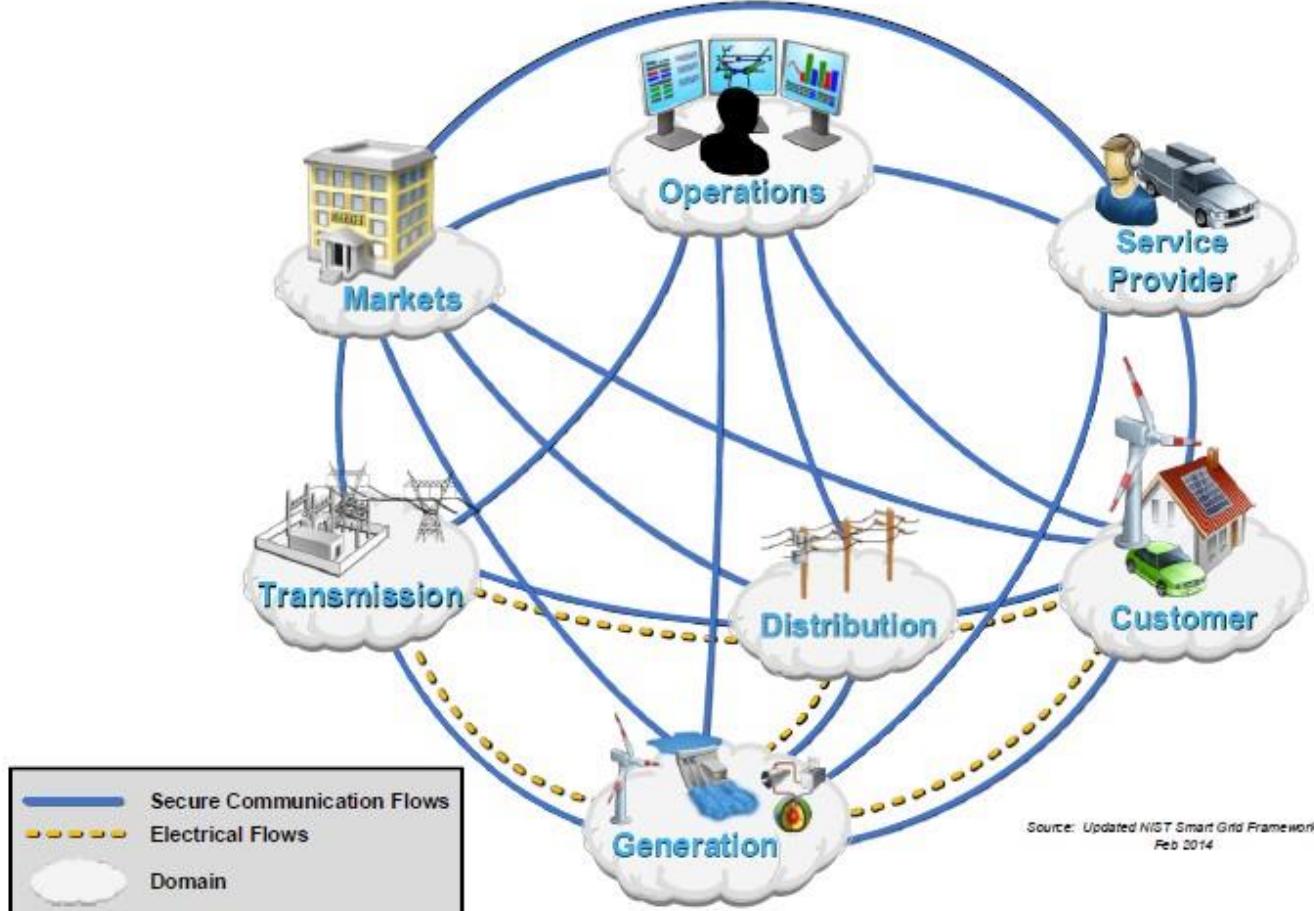
Modelling Approach – Dynamic Bayesian Network

- Identify Quantifiable Factors which Influence the Rate of Convergence
 - Policy – Legislation, Directives, Control Documents, Vision Statements
 - Economic – Financial/Quantifiable Factors to Close the Business Case
 - Societal – Public or Subversive Support or Resistance
 - Technological – Capability to Interoperate, Capacity to Contribute
- Specify the Systems and the System of Systems; Determine Metrics for Functionality
- Construct DBN and Relative Conditional Tables for each ARC in the Model Based on Relevant Observations or Expert Elicitation
- Validate the Model; Use the Model to Explore Contributions of and Dynamics with the Factors which Influence

Dynamic Bayesian Networks are Directed Acyclic Graphical models of Stochastic processes

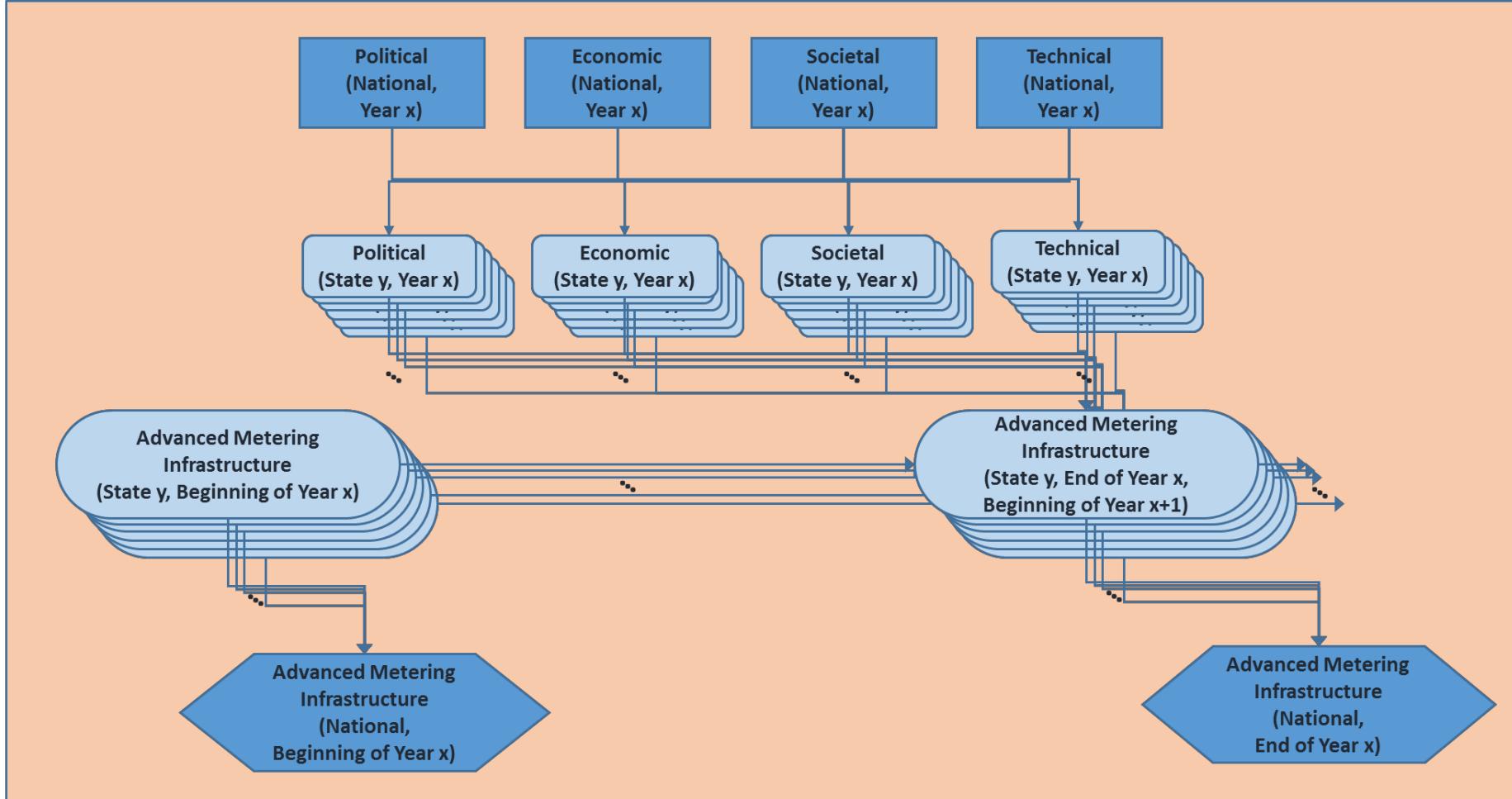
Background: U.S. Smart Grid Framework

Conceptual Model



The Advance Metering Infrastructure (AMI) is crucial for enabling the U.S. Smart Grid

Causal Map of AMI Deployment (one year)

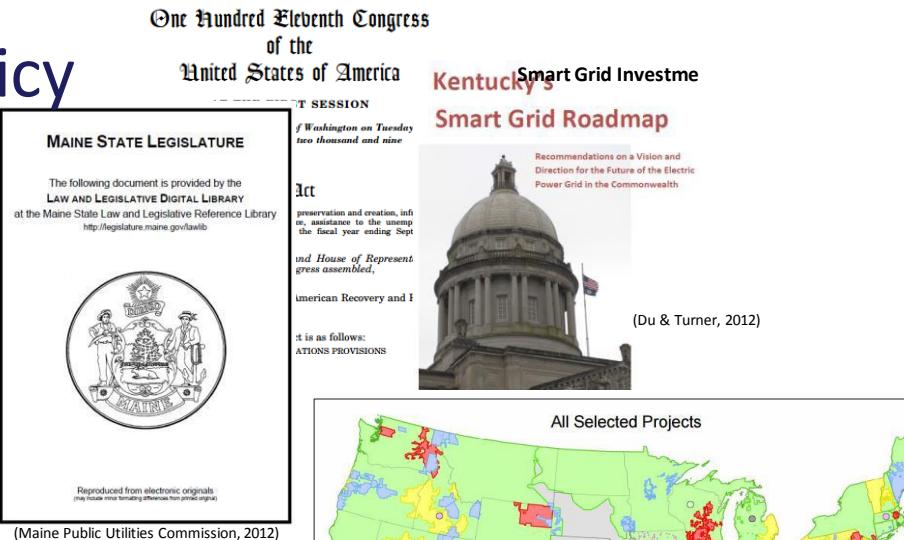


The Grid of each State is a constituent system



Smart Grid - Factors which Influence

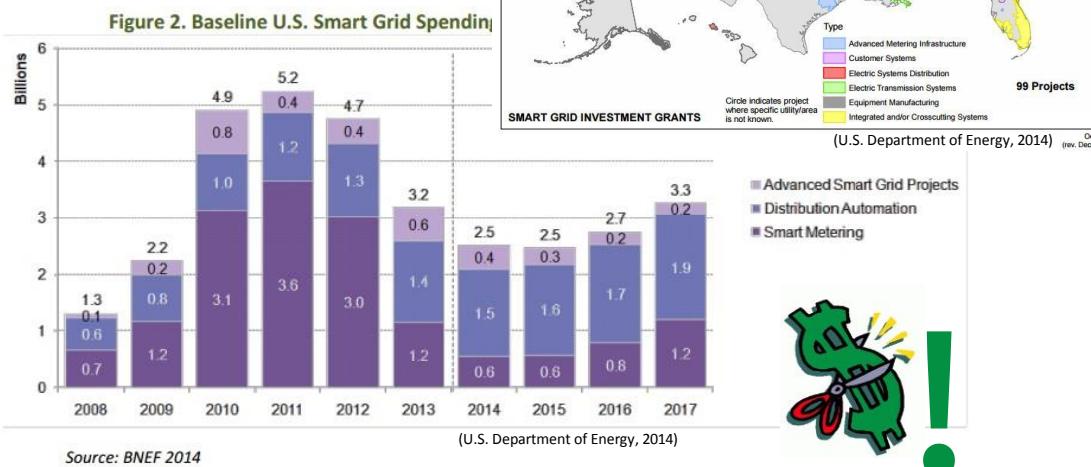
Policy



Societal



Economic



Technological

NIST Special Publication 1108r3

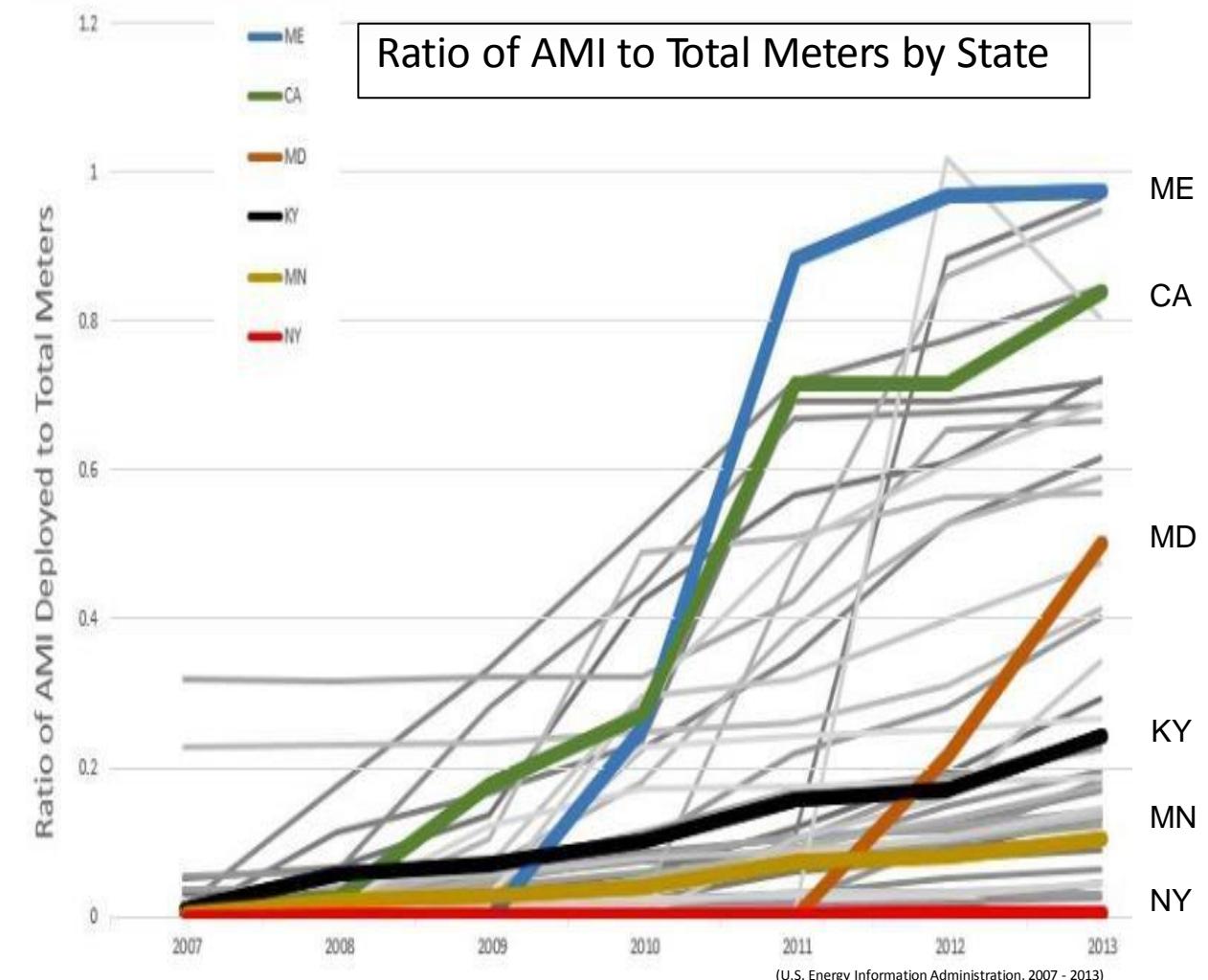
NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0



Smart Grid – Factors which Influence AMI Deployment

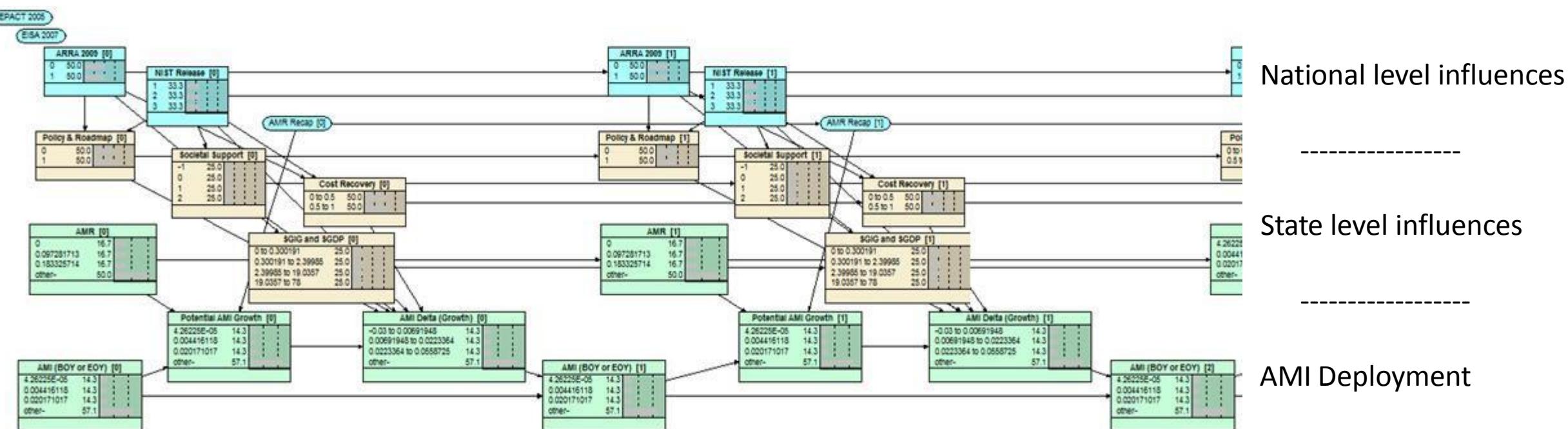
	New York	2008	2009	2010	2011	2012	2013	2014
	Minnesota	2008	2009	2010	2011	2012	2013	2014
	Kentucky	2008	2009	2010	2011	2012	2013	2014
	Maryland	2008	2009	2010	2011	2012	2013	2014
	California	2008	2009	2010	2011	2012	2013	2014
Legislative	MAINE roadmap	0	0	1	1	1	1	1
	policy statement	0	0	1	1	1	1	1
	resistence	-1	-1	-1	-1	-1	-1	-1
Societal	opt-out	0	0	0	1	1	1	1
	customer education pr	1	1	1	1	1	2	2
Economical	arra funding	0	0	51.43	257.6	395.4	405.2	237
Technological	demonstration project			126				
Evidence	AMI FOM (Growth)	0	0	0.255	0.628	0.087	0.005	TBD

State Public Utility Commissions and Utility Industries Deploy the Smart Grid Constituent Systems Independently



Conceptual Dynamic Bayesian Network

- Factors which Influence may be directed towards one system or many
- Systems may be closely related or diverse
- Time Phased Convergence of System Capability (and resultant Functionality) may be depicted
- A SoS-level DBN is comprised of nested System-level DBN



Sensitivity Analysis (Using Netica)

Policy & Roadmap [0]	Policy & Roadmap [1]	Policy & Roadmap [2]	Policy & Roadmap [3]	Policy & Roadmap [4]	Policy & Roadmap [5]	Policy & Roadmap [6]
Society Support [0]	Society Support [1]	Society Support [2]	Society Support [3]	Society Support [4]	Society Support [5]	Society Support [6]
Cost Recovery [0]	Cost Recovery [1]	Cost Recovery [2]	Cost Recovery [3]	Cost Recovery [4]	Cost Recovery [5]	Cost Recovery [6]
SGIG and SGDP [0]	SGIG and SGDP [1]	SGIG and SGDP [2]	SGIG and SGDP [3]	SGIG and SGDP [4]	SGIG and SGDP [5]	SGIG and SGDP [6]
AMI Delta (Growth) [0]	AMI Delta (Growth) [1]	AMI Delta (Growth) [2]	AMI Delta (Growth) [3]	AMI Delta (Growth) [4]	AMI Delta (Growth) [5]	AMI Delta (Growth) [6]

Counter – Improvised Explosive Device SOS

Factors which Influence

Policy



Department of Defense
DIRECTIVE

SUBJECT: Joint Improvised Explosive Device Defeat Organization
References: (a) Title 10, United States Code
(b) Deputy Secretary of Defense Memorandum, "Joint Improvised Explosive Device Defeat Organization" dated 14, 2006
(c) DOD Directive 2000.19, "Joint Improvised Explosive Device Defeat Organization" dated 14, 2006
(d) DOD Directive 5100.18, "DOD Committee on Defense Strategy and Planning" dated 8, 1999
(e) Through 18, 1999 Enclosure 1

1. REISSUANCE AND PURPOSE
Under the authority vested in the Secretary of Defense by statute consistent with Reference (b), this Directive:

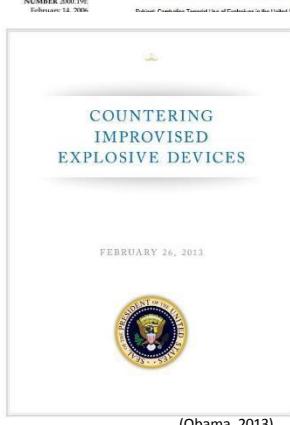
1.1. Changes the name of the Joint Improvised Explosive Device Defeat Organization (JIEDDO) to the Joint Improvised Explosive Device Defeat Organization (JIEDDO).

1.2. Revises Reference (c) to establish the JIEDDO as a joint agency within the Defense Science and Technology Agency to support the mission, relationships, and authorities as prescribed herein.

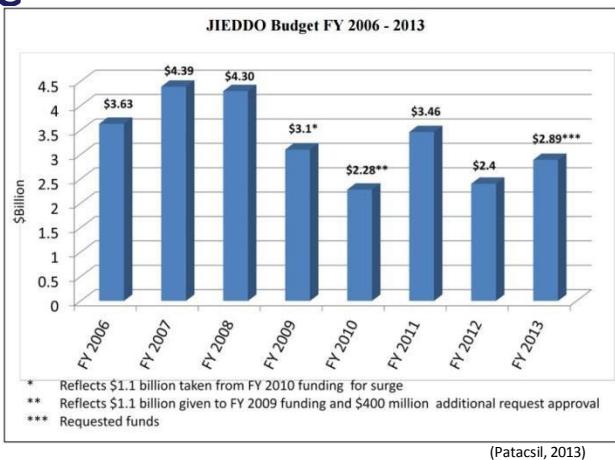
1.3. Establishes a JIEDDO Senior Resource Steering Group (Process Team (JPT)), a JIEDDO Systems Integration Board (JSIB) and a Technical Board (TB), a JIEDDO Lab Board (LB), and a JL Board defined in Enclosure 4, and consistent with Reference (1) and D (Reference (c)).

1.4. Designates the Secretary of the Army as the DOD Executive Agent for the JIEDDO under Reference 5101.1 (Reference (d)) and provides administrative support as defined in Enclosure 3.

(England, 2006)



Economic



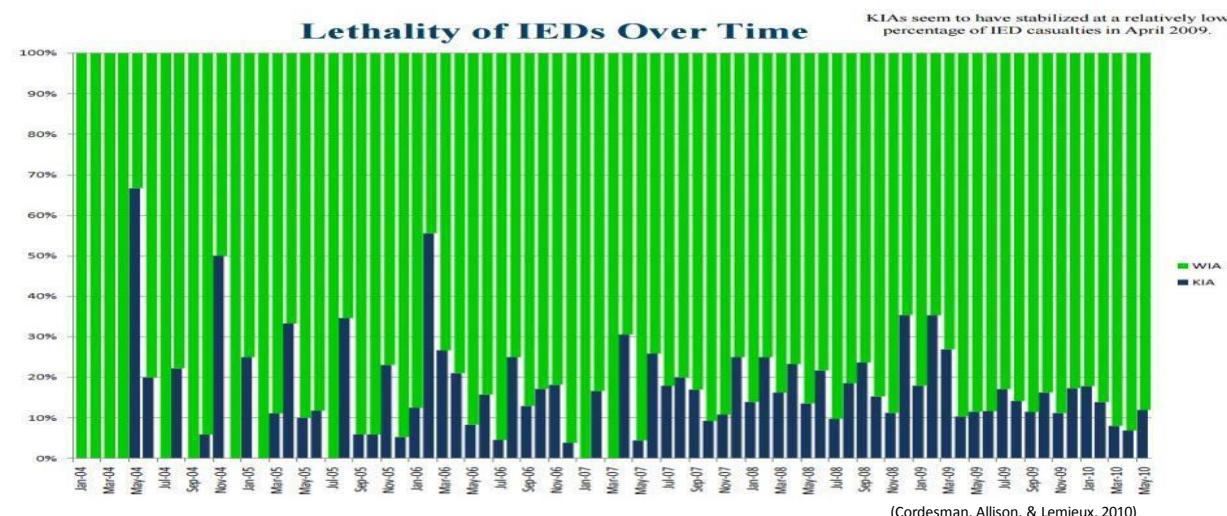
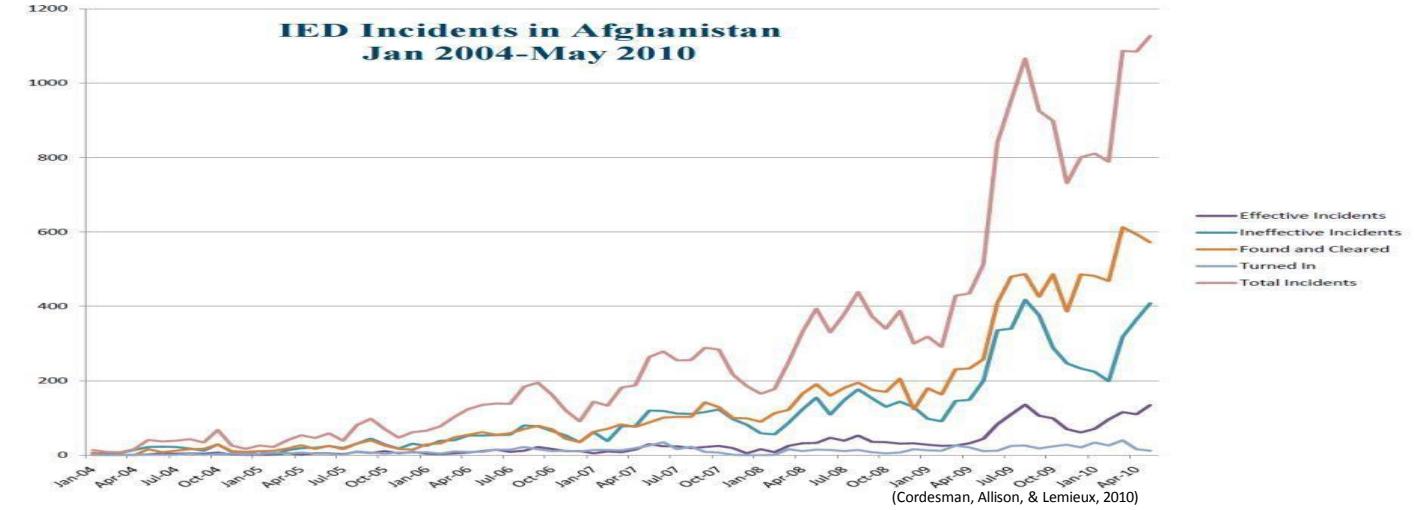
Societal



Technological



Counter – Improvised Explosive Device SOS Systems and Functionality



The C-IED SOS and Factors are Dynamic

Expected Outcomes

- Application of a Dynamic Bayesian Network (or other forms of Artificial Intelligence) to evaluate convergence will advance the state of the art of architecting System of Systems
 - The model will improve the ability to describe current and forecasted functionality
- Evaluating the SoS within the PEST framework will heighten the importance of acknowledging and influencing the environment
- A convergence vector will be developed to:
 - Provide translation of technical progress to business capability in order to communicate status to stakeholders and customers
 - Make comparative decisions among factors influencing the convergence of Systems of Systems.

100 Drones as an SoS



“Humanity is curious, and humanity is equipped with hope. But that driving force is in all of us. And makes us do things that are just like...one would say crazy probably. And others would say...astonishing.”



Horst Hörtner, Director of the Ars Electronica Futurelab, spoke those words after establishing a Guinness world record by simultaneously operating 100 unmanned aerial vehicles. The vehicles flew as a swarm, as a system of systems, to create a three-dimensional light show in sync with a live rendition of Beethoven's Fifth Symphony. (YouTube, 2016: [100 Dancing Drones Set World Record](#))

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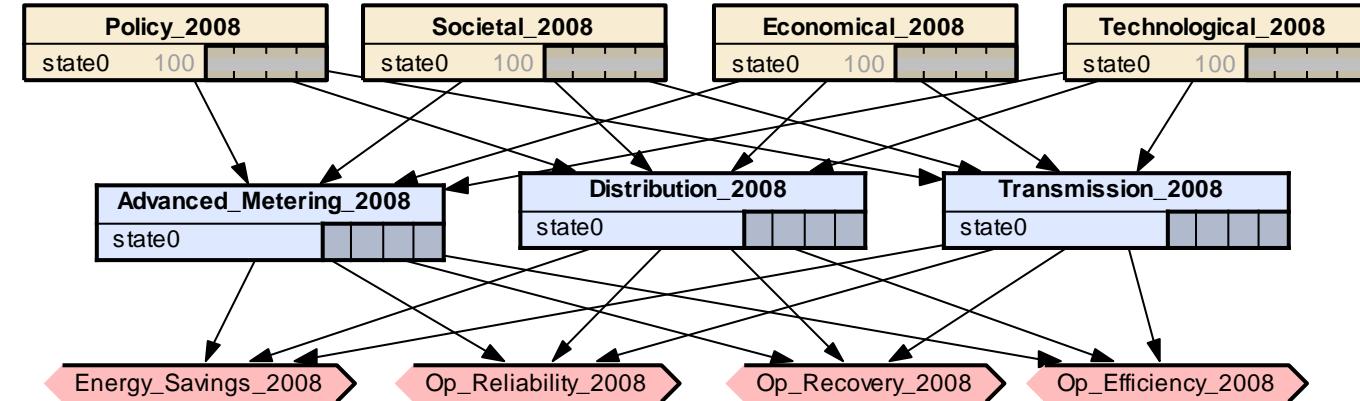
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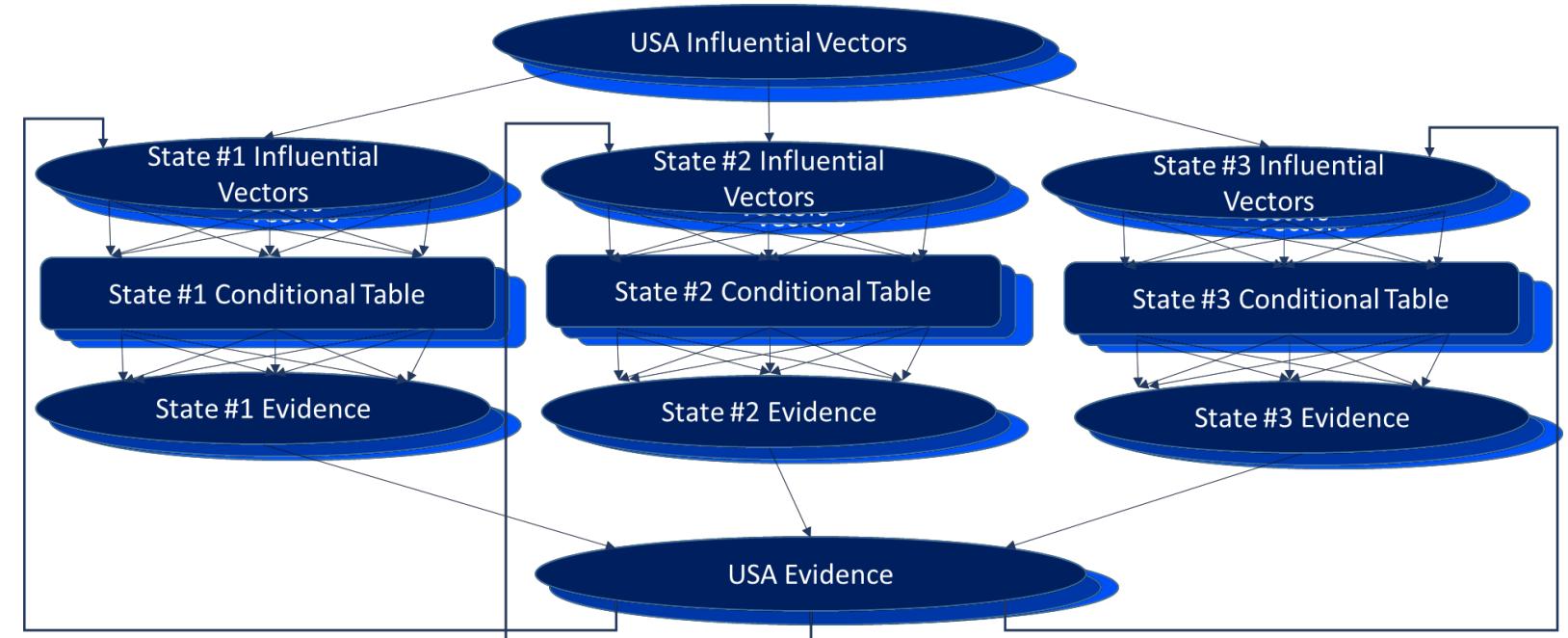
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Dynamic Bayesian Model of Smart Grid

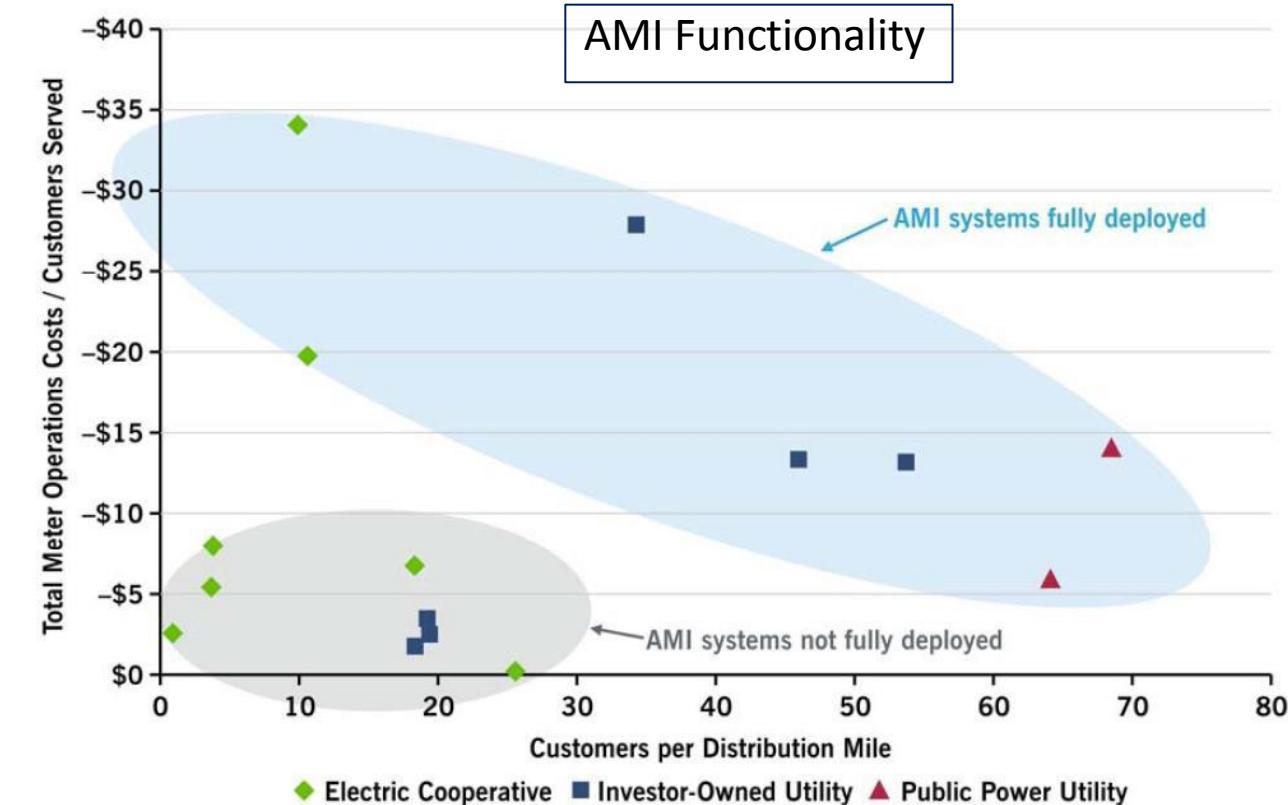
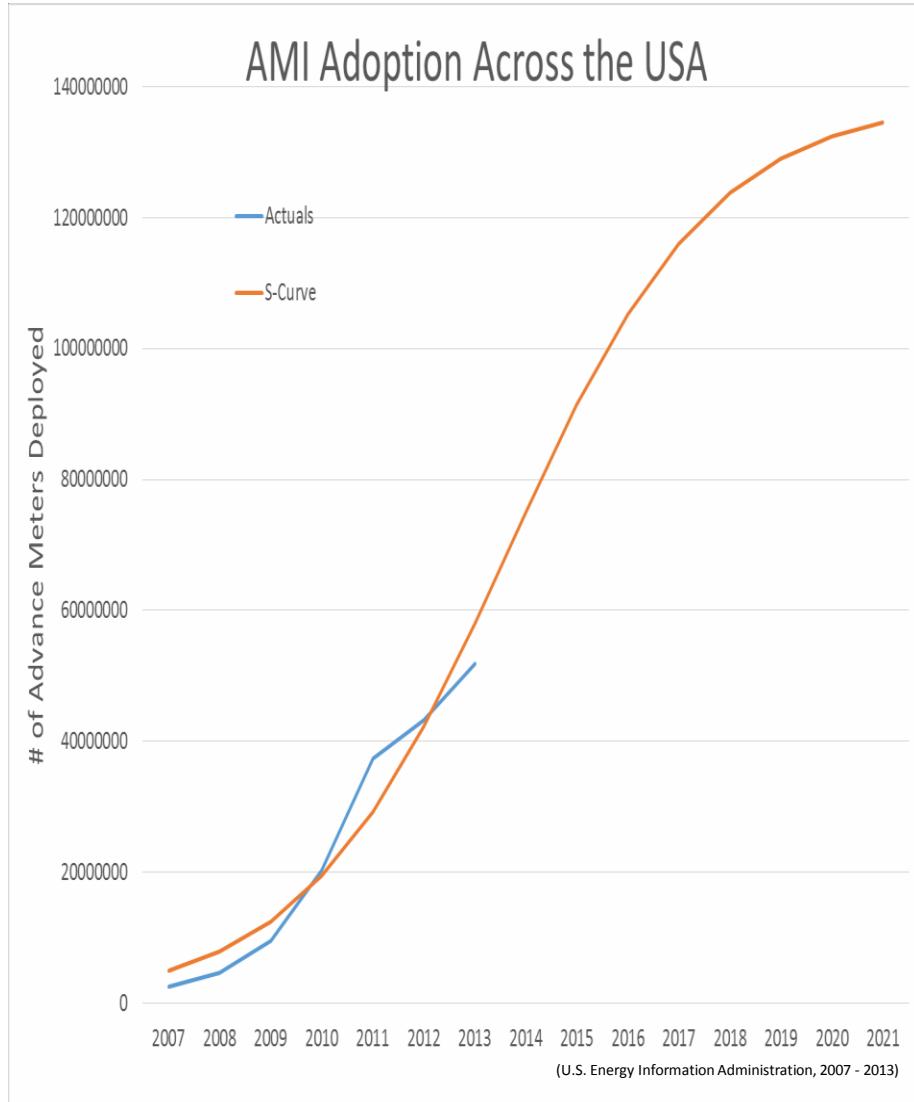
System-level:
Single State; Single Year



System of Systems:
Multiple States; Multiple Years



Smart Grid AMI – Phased SOS Deployment



- Data represents project-level changes in meter operations costs
- Data are from 15 Smart Grid Investment Grant (SGIG) Projects
 - Represents 3.7 million operating smart meters
 - Based on operational experiences from April 1, 2011 to March 31, 2012

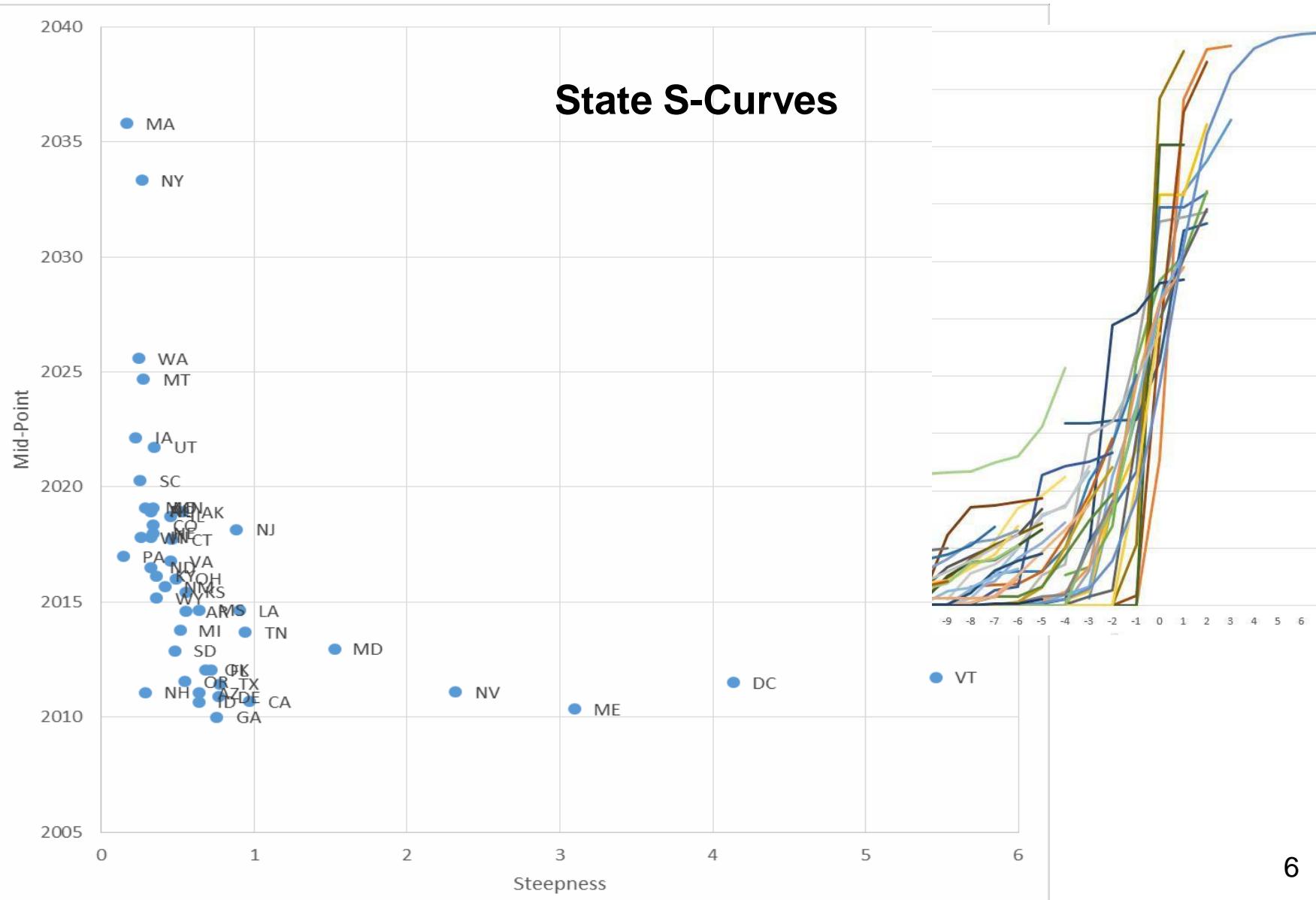
(U.S. Department of Energy, 2012)



Introduction

- Several industries including Defense, Transportation, Health Care and Energy are **pursuing increasingly ambitious functionality** through Systems of Systems
- The **functionality evolves over time** to provide a highly sophisticated and integrated capability
- System of Systems engineers need to be able to **describe the status** of the System of Systems to stakeholders and customers
- This presentation describes a modeling approach which will **quantify the relative rate of convergence** of a System of Systems
- The model will incorporate representations of **factors which influence** the rate of convergence
- Observations from **analyzing multiple case studies** will be instrumental for refining the construct of the model and the representation of the factors
- The analysis will focus on documented, incremental functionality of System of Systems such as the **Smart Grid** and the operational infrastructure created collaboratively by the Joint Improvised Explosive Device Defeat Capability Approval and Acquisition Management Process
- **The model will advance the state of the art** of architecting System of Systems by improving the ability to describe current and forecasted functionality
- It is envisioned that the convergence metric will provide **translation of technical progress to business capability** that can be used to communicate status to stakeholders and customers and be used to make **comparative decisions** among competing Systems of Systems.

Relative Comparison of the Rate of Convergence of Collaborative Systems of Systems: A Quantified Multi-Case Study



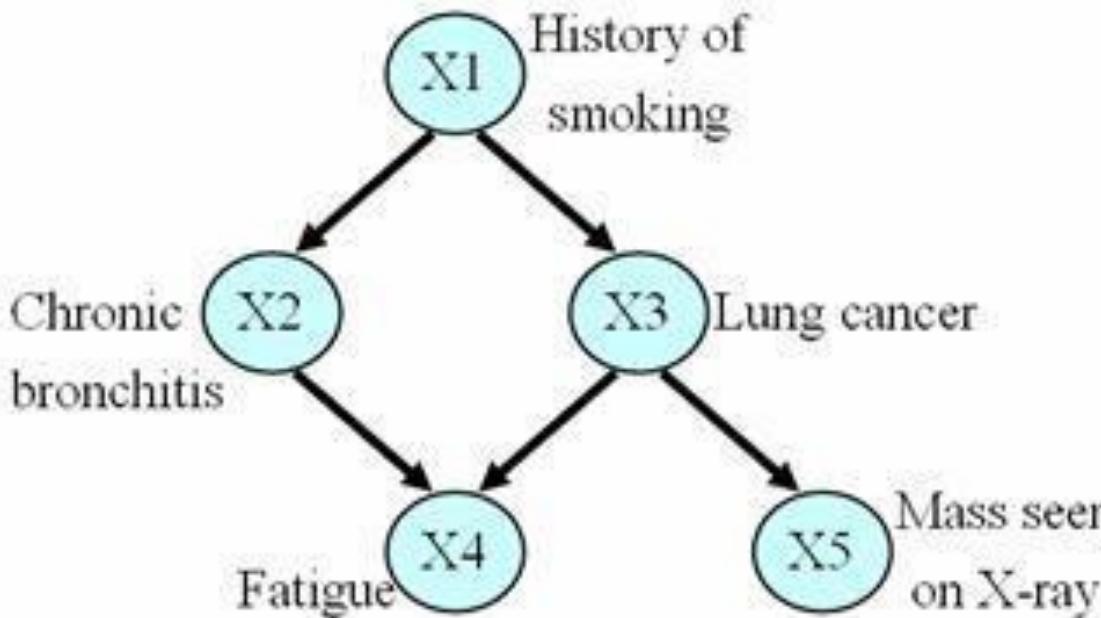
Bayes Theorem and Bayes Networks

- Bayes Theorem is used to determine the probability of a Hypothesis given an Event.

$$P(H | E) = \frac{P(H)P(E | H)}{P(E)}$$

- Bayes Networks may be used to draw inferences from multiple Hypotheses based on multiple Events and, once trained, may be used to predict the probability of an Event given a Cause.

$$P(E_i | C_1) = \frac{P(E_i)P(C_1 | E_i)}{P(E_1)P(C_1 | E_1) + P(E_2)P(C_1 | E_2) + \dots + P(E_n)P(C_1 | E_n)}$$



Example Conditional probabilities

$P(X1=\text{no})=0.8$	$P(X1 = \text{yes})=0.2$
$P(X2=\text{absent} X1=\text{no})=0.95$	$P(X2=\text{present} X1=\text{no})=0.05$
$P(X2=\text{absent} X1=\text{yes})=0.75$	$P(X2=\text{present} X1=\text{yes})=0.25$
$P(X3=\text{absent} X1=\text{no})=0.99995$	$P(X3=\text{absent} X1=\text{no})=0.00005$
$P(X3=\text{absent} X1=\text{yes})=0.997$	$P(X3=\text{absent} X1=\text{yes})=0.003$
$P(X4=\text{absent} X2=\text{absent},$ $X3=\text{absent})=0.95$	$P(X4=\text{present} X2=\text{absent},$ $X3=\text{absent})=0.05$
$P(X4=\text{absent} X2=\text{absent},$ $X3=\text{present})=0.5$	$P(X4=\text{present} X2=\text{absent},$ $X3=\text{present})=0.5$
$P(X4=\text{absent} X2=\text{present},$ $X3=\text{absent})=0.9$	$P(X4=\text{present} X2=\text{present},$ $X3=\text{absent})=0.1$
$P(X4=\text{absent} X2=\text{present},$ $X3=\text{present})=0.25$	$P(X4=\text{present} X2=\text{present},$ $X3=\text{present})=0.75$
$P(X5=\text{absent} X3=\text{absent})=0.98$	$P(X5=\text{present} X3=\text{absent})=0.02$
$P(X5=\text{absent} X3=\text{present})=0.4$	$P(X5=\text{present} X3=\text{present})=0.6$

"In the light of all the evidence on tobacco, and after careful consideration of all the criticisms of this evidence that have been made, we find ourselves unable to agree with the proposition that cigarette smoking is a harmless habit with no important effects on health or longevity" (Cornfield (1959))

From: Cooper, G. (1999). An overview of the representation and discovery of causal relationships using bayesian networks. *Computation, Causation, and Discovery*, , 4-62.

Based on: Cornfield, J., Haenszel, W., Hammond, E. C., Lilienfeld, A. M., Shimkin, M. B., & Wynder, E. L. (2009). Smoking and lung cancer: Recent evidence and a discussion of some questions. *International Journal of Epidemiology*, 38(5), 1175-1191. doi:10.1093/ije/dyp289

Dynamic Bayesian Networks

- DBNs are directed acyclic graphical models of stochastic processes
- Incorporates:
 - Multi-dimensional inputs (prior knowledge)
 - Multi-dimensional outputs (observations)
 - Time delay information

$$\begin{array}{c}
 \text{?} \quad \text{?} \quad \text{?} \quad \text{?} \quad c \quad \text{?} \quad e \\
 \text{?} \quad \text{?} \quad \text{?} \quad \text{?} \quad c \quad \text{?} \quad e \quad E \quad e \quad ?_1, \dots, E \\
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 \text{?} \quad \text{?} \quad \text{?} \quad \text{?} \quad c \quad \text{?} \quad e \quad E \quad e \quad ?_1, \dots, E \quad \text{?} \quad \text{?} \quad \text{?} \quad E \quad e \\
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 \end{array}$$

Equation 1. Bayesian Network model with Probability of Outcome as Dependent Variable

and

$$\begin{array}{c}
 \text{?} \quad E \quad e \quad ? \quad ? \\
 \text{?} \quad E \quad e \quad ? \quad ? \quad ? \quad ? \quad c \quad ? \quad e_1, \dots, \\
 \hline
 \text{?} \quad ? \quad ? \quad c \quad ? \quad ? \quad ? \quad e, \dots, \text{?} \quad ? \quad ? \quad c \quad ? \quad e \\
 \text{?} = \quad \text{?} \quad ? \quad ? \quad ? \quad c \quad ? \quad e \quad E \quad e
 \end{array}$$

Equation 2. Bayesian Network model with Probability of Event as Dependent Variable

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