Modeling the Electricity Sector for Energy Policy and Strategy Analysis: An Overview of Models Used in Electric System Analysis and Planning

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Workshop on:

"Models to Inform Planning for the Future of Electric Power in the US"

NASEM Committee on Future of Electric Power in the US
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Outline of Talk

- Why do we want to model the electricity sector?
- Why modeling the electricity sector has always been challenging
- Why this challenge has gotten harder over the last 30 years
- Overview of current methods and models
- New tools & opportunities
- Current/future directions

Why Do We Want to Model The Electricity Sector?

- We're interested in understanding a future that has little historical precedent (e.g. high renewables penetration, electrification of transport & households)
  - Current observations are of little use and controlled experiments are impossible
  - Must take into account many complex interactions within and across sectors
  - Even inaccurate forecasts can be useful for exploring possible futures, gathering intuition about complex dynamics, and communicating ideas
- Can tell us about likely costs, market dynamics, environmental impacts, and distributional impacts of different technologies and policies
- **BUT: Choosing/designing the right model for a given question remains an ongoing challenge**
  - **Little consensus for when certain details can be ignored**
  - **Cost of building a new model encourages use of sub-optimal existing models**

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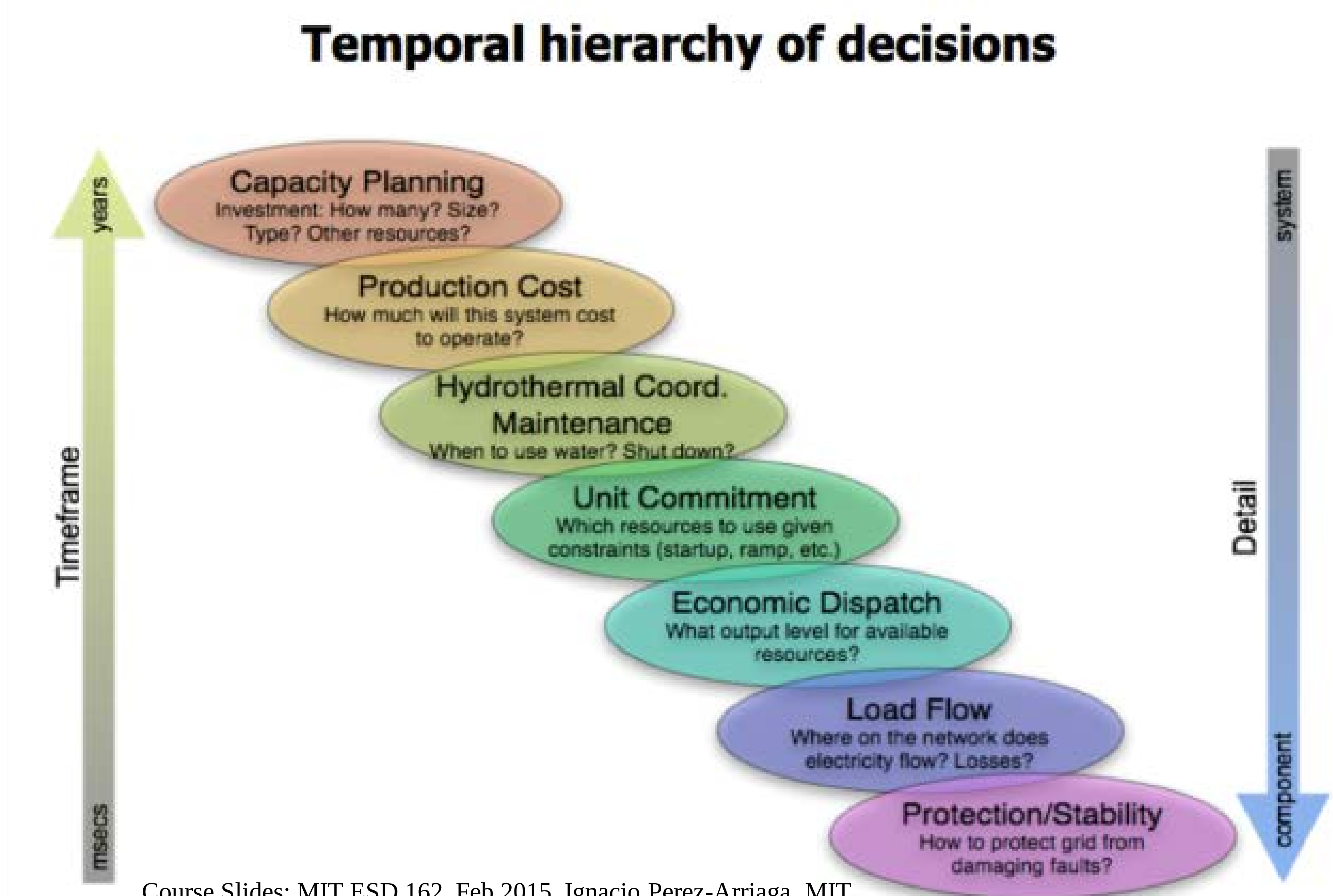
A Couple of Motivational Questions

- What are the systems impacts of large numbers of EVs?

- How do we minimize fire risks of downed power lines?

NYT Photo of Camp Fire

Modeling the Electricity Sector Has Always Been Challenging (1)



Course Slides: MIT ESD.162, Feb 2015, Ignacio Perez-Arriaga, MIT

Modeling the Electricity Sector Has Always Been Challenging (2)

- Non-convexities
  - E.g., Hydro-Electricity, Power Flows, etc.
- Multiple, overlapping jurisdictions
  - Multiple federal, state, and local
- Multiple, often conflicting stakeholders
  - Producers, consumers, regulators, public interest groups
- Heterogeneity across jurisdictions and stakeholders
- Pervasive uncertainties
  - Load forecasting, generation costs, regulatory uncertainties, generation outages, transmission faults, etc.

This Challenge Has Gotten More Difficult: New Constraints on Electricity System Operation

- Transition to deregulated markets
- Renewable resource availability
- Renewable siting and production
- Distribution line siting
- Distributed Energy Resources (DERs)
- Water usage quantity and quality
- GHG emission limits
- Demand response
- Affordable electricity storage
- Climate change
- Fire risks
- Community choice aggregators
- Cyber threats and responses
- Etc.

The Electricity System as an Optimization Problem

Minimize Cost
OR
Maximize Revenue
s.t.
Supply = Demand
Transmission constraints
Operational constraints
Reliability constraints

- When constraints are binding we get markets to provide that service.
- The system is changing, and different constraints are becoming binding.
- Thus new types of markets are being considered & implemented.

This has made the electricity sector harder to model!

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Increasing Importance of Multisector Interactions

- Water constraints due to climate change
  - Hydroelectric
  - Cooling resources
- Wildfire concerns
- Resilience of coastal infrastructure
- Revenue recycling and income distribution
- Transportation-technology, modal choice and land use planning

Many Ways to Categorize Models

- Optimization vs simulation
- Timestep aggregation
- Foresight of agents
- Scope & aggregation of regions and systems
  - – Single electricity system
  - – Linked electricity systems with transmission
    - Heterogeneity of multiple linked systems
  - – Regional to national electricity only or energy only
  - – Partial vs general equilibrium
  - – Earth & human system integrated

The Electricity System as an Optimization Problem

Minimize Cost OR *Maximize Revenue*

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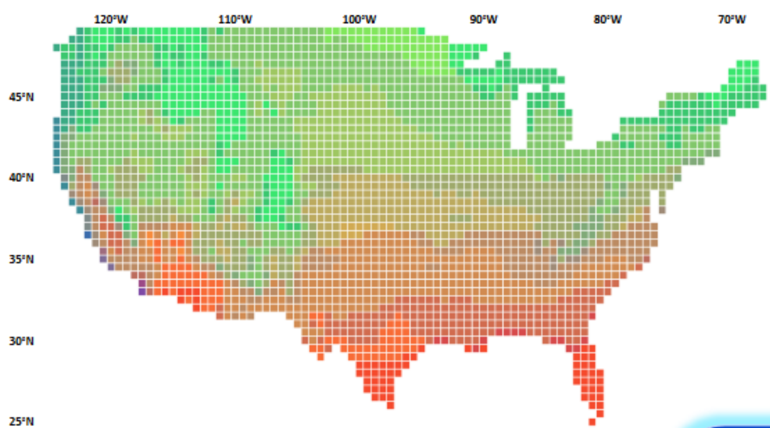
US-REGEN-A US Electricity Sector Model

U.S. Regional Economy, GHG, and Energy (US-REGEN)

EPRI's In-House Energy-Economic Model

Energy End-Use



- Climate zones
- Building types
- Household characteristics
- Industrial mix
- End-use technology detail

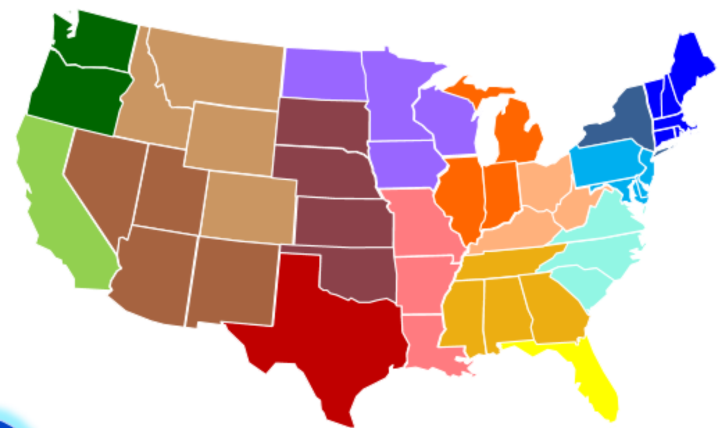
Synchronized Hourly Load, Renewables, and Prices

Model Outputs:

Generation, capacity, prices, and end-use mix

Emissions, air quality, and water

Electric Generation



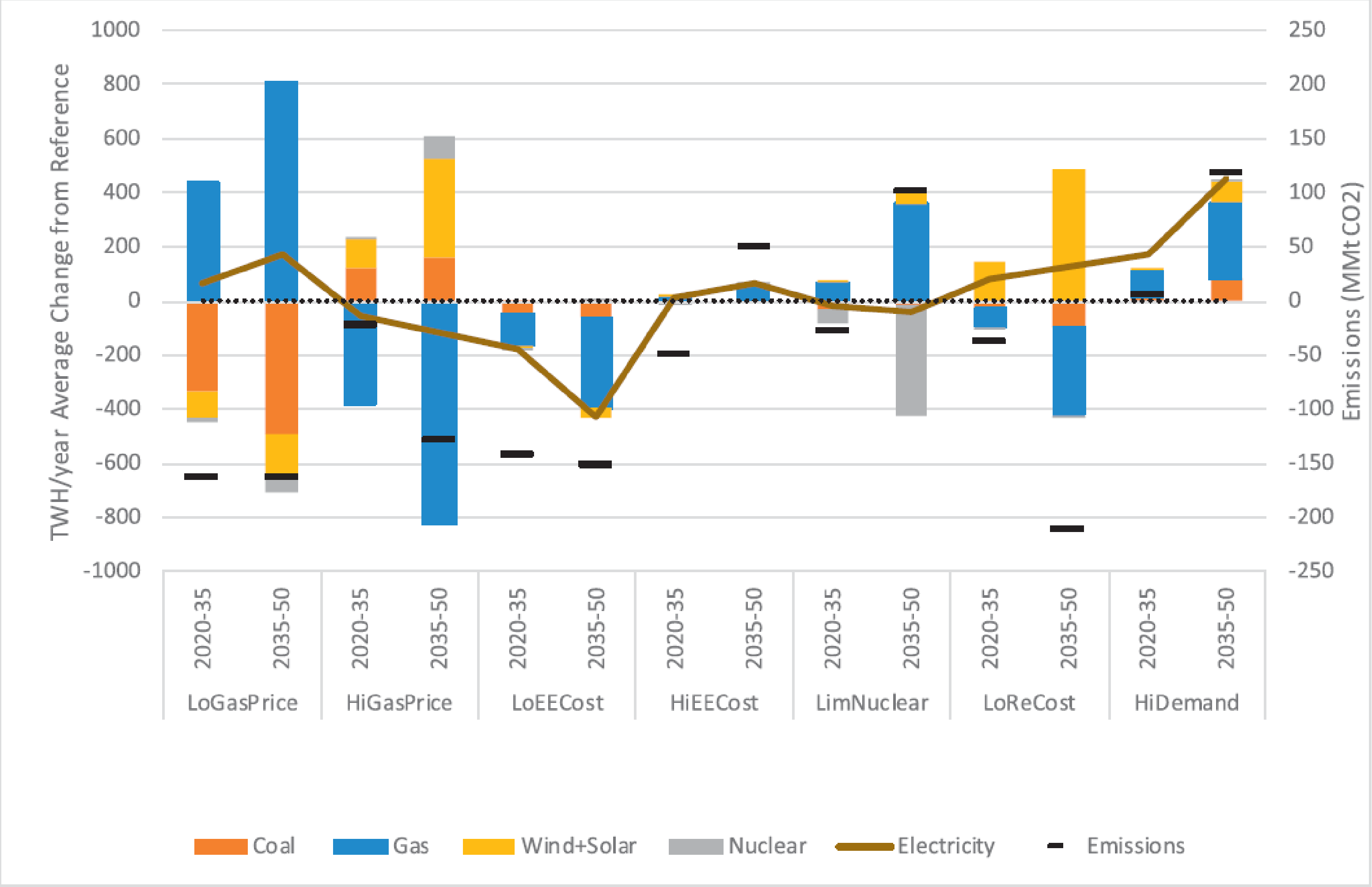
- Investment and dispatch
- Transmission
- Intermittent renewables
- Energy and capacity requirements
- State-level policies and constraints

Model Name	Ability to incorporate distributed generation/energy resources	Demand representation (load duration curve, calendar time, number of time blocks..)	Spatial aggregation
E4ST	Represented as being at the nearest node. More detailed models can be used, that include lower-voltage branches. Representation of lowest-voltage distribution branches would be inaccurate because they are often imbalanced.	Within each simulated year, 36 time blocks represent the joint frequency distribution of demand, wind, and sun. Any number of years can be simulated.	Model of US and Canada (EI, Quebec, WECC, ERCOT) has approximately 8,000 nodes.
ReEDS	Currently limited to exogenous input from NREL's dGen model, but iterative approaches have been used in the past	17 timeslices in default version (4 representative blocks per 4 seasons, plus summer peaking period), with infra-timeslice metrics to better represent variability	North America, with 205 balancing areas and 454 renewable resource regions
EMT	Can exogenously incorporate via SIIP, degree of difficulty to establishing endogenous representation within EMT depends on chosen representation (e.g. EPEC, agent-based, ...)	Hourly in most cases but scalable to include representative days or timeslices	Adaptable to multiple regional scales, currently working with test systems
REGEN	DER adoption treated in the end-use model	Endogenous hourly load shapes from the REGEN end-use model; for some versions of REGEN, intra-annual dispatch conducted over ~120 representative hours	Customizable (typically state-based regions)

EMF 32:National Generation (Twh/Yr) By Technology Under Different Years (Rows)

J.E. Bistline et al. / Energy Economics 73 (2018) 307–325

EMF 32: Electricity Generation Changes by Scenario (Twh/Year), and Emissions Relative to the Reference Scenario (MMt CO2 -Right Axis)



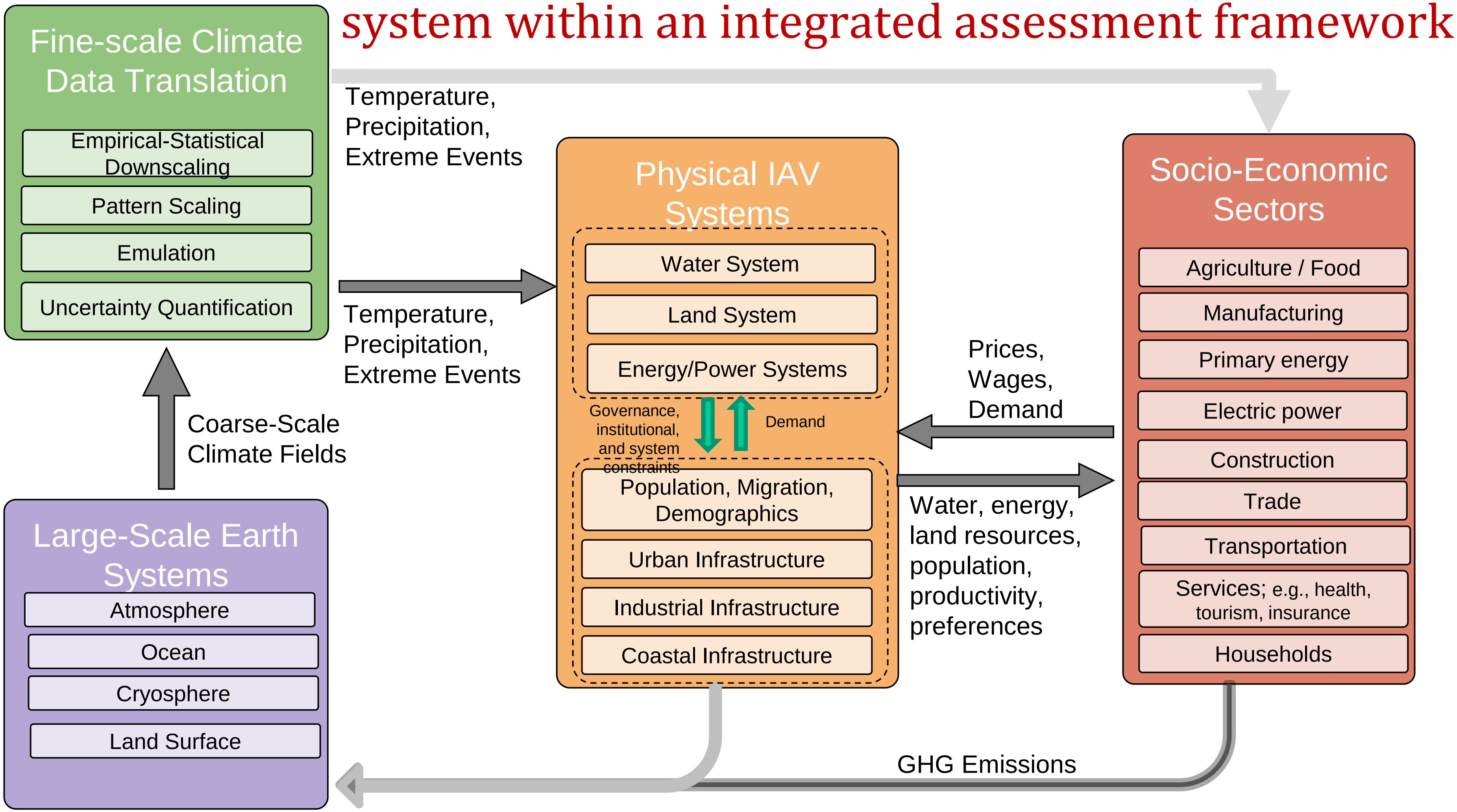
J.R. Creason et al. / Energy Economics 73 (2018) 290–306

Program on Coupled Human and Earth Systems

- As an example of an other-end-of-the-spectrum modeling framework that is multisector
- But at the end of the day it still has to represent the electricity system faithfully

PCHES
Program on Coupled Human and Earth Systems

PCHES: A Multi Sector Dynamics Modeling Framework: Components of an integrated IAV system within an integrated assessment framework



CHALLENGES,CRITIQUES, & OPPORTUNITES

Continuing Challenges

- Characterizing Uncertainty
  - Multiple agents represented in the models
  - Multiple stakeholder users of models
- Incorporating Complexity
  - Technical complexity
  - Market complexity
  - Institutional complexity
- Distributional implications
- Including small-scale resources
  - EVs, Demand Response, BTM solar & storage, other DERs, etc.
- Multi-sector feedbacks

Ongoing Critiques

- Communicating impacts of alternative assumptions
- Communicating Uncertainty
  - Multiple stake holders using the models
  - Probability & scenarios
  - Need more focus on decisions of most interest
- "Right Scaling"
  - Spatial dis-aggregation
  - Temporal dis-aggregation
  - Degree of complexity needed to answer questions

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Some Current Trends & Opportunities

- Machine learning and data assimilation
- Incorporation of “behavioral economics”
- Incorporation of institutional considerations
- Re-dedication to model diagnostics goals, enabled by more data and compute power

At the End of the Day: Model Design & Selection Matters

- Choosing/designing the right model for a given question remains an ongoing challenge
  - Many disagreements among modelers hinge on what assumptions are appropriate for a given question
  - Often its not the models themselves, its how they are used
- Little consensus for when certain details can be ignored (probably application and model specific)
  - Sometimes making the more complicated model is the only way to show a simpler model is sufficient
- Cost of building a new model encourages use of sub-optimal existing models
  - Institutionally-supported models could build in more flexibility to provide better options for specific questions

Thank You

This Modeling Challenge has Gotten More Difficult Over the Last 30 years

- Transition to deregulated markets
- New constraints and considerations imposed by renewable generation, climate change, etc.

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The Long and Winding Transition From Integrated Utilities to Deregulated Markets

Minimize Cost

s.t. regulatory requirements

Single vertically integrated utility

– Generation
– Transmission
– Distribution

Pros: single planner

Cons: does not reveal true cost, difficult to incentivize efficiency

Maximize Revenue

Wholesale market for generation

Transmission system operators

Distribution system efficiency

Pros: easier to incentivize efficiency

Cons: markets are inevitably imperfect & complex

TYPES OF MODELS

Single utility systems

Electricity systems (multi-utility, multi-state, US, etc.)

Energy systems

Energy and economic system (e.g., CGE and revenue recycling)

Multi-sector dynamics (e.g., energy, water, land, food. etc.)

[maybe delete this list]

Multi-System Models

- Transmission models as a Bridge?
- Electricity systems models
- Energy systems models (fossils, renewables, nuclear, NETs)
- Energy and economy models (CGE, revenue recycling)
- Multi-sector dynamics models (e.g., energy, water, land)

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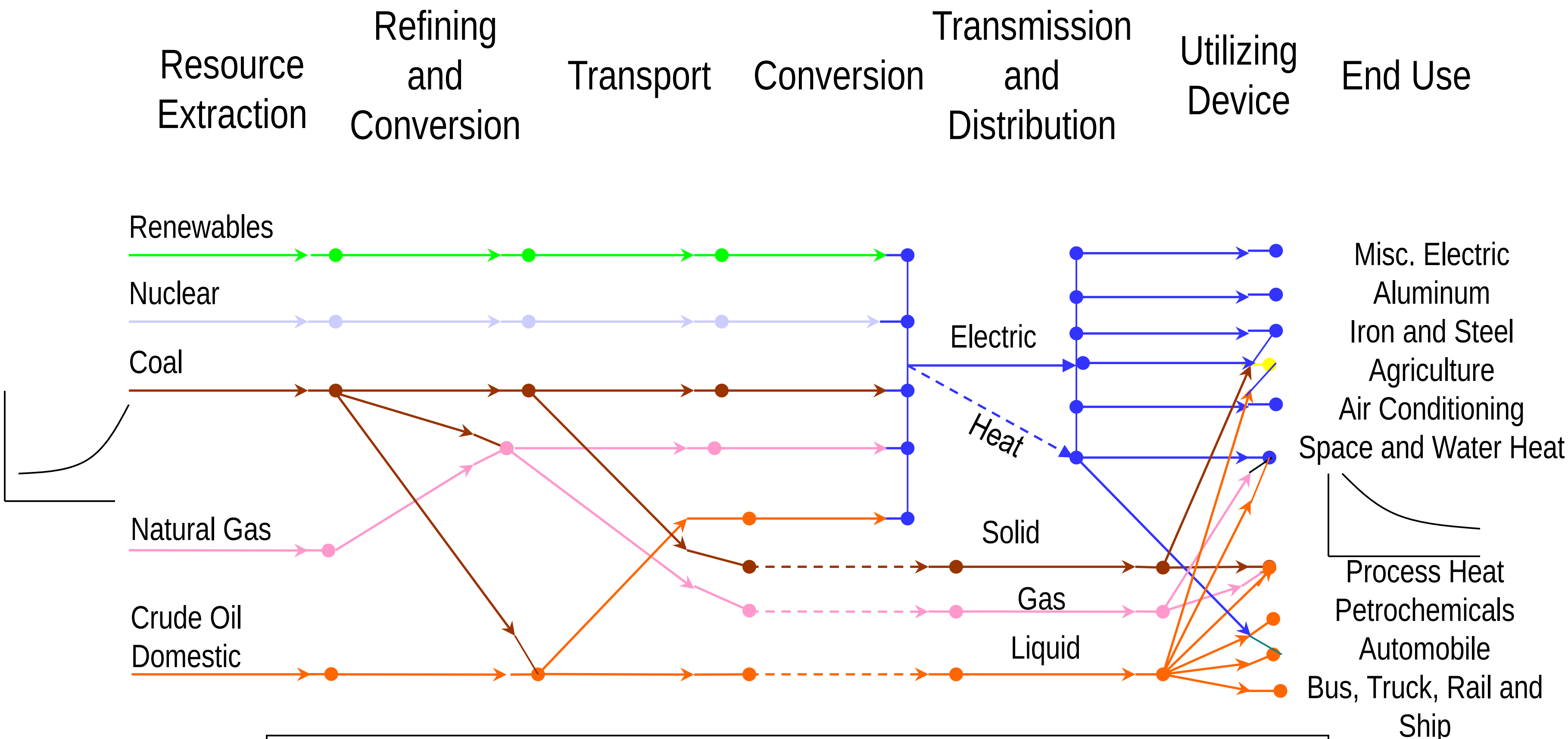
Energy System Network Models



<u>Optimization Model</u>

Objective: Minimize Energy System Costs, Inc. Welfare Loss

Constraints: Satisfy Energy Demands
Only Use Available Resources
Convert Energy Forms at Efficiencies of Available Technologies

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Some Types of Markets

- Energy – all markets
- Day-ahead, hourly, real time
- Capacity – some markets
- Ancillary services – examples include
  - Spinning reserves
  - Non-spinning reserves
  - Black start
  - Regulation up
  - Regulation down
  - CA: ”flexiramp” product ← NEW

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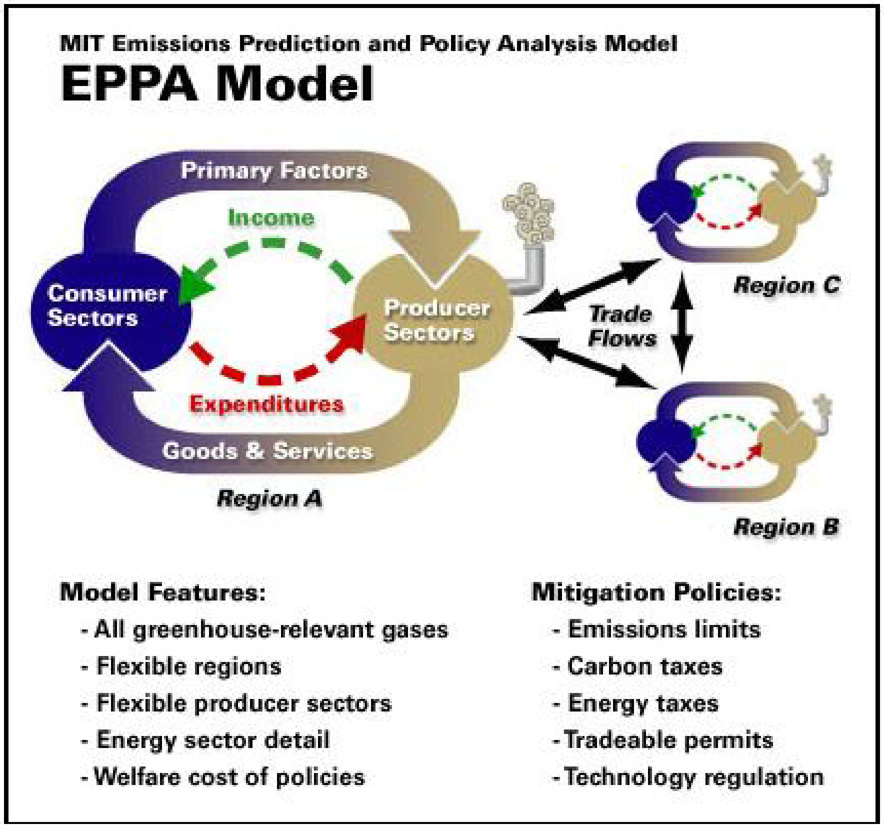
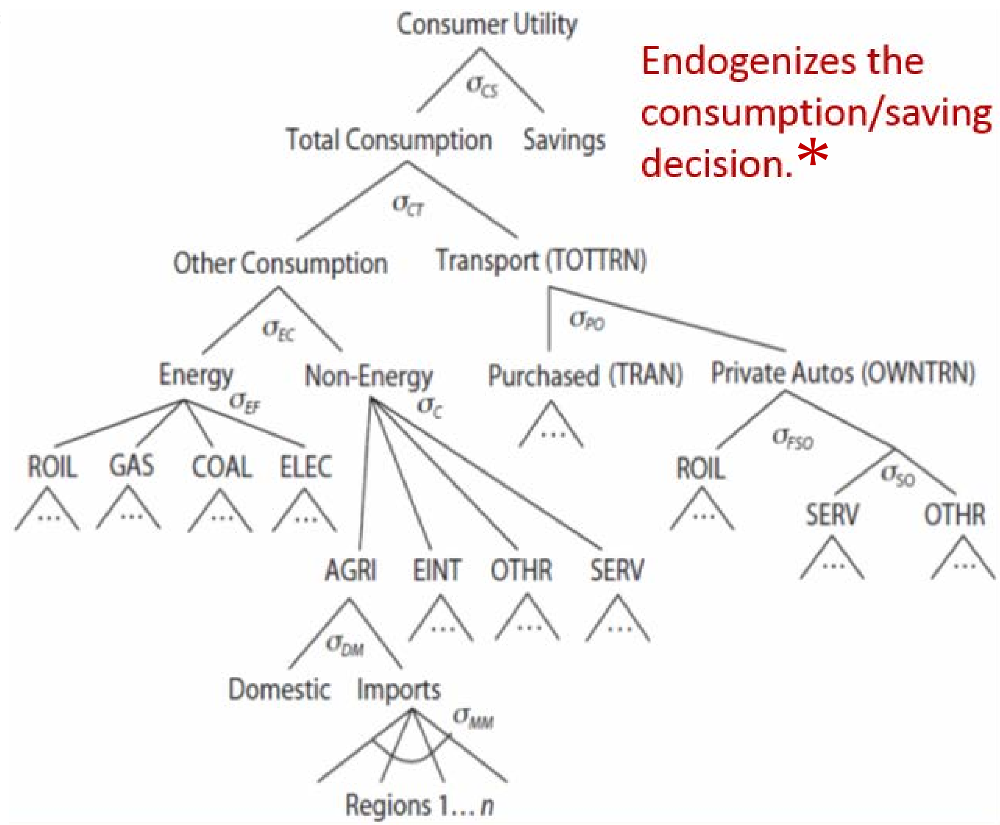
This slide may be unnecessary

General Economic Equilibrium & Growth Models





Endogenizes the consumption/saving decision.*

*Can incorporate economic growth by considering optimal split of economic output between consumption and investment/savings

Some Relevant EMF Studies

EMF 3: Electric Load Forecasting

EMF 10: Electric Markets and Planning

EMF 15: Markets for Power

EMF 17: Prices/Emissions in Restructured Elec. Mkts.

EMF 24: US Technology Strategies for GHG Mitigation

More Recent EMF Studies

EMF

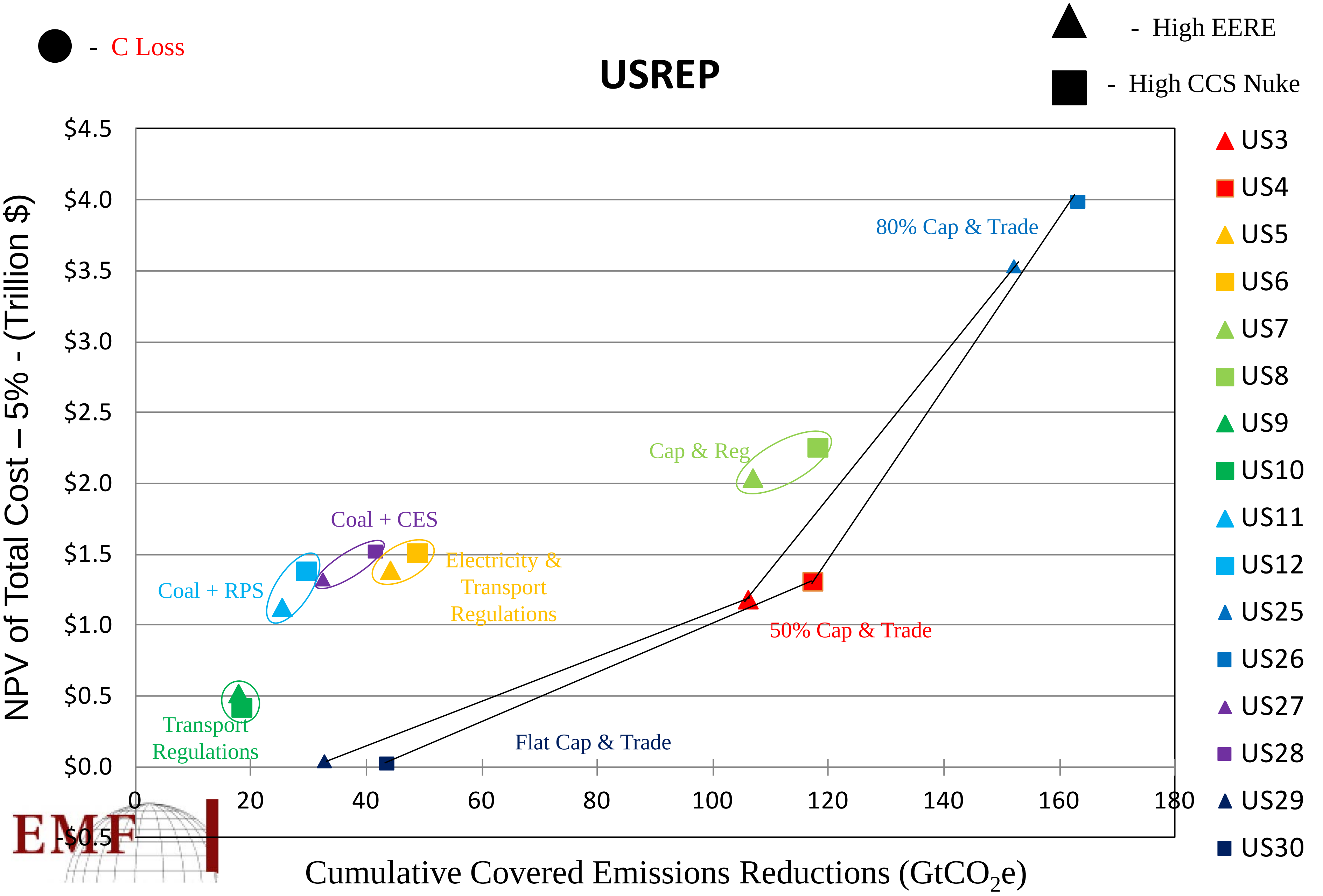
Finished in 2018/19:

- EMF 32: U.S. Greenhouse Gas Reduction Options & Revenue Recycling (

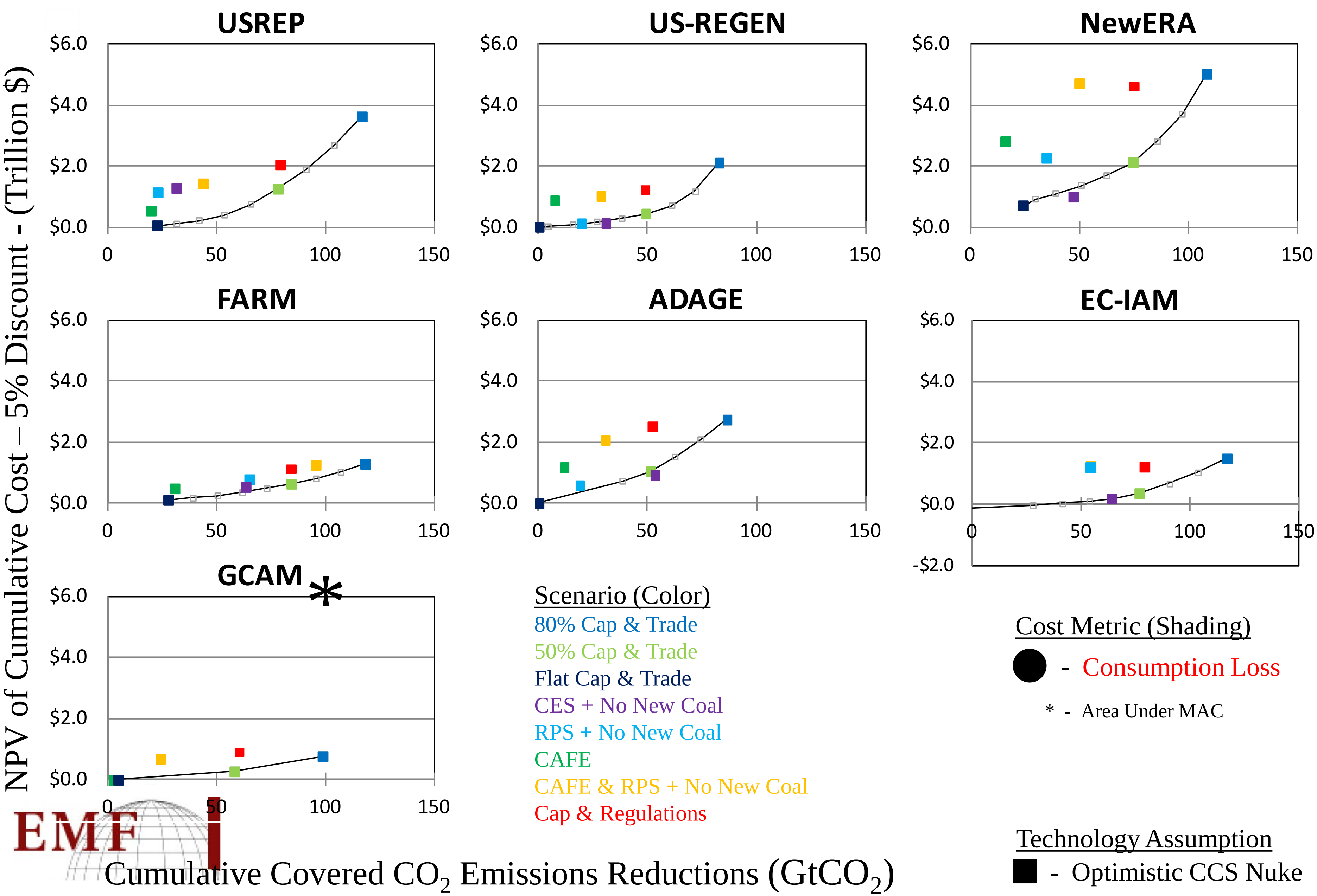
In Progress (finishing in):

- EMF 34 (May 2020): North American Energy Systems Integration
- EMF 35 (2020):Japan Model Intercomparison Project (Japanese Leadership)
- EMF 36 (2021): Int. Trade and Coalitions (German Leadership)
- EMF 37 (2022): High Electrification Scenarios for North America

Example #2: EMF 24-US Technology
Net Present Value of Cumulative Cost vs. Cumulative Abatement



Net Present Value of Cumulative Cost vs. Cumulative Abatement



Model	Developer	Intertemporal approach	Demand representation (load duration curve, calendar time, number of time blocks..)	Regional detail	Solution algorithm	Ability to incorporate distributed generation/energy resources	Links to other models	Plans for adding new features/capabilities
Engineering, Economic, and Environmental Electricity Simulation Tool (E4ST)	D Shawhan, P Picciano, RD Zimmerman, W Schulze, B Mao, C Murillo-Sanchez, D Tylavsky, Di Shi, J Taber et al. at Resources for the Future, Cornell U, and AZ State University	Recursive. Seeking funding to add perfect foresight and stochastic optimization over future circumstances.	Within each simulated year, 36 time blocks represent the joint frequency distribution of demand, wind, and sun. Any number of years can be simulated.	Model of US and Canada (EI, Quebec, WECC, ERCOT) has approximately 8,000 nodes.	Linear program. We use Gurobi's interior-point barrier method. E4ST is also capable of non-linear modeling.	Represented as being at the nearest node. More detailed models can be used, that include lower-voltage branches. Representation of lowest-voltage distribution branches would be inaccurate because they are often imbalanced. E4ST does not currently represent imbalanced, but could.	None yet.	The next planned additions include CO2 direct air capture as a price-responsive electricity use, hot dry rock geothermal, and sequential hours.
Regional Energy Deployment System (ReEDS)	NREL	Model can be ran as either a sequential/myopic, window, or full-foresight/intertemporal representation	17 timeslices in default version (4 representative blocks per 4 seasons, plus summer peaking period), with infra-timeslice metrics to better represent variability	North America, with 205 balancing areas and 454 renewable resource regions	Linear program (Typically solved with CPLEX)	Currently limited to exogenous input from NREL's dGen model, but iterative approaches have been used in the past	ReEDS-to-PLEXOS; ReEDS-USREP; ReEDS-NANGAM; ReEDS 2.0 Demand Side	Yes. These include 8760 (hourly) timeslices and county-level geographical representation. Recent improvements have included varying durations of battery storage technologies.
Electricity Markets Toolkit (EMT), which is linked to the Scalable Integrated Infrastructure Planning (SIIP) modeling framework	NREL	currently myopic/sequential, with some foresight and stochastic treatment in limited cases	Hourly in most cases but scalable to include representative days or timeslices	Adaptable to multiple regional scales, currently working with test systems	Various solving approaches, including surrogate/EPEC, agent-based, and MILP; some also coupled with decomposition techniques	Can exogenously incorporate via SIIP, degree of difficulty to establishing endogenous representation within EMT depends on chosen representation (e.g. EPEC, agent-based, ...)	EMT with SIIP suite which includes transportation, economic, and power system models with plans for more sectors to be included	Plans for new features to represent multiple market designs and products related to ancillary services
Regional Economy, Greenhouse Gas, and Energy (REGEN)	EPRI	Intertemporal, perfect foresight	Endogenous hourly load shapes from the REGEN end-use model; for some versions of REGEN, intra-annual dispatch conducted over ~120 representative hours	Customizable (typically state-based regions)	LP (electric model without price-responsiveness), QCP (electric model with elastic demand), MILP (unit commitment model)	DER adoption treated in the end-use model	REGEN electric sector model linked to REGEN end-use model and unit commitment model; working to integrate with production cost models	Increased spatial and temporal granularity; linking to reliability and production cost models; adding emerging low-carbon fuel pathways to the end-use model; applying decomposition methods to solve more detailed models

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