

21st Century National Energy & Transportation Infrastructures: Long-Term Planning for Cost, Sustainability, and Resilience



<http://www.ece.iastate.edu/research/research-projects/netscore-21.html>

<http://www.youtube.com/NETSCORE21>.

National Energy & Transportation Sustainability, Cost, & Resiliency
NETSCORE21
Research Project

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Acknowledgement to NETSCORE21 Faculty & Students



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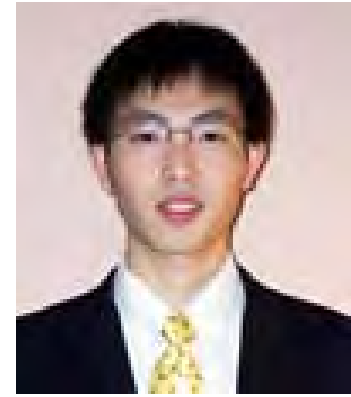
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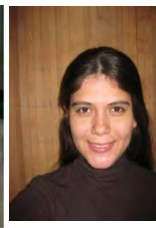
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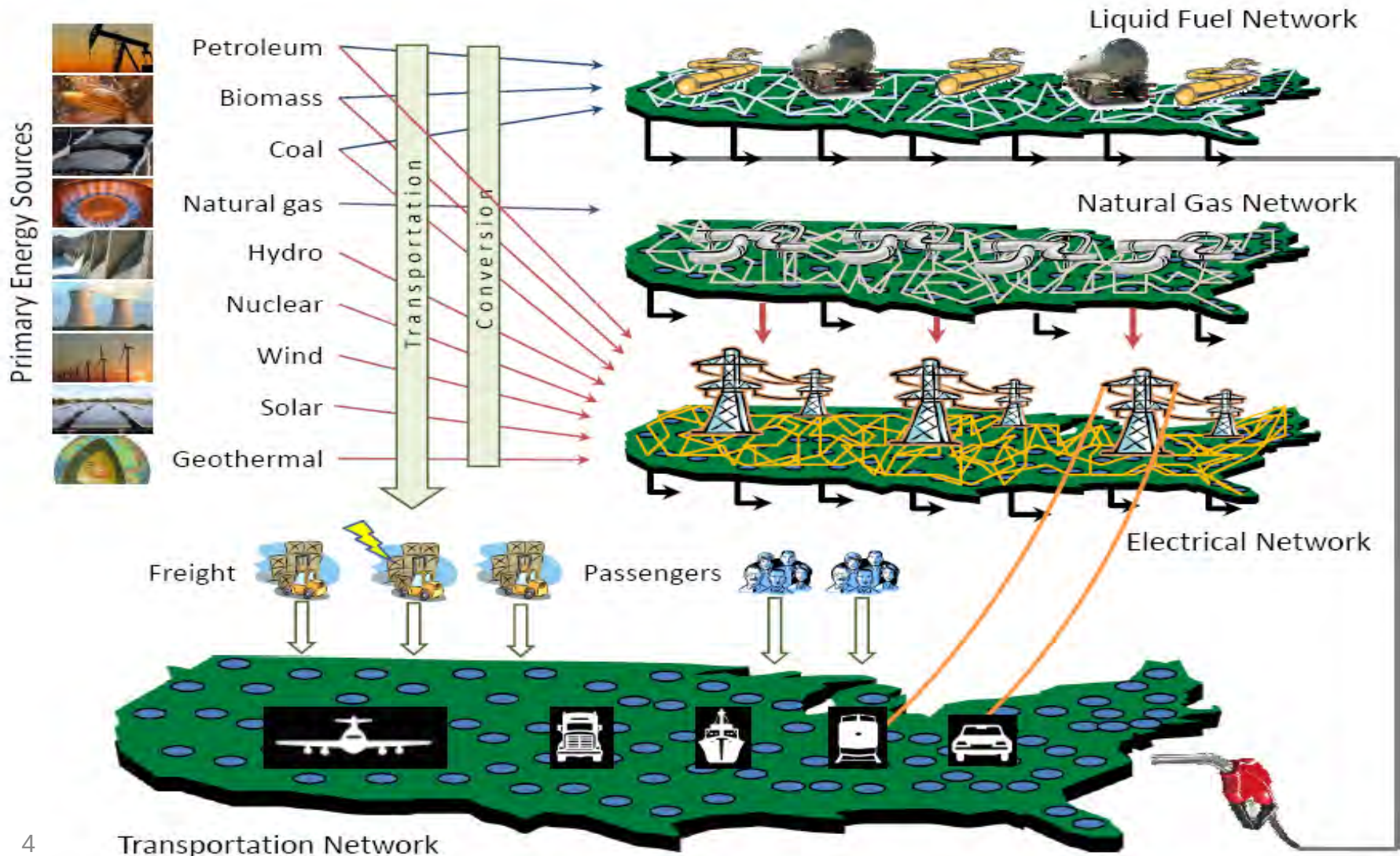
Presentation Outline

1. Objective and orientation
2. Modeling approach
3. Data
4. Results
5. Current efforts
6. Conclusions

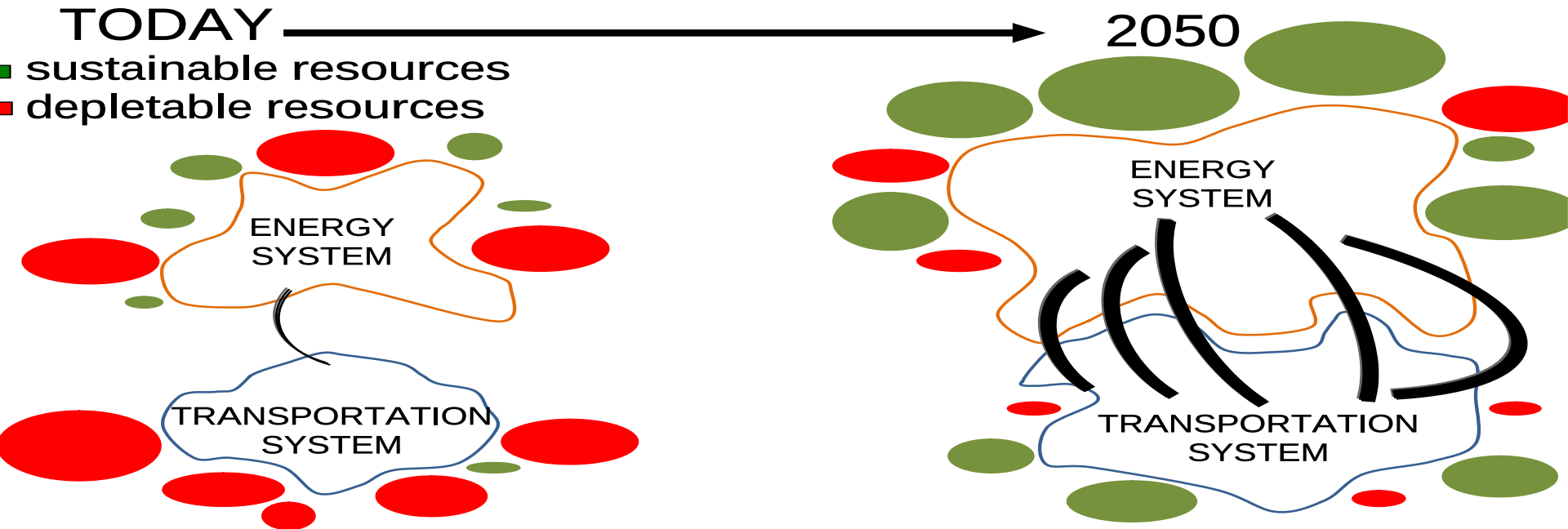
OBJECTIVE OF WORK DESCRIBED IN TODAY'S SEMINAR:

**Provide 40-year national modeling process
for energy and transportation systems.**

Orientation: Long-term, multi-sector (fuel, electric, transportation), national planning



Orientation: Long-term, multi-sector (fuel, electric, transportation), national planning



- A way to probe future infrastructure trajectories
- Separates “good” from “bad” choices
- Informs societal dialogue and political debate

NETPLAN V1

Multiobjective optimization

Evolutionary algorithm

Selects new solution population based dominance and crowding in terms of cost, sustainability, resiliency

NSGA-II:
Search & selection

Investment biases: minimum investments, subsidies, emission limits

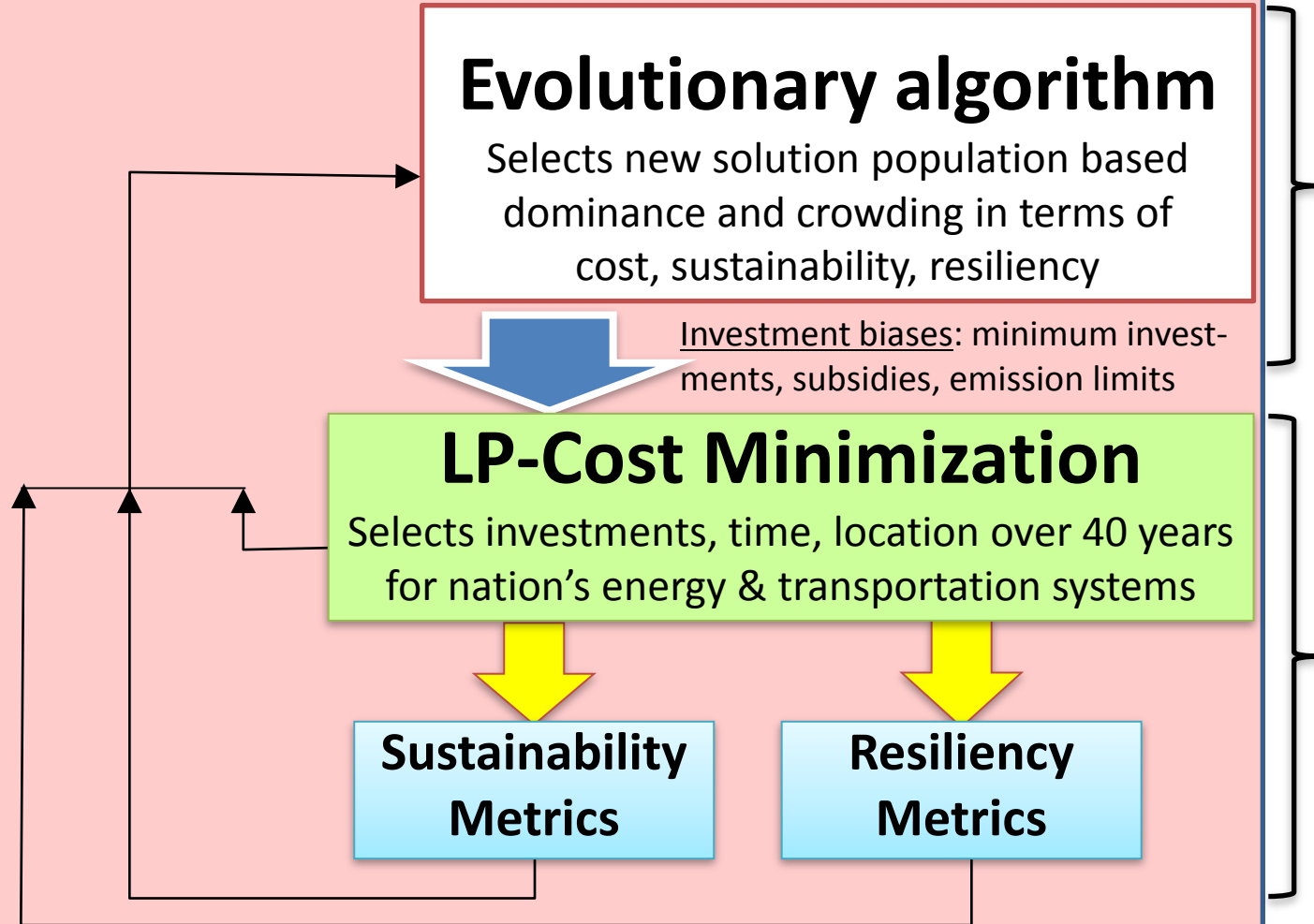
LP-Cost Minimization

Selects investments, time, location over 40 years for nation's energy & transportation systems

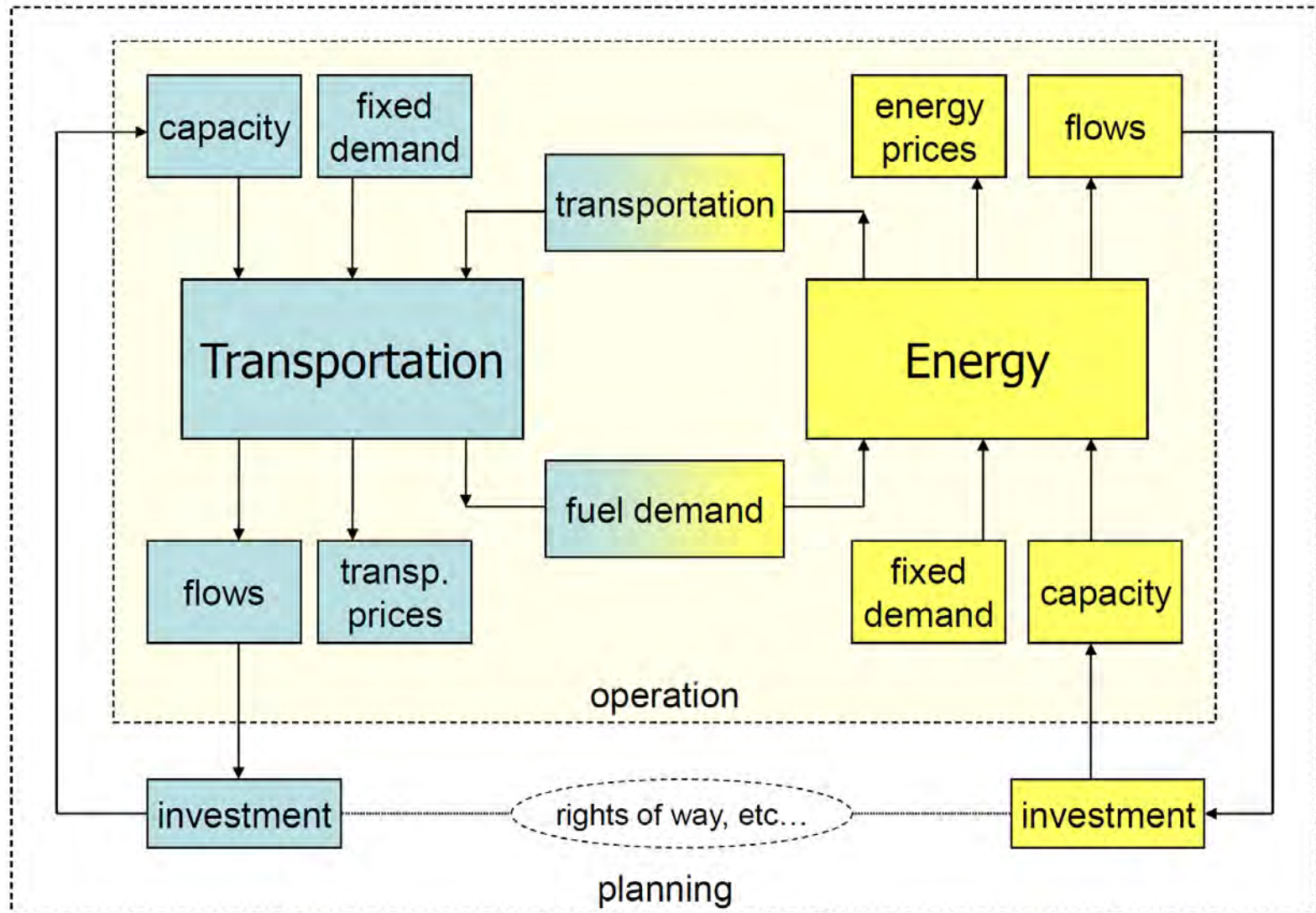
Evaluation
(fitness functions)

**Sustainability
Metrics**

**Resiliency
Metrics**

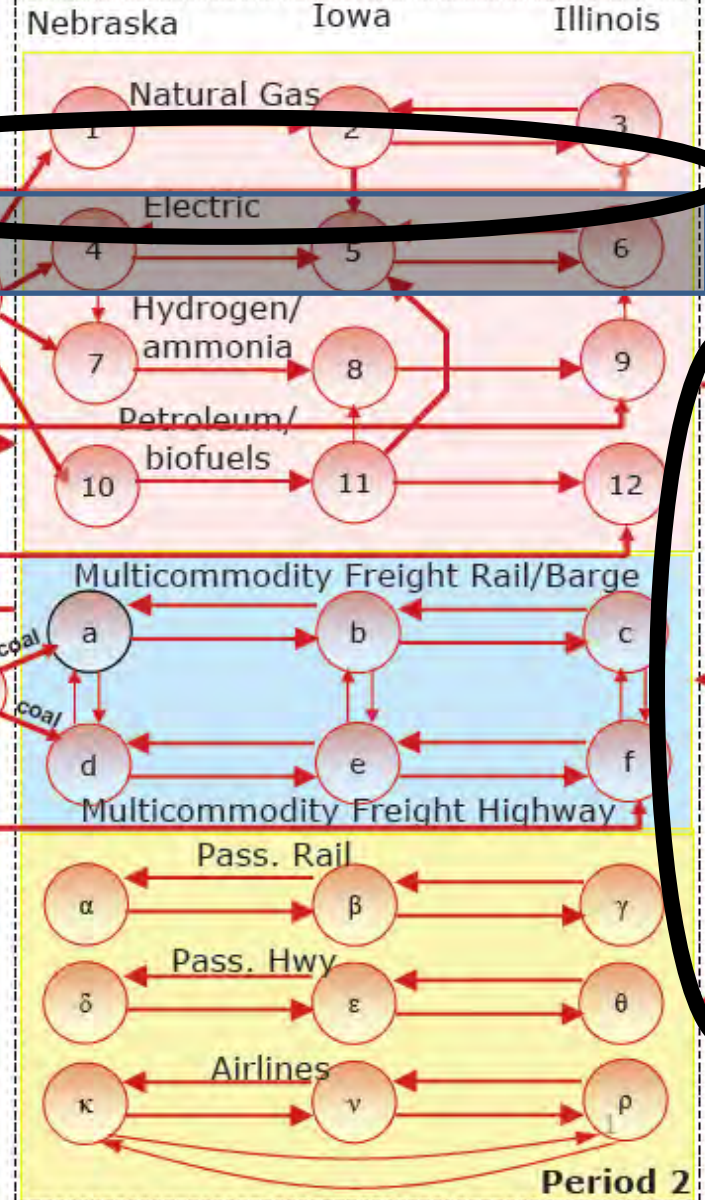
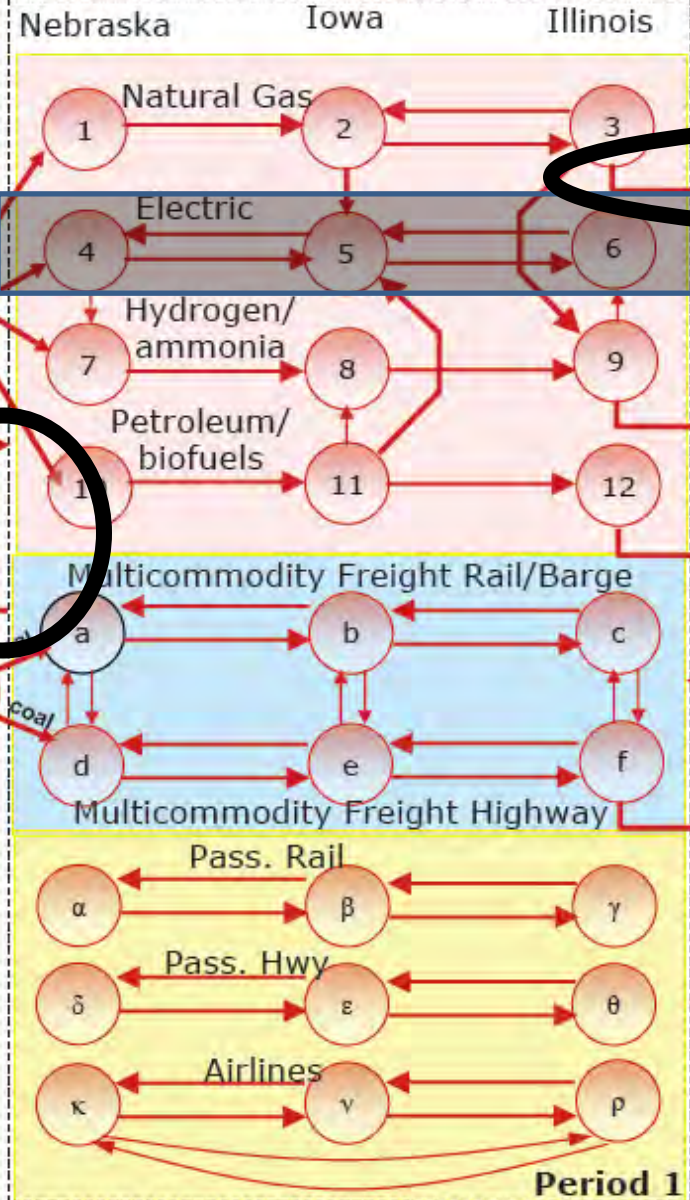


Conceptual Cost-Minimization Model



Electric can be modeled with DC power flow

Energy loads commodity transport system



Storage

LP-Cost Minimization

Selects investments, time, location over 40 years for nation's energy & transportation systems

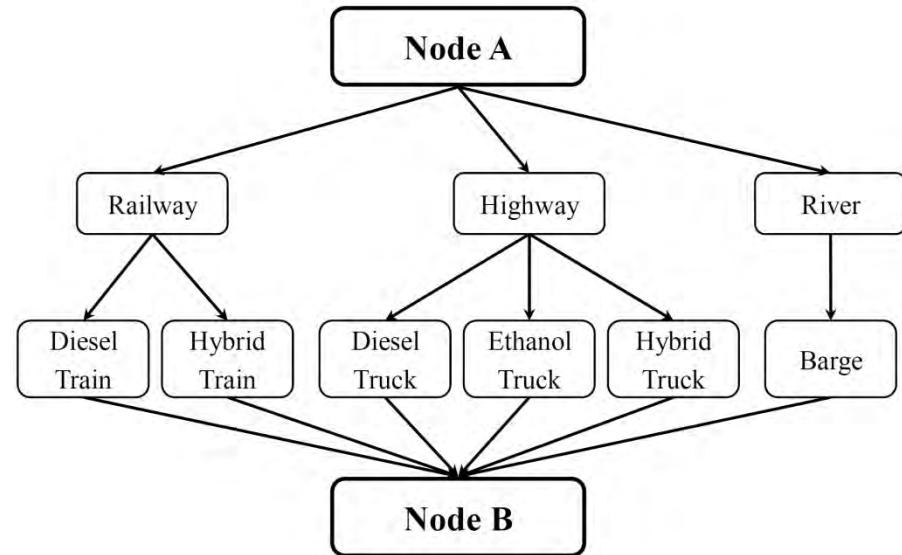
Commodity & passenger networks load energy system

Energy system modeling for cost minimization model

- Generalized flow transportation model
- Commodity: energy
- Paths
 - Electric transmission
 - Gas pipelines
 - Liquid fuel pipelines
 - Conversion
- Decision variables
 - Flow across the system
 - Capacity investment in arcs

Transportation modeling

- Multicommodity flow
 - Coal, cereal grains, foodstuffs, chemicals, gravel, wood
 - Routes fixed
 - Arc demand forecasted
- Infrastructure
 - Highway, railway, ports
- Fleet
 - Trains, trucks, barges
- Decision Variables
 - Amount of each arc's freight allocated to each possible mode
 - Investment on infrastructure and fleet
- Passenger transportation not fully developed yet



Mathematical formulation for cost minimization problem

$$\min \{CostOp^E + CostInv^E + CostOp^T + CostFleetInv^T + CostInfInv^T\} \quad (3.2)$$

subject to:

Meet energy demand at the appropriate nodes

$$\sum_i \eta_{(i,j)}(\mathbf{t}) e_{(i,j)}(\mathbf{t}) - \sum_i e_{(j,i)}(\mathbf{t}) = d_j^E(\mathbf{t}) + d_j^{ET}(\mathbf{t}) \quad j \in \mathcal{N}_d^E \quad (3.3)$$

DC power flow equations

$$e_{(i,j)}(\mathbf{t}) - e_{(j,i)}(\mathbf{t}) = b_{(i,j)} \left(\theta_i(\mathbf{t}) - \theta_j(\mathbf{t}) \right) P_E \Delta(\mathbf{t}), \quad (i,j) \in \mathcal{A}_{DC}^E \quad (3.4)$$

Generation capacity must cover peak demand at electric nodes

$$\sum_i cf_{(i,j)}(\mathbf{t}) eCap_{(i,j)}(\mathbf{t}) \geq peakD_j^E(\mathbf{t}), \quad j \in \mathcal{N}_p^E \quad (3.5)$$

Transportation demand for non-energy commodities

$$\sum_m f_{(i,j,k,m)}(\mathbf{t}) = d_{(i,j,k)}^T(\mathbf{t}), \quad k \in \mathcal{K} \setminus \mathcal{K}_e \quad (3.6)$$

Transportation demand for energy commodities

$$\sum_m f_{(i,j,k,m)}(\mathbf{t}) = heatContent_k^{-1}(\mathbf{t}) e_{(n_{(i,k)}^E, n_{(j,k)}^E)}(\mathbf{t}), \quad k \in \mathcal{K}_e \quad (3.7)$$

Fleet upper bound for transportation flows

$$\sum_k f_{(i,j,k,m)}(\mathbf{t}) \leq fleetCap_{(i,j,m)}(\mathbf{t}) \Delta(\mathbf{t}) \quad (3.8)$$

Infrastructure upper bound for transportation flows

$$\sum_k \sum_{m \in \mathcal{M}_t} f_{(i,j,k,m)}(\mathbf{t}) \leq infCap_{(i,j,l)}(\mathbf{t}) \Delta(\mathbf{t}) \quad (3.9)$$

Decision variables:

$$\text{Energy flows:} \quad 0 \leq lb_{e_{(i,j)}}(\mathbf{t}) \leq e_{(i,j)}(\mathbf{t}) \leq eCap_{(i,j)}(\mathbf{t}) \Delta(\mathbf{t}) \quad (3.10)$$

$$\text{Energy capacity inv.:} \quad lbInv_{(i,j)}(\mathbf{t}) \leq eInv_{(i,j)}(\mathbf{t}) \leq ubInv_{(i,j)}(\mathbf{t}) \quad (3.11)$$

$$\text{Transportation flows:} \quad f_{(i,j,k,m)}(\mathbf{t}) \geq 0 \quad (3.12)$$

$$\text{Fleet inv.:} \quad lbFleetInv_{(i,j,m)}(\mathbf{t}) \leq fleetInv_{(i,j,m)}(\mathbf{t}) \leq ubFleetInv_{(i,j,m)}(\mathbf{t}) \quad (3.13)$$

$$\text{Infrastructure inv.:} \quad lbInfInv_{(i,j,l)}(\mathbf{t}) \leq infInv_{(i,j,l)}(\mathbf{t}) \leq ubInfInv_{(i,j,l)}(\mathbf{t}) \quad (3.14)$$

$$\text{Phase angles:} \quad -\pi \leq \theta_i(\mathbf{t}) \leq \pi \quad (3.15)$$

Minimize operational and investment cost

Meet energy demand

DC power flow

Meet electric peak demand

Meet transportation demand

Max. fleet capacity

Max. transportation infrastructure capacity

Energy flows and investments

Transportation flows and investments

Compact notation and decomposition

$$\min \begin{bmatrix} \text{CostInv}^\top & \text{CostOp}_1^\top & \text{CostOp}_2^\top & \dots \end{bmatrix} \begin{bmatrix} \text{capInv} \\ \text{flows}_1 \\ \text{flows}_2 \\ \vdots \end{bmatrix}$$

subject to:

$$\begin{bmatrix} \mathbf{C}_0 & \mathbf{0} & \mathbf{0} & \dots \\ \mathbf{C}_1 & \mathbf{D}_1 & \mathbf{0} & \dots \\ \mathbf{C}_2 & \mathbf{0} & \mathbf{D}_2 & \dots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix} \begin{bmatrix} \text{capInv} \\ \text{flows}_1 \\ \text{flows}_2 \\ \vdots \end{bmatrix} \leq \begin{bmatrix} \mathbf{b}_0 \\ \mathbf{b}_1 \\ \mathbf{b}_2 \\ \vdots \end{bmatrix}$$

$$\min \quad \text{CostInv}^\top \cdot \text{capInv} + z_1 + z_2 \dots$$

subject to:

$$\mathbf{C}_0 \cdot \text{capInv} \leq \mathbf{b}_0$$

$$\min \quad \zeta_i = \text{CostOp}_i^\top \cdot \text{flows}_i$$

subject to:

$$\mathbf{C}_i \cdot \text{flows}_i \leq \mathbf{b}_i - \mathbf{D}_i \cdot \text{capInv}^*$$

Transportation system loading on energy

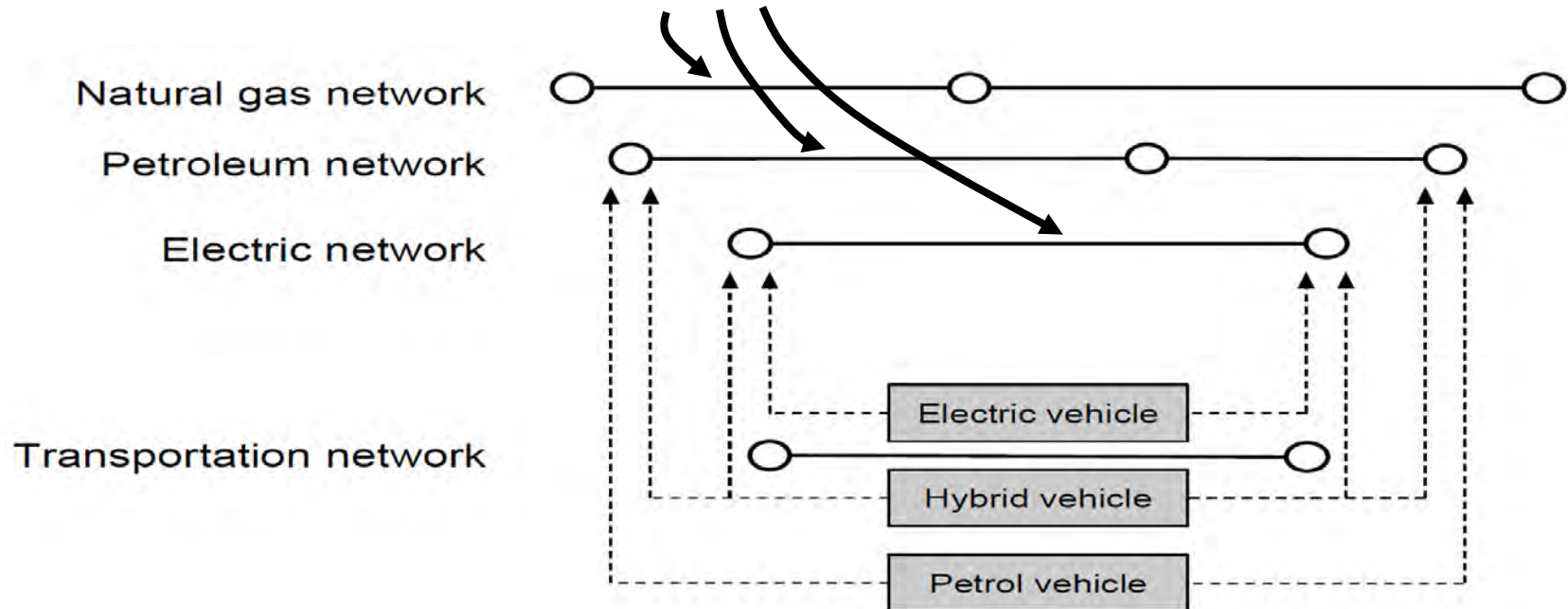
Every mode of transportation produces a demand in the energy networks

Meet energy demand at the appropriate nodes

$$\sum_i \eta_{(i,j)}(t) e_{(i,j)}(t) - \sum_i e_{(j,i)}(t) = d_j^E(t) + d_j^{ET}(t) \quad j \in \mathcal{N}_d^E$$

$$d_j^{ET}(t) = \sum_{(a,b) \in \mathcal{A}_j^T} \sum_{m \in \mathcal{M}_j} \text{fuelCons}_{(a,b,m)}(t) \sum_k f_{(a,b,k,m)}(t)$$

$$\text{MWHR} = \text{MWHR/TON} \times \text{TON}$$



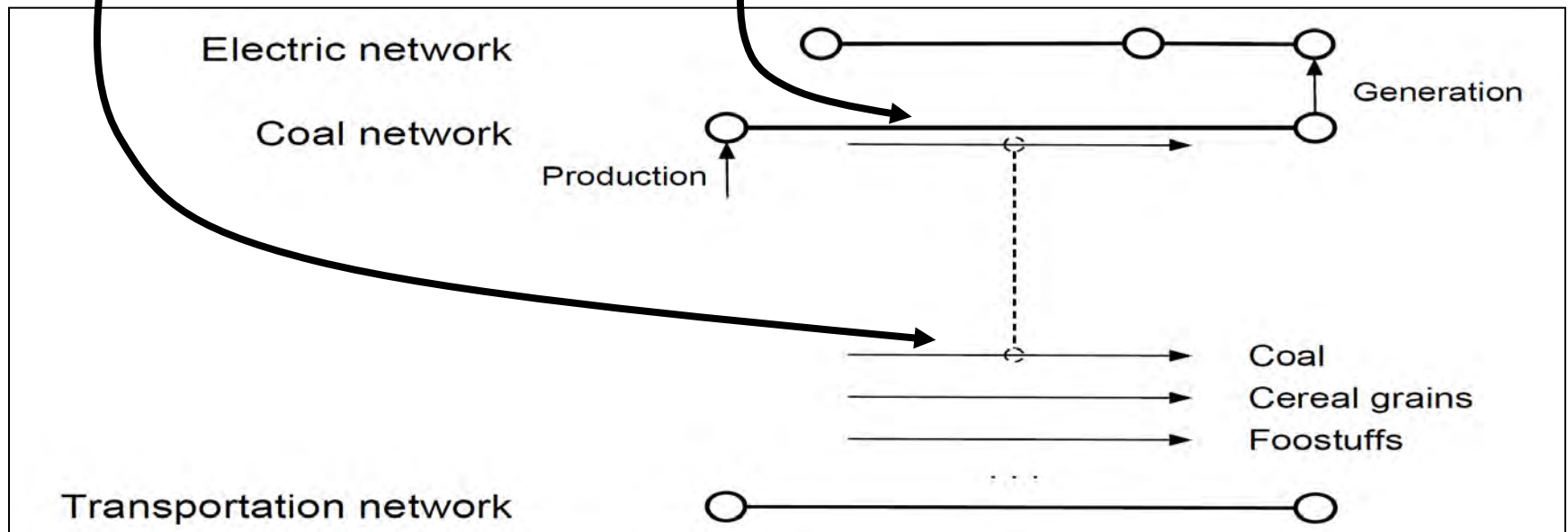
Energy system loading on transportation

“Energy commodities” (e.g., coal) are represented in the transportation network (as transported tons) and the energy network (as MWh). Both flows are coordinated.

Transportation demand for energy commodities

$$\sum_m f_{(i,j,k,m)}(t) = \text{heatContent}_k^{-1}(t) e_{(n_{(i,k)}^E, n_{(j,k)}^E)}(t), \quad k \in \mathcal{K}_e$$

TONS = TONS/MWHR × MWHR



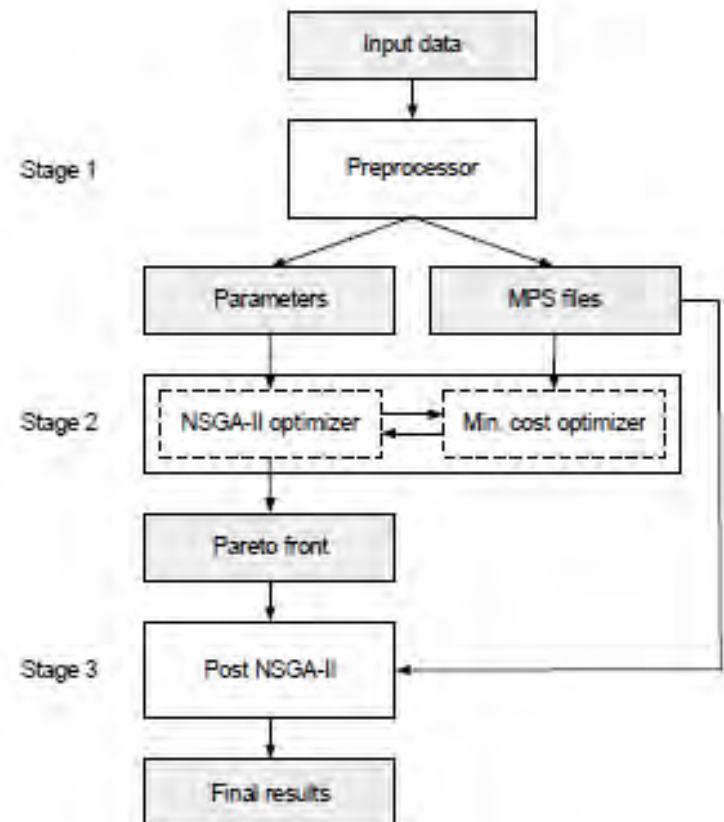
Summary of networks represented in cost-minimization problem

Network	Flow	Commodities	Units	Infrast.	Fleet	Demand
Energy	Single comm.	Electric	MWh	Electric	N/A	Nodes
		Natural gas		Pipeline		
		H ₂ , NH ₃		Pipeline		
		Petroleum		Pipeline		
Energy comm. (coal)	Multicomm.	Bituminous	Tons	Rail	Diesel, elect.	Nodes
		Subbitmns		Barge	Diesel	
		Lignite		Highway	Diesel, hybrid	
Freight	Multicomm.	Grains	Tons	Rail	Diesel, elect.	Arcs
		Chemicals		Barge	Diesel	
		Gravel, etc.		Highway	Diesel, hybrid	
Passenger	Multicomm.	50 mph	People or vehicles	Highway	Gasoline, elect.	Arcs
		100 mph		Rail	Diesel, elect.	
		200 mph		Rail	Electric	
		500 mph		Air	Petroleum	

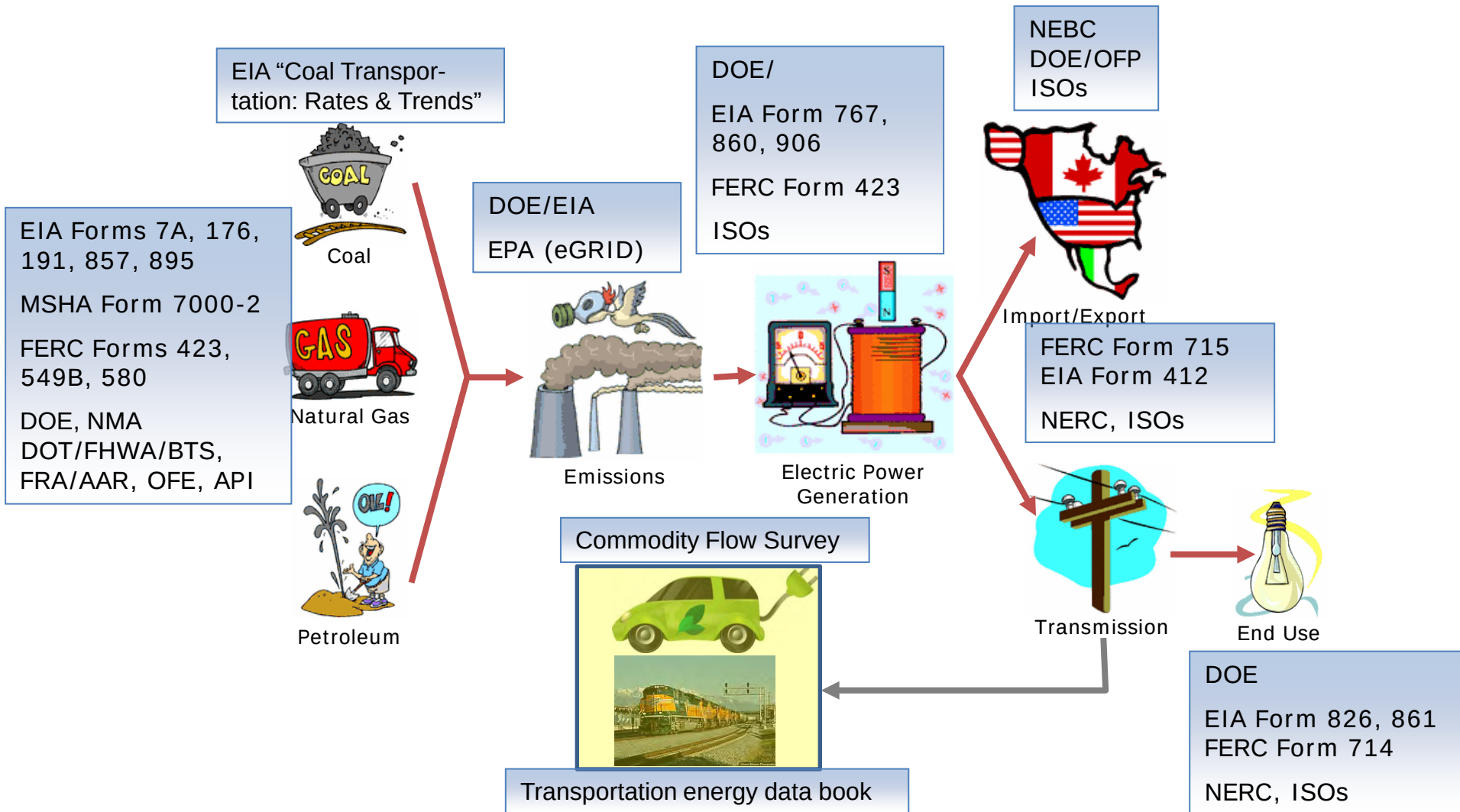
Energy and energy commodity networks have demand specified at nodes, whereas freight and passenger networks have demand specified at arcs. Allocation of transportation load across modes (infrast/fleet) is decision.

Additional Modeling/Computational Attributes

- DC flow representation available for transmission
- Different time steps modeled for different networks
- NETPLAN is C++ pre, post-processor, coordinator for NSGA-II and CPLEX optimizer.
 - Load for each elect syst time interval (month) may be segmented to reflect peak & off-peak conditions.
- Source code:
<http://github.com/eibanez/NETPLAN>
(but no support)



US data set



NETSCORE21 Technology Database

Technologies:

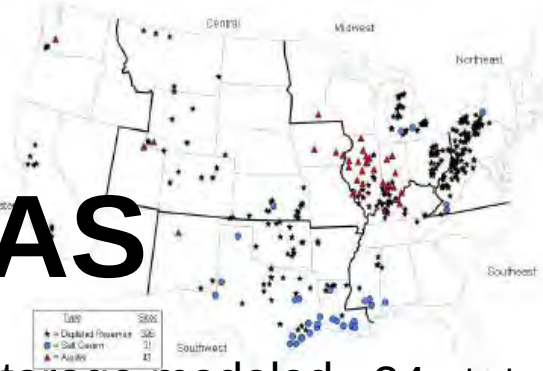
1. Nuclear
2. Pulverized Coal*
3. NGCC*
4. CT
5. Hydro
6. Inland Wind
7. Oil
8. IGCC*
9. Solar PV
10. Fuel Cell
11. Geo Thermal
12. Solar Thermal
13. MSW
14. LF Gas Recovery
15. IBGCC
16. OTEC
17. Offshore Wind
18. Tidal Power
19. IPCC
20. Wave Power

Attributes (Low, Med, Hi):

- Invest Cost (million\$/MW)
- Fixed O&M Cost (\$/kW-yr)
- Variable O&M Cost (\$/MWh)
- Heat Rate (MMBTU/MWh)
- Calculated Efficiency (%)
- Fuel Use NO_x (kg/MWh)
- Fuel Use SO_x (kg/MWh)
- Fuel Use PM (kg/MWh)
- Fuel Use NMVOC (kg/MWh)
- Fuel Use GHG (kg/MWh)
- Construction GHG (kg/MWh)
- Direct Land Usage (m²/MWh)
- Lifetime (years)
- Lead/Lag Time (years)
- FOR (%)
- Capacity Factor (%)
- Sources

Model implementation: Energy

Nat GAS



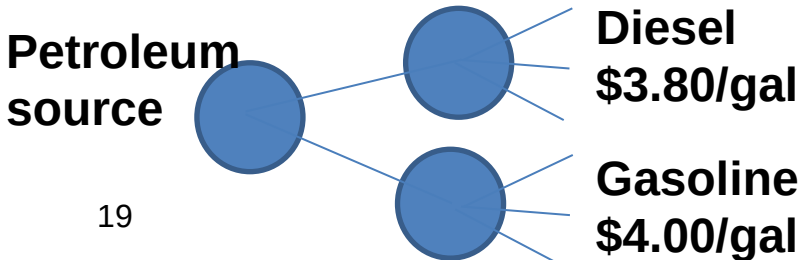
Gulf/Tx/Canadian resources & storage modeled.
Demand: nonpower (1% growth), power by state.
Gas pipelines modeled between adjacent states.
Gas network uses monthly step sizes.

24 states comprise coal resources.
Demand is all power by state.
Coal resources connected to all states.
Coal network uses yearly step sizes.

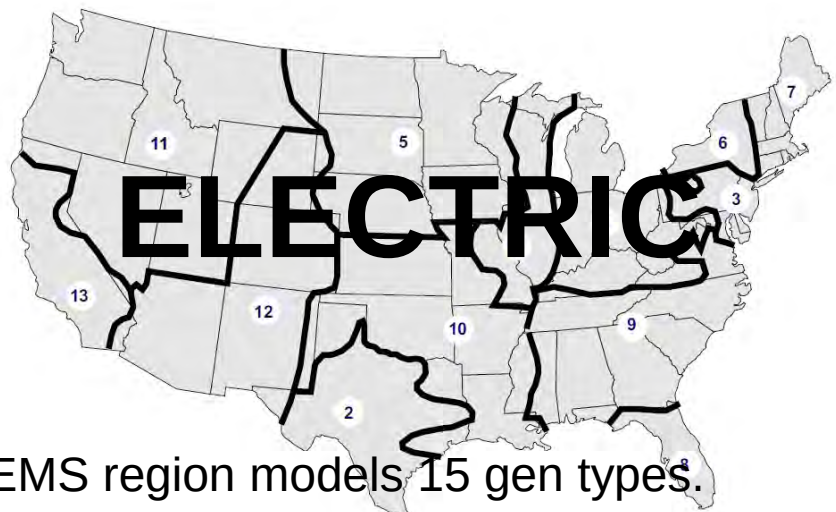
PETROLEUM



Have not yet developed detailed model.
So now using single petroleum source
node with unlimited supply.

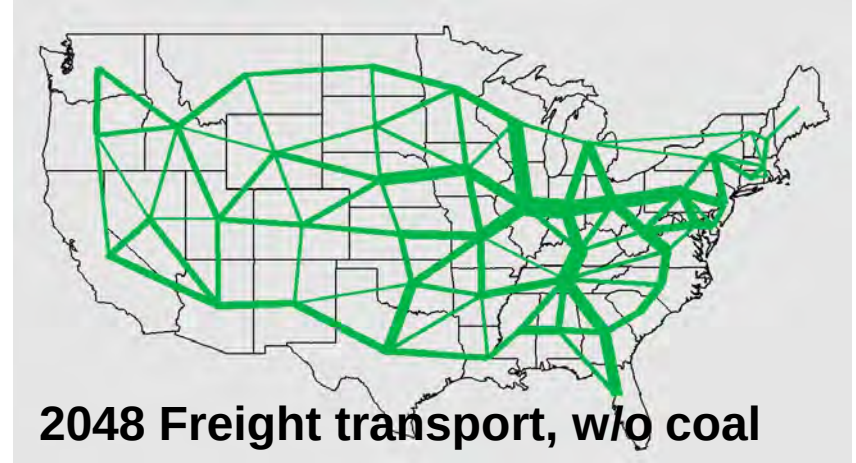
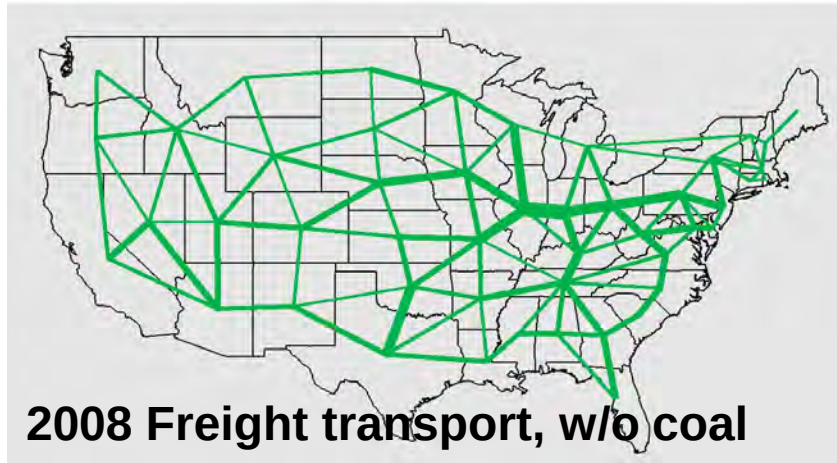


ELECTRIC



Each NEMS region models 15 gen types.
State demand transformed to regions (1.5% growth)
Trans modeled between adjacent regions.
Electric network uses monthly step sizes.

Model implementation: Transportation



FREIGHT

Modes are rail-diesel, rail-electric, and highway-diesel.

Projected freight demand is obtained from DOT “Commodity Flow Survey”

State-to-state freight transport is pre-fixed (no route optimization), added to coal transport as demanded by energy network.

Distances, capacities (based on existing demand) estimated for each arc.

Locational fuel demand based on terrain estimated for each mode (gal/1000ton-miles).

Transport network uses yearly time steps.

PASSENGER

Modes are highway-gasoline and highway-PHEV20.

New vehicle sales based on (a) existing vehicle population distributed among 13 regions in proportion to electric demand; (b) 12 year life; (c) 1% annual growth.

Assumptions made on each vehicle’s driving distance and electric, gasoline demand.

Summary of cost-minimization model

System	Type	Size
Coal	Production	24 nodes
	Demand	49 nodes
Natural gas	Production	25 nodes
	Demand	50 nodes
	Pipelines	108 arcs
	Import pipelines	9 arcs
	Storage	30 nodes
Electricity	Generation	203 arcs
	Demand	13 nodes
	Generation	203 arcs
	Transmissions	19 arcs
	Import transmission	8 arcs
Petroleum	Gasoline	13 nodes
	Diesel	13 nodes
Freight	Transportation	95 arcs
	Coal demand	49 nodes
Passenger	Vehicles	13 arcs

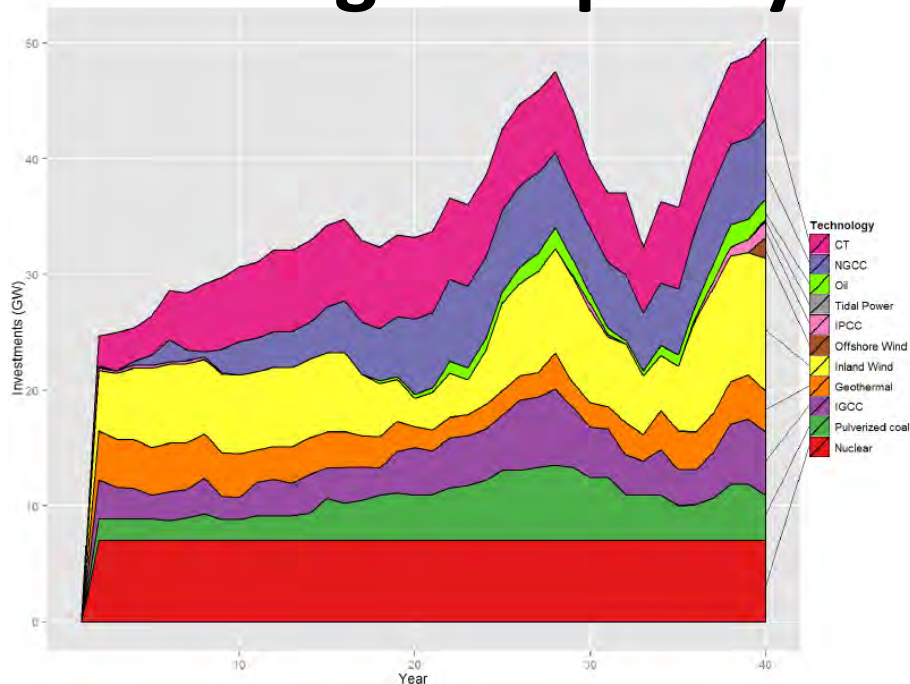
- 748,394 variables, 472,920 constraints
- ~17 minutes/solution on 1.6 GHz processor, 24 GB RAM

How to validate this model?

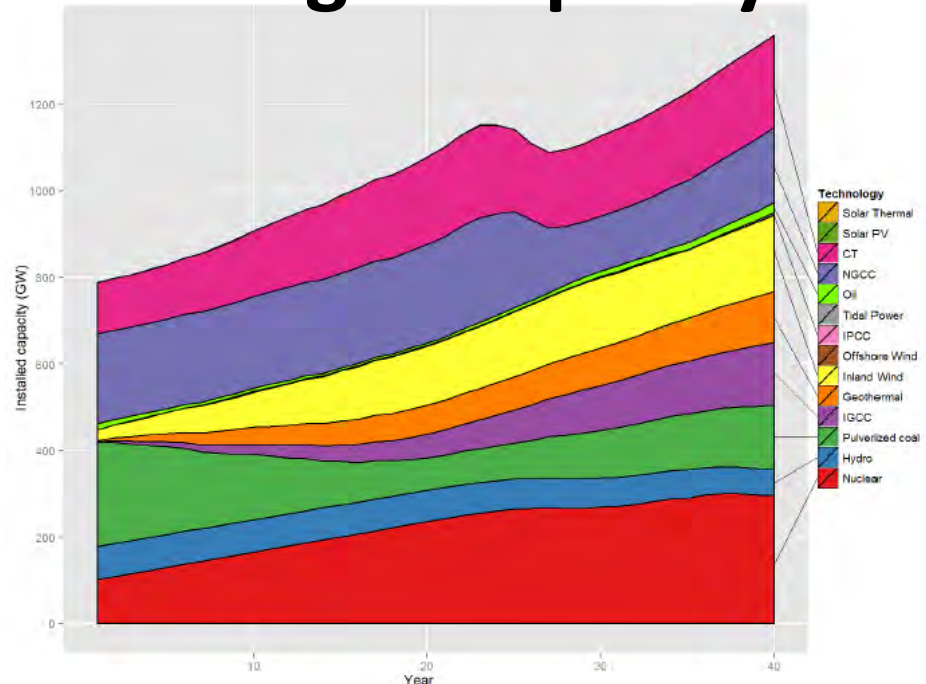
- Perform sensitivity analysis on solutions
- Simulate past period of time
- Repeat analysis with other models
 - NEMS, ReEDS, **MARKAL/TIMES**, PRISM, IPM
- Compare model results to those of other studies
 - EIA's "Annual Energy Outlook"
 - DOE's "20% Wind Energy by 2030"
 - NERC's 10 year forecast
 - Union of Concerned Scientists 2030 report (NEMS)
 - NAE 2035 report
 - NREL Renewable Energy Futures Report
 - EEI Potential Impacts of Env Regulation on U.S. Gen Fleet

Min cost solution

Added gen capacity



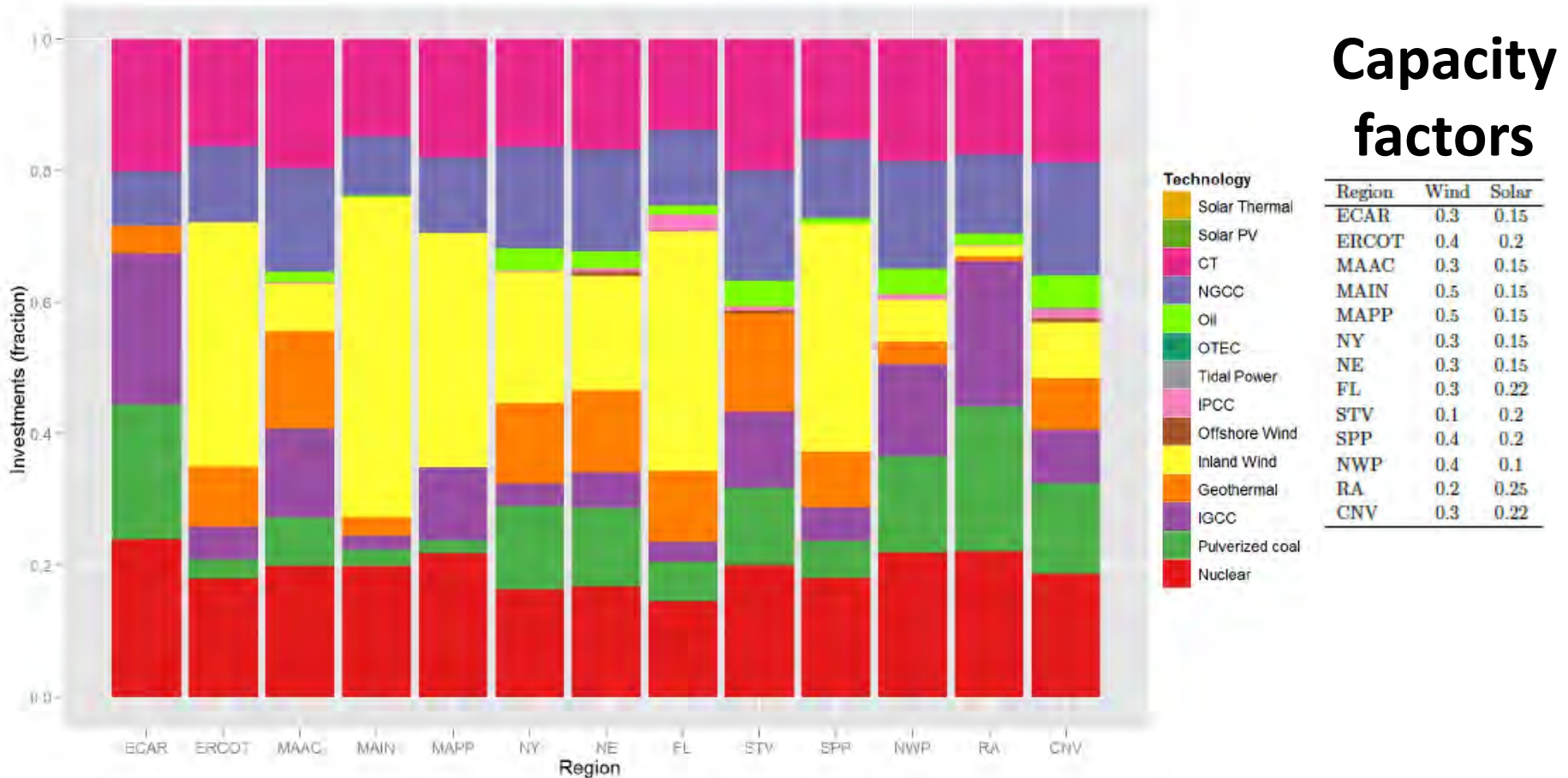
Total gen capacity



- Strong investment in nuclear, IGCC, geothermal, and on-shore wind
- Dip in total capacity in years 25-28 due to retirement of NGCC and CTs (30 year lives assumed), compensated by heavy investment in wind.
- Investment in NGCC and CTs are high, but little energy → covers peak.

Min cost solution

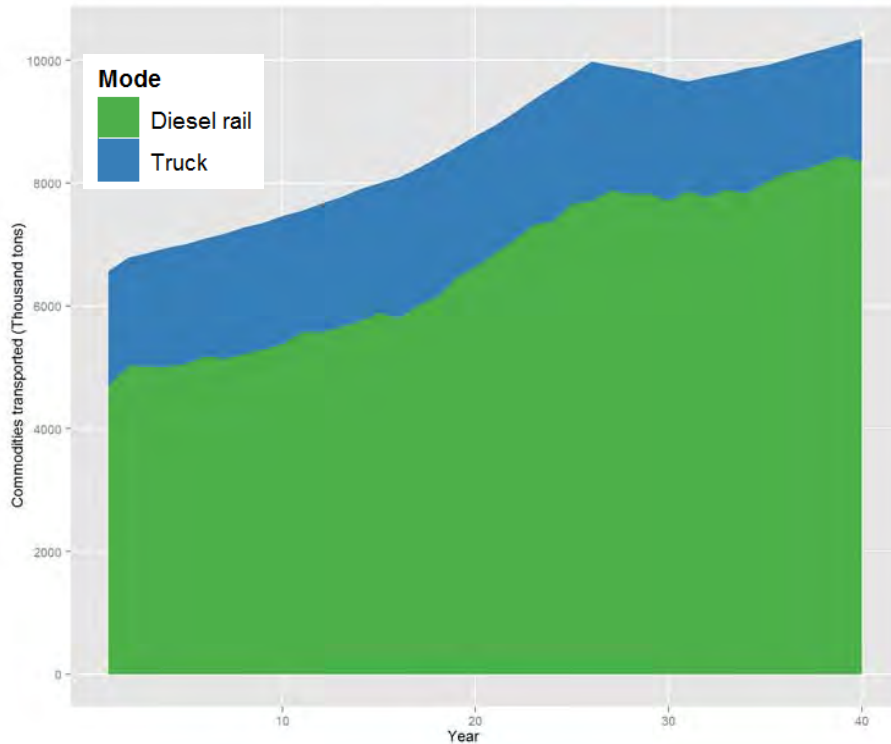
Gen capacity investment by region



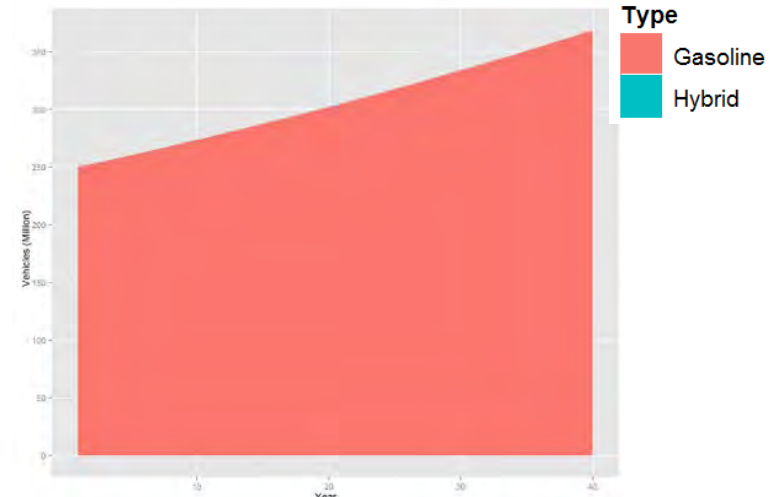
- Nuclear, NGCC, and CTs show consistent investment levels across areas.
- Distribution of remaining gen technologies mainly driven by wind CF.

Min cost solution

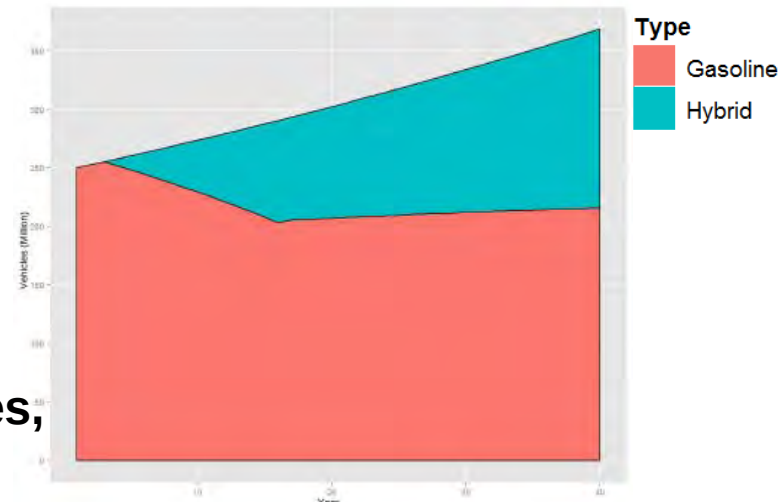
Freight transport (millions tons)



Passenger transport (vehicles)



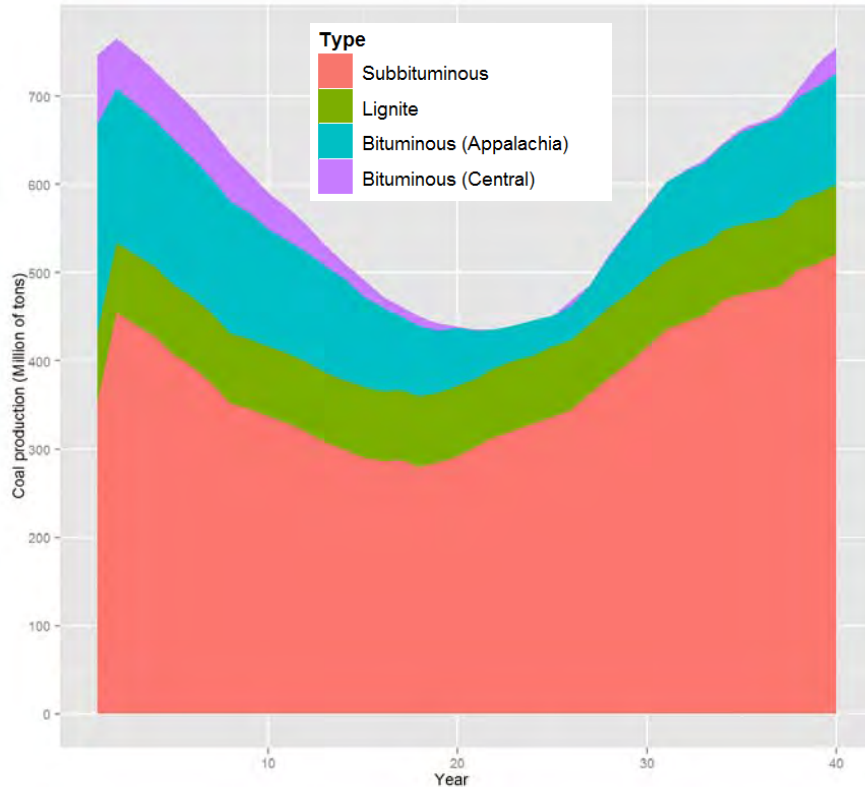
With no change in existing prices, transportation growth occurs only in petroleum-based vehicles.



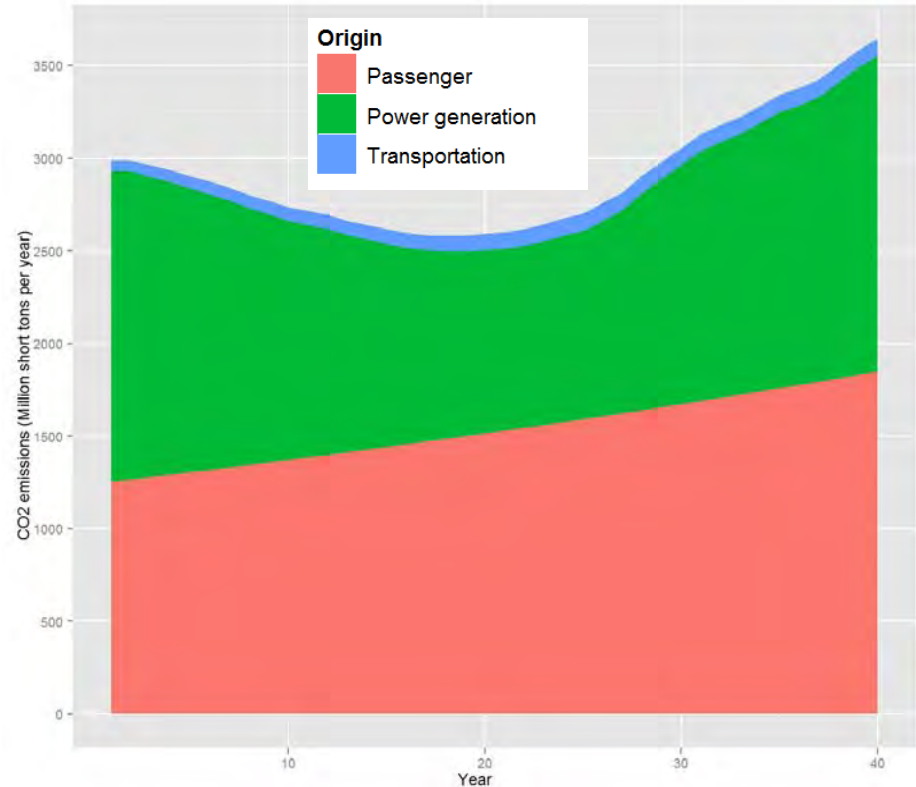
With a doubling of gasoline prices, PHEV purchases dominate.

Min cost solution

Coal production (millions of tons)



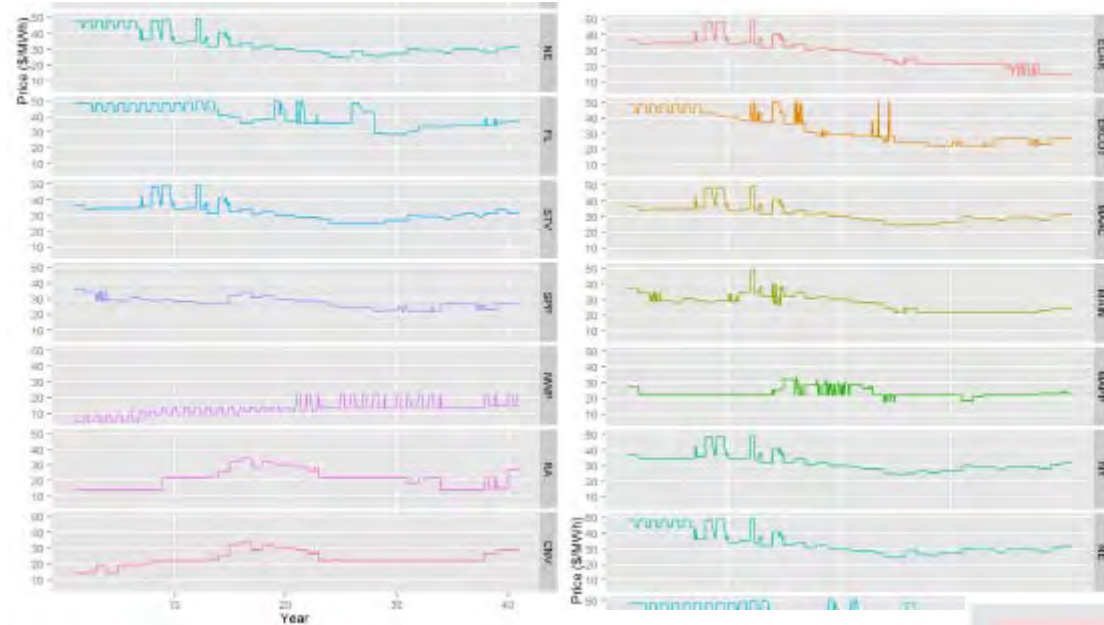
GHG emissions (millions of tons)



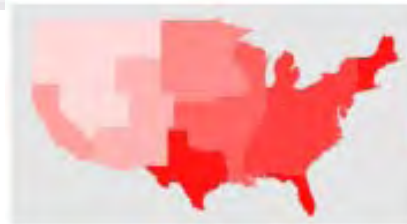
- Coal demand, GHG emissions decrease as nuclear, wind, geothermal replace pulverized coal.
- As electricity demand increases, following year 20, use of coal increases in both pulverized coal (low inv cost) and IGCC (low op cost).

Min cost solution

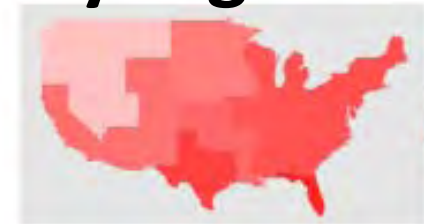
LMPs over 40 years, by region



Avg LMPs for each decade by region



(a) Years 1-10



(b) Years 11-20



(c) Years 21-30



(d) Years 31-40

Prices become more spatially uniform as most economic resources are utilized in each region.

Energy production for different emissions reductions



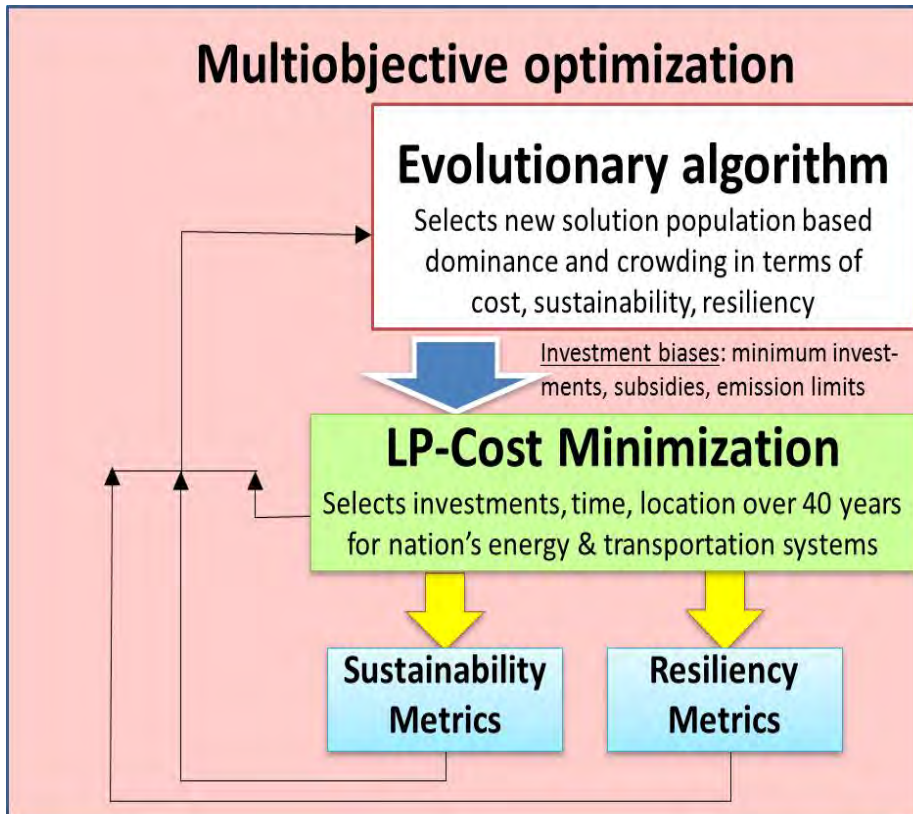
20% reduction

40% reduction

28

Multiobjective Solver: NSGA-II

A solution dominates another one if all its objective values are equal or better and at least one of them is strictly better.



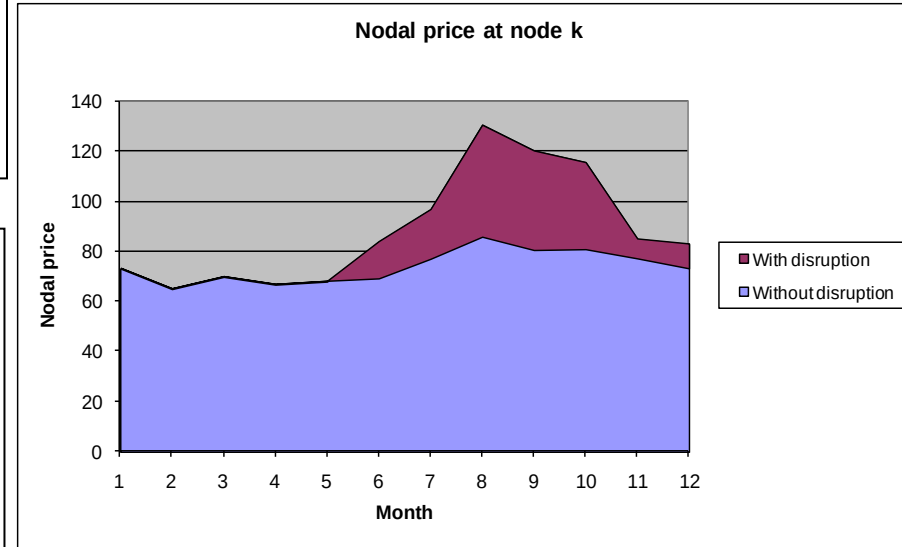
Gives the Pareto-optimal front, the set of solutions for which no objective value may be improved without degrading at least one other objective value.

- NSGA-II evolutionary algorithm proposes candidate solutions in terms of minimum investment levels for certain technologies
- Cost minimization with minimum investments produces technology portfolios and energy flows
- Sustainability metrics are computed based on energy flows
- Resiliency metrics are computed based on computed system failures tested with calculated portfolio
- Metrics returned to NSGA-II ; next generation generated via tournament selection, recombination, mutation, followed by sorting based on dominance and crowding.

Resilience Assessment

RESILIENCE: Ability to minimize and recover from the consequences of an event.

Concept: Resilience must consider events and consequences which exhibit measureable changes with design variation.



Extreme Events: Simulate total failure of each of 14 major technologies at year 25.

Societal consequences: Average the

- ▶ one year national operational cost increase
- ▶ across all 14 events with respect to the no-event case.

- 40 years
- National

Model Size and Computation Time

- Min cost model has
748,394 variables, 472,920 constraints
- 20 solutions/generation
- 82 generations
- 472 hours computing on single CPU
- Average min per LP solution: 17

Pareto-Optimal Solutions after 200 Generations

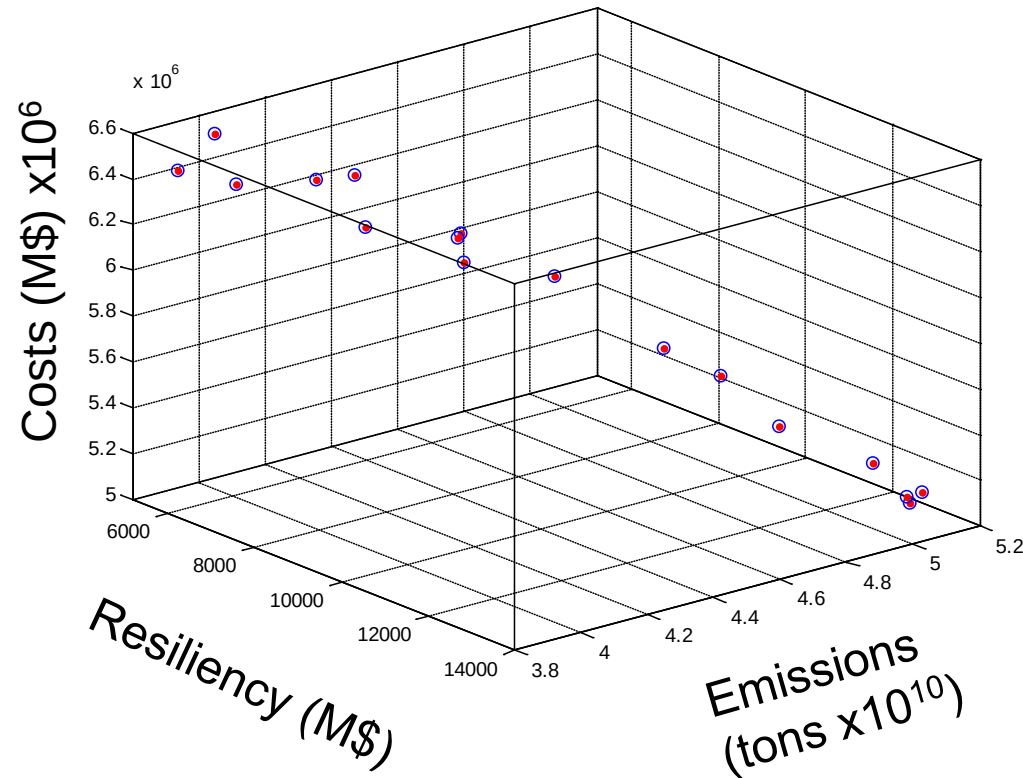
Pareto Optimal Solutions from NSGA-II

S. No	Cost (M\$)	EmCO ₂ (Short ton)	Resiliency (M\$)
1	4.37E+06	5.32E+10	3.37E+05
2	4.38E+06	5.27E+10	3.20E+05
3	4.43E+06	5.25E+10	3.62E+05
4	5.11E+06	5.07E+10	1.34E+04
5	5.13E+06	5.12E+10	1.33E+04
6	5.18E+06	5.02E+10	1.37E+04
7	5.24E+06	5.05E+10	1.27E+04
8	5.37E+06	4.91E+10	1.16E+04
9	5.56E+06	4.84E+10	1.08E+04
10	5.63E+06	4.79E+10	9.86E+03
11	5.93E+06	4.61E+10	8.74E+03
12	5.99E+06	4.44E+10	7.94E+03
13	6.05E+06	4.51E+10	7.33E+03
14	6.11E+06	4.42E+10	7.95E+03
15	6.17E+06	4.24E+10	7.20E+03
16	6.31E+06	4.31E+10	6.42E+03
17	6.37E+06	4.16E+10	6.68E+03
18	6.39E+06	3.97E+10	6.29E+03
19	6.48E+06	3.84E+10	5.95E+03
20	6.52E+06	4.03E+10	5.32E+03

Least cost,
least resilient

Highest cost,
most resilient

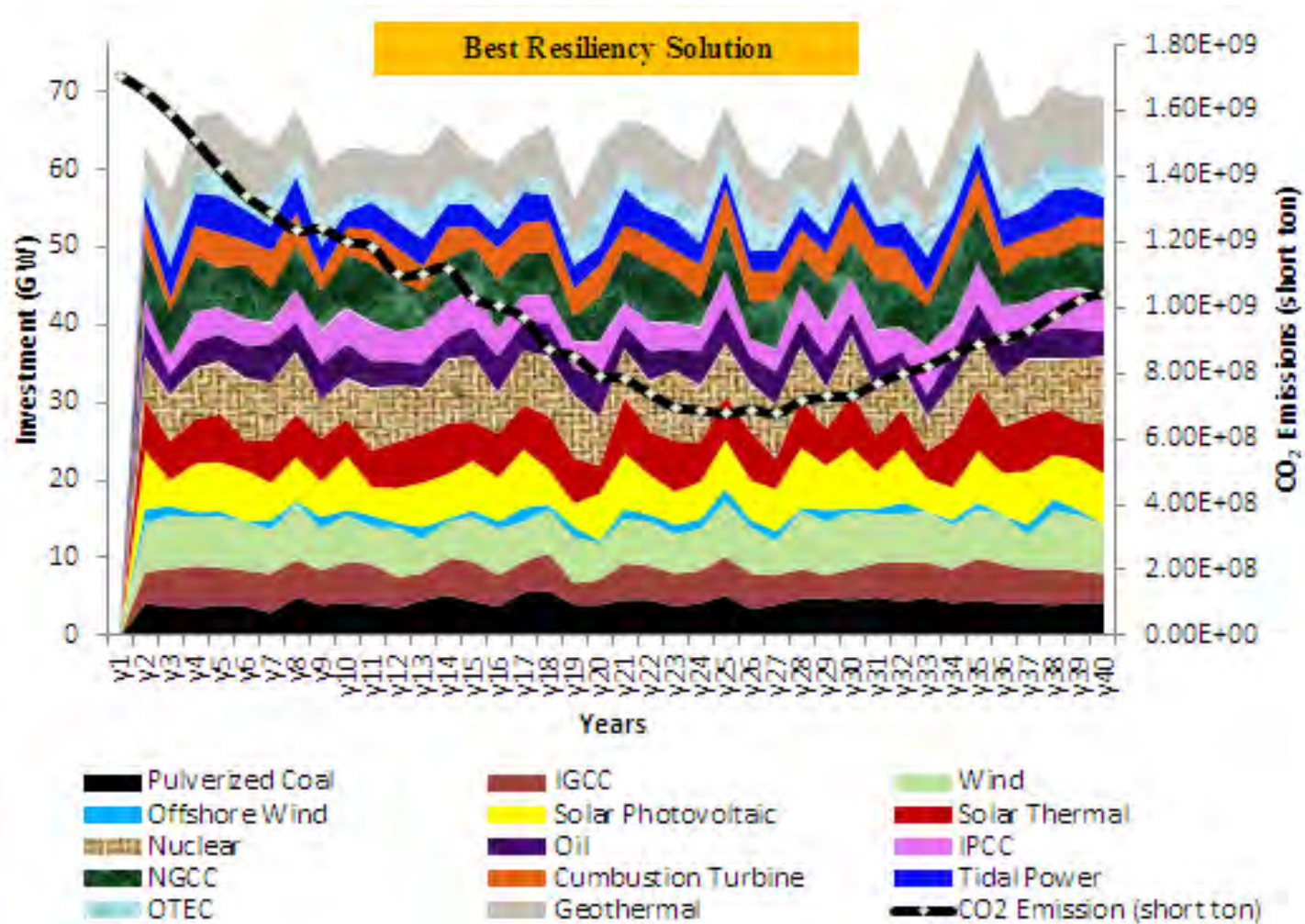
Fig. 10 Pareto front in 3-D solution space



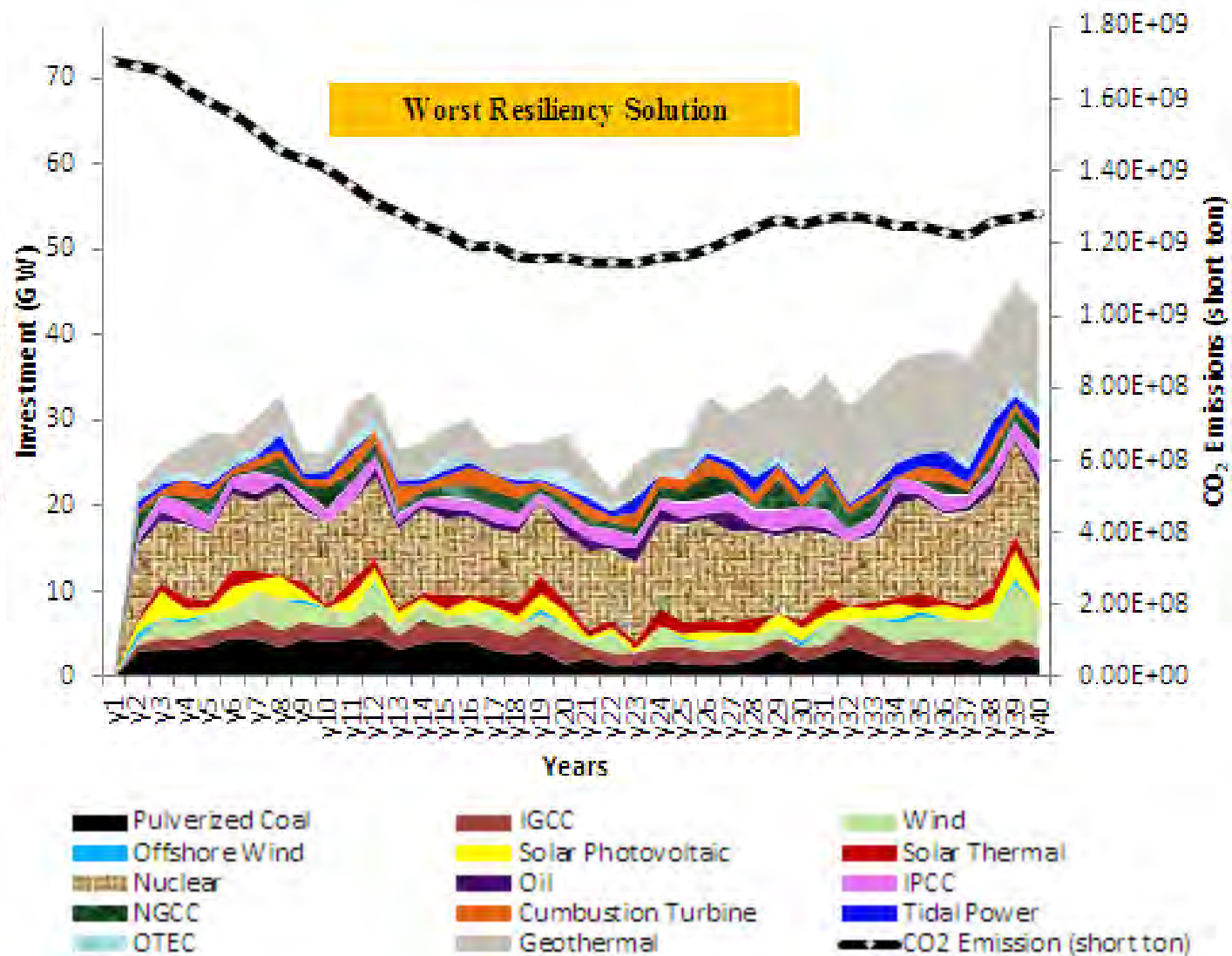
Events: For each 40 year investment strategy, simulate total failure of each of 14 technologies at year 25.

Resiliency metric: Averaged the 1 year operational cost increase across all 14 events with respect to the no-event case.

Yearly Generation Investment and CO₂ Emission for Most Resilient Solution



Yearly Generation Investment and CO₂ Emission for Least Resilient Solution



Current Model Improvement Efforts

- **Impact of variable generation**
 - **Cycling costs (increased maint & FOR, decreased life)**
 - **Investment costs of more high-ramp capability**
 - ➔ **CTs, demand control, storage, large control areas**
- **Transmission optimization**
- **Emissions control equipment:**
 - **Fluidized gas desulfurization**
 - **Carbon capture & sequestration**
- **Hydrogen production & transport**
- **Data enhancement**
 - **Enhancement of generation & transmission data**
 - **Liquid petroleum refining & transport**
- **Identification of key uncertainties & modeling**
- **Deployment on parallelized HPC**
- **Improved passenger transport**

Current Study Efforts

- What technologies and topologies should be used in designing a national electric transmission superhighway system?**
- What is the best mix of electricity, petroleum, and biofuels to supply our automotive needs?**
- To what extent can electric high-speed rail reduce energy use and transportation-related emissions while competing with air and highway travel?**

Conclusions

- **We developed NETPLAN, a computational model that is**
 - multisector: fuels, electric, and freight/passenger transport
 - multiobjective: cost, resilience, and sustainability metrics
 - an optimization model: (not equilibrium), & so policy-*driving*.
 - long-term/national and represents transmission/transport
- **We conceive of large, catastrophic, Katrina-like events to define resilience in terms of their cost-consequence**
- **The model allows exploration of how different technologies, costs, resilience, and emissions/other environmental objectives affect long-term investment portfolios.**
- **NETPLAN is useful for identifying policy directions which balance cost, resilience, and environmental needs.**
- **We need to make use of software tools which perform systematic engineering evaluation to peer into the future and appropriately guide legislative decision-making.**