Integrated Energy/Transportation Continent-wide Infrastructure Design

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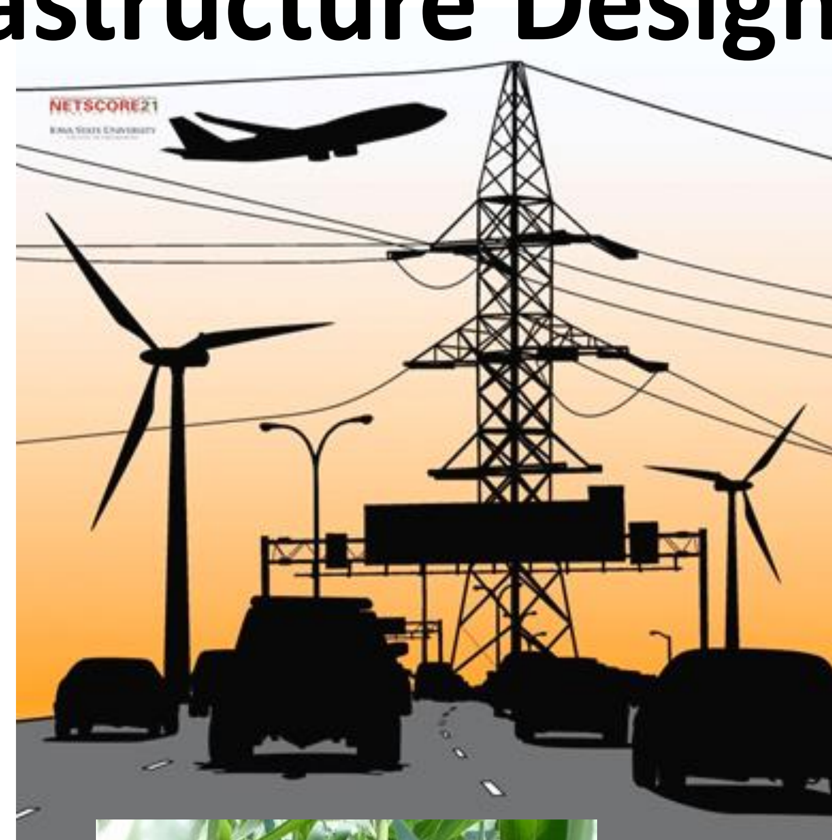

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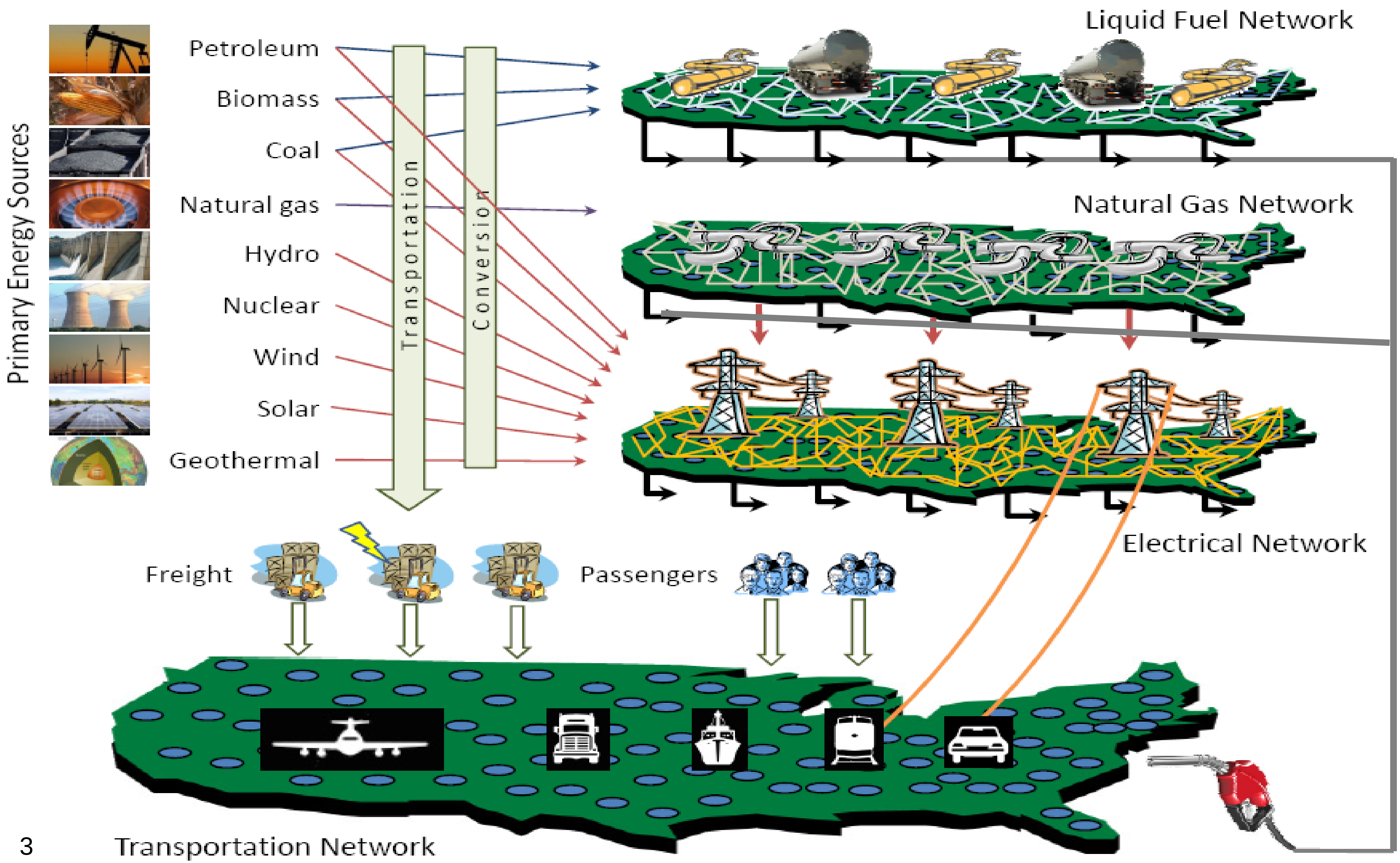
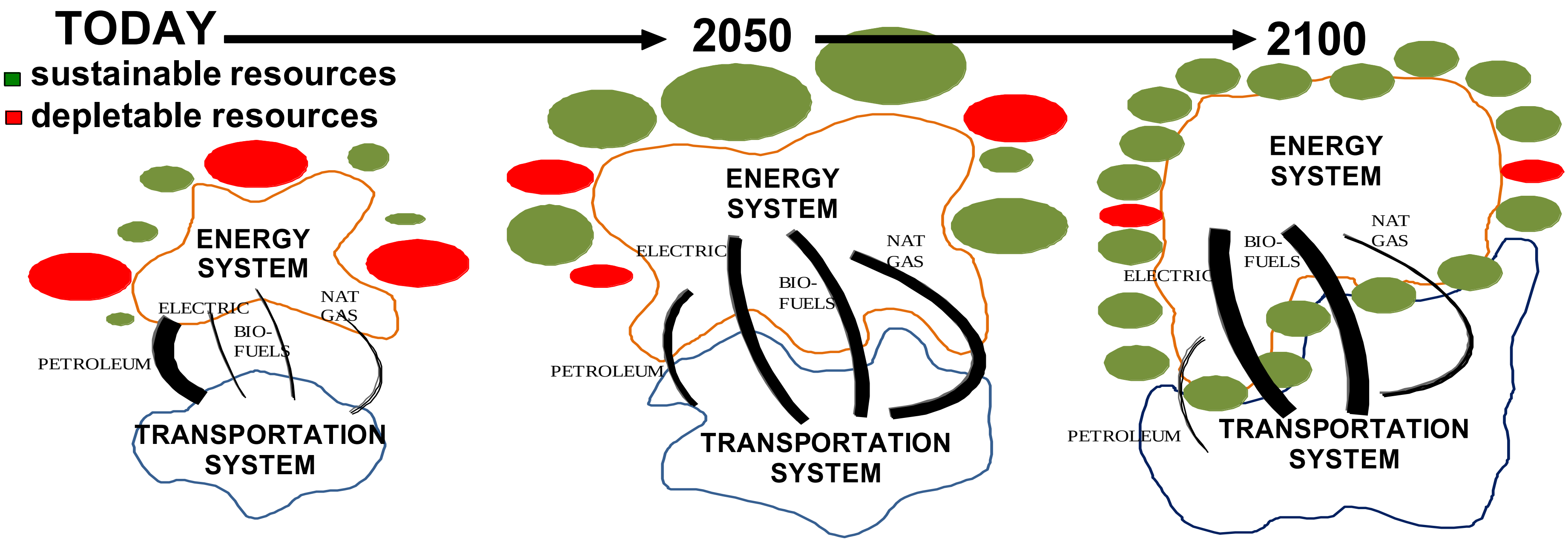
Overview

1. Energy and transportation interdependencies
2. Modeling approach
3. Design results
   a. High-speed rail
   b. Resilience
   c. Flex-fuel polygeneration
   d. Natural gas & light-duty vehicles
   e. Biomass: bio-fuels and biopower
4. Policy and awareness

Infrastructure view: <u>Multi-sector</u> (fuel, electric, transportation), <u>continental</u>, long-term planning

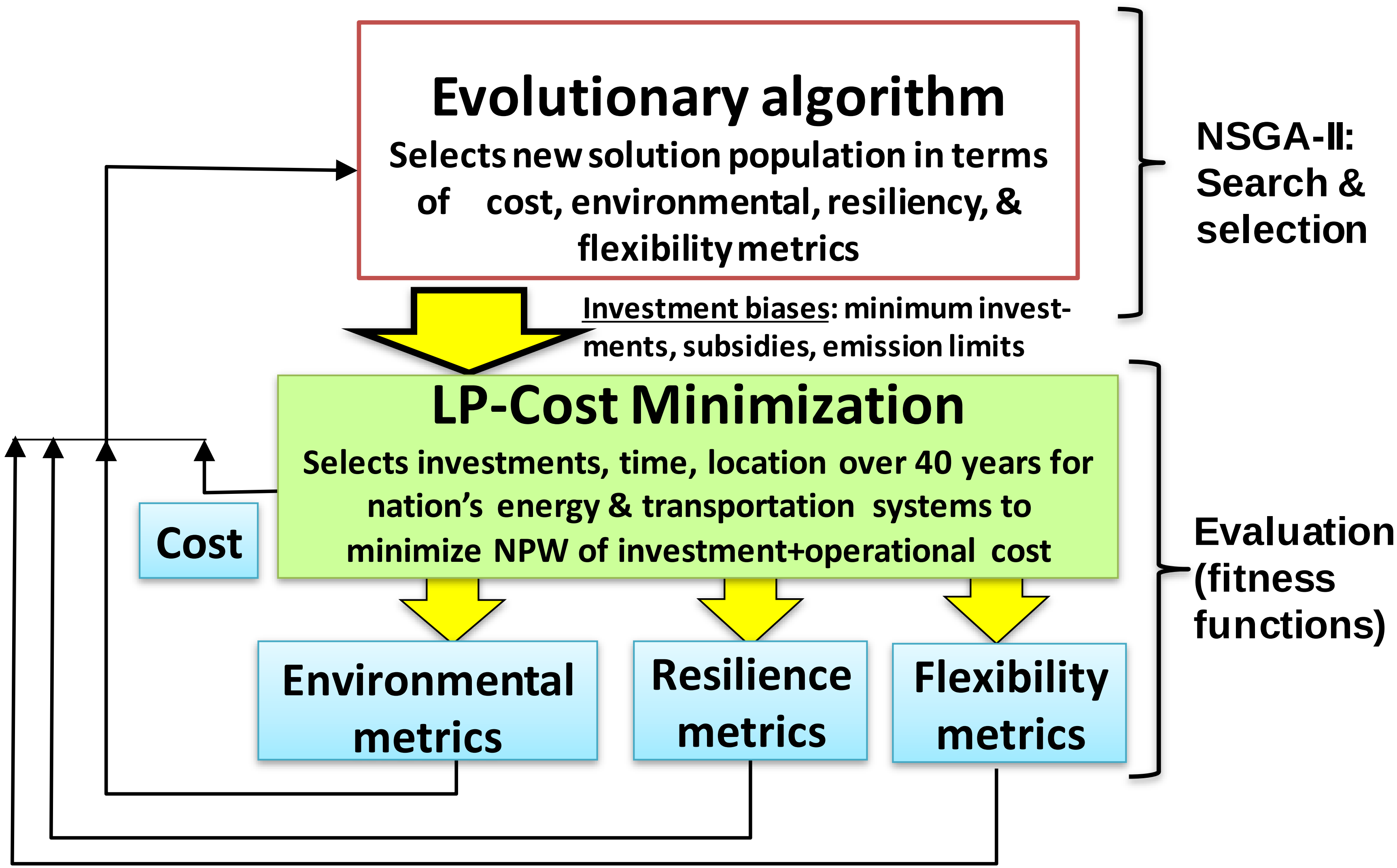


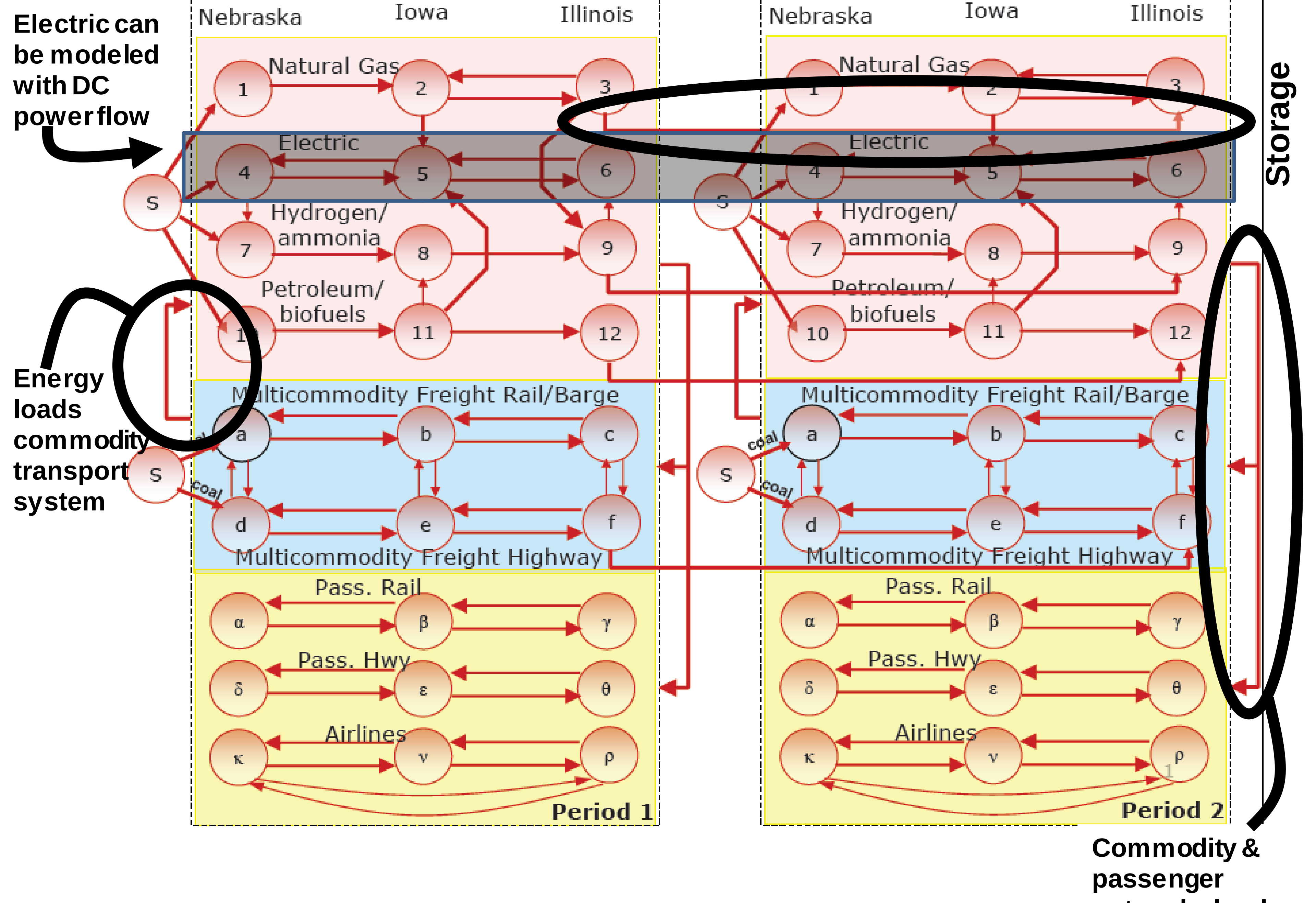
Infrastructure view: Multi-sector (fuel, electric, transportation), continental, long-term planning



- Probes future infrastructure designs via computation
- Separates "good" from "bad" choices & informs societal dialogue and political debate
- 100-year infrastructure designs: a sustainability practice

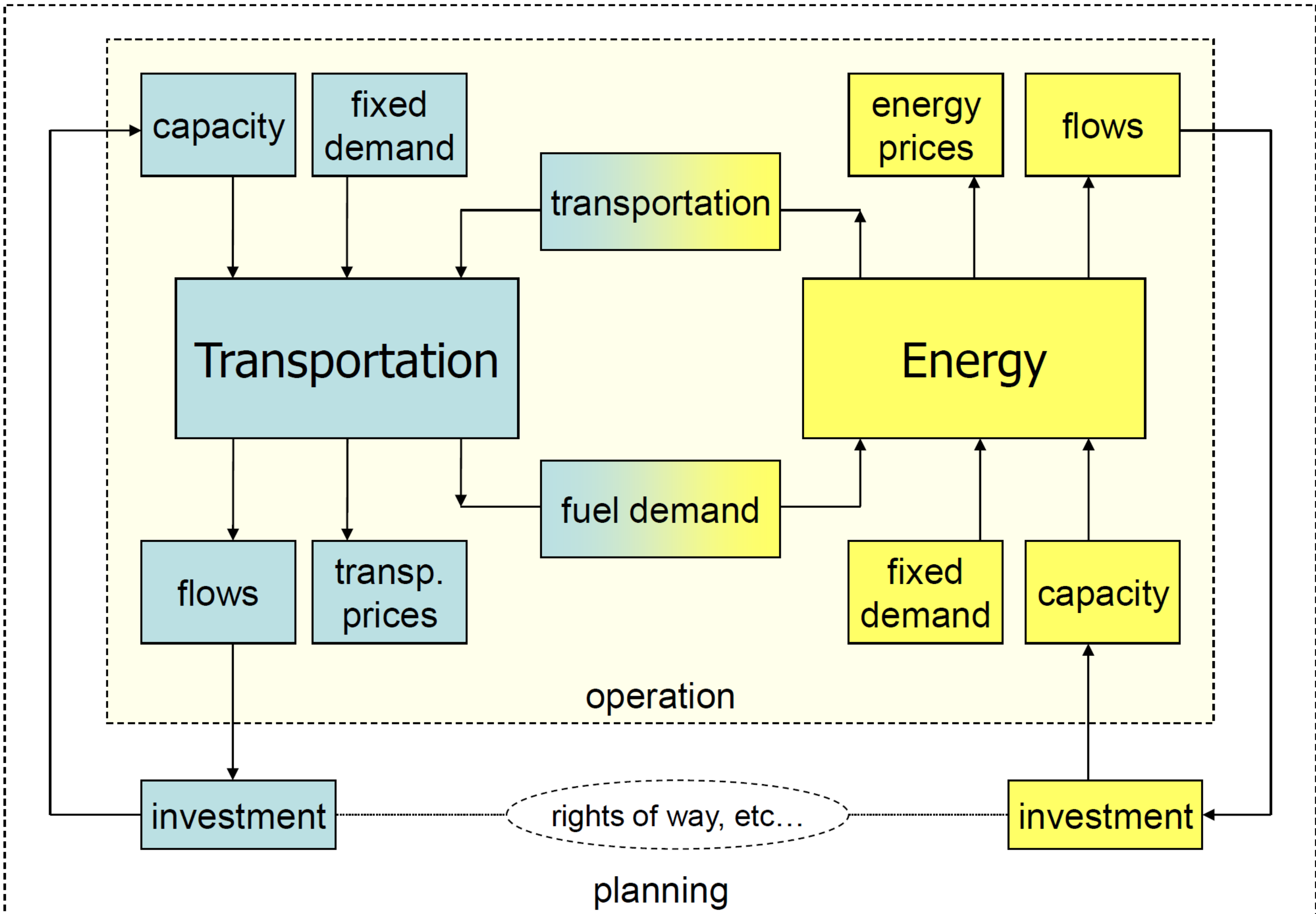
Modeling: NETPLAN, multi-objective optimization





LP Cost Minimization: Multi-period w/network structure

Conceptual Cost-Minimization Model



Modeling: mathematical formulation for cost minimization problem

(i,j) are arcs. m is mode. k is commodity.

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

Minimize operational and investment cost

subject to:

Meet energy demand at the appropriate nodes

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

Meet energy demand

Yellow is energy commodity.

DC power flow equations

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

DC power flow

Generation capacity must cover peak demand at electric nodes

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

Meet electric peak demand

Transportation demand for non-energy commodities

$$\sum_m f_{(i,j,k,m)}(\mathbf{t}) = d^T_{(i,j,k)}(\mathbf{t}), \quad k \in \mathcal{K} \backslash \mathcal{K}_e \qquad (3.6)$$

Transportation demand for energy commodities

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

Meet transportation demand

Fleet upper bound for transportation flows

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

Max. fleet capacity

Infrastructure upper bound for transportation flows

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

Max. transportation infrastructure capacity

Decision variables:

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

Energy capacity inv.: $lbeInv_{(i,j)}(\mathbf{t}) \leq eInv_{(i,j)}(\mathbf{t}) \leq ubeInv_{(i,j)}(\mathbf{t})$ (3.11)

Energy flows and investments

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

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

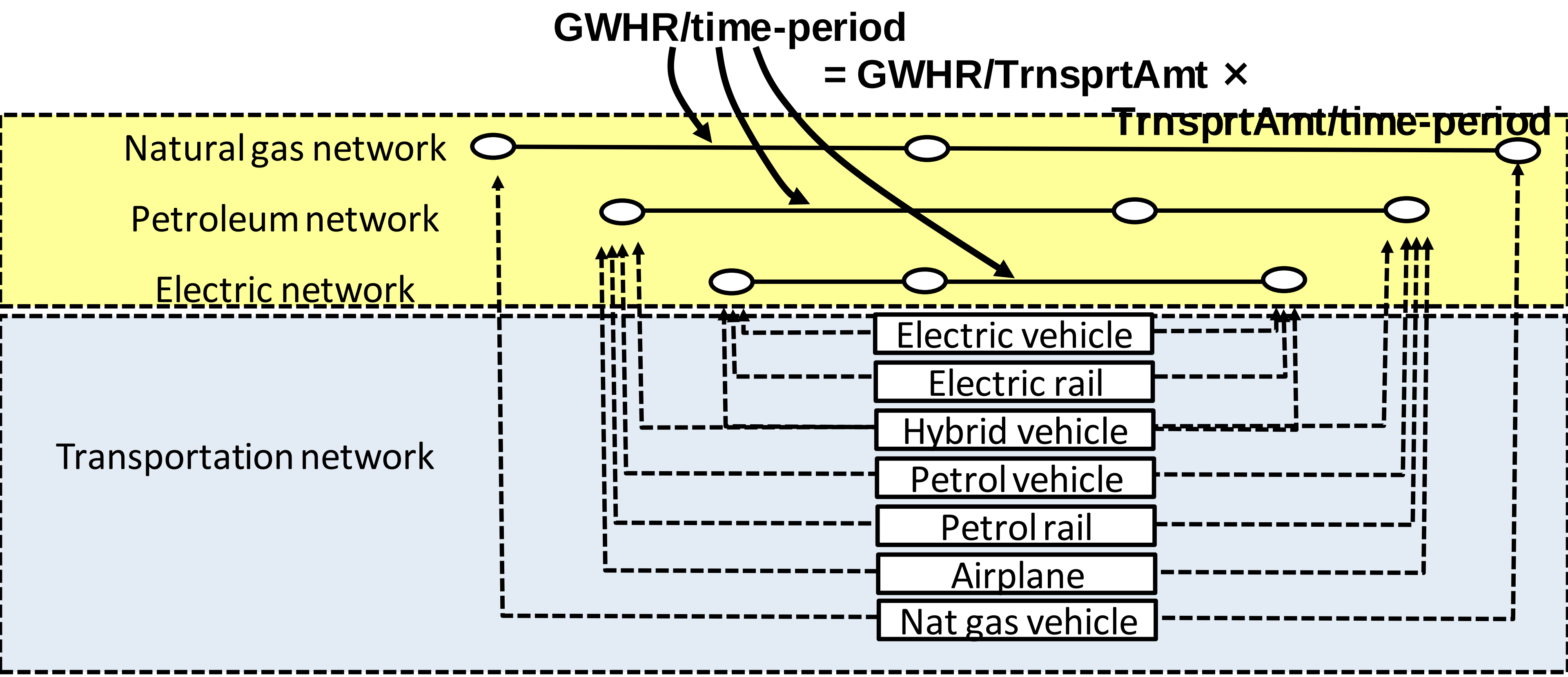
Infrastucture inv.: $lbInfInv_{(i,j,l)}(\mathbf{t}) \leq infInv_{(i,j,l)}(\mathbf{t}) \leq ubInfInv_{(i,j,l)}(\mathbf{t})$ (3.14)

Transportation flows and investments

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

Transportation system loading on energy

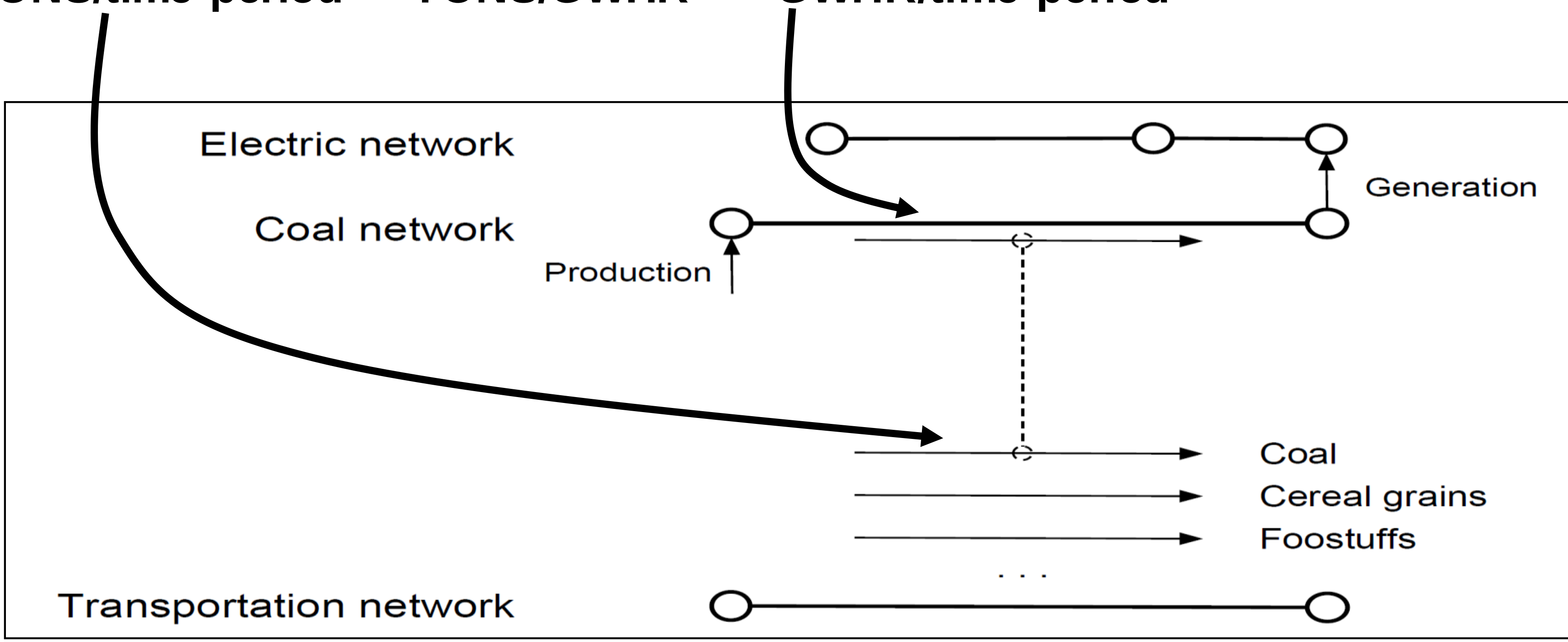
Every transportation mode produces demand in energy networks



Energy system loading on transportation

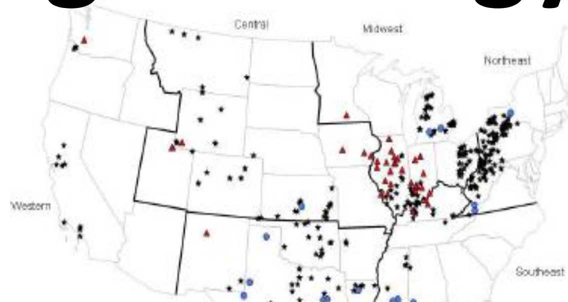
“Energy commodities” (e.g., coal, bio-energy feedstocks) are represented in the transportation network (as transported tons) and the energy network (as MWh). Both flows are coordinated.

TONS/time-period = TONS/GWHR × GWHR/time-period



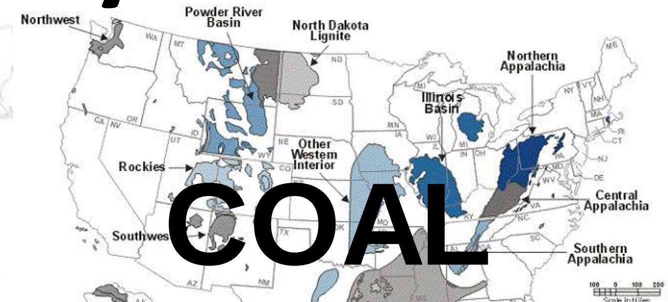
Modeling of energy system

Nat GAS



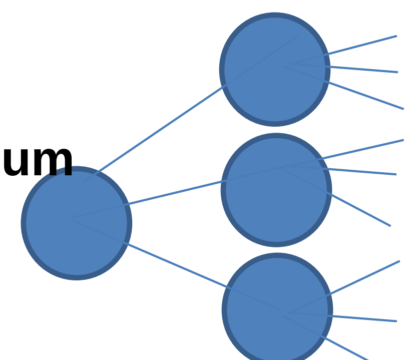
Gulf/Tx/Canadian resources & storage modeled.
Demand: nonpower (1% grwth), power by state.
Gas pipelines modeled between adjacent states.
Gas network uses monthly step sizes.

COAL

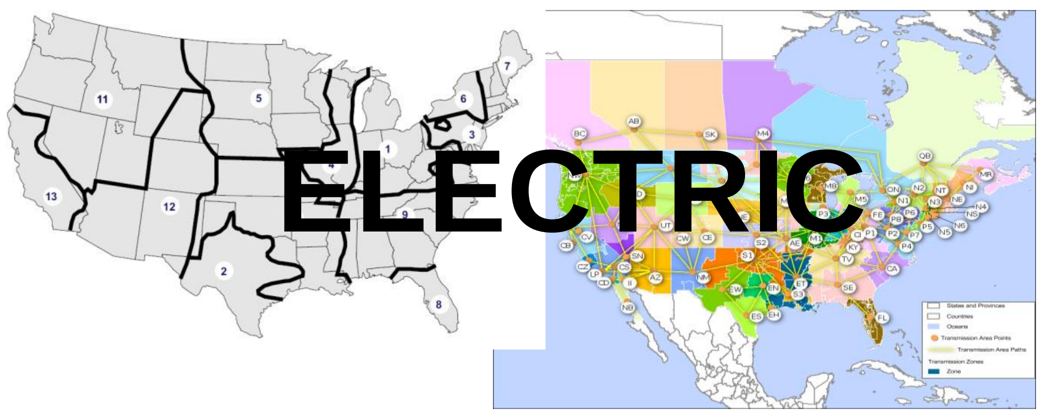


24 states comprise coal resources.
Demand is all power by state.
Coal resources connected to all states.
Coal network uses yearly step sizes.

PETROLEUM



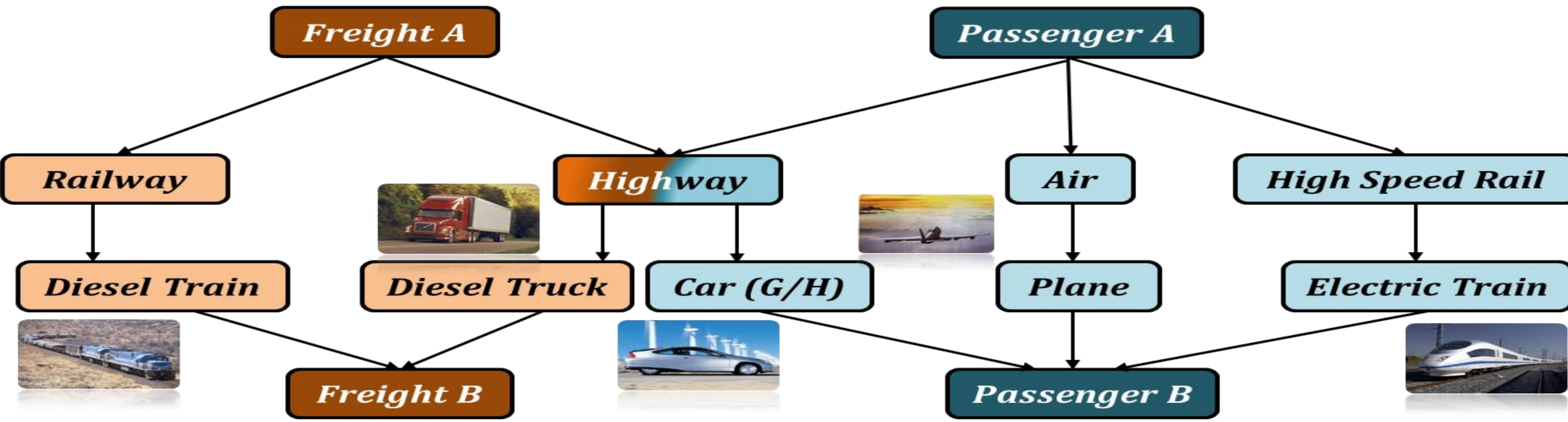
ELECTRIC

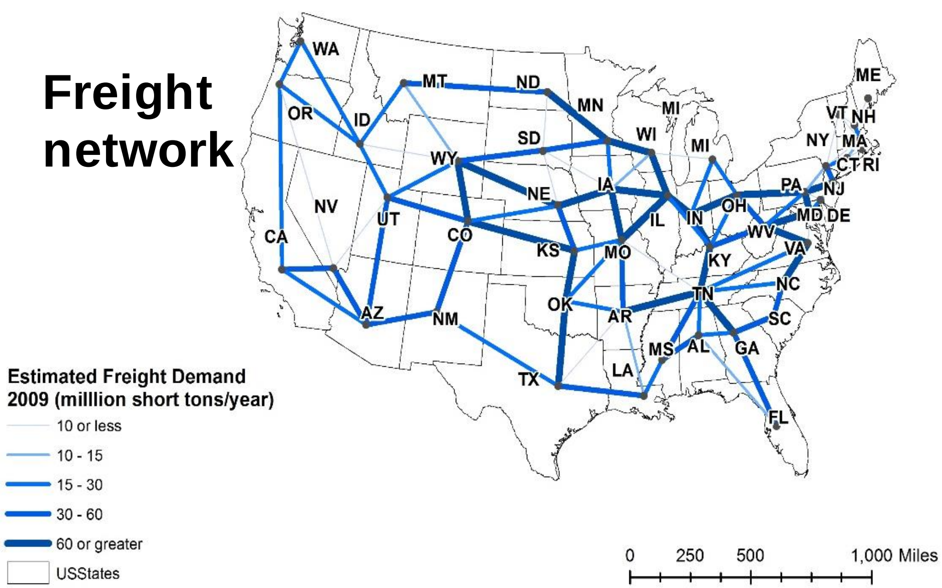


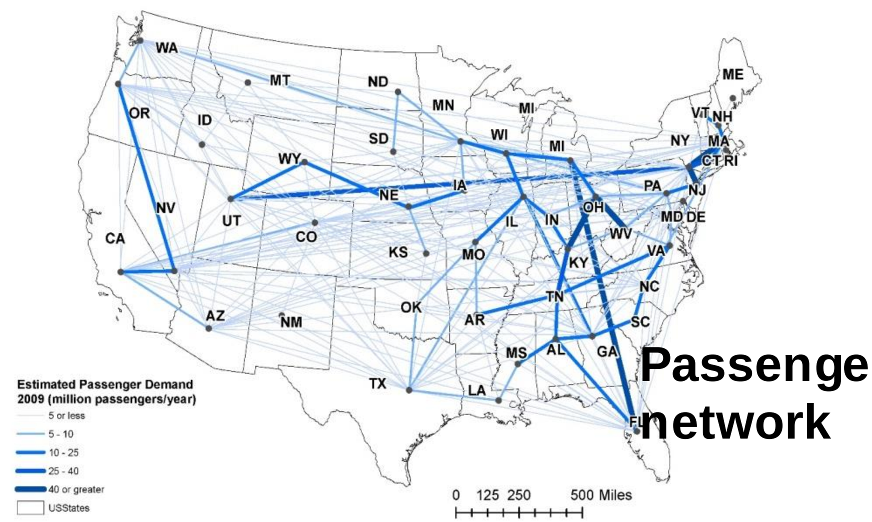
Each node models 15 gen types.
Existing trans modeled between nodes.
Electric network uses monthly step sizes.

…also bio-energy resources; more on that later

Modeling of transportation







Transportation demand is specified node-to-node, except for energy commodities.

Summary of networks represented in cost-minimization problem

Network	Flow	Commodities	Units	Infrast.	Fleet	Demand
Energy	Single comm.	Electric Natural gas H_2, NH_3 Petroleum	GWhr/ time-period	Electric Pipeline Pipeline Pipeline	N/A	Nodes
Energy comm. coal & bio.	Multicomm.	Bituminous Subbitmns Lignite	Tons/ time-period	Rail Barge Highway	Diesel, elect. Diesel Diesel, hybrid	Nodes
Freight	Multicomm.	Grains Chemicals Gravel, etc.	Tons/ time-period	Rail Barge Highway	Diesel, elect. Diesel Diesel, hybrid	Arcs
Passenger	Single comm.		Pssngrs/ time-period 600mph air 150mph HSR 65mph LDV	Highway Rail Rail Air	Gasoline, elect. Diesel, elect. Electric Petroleum	Arcs

Study: Does high-speed rail make sense?

An Optimization Model of Energy and Transportation Systems: Assessing the Impact of High-Speed Rail on U.S. Interstate Passenger Transportation Investments

Venkat Krishnan[*1], Eirini Kastrouni[2], V. Dimitra Pyrialakou[3], Konstantina Gkritza[3], and James D. McCalley[1]

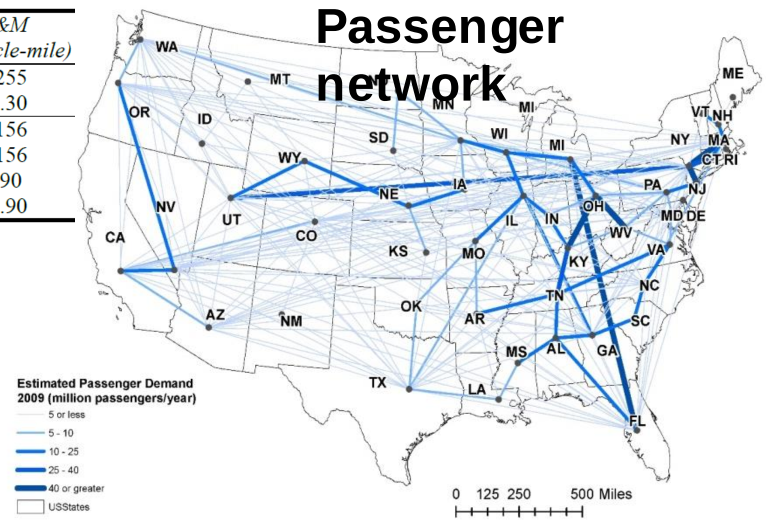
Modeling assumptions:

- Long-distance travel only: 95 state-state + 140 additional heavily-traveled routes
- Possible travel modes are highway, air, HSR
- Travel time penalized 24$/hr for all modes in optimization but reported separately
    - Cost includes investment + operational cost of energy & transportation
    - Fixed transport infrstrctre modeled with ∞ capacity➔investment only in fleets
    - Transport demand grows 3%/year

Fleet Operational Characteristics

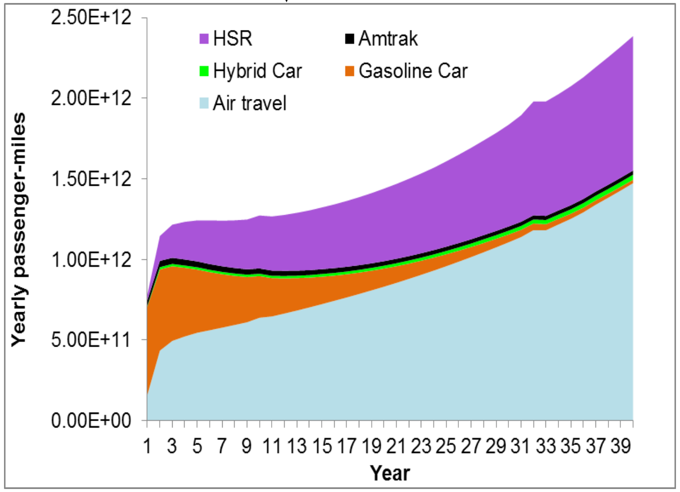
Mode	*Fuel (Gallon / vehicle-mile)*	*Electricity (kWh / vehicle-mile)*	*Occupancy, η (k-tons or Passengers)*	*O&M ($/vehicle-mile)*
Diesel Truck	0.169	-	0.025	0.255
Diesel Rail	16.65	-	11.50	47.30
Gasoline Car	0.044	-	1.630	0.156
Plug-in Hybrid Electric Car	0.026	0.340	1.630	0.156
Airplane	2.248	-	229.0	8.90
HSR Train	-	14.924	260.0	46.90

Passenger network



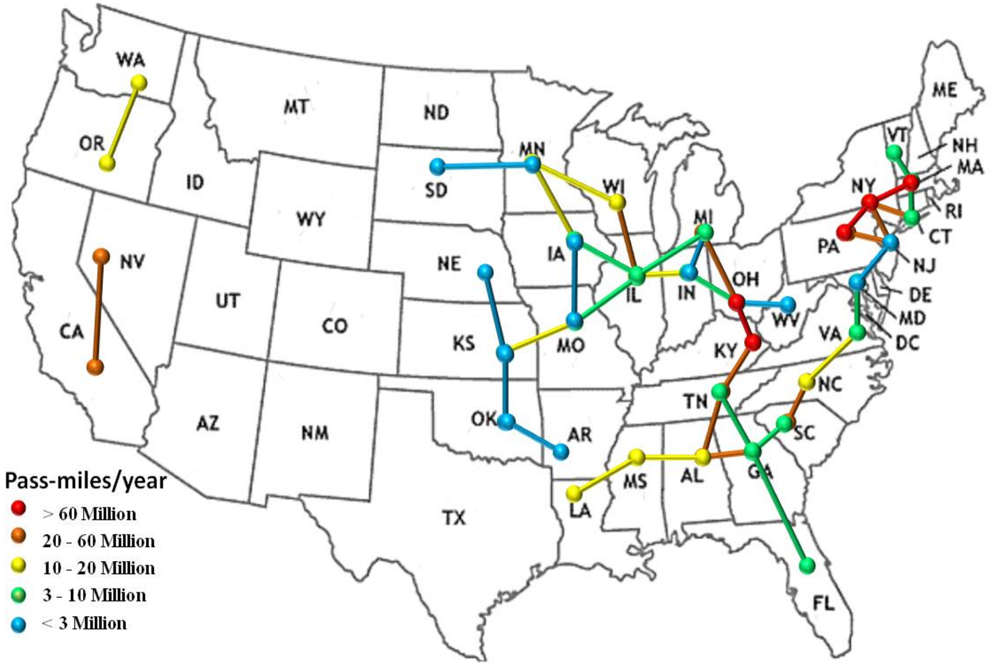
Design: High-speed rail (HSR)

Attribute	*No HSR*	*With HSR*
HSR penetration (%)	0	30.5
Total Cost (T$)	11.61	11.15
Emissions (e10 short tons)	2.59	2.51 (-3.1%)
Gasoline (E+3 MGallon)	29.84	19.92 (-33.2%)
Jet Fuel (E+3 MGallon)	320.55	211.25 (-34.1%)
Electric Energy (E+6 TWh)	194.23	198.24 (+2.06%)
Cost Savings (B$)	Reference	460

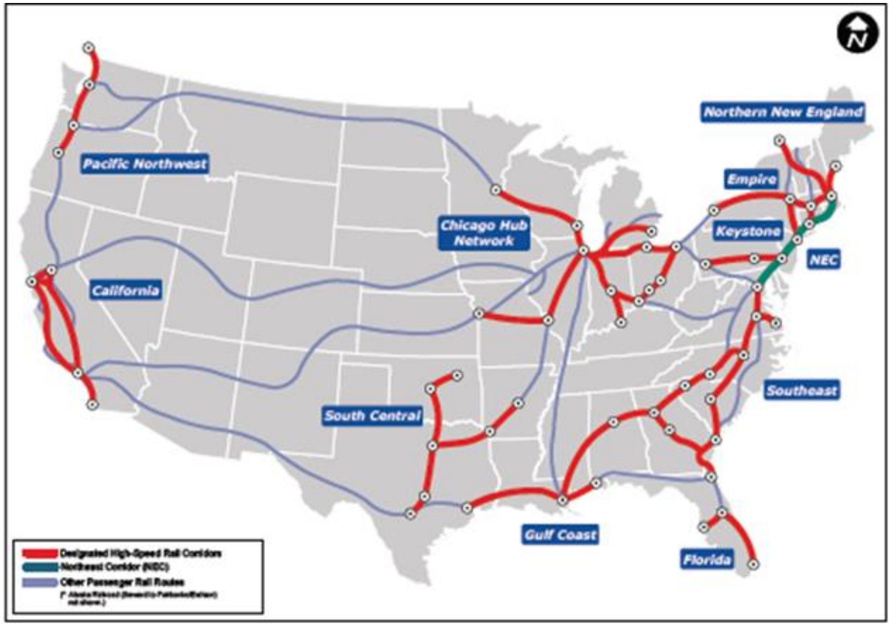


Design: High-speed rail (HSR)

Results are similar to the high-speed rail corridors designated by DOT.



Netplan Results



DOT Designations

Design: High-speed rail (HSR)

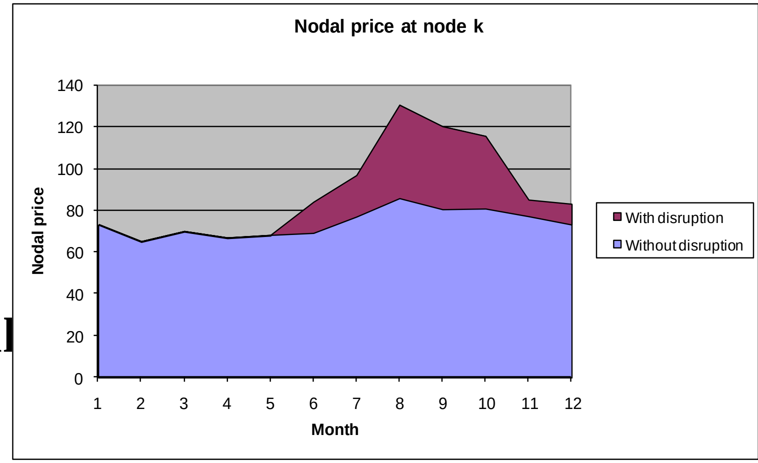
Modeling problem: Decision on LDV vehicles is not made based on long-distance travel alone.

➔So fix m_{LDV}% of travel miles to be optimized over LDVs choices only, where 100% indicates 2009LDV mode share.

Scenarios (Base: RF_CAP2.0)			*HSR pen.*	*Air pen.*	*LDV pen.*	*Cost*	VoTT	*CO_2 Emissions (e9 short ton)*			
Name	***Eqs.(29-30)***	***m_{LDV}(%)***	*(%)*	*(%)*	*(%)*	*(T$)*	(T$)	Total	Passenger	Power	Freight
Base	*No*	-	30.5	63.86	5.64	11.15	5.87	25.1	2.46	20.7	1.94
S1	*Yes*	*100*	11.2	14.8	74	12.86	8.91	30.7	4.5	24.2	1.94
S2	*Yes*	*50*	21.6	12.4	66	12.13	7.47	29.4	2.71	24.7	1.94
S3	*Yes*	*25*	38.1	18.7	43.2	11.85	6.90	28.8	1.9	25	1.94

Resilience

<u>Resilience</u>: Ability to minimize & recover from event consequences of extreme events.



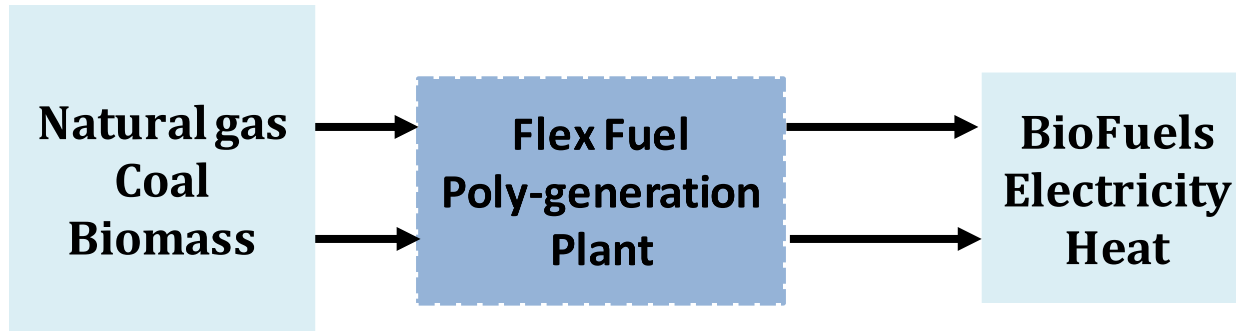
<u>Conceived Extreme Events</u>:

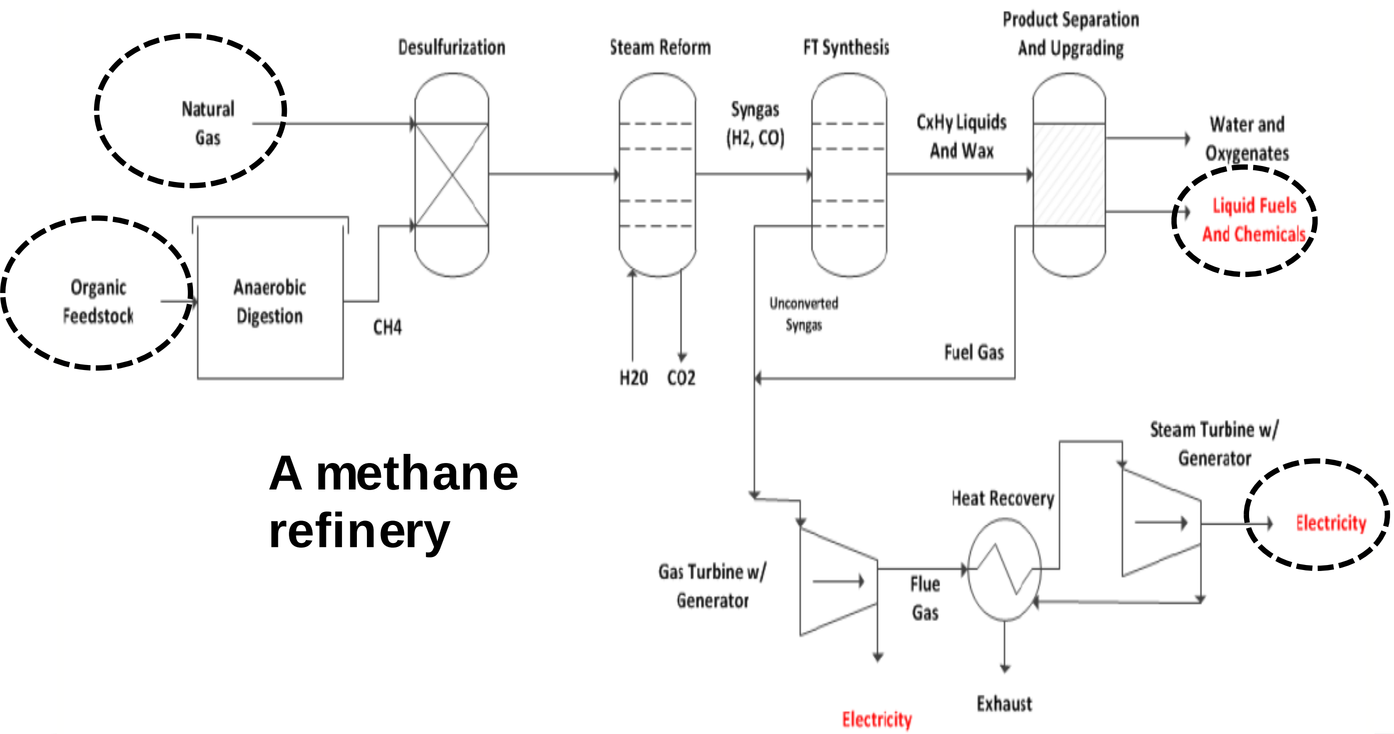
- **Rita/Katrina**
- **6 mnth loss of rail access to Powder River Basin coal**
- **1 yr interruption of 90% of Middle East oil;**
- **Permanent loss of U.S. nuclear supply;**
- **6 mnth interruption of Canadian gas supply;**
- **1 yr loss of US hydro due to extreme drought;**
- **Sustained flooding in Midwest destroying crops, reducing biofuels, interrupting E-W rail system.**

<u>Experiment</u>: For a 40 year investment strategy, simulate total failure of each of 14 generation technologies at year 25.
<u>Resilience metric:</u> Averaged the 1 year operational cost increase across 14 events with respect to the no-event case.

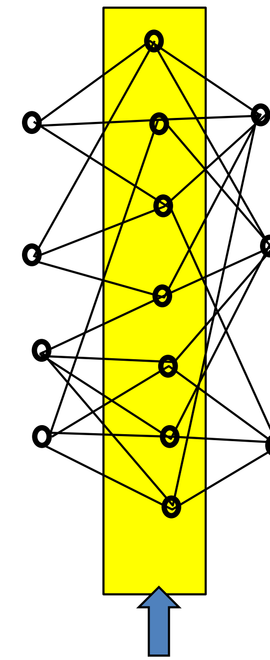
FINDINGS: RESILIENCE IMPROVES WITH
- **INTERCONNECTEDNESS**
- **DIVERSIFICATION**

Design: Flex Fuel Poly-generation





A methane refinery



Energy converters

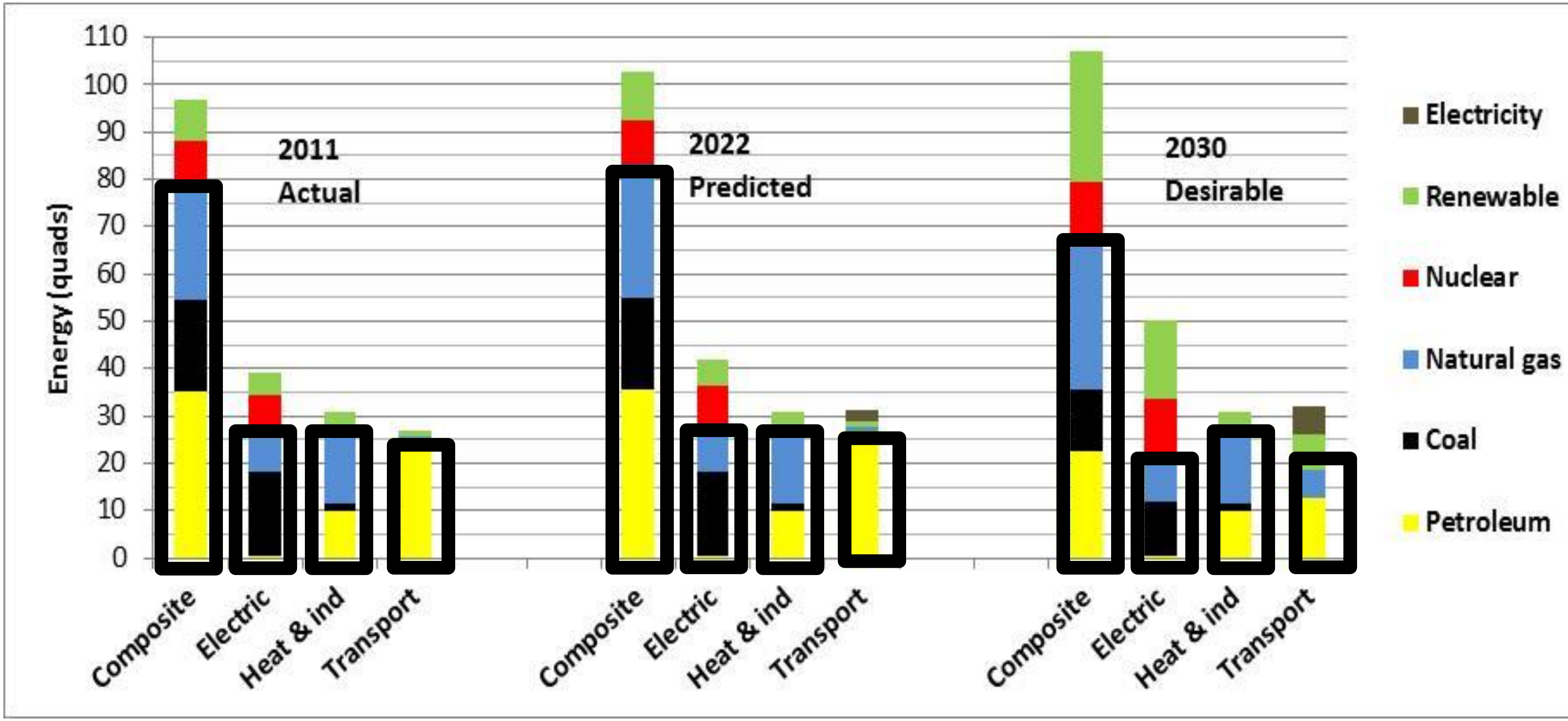
Multiple input, Multiple output: creates nodes with multiple connections, increases network density and thus system resilience.

Issues with natural gas

Lifetime: Infrastructure investments live for 40-60 years; not easy to "turn" once developed.
Depletability: R/P ratios 10-90 yrs: how volatile will price be as exports grow & as gas depletes?
Fracking: Will public resistance grow?
CO_2 emissions: Can coal-to-gas shift reduce enough?
Diversification: How will resilience for all energy sectors change? For each energy sector?

A resilience criterion: Balance portfolio in all sectors' & within each sector.

US Energy Portfolios



<u>A resilience criterion</u>: Balance portfolio in all sectors' & within each sector.

Light-duty vehicles and generation costs

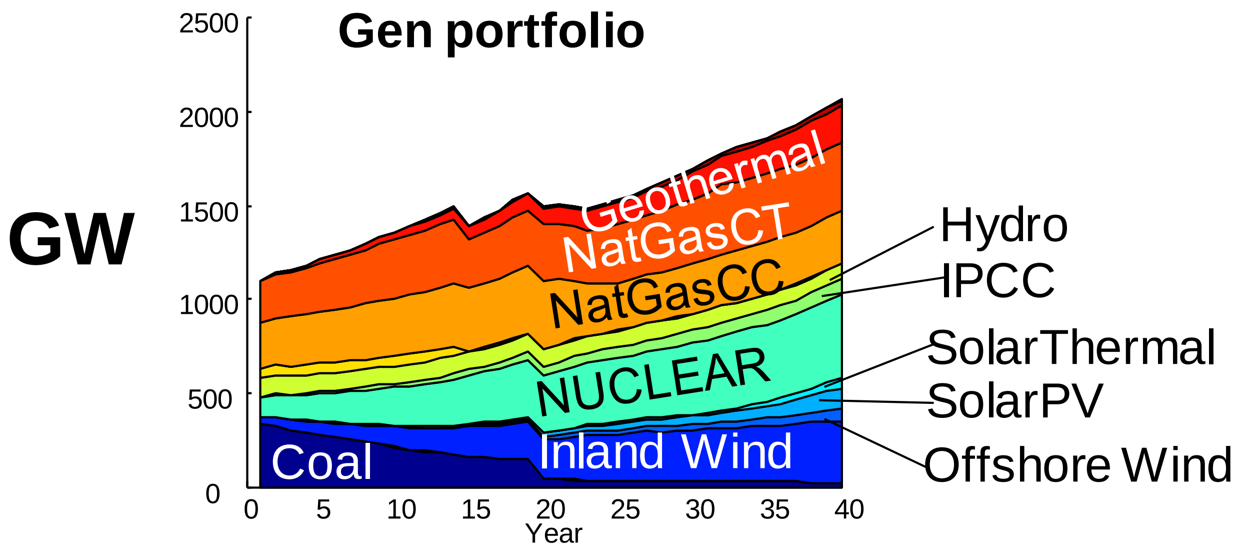
Passenger Vehicles		
	Year 1	Year 20
Gasoline	$24,000	$24,000
Conventional Hybrid	$28,000	$26,000
Plugin Hybrid,20m	$35,000	$31,000
Plugin Hybrid,40m	$41,000	$34,000
Plugin Hybrid,60m	$50,000	$36,000
Battery Elctrc,100m	$45,000	$35,000
Compressed Nat Gas	$27,000	$27,000

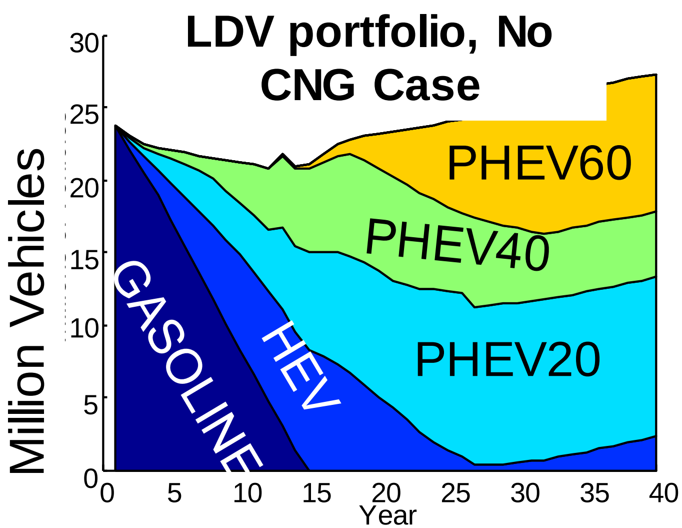
Electric generation (million$/GW)	
Coal	2844
IGCC	3221
NGCC	1003
Gas Turbine	665
Nuclear	5339
Onshore Wind	2438
Offshore Wind	5975
Oil	1655
IPCC	3311
Solar PV	4755
Solar Thermal	4692
Geothermal	4141
Tidal Power	18286
Oceanic Thermal	6163

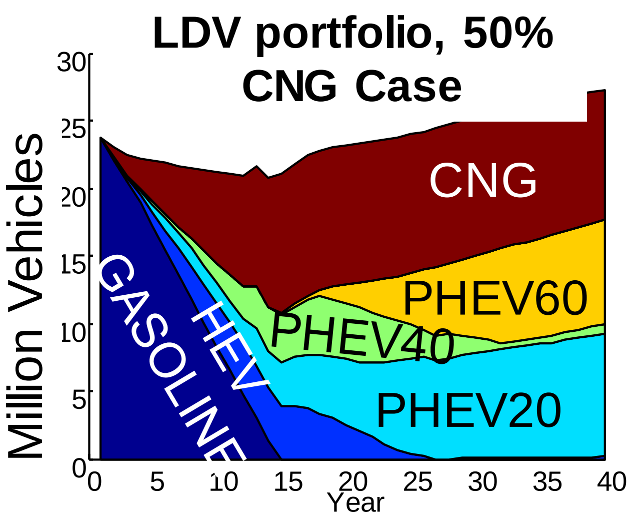
Gasoline $3.80/Gallon
Natural gas $3/MMBTU

Both increase 1.25%/year

Design: natural gas (NG) & light-duty vehicles (LDV)







➔Total 40 year cost is 8% less for the 50% CNG case.

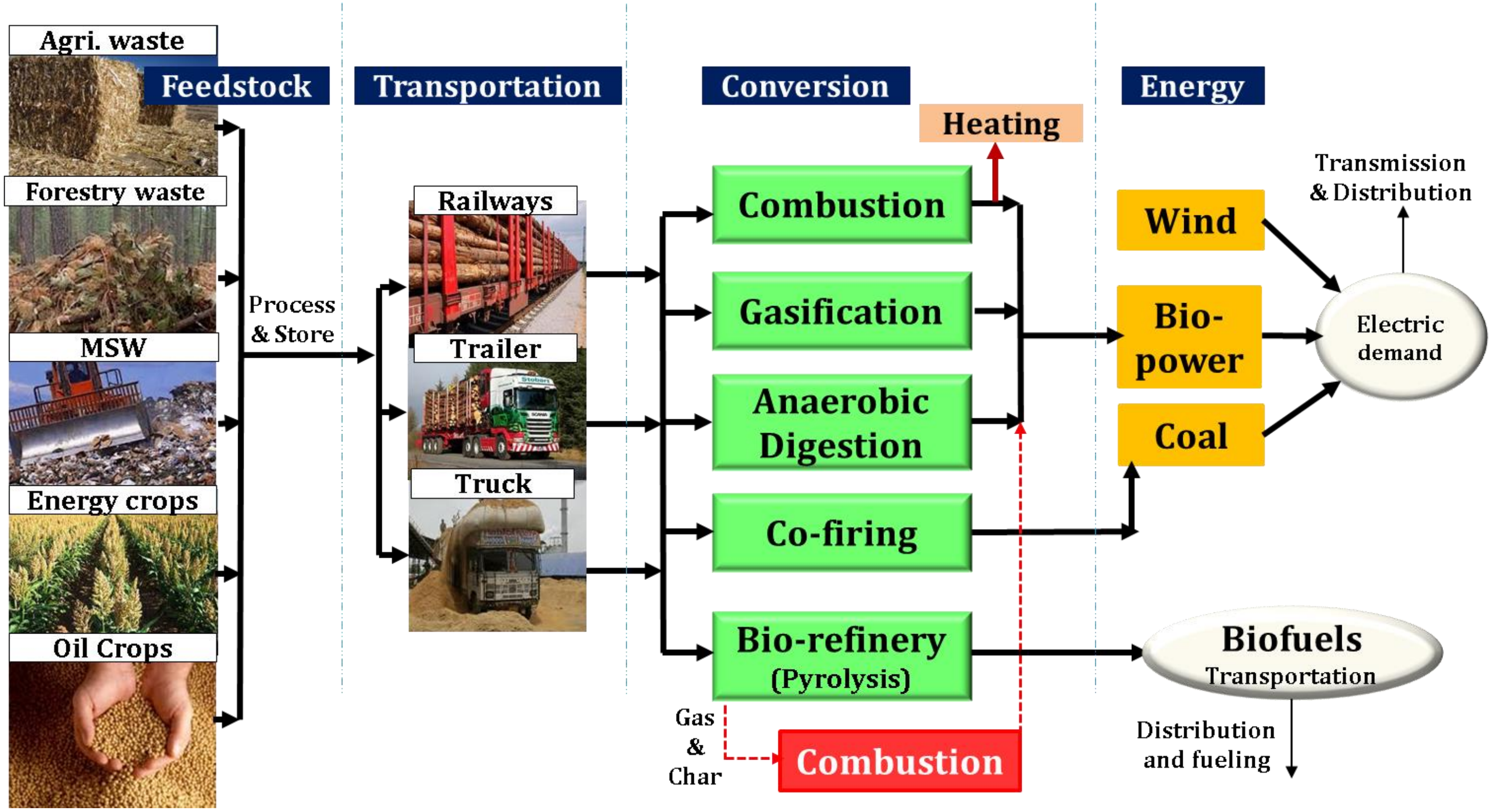
➔Total 40 year CO_2 emissions is 2% less for the CNG case.

➔We obtain desirable diversification while improving cost & emissions.

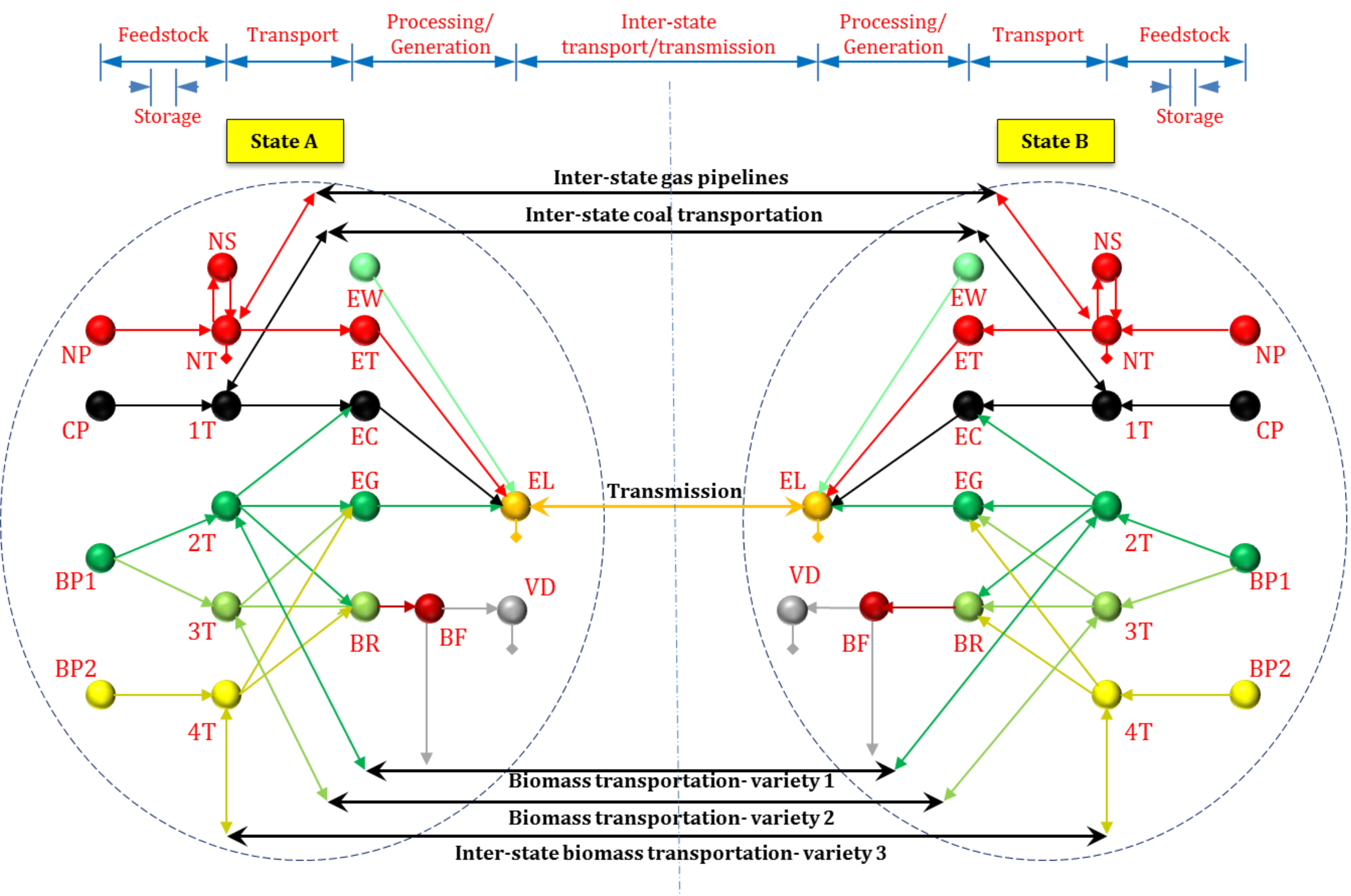
The Role of Bio-renewables in National Electric and Transportation Systems Portfolio Planning for Low Carbon Economy

Venkat Krishnan, James D. McCalley, and Robert Brown

Objective: Investigate the national scale potential of bio-renewables to compete with and complement other energy & transportation infrastructure expansion solutions, and assess the long-term impacts of the resulting portfolios in terms of cost and emissions.



Modeling of Energy System with feedstock/biomass Pathways



LEGEND

Nodes

BP1 - Forestry feedstock
BP2 - Agriculture feedstock
VD - Personal vehicle demand
EL - Electricity demand
NT - Gas demand

Arcs

Feedstock

NP-NT - Gas production
CP-1T - Coal production
BP1-2T - Biomass type 1
BP1-3T - Biomass type 2
BP2-4T - Biomass type 3
NT-NS - Gas storage
BF-VD - Bio-fuels

Transportation

NT-NT - Gas pipeline
1T-EC - Coal transportation
2T-EG - Feedstock transport
EL-EL - Electric transmission

Processing plants

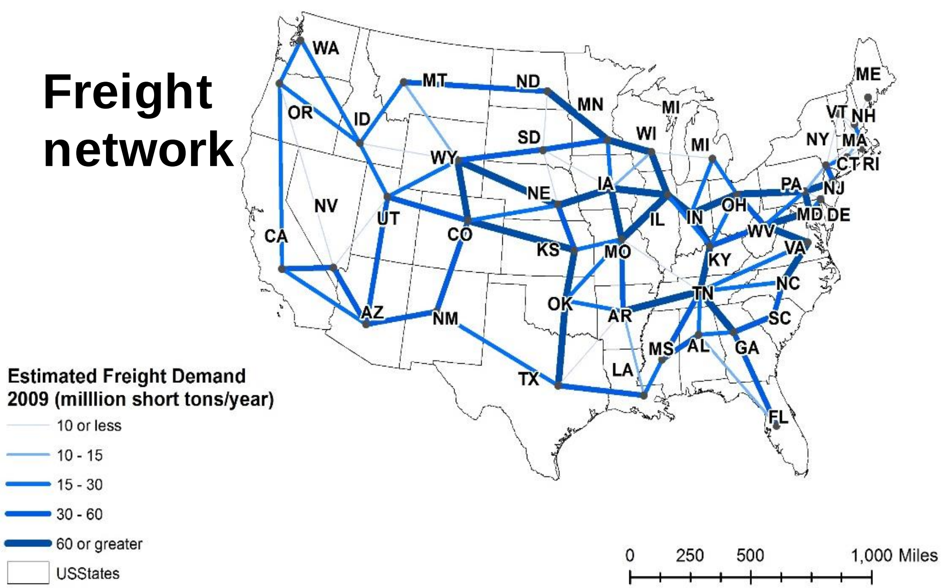
ET-EL - Gas turbine
EC-EL - Coal generation
EW-EL - Wind generation
EG-EL - Biomass gasification
BR-BF - Bio-refinery

note: Links with transportation sector not explicitly shown

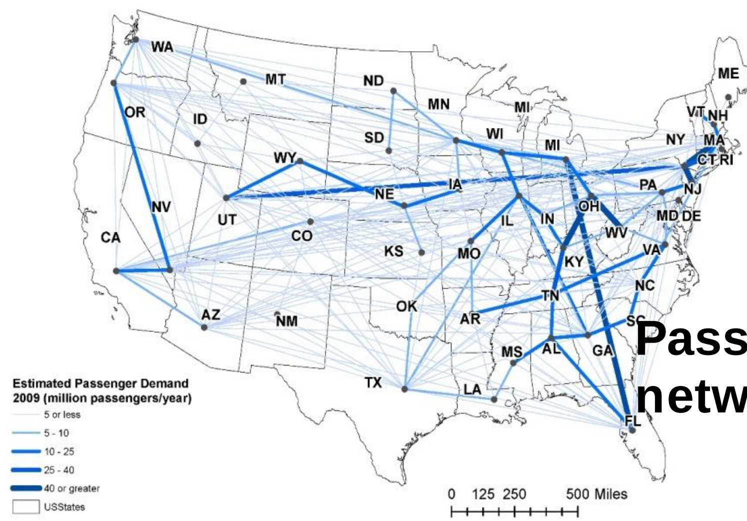
Other Features of this Study

1. This study focuses on energy, and freight and passenger transportation.
2. A key feature is in capturing the geographical variation in energy and transportation demand, resource capacities and cost, transfer capacities, and topologies of the various networks involved.
3. We accommodate different varieties of coal in each state.
4. Biomass is assumed to be zero CO_2 emitter when used in the conversion process (but emissions from processing and transporting are modeled).
5. Passenger transportation is modeled explicitly for long-distance trips but only via demand on the energy system for short-distance trips; freight transport at interstate level only.
6. The freight and passenger (long distance) network is same as in HSR study (see below).

Freight network



Passenger network



Biomass feedstock availability (MMton/yr)

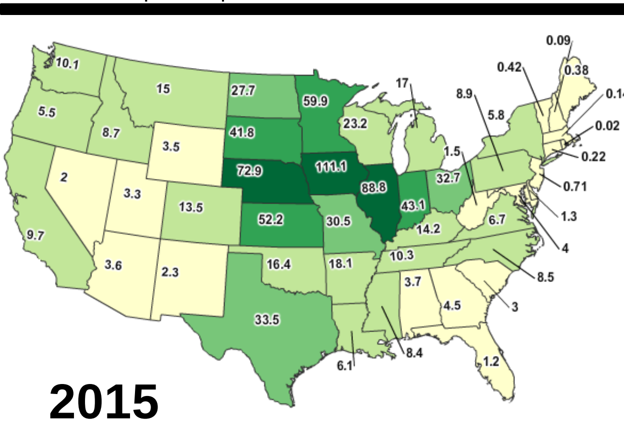
Primary Ag feedstocks: barley & barley straw, corn & corn stover, oats & oats straw, sorghum & sorghum stubble, wheat & wheat-straw, cotton, hay, rice, soybeans, annual energy crops, perennial grass, and coppice & non-coppice woody crops.

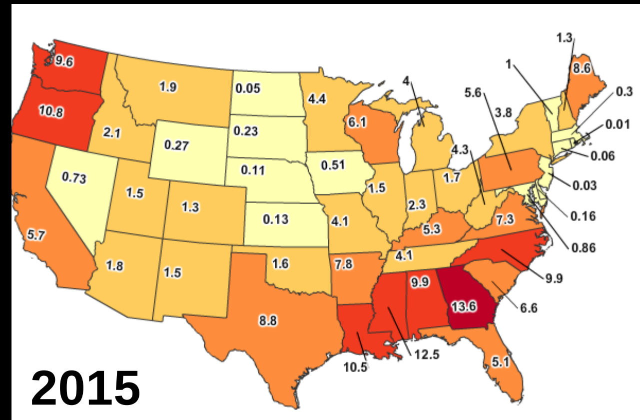
Forest feedstocks: conventional wood, logging residues, simulated thinnings from forestlands, and treatment thinnings

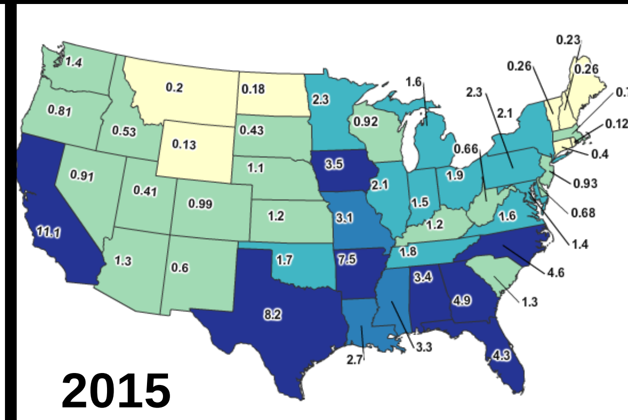
Secondary feedstocks: mill residues, urban wood wastes (construction and demolition), municipal solid waste, cotton trash & residue, animal fats and waste oils, manure, orchard & vineyard prunings, rice hulls, rice straw, sugarcane trash, and wheat dust

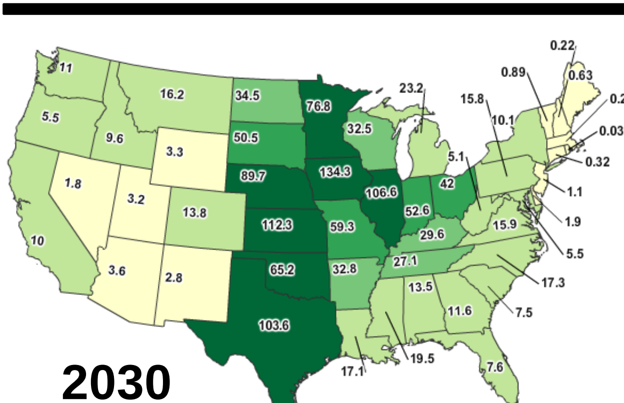
SUPPLY CURVES, IN INTERVALS OF $10

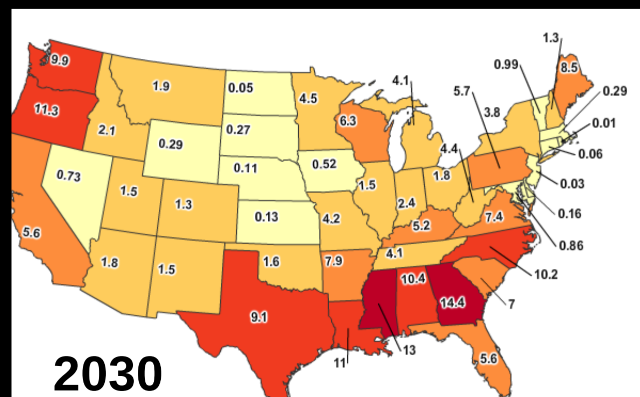
$40-$80/metric-ton	$10-$200/metric-ton	$10-$60/metric-ton

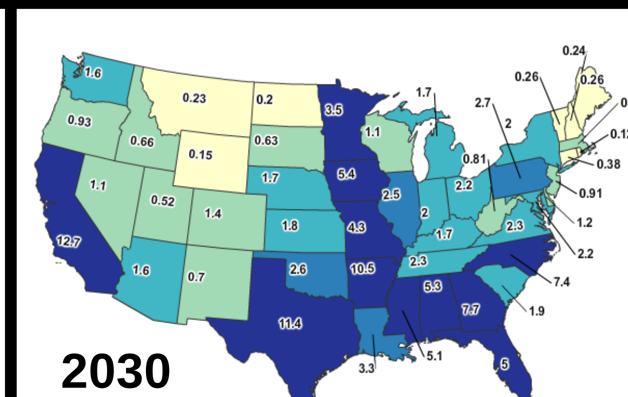












- U.S. Department of Energy, "*U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*," R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2011/224, Oak Ridge National Laboratory, Oak Ridge, TN. 227p, 2011.
- Bioenergy Knowledge Discovery Framework, US department of Energy, https://bioenergykdf.net/
- STATPLANET & STATTrends, USER GUIDE, v.3.2 May 2013, http://www.statsilk.com/software/statplanet

Study Results

1. **Reference case**
2. **CO_2 constraint:** On year 5, emissions=90% of year 5 emissions in the reference case, and thereafter, yearly emissions decrease at 2% per year till year 40.
3. **Petroleum Price Hike**: Petroleum price (only for gasoline and jet fuels) is hiked at 3% per year

Study Results

COST AND EMISSIONS FOR THREE SCENARIOS

Costs increase.
Emissions decrease.

Scenario	*Cost* (Trillion $)	*40-year CO2 Emissions (Billion short tons)* Total	Power	Freight	Passenger	Biomass network	Fuel production
Reference	34.7299	155	49.6	2.8	88.8	0.003721	13.5
CO2 constraint	35.0122	126	27.2	2.59	84.5	0.003759	12.2
CO2 constraint + petroleum price hike	40.6038	125	39	2.7	70.4	0.003853	13.2

TRANSPORTATION FUEL COMPOSITION FOR THREE SCENARIOS

Ethanol does not get used until petroleum price goes very high.

	40-year volume (MM Gallon)		
Transportation fuel	*Reference*	*CO2 constraint*	*CO2 constraint + petroleum price hike*
Ethanol	0	0	1348.1
Bio-diesel	1337.8	1354.5	37
Gasoline	6319819.9	6009633.3	4943569.1
Diesel	189819.7	175191.4	182948.7
Jetfuel	308718.3	296665.3	306655.7

LONG-DISTANCE TRAVEL PORTFOLIO FOR THREE SCENARIOS

PHEVs are the LDV of choice once we constraint CO_2.

	40-year Interstate vehicle (total trips)		
LDV (vehicles)/	*Reference*	*CO2 constraint*	*CO2 constraint + petroleum price hike*
Converntional LDVs	12233277	10820483.3	5971070.7
PHEVs	0	1412794.6	6262207.1
Air	356552625.8	327674254.2	352317819
HSR	73425183.3	98860366.1	77155062.2

Other questions to explore

- Food, water, biofuels and steam power plants:
  - Water withdrawal=41/39% agrcltre/power; consumption=85/3%. How to utilize our limited land / water resources to achieve good balance between energy production & human consumption?
- Passenger transportation and energy:
  - What is the best technology portfolio (ICE, PHEV, CNG, metro-rail, high-speed rail) & fuel portfolio (petroleum, electric, natural gas, and biofuels) for future passenger transportation systems?
- Freight transportation and energy:
  - How should location of electric resources, NG pipelines, & electric transmission be balanced with cost & benefits of transporting fuels?
  - Are there attractive combinations of geographic relocation for energy-intensive industries AND growth in technology / location of electric infrastructure? Could reduction in coal usage free freight transport to move products of relocated industries?

Public Education and Policy

*2006 survey:

What is the impact of nuclear power plants on CO_2 emissions?

80% got it wrong

**2008 survey:

Which costs more today: electricity from wind turbines or electricity from coal-fired plants?

82% said coal

#2009 survey (women):

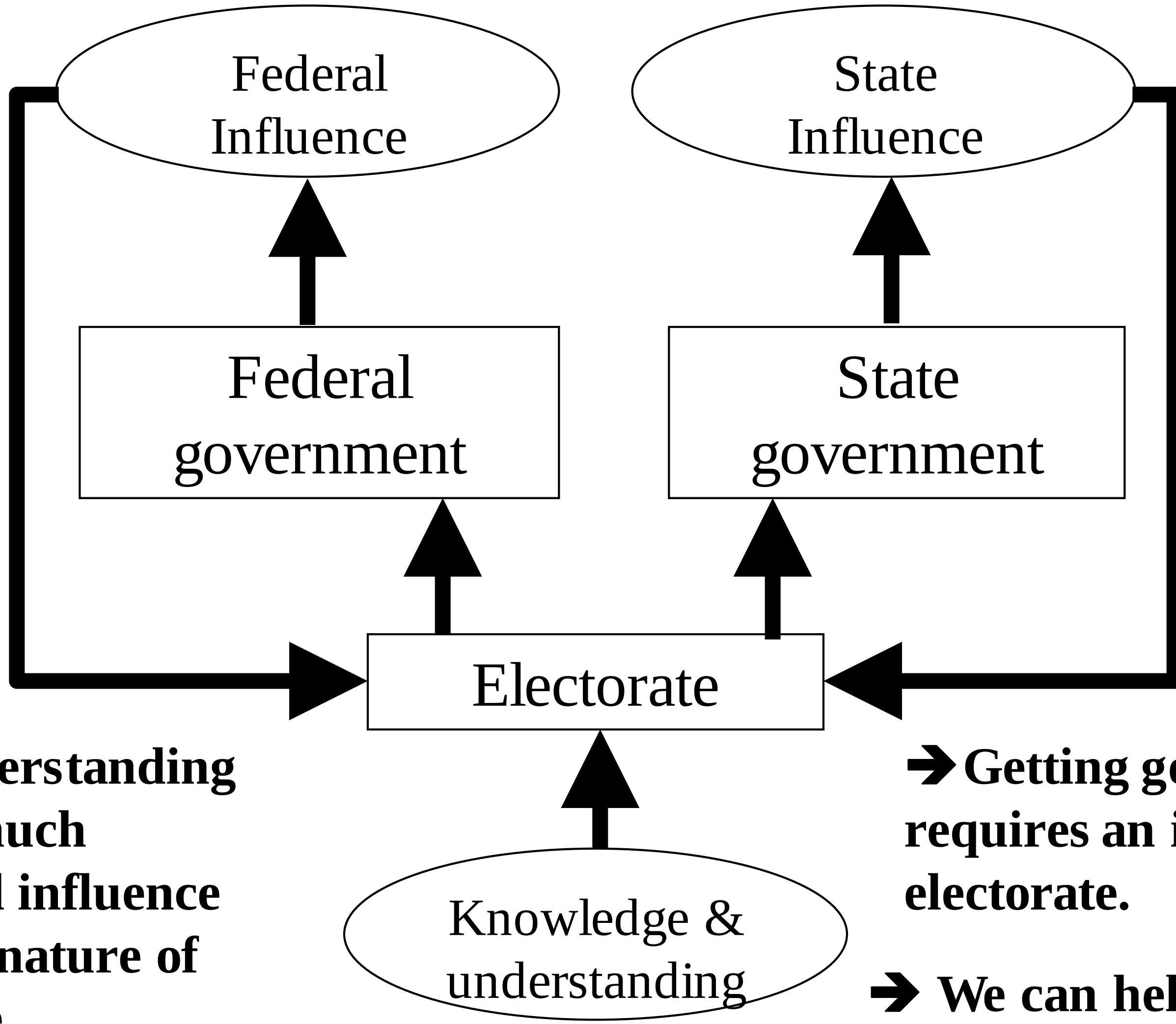
67% identify coal power plants as a big cause or somewhat of a cause of global warming, 54% think the same about nuclear energy; 43% don't know that coal is the largest source of US electricity.

##2003, 2007 survey:

For both survey years, "People see alternative fuels (hydro, solar, wind) as cheap and conventional fuels as expensive."

*T. Curry, et al., "A survey of public attitudes towards climate change and climate change mitigation technologies in the United States: Analyses of 2006 Results," Publication LFEE 2007-01-WP, MIT Laboratory for Energy and the Environment.
#M. D;Estries, "Survey: Women fail on energy knowledge," July 3, 2009, report on a survey commissioned by Women Impacting Public Policy and Women's Council on Energy and the Environment.
**H. Klick and E. Smith, "Public understanding of and support for wind power in the United States,"Renewable Energy, Vol. 35, July 2010, pp. 1585-1591.
S. Ansolabehere, "Public attitudes toward America's energy options," MIT-NES-TR-008, June 2007.

Public Education and Policy

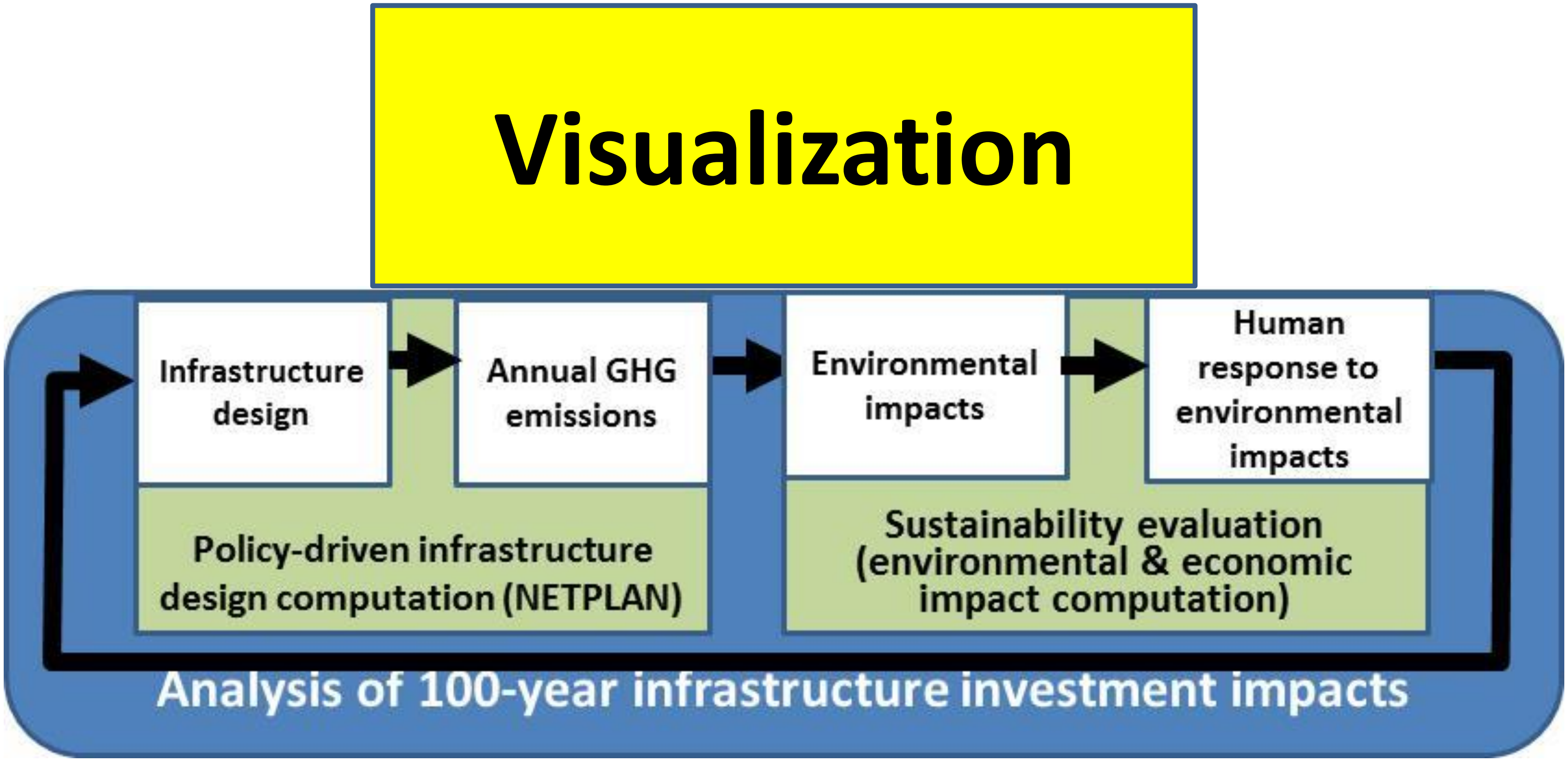


➔ **Public understanding affects how much governmental influence occurs & the nature of that influence.**

➔ **Getting good policy requires an informed electorate.**

➔ **We can help electorate (& policy-makers) see the impact on their lives of various infrastructure designs.**

Developing and communicating sustainable infrastructure pathways



Intent is that this system would be publicly available via internet.

Concluding comment

There is need to centrally ***design***, at the continental level, interdependent infrastructure systems. This need is driven by 3 attributes of these infrastructure systems:

- Economies of scale (still) motivate centralized designs to avoid inefficient infrastructure investment (III);
- Interdependencies are numerous; building it without representing them leads to III.
- Infrastructure lives for 50 years or more, and climate impacts take decades to turn;

  ➔free markets appear too short-term to adequately respond to these issues, and the consequences of getting it wrong are potentially severe.

Computational models are our means of developing, testing, and assessing our designs.