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

James McCalley
Harpole Professor of Electrical & Computer Engineering
Iowa State University
PSERC Webinar, June 7, 2011

A project funded by the US NSF via the 2008 Solicitation for Emerging Frontiers in Research & Innovation - Resilient and Sustainable Infrastructures (EFRI-RESIN)
Acknowledgement to
NETSCORE21 Faculty & Students

Dionysios Aliprantis, EE
Robert Brown, ME
Nadia Gkritza, CE
Jim McCalley, EE
Arun Somani, CpE
Lizhi Wang, IE

Di Wu, EE
Josh Gifford, ME
Catherine Rentziou, CE
Lizbeth Gonzales, EE
Yang Gu, EE
Eduardo Ibanez, EE
Jose Villarrel, EE
Diego Mejia, EE
Jinxu Ding, CpE
Zhaoyang Duan, IE
Ying Zhou, IE

Joseph Slegers, EE
Steve Lavrenz, CE
Keith Johnson, EE
McNair Scholar
Jeff Brown Business
Qi Qihui, EE
Eirini Kastrouni, CE
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

Investment biases: minimum investments, subsidies, emission limits

LP-Cost Minimization

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

Sustainability Metrics

Resiliency Metrics

NSGA-II: Search & selection

Evaluation (fitness functions)
Electric can be modeled with DC power flow

Energy loads commodity transport system

LP-Cost Minimization
Selects investments, time, location over 40 years for nation’s energy & transportation systems
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

\[
\begin{align*}
\text{min} & \quad \{ \text{CostOp}^E + \text{CostInv}^E + \text{CostOp}^T + \text{CostFleetInv}^T + \text{CostInfInv}^T \} \\
\text{subject to:} & \\
\text{Meet energy demand at the appropriate nodes} & \\
\sum_i \eta_{i,j}(t)c_{i,j}(t) - \sum_i c_{i,j}(t) - d_k^E(t) + d_k^PT(t) & = 0, \quad j \in N_k^E, \quad k \in N_k^E \\
\text{DC power flow equations} & \\
c_i(t) - c_j(t) & = b_{i,j}(t)(\theta_i(t) - \theta_j(t)) f_{k}(t), \quad (i,j) \in A^E_{DC}, \quad (i,j) \in A^E_{DC} \\
\text{Generation capacity must cover peak demand at electric nodes} & \\
\sum_i c_i(t) &= \text{peak} D_k^E(t), \quad j \in N_k^E \\
\text{Transportation demand for non-energy commodities} & \\
\sum_m f_{i,j,k,m}(t) & = d_k^F(t), \quad k \in K \setminus K_e \\
\text{Transportation demand for energy commodities} & \\
\sum_m f_{i,j,k,m}(t) & = \text{heatContent}^{-1}_k(t) \cdot c_{i,j}(t) \cdot e^F(t), \quad k \in K_e \\
\text{Fleet upper bound for transportation flows} & \\
\sum_k f_{i,j,k,m}(t) & \leq \text{FleetCap}_{i,j}(t) \cdot \Delta(t) \\
\text{Infrastructure upper bound for transportation flows} & \\
\sum_k \sum_m f_{i,j,k,m}(t) & \leq \text{InfCap}_{i,j}(t) \cdot \Delta(t) \\
\text{Decision variables:} & \\
\text{Energy flows:} & \quad 0 \leq b_{i,j}(t) \leq c_{i,j}(t) \leq \text{Cap}_{i,j}(t) \cdot \Delta(t) \\
\text{Energy capacity inv.:} & \quad \text{Inf}_{i,j}(t) \leq \text{Cap}_{i,j}(t) \cdot \Delta(t) \leq \text{ub Inf}_{i,j}(t) \\
\text{Transportation flows:} & \quad f_{i,j,k,m}(t) \geq 0 \\
\text{Fleet inv.:} & \quad \text{lb Fleet}_{i,j,k,m}(t) \leq \text{Fleet}_{i,j,k,m}(t) \leq \text{ub Fleet}_{i,j,k,m}(t) \\
\text{Infrastructure inv.:} & \quad \text{Inf}_{i,j}(t) \leq \text{Inf}_{i,j}(t) \leq \text{ub Inf}_{i,j}(t) \\
\text{Phase angles:} & \quad -\pi \leq \theta_{i,j}(t) \leq \pi 
\end{align*}
\]
Compact notation and decomposition

\[
\begin{align*}
\text{min} \quad & \begin{bmatrix} \text{CostInv}^T & \text{CostOp}_1^T & \text{CostOp}_2^T & \ldots \end{bmatrix} \begin{bmatrix} \text{capInv} \\ \text{flows}_1 \\ \text{flows}_2 \\ \vdots \end{bmatrix} \\
\text{subject to:} \\
\begin{bmatrix} C_0 & 0 & 0 & \ldots \\ C_1 & D_1 & 0 & \ldots \\ C_2 & 0 & D_2 & \ldots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix} & \begin{bmatrix} \text{capInv} \\ \text{flows}_1 \\ \text{flows}_2 \\ \vdots \end{bmatrix} \leq \begin{bmatrix} b_0 \\ b_1 \\ b_2 \\ \vdots \end{bmatrix}
\end{align*}
\]

\[
\begin{align*}
\text{min} \quad & \text{CostInv}^T \cdot \text{capInv} + z_1 + z_2 \ldots \\
\text{subject to:} \\
C_0 \cdot \text{capInv} & \leq b_0
\end{align*}
\]

\[
\begin{align*}
\text{min} \quad & \zeta_i = \text{CostOp}_i^T \cdot \text{flows}_i \\
\text{subject to:} \\
C_i \cdot \text{flows}_i & \leq b_i - D_i \cdot \text{capInv}^*
\end{align*}
\]
Transportation system loading on energy

Every mode of transportation produces a demand in the energy networks

Meet energy demand at the appropriate nodes

\[ \sum_i \eta_{i,j}(t)e_{i,j}(t) - \sum_i e_{j,i}(t) = d^E_j(t) + d^{ET}_j(t) \quad j \in N^E_d \]

\[ d^{ET}_j(t) = \sum_{(a,b) \in A^T_j} \sum_{m \in M_j} fuelCons_{(a,b,m)}(t) \sum_k f_{(a,b,k,m)}(t) \]

\[
\text{MWHR} = \frac{\text{MWHR/TON}}{\text{TON}}
\]
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.

\[
\sum_{m} f_{(i,j,k,m)}(t) = heatContent_{k}^{-1}(t) e_{(n_{E}^{(i,k)},n_{E}^{(j,k)})}(t), \quad k \in \mathcal{K}_{e}
\]

\[
\text{TONS} = \frac{\text{TONS}}{\text{MWHR}} \times \text{MWHR}
\]
Summary of networks represented in cost-minimization problem

<table>
<thead>
<tr>
<th>Network</th>
<th>Flow</th>
<th>Commodities</th>
<th>Units</th>
<th>Infrast.</th>
<th>Fleet</th>
<th>Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>Single comm.</td>
<td>Electric</td>
<td>MWh</td>
<td>Electric</td>
<td>N/A</td>
<td>Nodes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Natural gas</td>
<td></td>
<td>Pipeline</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>H₂, NH₃</td>
<td></td>
<td>Pipeline</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Petroleum</td>
<td></td>
<td>Pipeline</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>Multicomm.</td>
<td>Bituminous</td>
<td>Tons</td>
<td>Rail</td>
<td>Diesel, elect.</td>
<td>Nodes</td>
</tr>
<tr>
<td>(coal)</td>
<td></td>
<td>Subbitmns</td>
<td></td>
<td>Barge</td>
<td>Diesel</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lignite</td>
<td></td>
<td>Highway</td>
<td>Diesel, hybrid</td>
<td></td>
</tr>
<tr>
<td>Freight</td>
<td>Multicomm.</td>
<td>Grains</td>
<td>Tons</td>
<td>Rail</td>
<td>Diesel, elect.</td>
<td>Arcs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chemicals</td>
<td></td>
<td>Barge</td>
<td>Diesel</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gravel, etc.</td>
<td></td>
<td>Highway</td>
<td>Diesel, hybrid</td>
<td></td>
</tr>
<tr>
<td>Passenger</td>
<td>Multicomm.</td>
<td>50 mph</td>
<td></td>
<td>Highway</td>
<td>Gasoline, elect.</td>
<td>Arcs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100 mph</td>
<td></td>
<td>Rail</td>
<td>Diesel, elect.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>200 mph</td>
<td></td>
<td>Rail</td>
<td>Electric</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>500 mph</td>
<td>People or vehicles</td>
<td>Air</td>
<td>Petroleum</td>
<td></td>
</tr>
</tbody>
</table>

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](http://github.com/eibanez/NETPLAN) (but no support)
US data set

EIA “Coal Transportation: Rates & Trends”

EIA Forms 7A, 176, 191, 857, 895
MSHA Form 7000-2
FERC Forms 423, 549B, 580
DOE, NMA
DOT/FHWA/BTS, FRA/AAR, OFE, API

DOE/EIA
EPA (eGRID)

DOE/EIA Form 767, 860, 906
FERC Form 423
ISOs

NEBC
DOE/OFP
ISOs

FERC Form 715
EIA Form 412
NERC, ISOs

Commodity Flow Survey

Transportation energy data book

Emissions

Electric Power Generation

Import/Export

Transmission

End Use

DOE
EIA Form 826, 861
FERC Form 714
NERC, ISOs
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 NOx (kg/MWh)
- Fuel Use SOx (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 (%)
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.

**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**
- 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.

Petroleum source

- Diesel $3.80/gal
- Gasoline $4.00/gal
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

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

- 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

- 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.

<table>
<thead>
<tr>
<th>Region</th>
<th>Wind</th>
<th>Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECAR</td>
<td>0.3</td>
<td>0.15</td>
</tr>
<tr>
<td>ERCOT</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>MAAC</td>
<td>0.3</td>
<td>0.15</td>
</tr>
<tr>
<td>MAIN</td>
<td>0.5</td>
<td>0.15</td>
</tr>
<tr>
<td>MAPP</td>
<td>0.5</td>
<td>0.15</td>
</tr>
<tr>
<td>NY</td>
<td>0.3</td>
<td>0.15</td>
</tr>
<tr>
<td>NE</td>
<td>0.3</td>
<td>0.15</td>
</tr>
<tr>
<td>FL</td>
<td>0.3</td>
<td>0.22</td>
</tr>
<tr>
<td>STV</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>SPP</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>NWP</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>RA</td>
<td>0.2</td>
<td>0.25</td>
</tr>
<tr>
<td>CNV</td>
<td>0.3</td>
<td>0.22</td>
</tr>
</tbody>
</table>
Min cost solution

Freight transport (millions tons)

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

Passenger transport (vehicles)

With a doubling of gasoline prices, PHEV purchases dominate.
Min cost solution

Coal production (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

Prices become more spatially uniform as most economic resources are utilized in each region.
Min cost solution
Energy production for different emissions reductions

0% reduction  20% reduction  40% reduction

Energy generated shifts from PC & IGCC to geothermal, wind (on+off-shore).
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.

- 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.

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.
Resilience Assessment

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

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

---

**Extreme Events:** Simulate total failure of each of 14 major technologies at year 25. Societyal consequences: Average the
- one year national operational cost increase
- across all 14 events with respect to the no-event case.
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 from NSGA-II

<table>
<thead>
<tr>
<th>S. No</th>
<th>Cost (MS)</th>
<th>EmCO₂ (Short ton)</th>
<th>Resiliency (MS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.37E+06</td>
<td>5.32E+10</td>
<td>3.37E+05</td>
</tr>
<tr>
<td>2</td>
<td>4.38E+06</td>
<td>5.27E+10</td>
<td>3.20E+05</td>
</tr>
<tr>
<td>3</td>
<td>4.43E+06</td>
<td>5.25E+10</td>
<td>3.62E+05</td>
</tr>
<tr>
<td>4</td>
<td>5.11E+06</td>
<td>5.07E+10</td>
<td>1.34E+04</td>
</tr>
<tr>
<td>5</td>
<td>5.13E+06</td>
<td>5.12E+10</td>
<td>1.33E+04</td>
</tr>
<tr>
<td>6</td>
<td>5.18E+06</td>
<td>5.02E+10</td>
<td>1.37E+04</td>
</tr>
<tr>
<td>7</td>
<td>5.24E+06</td>
<td>5.05E+10</td>
<td>1.27E+04</td>
</tr>
<tr>
<td>8</td>
<td>5.37E+06</td>
<td>4.91E+10</td>
<td>1.16E+04</td>
</tr>
<tr>
<td>9</td>
<td>5.56E+06</td>
<td>4.84E+10</td>
<td>1.08E+04</td>
</tr>
<tr>
<td>10</td>
<td>5.63E+06</td>
<td>4.79E+10</td>
<td>9.86E+03</td>
</tr>
<tr>
<td>11</td>
<td>5.93E+06</td>
<td>4.61E+10</td>
<td>8.74E+03</td>
</tr>
<tr>
<td>12</td>
<td>5.99E+06</td>
<td>4.44E+10</td>
<td>7.94E+03</td>
</tr>
<tr>
<td>13</td>
<td>6.05E+06</td>
<td>4.51E+10</td>
<td>7.33E+03</td>
</tr>
<tr>
<td>14</td>
<td>6.11E+06</td>
<td>4.42E+10</td>
<td>7.95E+03</td>
</tr>
<tr>
<td>15</td>
<td>6.17E+06</td>
<td>4.24E+10</td>
<td>7.20E+03</td>
</tr>
<tr>
<td>16</td>
<td>6.31E+06</td>
<td>4.31E+10</td>
<td>6.42E+03</td>
</tr>
<tr>
<td>17</td>
<td>6.37E+06</td>
<td>4.16E+10</td>
<td>6.68E+03</td>
</tr>
<tr>
<td>18</td>
<td>6.39E+06</td>
<td>3.97E+10</td>
<td>6.29E+03</td>
</tr>
<tr>
<td>19</td>
<td>6.48E+06</td>
<td>3.84E+10</td>
<td>5.95E+03</td>
</tr>
<tr>
<td>20</td>
<td>6.52E+06</td>
<td>4.03E+10</td>
<td>5.32E+03</td>
</tr>
</tbody>
</table>

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 CO$_2$ Emission for Most Resilient Solution
Yearly Generation Investment and CO$_2$ Emission for Least Resilient Solution

![Diagram showing yearly generation investment and CO$_2$ emission for least resilient solution. The graph illustrates the investment (GW) and CO$_2$ emissions (short ton) over different years, with various energy sources depicted.]
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.