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Risk reduction assessment of innovative solutions to interdependent cascading infrastructure failures

Rae Zimmerman, PhD
Research Professor and Professor Emerita of Planning and Public Administration
Director, Institute for Civil Infrastructure Systems
Wagner Graduate School of Public Service
New York University
rae.zimmerman@nyu.edu

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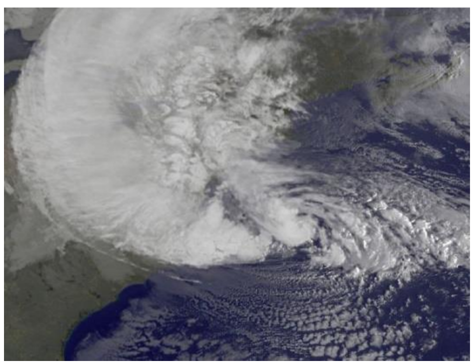
The Backdrop:
Selected Natural and Human Hazards
Affecting Infrastructure

Source: NOAA (2006) NOAA Celebrates 200 years

Source: Hollis Stambaugh and Harold Cohen (2010) Bridge Collapse and Response Minneapolis, Minnesota USFA-TR-166/August 2007. U.S. Fire Administration/Technical Report Series I-35W U.S. DHS, FEMA, U.S. Fire Administration, National Fire Programs Division.

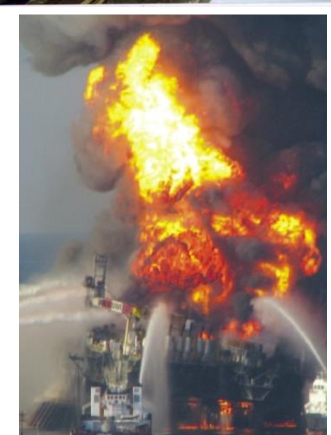


NOAA (2013) Service Assessment, Hurricane/Post Tropical Cyclone Sandy, Cover page

MTA

NOAA (2016) Service Assessment The Historic SC Floods of Oct 1-5, 2015, Photos by NWS Weather Forecast Offices and USGS, pp. 15, 22.

NYC Environmental Protection



U.S. Coast Guard photo, National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling (2011) p. 88

Infrastructure Interconnections: Attribute Summary

- Generic infrastructure interconnections “lifeline infrastructures”:
  - Electric Power – with Transportation, Water, and IT;
  - Transportation – with Water and IT;
  - Water – IT
- Specification of the direction and magnitude of flows of goods, services, and/or information among infrastructures
- Scale: Component-level connections (ranging from small parts to large multiple interrelated systems*)
- Types:
  - Temporal Interconnections
  - Physical*
  - Cyber*
  - Spatial Interconnections (geographic)*
  - Logical*
- Implications: Impact and Likelihood of Cascading Failures from Interconnections

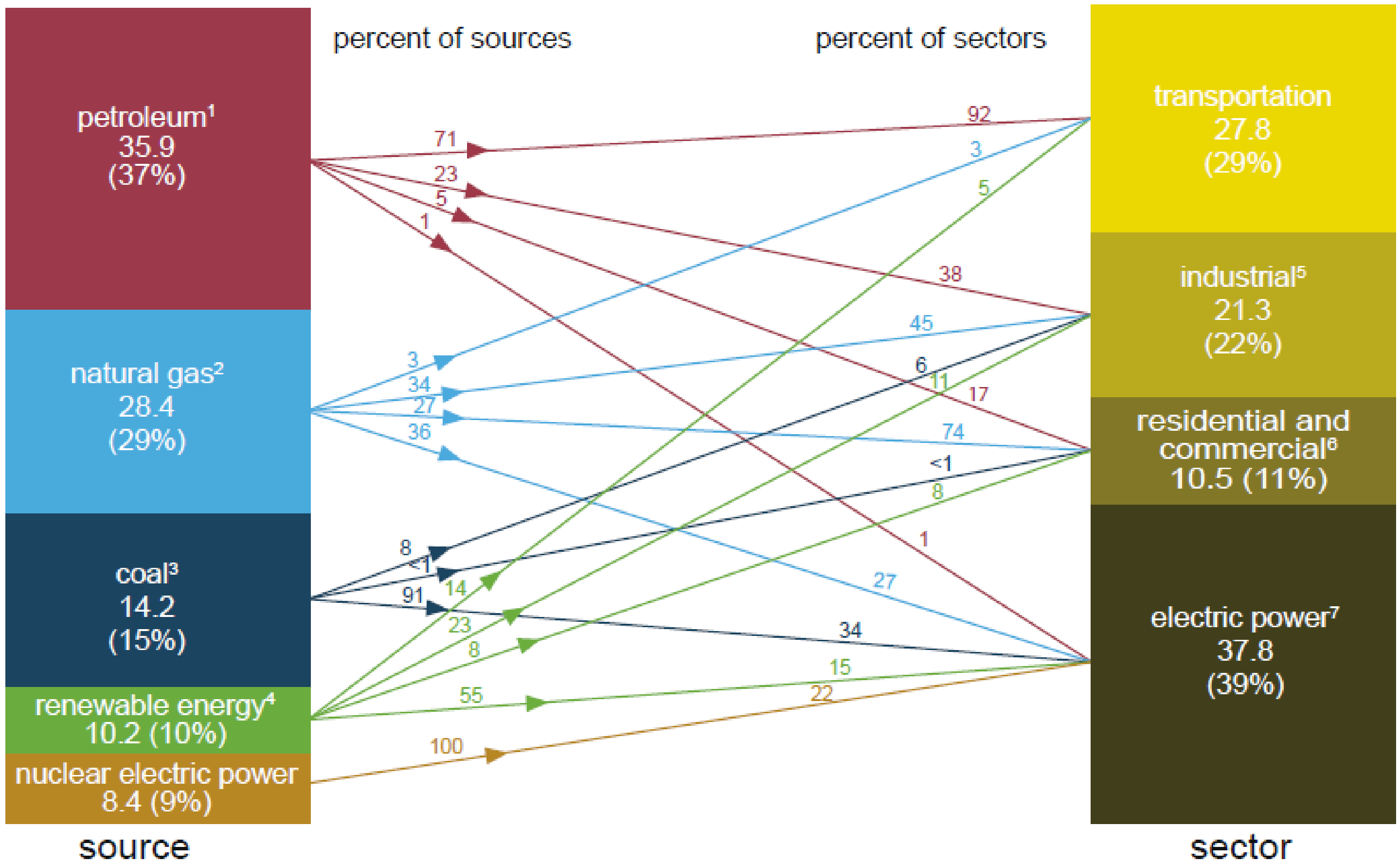
Source: C. Perrow (1984) Normal Accidents: Living with High-Risk Technologies, New York: Basic Books, pp. 89-100, and *cited in Rinaldi, Peerenboom and Kelly (2001), p. 21.

How Complex Interconnections Can Become:

Energy Sources and Connections to Other Sectors (Quadrillion Btus), U.S., 2016

U.S. primary energy consumption by source and sector, 2016

Total = 97.4 quadrillion British thermal units (Btu)



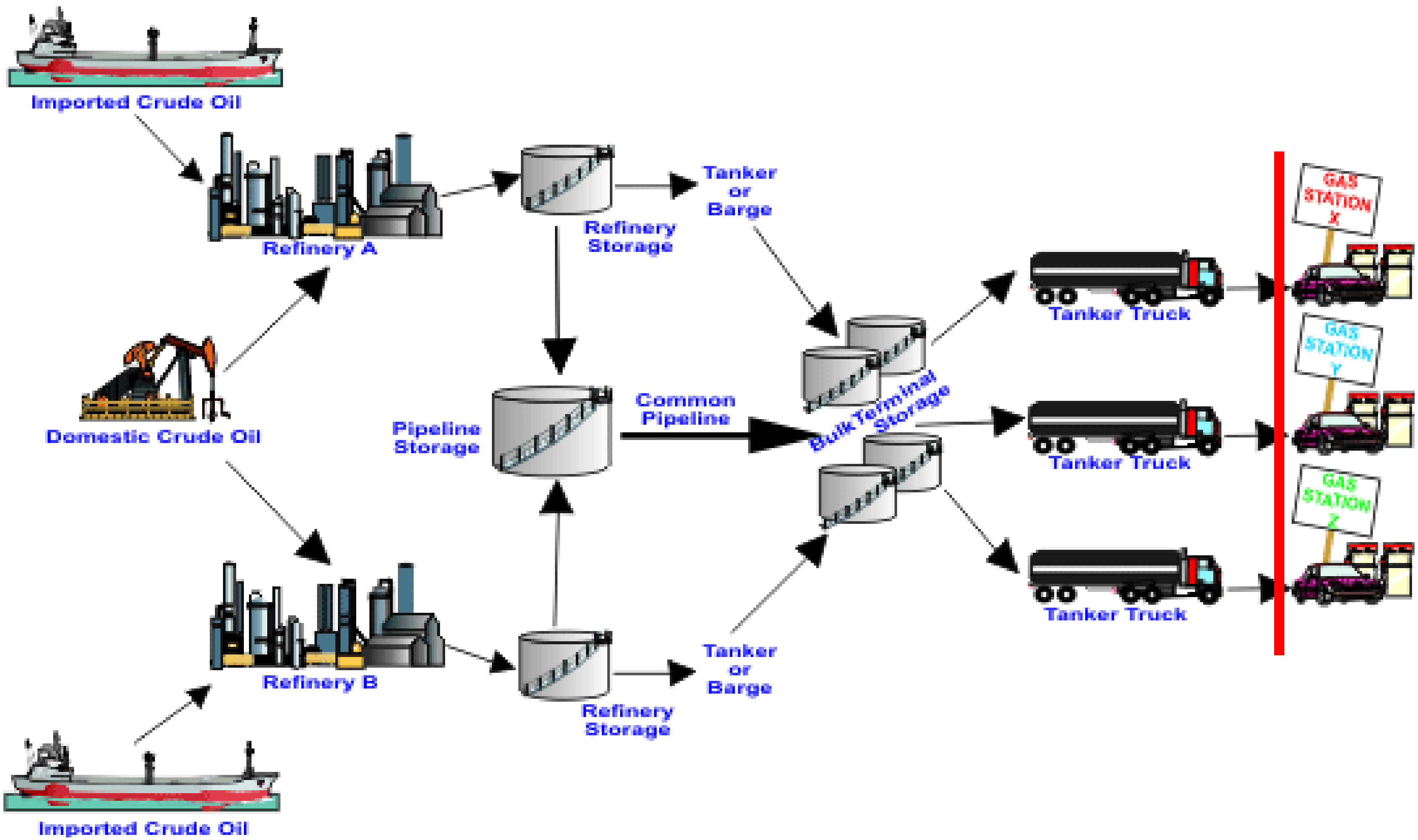
¹ Does not include biofuels that have been blended with petroleum—biofuels are included in "Renewable Energy."
² Excludes supplemental gaseous fuels.
³ Includes -0.02 quadrillion Btu of coal coke net imports.
⁴ Conventional hydroelectric power, geothermal, solar, wind, and biomass.
⁵ Includes industrial combined-heat-and-power (CHP) and industrial electricity-only plants.
⁶ Includes commercial combined-heat-and-power (CHP) and commercial electricity-only plants.
⁷ Electricity-only and combined-heat-and-power (CHP) plants whose primary business is to sell electricity, or electricity and heat, to the public. Includes 0.24 quadrillion Btu of electricity net imports not shown under "Source."

Notes: • Primary energy is energy in the form that it is accounted for in a statistical energy balance, before any transformation to secondary or tertiary forms of energy occurs (for example, coal before it is used to generate electricity). • The source total may not equal the sector total because of differences in the heat contents of total, end-use, and electric power sector consumption of natural gas. • Data are preliminary. • Values are derived from source data prior to rounding. • Sum of components may not equal total due to independent rounding.

Sources: U.S. Energy Information Administration, *Monthly Energy Review* (April 2017), Tables 1.3, 1.4a, 1.4b, and 2.1–2.6.

Source: U.S. Department of Energy, Energy Information Administration https://www.eia.gov/totalenergy/data/monthly/pdf/flow/css_2016_energy.pdf

Energy-Transportation: Supply Chain



Source: U.S. Environmental Information Administration (EIA) http://www.eia.gov/energyexplained/images/new_flow_chart.png. (Red line added to indicate disruptions during Hurricane Sandy).

Spatial Interconnectivity:
Proximity of Water Supply and Telecom and Water Drainage/Transportation

Water Tanks and Telecommunications Cell Sites

Drainage Line and Roadway Overpass

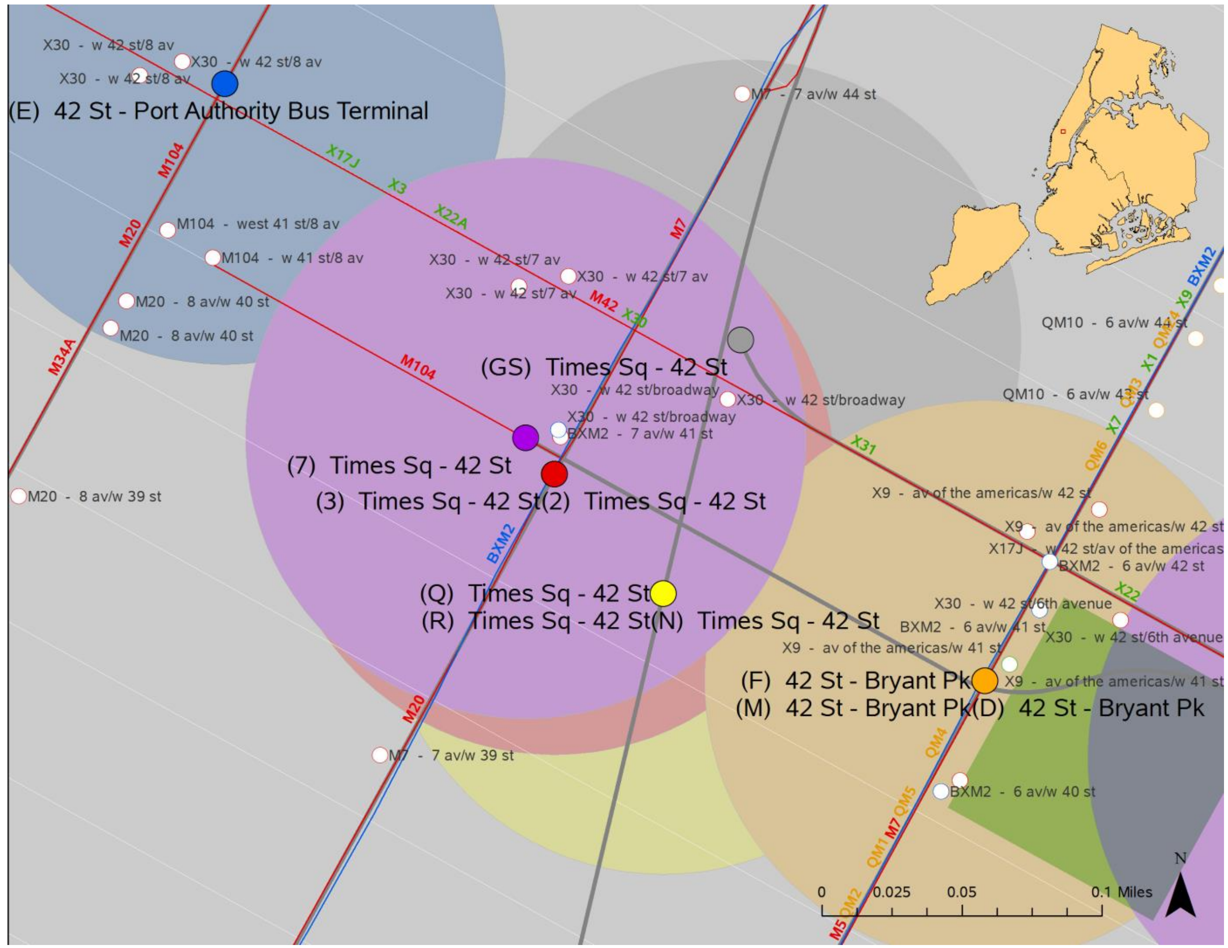
Source: Photos by Rae Zimmerman in New York City.

Functional and Spatial Interconnections: Intra-Transit Multi-Modal Bus Connections at Subway Stations, NYC

Connectivity of Subway Stations and Buses Stopping

Connectivity is important for flexible, multi-modal connections, greater access to transit, and evacuation

Number and distances of buses are defined within a 0.1 mile radius of each subway station



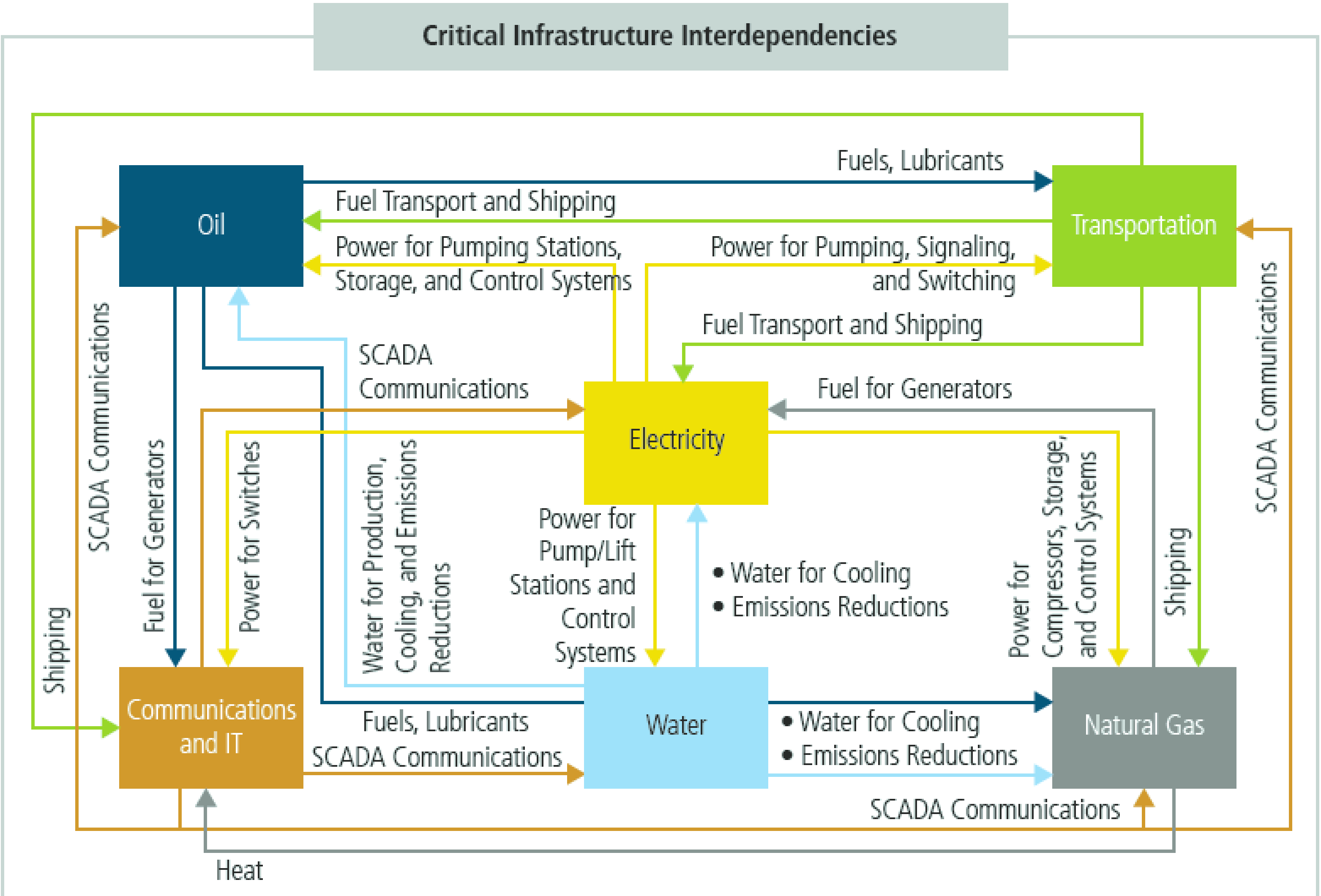
Source: R. Zimmerman, C.E. Restrepo, J. Sellers, A. Amirapu, and Theodore R. Pearson (2014) "Promoting Transportation Flexibility in Extreme Events through Multi-Modal Connectivity," U.S. Department of Transportation Region II Urban Transportation Research Center, New York, NY: NYU-Wagner, June. Final report available at: http://www.utrc2.org/sites/default/files/pubs/Final-NYU-Extreme-Events-Research-Report.pdf

Collision Points: Infrastructure Interdependencies and Accidents - Electric Power and Transit Interconnections

- 2003 northeast U.S. and Canada blackout: Transit rail (electrified) took about 1.3 times and traffic signals 2.6 times as long to be restored relative to electric power restoration.[1]
- The Metro-North railway outage: Large power line impairment lasted over a week.[2]
- September 29, 2011 Lightening Strike on a LIRR Computer:[3] Highly centralized network (most trains go through Jamaica station), high volume of traffic (81 million annually), few rail alternative; Multiple failures at the same time increased consequences dramatically - lightening strike disables trains west of Jamaica, programming error, third rail shut, 17 stranded trains, 9 standing trains. Opportunities for Intervention: More communication, computer training, securing facilities from natural hazards, travel alternatives
- Transformer explosions impairing transit: July 29, 2001 (NYC); power outages caused closures of San Francisco Bay Area and Chicago transit lines.[4]
- December 19, 2009: Eurostar trains were halted between London, Paris and Brussels from an electrical problem related to a water problem due to temperature differentials.[5]

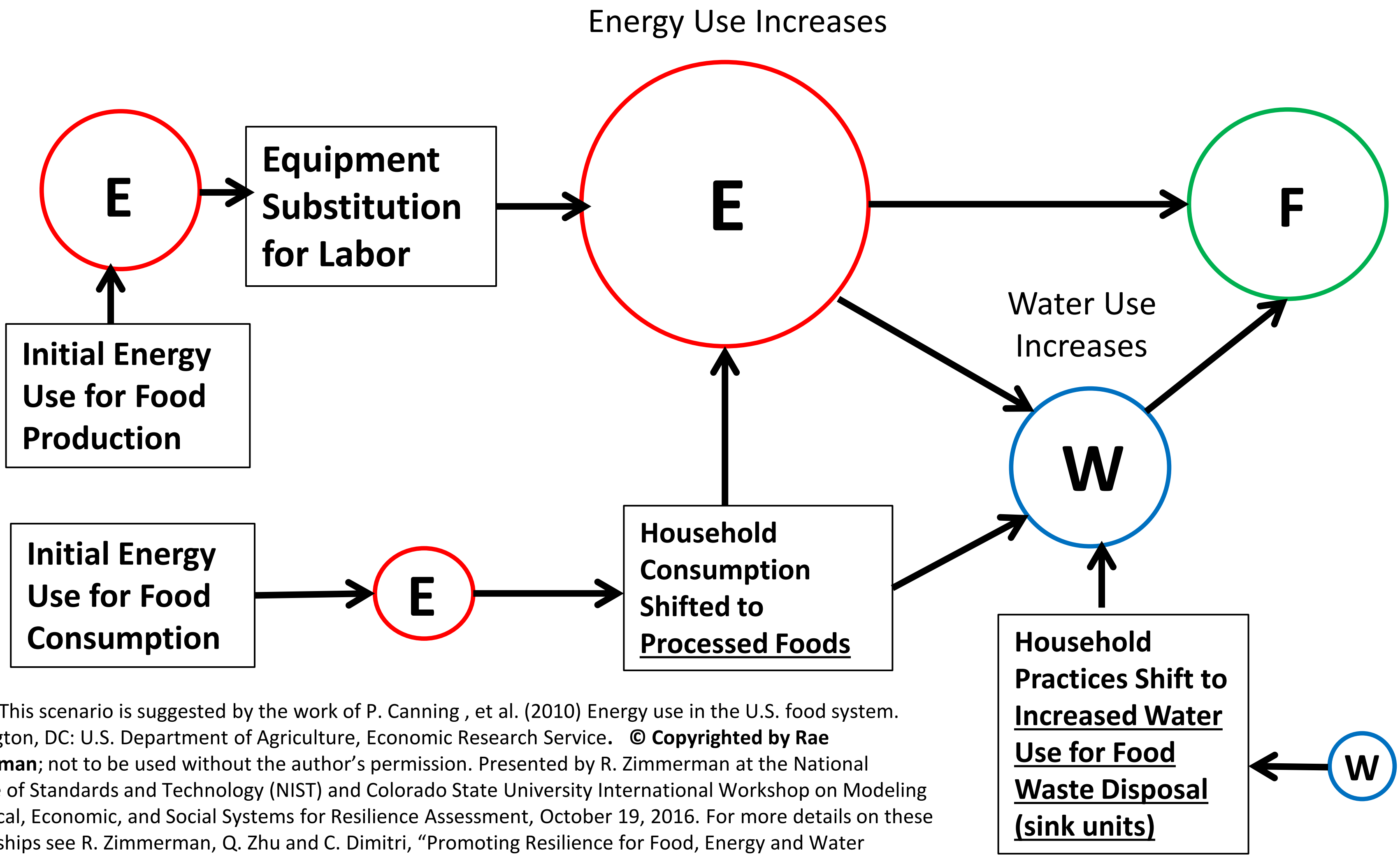
Sources:
[1]R. Zimmerman and C. E. Restrepo (2006) “The Next Step: Quantifying Infrastructure Interdependencies to Improve Security,” International Journal of Critical Infrastructures, Vol. 2, Nos. 2/3, pp. 215-230; p. 223.
[2]M. Flegenheimer (September 25, 2013) Power Failure Disrupts Metro North’s New Haven Line; May Last Days, New York Times http://www.nytimes.com/2013/09/26/nyregion/metro-norths-new-haven-line-suspended-after-power-loss.html
[3] MTA (October 2011), Preliminary review September 29, 2011 lightning strike at Jamaica, New York, NY, USA: MTA.
[4]Summarized and references contained in R. Zimmerman (2005) “Mass Transit Infrastructure and Urban Health,” J. of Urban Health, 82(1), pp. 21-32; pp.27-28.
[5] C. Garnet and M. C. Gressier (February 12 2010) Eurostar Independent Review

Lifeline Interdependencies



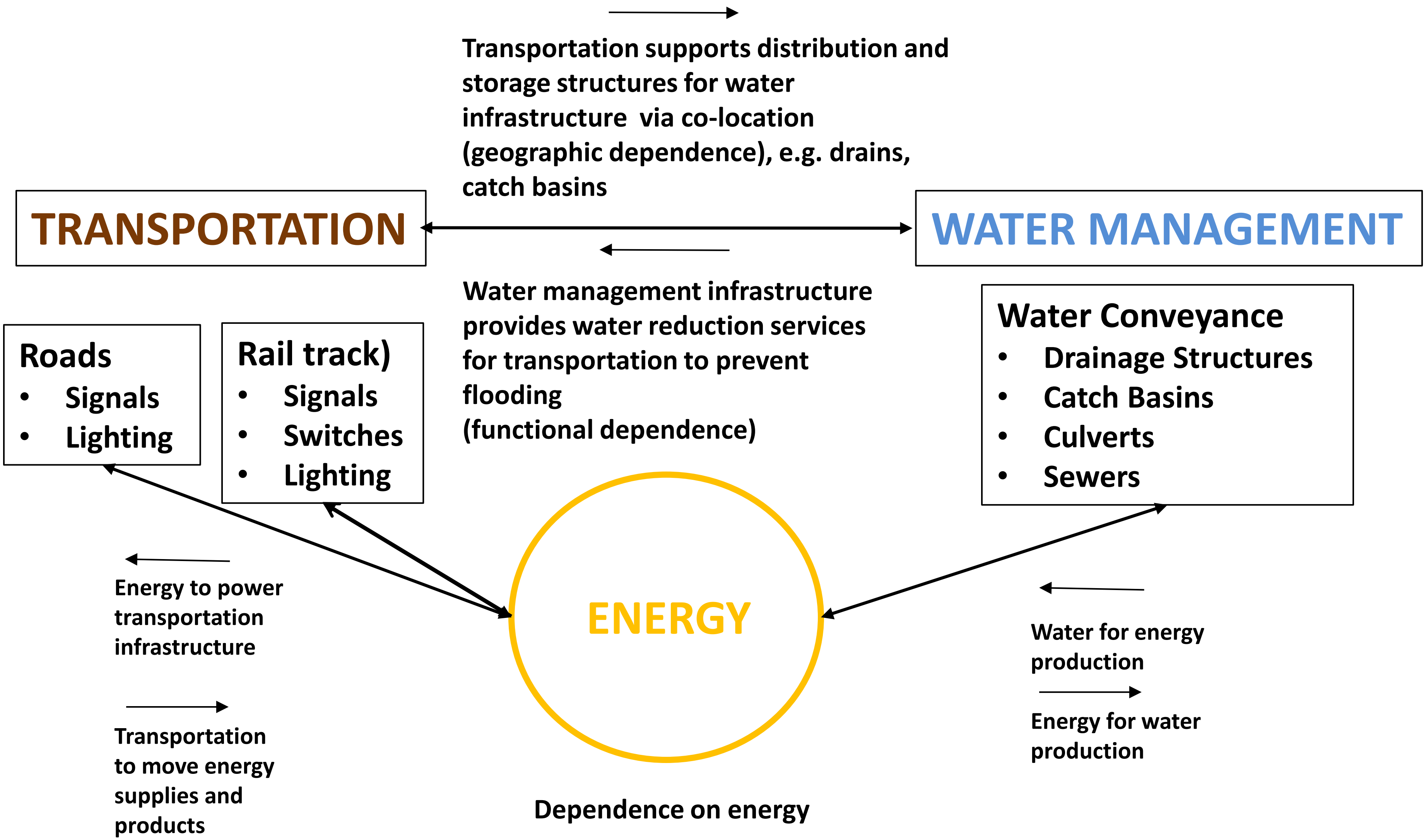
Source: U.S. Department of Energy (DOE). January 2017. Quadrennial Energy Review: Transforming the Nation's Electricity System: The Second Installment of the QER, p. 1-9, figure 1-2. https://energy. gov/sites/prod/files/2017/02/f34/Quadrennial%20Energy%20Review-Second%20Installment%20%28Full%20Report%29.pdf

Applications of Interdependency Concepts
Interconnection Model Adapted to the Effect of Energy and Water Use Practices in the Food Sector



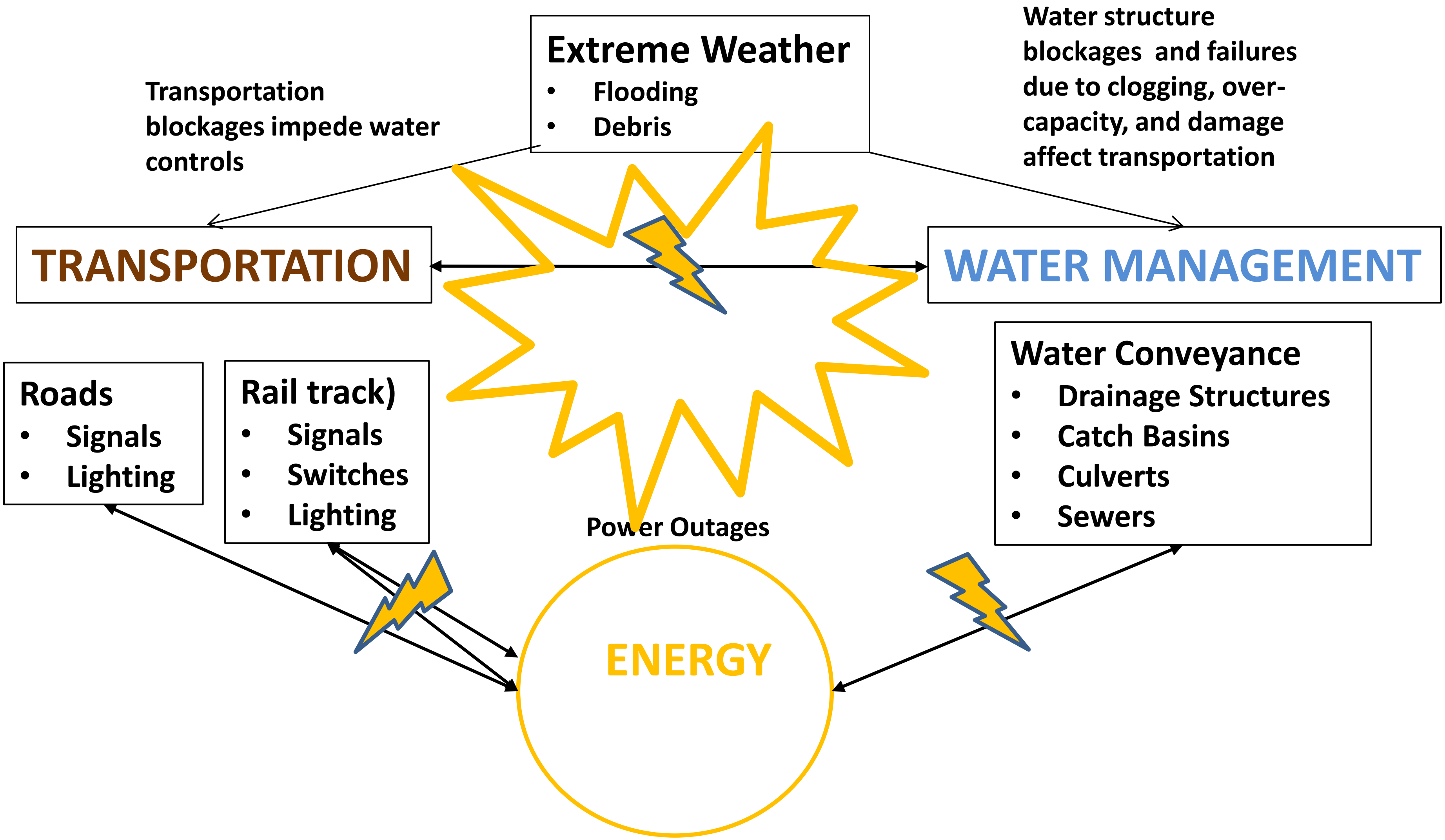
Source: This scenario is suggested by the work of P. Canning , et al. (2010) Energy use in the U.S. food system. Washington, DC: U.S. Department of Agriculture, Economic Research Service. Presented by R. Zimmerman at the National Institute of Standards and Technology (NIST) and Colorado State University International Workshop on Modeling of Physical, Economic, and Social Systems for Resilience Assessment, October 19, 2016. For more details on these relationships see R. Zimmerman, Q. Zhu and C. Dimitri, "Promoting Resilience for Food, Energy and Water Interdependencies," Journal of Environmental Studies and Sciences, Vol. 6, Issue 1, 2016, pp. 50-61.

Effects of Extreme Events: Interdependencies under Normal (non-disruptive) Conditions



Source: Developed by Professor Rae Zimmerman

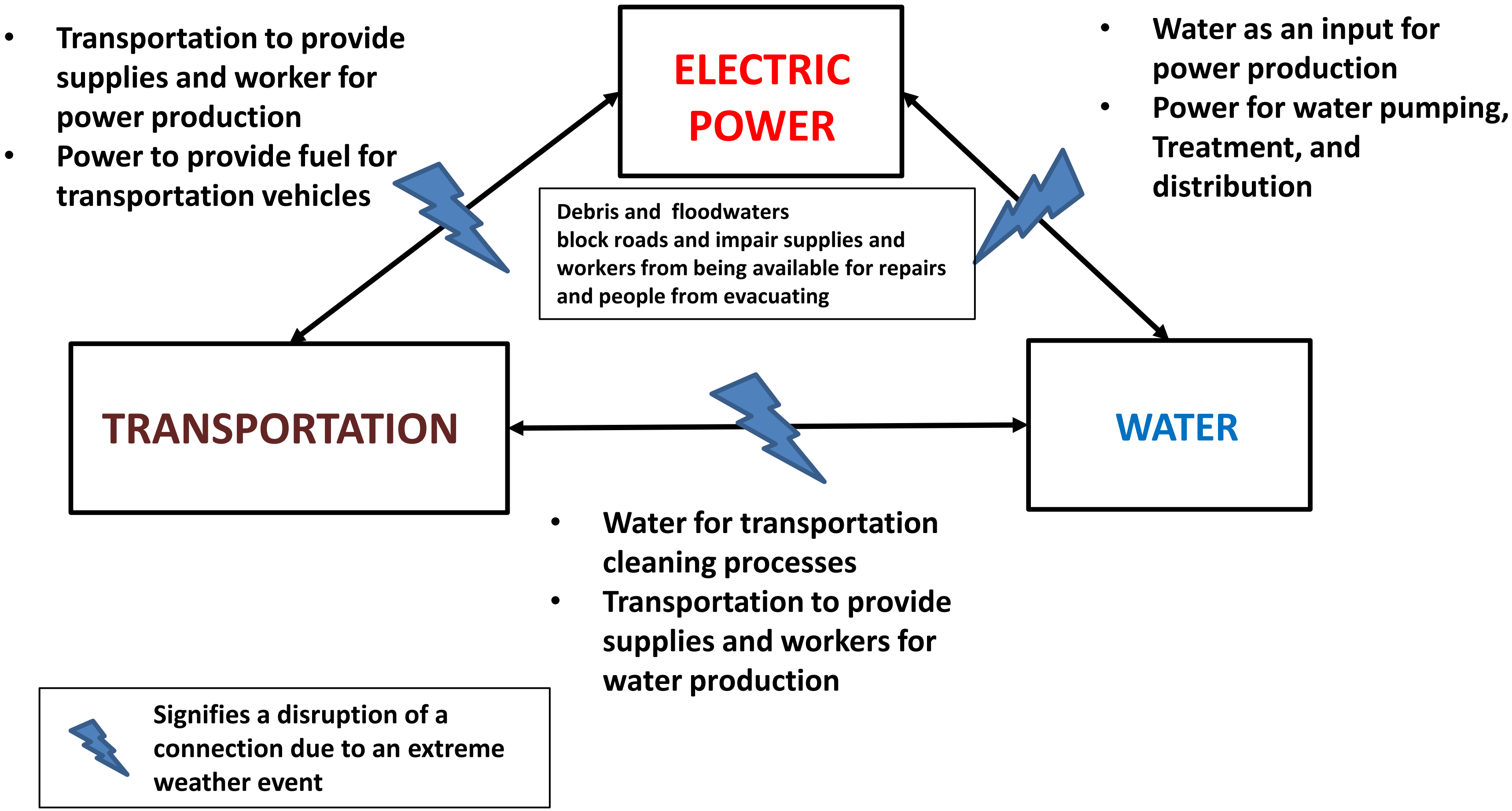
Dysfunctional Interconnected Infrastructure in Extreme Weather



Choke points at the intersection of different interconnected infrastructure systems

APPLICATION

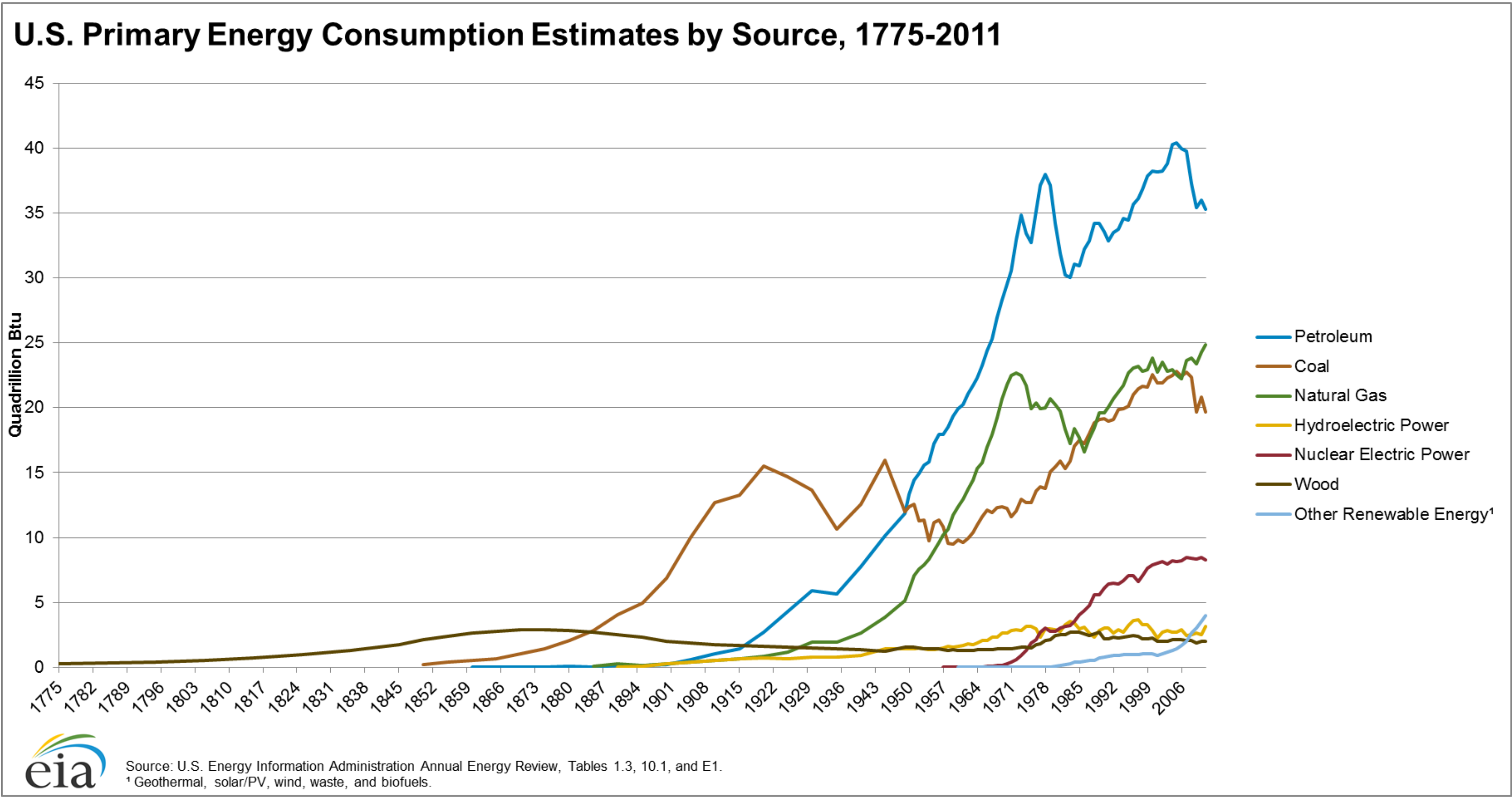
Generic Effect of an Extreme Event on Infrastructure Interconnections (Interdependencies, Dependencies)



Source: Extracted and generalized from concepts in Rae Zimmerman, Quanyan Zhu, Francisco De Leon, and Zhan Guo, Conceptual Modeling Framework to Integrate Resilient and Interdependent Infrastructure in Extreme Weather," Journal of Infrastructure Systems, manuscript accepted for publication, in press. Copyrighted, not for distribution.

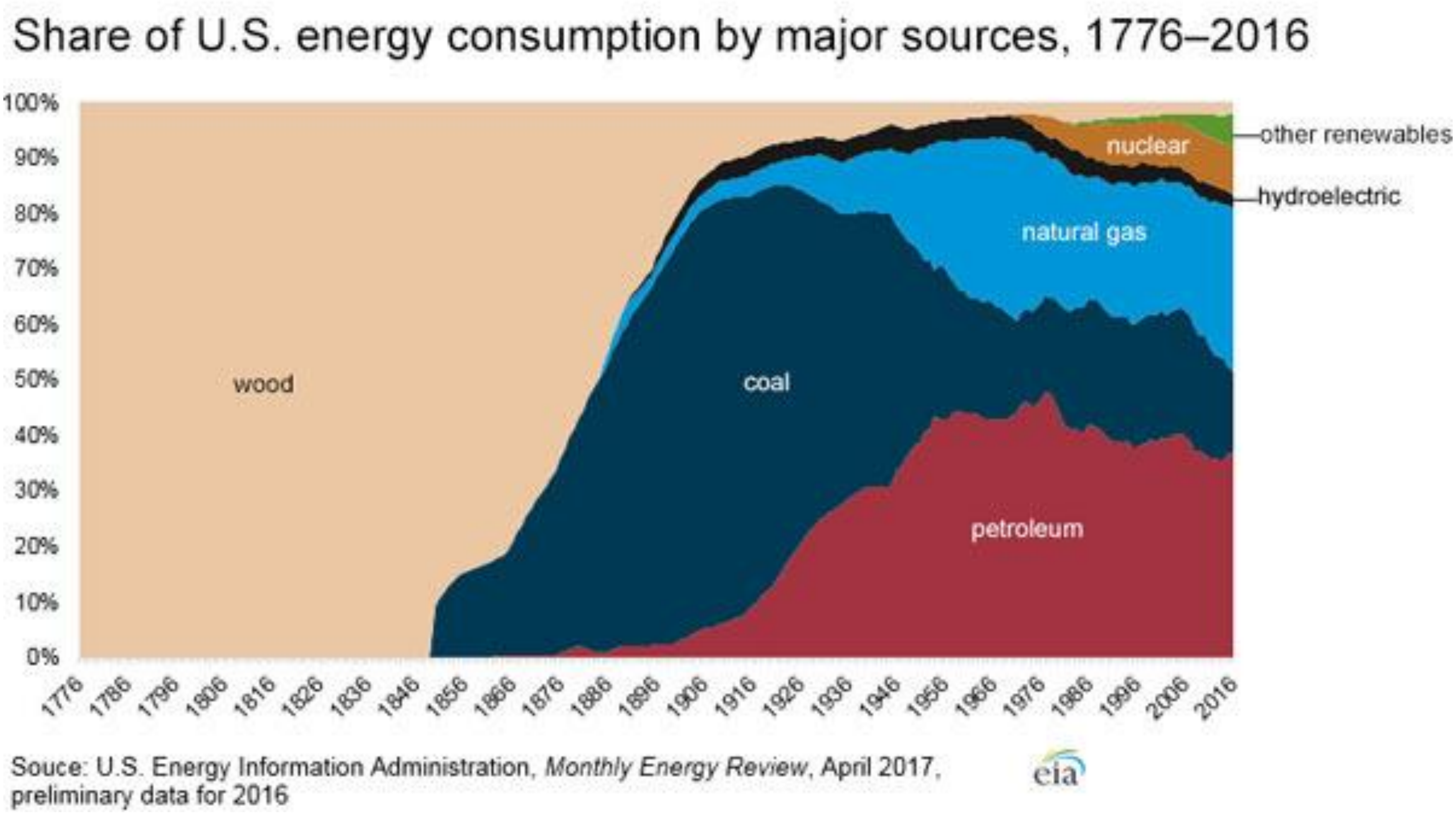
Relationships among the sectors portrayed by linkages change over time as the system moves from normal conditions through storm disruptions and then recovery.

Introducing Renewables
Role of Renewable Energy Sources Relative to Other Sources, 1775-2011



Source: http://www.eia.gov/totalenergy/data/annual/perspectives.cfm

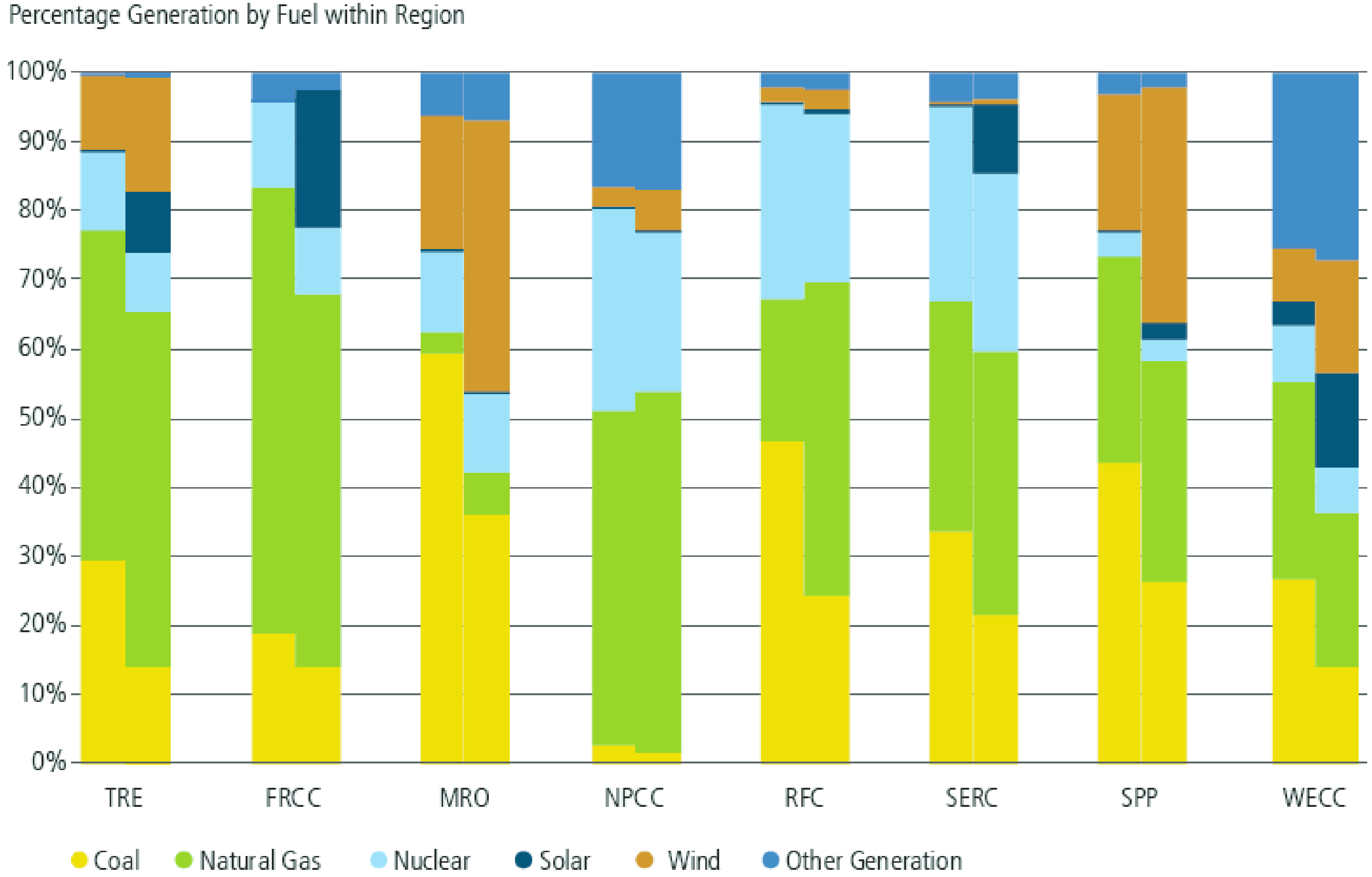
Trends in Energy Consumption by Energy Source, 1776-2016



Source: U.S. Energy Information Administration. April 2017. Monthly Energy Review. https://www.eia.gov/energyexplained/?page=renewable_home

Uneven Distribution of Renewables
Renewables by U.S. NERC Region, 2016-2040

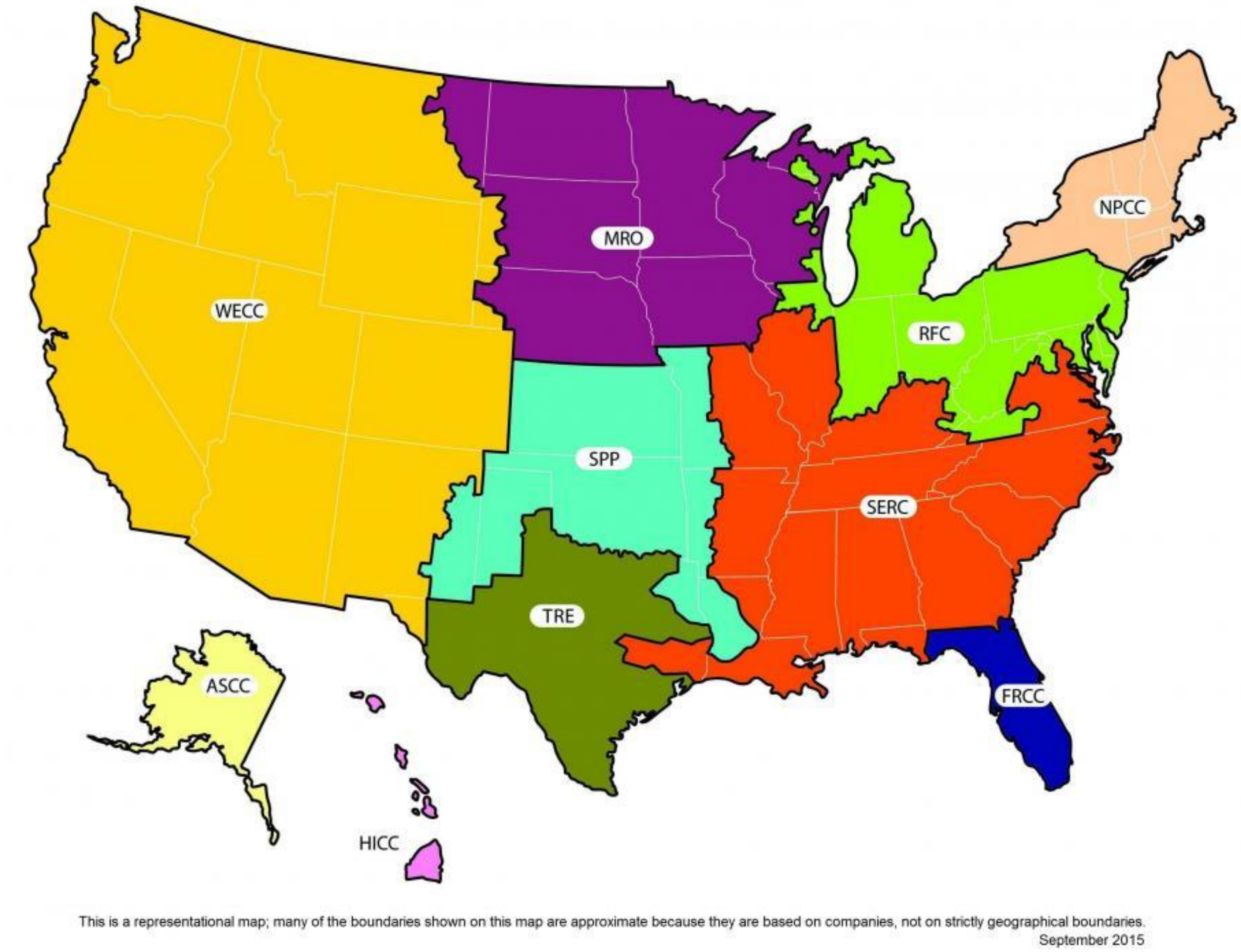
Figure 1-6. Comparison between Generation Fuel Mix by North American Electric Reliability Corporation Region, 2016–2040 [59]



TEXAS FLORIDA UPPER MW UPPER NE MID-ATL SOUTHWEST LOWERMW WEST COAST

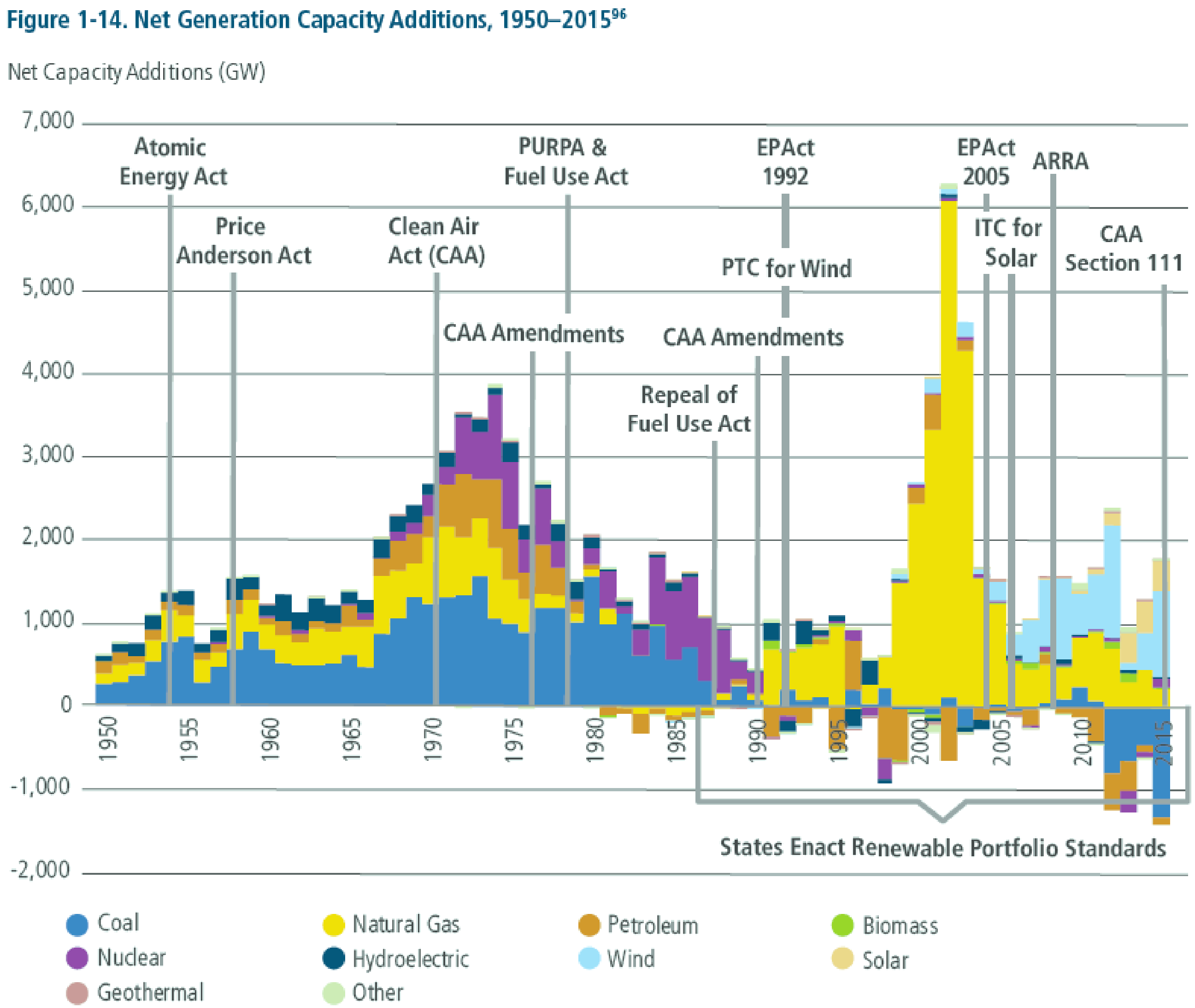
Source: U.S. Department of Energy (DOE). January 2017. Quadrennial Energy Review: Transforming the Nation's Electricity System: The Second Installment of the QER, p. 1-19. https://energy. gov/sites/prod/files/2017/02/f34/Quadrennial%20Energy%20Review-Second%20Installment%20%28Full%20Report%29.pdf

Map of NERC Regions



Source: U.S. EPA (September 2015 North American Reliability Corporation (NERC) region representational map
https://www.epa.gov/energy/north-american-reliability-corporation-nerc-region-representational-map

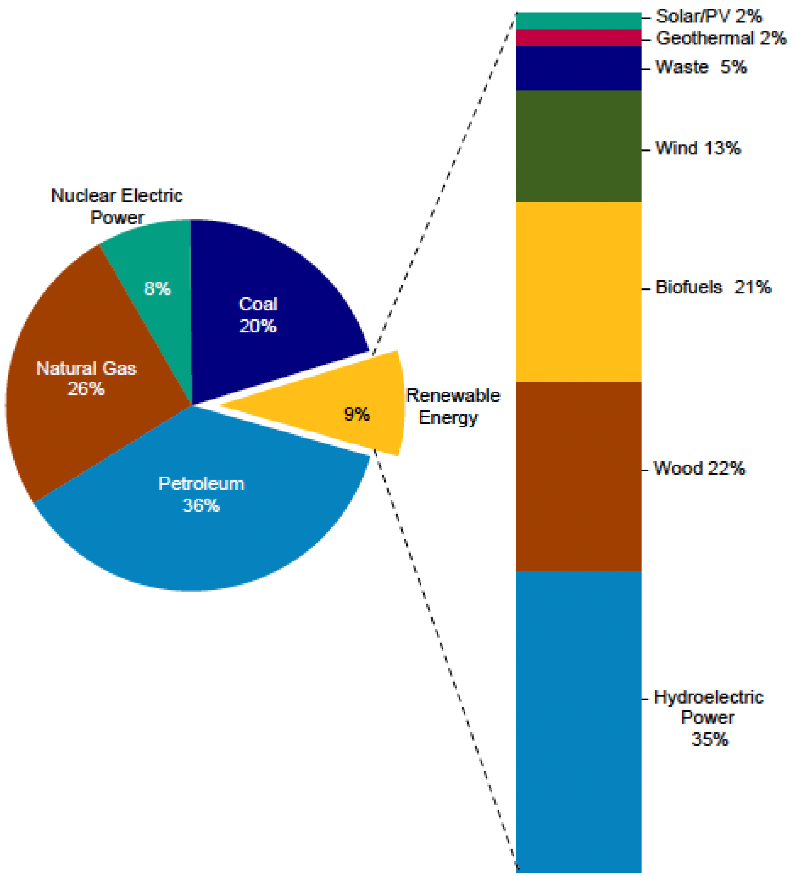
Changes in Renewables with Legislation



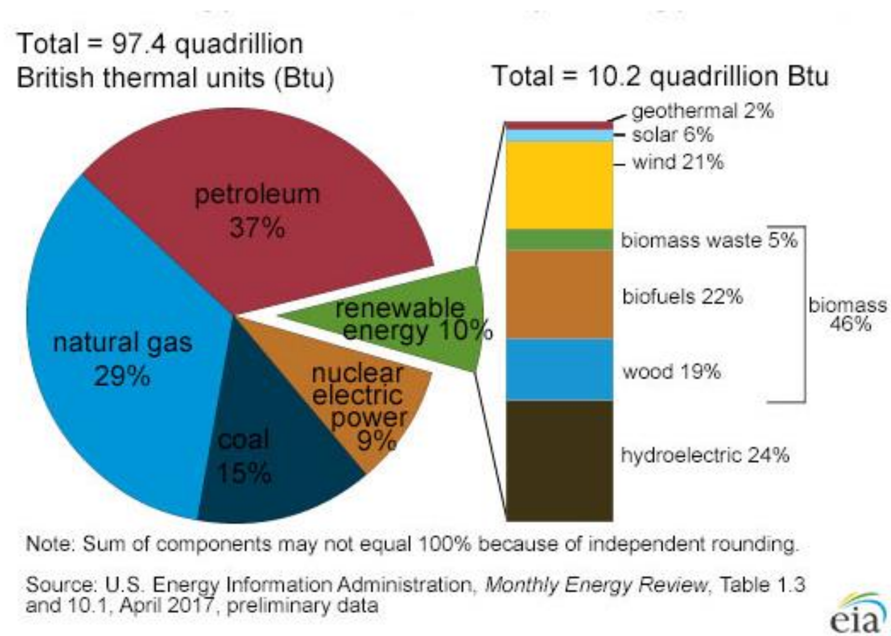
Source: U.S. Department of Energy (DOE). January 2017. Quadrennial Energy Review: Transforming the Nation's Electricity System: The Second Installment of the QER, p. 1-30. https://energy. gov/sites/prod/files/2017/02/f34/Quadrennial%20Energy%20Review-Second%20Installment%20%28Full%20Report%29.pdf

Shifts in Renewable Energy Consumption by Type of Renewable Energy, 2011 and 2016

2011



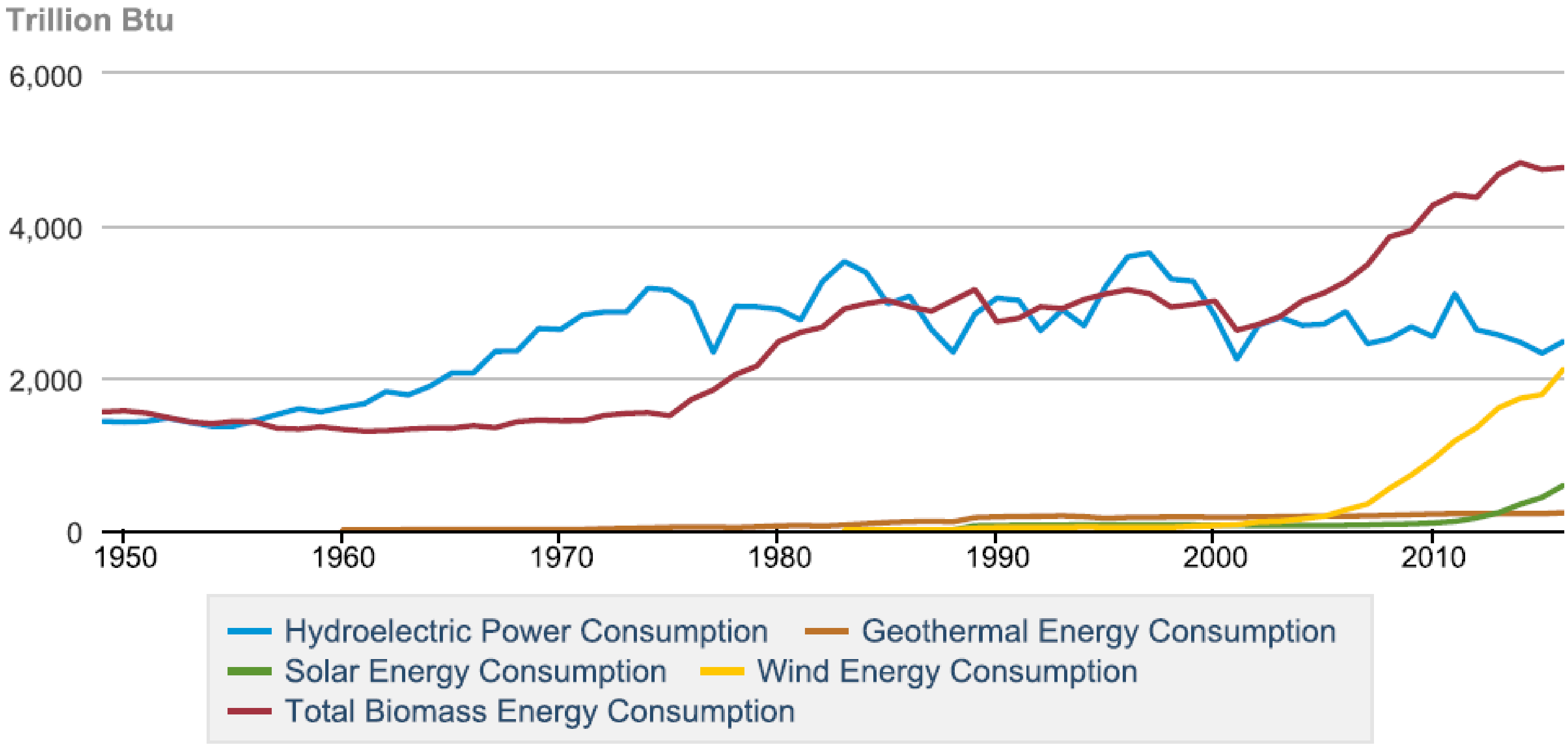
2016



Source: EIA (September 2012) Annual Energy Review, p. 9:
Total energy consumption = 97.301 quadrillion Btu
Renewable energy consumption = 9.135 quadrillion Btu

Source: EIA (April 2017) Monthly Energy Review EIA (November 2017) Monthly Energy Review (p. 3):
Total Energy Consumption (2016 end year total) = 97.496 quadrillion BTU
Renewable Energy Consumption=10.164

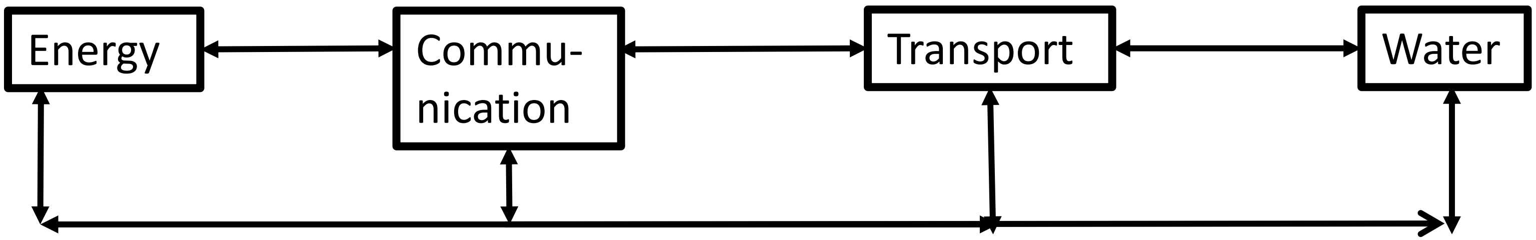
Renewable Energy Consumption Trends by Source



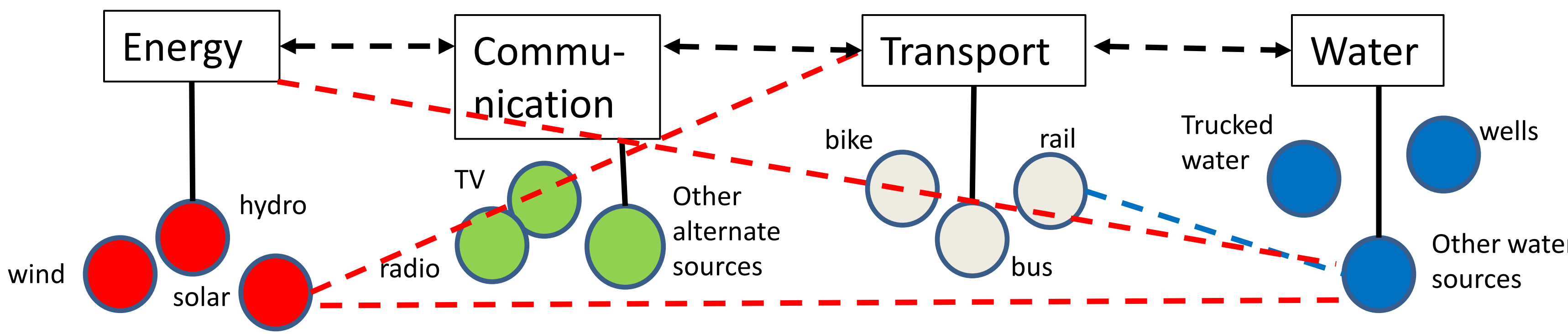
Source: https://www.eia.gov/totalenergy/data/browser/?tbl=T10.01#/?f=M&start=200001

From Failure Modes to Resilience: A Basis for Modeling

Note: Only two-way, simple infrastructure interconnections are shown, but more complex interconnections occur involving more infrastructures.
Created by R. Zimmerman, NYU-Wagner School.



<u>Conventional</u> infrastructure interdependencies are potentially vulnerable to breaks in single links that can cause cascading damages across multiple infrastructure systems.



<u>Distributed or alternative infrastructure</u> systems enable more flexible, relatively simpler interconnections by adding additional resources that can perform and connect independently (dashed lines) or through traditional interdependent system linkages (dashed double arrows). Lines exemplify linkages.

Green Infrastructure: Another Renewable What It Looks Like: Roadway/Roadside Water Capture

Bioretention facility

Source: U.S. EPA (December 2009) Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects under Section 438 of the Energy Independence and Security Act, p. 9, 13, 7, 21. http://www.epa.gov/owow/NPS/lid/section438/pdf/final_sec438_eisa.pdf

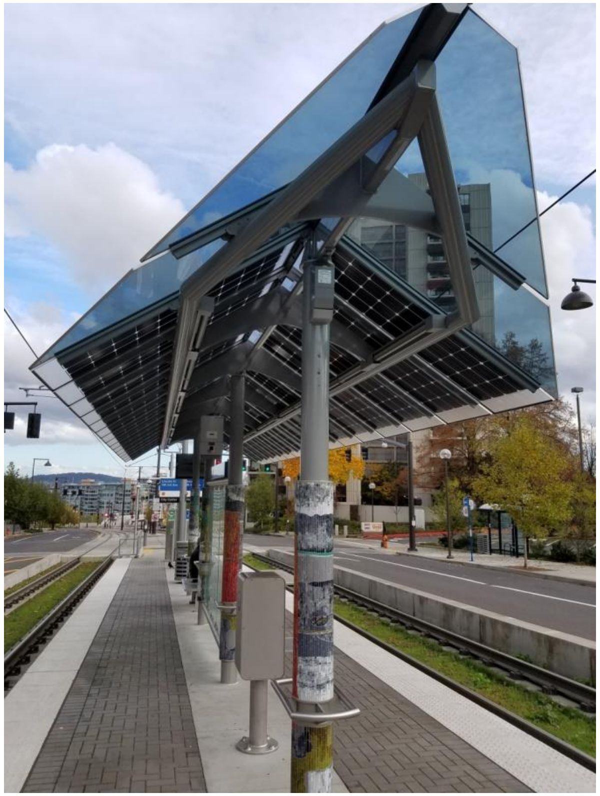
Figure 2: Portland's first Green Streets project at NE 35th and Siskiyou features curb cuts, bump outs and swales.

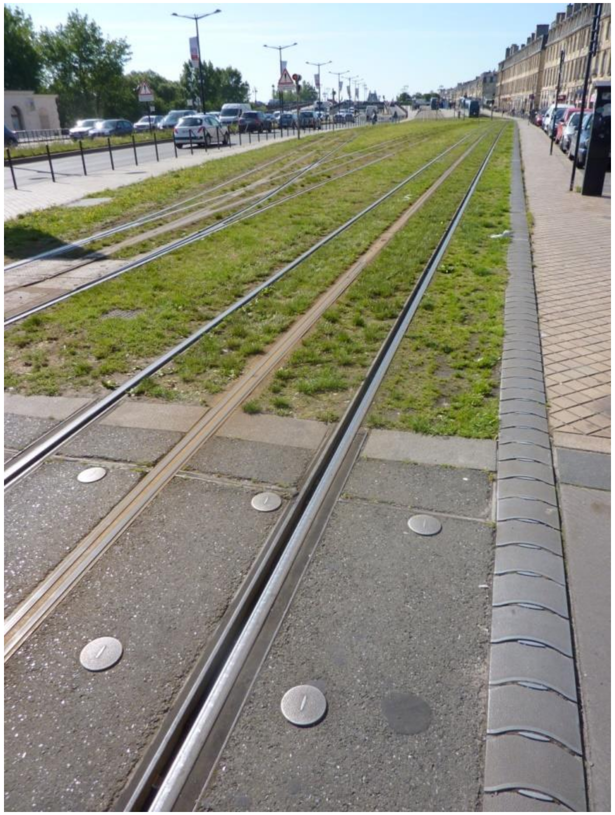
Bioswale

Source: U.S. EPA (August 2010) Green Infrastructure Case Studies: Municipal Policies for Managing Stormwater with Green Infrastructure. Washington, DC: U.S. EPA, p. 54. http://www.epa.gov/owow/NPS/lid/gi_case_studies_2010.pdf

Source: Photo by R. Zimmerman 2012. Salt Lake City, Utah

Green Transit

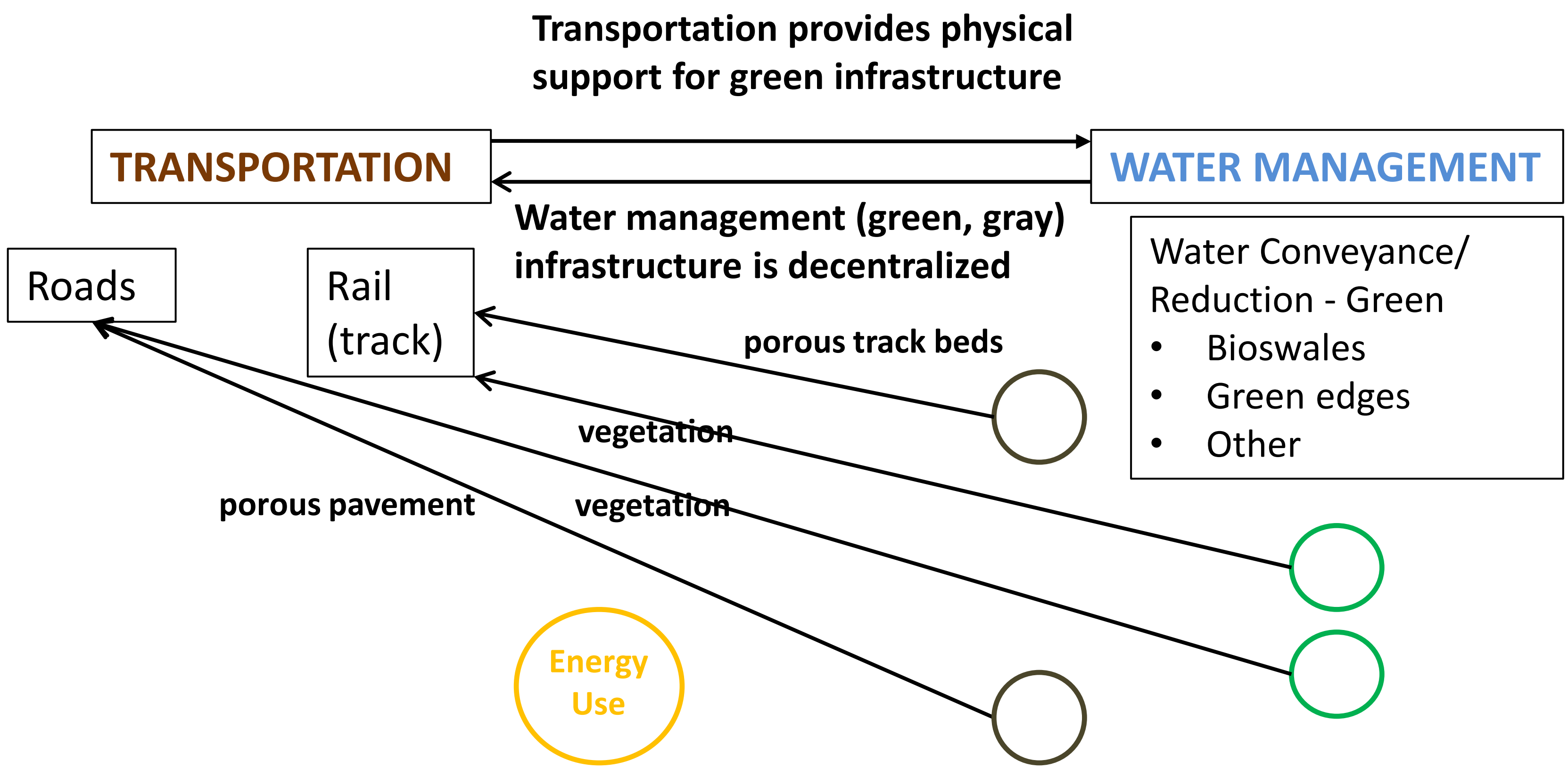




TriMet, Portland OR
Source: Photo by R. Zimmerman, October 2016.

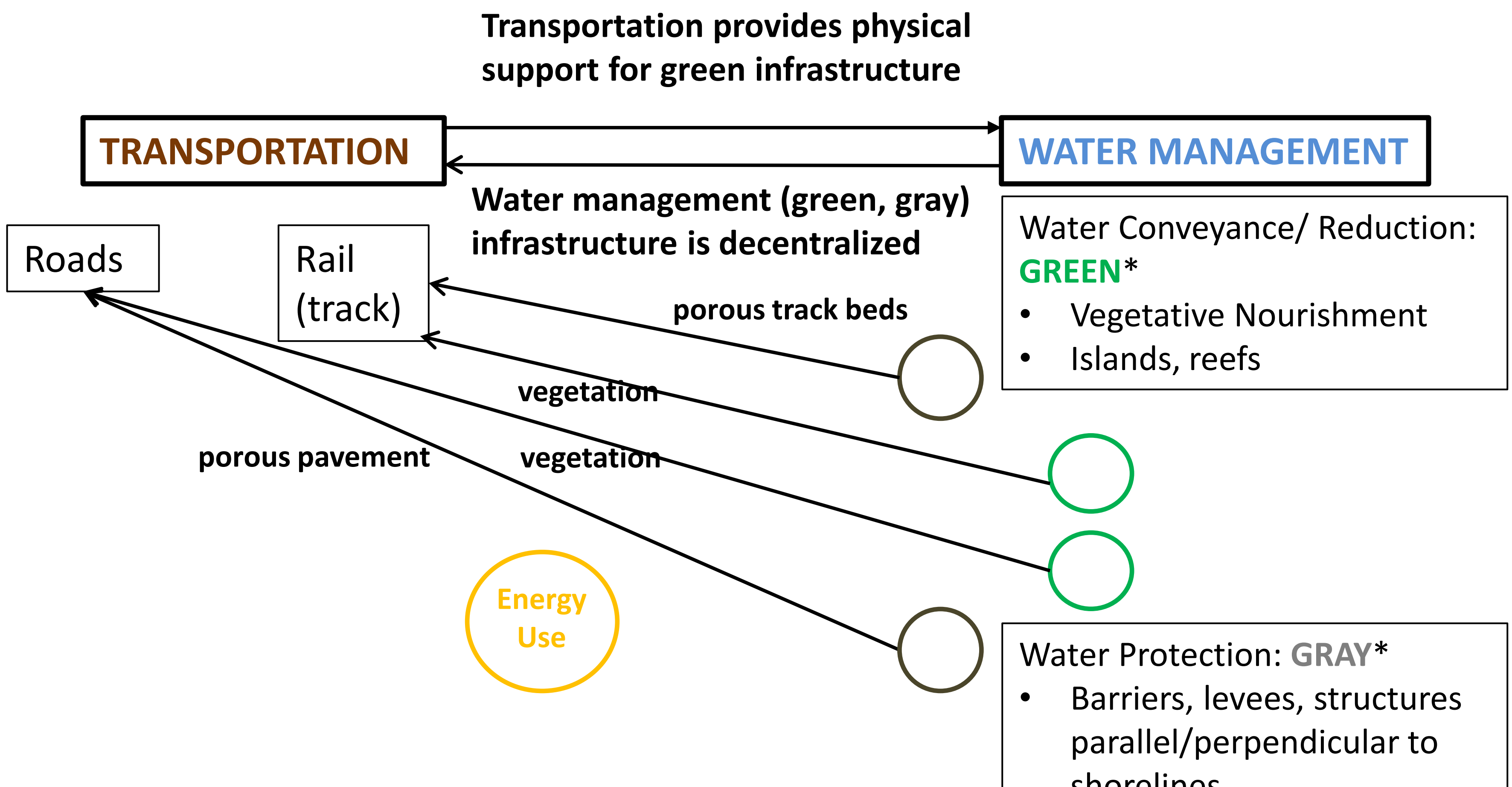
Bordeaux, France
Source: Photo by R. Zimmerman, June 2012.

APPLICATION: Risk Reduction through
Water Management Infrastructure Re-design with Green and Modified Gray Infrastructure Under Normal Conditions



Note: Extreme events can impair green infrastructure where floodwaters and debris overwhelm them. Green infrastructure is meant to support water management under normal conditions so that flood volumes can be reduced when extreme events do happen.

Water Management Infrastructure Re-design with Green Infrastructure and Modified Gray Infrastructure: For Protection in Extreme Conditions



*Suggested by Georgetown Climate Center (2017) Rebuilding with Resilience, p. 9

Note: Extreme events can impair green infrastructure where floodwaters and debris overwhelm them. Green infrastructure is meant to support water management under normal conditions so that flood volumes can be reduced when extreme events do happen.

Introducing Energy Infrastructure Interconnections

Gray infrastructures consumes energy in a number of ways:

- the use of fuels to power equipment
- the use of electric power in the operation of equipment

Gray infrastructure can reduce energy usage by:

- relying on renewable energy to run equipment
- Using materials that are less energy intensive

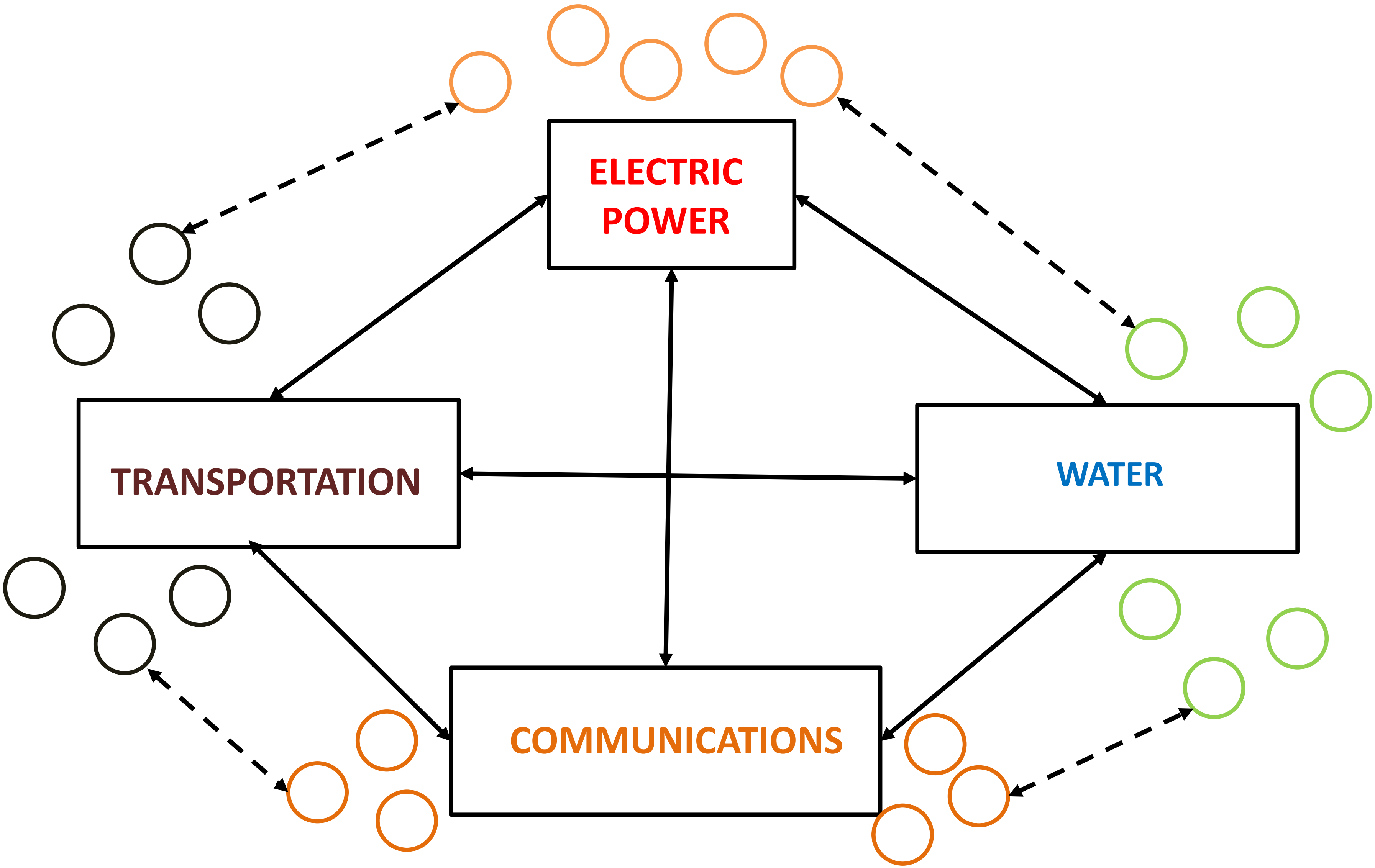
Green infrastructure supports energy reduction in:

- reducing reliance on the gray infrastructure equipment requiring fossil-fuel based energy

Green infrastructure consumes energy if:

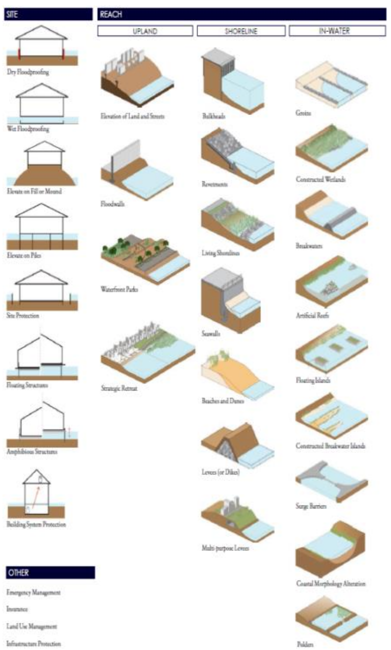
- vegetation requires energy under conditions where sunlight is not present and for irrigation when water is scarce

DECENTRALIZED AND RENEWABLE INFRASTRUCTURES



Source: Developed by Rae Zimmerman. Copyrighted, not for distribution. Relationships among the sectors portrayed by linkages change over time as the system moves from normal conditions through storm disruptions and then recovery.

We Know Some Solutions to Prevent or Reduce Infrastructure Destruction in Extreme Events



Source: New York City Department of City Planning (2013) Coastal Climate Resilience, Urban Waterfront Adaptive Strategies, New York, NY: NYC DCP, p. 5. http://www.nyc.gov/html/dcp/pdf/sustainable_communities/urban_waterfront_print.pdf

Beachgrass planting, Delaware. Source: http://www.dnrec.delaware.gov/swc/shoreline/pages/duneprotection.aspx

LAND

PlaNYC Brooklyn-Queens Waterfront, Chapter 14, p. 256 http://www.nyc.gov/html/sirr/downloads/pdf/final_report/Ch14_Brooklyn_Queens_FINAL_singles.pdf, MMR:

WATER

Electric Power Distribution

- Sealants
- Disconnection
- Submersion
- Etc.

Source: Con Ed and Orange & Rockland Utilities (June 20, 2013) Post Sandy Enhancement Plan, p. 33, 34, 39, 40, 46 http://www.coned.com/publicissues/PDF/post_sandy_enhancement_plan.pdf

Source: Metropolitan Transportation Authority of the State of New York, "Tunnel Plug," from MTA Flickr photos.

INFRASTRUCTURE

TriMet, Portland OR Source: Photo by R. Zimmerman, October 2016.

Source: Photo by R. Zimmerman 2012

Source: Photos from MTA

Small Technological Fixes for Flooding of Underground Transit: Street and Subway Flooding Protection Using Elevated Grate Barriers, NYC

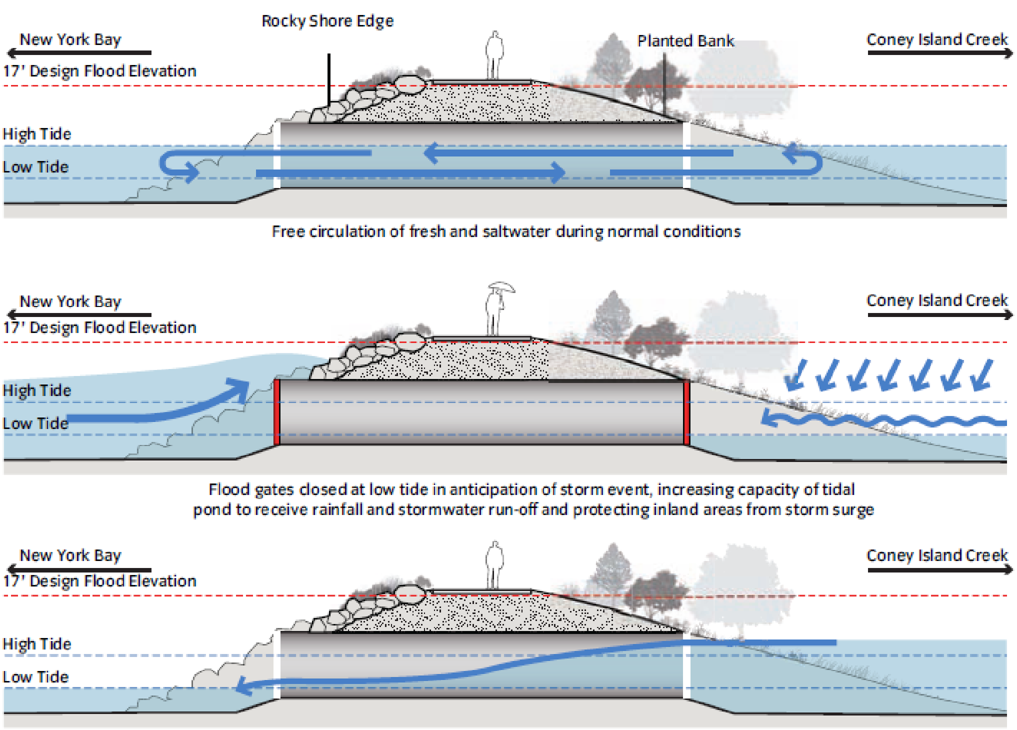
Source: Photos from MTA

Source: Photo by R. Zimmerman 2012

Other New York City Area Restoration Concepts and Plans: Southern Brooklyn (Coney Island Creek)

Conceptual rendering of Coney Island Creek wetlands and tidal barrier, with Rockaway Inlet barrier

Conceptual Coney Island Creek culvert



Free circulation of fresh and saltwater during normal conditions

Flood gates closed at low tide in anticipation of storm event, increasing capacity of tidal pond to receive rainfall and stormwater run-off and protecting inland areas from storm surge

Flood gates opened at low tide following storm to release excess water from tidal pond and flush creek system

Source: http://www.nyc.gov/html/sirr/downloads/pdf/final_report/Ch17_SouthernBrooklyn_FINAL_singles.pdf, p. 351, 352

Observations and Conclusions

- Introduction of renewable infrastructures can provide more flexibility to reduce some of the adverse effects of infrastructure interdependencies
- This is especially true in extreme events
- Renewable infrastructures have their own set of interdependencies that need to be considered

Acknowledgement

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- Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP) Type 1—"Reductionist and integrative approaches to improve the resiliency of multi-scale interdependent critical infrastructure," funded by the NSF (1541164)
- "RIPS Type 1: A Meta-Network System Framework for Resilient Analysis and Design of Modern Interdependent Critical Infrastructures" funded by the NSF (1441140)
- "Dynamic Resiliency Modeling and Planning for Interdependent Critical Infrastructures," funded by the Critical Infrastructure Resilience Institute, U. of Illinois, Urbana-Champaign, part of the Homeland Security Center of Excellence funded by the U.S. Department of Homeland Security
- "RAPID / Collaborative Research: Collection of Perishable Hurricane Sandy Data on Weather-Related Damage to Urban Power and Transit Infrastructure," UW, LSU, funded by the NSF.
- "Promoting Transportation Flexibility in Extreme Events through Multi-Modal Connectivity" funded by U.S. DOT's University Transportation Research Center (II)

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