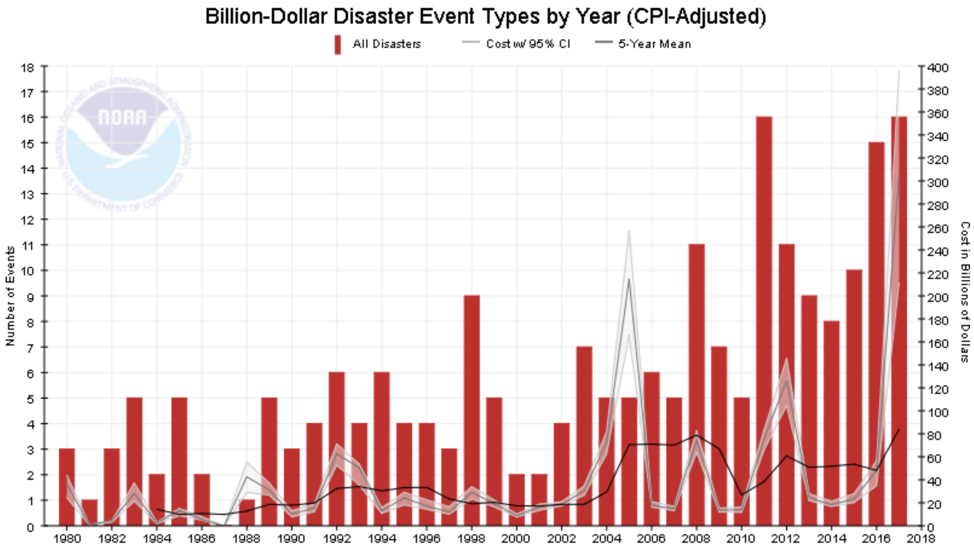
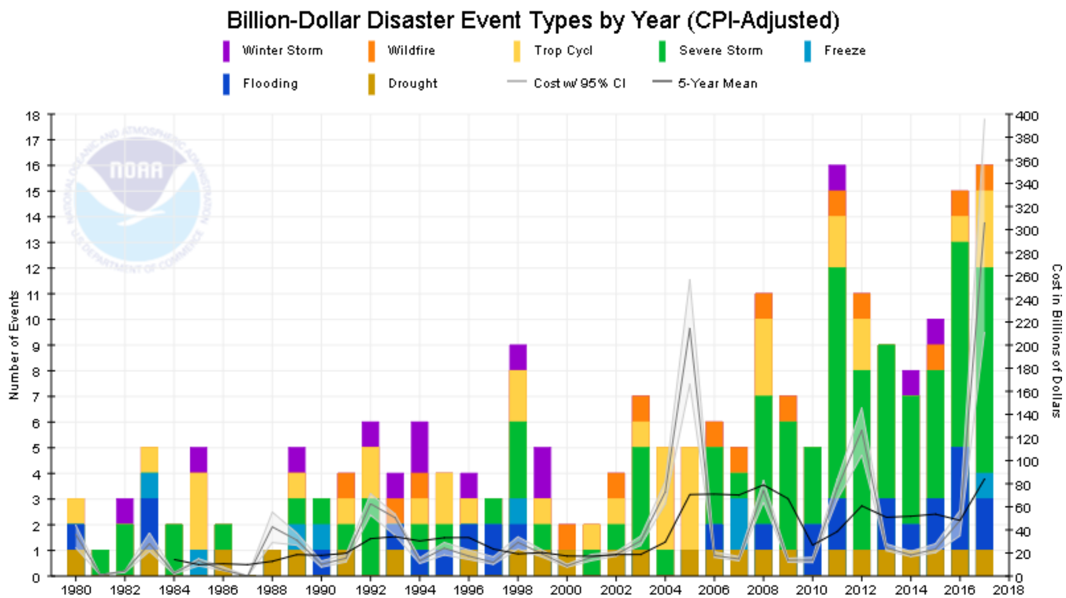
New York Energy Transition in the Context of Recent Hurricanes

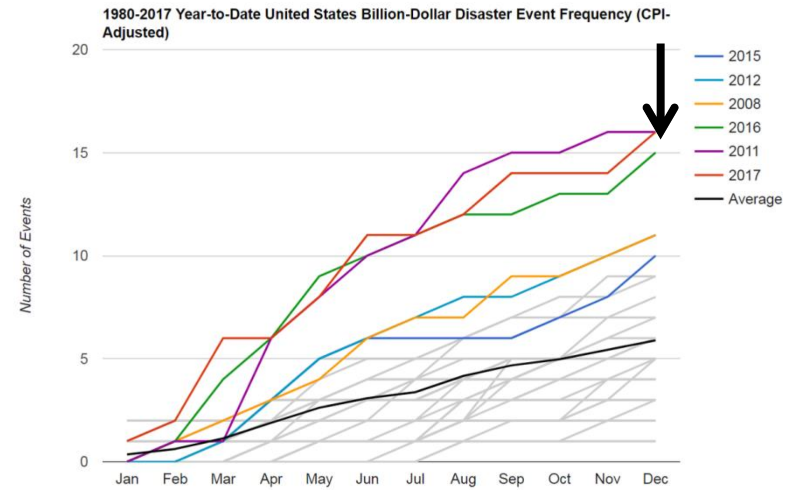
Rae Zimmerman, PhD
Research Professor and Professor Emerita of Planning and Public Administration
Wagner Graduate School of Public Service
New York University
rae.zimmerman@nyu.edu
http://wagner.nyu.edu/zimmerman

Workshop on Deploying Sustainable Energy during Transition: Implications of Recovery, Renewal, and Rebuilding, National Academies of Sciences, Engineering, and Medicine, Roundtable on Science and Technology for Sustainability (STS Roundtable), National Academies' Science and Technology for Sustainability Program
January 30, 2018

I. The Threats: Extreme Weather Trends







Source: NOAA National Centers for Environmental Information (2017) Calculating the Cost of Weather and Climate Disasters 7 things to know about NCEI's U.S. billion-dollar disasters data https://www.ncei.noaa.gov/news/calculating-cost-weather-and-climate-disasters

Source: NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2017). https://www.ncdc.noaa.gov/billions/. Accessed 1/11/18

Record Climate Change Findings, U.S., 2014 - 2017

- According to NOAA's preliminary analysis of average annual temperature, based on the 20th century average 2017 was the third warmest year, 2016 was second warmest and 2012 was first. "The five warmest years on record for the contiguous U.S. have all occurred since 2006."
  Source: NOAA National Centers for Environmental Information (January 2018), State of the Climate: National Climate Report for Annual 2017, published online January 2018, retrieved on January 29, 2018 from https://www.ncdc.noaa.gov/sotc/national/201713.
- Extreme heat events reflected in the 2015 temperature extremes reached record levels for both the first half of 2015 and the month of July.
- 2014 experienced record increases in the major greenhouse gas concentrations, "the highest annual global surface temperature in at least 135 years of modern record keeping", and record levels for global mean sea level (p. Sxvi).
  Source: Blunden, J. and D. S. Arndt, Eds., 2015: State of the Climate in 2014. Bull. Amer. Meteor. Soc., 96 (7), S1–S267. http://journals.ametsoc.org/doi/suppl/10.1175/2015BAMSStateoftheClimate.1/suppl_file/10.1175_2015bamsstateoftheclimate.3.pdf
- The joint occurrence of storm surge and precipitation (previously considered separately) is anticipated to dramatically contribute to major urban coastal area flooding. Evidence points to the increase in such joint events and that the effects are greater for the Atlantic coast than the Pacific coast.
  Source: Thomas Wahl, Shaleen Jain, Jens Bender, Steven D. Meyers and Mark E. Luther (2015) Increasing risk of compound flooding from storm surge and rainfall for major US cities, Nature Climate Change, published on line,.27 JULY 2015
- "The Antarctic Ice Sheet stores water equivalent to 58 m in global sea-level rise. . . . burning the currently attainable fossil fuel resources is sufficient to eliminate the ice sheet. . . With cumulative fossil fuel emissions of 10,000 gigatonnes of carbon (GtC), Antarctica is projected to become almost ice-free with an average contribution to sea-level rise exceeding 3 m per century during the first millennium."
  Source: Ricarda Winkelmann, Anders Levermann, Andy Ridgwell, and Ken Caldeira (2015) Combustion of available fossil fuel resources sufficient to eliminate the Antarctic Ice Sheet Sci. Adv. 2015;1:e1500589 11 September 2015, pp. 1-5.
- Hurricanes: The change in the frequency of such events may be uncertain, but there are apparently indications that hurricanes in the more severe category are increasing.
  Emanuel, Kerry (2005) Increasing Destructiveness of tropical cyclones over the past 30 years, Nature, 436, pp. 686-688.

Hurricanes: Losses

1980-2017 events greater than $1 billion each:

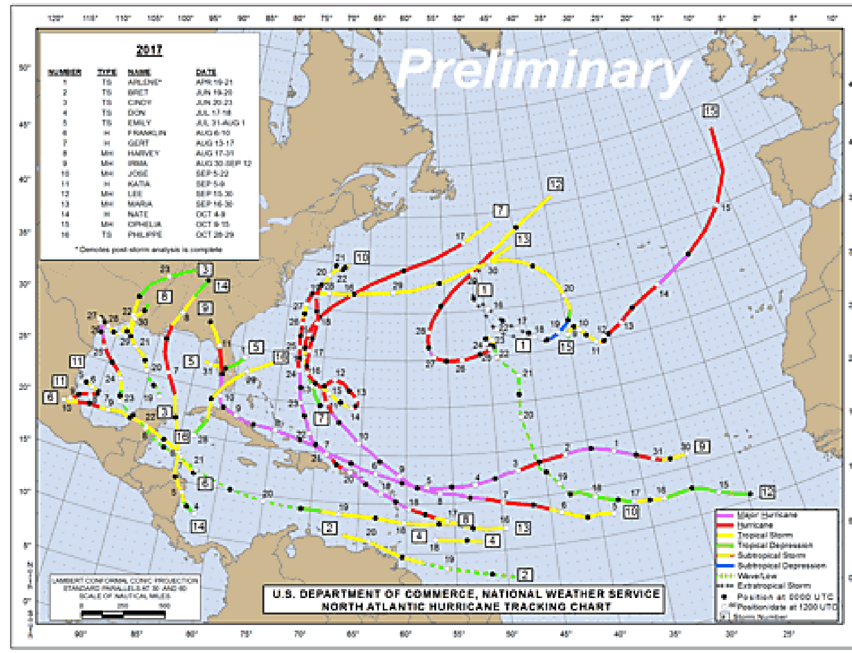
- **In the U.S. while tropical cyclones accounted for only 17.4% of events (38), they accounted for 55.3% of the total losses ($850.5 billion)**
- **Severe storms while accounting for 41.6% of events (91) accounted for only 13.4% of the total losses ($206.1 billion)**

Sources: NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2018). https://www.ncdc.noaa.gov/billions/summary-stats

Reported Hurricanes, 2017 Season

(Atlantic, Caribbean, Gulf of Mexico, mid-April through October 2017, NHC)

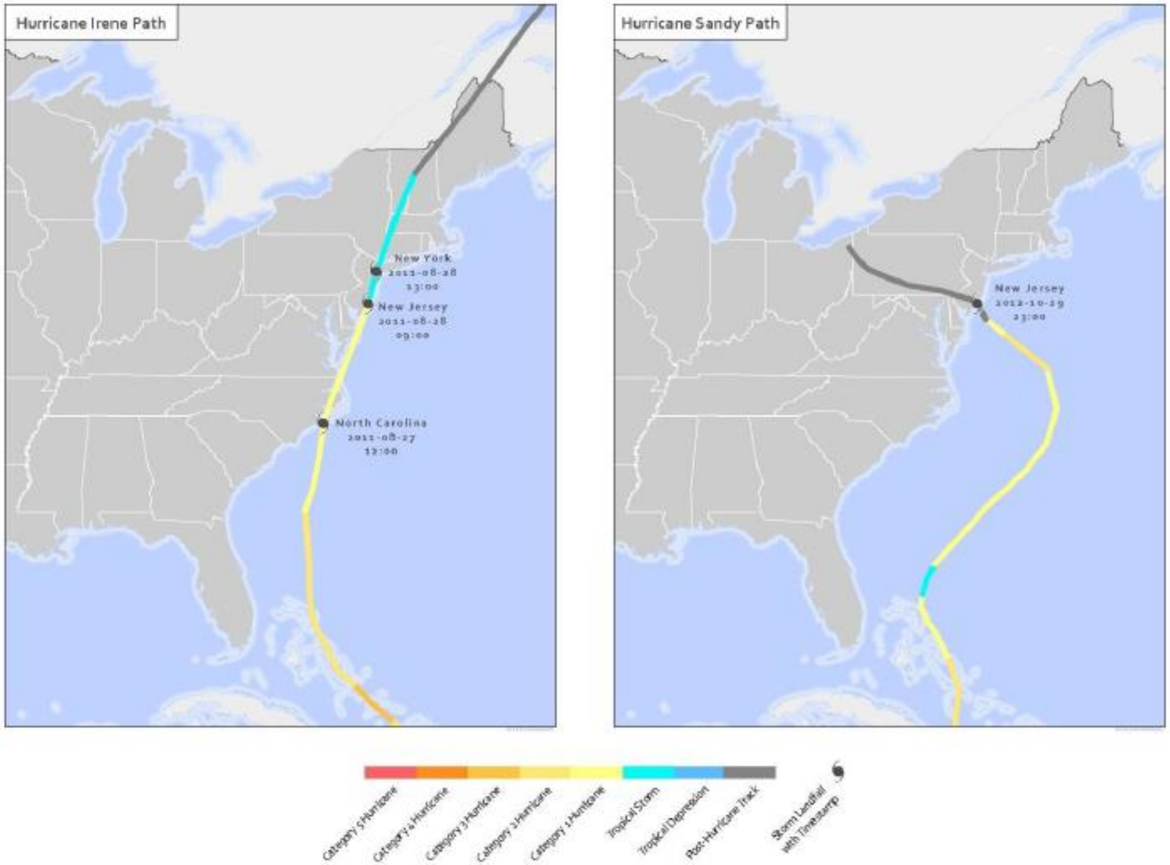
“Name	Dates	Max wind (mph)
TS Arlene	19-21 Apr	50*
TS Bret	19-20 Jun	45
TS Cindy	20-23 Jun	60
TD Four	5-7 Jul	30*
TS Don	17-18 Jul	50
TS Emily	31 Jul-1 Aug	45
H Franklin	6-10 Aug	85
H Gert	13-17 Aug	105
MH Harvey	**17 Aug-1 Sep**	**130**
MH Irma	**30 Aug-12 Sep**	**185**
MH Jose	5-22 Sep	155
H Katia	5-9 Sep	105
MH Lee	15-30 Sep	115
MH Maria	**16-30 Sep**	**175**
H Nate	4-9 Oct	90
MH Ophelia	9-15 Oct	115
TS Philippe	28-29 Oct	60”



Many weather extremes occurring at the same time and about the same place . . .

Source: NWS National Hurricane Center NWS National Hurricane Center Miami FL (800 AM EDT Wed Nov 1 2017) Monthly Atlantic Tropical Weather Summary NWS National Hurricane Center Miami FL http://www.nhc.noaa.gov/text/MIATWSAT.shtml (through October 30, 2017). Note: * Denotes a storm for which the post-storm analysis is complete. MH=major hurricane, H=Hurricane, TS=Tropical Storm

Hurricanes in the NYC area: Hurricane (Tropical Cyclone) Irene and Sandy Comparisons



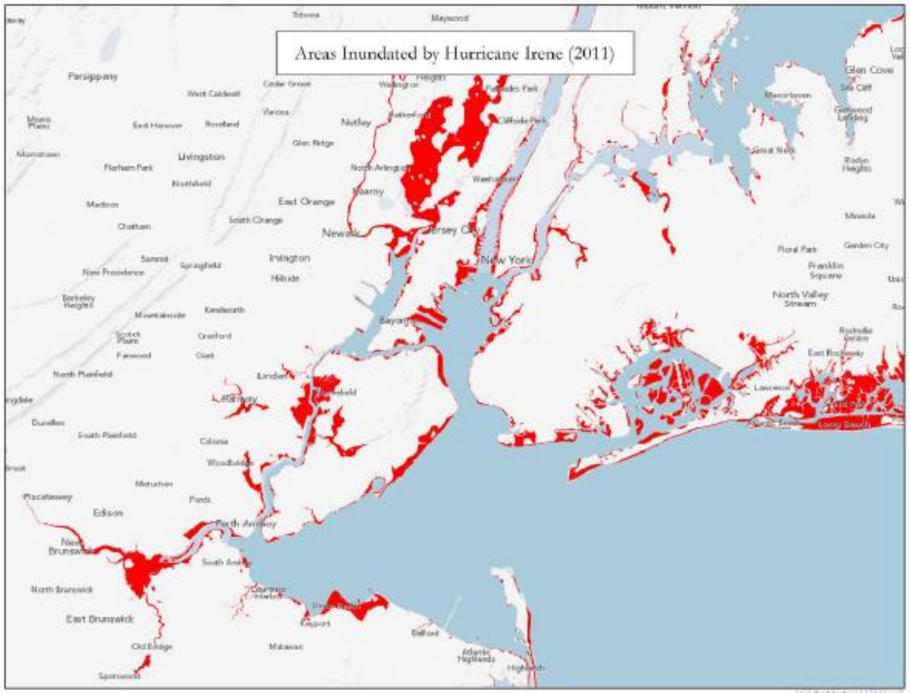
Irene, 8/26/11

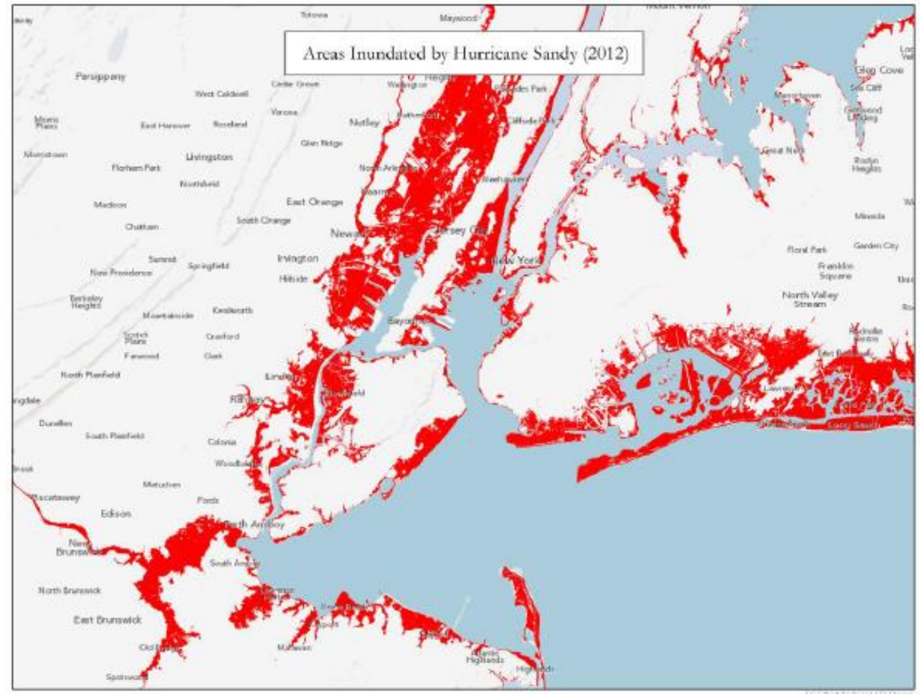
Sandy, 10/28/12

Wind speeds: Hurricane Irene ~52-63 mph*; Hurricane Sandy: ~80 mph**
Storm surge: Hurricane Irene ~4-6 ft.*; Hurricane Sandy >8 ft.**

Source: Maps and images from U. S. DOE (2013) Comparing the Impacts of Northeast Hurricanes on Energy Infrastructure, p. iv, 3. http://energy.gov/sites/prod/files/2013/04/f0/Northeast%20Storm%20Comparison_FINAL_041513c.pdf .
*NHC (12/14/11) Tropical Cyclone Report Hurricane Irene, p. 3, 21 wind, p. 6, 43 surge; NOAA (May 2013) Service Assessment Hurricane/Post-Tropical Cyclone Sandy October 22-29, 2012, p. 9 wind; p. 13 surge. http://www.weather.gov/media/publications/assessments/Sandy13.pdf
Note: These are considered the most severe hurricanes to hit the region since Hurricane Gloria in 1985 NOAA 8/31/11 Irene by the Numbers, p. 1, though there is a long history of hurricanes affecting the area (Wikipedia List of New York hurricanes https://en.wikipedia.org/wiki/List_of_New_York_hurricanes#/.

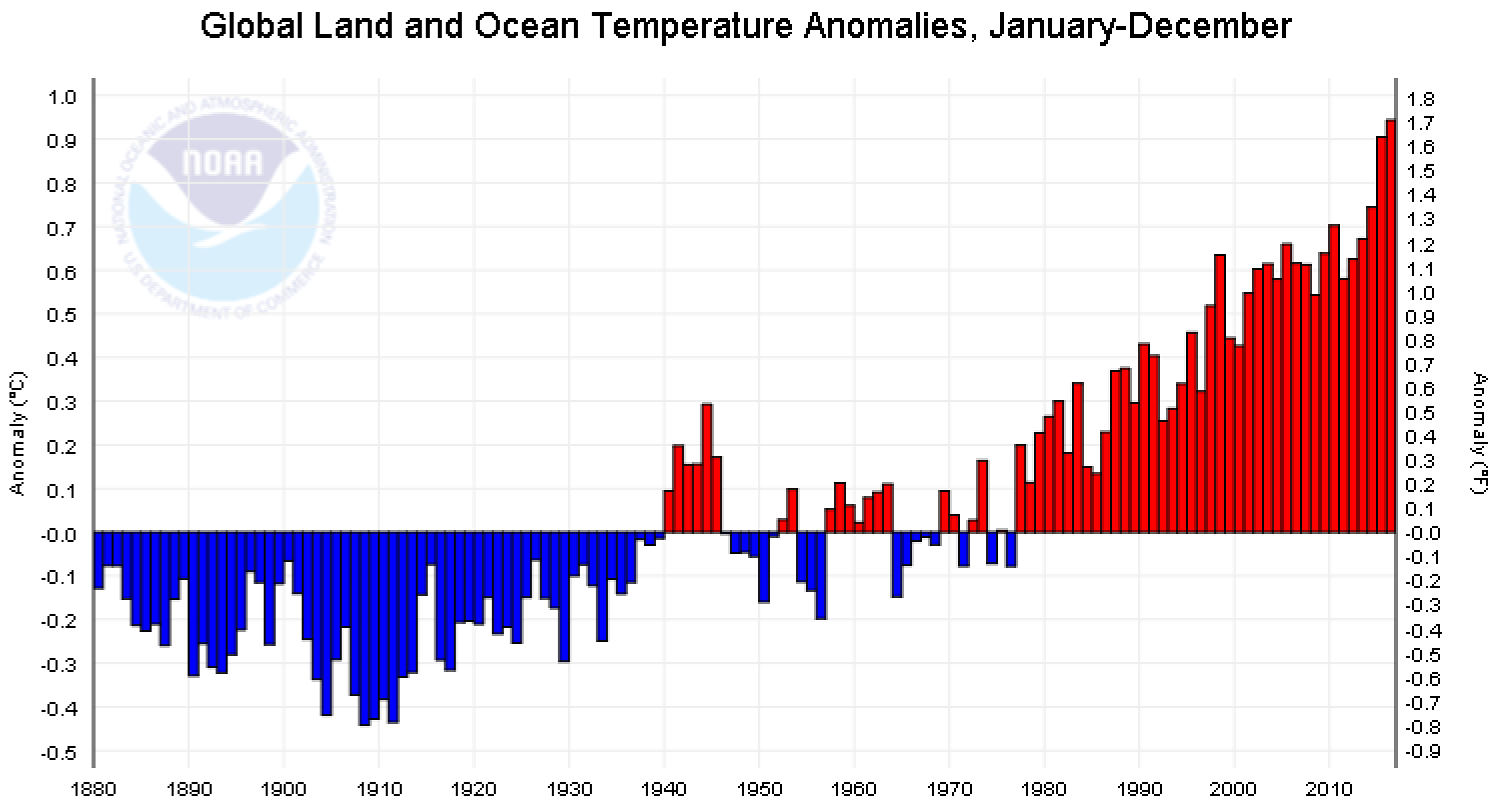
Hurricane Irene and Sandy Comparisons: Flooded Areas, NY Metropolitan Area





Source: U. S. DOE (2013) Comparing the Impacts of Northeast Hurricanes on Energy Infrastructure., p. 6 citing FEMA
http://energy.gov/sites/prod/files/2013/04/f0/Northeast%20Storm%20Comparison_FINAL_041513c.pdf

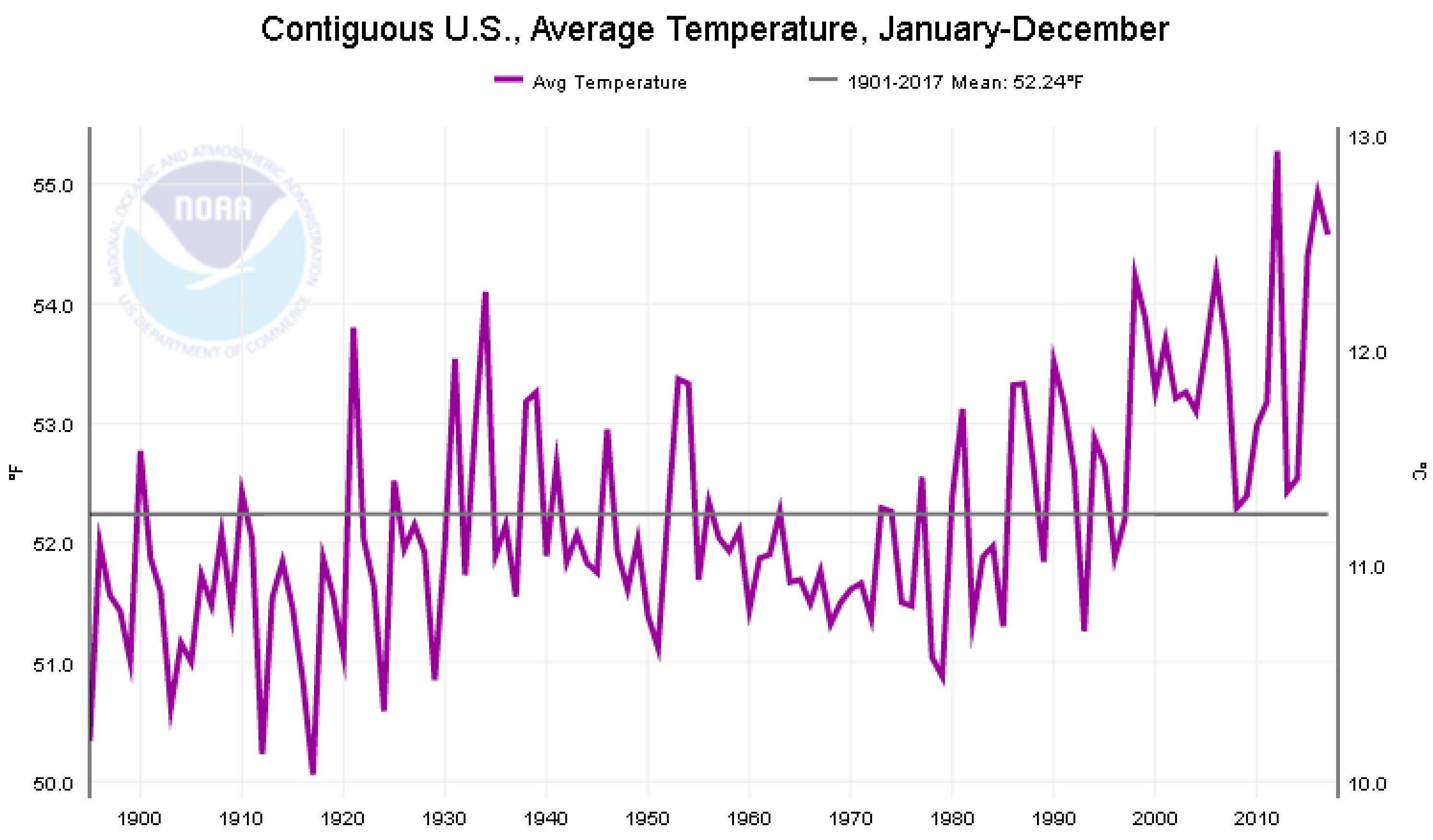
Extreme Events: Heat



Official citation: NOAA National Centers for Environmental information, Climate at a Glance: Global Time Series, published June 2017, retrieved on June 24, 2017 from http://www.ncdc.noaa.gov/cag/

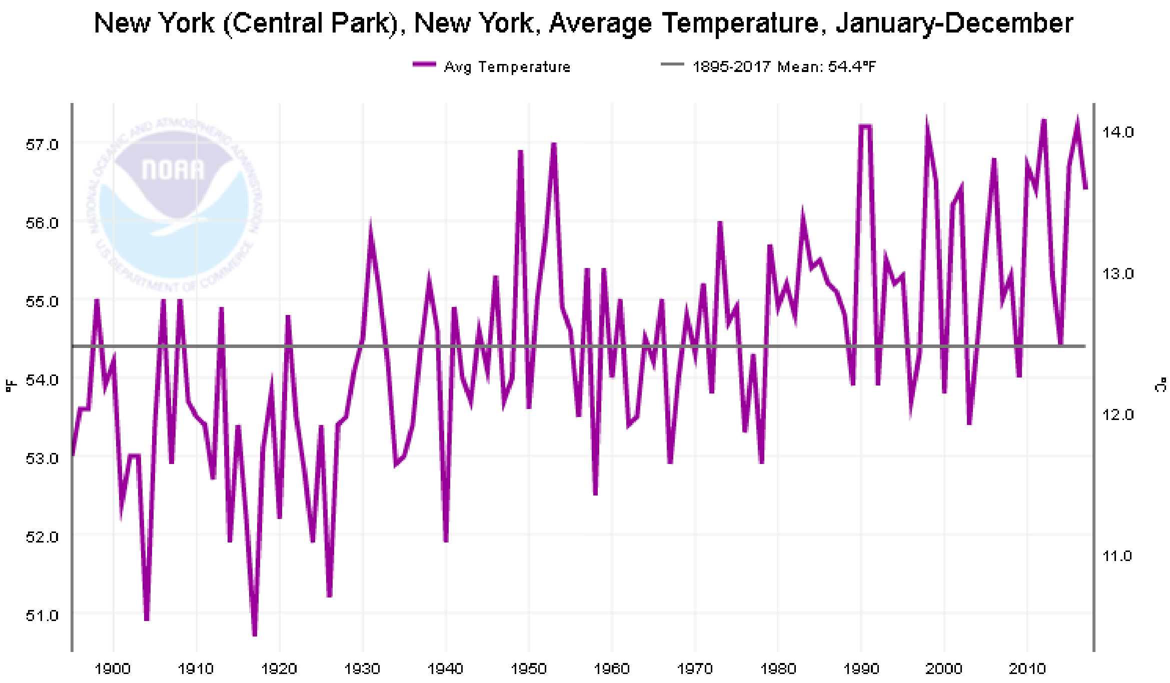
Source: NOAA National Centers for Environmental Information Climate at a Glance Global land and ocean temperature anomalies Year to Date 1888 to 2017 https://www.ncdc.noaa.gov/cag/time-series/global. Note: “Global and hemispheric anomalies are with respect to the 20th century average. Continental anomalies are with respect to the 1910 to 2000 average.”

Extreme Events: Temperature, U.S.



Official citation: NOAA National Centers for Environmental information, Climate at a Glance: Global Time Series, published June 2017, retrieved on June 24, 2017 from http://www.ncdc.noaa.gov/cag/
Source: NOAA National Centers for Environmental Information Climate at a Glance Global land and ocean temperature anomalies Year to Date 1888 to 2017 https://www.ncdc.noaa.gov/cag/time-series/global. Note: “Global and hemispheric anomalies are with respect to the 20th century average. Continental anomalies are with respect to the 1910 to 2000 average.”

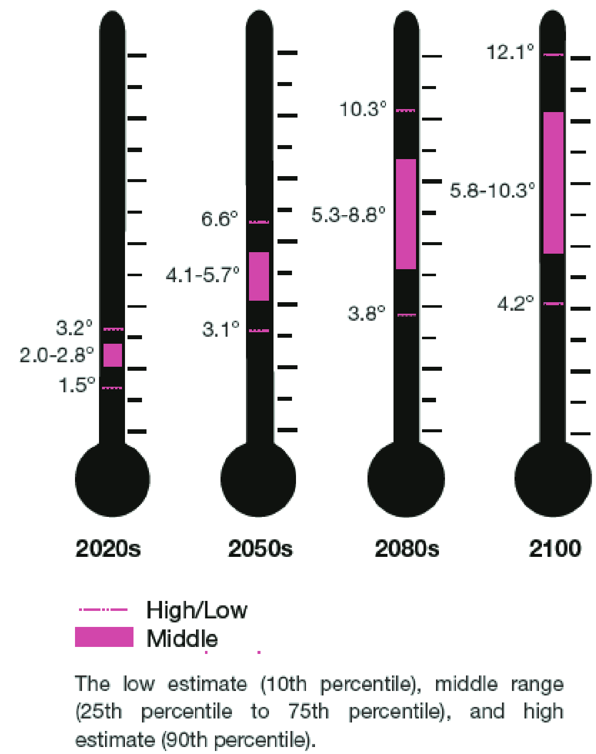
Extreme Events: Temperature, NYC

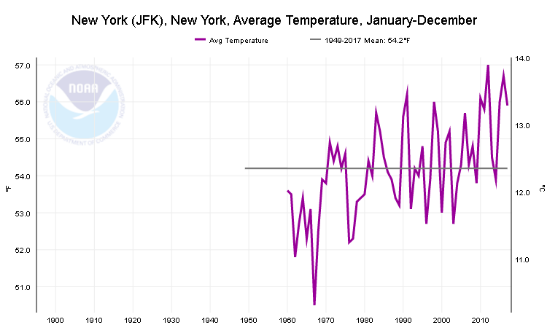


Expected Temperature Increases in NYC through the End of the Century

Temperature - Mean Annual Changes

Baseline (1971 - 2000) 54°F

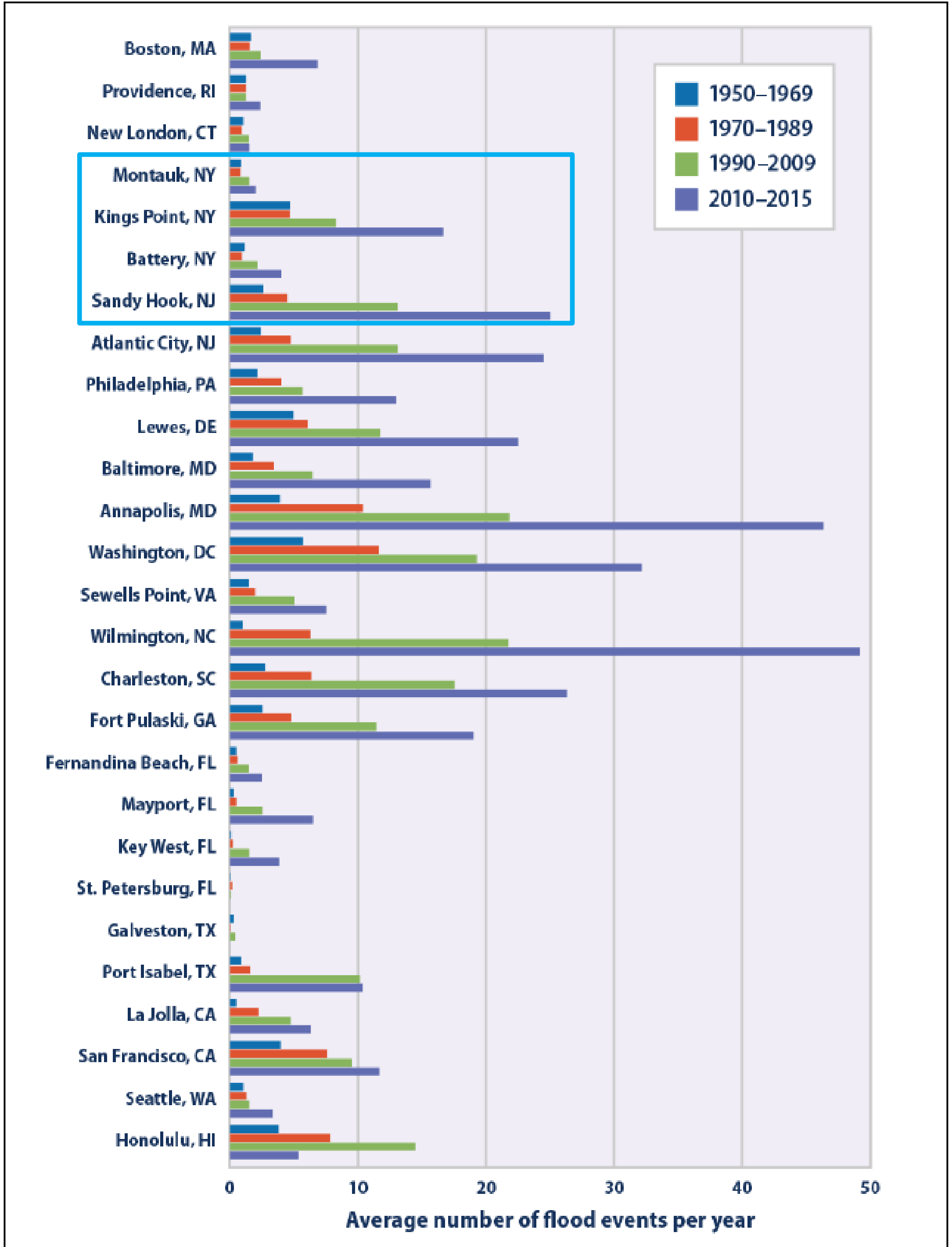




Official citation: NOAA National Centers for Environmental information, Climate at a Glance: Global Time Series, published June 2017, retrieved January 19, 2018 from http://www.ncdc.noaa.gov/cag/

Source: NOAA National Centers for Environmental Information Climate at a Glance Global land and ocean temperature anomalies Year to Date 1888 to 2017 https://www.ncdc.noaa.gov/cag/time-series/global. Note: “Global and hemispheric anomalies are with respect to the 20th century average. Continental anomalies are with respect to the 1910 to 2000 average.

Source: NYC (2016) Roadmap to 80x50, p. 5 http://www1.nyc.gov/assets/sustainability/downloads/pdf/publications/New%20York%20City's%20Roadmap%20to%2080%20x%2050_20160926_FOR%20WEB.pdf



Extreme Events: <u>Coastal Flooding</u> Trends by U.S. City Annual Average Coastal Flooding, 1950-2015, NY area in comparison with other cities

Source: U.S. EPA (2016) Climate Indicators https://www.epa.gov/climate-indicators, Figure 2. "Average Number of Coastal Flood Events Per year, 1950-2015." "This graph shows the average number of days per year in which coastal waters rose above the local threshold for minor flooding at 27 sites along U.S. coasts. The data have been averaged over multi-year periods for comparison. Data source cited: NOAA, 2016.

Climate Change Threats: Selected Historical Trends, New York City*

Trends, 1900-2013 (Central Park)

- Annual Mean Air Temperature: **0.3°F/decade increase*** (*Horton et al. 2014, p. 4*; Horton et al. 2015 Chapter 1, p. 22**)
- Mean Annual Precipitation: **0.8 inches/decade increase** (*Horton et al. 2014, p. 4*; Horton et al. 2015 Chapter 1, p. 23**)
- Sea Level Rise (at the Battery): **1.2 inches/decade increase**; this is about double the rate that is occurring globally, and about 40% of the increase is from land subsidence (Horton et al. 2015 Chapter 2, pp. 36, 37***)

Extreme Events (*Horton et al. 2014, pp. 12, 14; Horton et al 2015 Chapter 1, pp. 24-26): Extremes are difficult to identify at local scales; are highly variable over time and infrequent; NYC has experienced extremes in precipitation (more but not statistically significant increase since 1900) and temperature.

Sources: Summarized from-
*R. Horton, D. Bader, C. Rosenzweig, A. DeGaetano, and W.Solecki (2014) Climate Change in New York State: Updating the 2011 ClimAID Climate Risk Information. New York State Energy Research and Development Authority (NYSERDA), Albany, New York. (http://www.nyserda.ny.gov/climaid) ;
**R. Horton, D. Bader, Y. Kushnir, C. Little, R. Blake, and C. Rosenzweig (2015) Chapter 1: Climate Observations and Projections, New York City Panel on Climate Change 2015 Report , C. Rosenzweig and W. Solecki (Editors), Annals of the New York Academy of Sciences, 1336: 18-35. doi: 10.1111/nyas.12586.
***R. Horton, C. Little, V. Gornitz, D. Bader, M. Oppenheimer (2015) Chapter 2: Sea Level Rise and Coastal Storms, New York City Panel on Climate Change 2015 Report , C. Rosenzweig and W. Solecki (Editors), Annals of the New York Academy of Sciences, 1336: 36-44. doi: 10.1111/nyas.12626
Earlier documents: New York City Panel on Climate Change, 2013: Climate Risk Information 2013: Observations, Climate Change Projections, and Maps. C. Rosenzweig and W. Solecki (Editors), NPCC2. Prepared for use by the City of NY Special Initiative on Rebuilding and Resiliancy, NY, NY p. 4. http://www.nyc.gov/html/planyc2030/downloads/pdf/npcc_climate_risk_information_2013_report.pdf

Selected Climate Change Projections, NYC and Region

Middle range: 25th-75th percentile/decade (1971-2000 base, Temp. & Ppt.)

- Temperature (*Horton et al. 2014, p. 9; **Horton et al. 2015 Ch. 1, p. 30; Base of 54 °F)
  - 2020s: +2.0° – 2.9°F
  - 2050s: +4.1° – 5.7°F
  - 2080s: +5.3° – 8.8°F
  - 2100: +5.8° – 10.4°F
- Precipitation (*Horton et al. 2014, p. 9; **Horton et al. 2015 Ch. 1, p. 30; Base of 50.1 in)
  - 2020s: +0-8%
  - 2050s: +4-11%
  - 2080s: +5-13%
  - 2100: -1 to +19%
- Sea Level Rise(*Horton et al. 2014, p.10;**Horton et al. 2015, Ch.2, p. 41; Baseline 0 in, 2000-2004)
  - 2020s: +4-8 inches
  - 2050s: +11-21 inches
  - 2080s: +18-39 inches
  - 2100: +22-50 inches

Sources: *R. Horton, D. Bader, C. Rosenzweig, A. DeGaetano, and W.Solecki (2014) Climate Change in New York State: Updating the 2011 ClimAID Climate Risk Information. New York State Energy Research and Development Authority (NYSERDA), Albany, New York. (http://www.nyserda.ny.gov/climaid) ;
**R. Horton, D. Bader, Y. Kushnir, C. Little, R. Blake, and C. Rosenzweig (2015) Chapter 1: Climate Observations and Projections, New York City Panel on Climate Change 2015 Report , C. Rosenzweig and W. Solecki (Editors), Annals of the New York Academy of Sciences, 1336: 18-35. doi: 10.1111/nyas.12586.
***R. Horton, C. Little, V. Gornitz, D. Bader, M. Oppenheimer (2015) Chapter 2: Sea Level Rise and Coastal Storms, New York City Panel on Climate Change 2015 Report , C. Rosenzweig and W. Solecki (Editors), Annals of the New York Academy of Sciences, 1336: 36-44. doi: 10.1111/nyas.12626
Earlier documents: New York City Panel on Climate Change, 2013: Climate Risk Information 2013: Observations, Climate Change Projections, and Maps. C. Rosenzweig and W. Solecki (Editors), NPCC2. Prepared for use by the City of NY Special Initiative on Rebuilding and Resiliancy, NY, NY p. 4.
http://www.nyc.gov/html/planyc2030/downloads/pdf/npcc_climate_risk_information_2013_report.pdf

II. Electricity Characteristics:

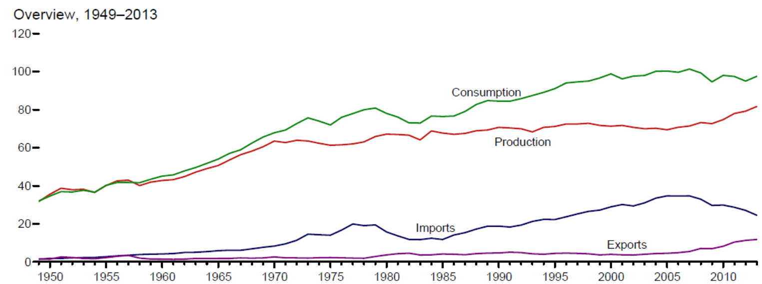
Factors Influencing Vulnerability to Consequences of Extreme Events and Climate Change

- **<u>Usage</u> and demand: U.S. usage and production has generally been increasing along with usage of the sectors that depend on it**
- **Underlying <u>Condition</u>**
  - **The ASCE infrastructure report card has consistently rated the energy sector as D+ in the last three ratings 2009, 2013, and 2017 which is equivalent to the average for all sectors rated.***
  - **The ASCE also has estimated total funding need from 2016 to 2025 for electricity at $934 billion (2015 constant $s), $757 billion is funded leaving a gap of $177 billion.****
- **<u>Outage</u> histories show increases in frequency and duration for numerous causes including weather.*****
- **Historically, electric power production and related components are located in <u>vulnerable coastal locations</u>, NYC is no exception.**
- **<u>Interdependencies</u> can exacerbate problems, especially in extreme weather situations**

Sources: *ASCE (2017) 2017 Infrastructure Report Card (p. 6) https://www.infrastructurereportcard.org/ **ASCE 2016 Failure To Act Closing The Infrastructure Investment Gap For America's Economic Future Update to Failure To Act: The Impact Of Infrastructure Investment On America's Economic Future, pp. 5, 11. https://www.infrastructurereportcard.org/wp-content/uploads/2016/10/ASCE-Failure-to-Act-2016-FINAL.pdf ***Simonoff, J.S., Restrepo, C.E., and Zimmerman, R. (2007) "Risk Management and Risk Analysis-Based Decision Tools for Attacks on Electric Power," *Risk Analysis*, Vol. 27, No. 3, pp. 547-570.

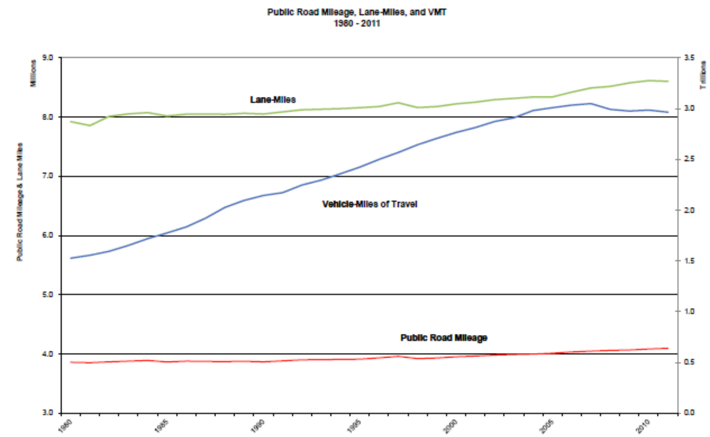
Increased Infrastructure Use and Limited Capacity

- Energy Usage and Production: Based on EIA data, consumption and production increase (particularly in residential, commercial and transportation sectors) with depressions during recession periods (most recently late 2000s); production rates exceed consumption rates (Source: EIA, Monthly Energy Review, 2014, Fig. 1.1 http://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf

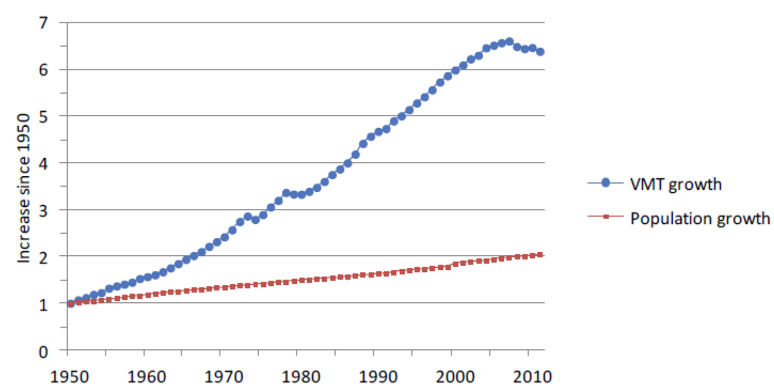


Other Infrastructures Dependent on Energy

- Transportation: According to FHWA data, Vehicle Miles of Travel and fuel consumption continue to increase in spite of fuel economy (Source of figure and findings: U.S. DOT, FHWA (April 2013) Highway Statistics 2011). APTA (2013) shows similar increases for public transit.
- Communications: Usage has been increasing exponentially, reflected in cell phone use (Source: CTIA (2014) Annual Wireless Industry Survey for 2013 http://files.ctia.org/pdf/CTIA_Survey_YE_2012_Graphics-FINAL.pdf
- Water: Total water use nationwide has increased primarily from residential use (U.S. EPA 2013), however, in NYC total water consumption and per capita water consumption has declined. But capacity in some areas has been limited by age and quality of water distribution systems (e.g., breakages, leaks).



U.S. DOT, FHWA (April 2013) Highway Statistics 2011, VMT-422 http://www.fhwa.dot.gov/policyinformation/statistics/2011/pdf/vmt422c.pdf



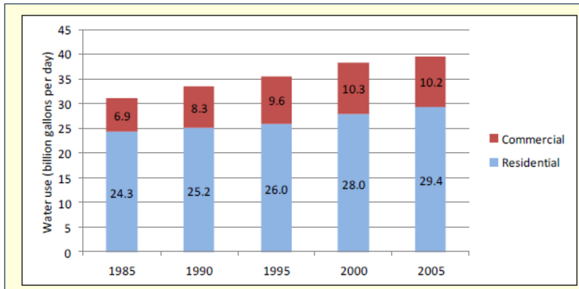


Exhibit 2-14: Water use in the building sector, 1985-2005. For the years 2000 and 2005, the split between commercial and residential use is based on extrapolation from 1995 data.
Source: U.S. Department of Energy 2012

Source: U.S. EPA (2013) Our Built and Natural Environments: A Technical Review of the Interactions among Land Use, Transportation, and Environmental Quality, Second edition. Washington, D.C.: EPA http://www.epa.gov/dced/pdf/b-and-n/b-and-n-EPA-231K13001.pdf, p. 17(water); p.26 (VMT)

New York City Energy Use Patterns and Trends

The NYS Independent System Operator (ISO) tracks usage forecasts with and without weather effects (2017b: 12, 16-17):

- **2010-2014: 4.7% annual usage decline for NYC (55,114 to 52,541 Gigawatt Hours), declining each year (NYS ISO, 2015: 10); NYS ISO considers is related to cooler summers and energy efficient appliances.**
- **2014-2015, 1.8% increase in usage (NYS ISO, 2016:**
- **2015-2016: 0.31% increase in annual usage (53,485 GWh to 53,653 GWh) (NYS ISO 2017a: 13).**
- **2017-2027 forecast: Declines in annual energy usage are anticipated with an increase in summer peak demand and a decrease in winter peak demand.**

Sources: NPCC3, Chapter 4 (forthcoming); citing NYS ISO reports NYS Independent System Operator (ISO) (2015) Power trends 2015. Rensselaer, NY: ISO. NYS Independent System Operator) (ISO). 2016. 2016 Power trends 2016. Rensselaer, NY: ISO. NYS Independent System Operator) (ISO). 2017a. 2017 Power trends 2017. Rensselaer, NY: ISO. NYS ISO. 2017b. 2017 Load & Capacity Data "Gold Book." http://www.nyiso.com/public/webdocs/markets_operations/services/planning/Documents_and_Resources/Planning_Data_and_Reference_Docs/Data_and_Reference_Docs/2017_Load_and_Capacity_Data_Report.pdf

Note: NYS ISO covers only NYS.

Infrastructure Vulnerabilities: Location, e.g., Coasts

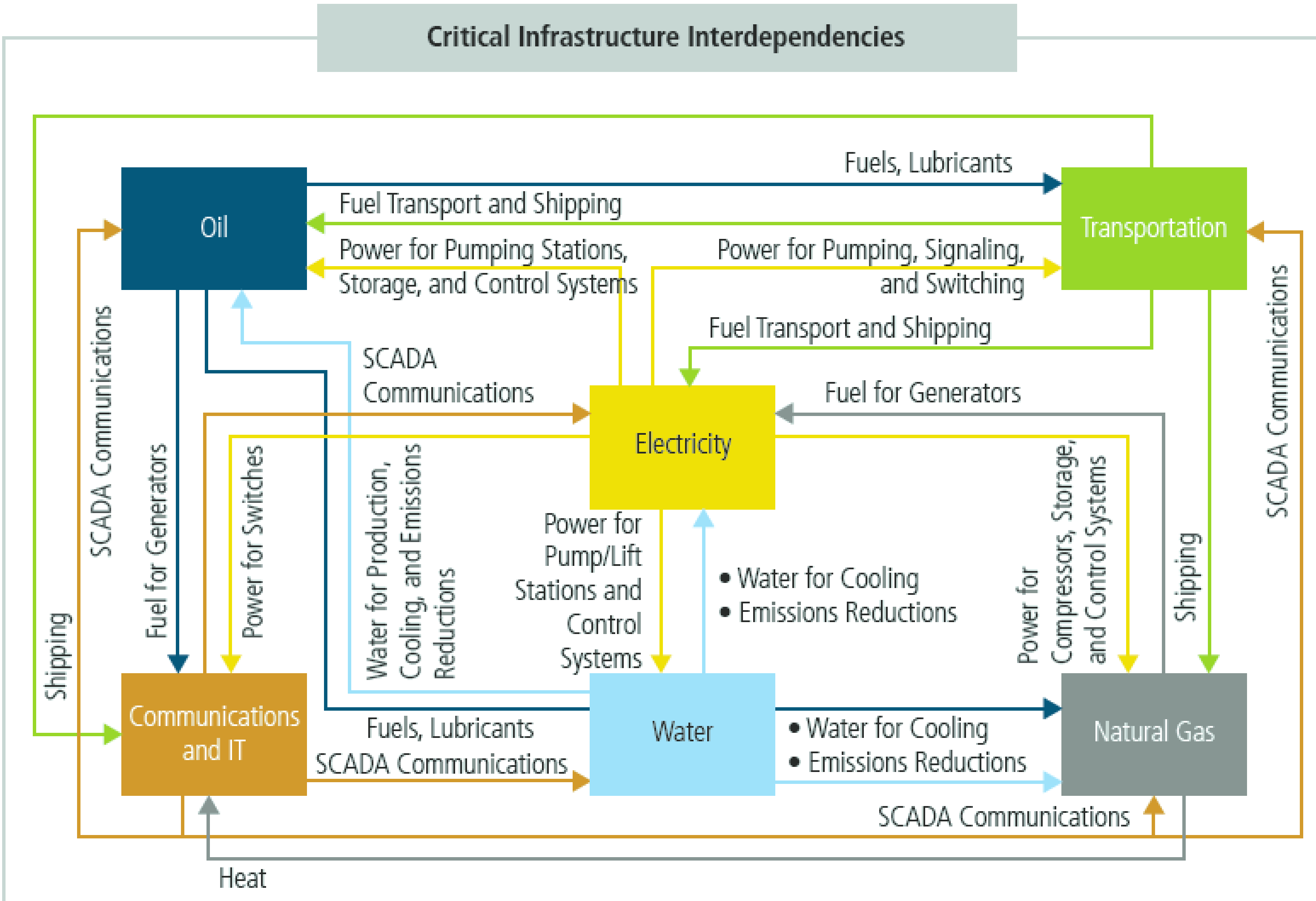
According to the NYC OEM's Hazard Mitigation Plan* 100% of power plants are located within "SLOSH" inundation zones

*Source: NYS Division of Homeland Security and Emergency Services (January 2014) 2014 NYS Hazard Mitigation Plan. Albany, NY: NYS, p. 125, available at http://www.dhses.ny.gov/oem/mitigation/documents/2014-shmp/2014-SHMP-full.pdf.

Source: R. Zimmerman and C. Faris (2010) "Infrastructure Impacts and Adaptation Challenges," Chapter 4 in Climate Change Adaptation in New York City: Building a Risk Management Response, New York City Panel on Climate Change 2010 Report, edited by C. Rosenzweig and W. Solecki. Prepared for use by the New York City Climate Change Adaptation Task Force. Annals of the New York Academy of Sciences, Vol. 1196. New York, NY, NY Academy of Sciences, pp. 63-85. P. 68.

Lifeline Infrastructure Interdependencies

Focusing on Electricity



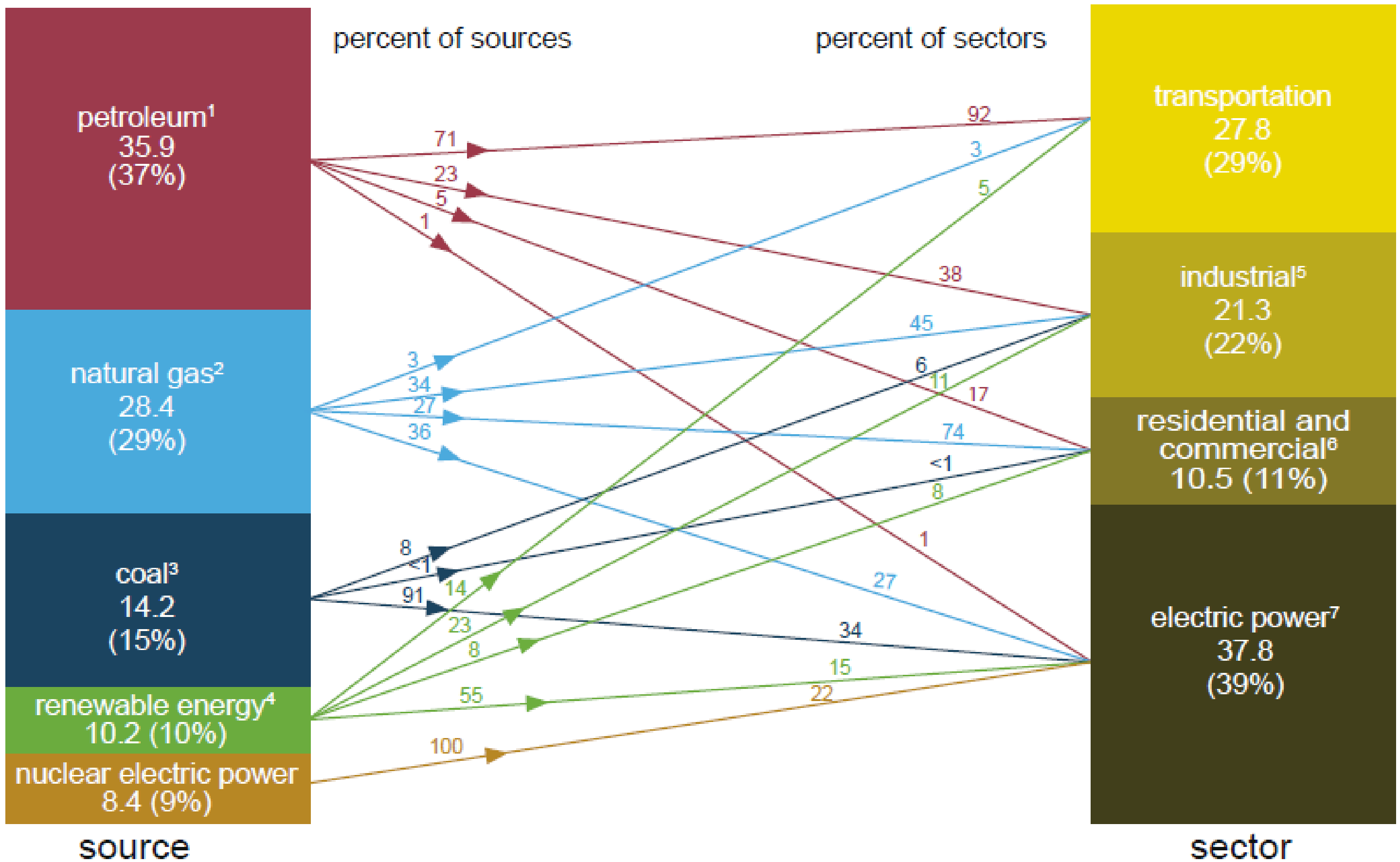
Source: U.S. Department of Energy (DOE) (January 2017) Quadrennial Energy Review: Transforming the Nation's Electricity System: The Second Installment of the QER, p. 1-9, figure 1-2. https://energy. gov/sites/prod/files/2017/02/f34/Quadrennial%20Energy%20Review-Second%20Installment%20%28Full%20Report%29.pdf

Interconnections: Energy and Other Sectors

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.

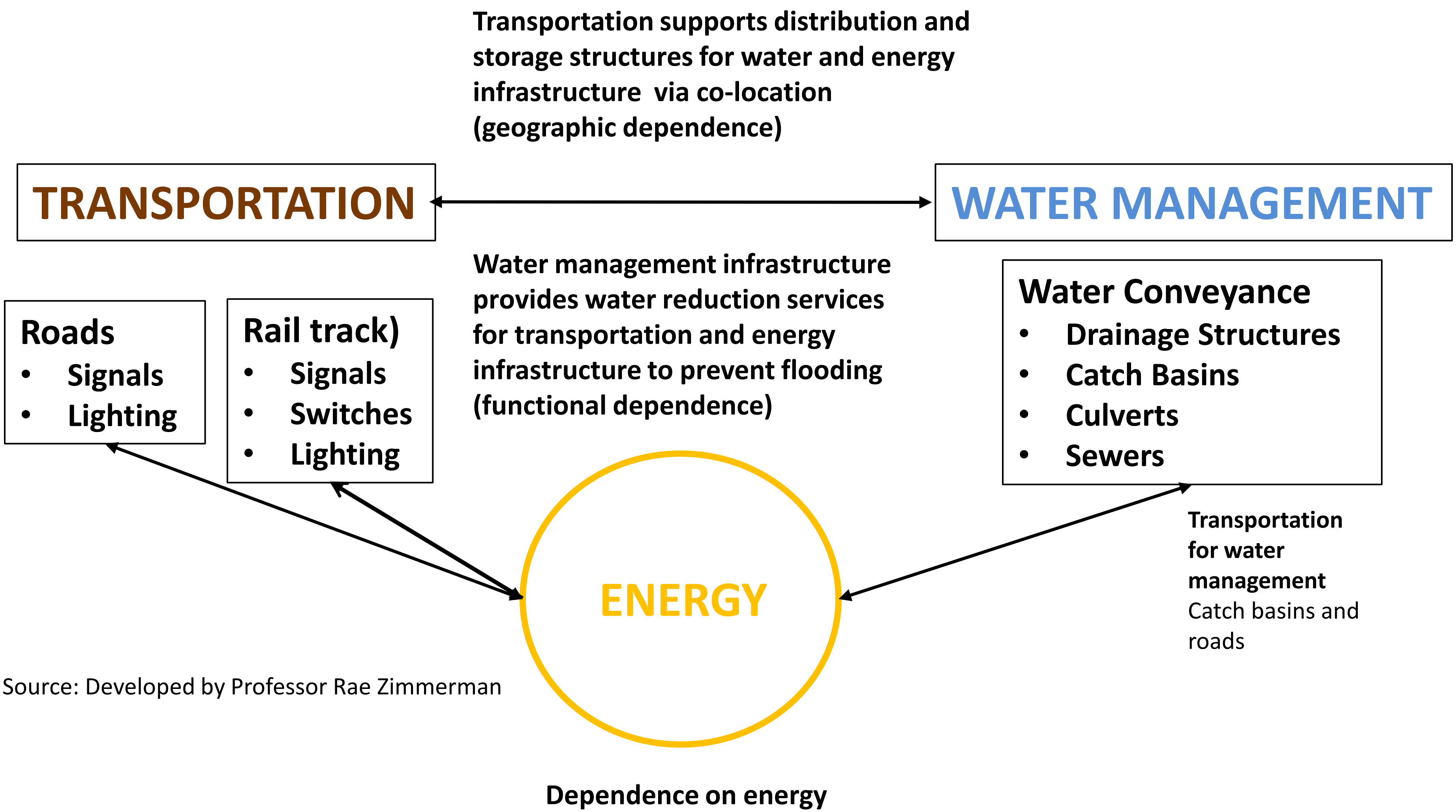
Source: U.S. Department of Energy, Energy Information Administration (2016) https://www.eia.gov/totalenergy/data/monthly/pdf/flow/css_2016_energy.pdf

NY Area Examples of Interdependency Impacts Collisions: 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.*
- The Metro-North railway outage: Large power line impairment lasted >week.**
- September 29, 2011 Lightening Strike on a LIRR Computer:*** 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)****

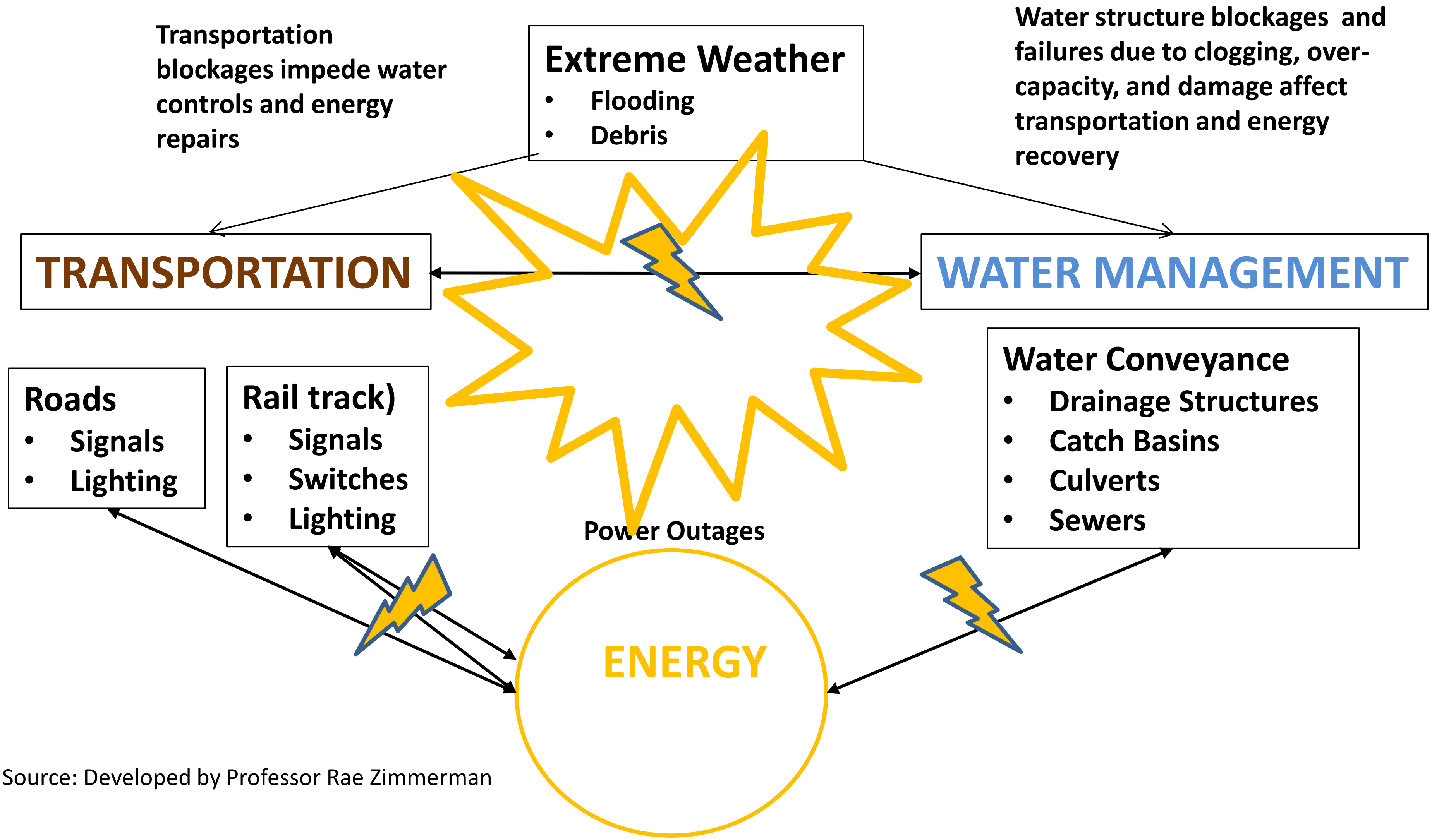
Sources:
*R. Zimmerman and C. E. Restrepo (2006) "The Next Step: Quantifying Infrastructure Interdependencies to Improve Security," International Journal of Critical Infrastructures, Vol. 2, Nos. 2/3, pp. 215-230; p. 223.
**Matt Flegenheimer (September 25, 2013) Power Failure Disrupts Metro North's New 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
***Metropolitan Transportation Authority (MTA) (October 2011), 'Preliminary review September 29, 2011 lightning strike at Jamaica', New York, NY, USA: MTA.
****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.

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



Source: Developed by Professor Rae Zimmerman

Dysfunctional Interconnected Infrastructure in Extreme Weather



Source: Developed by Professor Rae Zimmerman

Choke points at the intersection of different interconnected infrastructure systems

III. Intersection of Weather, Climate & Electricity:

Hurricane Irene and Sandy Impact Comparisons

Electric Power Outage and Petroleum System Impacts

	Irene	Sandy
“Electric Customer Outages (millions)	6.69	8.66
Petroleum Refining Capacity Shut (barrels per day)	238,000	308,000
Petroleum Product Terminals Shut (number)	25	57”*

Facilities located in flooded areas – NYS only**		
Electric Power Plants	12	24
Electric Substations	12	28
Petroleum Terminals	7	13

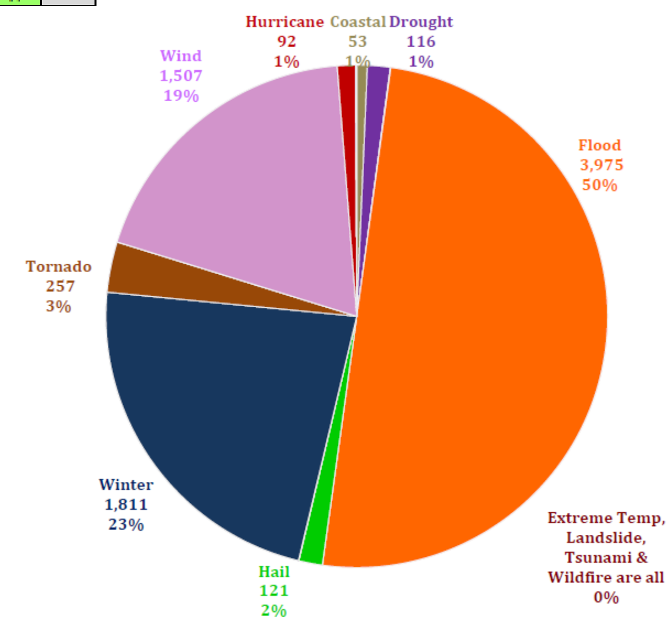
New York State:***	Irene	Sandy
Peak Power Outages	941,914	2,097,931
Percentage of Total Customers	10%	23%

Source: U. S. DOE (2013) Comparing the Impacts of Northeast Hurricanes on Energy Infrastructure. *p. v; **summarized from p. 5; *** p. 41
http://energy.gov/sites/prod/files/2013/04/f0/Northeast%20Storm%20Comparison_FINAL_041513c.pdf

Risk-Based Approach: Combining Hazards and Consequences to Prioritize Response Resources, NYS

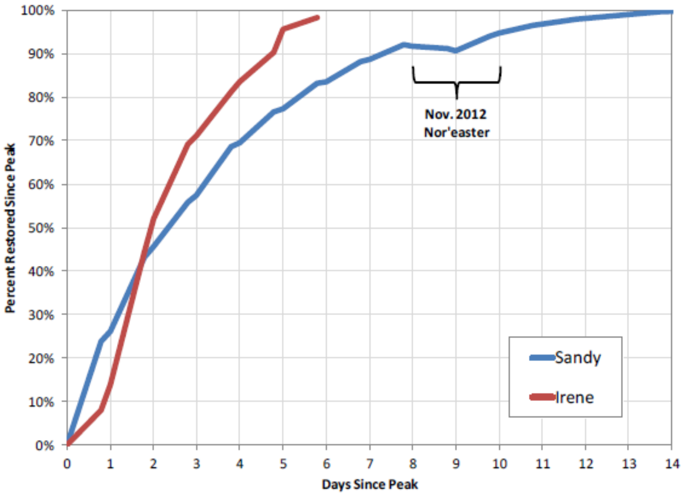
Primary Hazards	Structural Damage	Utility Outage	Chemical Release/Spill	Commodity Shortage	Emergency Comm. Failure	Erosion	Structural Fire	Environmental Impact	Economic -Direct or Indirect	Disease/Public Health	Impact to Responders and/or Program Operation	Flooding	Landslide	Dam/Levee Failure	Storm Surge	Tornado	Wildfire	Hail	Tsunami
Hurricane/TS/Nor'Easter	X	X	X	X	X	X	X	X	X	X	X	X			X	X			
Climate Change	X	X		X	X	X		X	X	X	X	X	X	X	X	X	X	X	
Flooding - Coastal	X	X	X			X	X	X	X	X	X	X	X						
Flooding - Inland	X	X	X			X		X		X	X		X	X					
Flooding - Ice Jam	X							X				X		X					
High Winds/Tornado	X	X	X																
Earthquake	X	X	X	X	X		X		X	X	X		X	X					
Coastal Erosion	X					X		X	X			X	X						
Extreme Temperatures								X	X	X									
Drought				X				X	X	X									
Severe Winter Storm	X	X		X	X		X												
Wildfire	X						X	X					X						
Tsunami	X	X	X	X		X				X		X							
Hailstorm								X											
Avalanche	X																		
Landslide	X					X													
Land Subsidence/Expansive Soils	X																		

*Hazard Ranking colors: red = high; orange = moderate; yellow = low

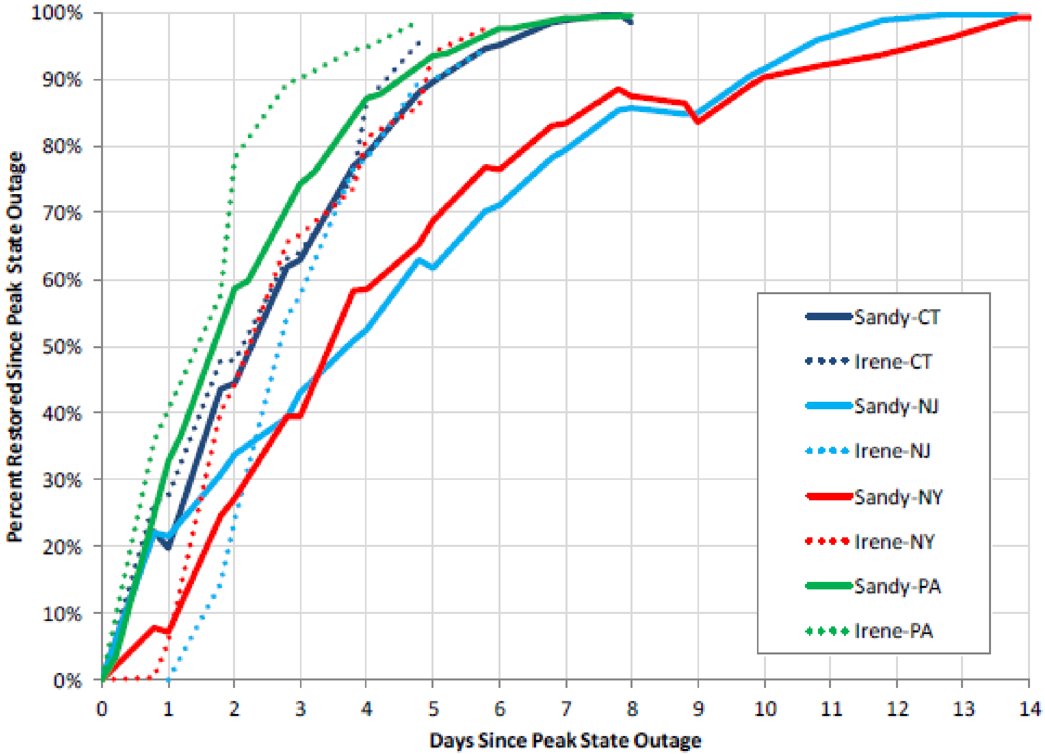


Source: NYS Division of Homeland Security and Emergency Services (January 2014) 2014 NYS Hazard Mitigation Plan. Albany, NY: NYS, p. 3.0-32, p. 3.0-50 available at http://www.dhses.ny.gov/oem/mitigation/documents/2014-shmp/2014-SHMP-full.pdf. Note: In another location or time period, the ranking of the primary hazards and the listing of consequences and assignment of hazards to the consequences might be different.

Hurricane Irene and Sandy Comparisons: Restoration, NY Metropolitan Area



Source: OE/ISER Emergency Situation Reports

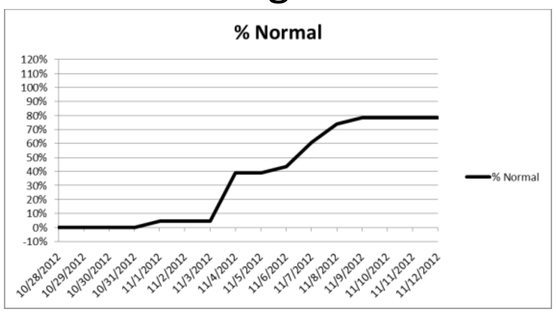


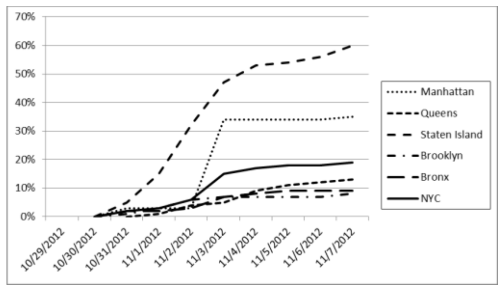
Source: OE/ISER Emergency Situation Reports

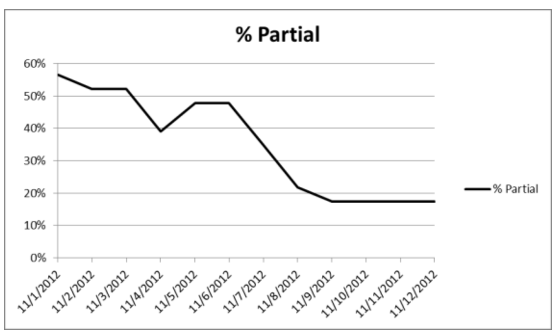
Source: U. S. DOE (2013) Comparing the Impacts of Northeast Hurricanes on Energy Infrastructure, p. 11, 12
http://energy.gov/sites/prod/files/2013/04/f0/Northeast%20Storm%20Comparison_FINAL_041513c.pdf

Recovery of Transit and Electric Power Post-Hurricane Sandy (Interdependent Infrastructures)

- Two weeks after Hurricane Sandy, about 80% of the transit lines were fully recovered and others were partially recovered along their routes.
- In 2012 after Hurricane Sandy compared to a similar period in 2011, system ridership declined on average about 14 %.



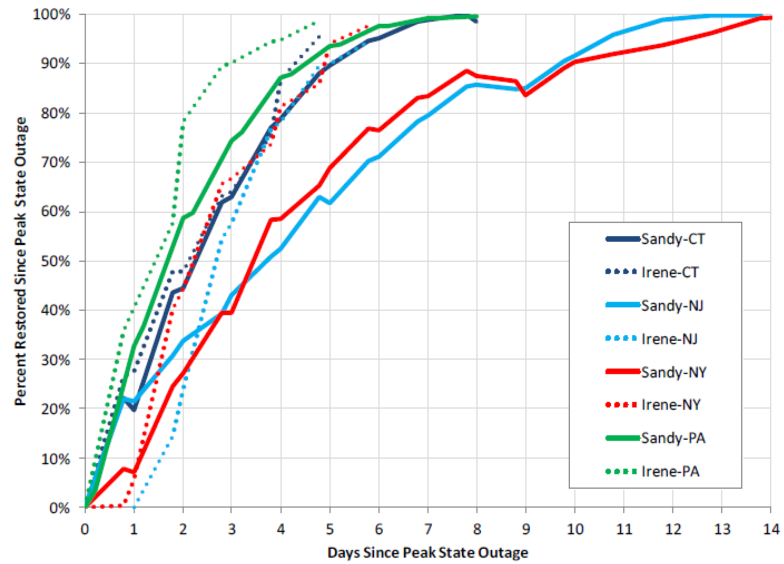




Source: R. Zimmerman, RAPID/Collaborative Research: Collection of Perishable Hurricane Sandy Data on Weather-Related Damage to Urban Power and Transit Infrastructure," NSF; R. Zimmerman (2014), "Planning Restoration of Vital Infrastructure Services Following Hurricane Sandy: Lessons Learned for Energy and Transportation," J. of Extreme Events, Vol. 1, No. 1.

Picture: MTA. Fixing A Train Tracks on the "flats" near Jamaica Bay

Figure 6. Comparison of Power Outage Restoration Percentages by Storm

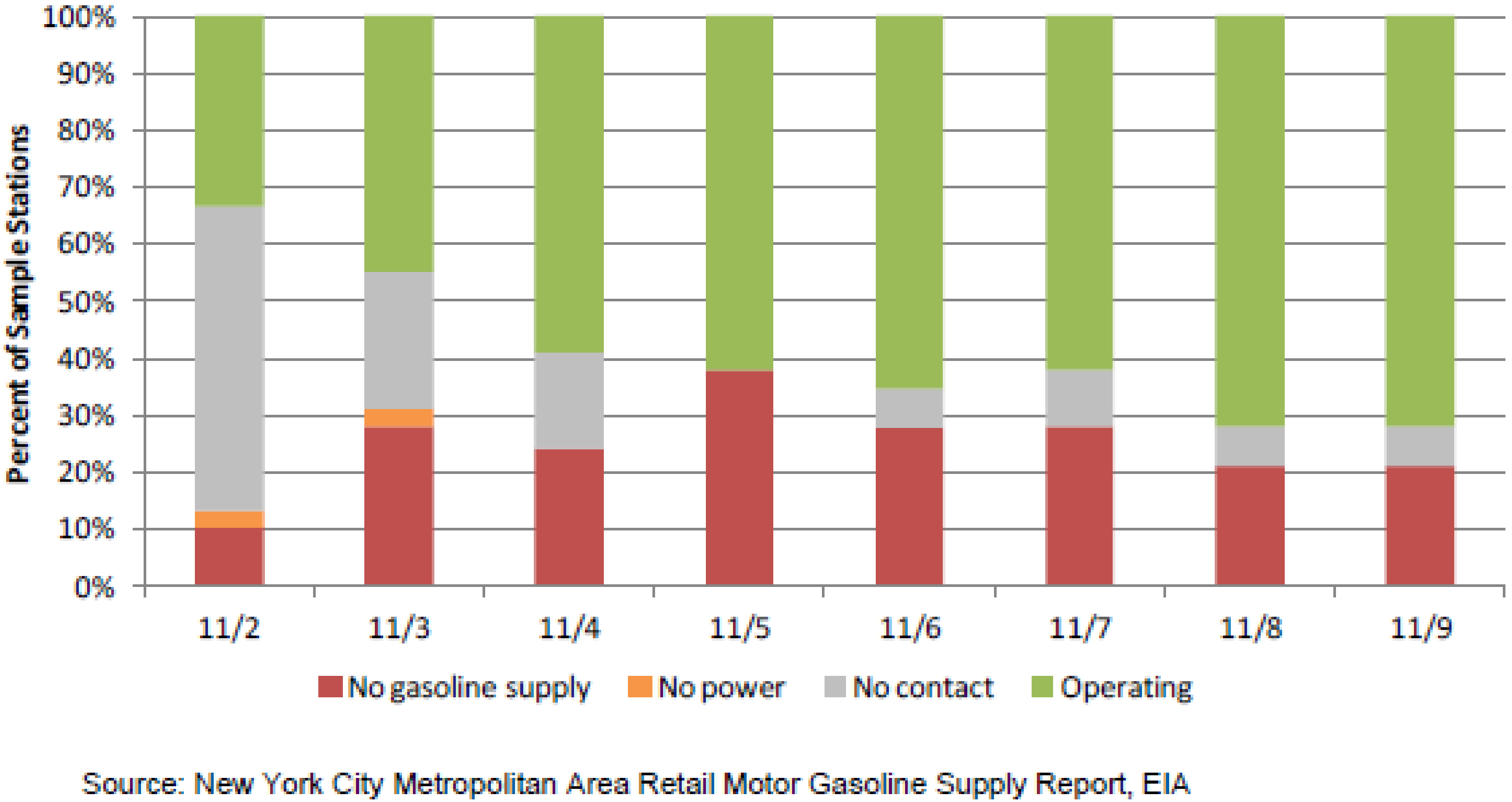


Electric power recovery followed patterns similar to transit.

U.S. Department of Energy (2013) Comparing the Impacts of Northeast Hurricanes on Energy Infrastructure. [Online], p. 11, 12 Available from: http://energy.gov/sites/prod/files/2013/04/f0/Northeast%20Storm%20Comparison_FINAL_041513c.pdf

Transit required electric power to function for third rails, signals, switches, ventilation, lighting, and to pump out excess water; energy required robust transit infrastructure for physical support and to transport workers to repair sites.

Hurricane Sandy: Recovery of other power-related infrastructure, NY Metropolitan Area



Source: U. S. DOE (2013) Comparing the Impacts of Northeast Hurricanes on Energy Infrastructure, p. 24.
http://energy.gov/sites/prod/files/2013/04/f0/Northeast%20Storm%20Comparison_FINAL_041513c.pdf

IV. How to Transition: Short-Term and Long-Term Consequence-Reduction Measures

Short-term, Measures but involving long-term thinking and strategies

- Barricade: Temporary and Permanent, intermittent operation
- Elevate, bury or submerge; land configurations
- Change materials and design to reduce exposure and consequences
- Remove or relocate vulnerable people and facilities
- Invoke mobile resource networks, e.g., “mutual assistance”; back-up resources
- Regulatory changes to expedite recovery

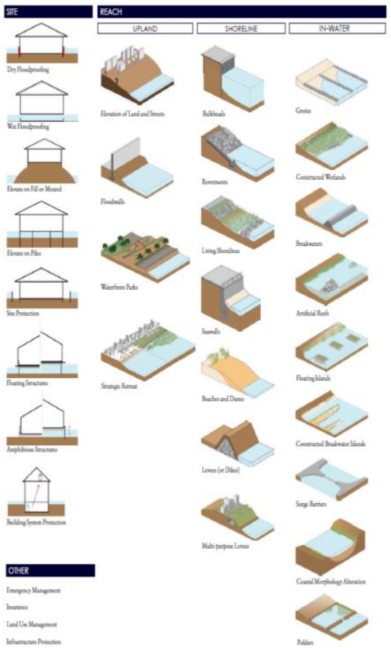
Long-term Sustainable Measures

- Reduce carbon dioxide emissions
- Renewable resources to support carbon dioxide reduction as well as impacts
- Provide alternative, distributed, and renewable resources
- Fortify / strengthen (water and physical damage resistance) through natural processes, e.g., green infrastructures
- Expand the use of alternative travel routes and decentralized travel modes
- Increase Interconnection among systems
- Move people, change land use, change behavior in the long-term

Short-Term Measures to Prevent or Reduce Infrastructure Destruction in Extreme Events

1. Land Configurations, Barriers, Elevation, Etc.

LAND



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

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:

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

BARRIERS

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

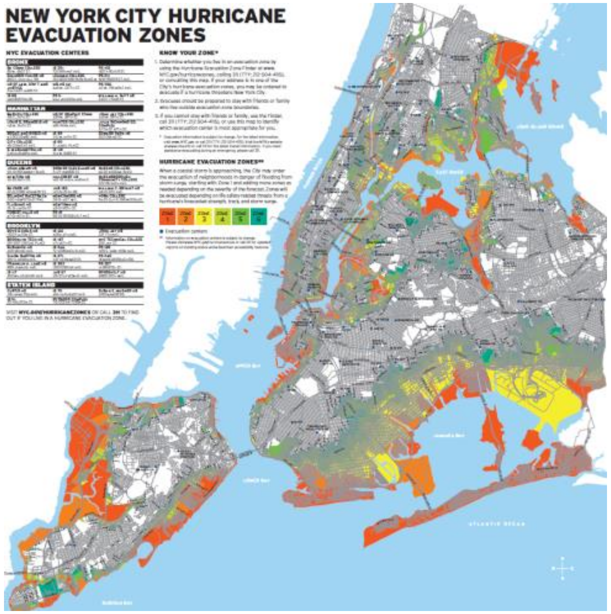
ELEVATION

Source: Photo by R. Zimmerman 2012

Source: Photos from MTA

2. Preparedness. Moving People to Safety

- Improved communications among victims and responders
- Moving away from hazards (assuming adequate time), e.g., pre- and post-event evacuation and shelter-in-place
- Health services to forestall post-event adverse health impacts
- Restoration technologies, e.g., pumps, debris removal to support infrastructure access
- Assembling financial resources
- Mobile resources: mobile generators and cell towers, portable bridges



3. Management: Mutual Assistance

- Routine networks that are activated in emergencies some of which are specific to electric power
- During Hurricane Irene and Hurricane Sandy these were invoked. Citing the Edison Electric Institute ("Understanding the Electric Power Industry's Mutual Assistance Network"), the U.S. DOE notes that clean-up operations and restoring power involved:
    - 50,000 mutual assistance workers for Hurricane Irene
    - 67,000 mutual assistance workers for Hurricane Sandy
- In addition, to workers, mutual assistance agreements also cover equipment and resources.

U.S. Department of Energy (2013) Comparing the Impacts of Northeast Hurricanes on Energy Infrastructure. [Online], p. 12-13 Available from: http://energy.gov/sites/prod/files/2013/04/f0/Northeast%20Storm%20Comparison_FINAL_041513c.pdf

4. Management: Energy Related Legislation and Regulation from Past Experiences

Numerous Permit and Environmental Review Exemptions and Exceptions*:

- Fuel restrictions under the Clean Air Act are waived when supplies are threatened by extreme events (e.g., almost all hurricanes; 47 fuel restrictions waived from 2005-2010, primarily for Hurricane Katrina)

During Hurricane Sandy numerous fuel and transportation exemptions were granted, not generally granted in Hurricane Irene:*,**

- Federal reserve ultra low sulfur diesel (ULSD) was released for fueling emergency equipment for over 120,000 barrels (>5 million gals) (U.S. DOE 2013, p. 29).
- Normally, foreign vessels are prohibited from transporting material within the U.S. under the Jones Act, but this was waived on November 2 and November 3, 2012, and shipments from the Gulf ports to the northeast amounted to about 2.7 million barrels (about 115 million gallons) of petroleum products, half of which was sent to the NY harbor area (U.S. DOE 2013, p. 30). A Jones Act waiver was also granted for a limited time for other hurricanes.
- Exemptions under the Clean Air Act for ULSD (NJ, NY area counties and PA) and Reformulated Gasoline (in 10 states and DC) were invoked in Hurricane Sandy from November 2, 2012 to November 12 (but extended to December 7 in NY and NJ (U.S. DOE 2013, p. 31-32).

*Summarized in R. Zimmerman (2012) Transport, the Environment and Security. Making the Connection, Cheltenham, UK and Northampton, MA: Edward Elgar Publishing, Ltd., pp. 161-162; 204-206).; U.S. Department of Energy (2013) Comparing the Impacts of Northeast Hurricanes on Energy Infrastructure. [Online], p. 11, 12 Available from: http://energy.gov/sites/prod/files/2013/04/f0/Northeast%20Storm%20Comparison_FINAL_041513c.pdf

Long-Term Measures: Moving Toward Sustainability

- Reduce carbon dioxide emissions
- Introduce renewable resources
- Provide alternative, distributed, and renewable resources
- Fortify / strengthen (for water and physical damage resistance) through natural processes, e.g., green infrastructures
- Use alternative, decentralized modes of travel
- Move people, change land use, change behavior in the long-term

1.Reducing NYC Share of Carbon Dioxide Emissions

Carbon Dioxide Intensity: NYS Energy-Related Carbon Dioxide

Figure 1. Energy-related emissions by state, 2014
million metric tons carbon dioxide

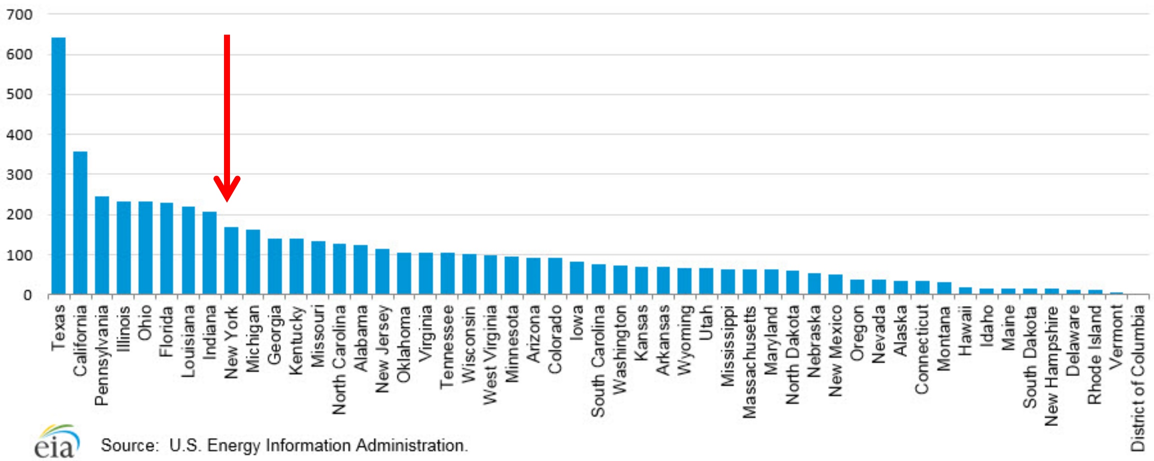
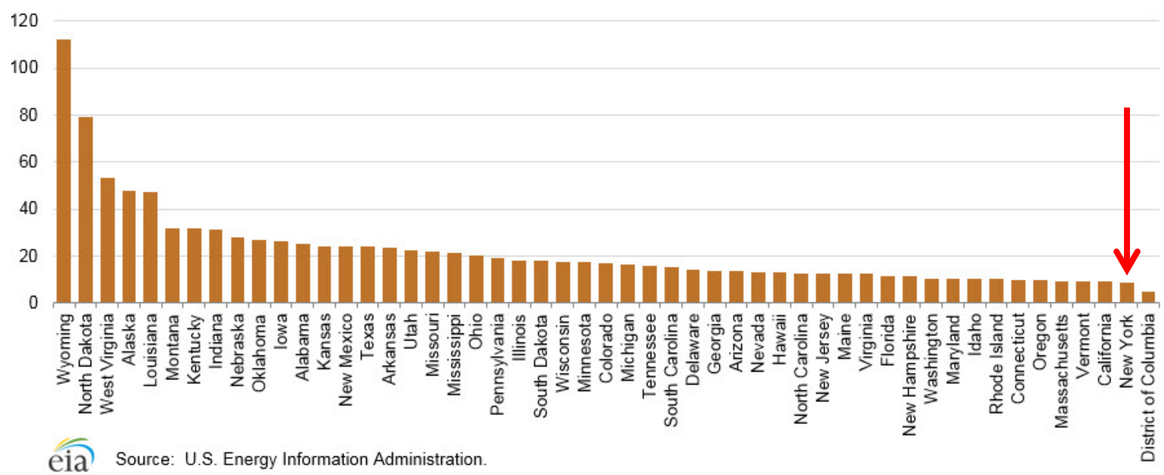
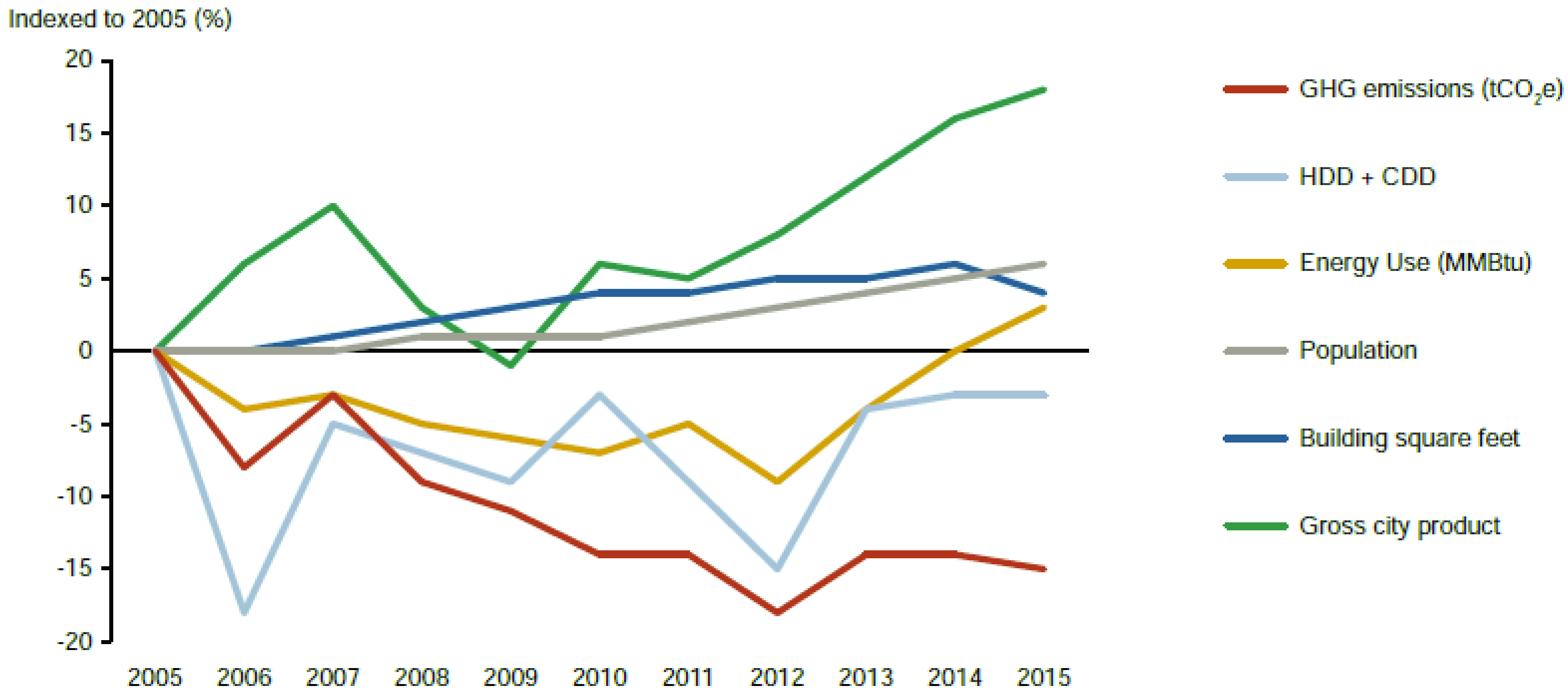


Figure 2. Per-capita energy-related carbon dioxide emissions by state, 2014
metric tons carbon dioxide per person



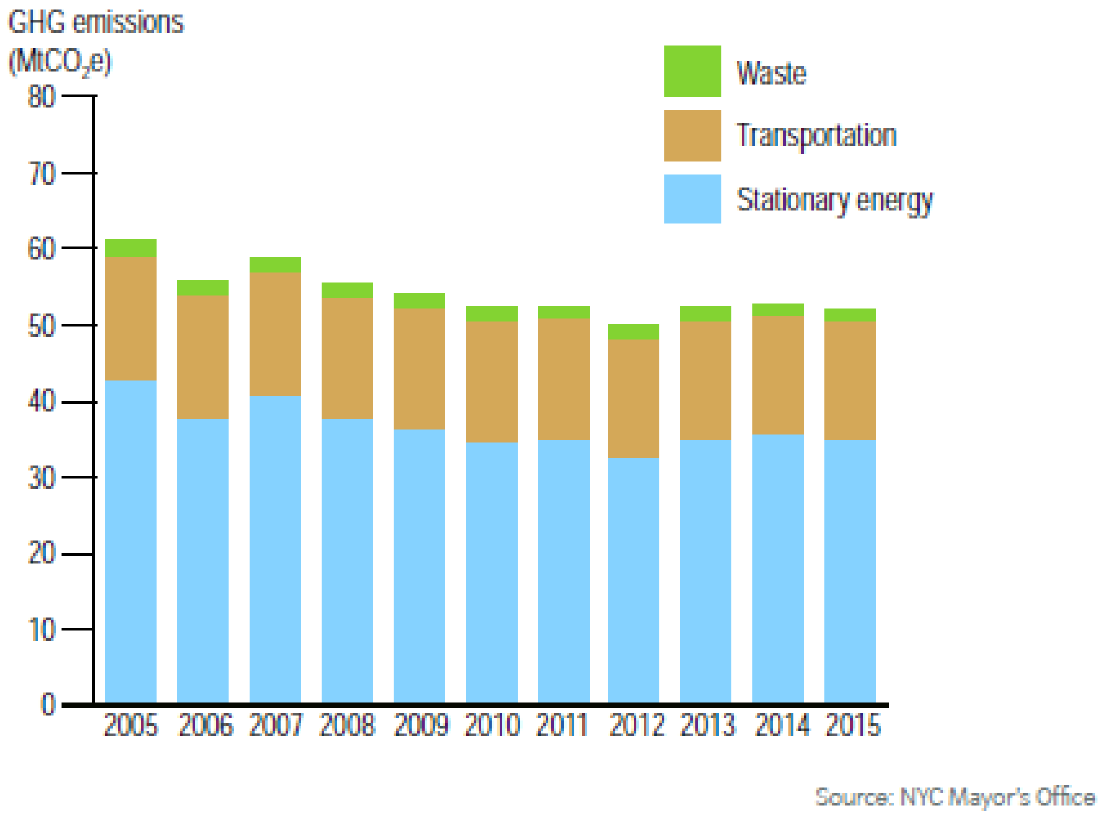
Source: U.S. Energy Information Administration (January 2017) Energy-Related Carbon Dioxide Emissions at the State Level, 2000-2014. https://www.eia.gov/environment/emissions/state/analysis/pdf/stateanalysis.pdf

NYC GHG Emissions and Other City Trends



NYC (April 2017) Inventory of New York City Greenhouse Gas Emissions in 2015, p. 7
http://www.dec.ny.gov/docs/administration_pdf/nycghg.pdf

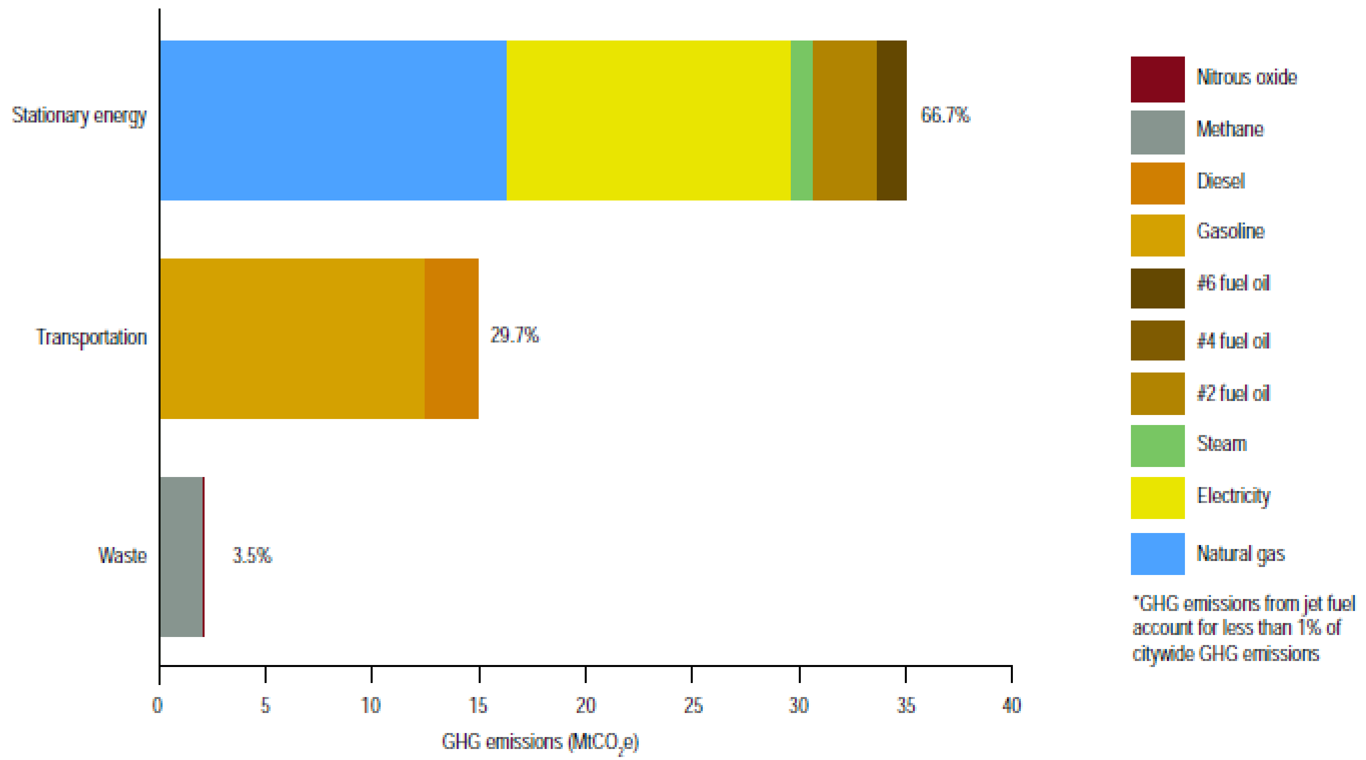
NYC Emission Trends by Source, 2005-2015



In NYC buildings contribute about 70% of greenhouse gas emissions compared with 19% in the U.S.*

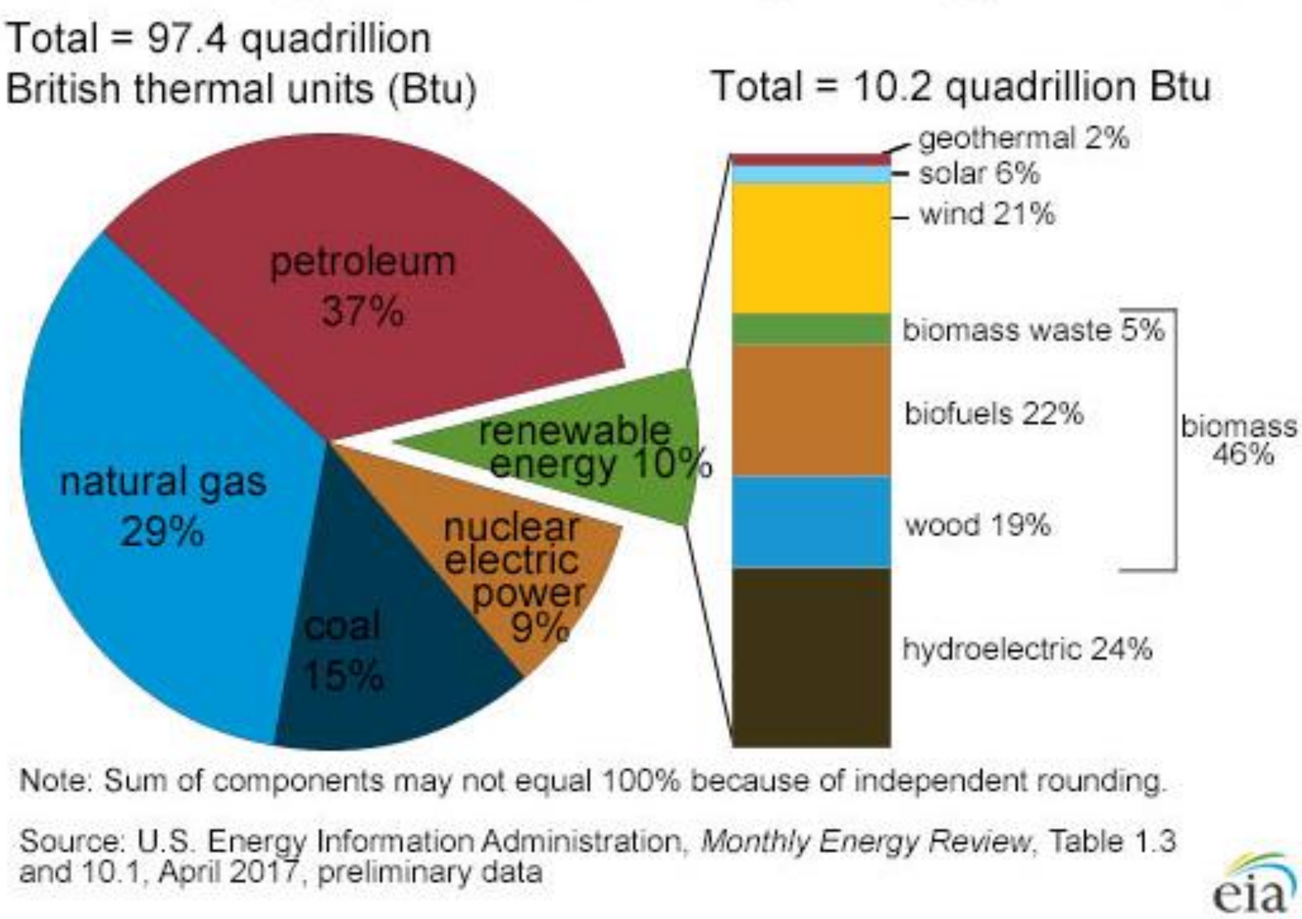
Source: Graph is from NYC (April 2017) Inventory of New York City Greenhouse Gas Emissions in 2015, p. 8
http://www.dec.ny.gov/docs/administration_pdf/nycghg.pdf
*The Council of the City of New York (December 19, 2017) New York To Become First U.S. City to Require Energy Grades To Be Publicly Posted At Commercial And Residential Buildings Intro. 1632A
http://legistar.council.nyc.gov/LegislationDetail.aspx?ID=3066694&GUID=A4E3E696-2927-4A44-BD39-4C2DCC8CAADD&Options=&Search=

NYC Emissions by Sector and Energy Source



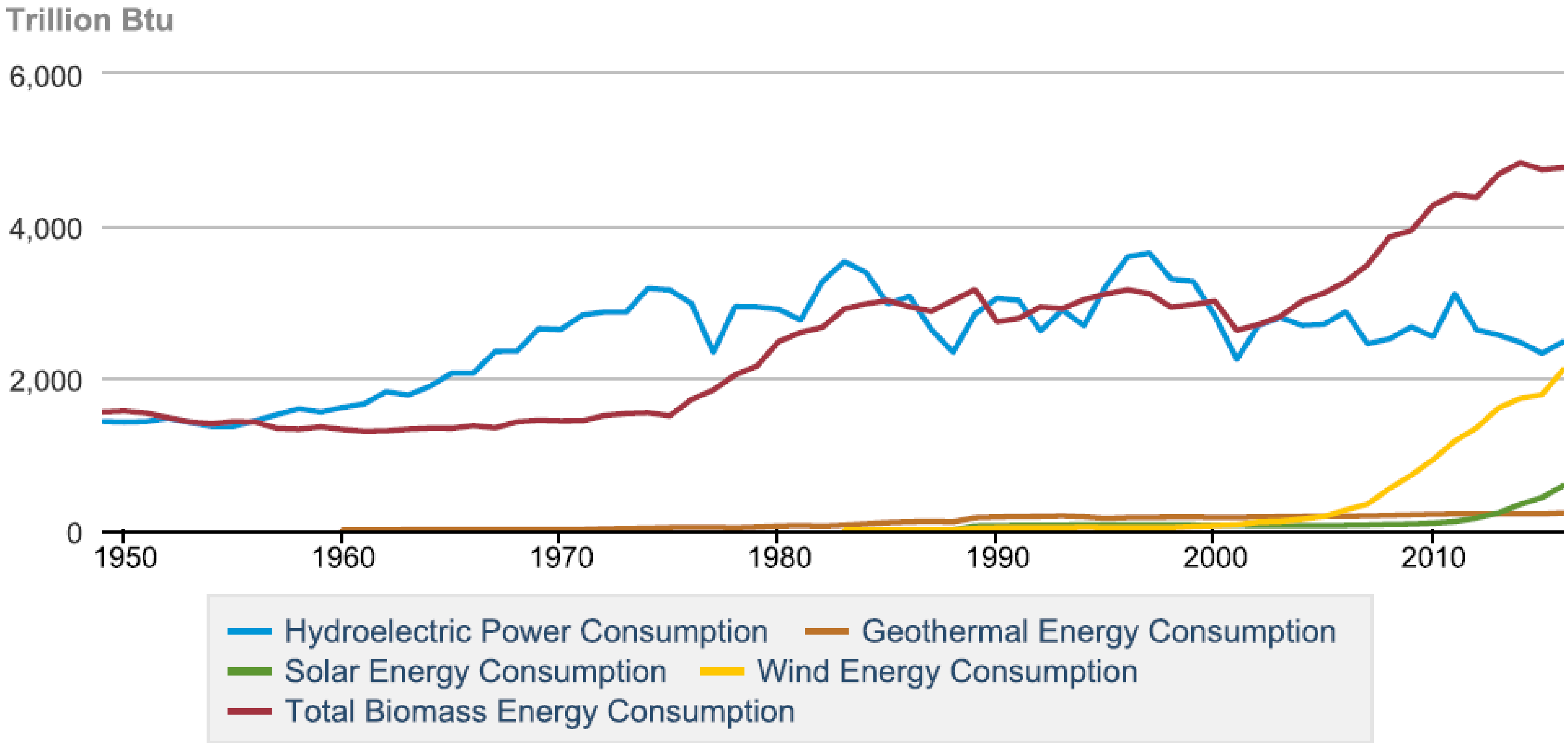
NYC (April 2017) Inventory of New York City Greenhouse Gas Emissions in 2015, p. 22
http://www.dec.ny.gov/docs/administration_pdf/nycghg.pdf

2. Renewable Energy Consumption by Renewable Type, U.S., April 2017 (preliminary)



Source: https://www.eia.gov/energyexplained/?page=renewable_home

Renewable Energy Consumption Trends by Source



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

3. Decentralized and Renewable Infrastructures

- **Transportation provides physical support for green infrastructure**
- **Green infrastructure reduces water impingement for transportation and energy infrastructure**

TRANSPORTATION ⇄ **WATER MANAGEMENT**

Water management (green, gray) infrastructure is decentralized

Roads

Rail (track)

porous track beds

vegetation

porous pavement

vegetation

Water Conveyance/ Reduction: **GREEN***
- Vegetative Nourishment
- Bioswales, green edges, etc.
- Islands, reefs

Water Protection: **GRAY***
- Barriers, levees, structures parallel/perpendicular to shorelines

- **Distributed energy, e.g., solar, wind (rail and road systems support energy distribution lines)**

*Options 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 supports water management under normal conditions to reduce flood volumes when extreme events do happen. Source: Developed by R. Zimmerman and presented at conferences. 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.

Selected Decentralization Strategies for NYC

- Solar Districts. Where a given building structure cannot accommodate solar panels due to space or other constraints, a district comprised of many housing units can pool the solar resources.

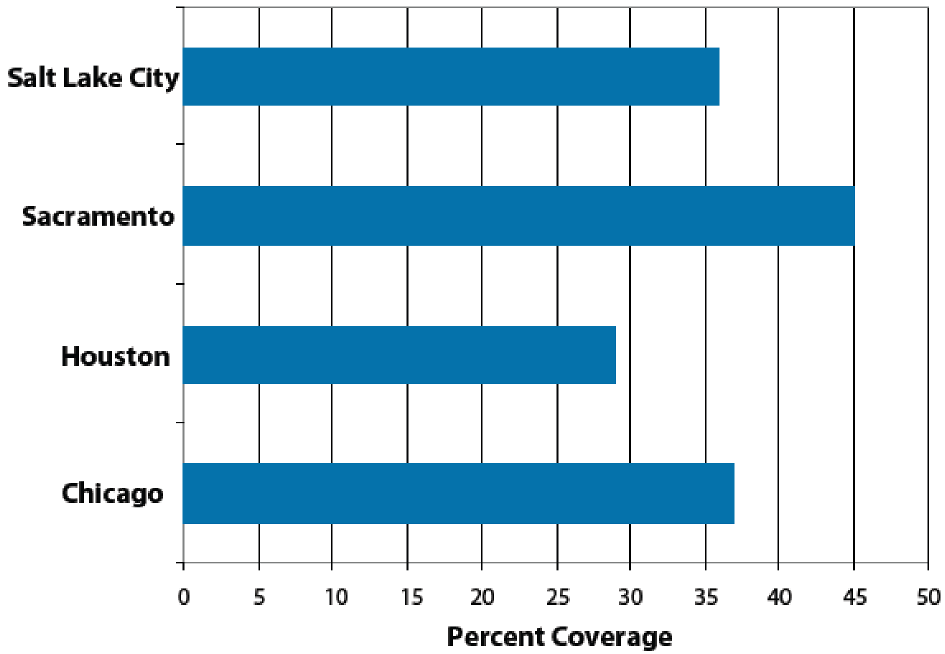
- Measuring and benchmarking energy use – NYC's experience:*
  - 2009: Under LL 84 NYC requires buildings greater than 50,000 sq ft to measure energy (as well as water) usage, a practice called benchmarking
  - 2016: Threshold is lowered to 25,000 sq ft
  - The City Council notes that benchmarking contributes to energy use reduction.

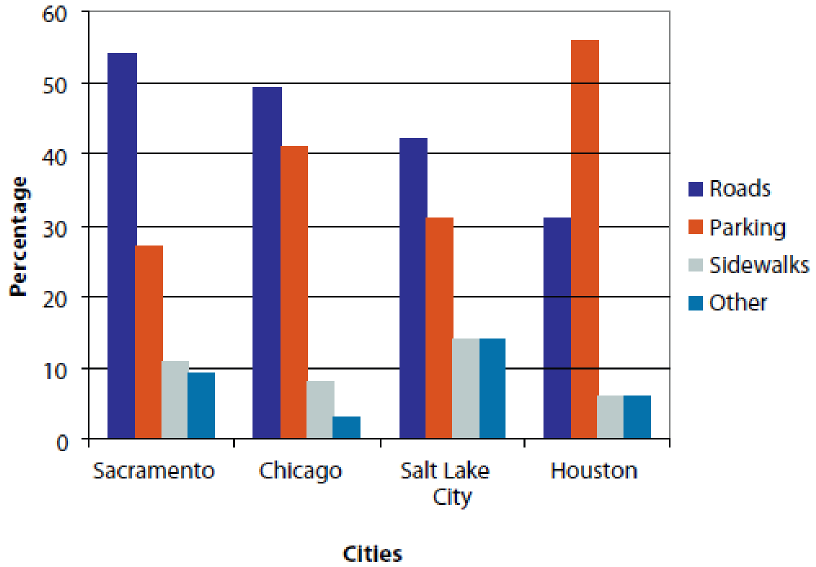
Source: *The Council of the City of New York (December 19, 2017) New York To Become First U.S. City to Require Energy Grades To Be Publicly Posted At Commercial And Residential Buildings Intro. 1632A http://legistar.council.nyc.gov/LegislationDetail.aspx?ID=3066694&GUID=A4E3E696-2927-4A44-BD39-4C2DCC8CAADD&Options=&Search=

4. Changing Land Use: Impervious Surfaces

Gray to Green Infrastructure

Selected U.S. Cities





Extent of pavement coverage by land use

Source: U.S. EPA (October 2008) Reducing Urban Heat Islands: Compendium of Strategies, Chapter 5, "Cool Pavements," p. 1 and p. 12, https://www.epa.gov/sites/production/files/2014-08/documents/coolpavescompendium_ch5.pdf Lawrence Berkeley National Labs.

In New York City Local Law 80 of 2013 includes provisions for testing permeable materials for roadways (NYC DOT 2016, p. 69).

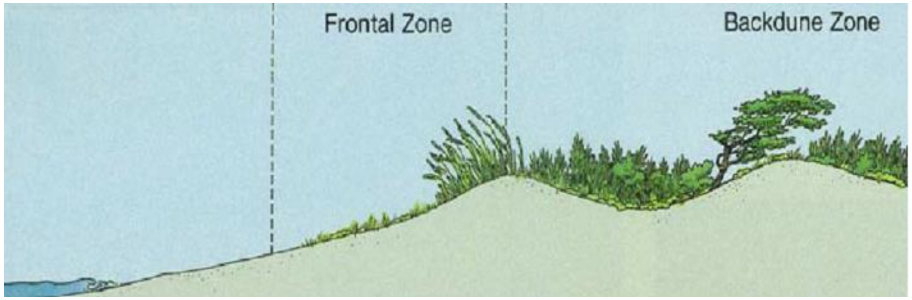
Green and Gray Infrastructure Working Together: Jamaica Bay Wastewater Treatment Plant

NYC DEP (2011) NYC Green Infrastructure Plan 2011 Update, p. 11
http://www.nyc.gov/html/dep/pdf/green_infrastructure/gi_annual_report_2012.pdf

Vegetative Fortification of Shorelines

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

Placement of vegetation in frontal zone*



Dune restoration is considered most successful where:**

- Native vegetation is used however imports are often needed given that only a few species are viable in the dune environment
- Disruptions are avoided such as pedestrian and vehicular traffic
- Sand is used as part of restorations, and where the supply is not sufficient imported sand should be similar to the sand in the restoration area.

Source: U.S. Department of Agriculture Natural Resources Conservation Service (July 2011) Coastal Shoreline and Dune Restoration Technical Note No: TX-PM-08-01, * p. 3, **p. 2-3
https://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/stpmctn10670.pdf

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

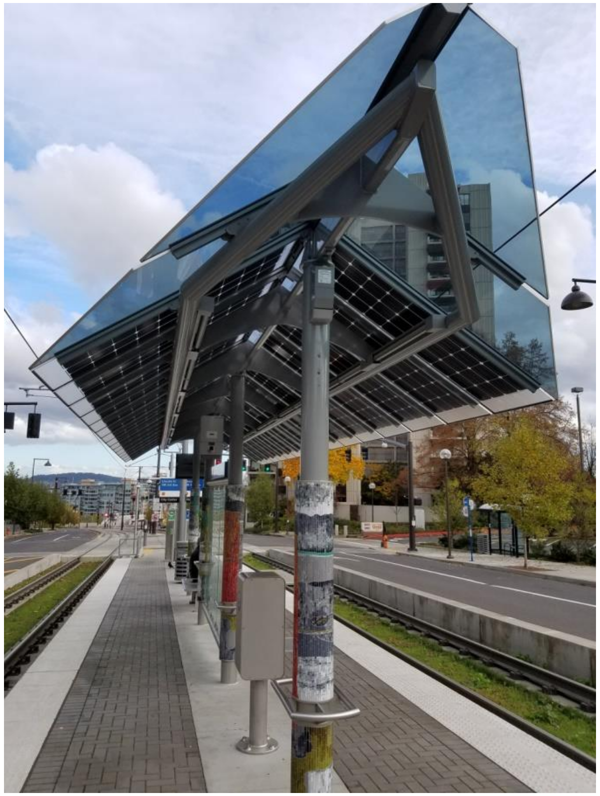
Figure 2: Portland's first Green Streets project at NE 35th and Siskiyou features curb cuts, bump outs and swales.

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.

5. Can Attitudes Change? Public Preferences, Pew Center 2015*

Comparison among different public preferences from Pew Center survey reveals that:

- **Global climate change was among the lowest priority groups (at 38% in 2015), but representing an increase of 10 percentage points since 2013.***
- **In contrast, "dealing with nation's energy problem" ranks higher at about 45-46% remaining about stable over the time periods.***
- **A bi-partisan difference has occurred, with democrats indicating higher percentages for priorities for environmental protection and global warming.****

Carroll Doherty, Rob Suls, and Rachel Weisel (January 15, 2015) Public's Policy Priorities Reflect Changing Conditions at Home and Abroad, Pew Research Center. http://www.people-press.org/files/2015/01/01-15-15-Policy-Priorities-Release.pdf, *p. 2, **p. 9.

6. Altering Infrastructure Usage: Transportation - U.S. Energy Efficient Travel Modes

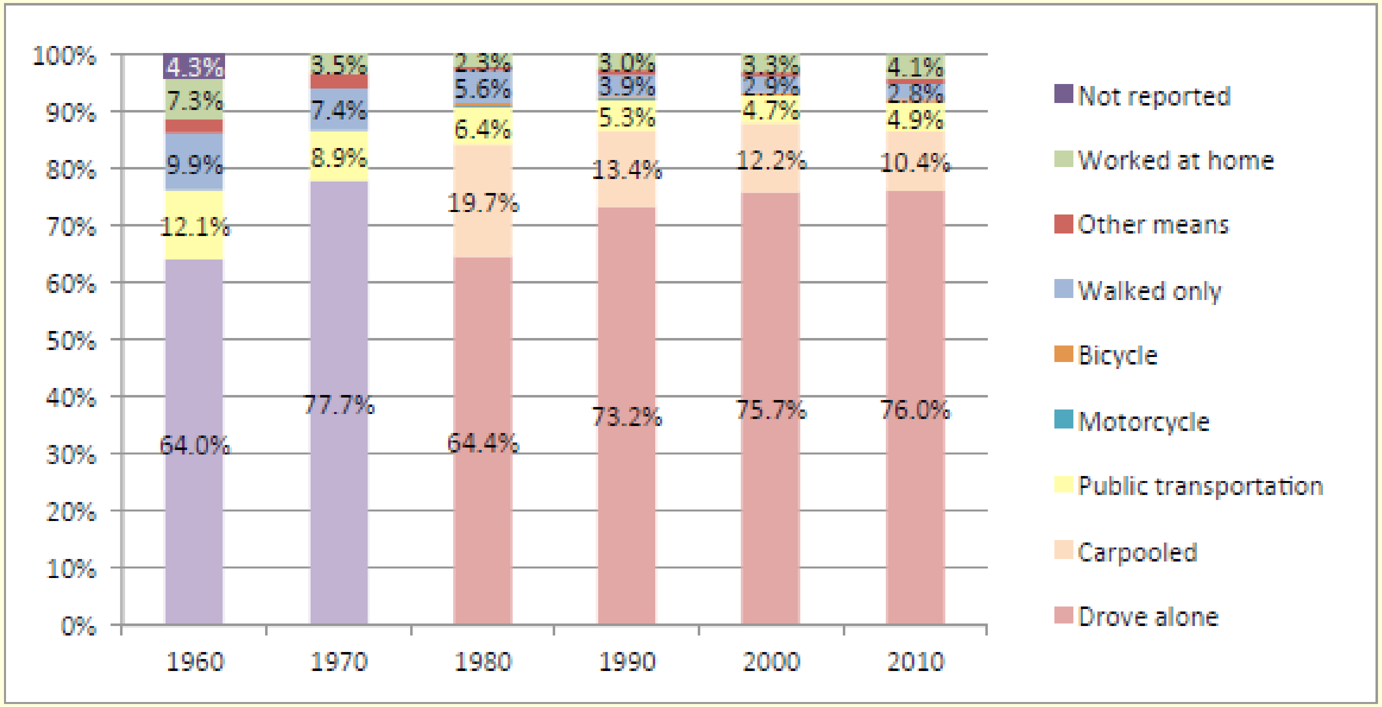
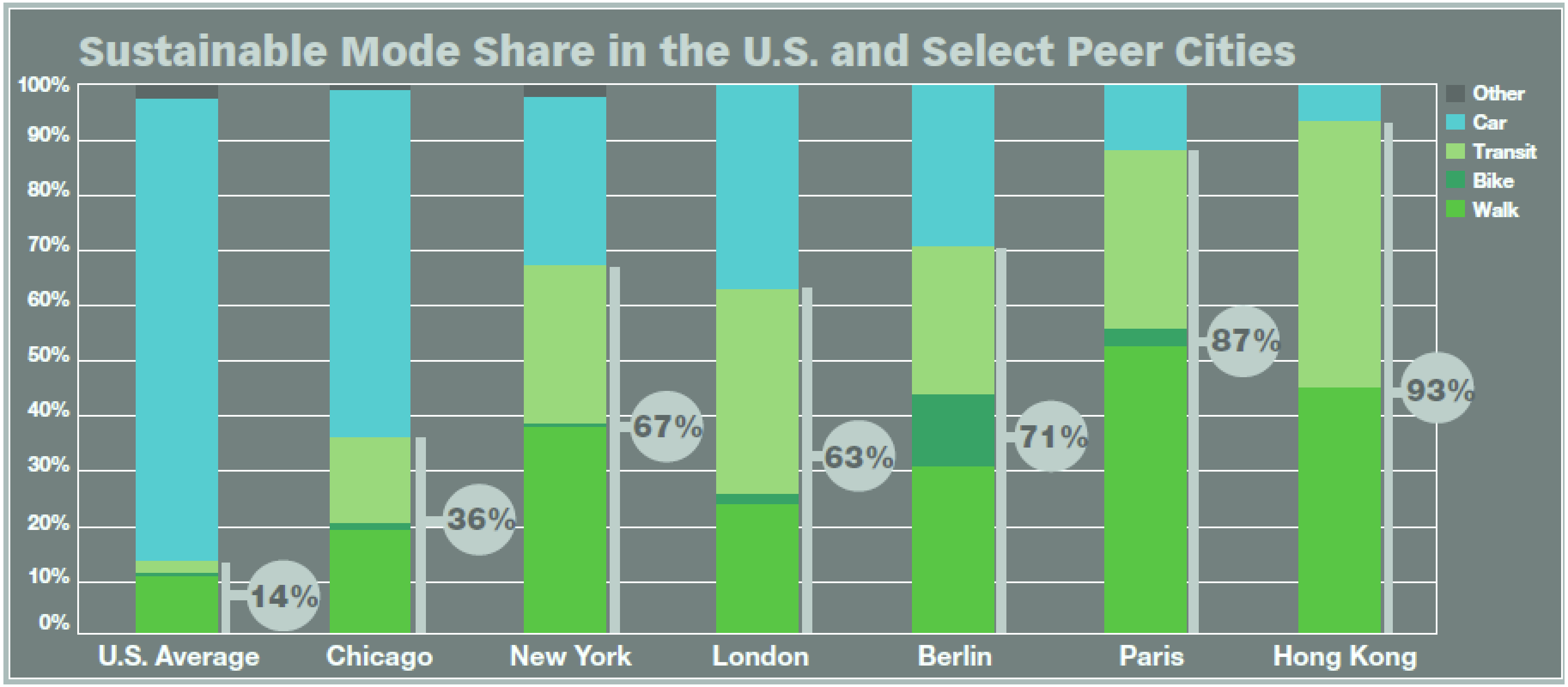


Exhibit 2-26: Means of transportation to work, 1960 to 2010. Data for 1960 and 1970 group carpooling and driving alone together and do not include bicycle or motorcycle use. Data for 1960 only include a "not reported" category.

Sources: Davis, Diegel, and Boundy 2012, Table 8.16 and U.S. Census Bureau, *Means of Transportation to Work for the U.S.* n.d.

Source: U.S. EPA (2013) Our Built and Natural Environments: A Technical Review of the Interactions among Land Use, Transportation, and Environmental Quality, Second edition. Washington, D.C.: EPA http://www.epa.gov/dced/pdf/b-and-n/b-and-n-EPA-231K13001.pdf, p. 29

Use of sustainable transportation modes (energy-efficient), NYC compared to selected other cities



Source: New York City Department of Transportation (DOT) (2016) Strategic Plan 2016: Safe·Green·Smart·Equitable, p. 15
http://www.nycdotplan.nyc/PDF/Strategic-plan-2016.pdf

V. Problems and Opportunities for Solutions

- **Factors Influencing Directions for Sustainable Energy:**
  - Increasing population growth and energy and other infrastructure locations serving population are in sensitive areas
  - Increasing consumption of natural resources is occurring often exceeding supplies and the capacity to sustain them
  - Increasing natural hazards and climate changes often target population and energy and other infrastructure services
- **Some Existing and Potential Solutions and New Directions:**
  - Improvements in energy-related areas are occurring with innovative adaptive, sustainable arrangements that include decentralization and flexible use
  - Renewable resource use and energy efficiency in infrastructure sectors is taking off, e.g., use of public transit and alternative vehicles, water recycling, and energy conservation
  - Funding and institutional adjustments are emerging for support

Reference List: Selected Author Publications

- R. Zimmerman, Q. Zhu, F. de Leon, and Z. Guo, "Conceptual Modeling Framework to Integrate Resilient and Interdependent Infrastructure in Extreme Weather," *Journal of Infrastructure Systems*, Vol. 23, Issue 4, December 2017, (online) 04017034-1 to 13. http://ascelibrary.org/doi/pdf/10.1061/(ASCE)IS.1943-555X.0000394
- R. Zimmerman, Q. Zhu, and C. Dimitri, "A Network Framework for Dynamic Models of Urban Food, Energy and Water Systems (FEWS)," *Journal of Environmental Progress & Sustainable Energy*, Vol. 37, Issue 1, January 2018, pp. 122-131. http://onlinelibrary.wiley.com/ Published online 22 AUG 2017, DOI: 10.1002/ep.12699.
- R. Zimmerman, "The Cyber and Critical Infrastructures Nexus: Interdependencies, Dependencies and Their Impacts on Public Services," White Paper, NYU Center for Cybersecurity, December 2017. http://cyber.nyu.edu/wp-content/uploads/2017/12/Zimmerman-122717updateEdited-White-Paper-Cyber-and-Critical-Infrastructures.pdf
- R. Zimmerman, "Financing Sustainable Infrastructure: Reconciling Disaster and Traditional Financial Resources," *Proceedings of the International Conference on Sustainable Infrastructure 2017,* Policy, Finance and Education, edited by Lucio Soibelman and Feniosky Peña-Mora, Vol. 2, 2017, pp. 176-187, Reston, VA: American Society of Civil Engineers, https://doi.org/10.1061/9780784481202; https://doi.org/10.1061/9780784481202.017
- R. Zimmerman, "Implications of Combined Infrastructure Concentration and Interdependency for Extreme Event Recovery," *Safety, Reliability, Risk, Resilience and Sustainability of Structures and Infrastructure*,12th International Conference on Structural Safety & Reliability (ICOSSAR 2017), edited by C. Bucher, B.R. Ellingwood and D.M. Frangopol, Vienna, Austria, 2017, pp. 2122-2131. Available at SSRN: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3087387. ISBN 9783903024281
- R. Zimmerman, "Effective Public Service Communication Networks for Climate Change Adaptation" In: *Climate Change Adaptation in North America: experiences, case studies and best practice*, edited by W. Leal Filho and J.M. Keenan. Berlin: Springer, 2017, pp. 241-259. DOI 10.1007/978-3-319-53742-9. ISBN 978-3-319-53741-2
- P.J. Marcotullio, A. Sarzynski, J. Sperling, A. Chavez, H. Estiri, M. Pathak, R. Zimmerman, Chapter 12, "Energy Transformation in Cities." In: *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*, edited by C. Rosenzweig, W. Solecki, P. Romero-Lankao, S. Mehrotra, S. Dhakal, and S. Ali Ibrahim. Cambridge, UK and New York, NY, USA, Cambridge University Press, 2018 in press. ARC3.2. Columbia University, NY.
- 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. Published online: February 12, 2016. DOI: 10.1007/s13412-016-0362-0
- R. Zimmerman, "Planning Restoration of Vital Infrastructure Services Following Hurricane Sandy: Lessons Learned for Energy and Transportation," *Journal of Extreme Events*, Vol. 1, No. 2, August 2014. DOI: 10.1142/S2345737614500043 http://www.worldscientific.com/DOI/pdf/10.1142/S2345737614500043.
- R. Zimmerman,*Transport, the Environment and Security. Making the Connection*, Cheltenham, UK &Northampton, MA: Edward Elgar Publishing, Ltd., 2012.
- J.S. Simonoff, C.E. Restrepo, and R. Zimmerman, "Risk Management and Risk Analysis-Based Decision Tools for Attacks on Electric Power," *Risk Analysis*, Vol. 27, No. 3, 2007, pp. 547-570.

Acknowledgements

This work was supported in part by the following grants as well as Professor Zimmerman's independent research:

- "Urban Resilience to Extreme Weather Related Events Sustainability Research Network (UREx SRN)" funded by The National Science Foundation (NSF) (#1444755) to Arizona State University.
- 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

This presentation in part draws from other presentations in connection with the grants above.

Disclaimer: Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the sponsors, the National Science Foundation or the U.S. Department of Homeland Security.