Net Zero Emissions
Why and How

Paul Debevec (debevec@uiuc.edu)
Osher Lifelong Learning Institute at
University of Illinois

Lecture 6

Issues from lecture 5
Storage, Nuclear Power, Transportation

Paul Debevec (debevec@uiuc.edu)
Osher Lifelong Learning Institute at
University of Illinois
March 9, 2020

Lecture 6 Outline

- Issues from lecture 5
- Energy storage
- Nuclear power
- Transportation
- Summary

Issue from lecture 5

Enough with the why.
Not enough about the how.
Nothing will change.

Optimists and pessimists

PNAS
Proceedings of the
National Academy of Sciences
of the United States of America

August 26, 2019
Optimism is associated with exceptional longevity in 2 epidemiologic cohorts of men and women

February 18, 2013
Forecasting Life Satisfaction Across Adulthood: Benefits of Seeing a Dark Future?

January 8, 2016
Optimism: How to Live Longer and Be Happier

March 23, 2013
Be Happy -- Just Think Negative Thoughts!!

Energy Storage

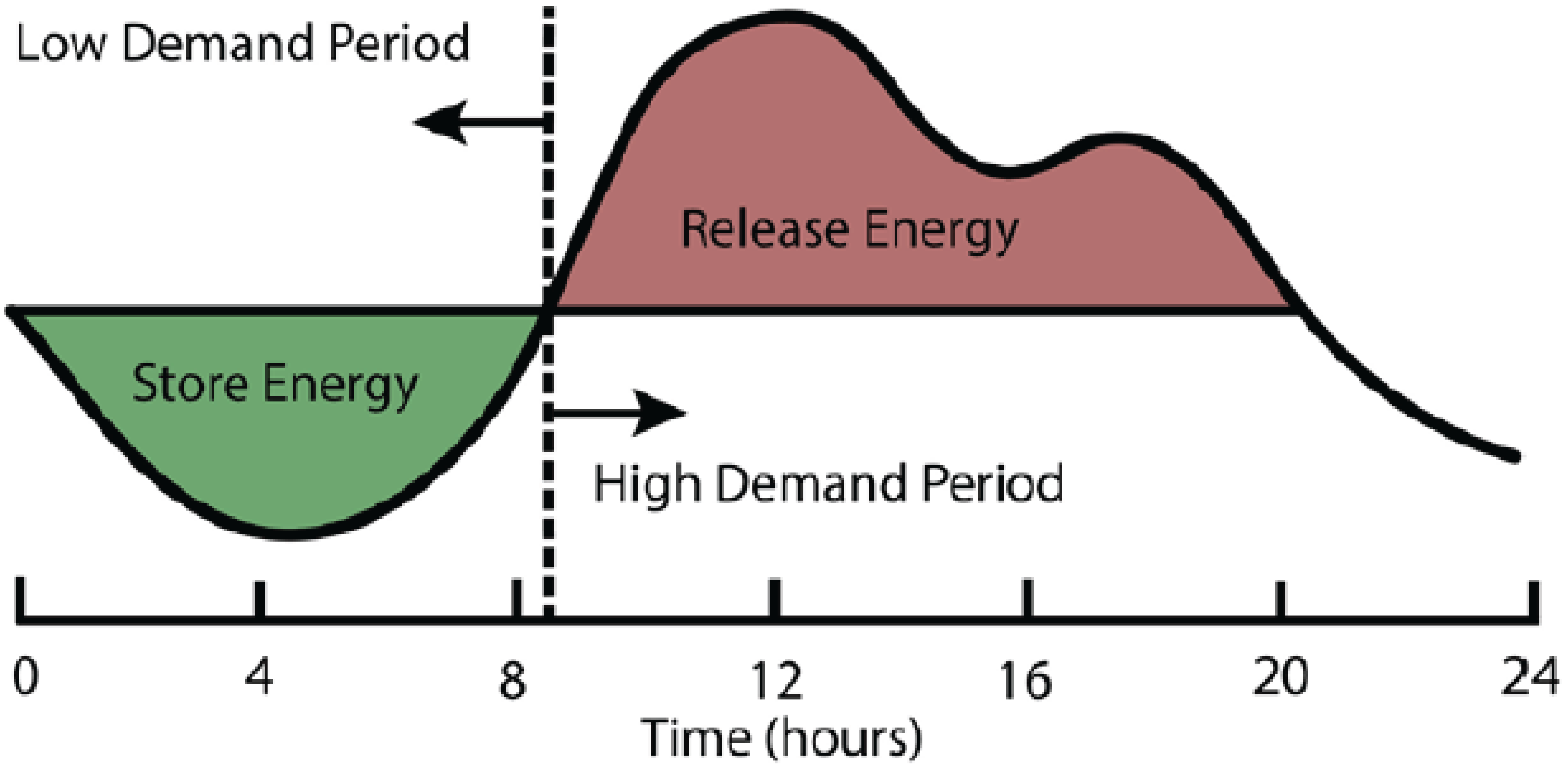
Energy Storage

- Motivation for storage
- U.S. storage statistics
- Pumped hydro
- Compressed air
- Mountain gravity
- Crane gravity
- Battery
- Battery limits
- The Big Question

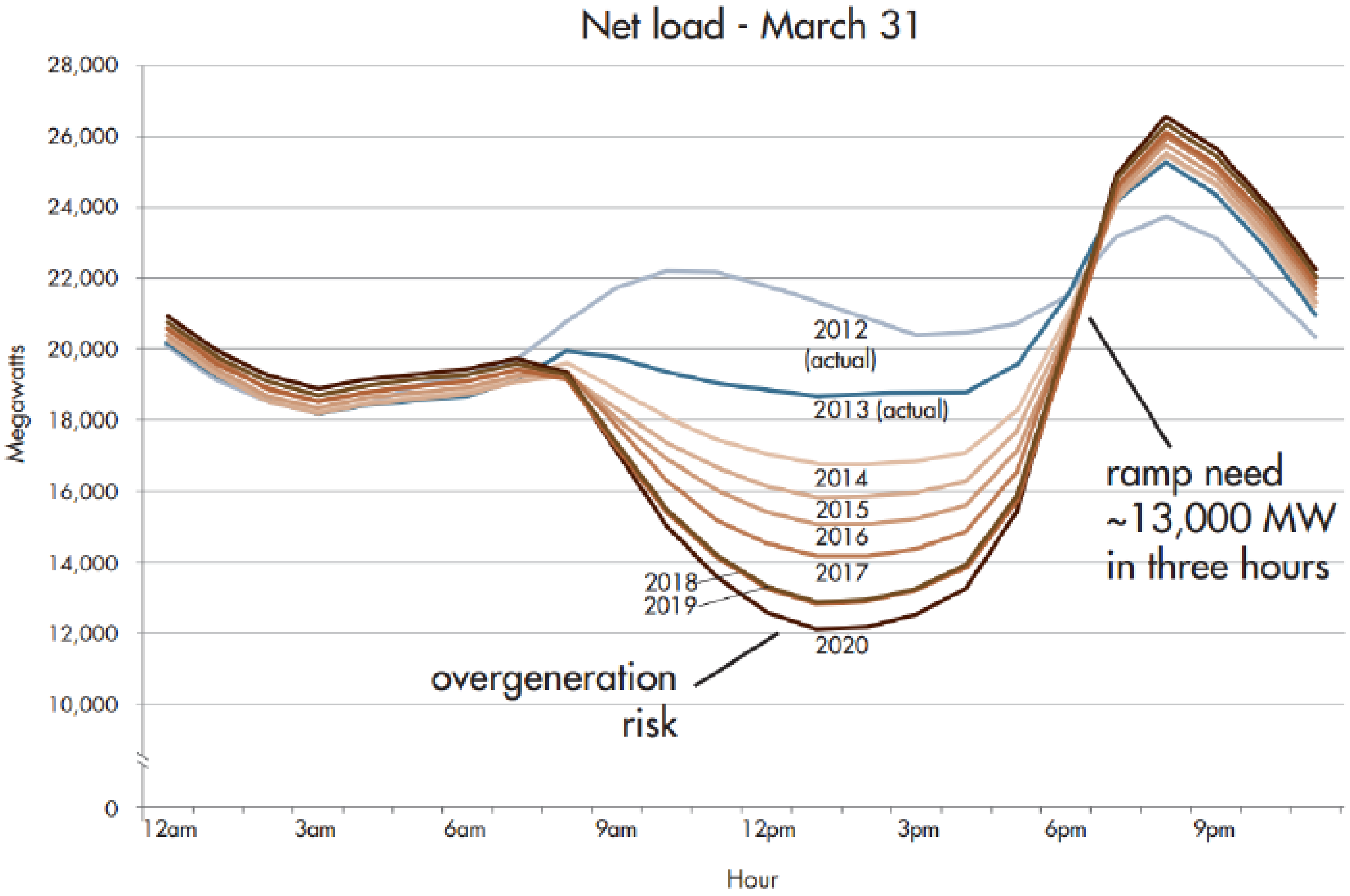
Motivation for Energy Storage

- Energy demand varies on many time scales – daily, weekly, seasonally
- Energy supply, especially solar and wind, also varies on various time scales
- Energy storage decouples supply and demand
- Energy storage provides peak capacity without additional equipment

Daily Energy Storage and Load Leveling[20]

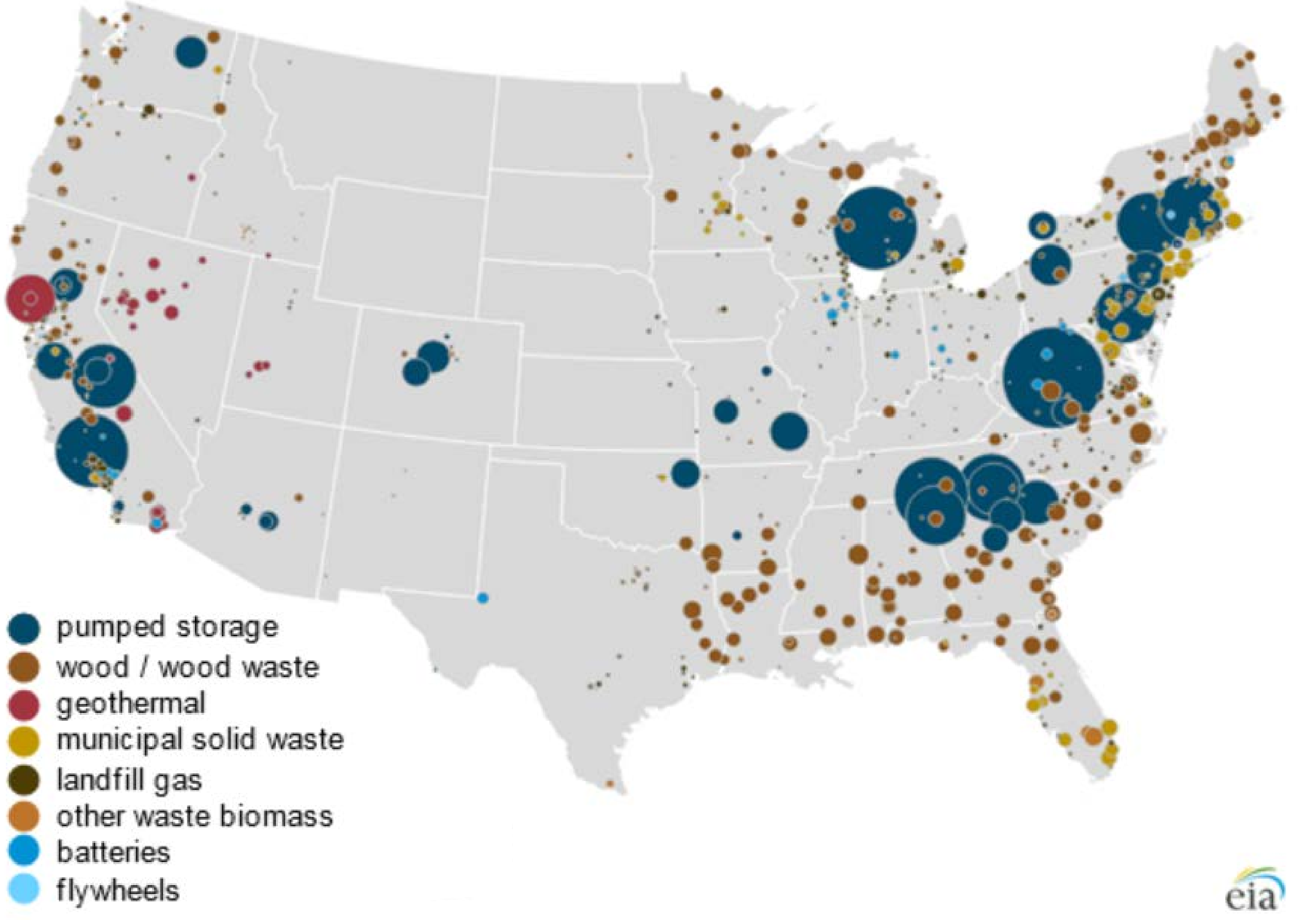


High Solar Penetration
CASIO Duck Curve
(Load Minus Solar Generation)



U.S. Energy Storage Facilities and Renewables Other than Wind and Solar

Distribution of energy storage and other renewable power plants in the Lower 48 states



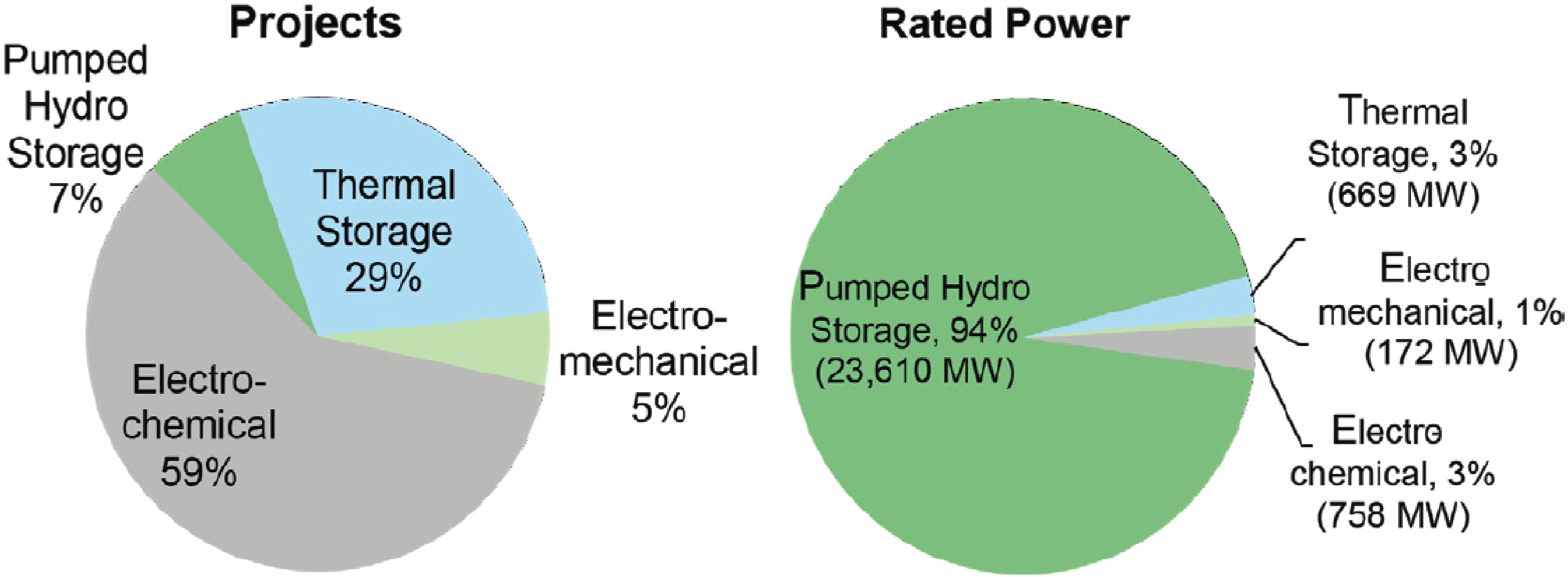
Source: U.S. Energy Information Administration, *Preliminary Monthly Electric Generator Inventory*
Note: Click to enlarge.

U.S. Storage Statistics (2018)

- total storage (operational and planned) = 31.2 GW
- total generation capacity 1,098 GW
- fossil / total = 79.3%
- hydro + nuclear / total = 10.9%
- non-hydro renewables / total = 8.7 %
- storage / total = 2.8%
- almost all storage is pumped-hydro

U.S. Energy Storage Projects by Technology Type in 2018[9]

(Including Announced Projects)



Maturity of Energy Storage Technologies

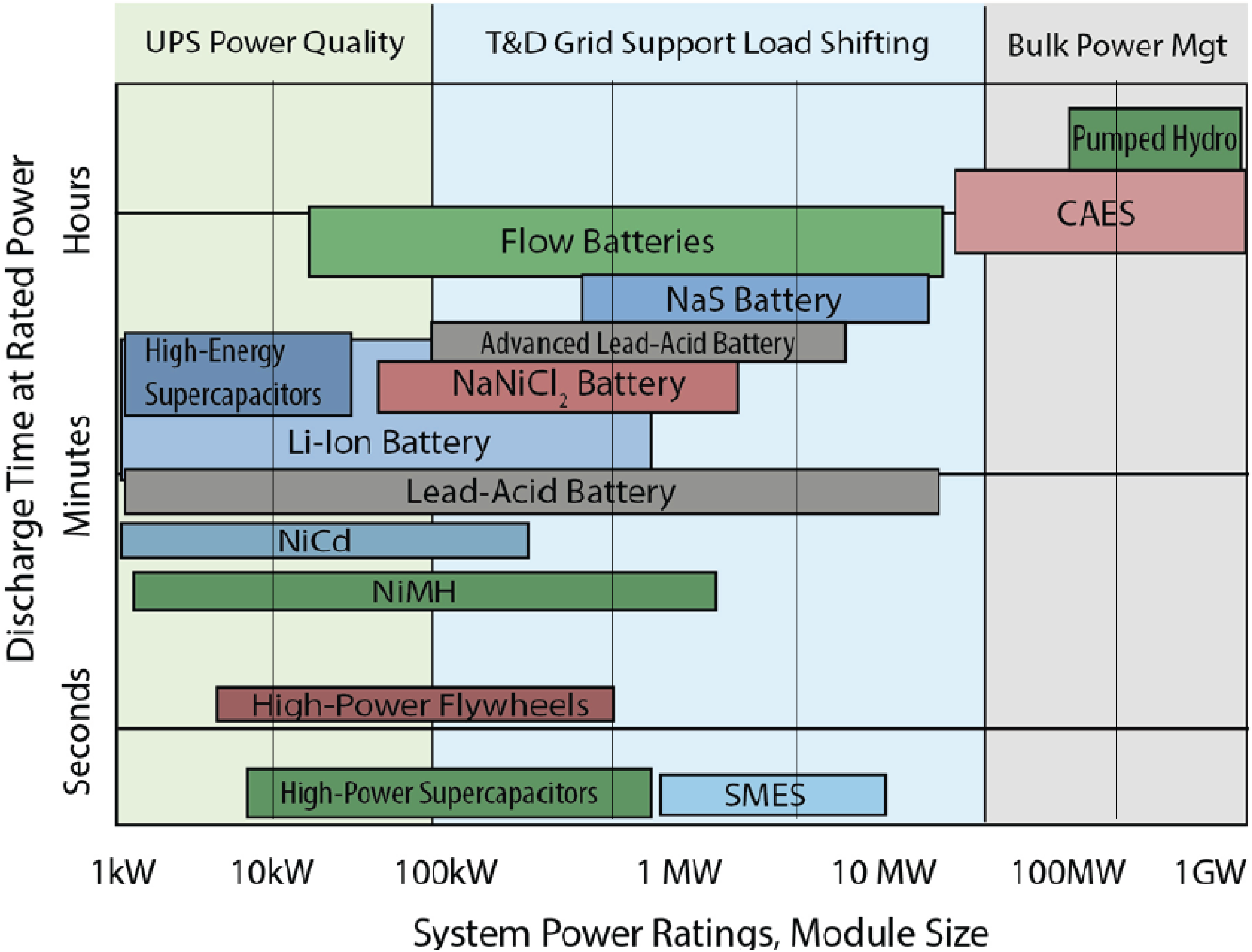
Deployed
- Pumped Hydro
- Compressed Air Energy Storage (CAES)
- Batteries (NaA, Li-ion, Pb-Acid)
- Flywheels

Demonstration
- Advanced Pb-acid and Flow Batteries
- Superconducting Magnetic Energy Storage (SMES)
- Electrochemical Capacitors

Early Stage Technologies
- Adiabatic CAES
- Hydrogen
- Synthetic Natural Gas

Storage technologies in the early stages of research, and that will likely not be commercially available in 3-5 years, have been omitted.

Characteristics of Energy Storage Technologies[12]



Pumped Hydro Energy Storage

Pumped Hydro Storage Facilities With Power >1GW in Operation

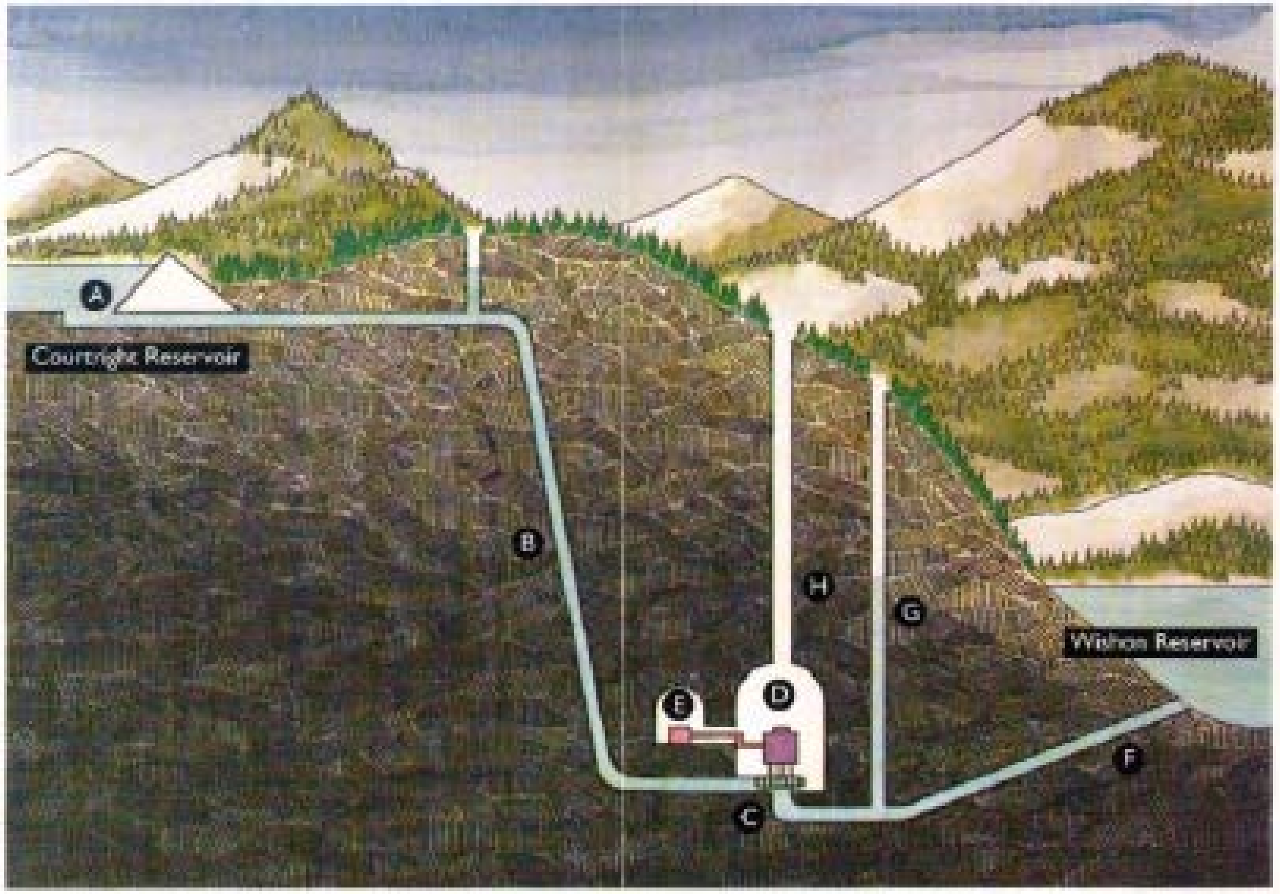
Pumped Hydro Storage Facilities With Power >1GW Under Construction

Rocky Mountain Hydroelectric Plant
Rome, Georgia

Ameren Missouri Taum Sauk Hydroelectric Power Station under Construction 2009

Ameren Missouri Taum Sauk Hydroelectric Power Station

Pacific Gas and Electric Company Helms Pumped Storage Plant

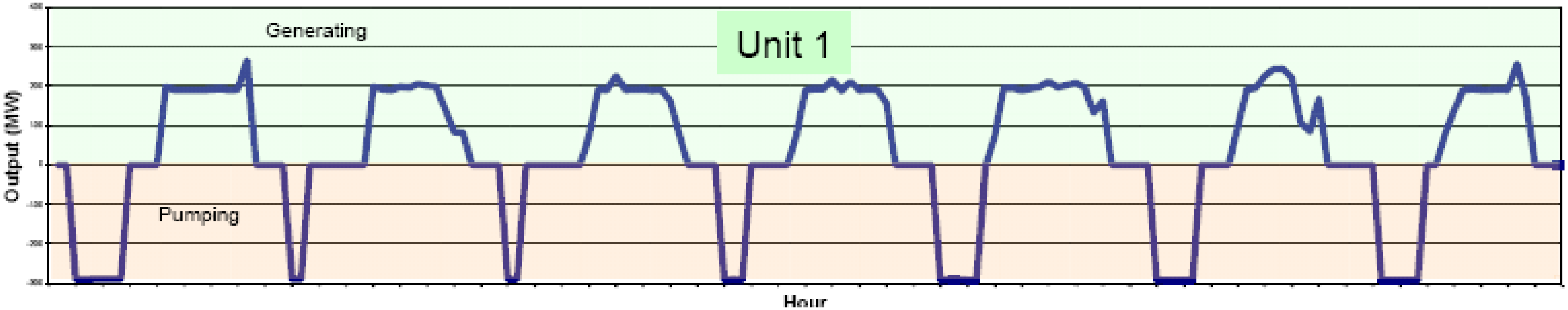


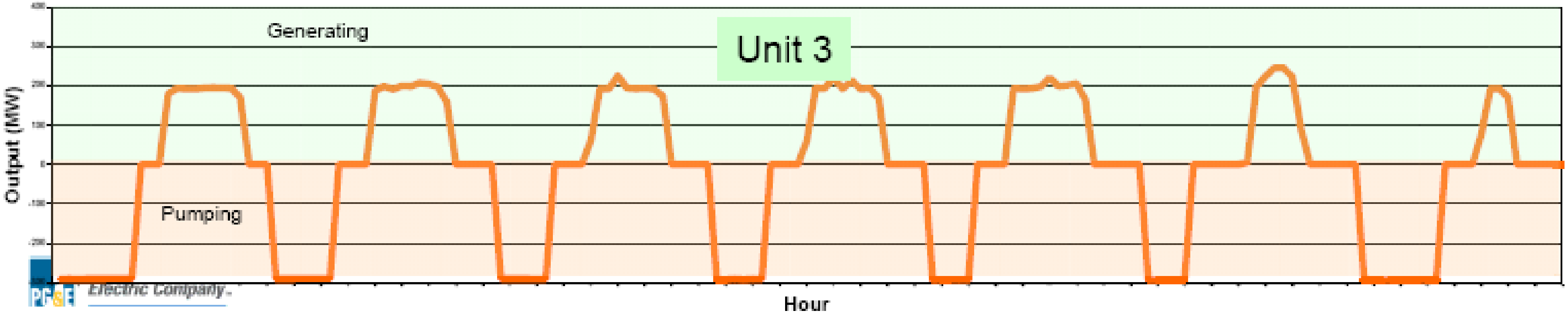
A-Courtright, B-Supply Tunnel, C-Turbine, D-Generator, E-Transformer, F-Wishon, G-Surge Chamber, H-Elevator

From Manho Yeung, Pacific Gas and Electric Company

Helms Operation – Typical Summer Week

total capacity 1,212 MW generating;
930 MW pumping





From Manho Yeung, Pacific Gas and Electric Company

Pumped Hydro Energy Storage Efficiency

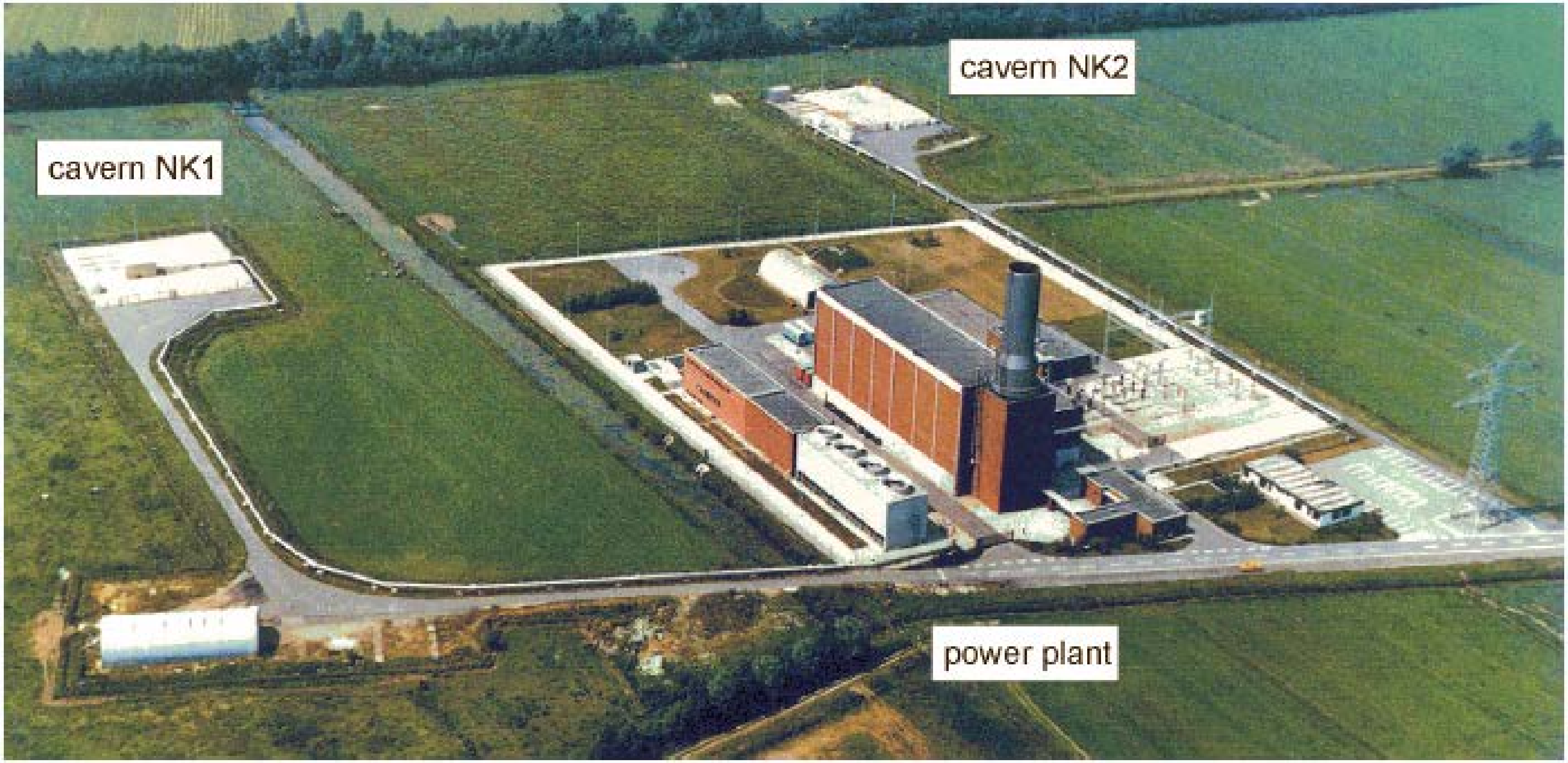
- Dead stop to full generation in eight minutes
- Dead stop to full pump in twenty minutes
- Generating ramp rate of 80 MW per minute per unit
- Generation efficiency typically 90%
- Pumping efficiency typically 86%
- Cycle efficiency is the product so 23% of energy is lost per cycle

CAES
Compressed Air Energy Storage

Compressed Air Energy Storage

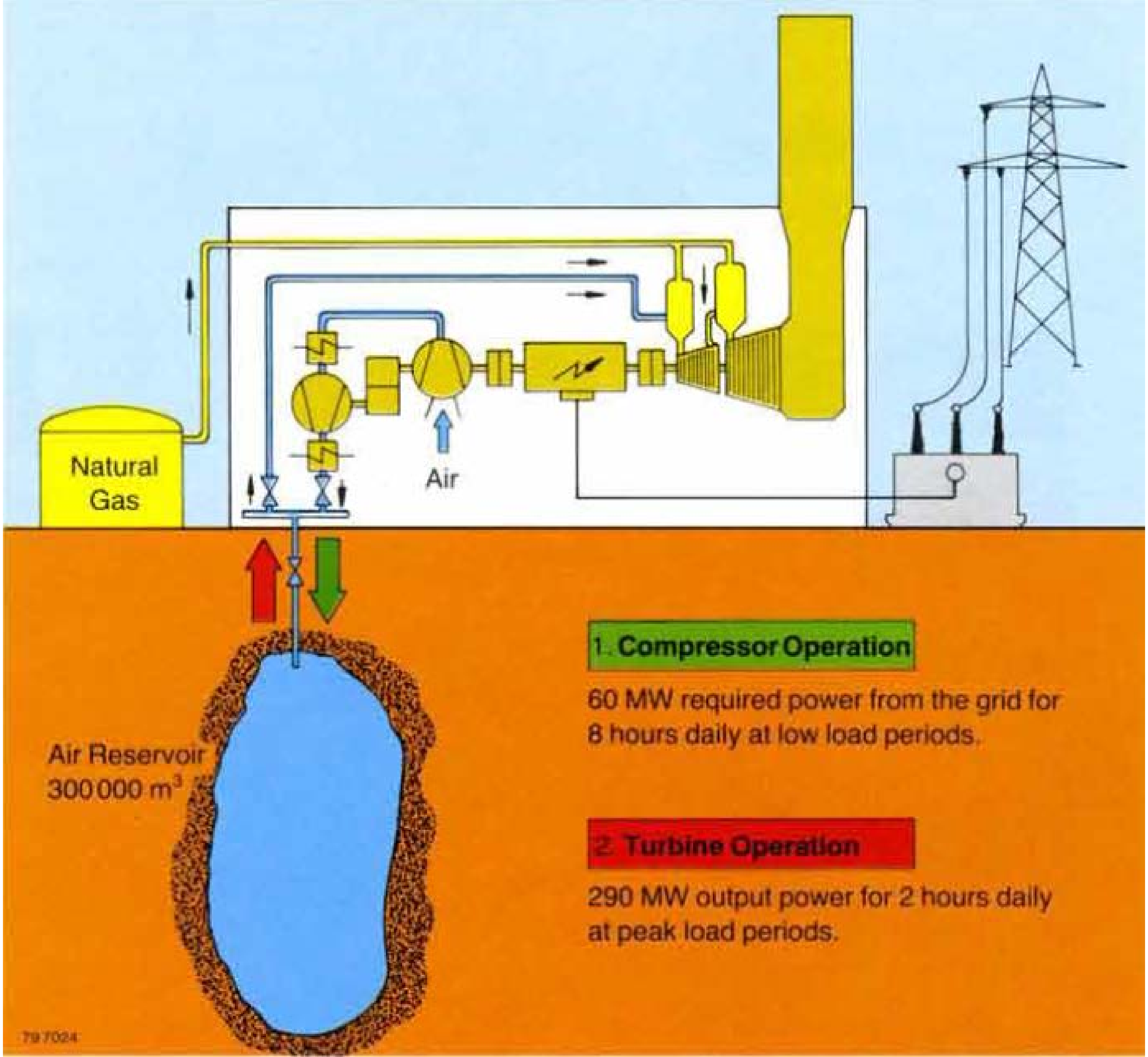
- Huntorf, Germany (operating since 1978)
  - 290 MW for 2 hours
  - 0.3×10^6 m^3 salt dome cavern
- McIntosh, AL (operating since 1991)
  - 110 MW for 26 hours
  - 0.6×10^6 m^3 salt dome cavern
- Seminole, TX (operating since 2012)
  - 1.6 MW for 150 hours
  - In conjunction with single 2 MW wind turbine
- Goderich, Ontario (operating since 2019)
  - 2 MW for 5 hours
  - In conjunction with thermal storage

E.N. Kraftwerke CAES Huntorf, Germany



From Dr Chris Bullough presentation at ALSTOM Power Technology Centre

PowerSouth CAES McIntosh, AL

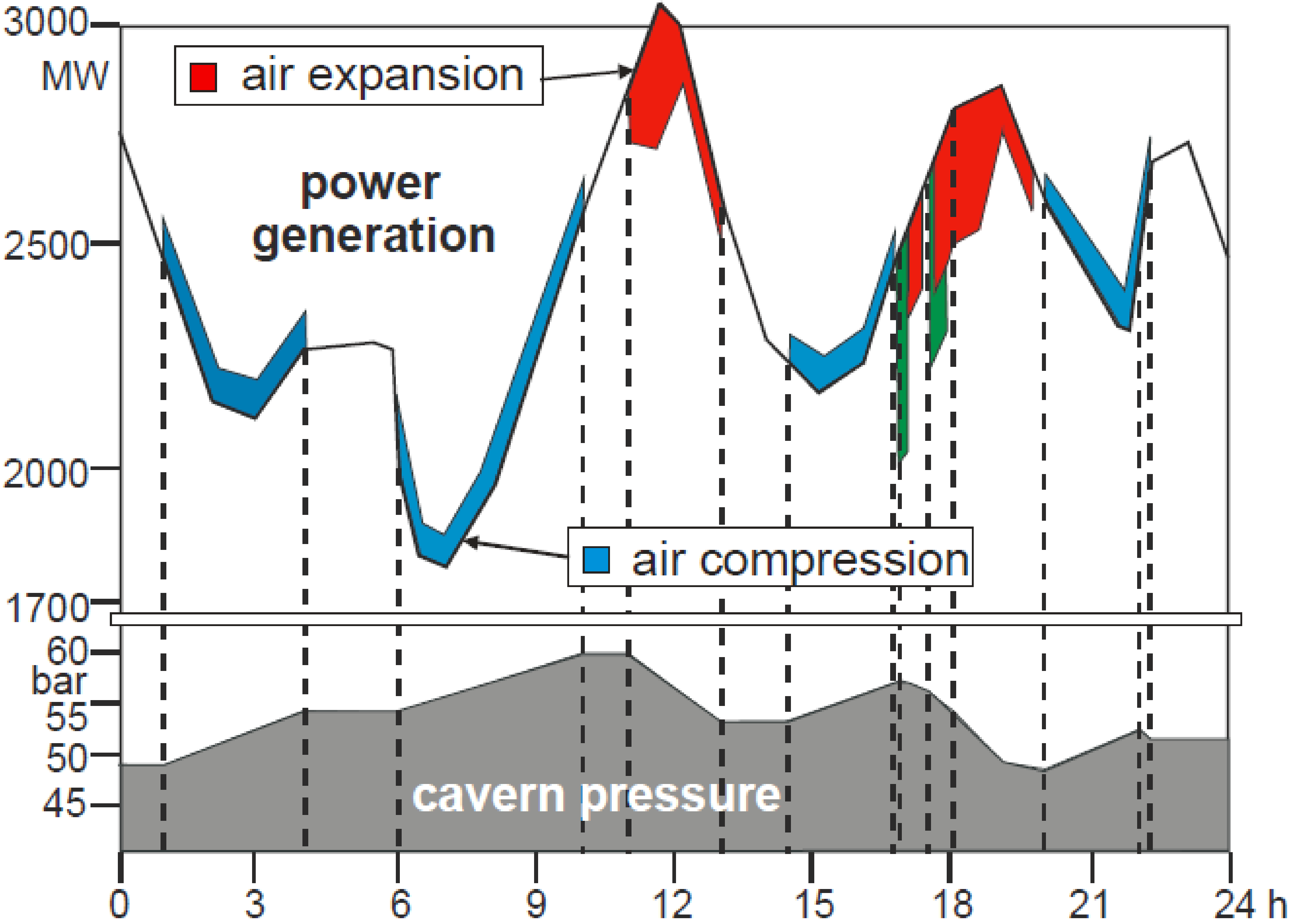


1. Compressor Operation

60 MW required power from the grid for 8 hours daily at low load periods.

2. Turbine Operation

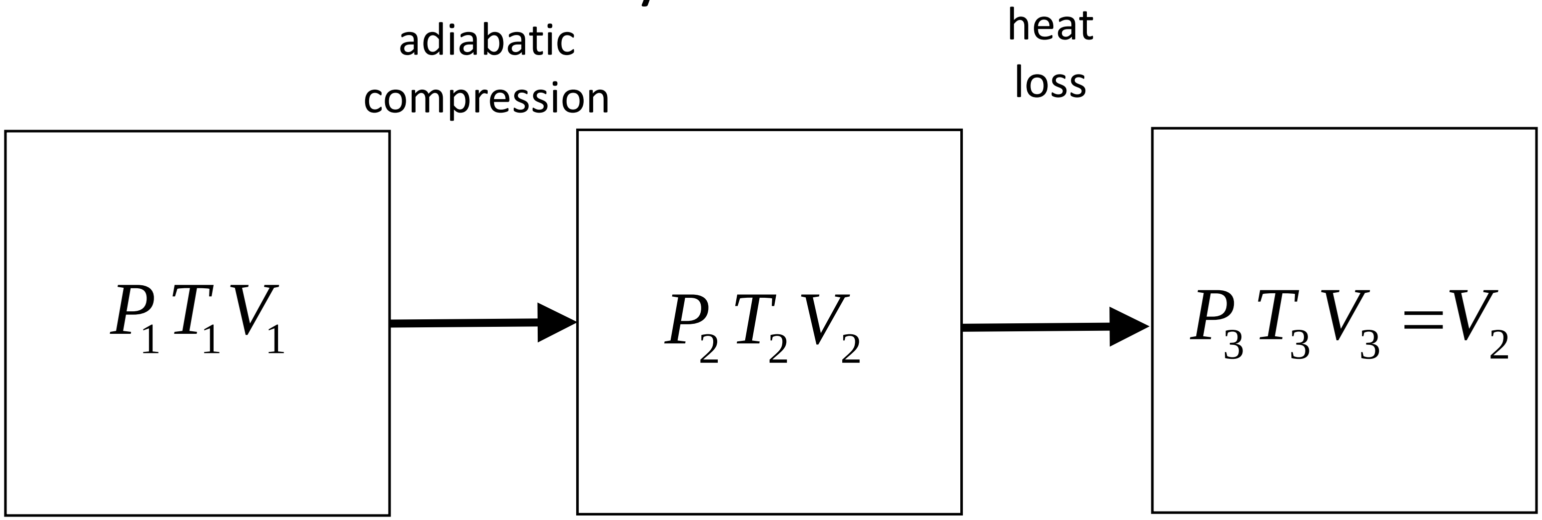
290 MW output power for 2 hours daily at peak load periods.


3000
MW
2500
2000
1700
60
bar
55
50
45
🟥 air expansion
🟦 air compression
power generation
cavern pressure
0
3
6
9
12
15
18
21
24 h

Huntorf Parameters

- Power generation (turbine) 290 MW ≤ 3 h
- Energy storage (compressor) 60 MW ≤ 12 h
- Maximum cavity pressure 70 bar
- Minimum cavity pressure 20 bar
- Regular operation 45 – 60 bar
- Maximum pressure reduction rate 15 bar / h
- Efficiency 41%

Thermodynamics of CAES



adiabatic compression

heat loss

$P_1 T_1 V_1$

$P_2 T_2 V_2$

$P_3 T_3 V_3 = V_2$

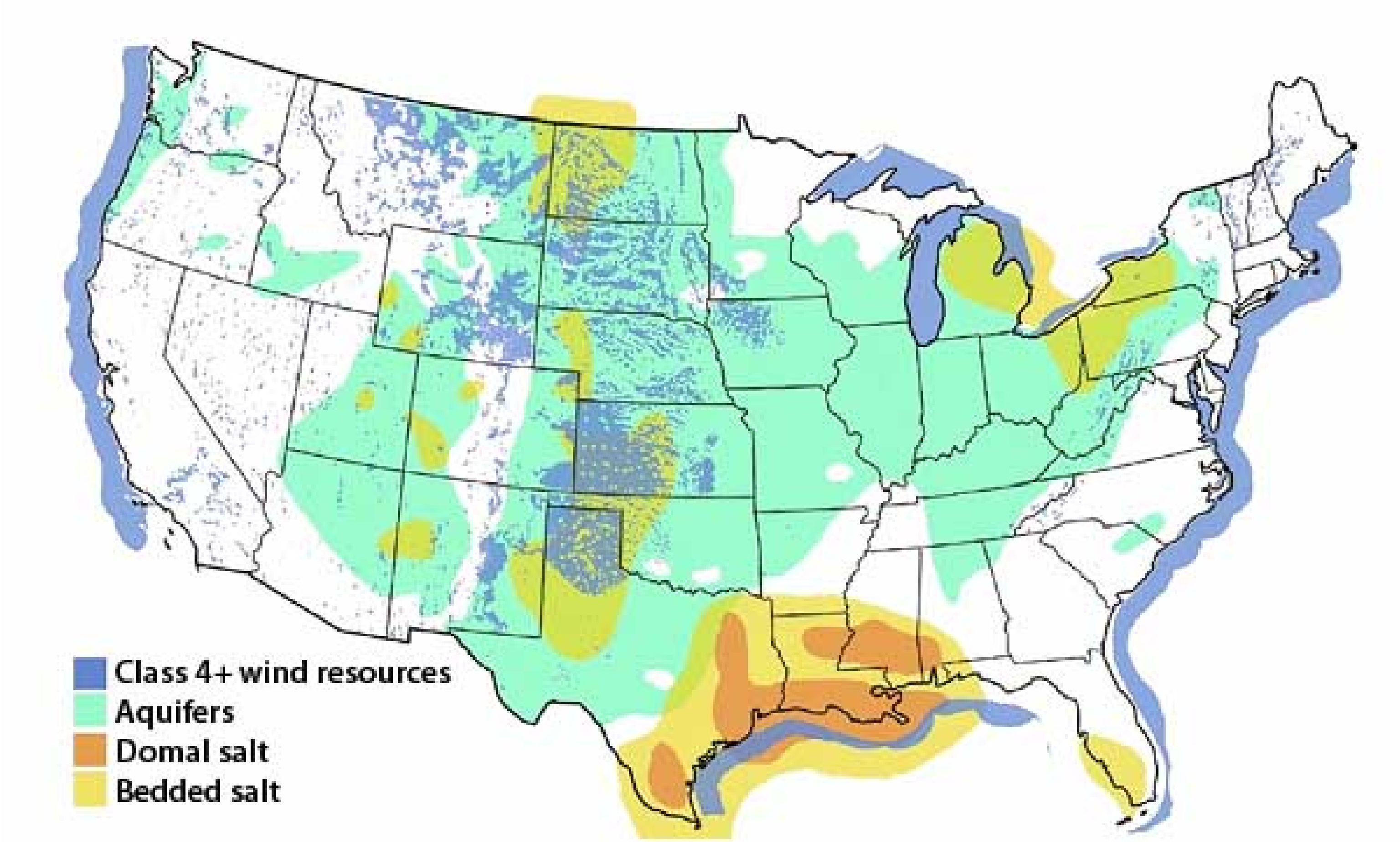
Compression ratio $r = \dfrac{P_2}{P_1}$ Temperature ratio $\dfrac{T_2}{T_1} = r^{(\gamma-1)/\gamma}$ $\gamma = \dfrac{C_p}{C_\mathrm{v}}$

Loss of available work ratio

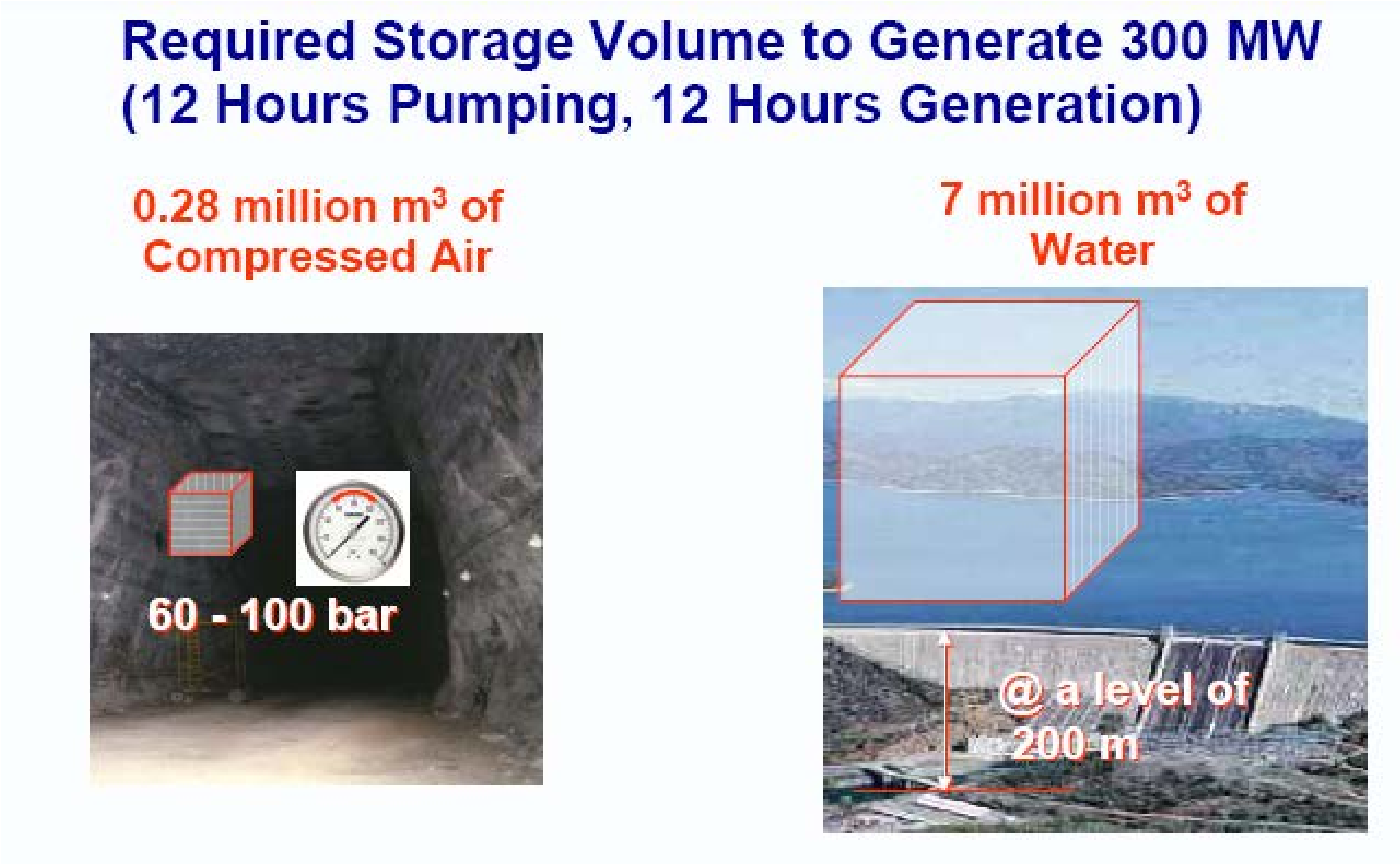
$$\frac{\Delta W}{W} = \frac{T_2/T_1 - T_3/T_1 - \ln\left(T_2/T_3\right)}{T_2/T_1 - 1}$$

Texas Dispatachable Wind 1, LLC
Seminole, TX CAES Plus Wind Demonstration

Geology Favorable for CAES and Class 4+ Winds



CAES and Pumped Hydro Comparison



Required Storage Volume to Generate 300 MW (12 Hours Pumping, 12 Hours Generation)

0.28 million m^3 of Compressed Air

60 - 100 bar

7 million m^3 of Water

@ a level of 200 m

From Dr Chris Bullough presentation at ALSTOM Power Technology Centre U.K.

Compressed Air Car (CAC)

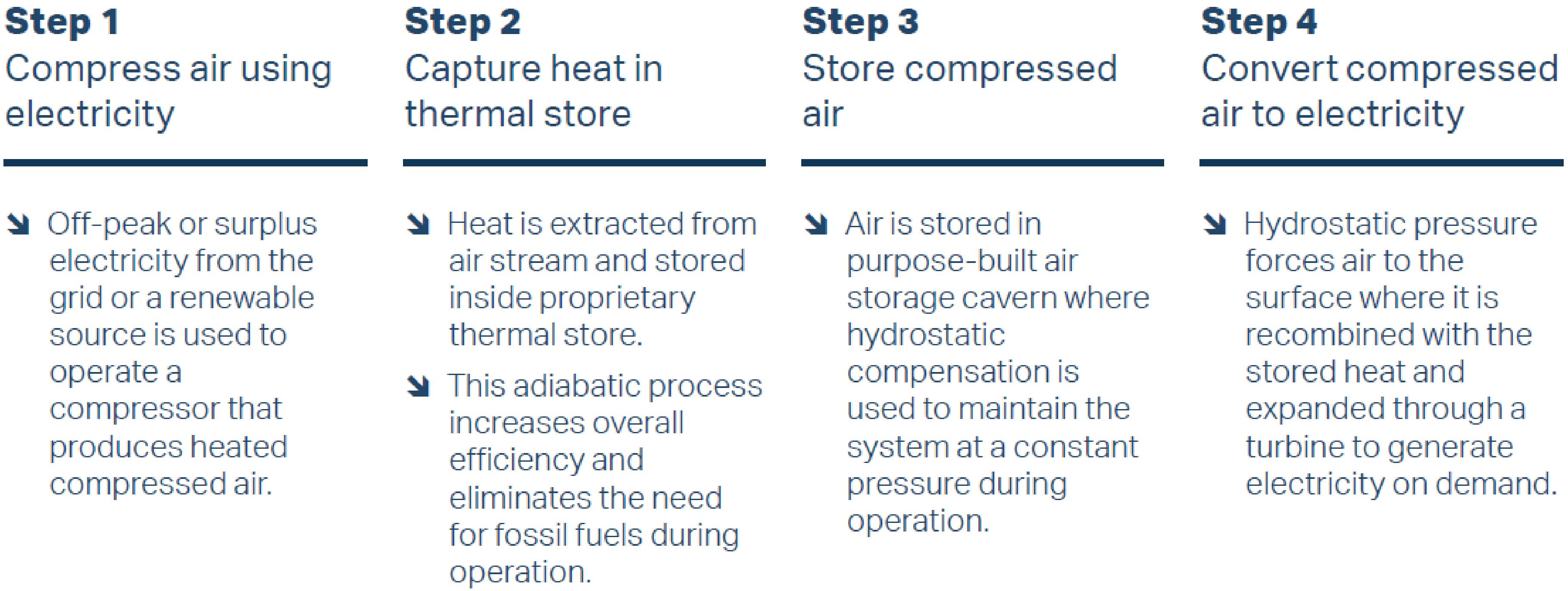
Tata Motors/Motor Development International ZMP Airpod

New CAES

Hydrostor Facility - Goderich, Ontario

2 MW power, 10 MWh storage

Hydrostor Operation Sequence



Step 1
Compress air using electricity

- Off-peak or surplus electricity from the grid or a renewable source is used to operate a compressor that produces heated compressed air.

Step 2
Capture heat in thermal store

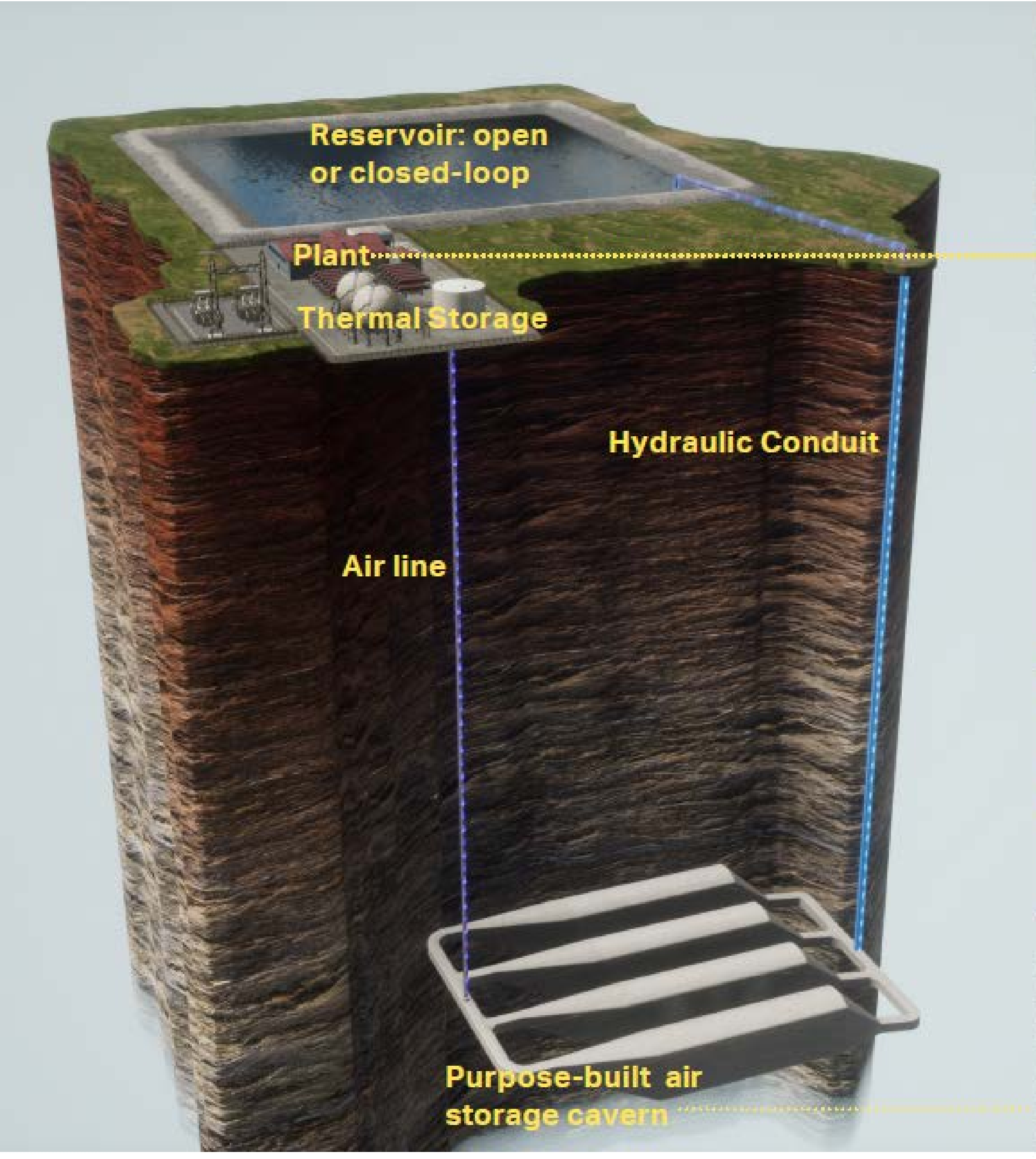
- Heat is extracted from air stream and stored inside proprietary thermal store.
- This adiabatic process increases overall efficiency and eliminates the need for fossil fuels during operation.

Step 3
Store compressed air

- Air is stored in purpose-built air storage cavern where hydrostatic compensation is used to maintain the system at a constant pressure during operation.

Step 4
Convert compressed air to electricity

- Hydrostatic pressure forces air to the surface where it is recombined with the stored heat and expanded through a turbine to generate electricity on demand.

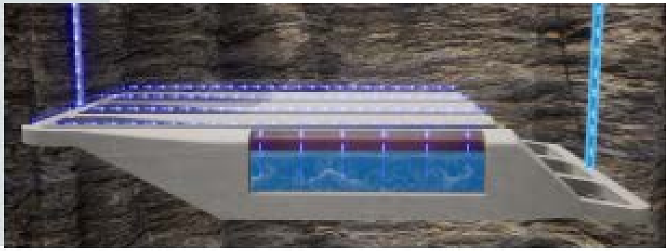


Charge

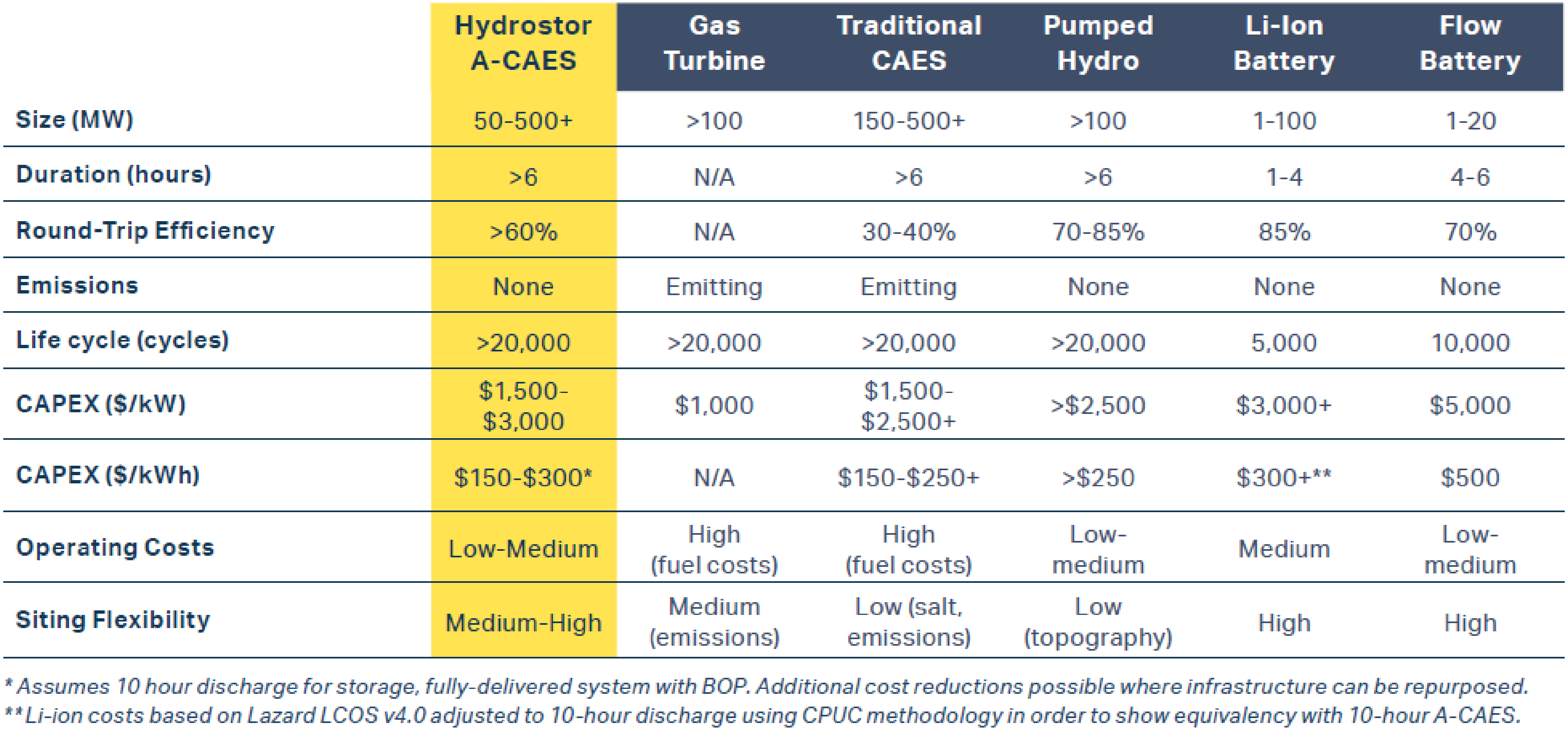
As compressed air is sent into the air storage cavern, water is displaced via a flooded decline or shaft.

Discharge

As water enters the air storage cavern, hydrostatic pressure forces air to the surface.



Storage Technology Comparison



	Hydrostor A-CAES	Gas Turbine	Traditional CAES	Pumped Hydro	Li-Ion Battery	Flow Battery
Size (MW)	50-500+	>100	150-500+	>100	1-100	1-20
Duration (hours)	>6	N/A	>6	>6	1-4	4-6
Round-Trip Efficiency	>60%	N/A	30-40%	70-85%	85%	70%
Emissions	None	Emitting	Emitting	None	None	None
Life cycle (cycles)	>20,000	>20,000	>20,000	>20,000	5,000	10,000
CAPEX ($/kW)	$1,500-$3,000	$1,000	$1,500-$2,500+	>$2,500	$3,000+	$5,000
CAPEX ($/kWh)	$150-$300*	N/A	$150-$250+	>$250	$300+**	$500
Operating Costs	Low-Medium	High (fuel costs)	High (fuel costs)	Low-medium	Medium	Low-medium
Siting Flexibility	Medium-High	Medium (emissions)	Low (salt, emissions)	Low (topography)	High	High

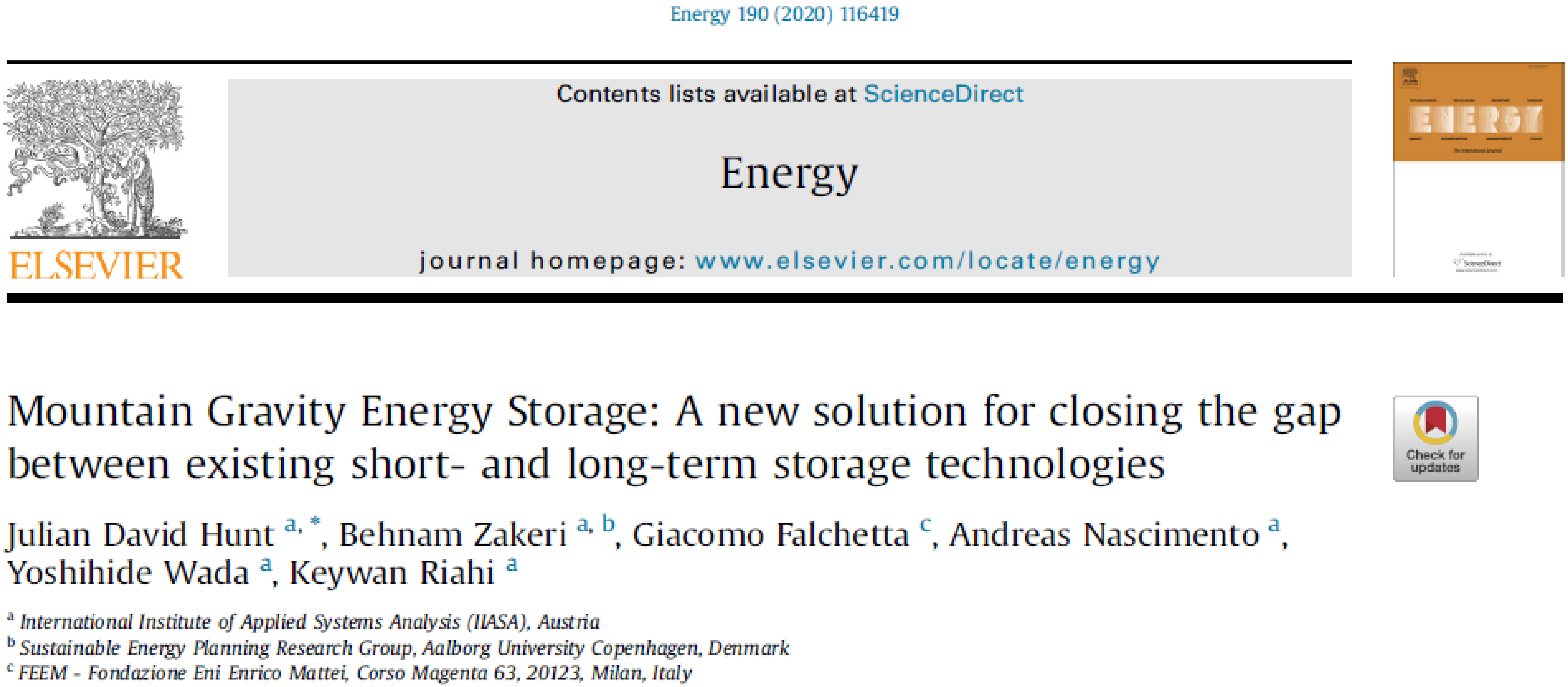
** Assumes 10 hour discharge for storage, fully-delivered system with BOP. Additional cost reductions possible where infrastructure can be repurposed.*

*** Li-ion costs based on Lazard LCOS v4.0 adjusted to 10-hour discharge using CPUC methodology in order to show equivalency with 10-hour A-CAES.*

Crane and Block Energy Storage

Switzerland Based Energy Vault

Another Alternative Energy Storage
Mountain Gravity



Energy 190 (2020) 116419

Contents lists available at ScienceDirect

Energy

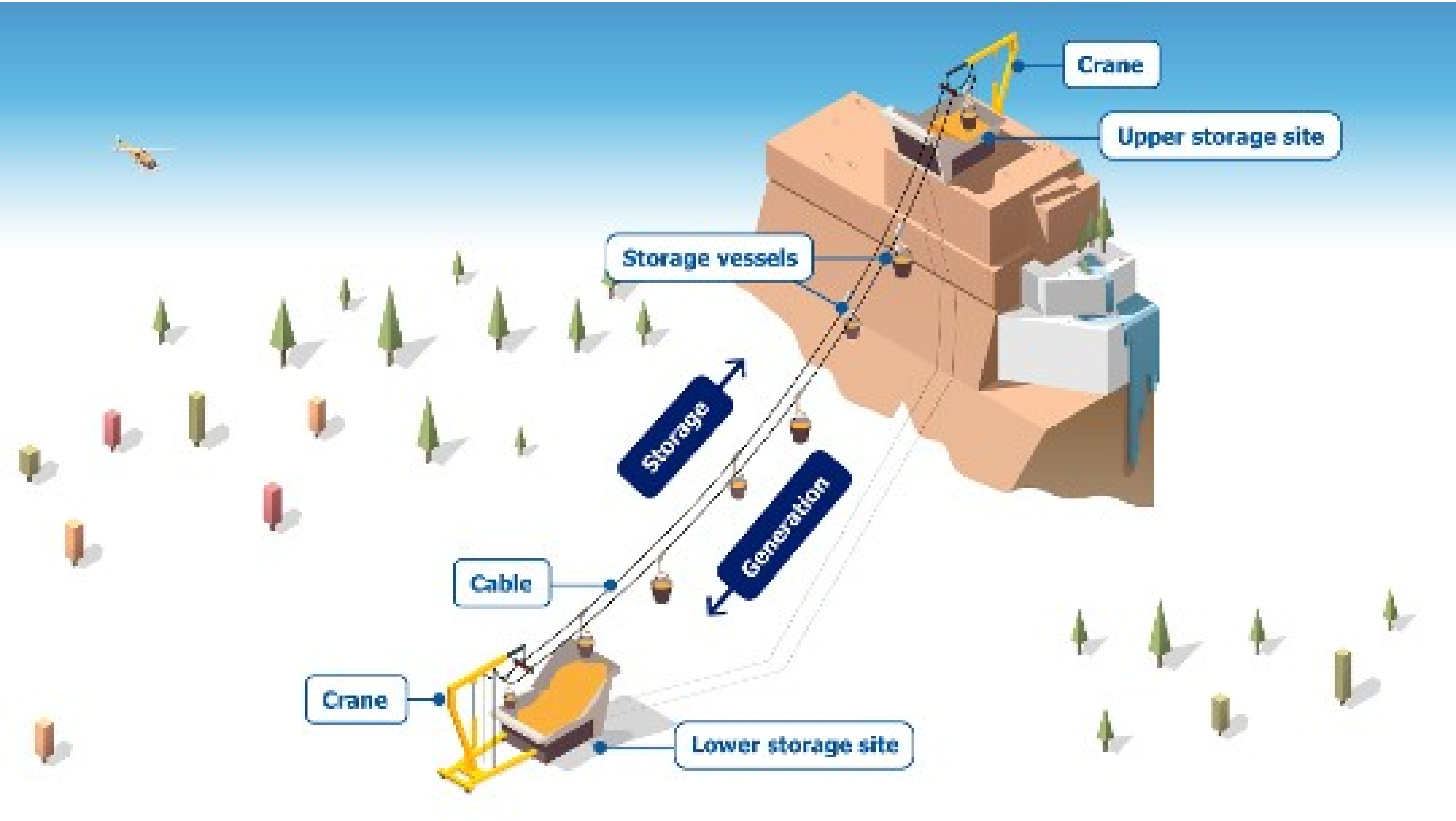
journal homepage: www.elsevier.com/locate/energy

Mountain Gravity Energy Storage: A new solution for closing the gap between existing short- and long-term storage technologies

Julian David Hunt [a, *], Behnam Zakeri [a, b], Giacomo Falchetta [c], Andreas Nascimento [a], Yoshihide Wada [a], Keywan Riahi [a]

[a] *International Institute of Applied Systems Analysis (IIASA), Austria*
[b] *Sustainable Energy Planning Research Group, Aalborg University Copenhagen, Denmark*
[c] *FEEM - Fondazione Eni Enrico Mattei, Corso Magenta 63, 20123, Milan, Italy*

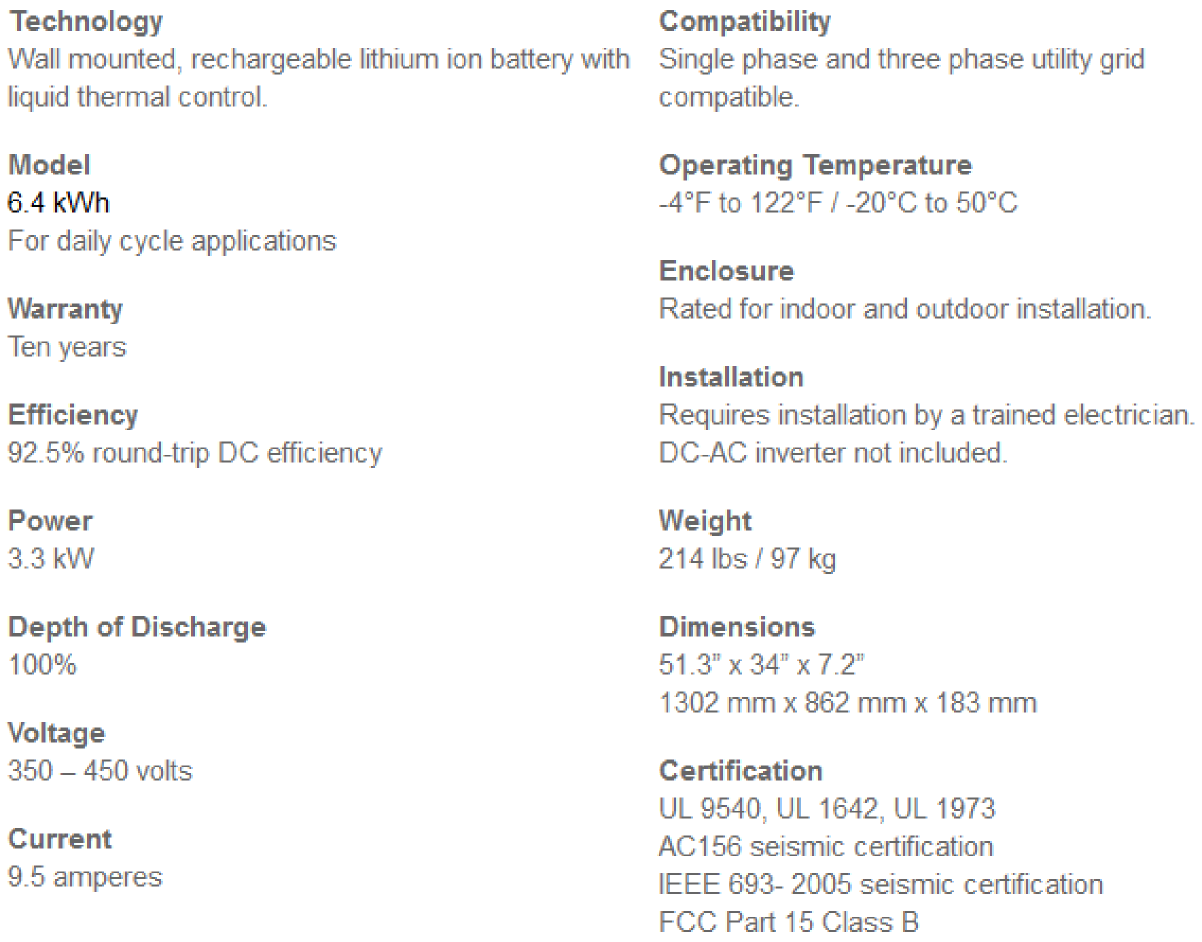
Mountain Gravity Energy Storage



Battery Energy Storage

Tesla Model S and Powerwall

Tesla Powerwall



Technology
Wall mounted, rechargeable lithium ion battery with liquid thermal control.

Model
6.4 kWh
For daily cycle applications

Warranty
Ten years

Efficiency
92.5% round-trip DC efficiency

Power
3.3 kW

Depth of Discharge
100%

Voltage
350 – 450 volts

Current
9.5 amperes

Compatibility
Single phase and three phase utility grid compatible.

Operating Temperature
-4°F to 122°F / -20°C to 50°C

Enclosure
Rated for indoor and outdoor installation.

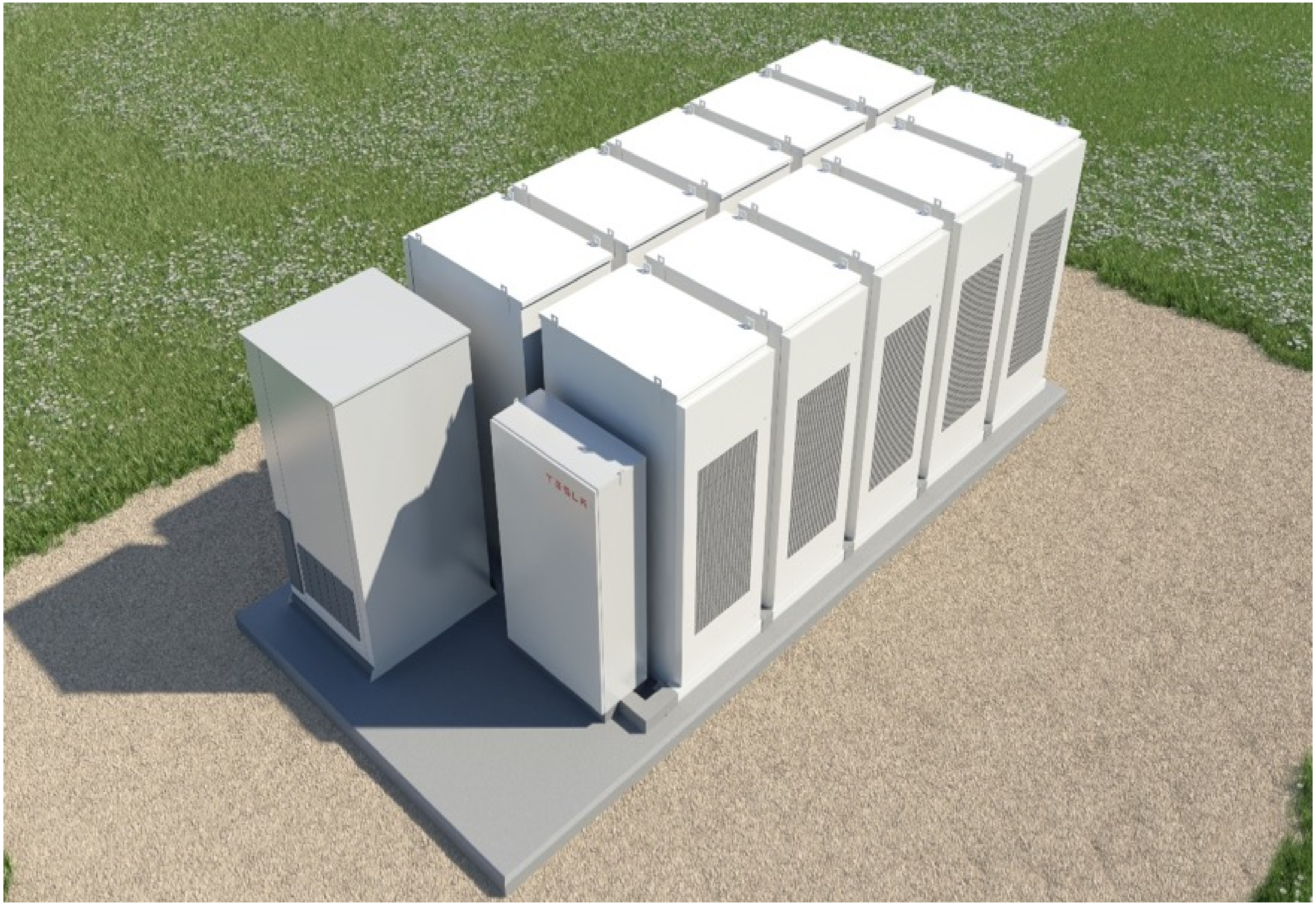
Installation
Requires installation by a trained electrician. DC-AC inverter not included.

Weight
214 lbs / 97 kg

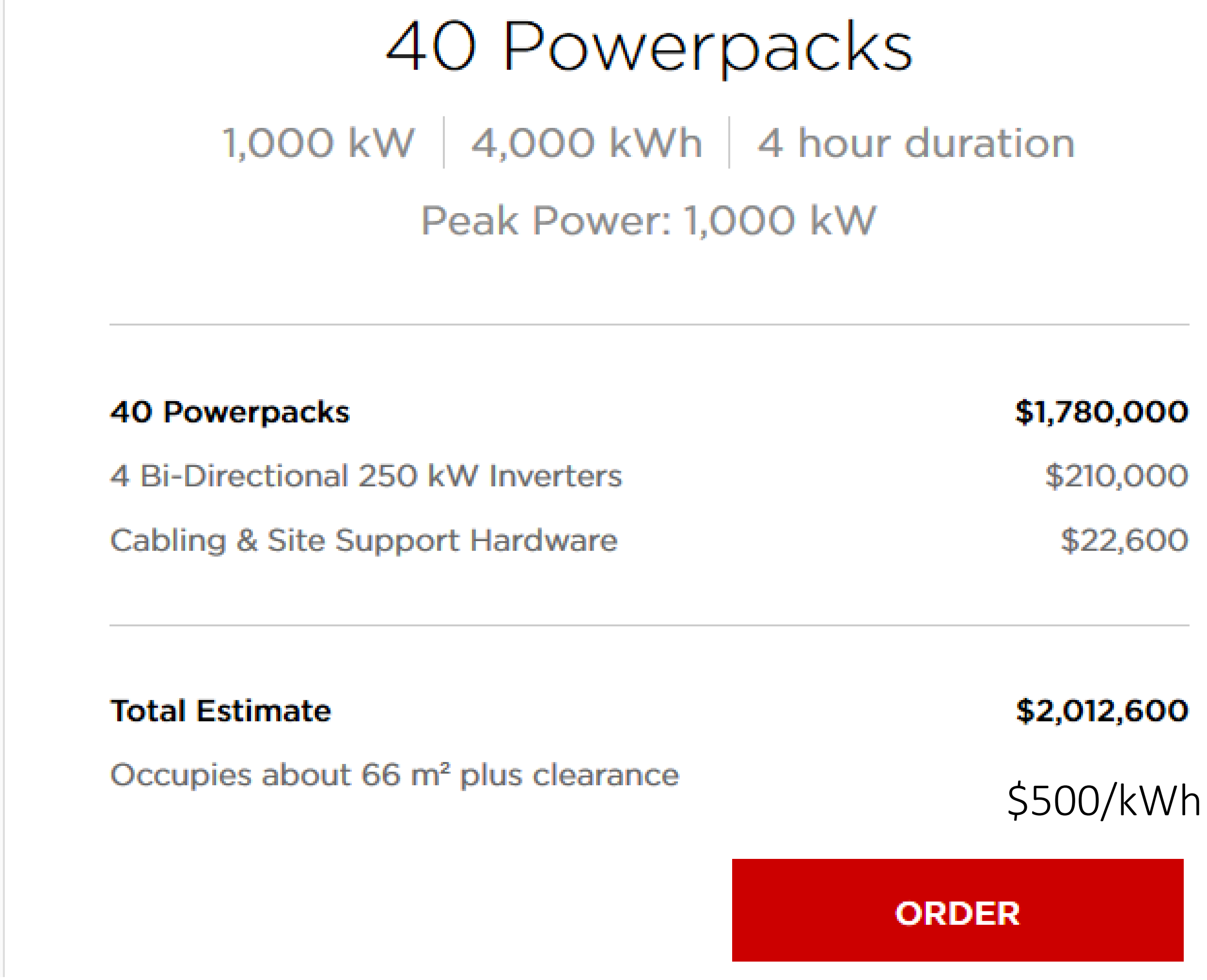
Dimensions
51.3" x 34" x 7.2"
1302 mm x 862 mm x 183 mm

Certification
UL 9540, UL 1642, UL 1973
AC156 seismic certification
IEEE 693- 2005 seismic certification
FCC Part 15 Class B

Tesla Powerpack



Tesla Powerpack Pricing
1 MW – 4 hour duration



40 Powerpacks

1,000 kW | 4,000 kWh | 4 hour duration

Peak Power: 1,000 kW

40 Powerpacks	**$1,780,000**
4 Bi-Directional 250 kW Inverters	$210,000
Cabling & Site Support Hardware	$22,600
Total Estimate	**$2,012,600**

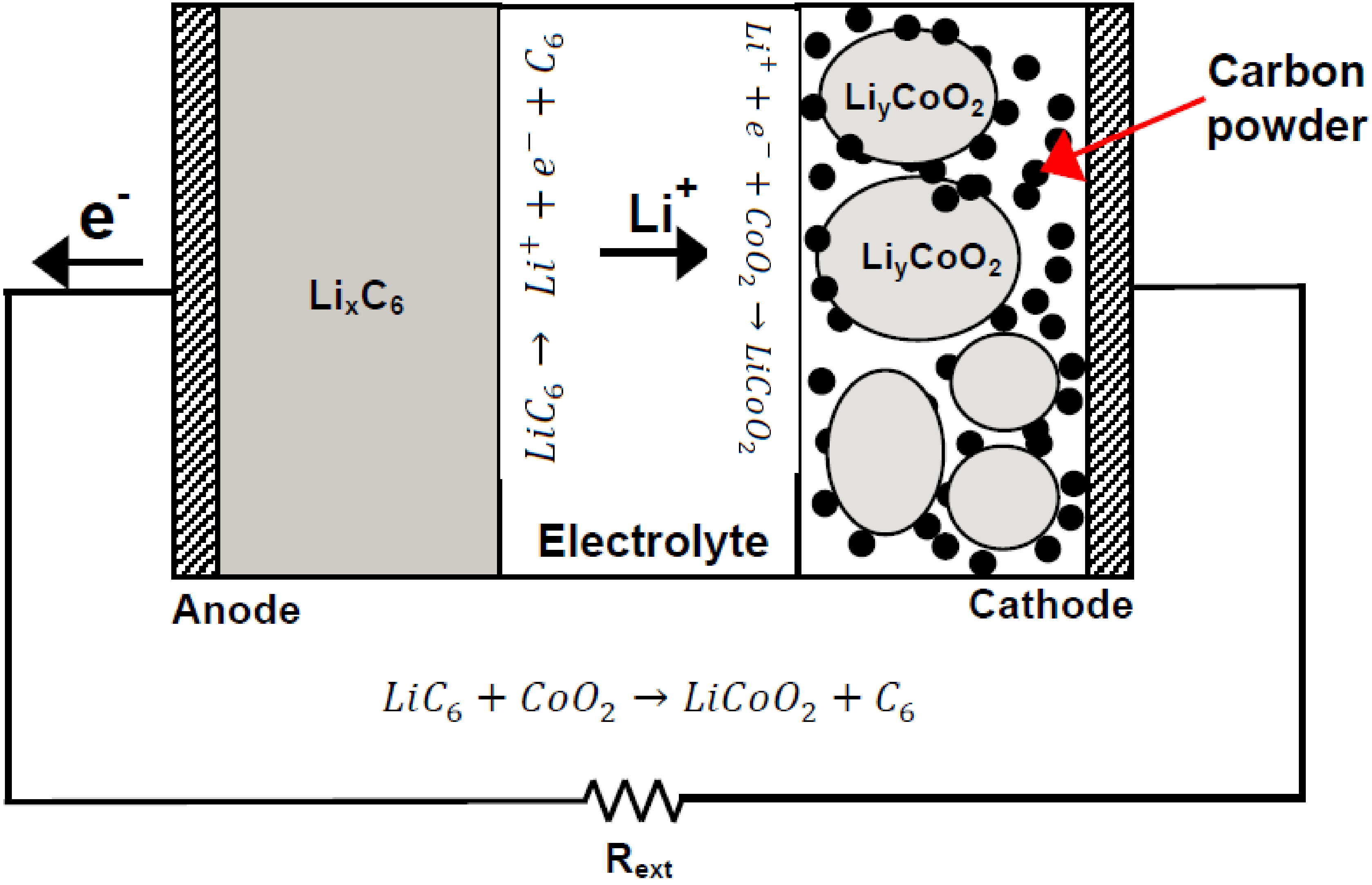
Occupies about 66 m² plus clearance

$500/kWh

Tesla Gigafactory
Storey County, Nevada

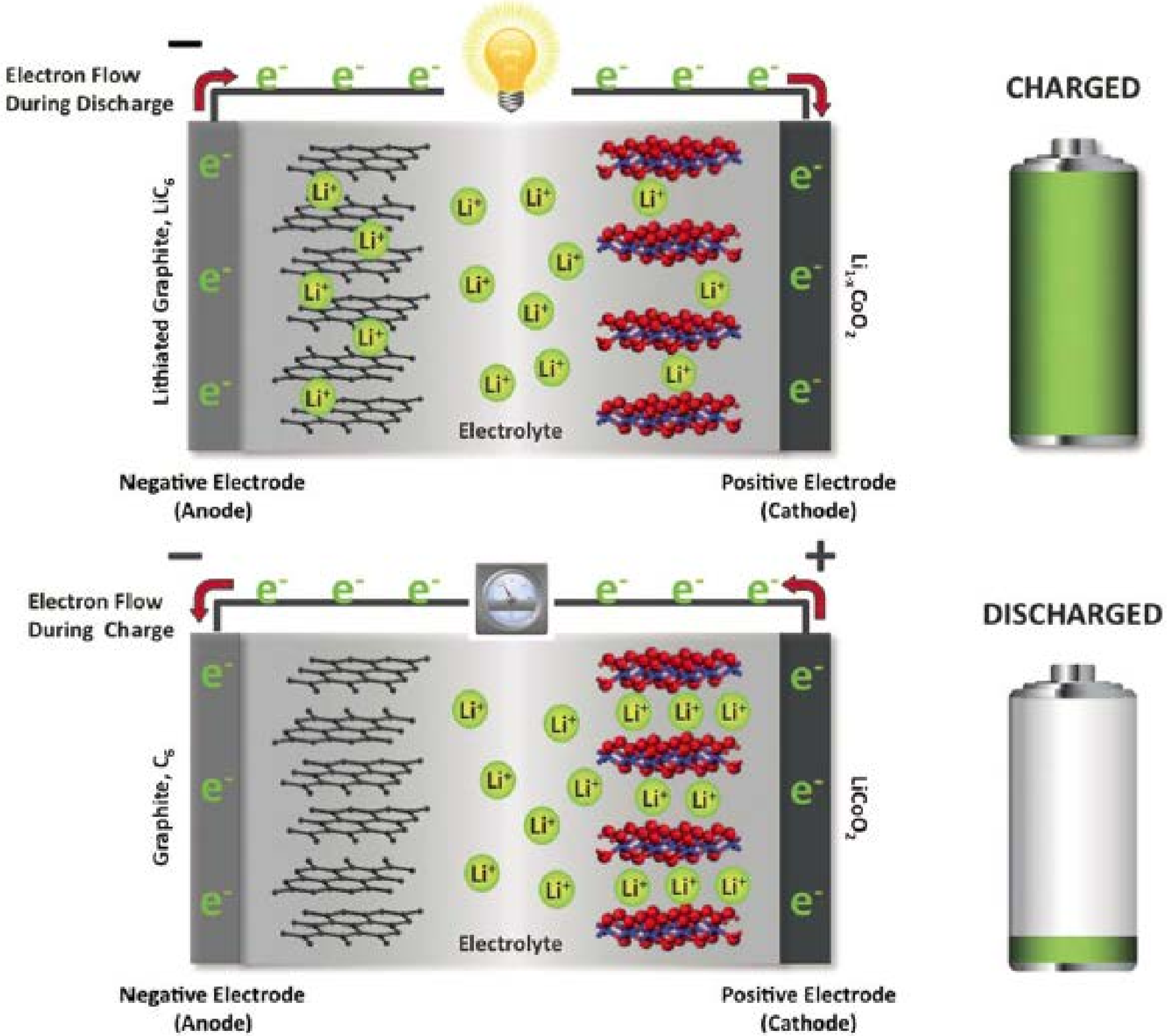
Lithium-Ion Battery

Lithium-Ion Battery Ion Flow



$$LiC_6 + CoO_2 \rightarrow LiCoO_2 + C_6$$

Lithium-Ion Battery Charge-Discharged



Some Battery Storage Facilities

Notrees Battery Storage Project (TX)
Duke Energy

153 MW wind farm with 40 minutes of 36 MW storage (24 MWh)

AES Laurel Mountain (WV)

98 MW wind farm with 15 minutes of 32 MW storage
8 MWh

Kyushu Electric - Buzen Substation

50 MW for 6 hours
300 MWh

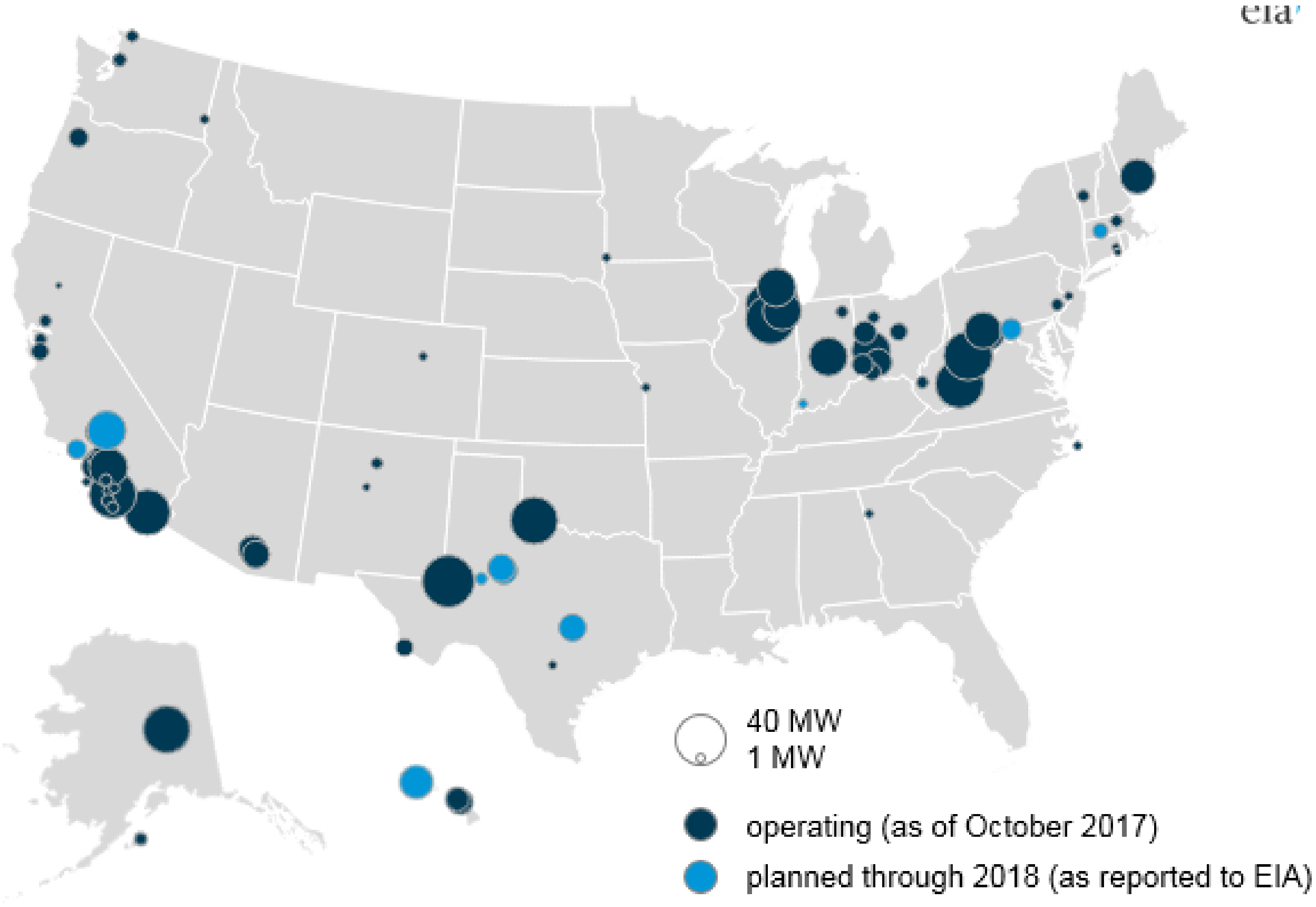
The New York Times

November 20, 2017

Australia Powers Up the World’s Biggest Battery — Courtesy of Elon Musk

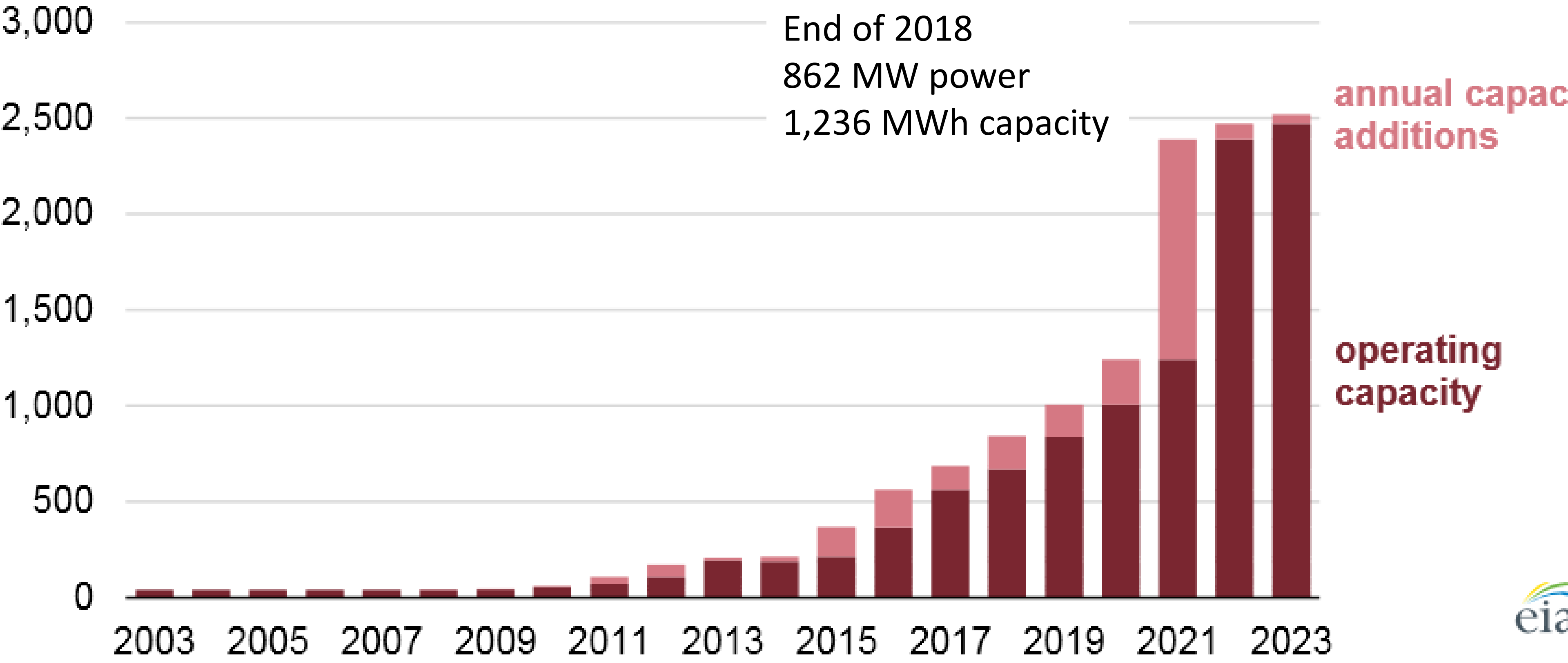
100 MW, 129 MWh of storage. Construction in 100 days. Approximately $250/kWh.

Operating and planned utility-scale battery power capacity



Today in Energy July 10, 2019
Utility Scale Battery Energy Storage

U.S. utility-scale battery storage power capacity (March 2019)
megawatts (MW)



End of 2018
862 MW power
1,236 MWh capacity

Source: U.S. Energy Information Administration, *Annual Electric Generator Report* and the *Preliminary Monthly Elec*

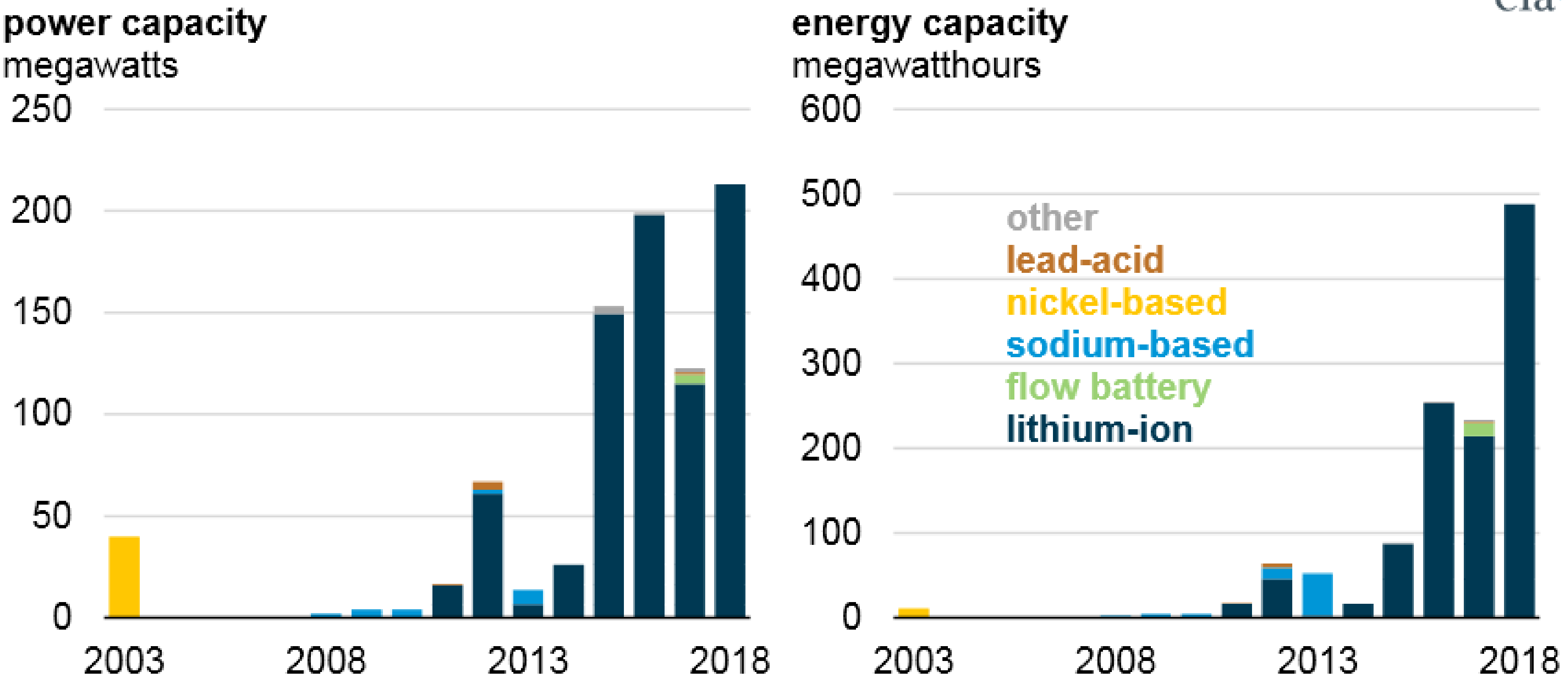
Battery Storage Systems Ratings

- **Power capacity or rating.** Measured in megawatts (MW), this is the maximum instantaneous amount of power that can be produced on a continuous basis and is the usual type of generator capacity discussed.
- **Energy capacity.** Measured in megawatthours (MWh), this is the total amount of energy that can be stored or discharged by the battery.

Independent Statistics & Analysis
U.S. Energy Information Administration

Today in Energy October 30, 2019
Utility Scale Battery Technology

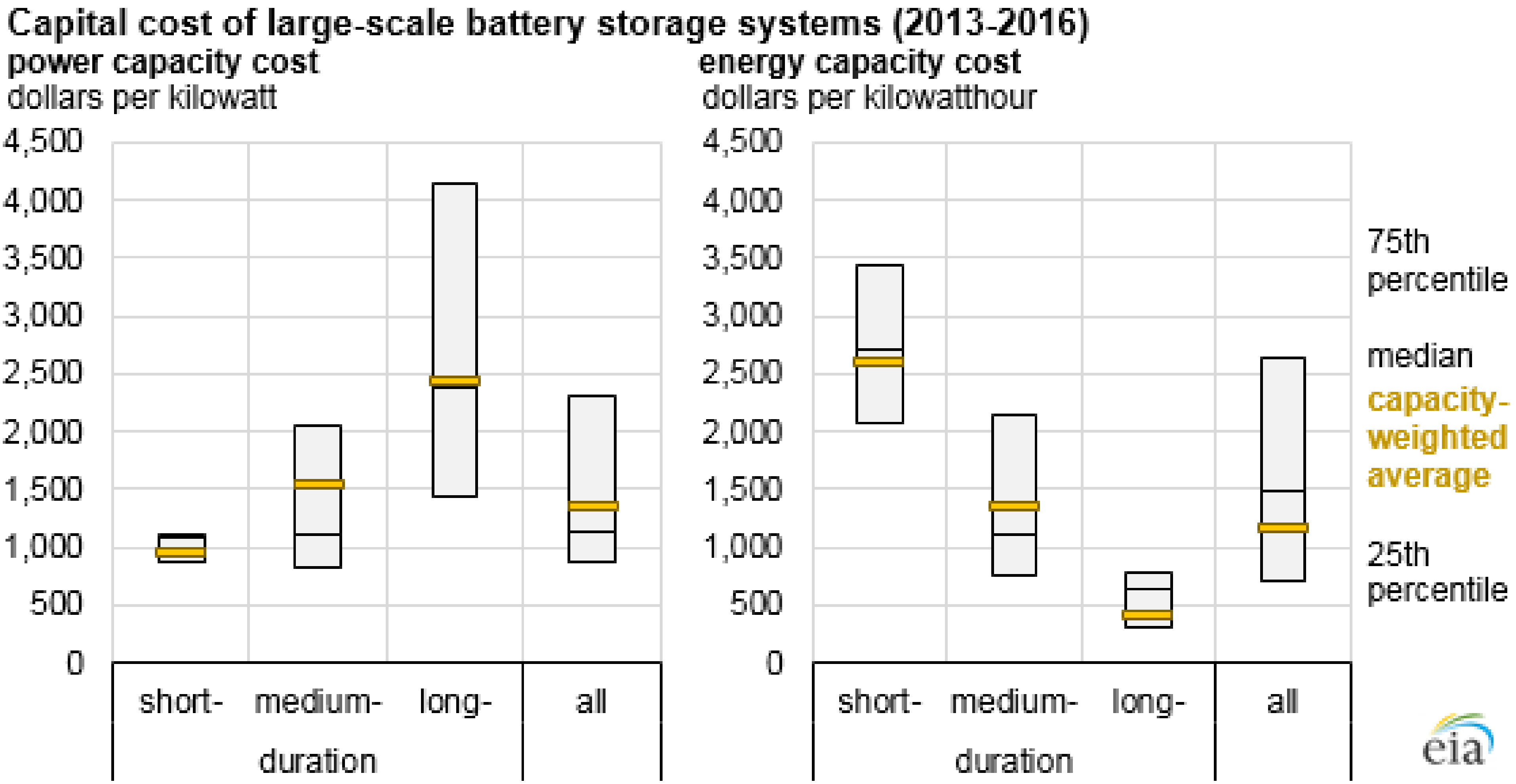
U.S. utilty-scale battery installations (2003-2018)



Source: U.S. Energy Information Administration, *Annual Electric Generator Report*

Independent Statistics & Analysis
U.S. Energy Information Administration

Today in Energy June 1, 2018
Utility Scale Battery Costs



Capital cost of large-scale battery storage systems (2013-2016)

The Big Question

How much storage is needed?

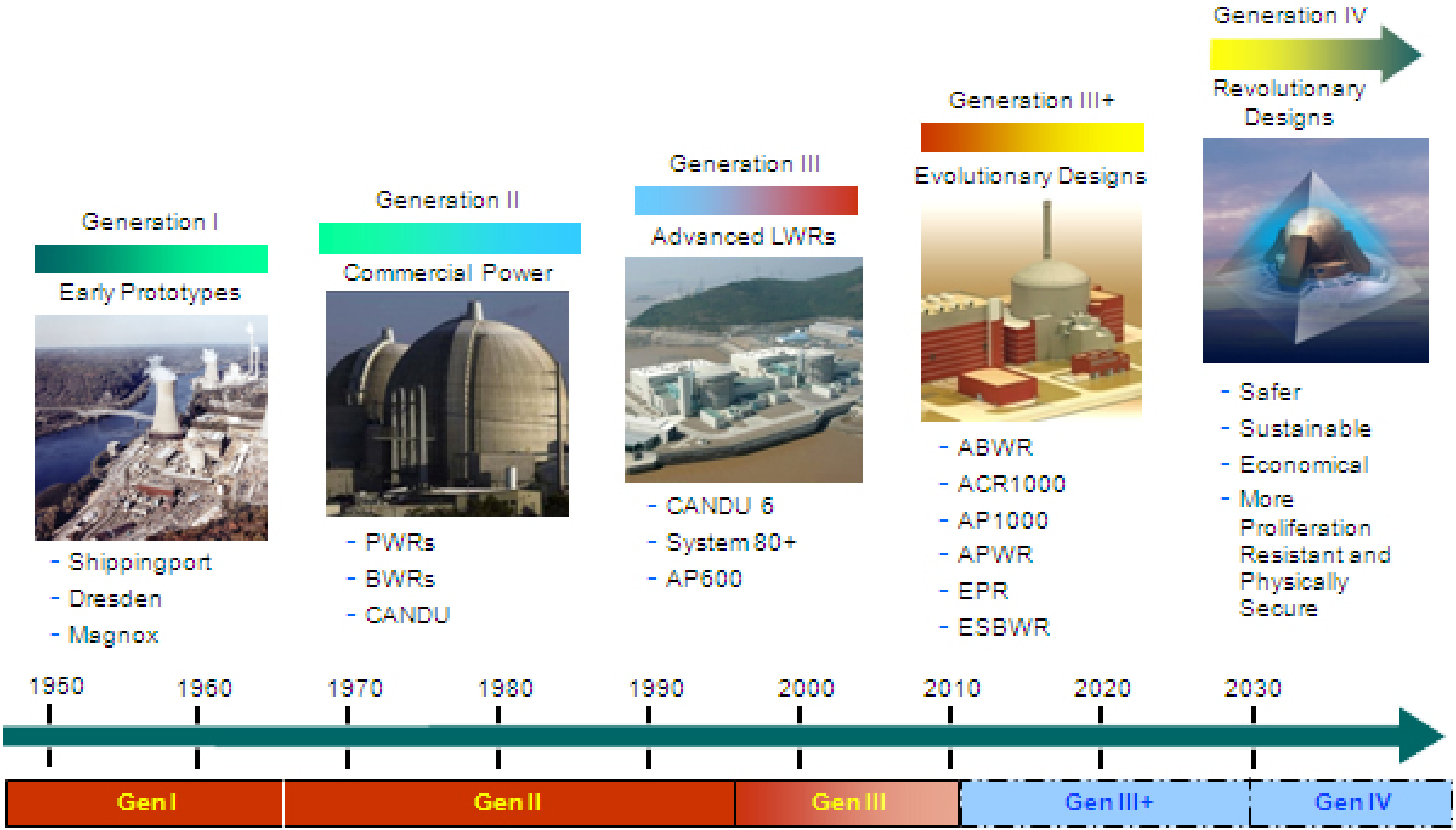
Nuclear power

Mostly Economic Issues With Nuclear Power

- Nuclear power plant technology
- Nuclear power emissions
- Is nuclear power a renewable?
- Status of nuclear power industry in the world
- Status of small modular reactors in the world
- Status of nuclear power industry in the U.S.
- Cause of nuclear power decline in the U.S.

Nuclear power plant technology

Timeline of Reactor Developments



Generation I

Early Prototypes

- Shippingport
- Dresden
- Magnox

Generation II

Commercial Power

- PWRs
- BWRs
- CANDU

Generation III

Advanced LWRs

- CANDU 6
- System 80+
- AP600

Generation III+

Evolutionary Designs

- ABWR
- ACR1000
- AP1000
- APWR
- EPR
- ESBWR

Generation IV

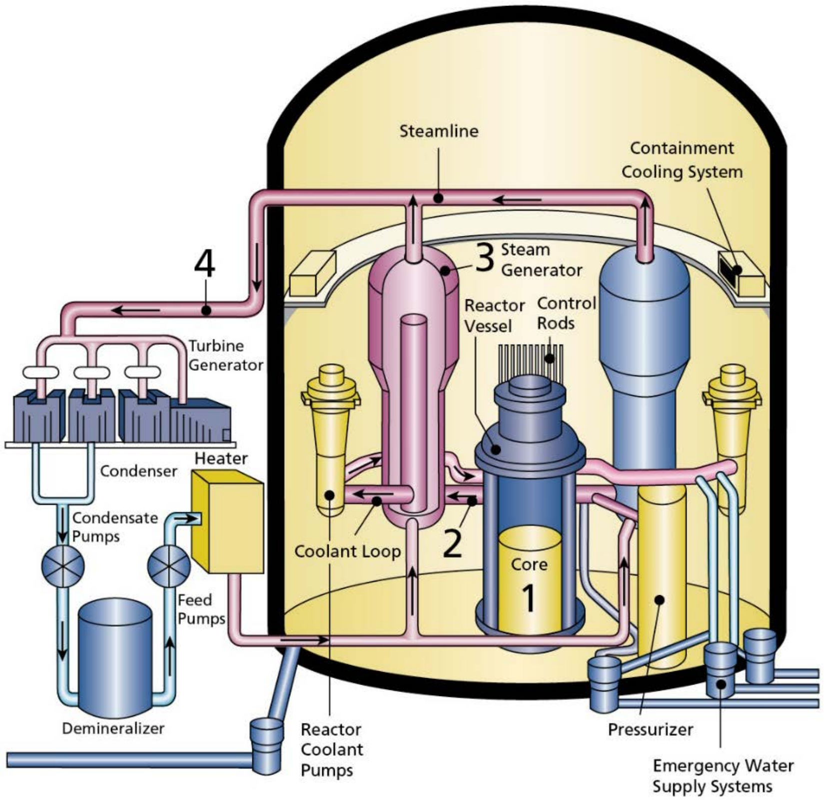
Revolutionary Designs

- Safer
- Sustainable
- Economical
- More Proliferation Resistant and Physically Secure

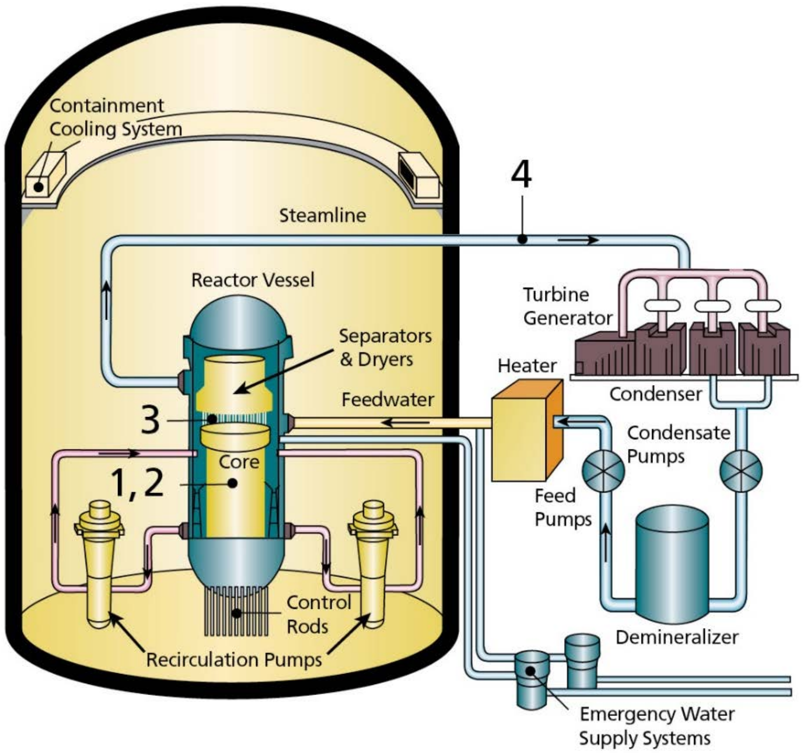
from OECD Nuclear Energy Agency

Light Water Reactor Types

pressurized water reactor

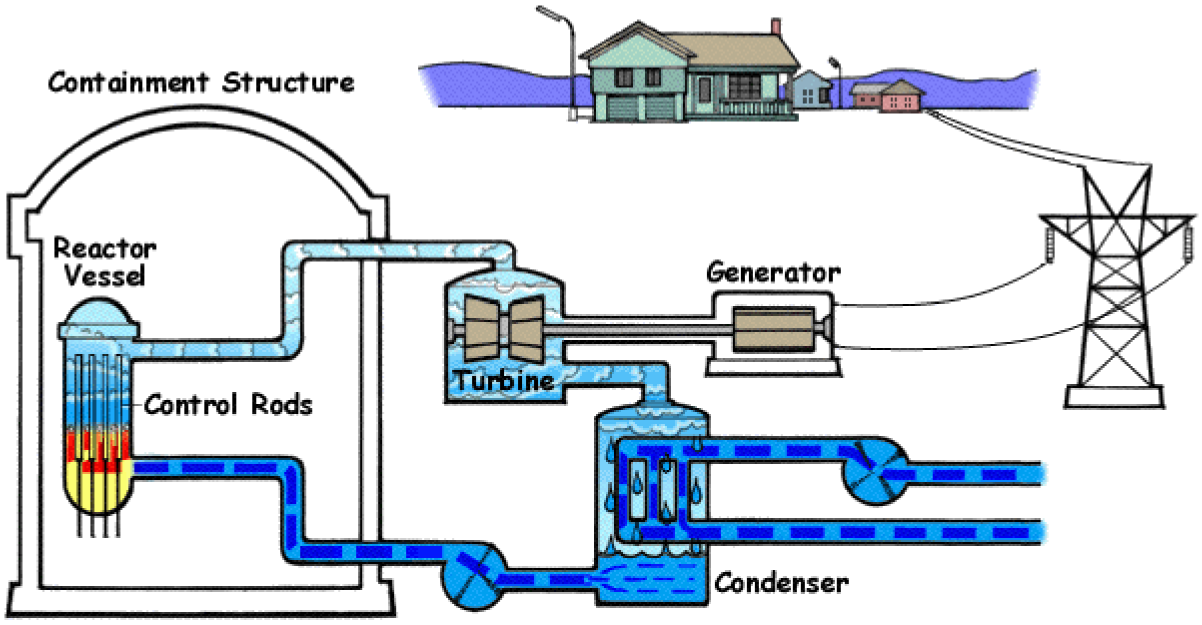


boiling water reactor

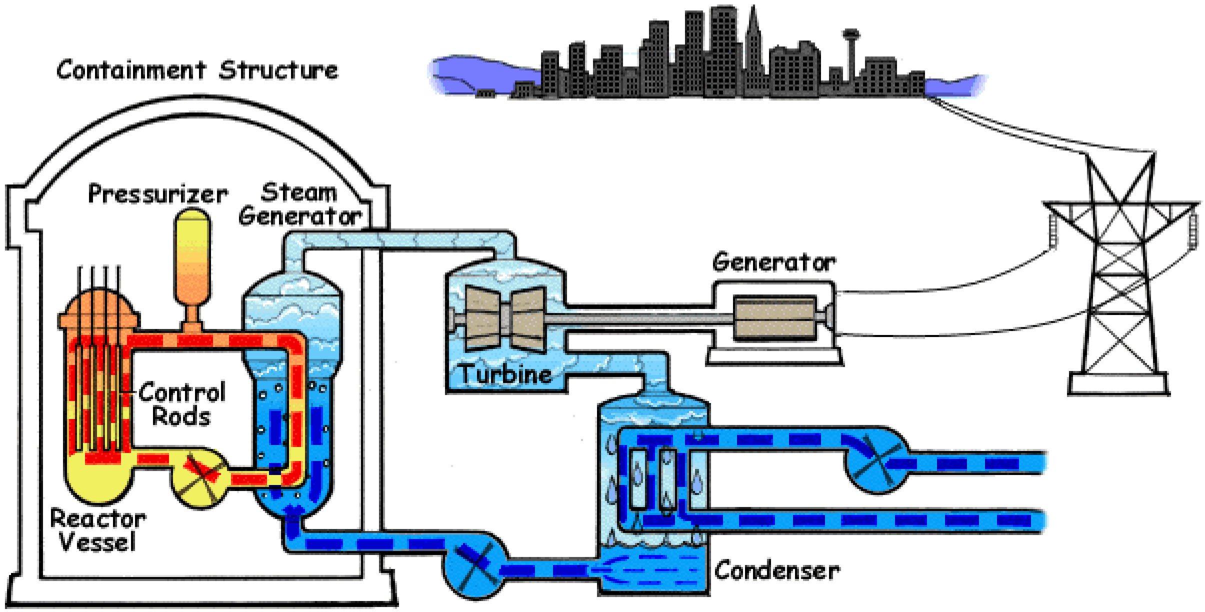


from U.S. Nuclear Regulatory Commission

Boiling Water Reactor (BWR)

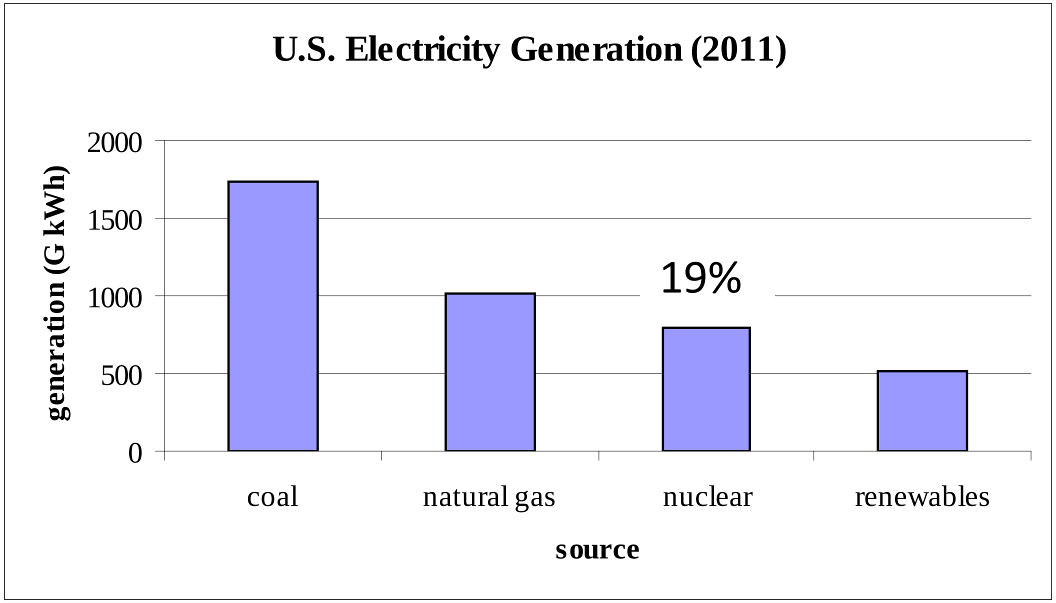


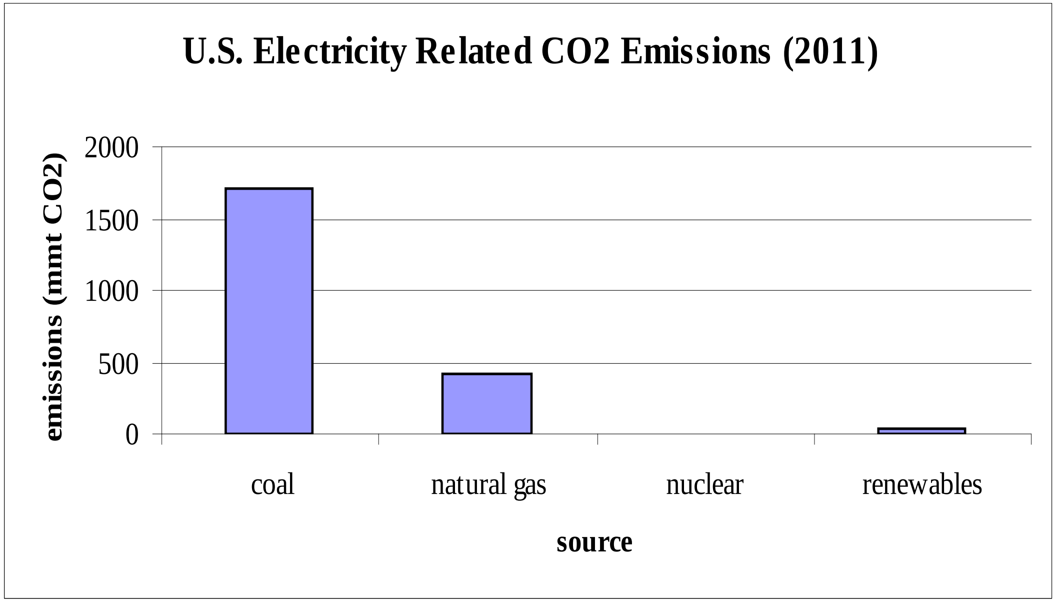
Pressurized Water Reactor (PWR)



Nuclear Power and Greenhouse Gas Emissions

U.S. Electricity and CO_2 Emissions (2011)

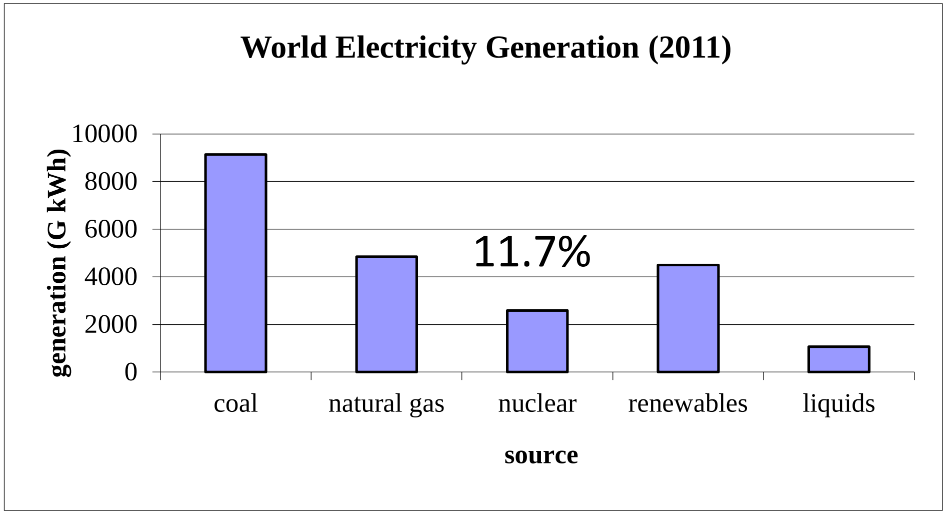


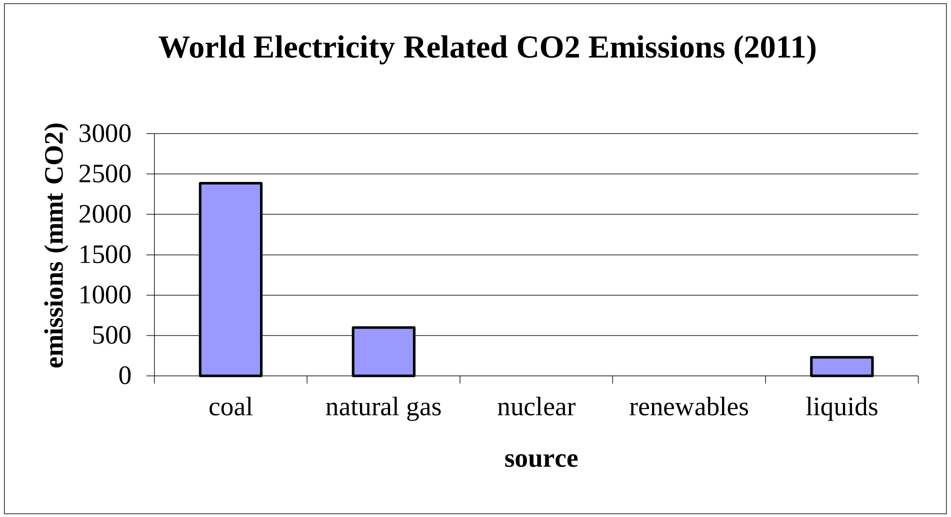


If nuclear generated electricity were generated by fossil fuels, annual emissions would increase by 611 MMT CO_2, a 28% increase.

data from EIA Annual Energy Review 2011, Tables 8.2a & 11.3e

World Electricity and CO_2 Emissions (2011)





If nuclear generated electricity were generated by fossil fuels, annual emissions would increase by 2,037 MMT CO_2, a 16% increase.

data from IEA Key World Energy Statistics 2013, pp 25-26

THE WALL STREET JOURNAL.

April 4, 2019

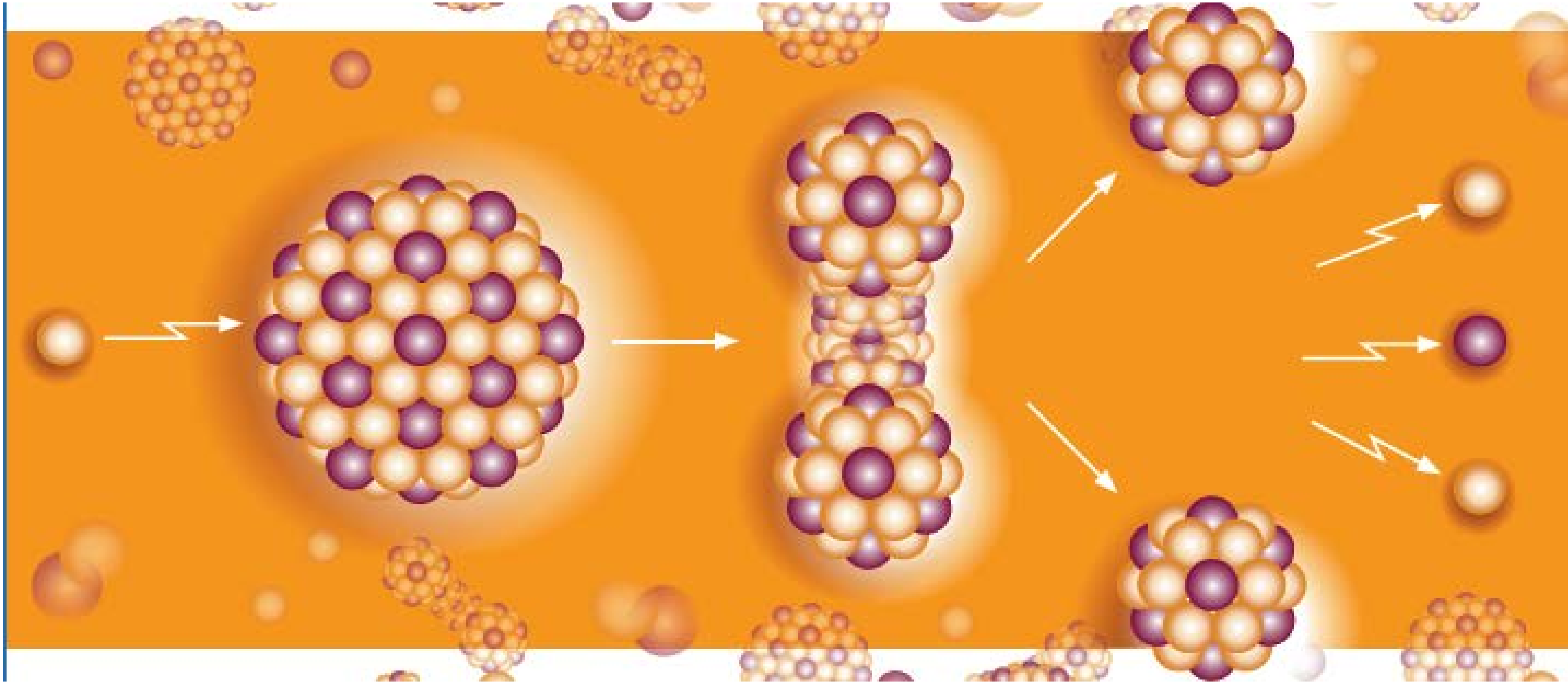
The Climate Needs Nuclear Power

James Hansen and Michael Shellenberger

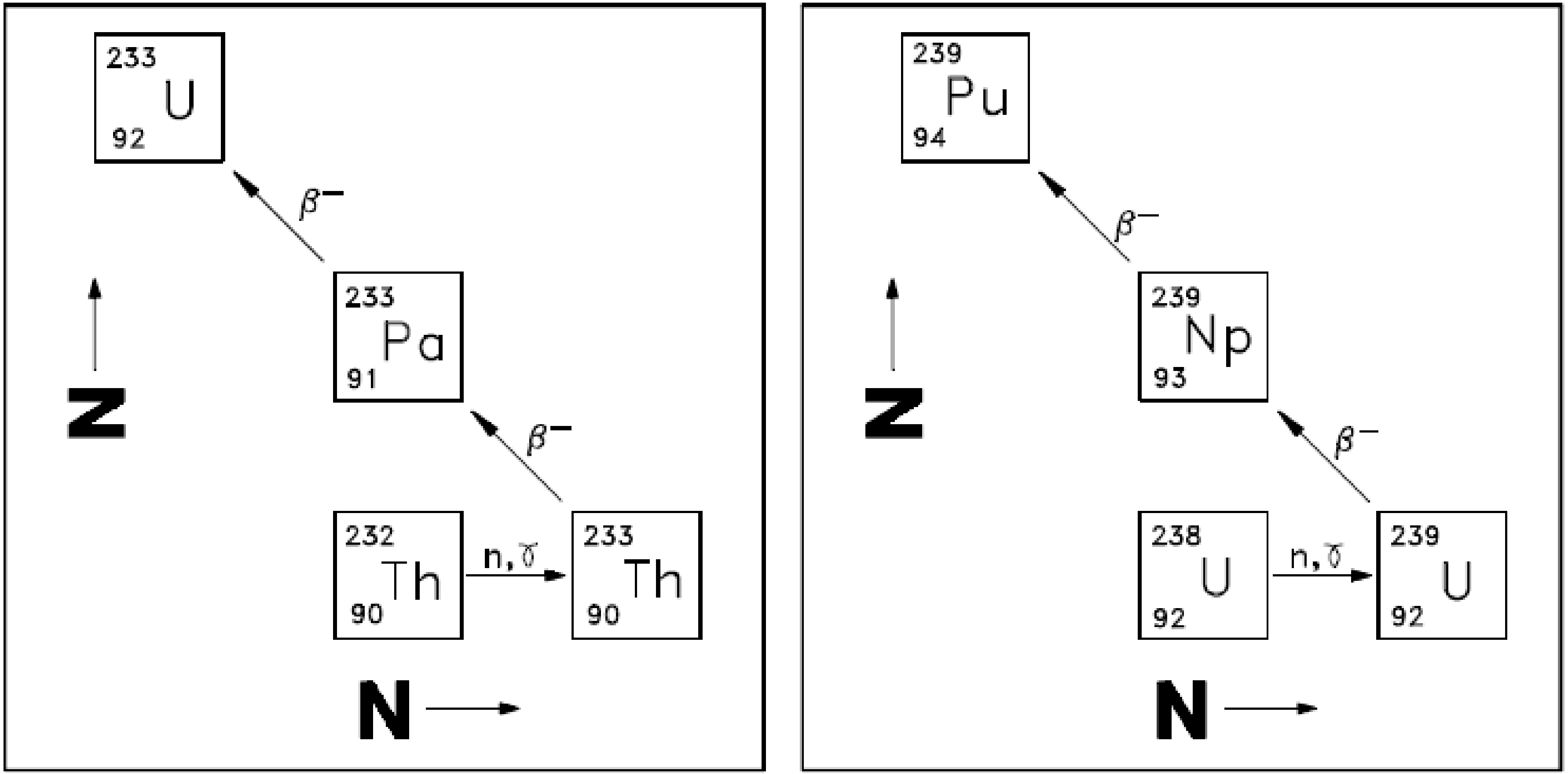
The Diablo Canyon nuclear-power plant in San Luis Obispo, Calif.

Is nuclear power renewable?

Nuclear Fission
United States Government Accountability Office

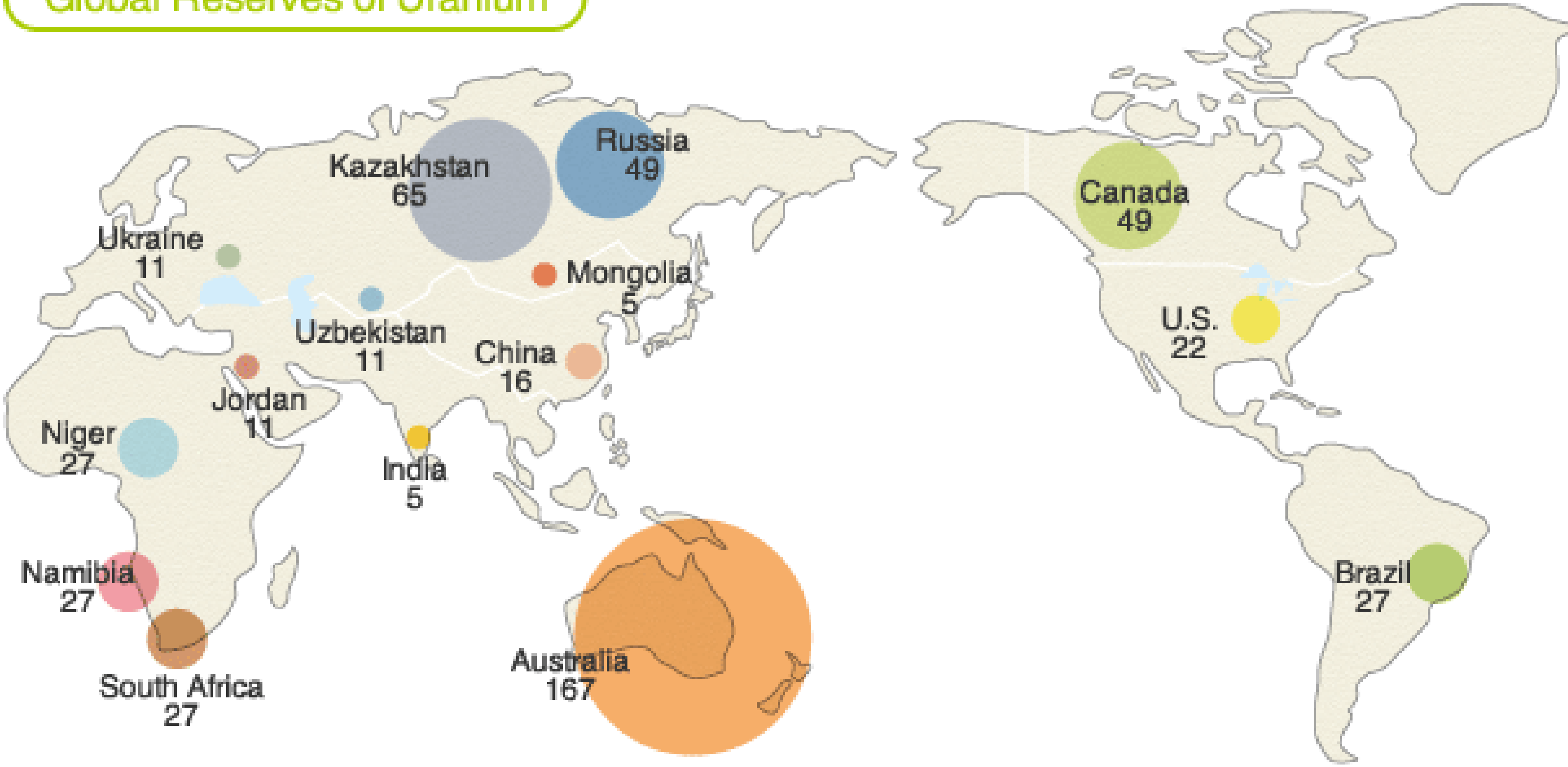


Conversion of Fertile Nuclides to Fissile Nuclides



Global Uranium Reserves

Global Reserves of Uranium



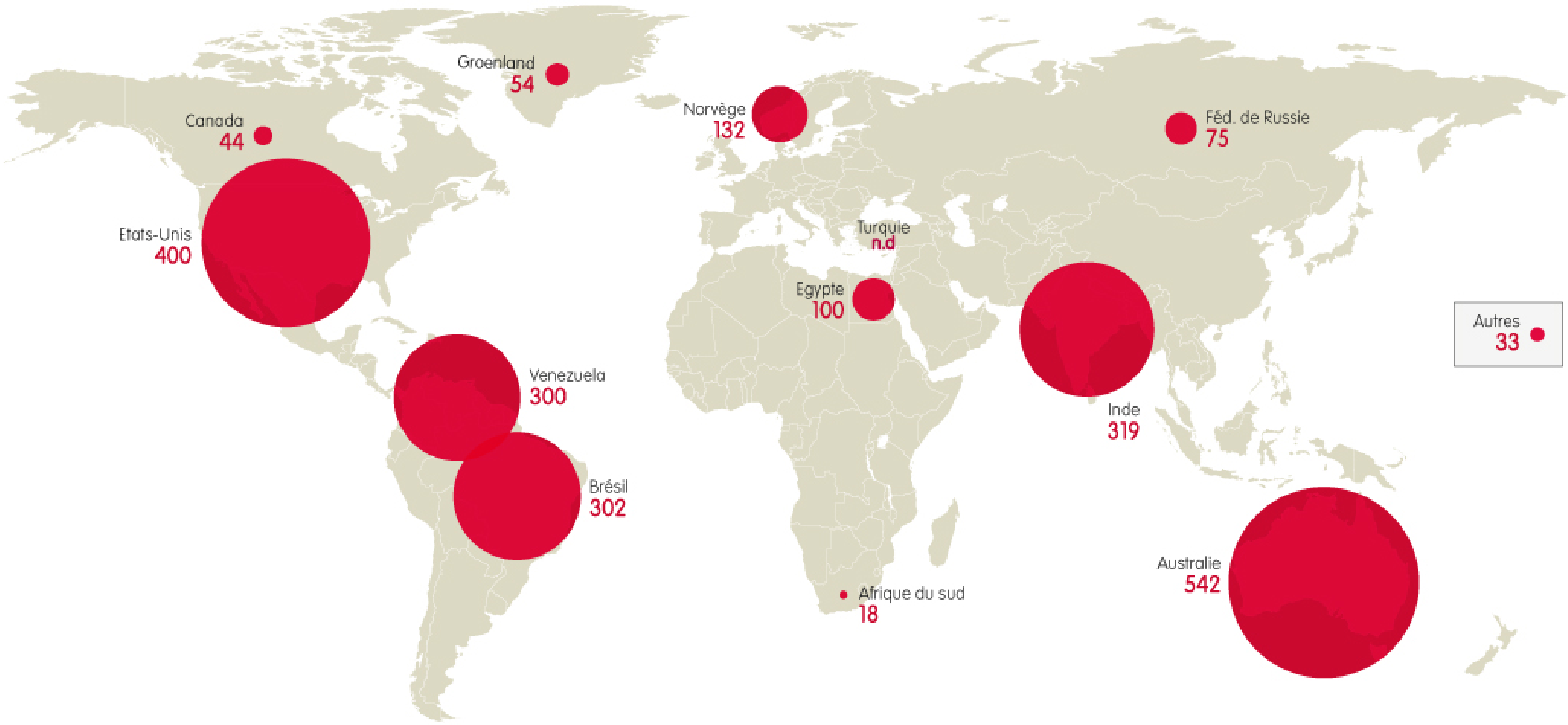
Unit: 10,000 tU

*Figures for in-situ resources in each country have been adjusted for estimated exploration loss and refining loss. (as of January 2009)

Source : Formulated using data in The graphical flip-chart of nuclear & energy-related topics 2012, The Federation of Electric Power Companies of Japan

Ressources mondiales en thorium

(milliers de tonnes de Th)



Identifiées <80 USD/KG Th

Total : 2 229

Source : « Uranium 2011 : ressources, production & demande » OECD 2012
Design : CEA/L.COLOMBEL, 2014

Sustainability:

How long can we power today's reactors with known reserves?

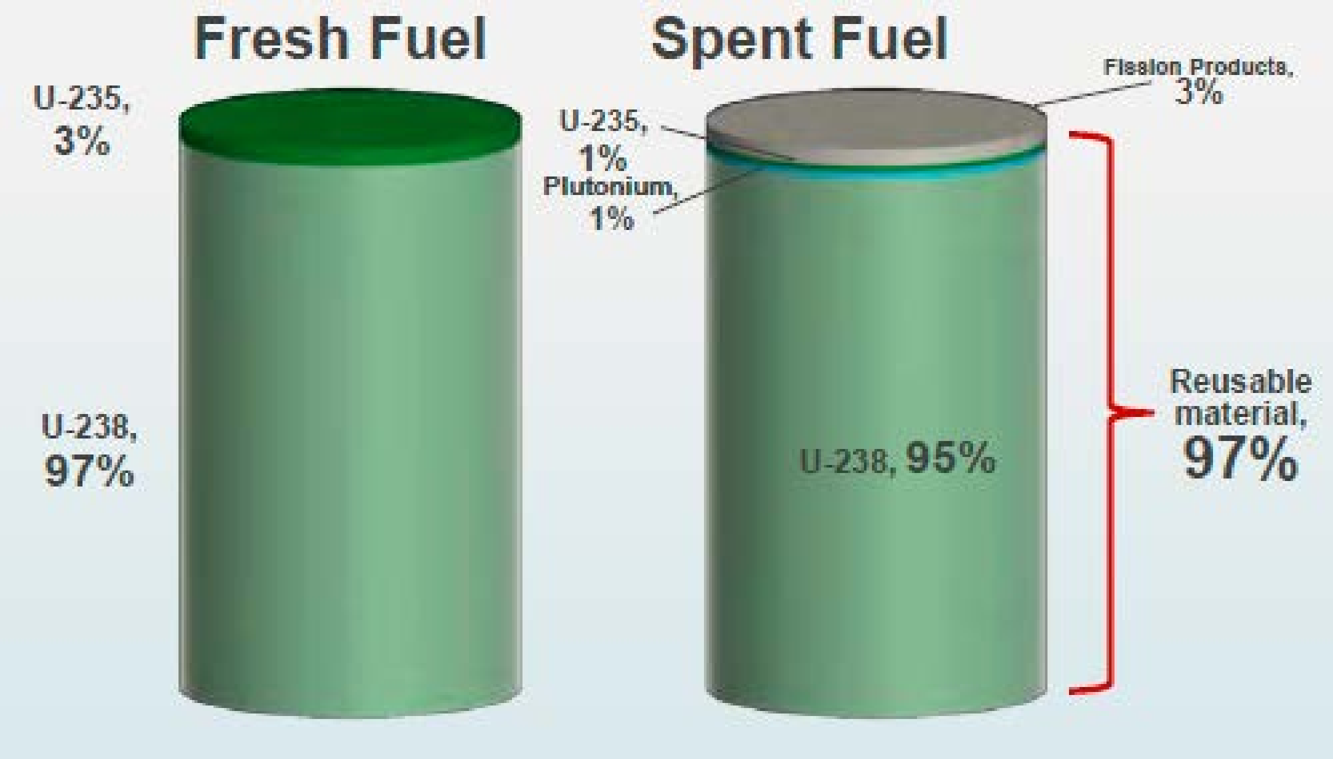
*Worldwide Annual Requirements, shown in metric tons (MT)***	
Pre-Fukushima	**82 years** (64,875 MT/yr)
Projected by 2035 – Assuming best case economic growth	**39 years** (136,000 MT/yr)
Projected by 2035 – Assuming mean case economic growth	**55 years** (96,000 MT/yr)

*Reasonably Assured Reserves of Uranium, shown in metric tons (MT)**	
Australia	1,661,000
Kazakhstan	629,000
Russia	487,200
Canada	468,700
Niger	421,000
South Africa	279,100
Brazil	276,700
Namibia	261,000
USA	207,400
China	166,100
Ukraine	119,600
Uzbekistan	96,200
Mongolia	55,700
Jordan	33,800
Other	164,000
TOTAL	**5,326,500**

- Assumes a 'once-through' burning of 3-5% enriched U
- Does not include unproven reserves (10.5B MT) and seawater (4.5B MT) → 230 years

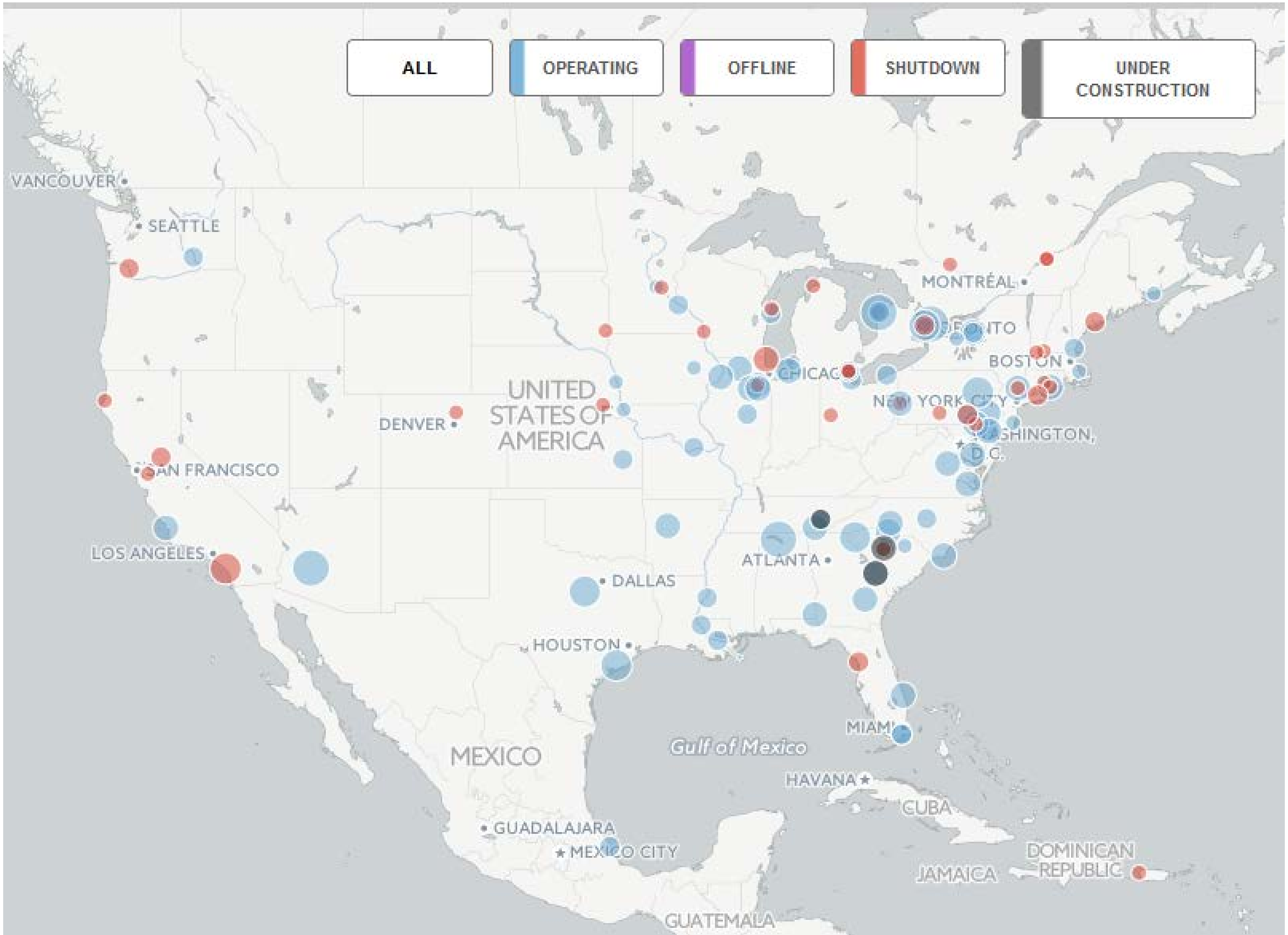
**World Nuclear Association, July 2016*
*** OECD Nuclear Energy Agency*

Reusable Fuel Material

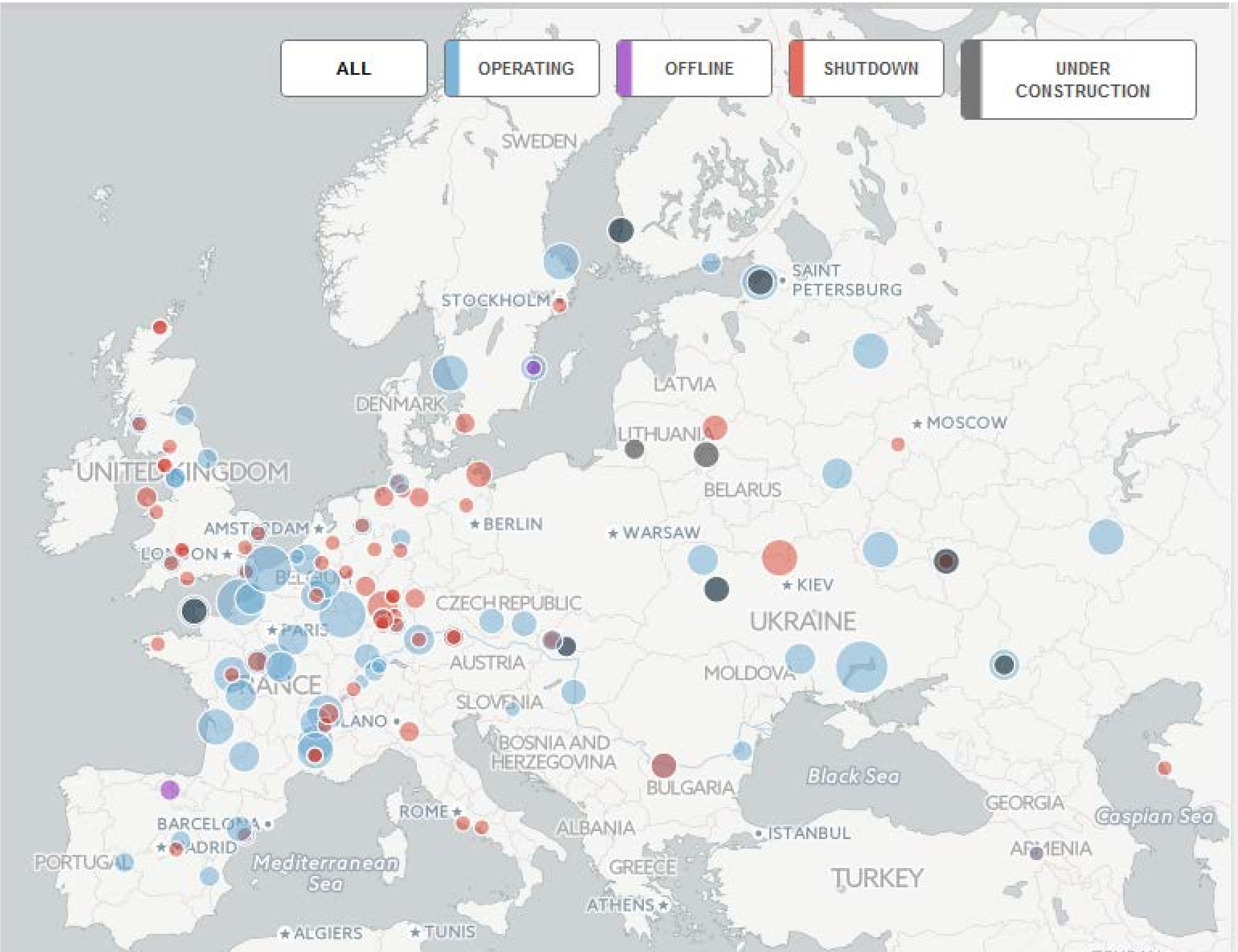


Status of the World Nuclear Power industry

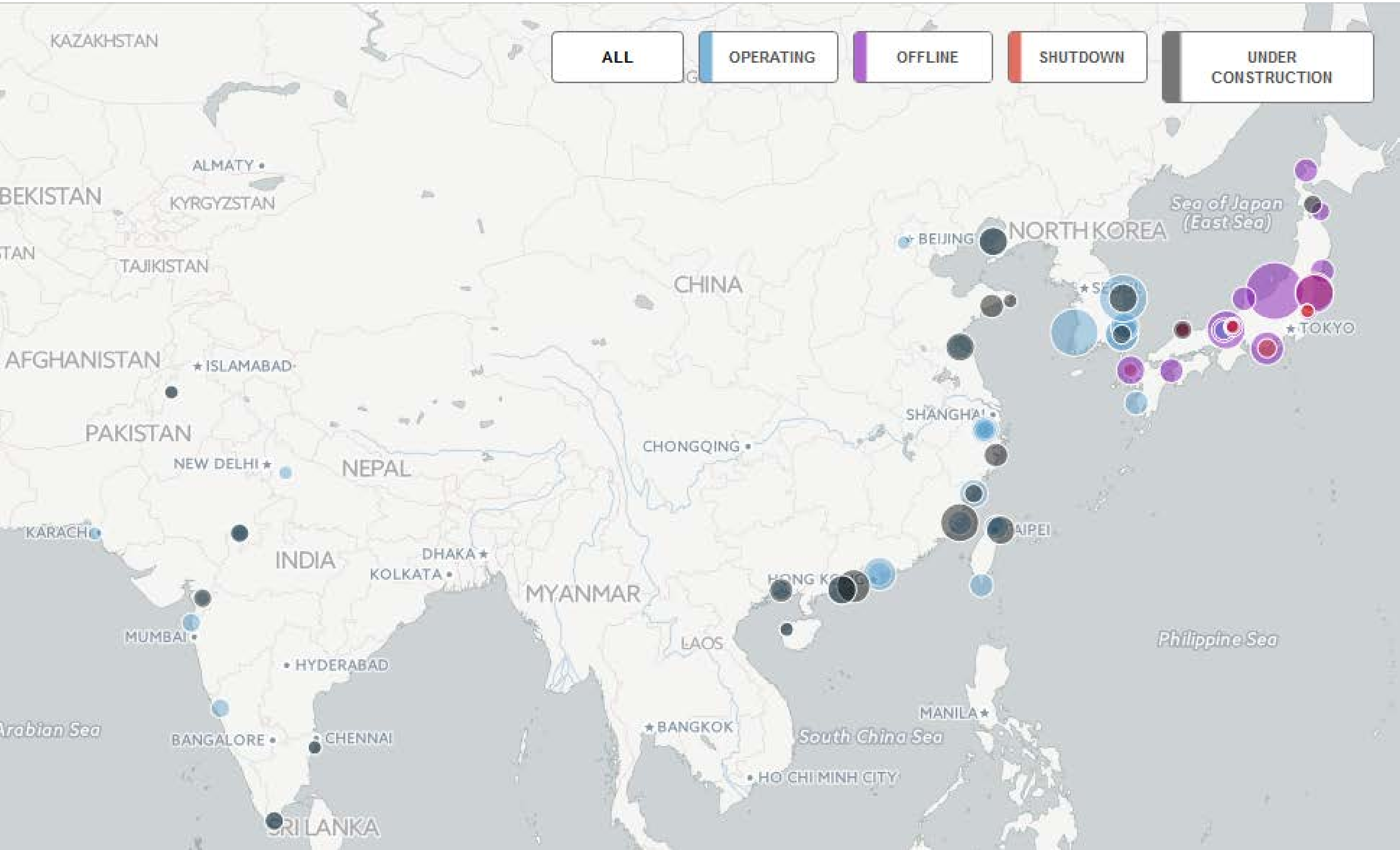
Reactors All Categories U.S.



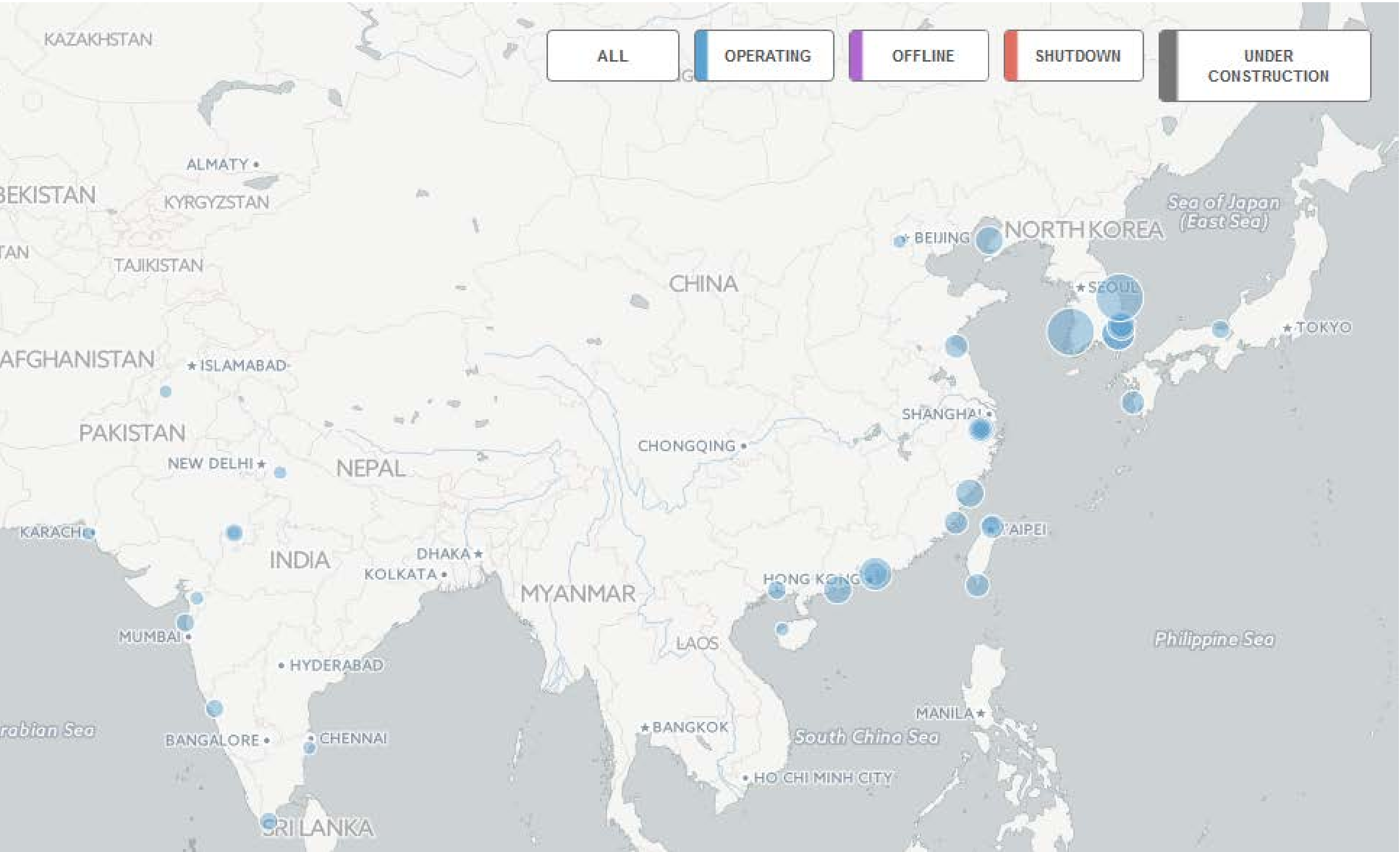
Reactors All Categories Europe



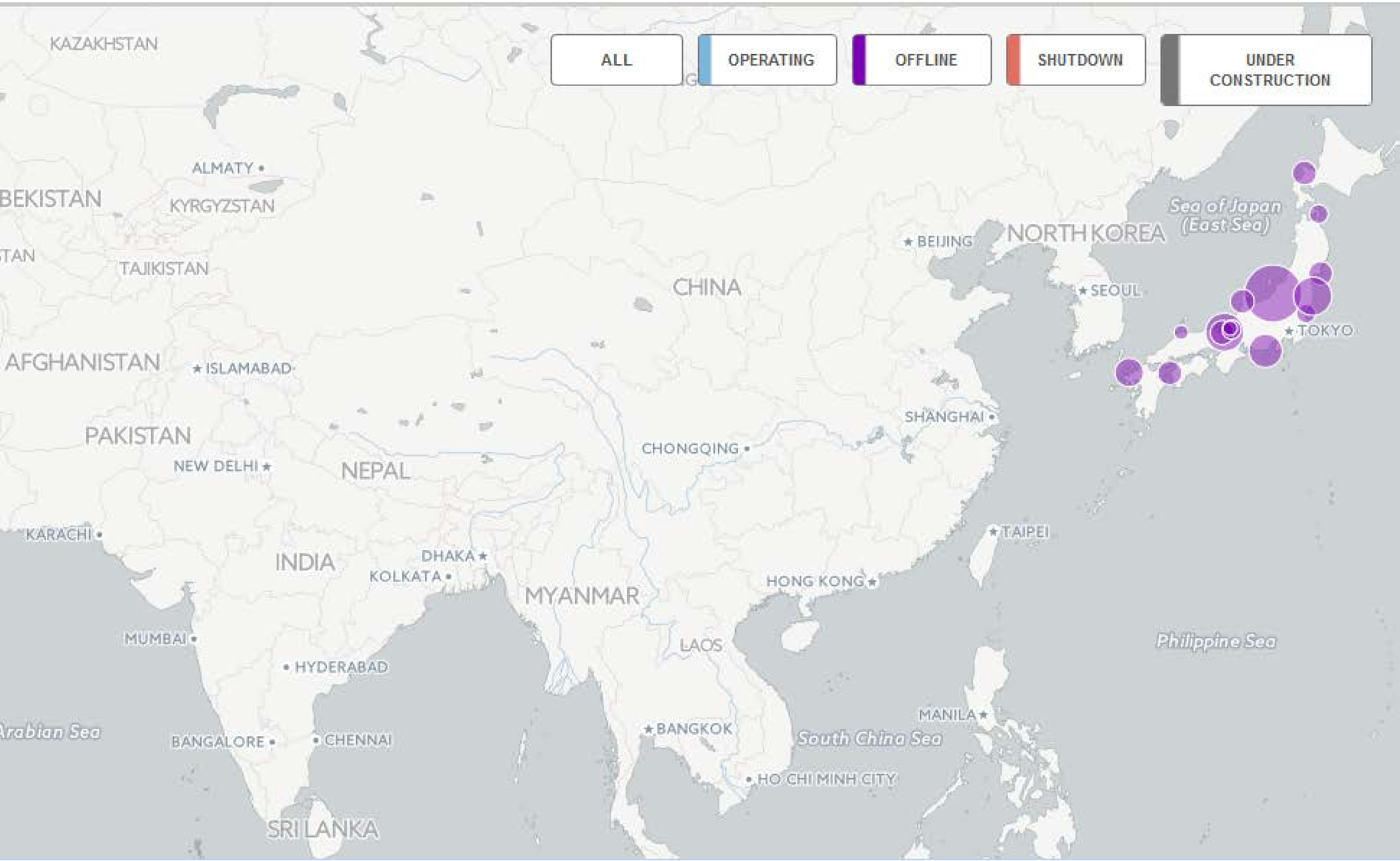
Reactors All Categories East Asia



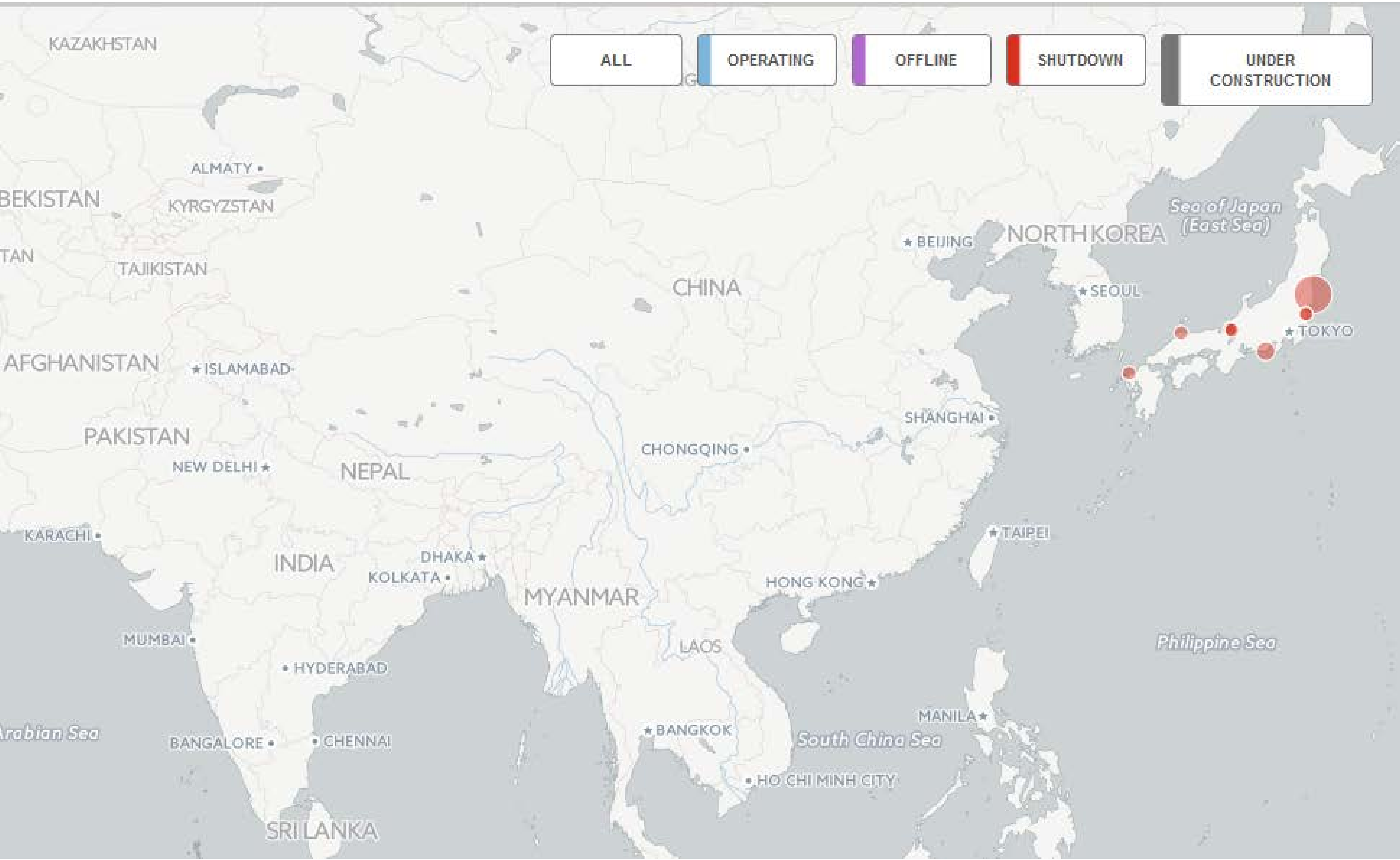
Operating Reactors East Asia



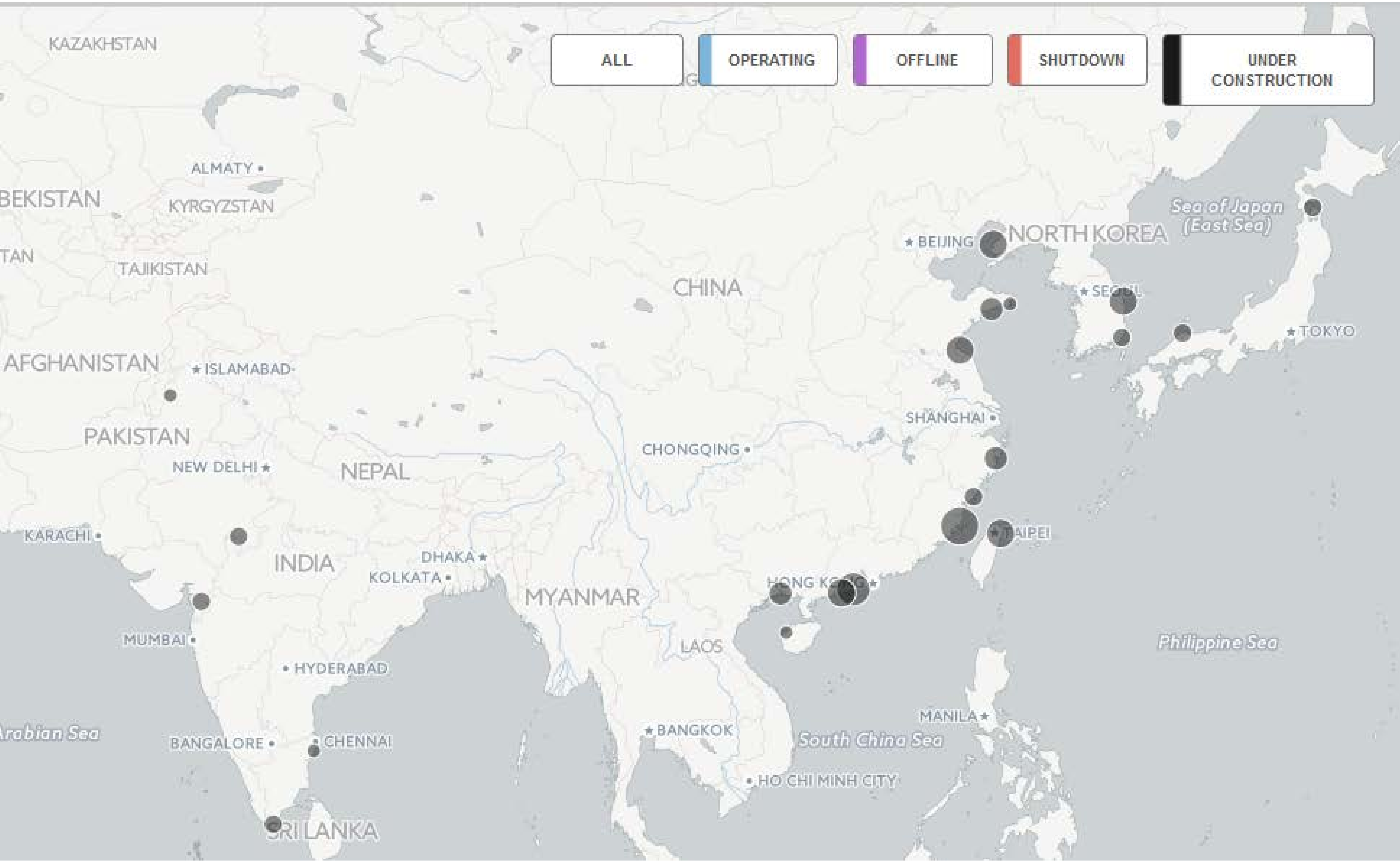
Offline Reactors East Asia



Shutdown Reactors East Asia



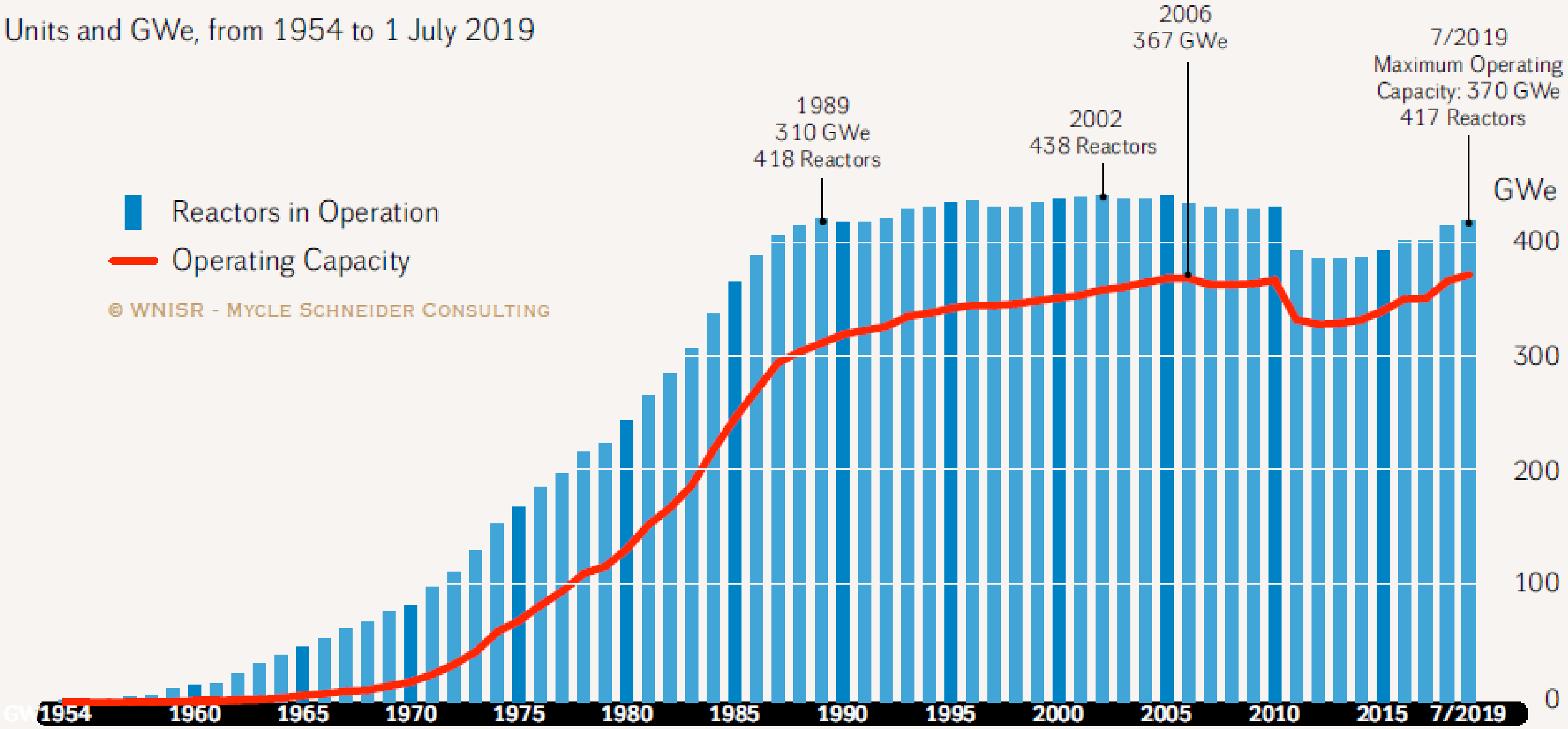
Reactors Under Construction East Asia



World Nuclear Reactor Fleet

Nuclear Reactors and Net Operating Capacity in the World

in Units and GWe, from 1954 to 1 July 2019



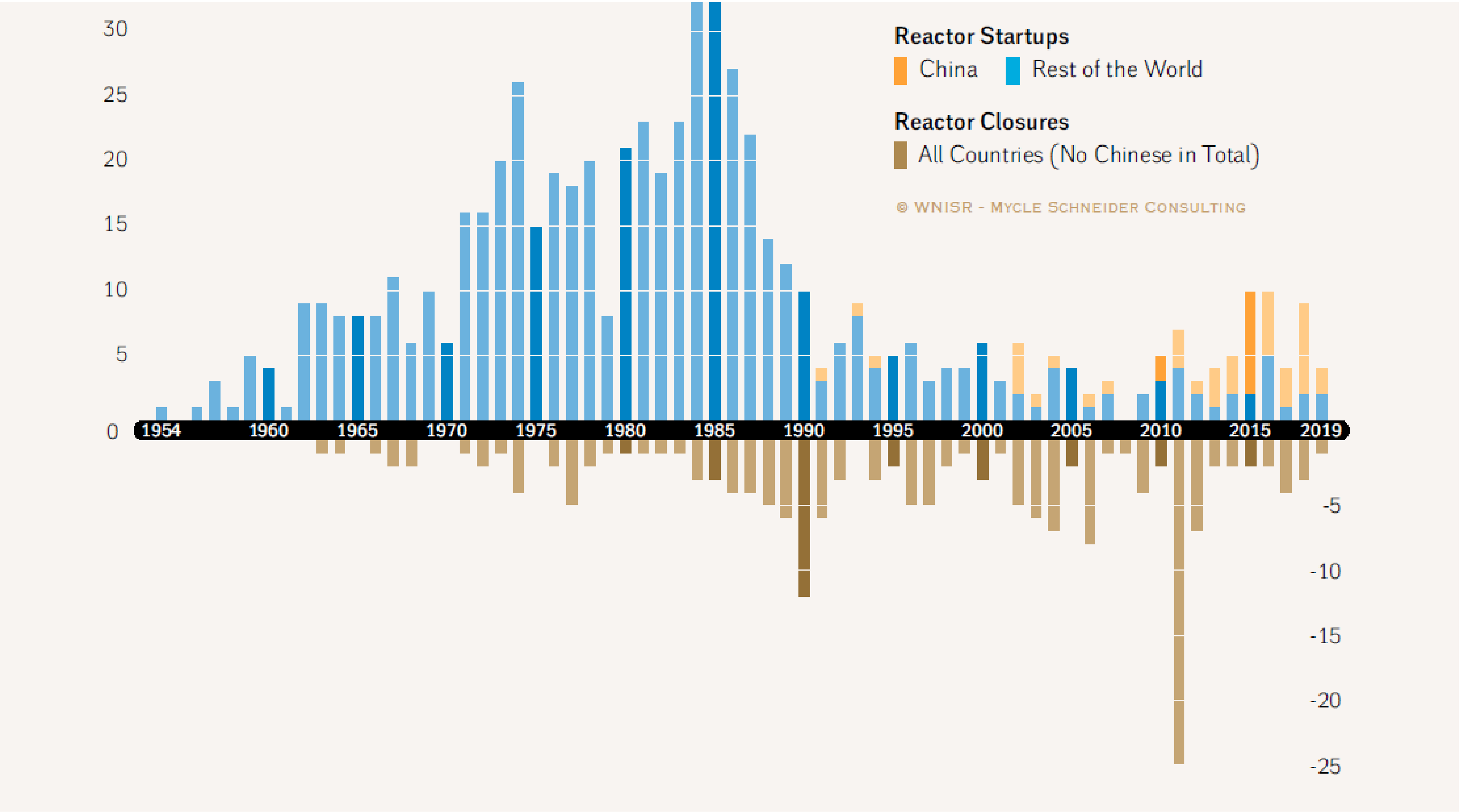
1989
310 GWe
418 Reactors

2002
438 Reactors

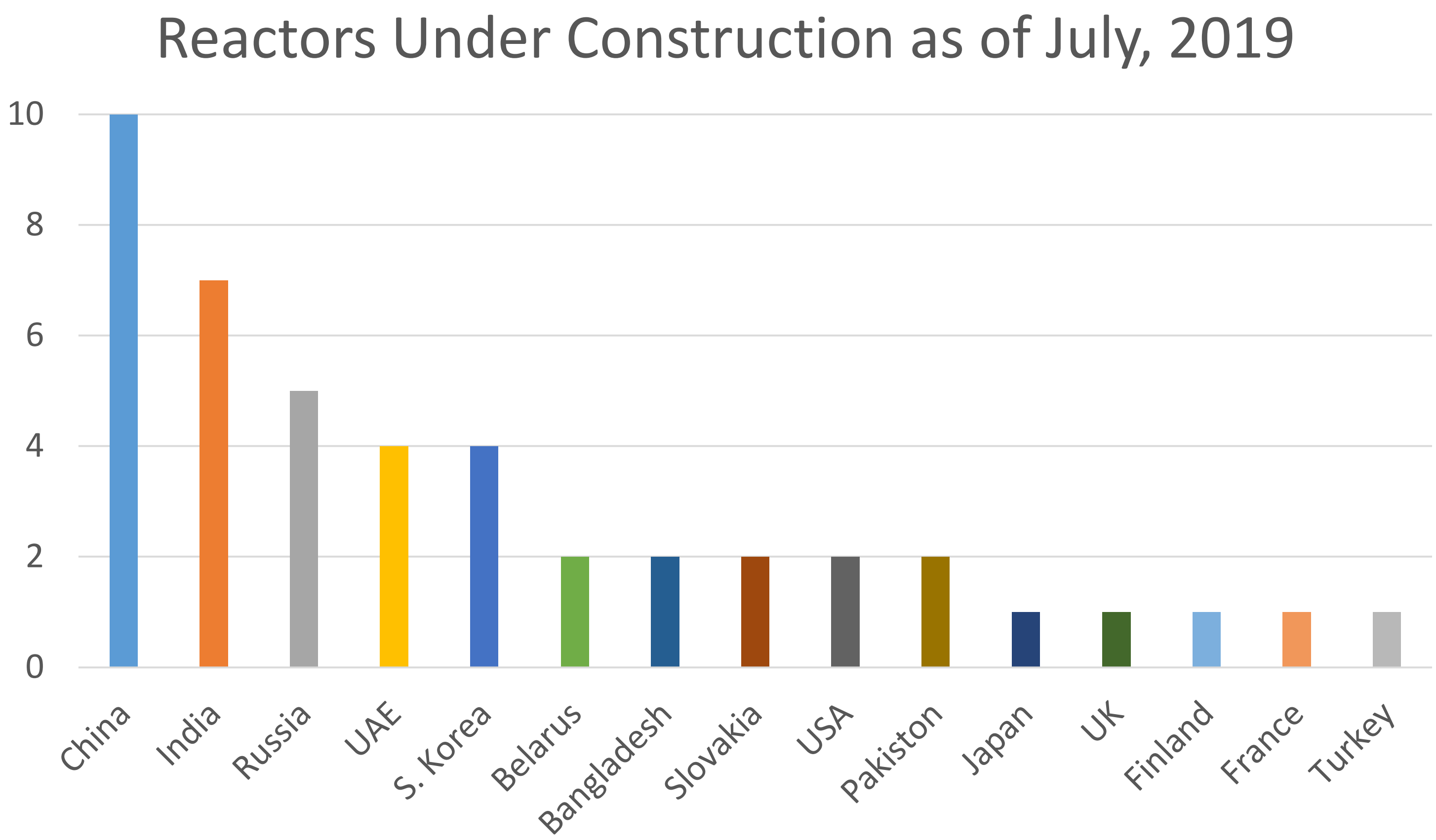
2006
367 GWe

7/2019
Maximum Operating
Capacity: 370 GWe
417 Reactors

World Reactor Startups and Closures

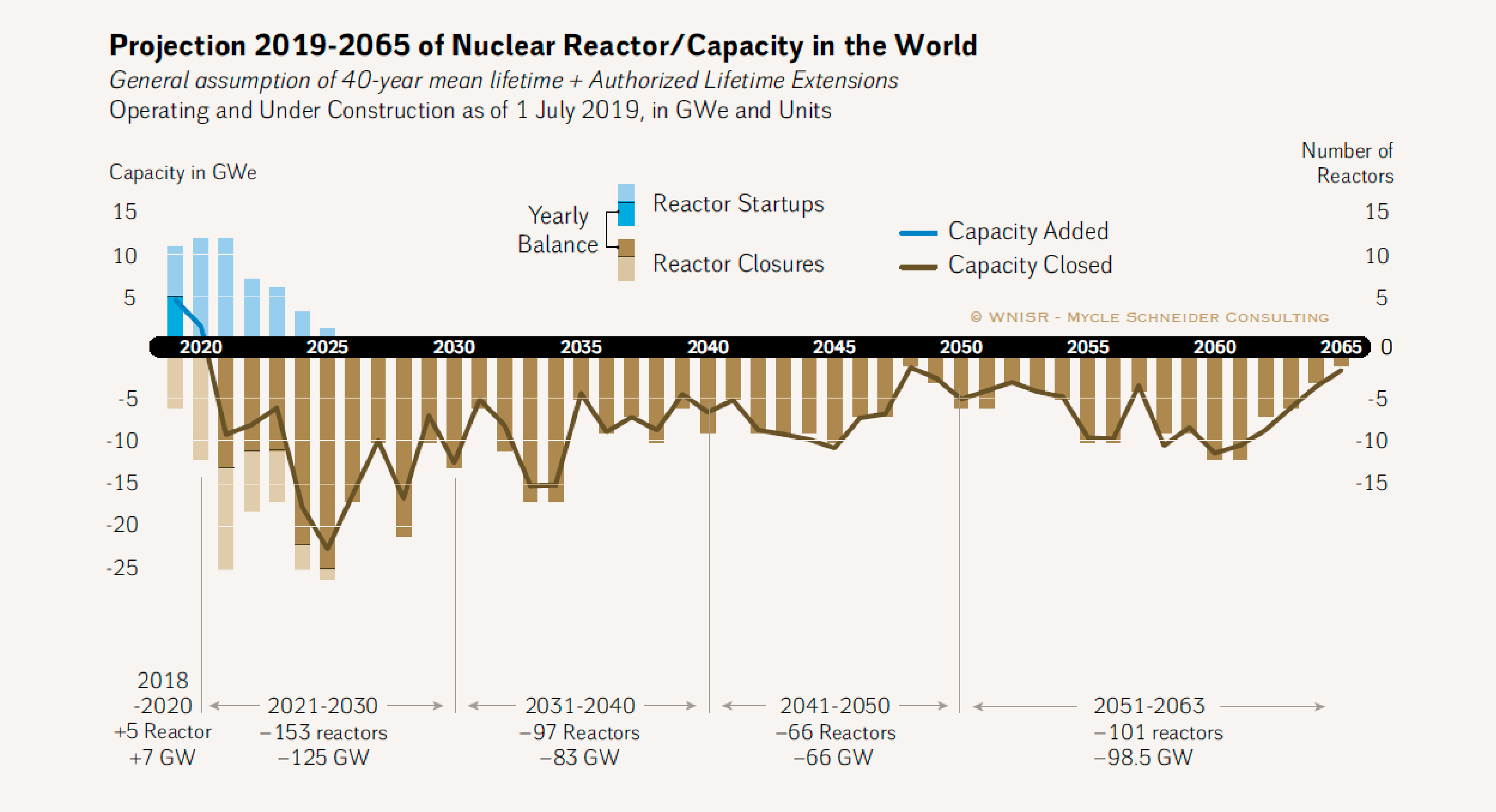


Country	Units	Capacity (MW net)	Construction Starts	Grid Connection	Units Behind Schedule
China	10	8 800	2012 - 2017	2020 - 2023	2-3
India	7	4 824	2004 - 2017	2019 - 2023	5
Russia	5	3 379	2007 - 2019	2019 - 2023	3
UAE	4	5 380	2012 - 2015	2020 - 2023	4
South Korea	4	5 360	2012 - 2018	2019 - 2024	4
Belarus	2	2 218	2013 - 2014	2019 - 2020	1-2
Bangladesh	2	2 160	2017 - 2018	2023 - 2024	0
Slovakia	2	880	1985	2020 - 2021	2
USA	2	2 234	2013	2021 - 2022	2
Pakistan	2	2 028	2015 - 2016	2020 - 2021	0
Japan	1	1 325	2007	?	1
Argentina	1	25	2014	2021	1
UK	1	1 630	2018	2025	0
Finland	1	1 600	2005	2020	1
France	1	1 600	2007	2022	1
Turkey	1	1 114	2018	2024	0
Total	**46**	**44 557**	**1985 - 2019**	**2019 - 2025**	**27-29**



Reactors Under Construction as of July, 2019

World Nuclear Reactor Fleet to 2065



Projection 2019-2065 of Nuclear Reactor/Capacity in the World

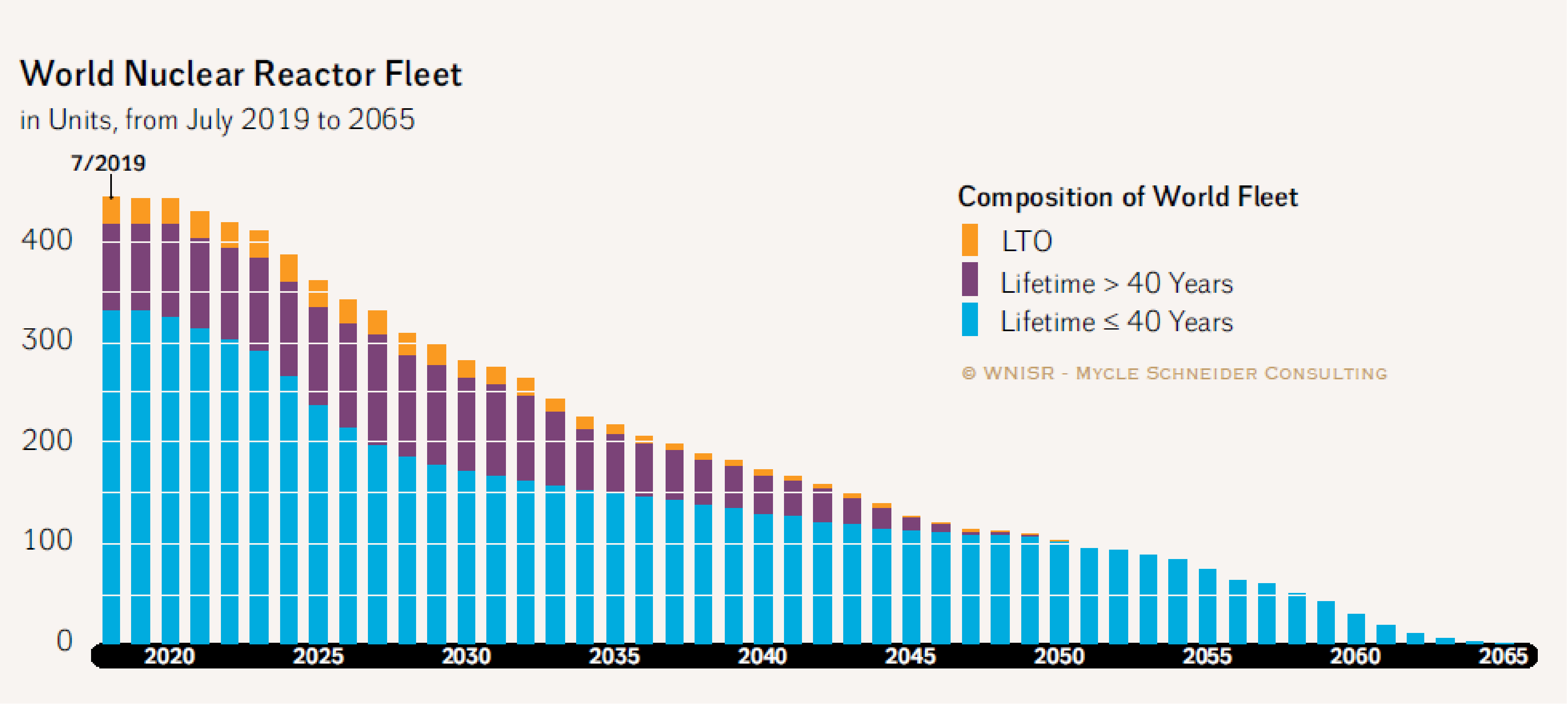
General assumption of 40-year mean lifetime + Authorized Lifetime Extensions

Operating and Under Construction as of 1 July 2019, in GWe and Units

© WNISR - Mycle Schneider Consulting

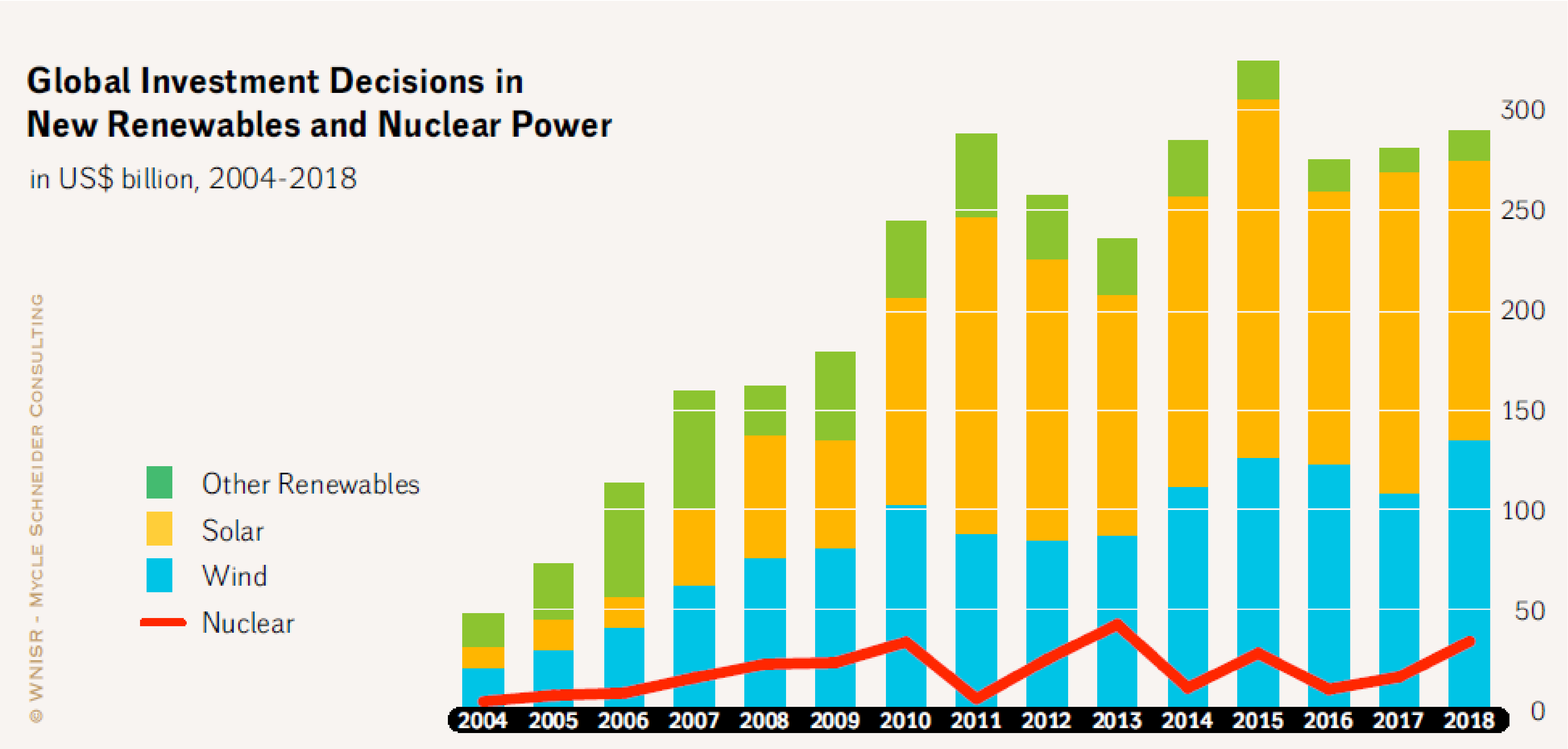
(Projection assumes only reactors currently operating or under construction.)

World Nuclear Reactor Fleet to 2065



(Projection assumes only reactors currently operating or under construction.)

Global Investments Nuclear and Renewables



Global Small Modular Reactor Status

Small Modular Reactor Status

- Canada: in design stage
- China: High-Temperature Reactor three years behind schedule
- India: Advanced Heavy Water Reactor construction start delayed
- Russia: two floating reactors built, one operational after long construction period
- S. Korea: System-Integrated Modular Advanced Reactor abandoned due to cost
- UK: Rolls-Royce design at early stage
- US: Single NuScale design under certification review

The Small Modular Reactor has not achieved breakthroughs either in technology or in commercial acceptance.

Status of Nuclear Power in the United States

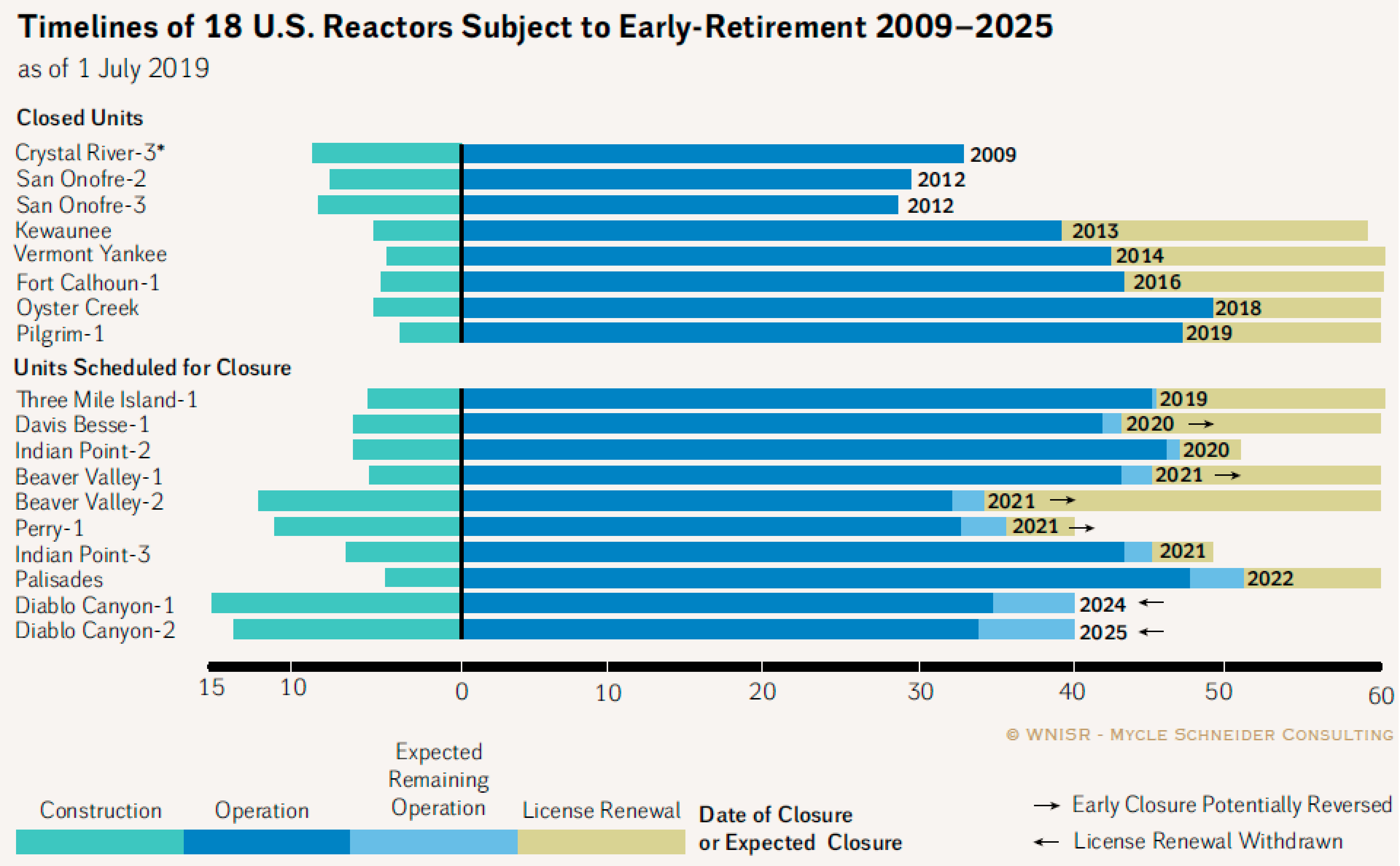
THE WALL STREET JOURNAL.

"The Real Deterrent to Nuclear Power"

February 5, 2013

- "Long before they consume even a pound of uranium, nuclear-power plants burn through copious quantities of cash."
- "Unlike a gas-fired plant, the bulk of a nuclear-power station's costs relate to construction and maintenance."
- "Big upfront cash outflows combined with uncertainty over future inflows…don't win many fans among investors or credit-rating firms."
- "…new nuclear works best in countries where consumers and financiers are shielded from its full costs…" [e.g. Brazil, Russia, India and China]

U.S. Reactors Early Retirement



Timelines of 18 U.S. Reactors Subject to Early-Retirement 2009–2025

as of 1 July 2019

U.S. Nuclear Power Plant Closures [Slideshow]
06/25/2016 | Aaron Larson

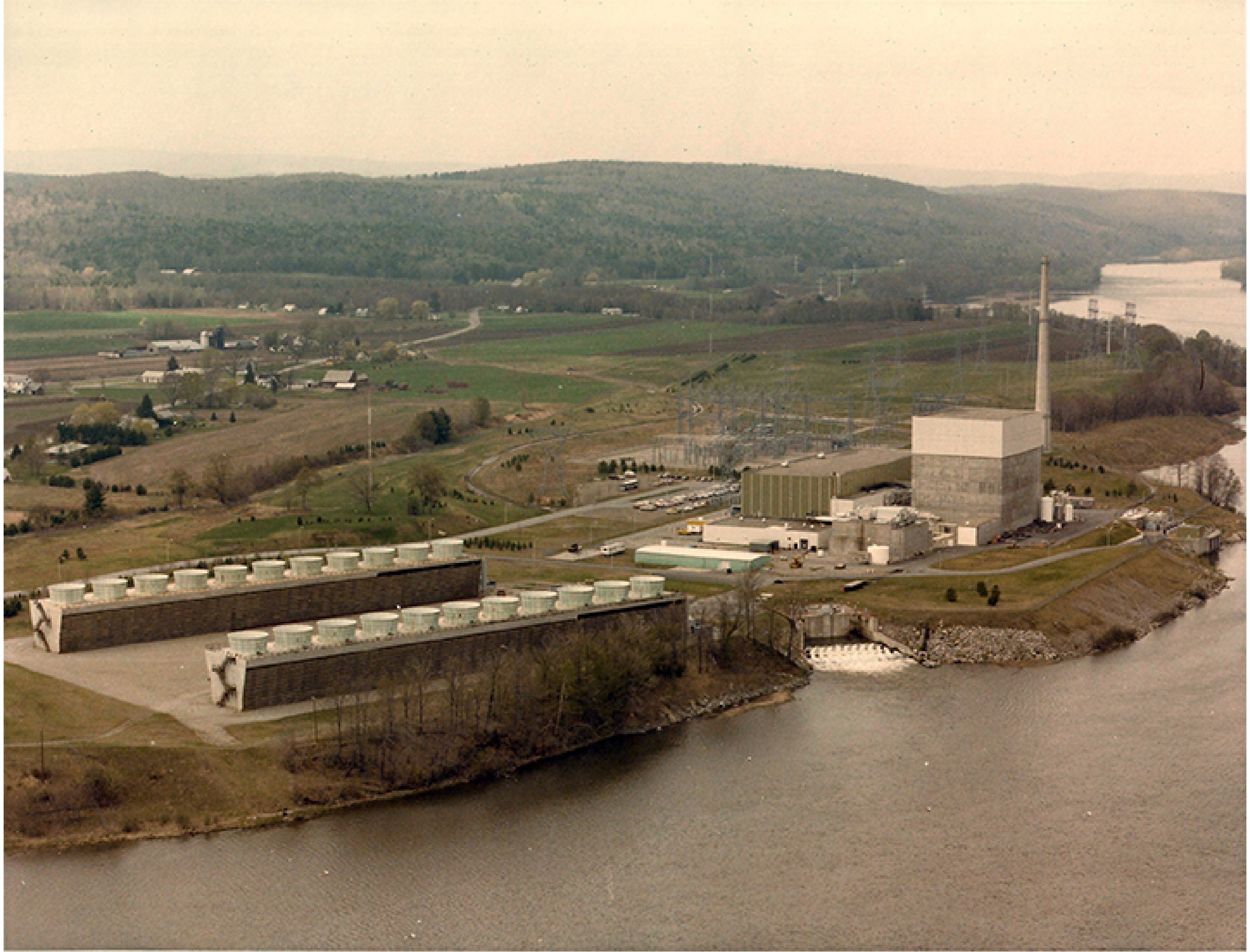
http://www.powermag.com/u-s-nuclear-power-plant-closures-slideshow/

San Onofre Nuclear Generating Station
Pendleton, CA
1983/1984 - 2012

Kewaunee Power Station
Carlton, WS
1974 - 2013

Crystal River Nuclear Plant
Crystal River, FL
1977 - 2013

Vermont Yankee Nuclear Power Plant
Vernon, VT
1972 - 2014



Fort Calhoun Nuclear Generating Station
Blair, NE
1973 - 2016

James A. FitzPatrick Nuclear Power Plant
Scriba, NY
1975 – 2017(?)
Kept open with New York state subsidy

Clinton Power Station
Clinton, IL
1987 – 2017(?)
Kept open by Illinois state subsidy

Quad Cities Generating Station
Cordova, IL
1973 – 2018(?)
Kept open by Illinois state subsidy

Pilgrim Nuclear Power Station
Plymonth, MA
1972 - 2019

Oyster Creek Nuclear Generating Station
Lacey Township, NJ
1969 - 2019

Diablo Canyon Power Plant
1985/1986 – 2024/2025
Avila Beach, CA
Possible California state subsidy

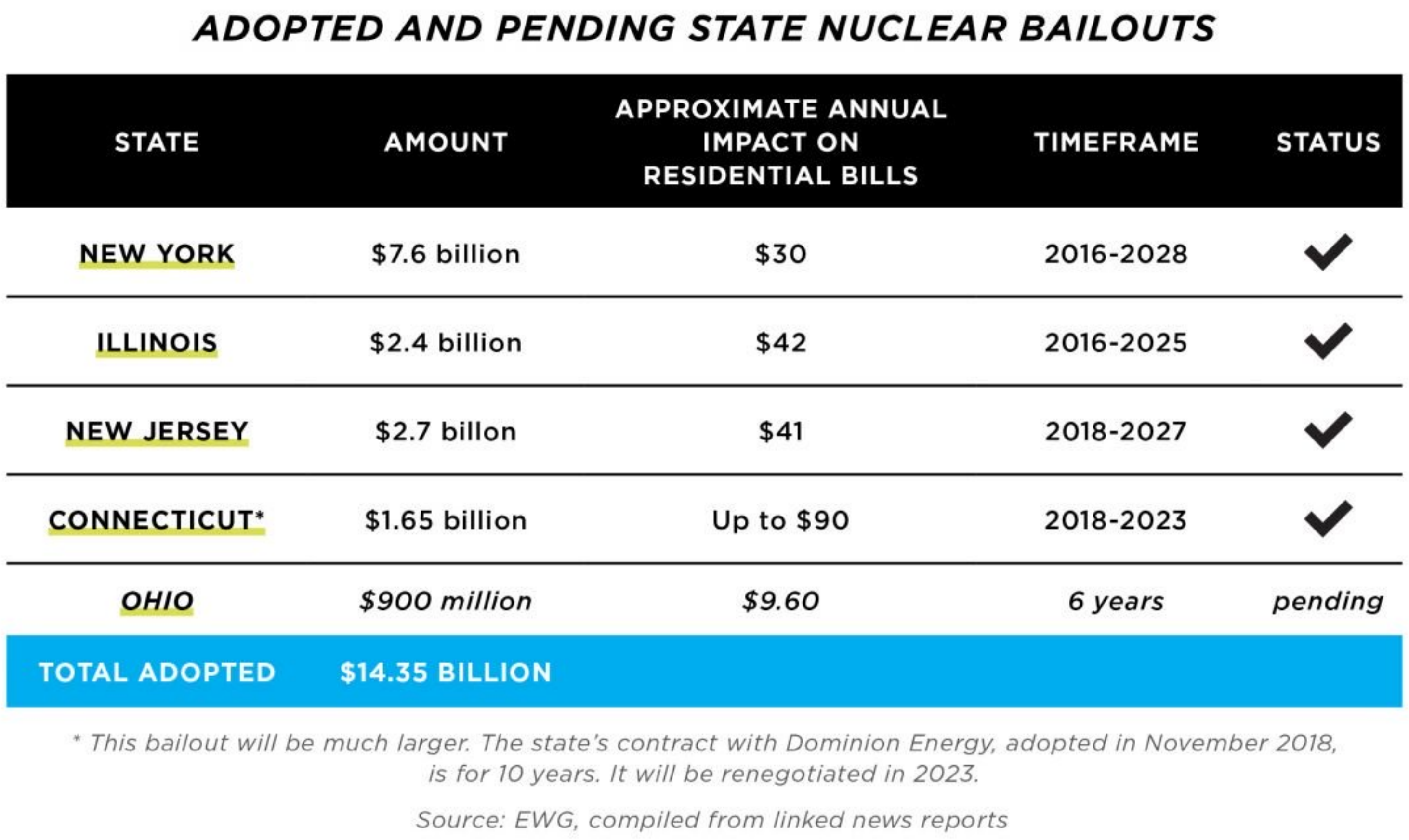
Nuclear Power Plant Closures
2012 - 2024

U.S. Recent Reactor Construction

- Watts Bar Unit 2
  - Spring City, TN
  - Operational in 2016
- V. C. Summer Units 2 & 3
  - Jenkinsville, SC
  - Construction stopped.
  - Petition for Approval of Abandonment filed with NRC.
- Plant Vogtle Units 3 & 4
  - Waynesboro, GA
  - Construction completion in 2021.

New Nuclear Power Plants
2016 - 2020

Energy Working Group
July 19, 2019



ADOPTED AND PENDING STATE NUCLEAR BAILOUTS

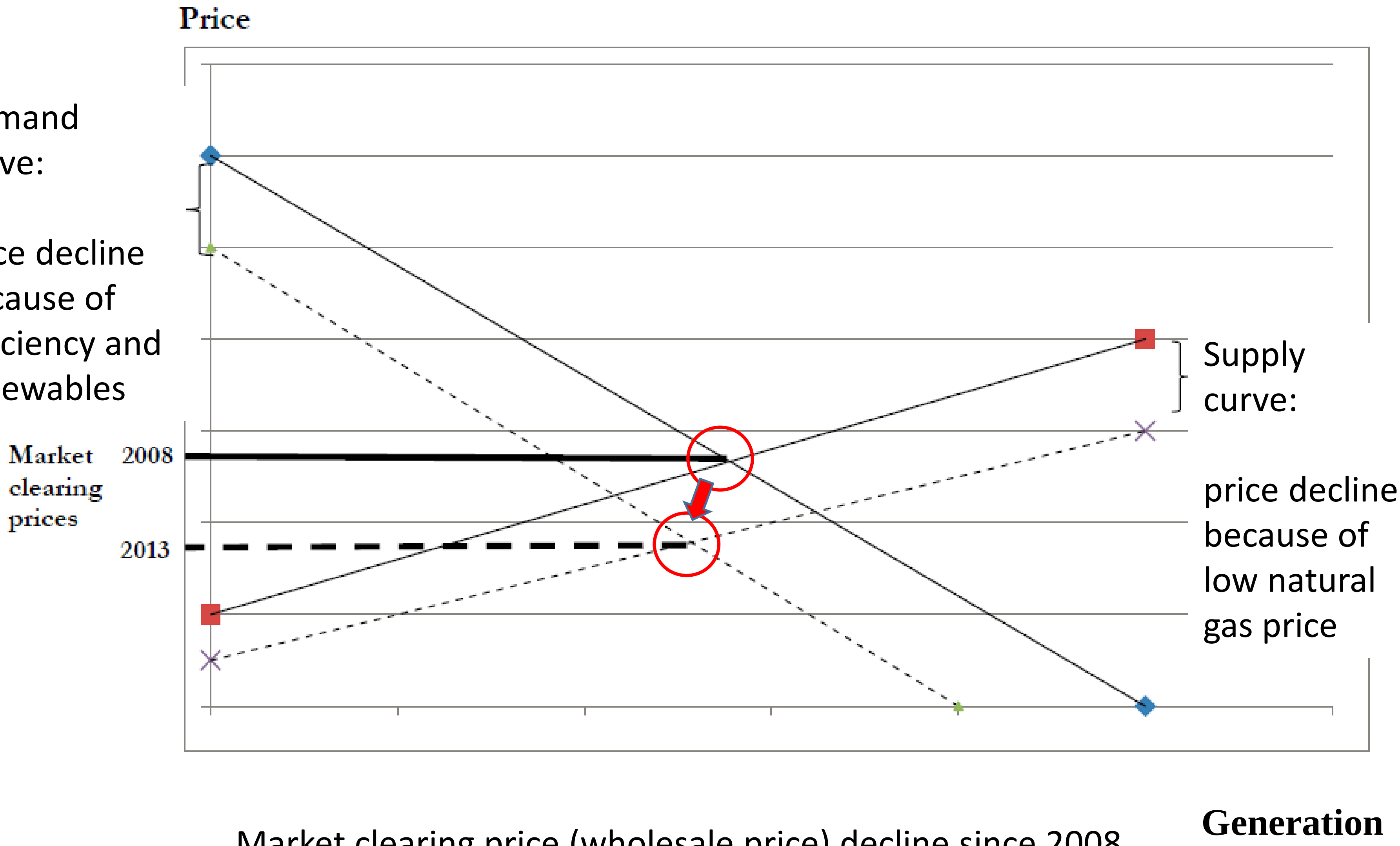
STATE	AMOUNT	APPROXIMATE ANNUAL IMPACT ON RESIDENTIAL BILLS	TIMEFRAME	STATUS
NEW YORK	$7.6 billion	$30	2016-2028	✓
ILLINOIS	$2.4 billion	$42	2016-2025	✓
NEW JERSEY	$2.7 billon	$41	2018-2027	✓
CONNECTICUT*	$1.65 billion	Up to $90	2018-2023	✓
OHIO	*$900 million*	*$9.60*	*6 years*	*pending*
TOTAL ADOPTED	**$14.35 BILLION**			

** This bailout will be much larger. The state's contract with Dominion Energy, adopted in November 2018, is for 10 years. It will be renegotiated in 2023.*

Source: EWG, compiled from linked news reports

Causes of U.S. Nuclear Power Industry Decline

Supply and Demand for Electricity



Demand curve:

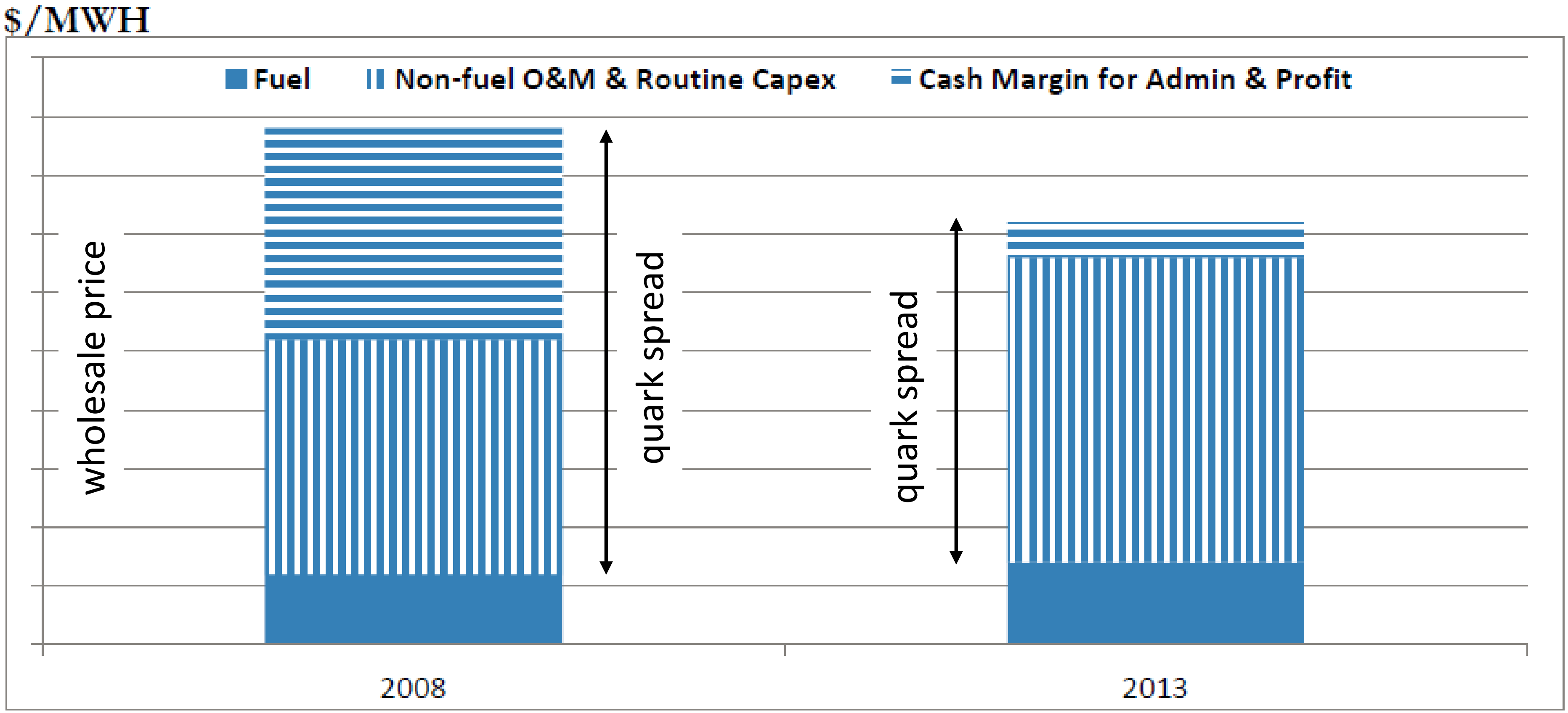
price decline because of efficiency and renewables

Supply curve:

price decline because of low natural gas price

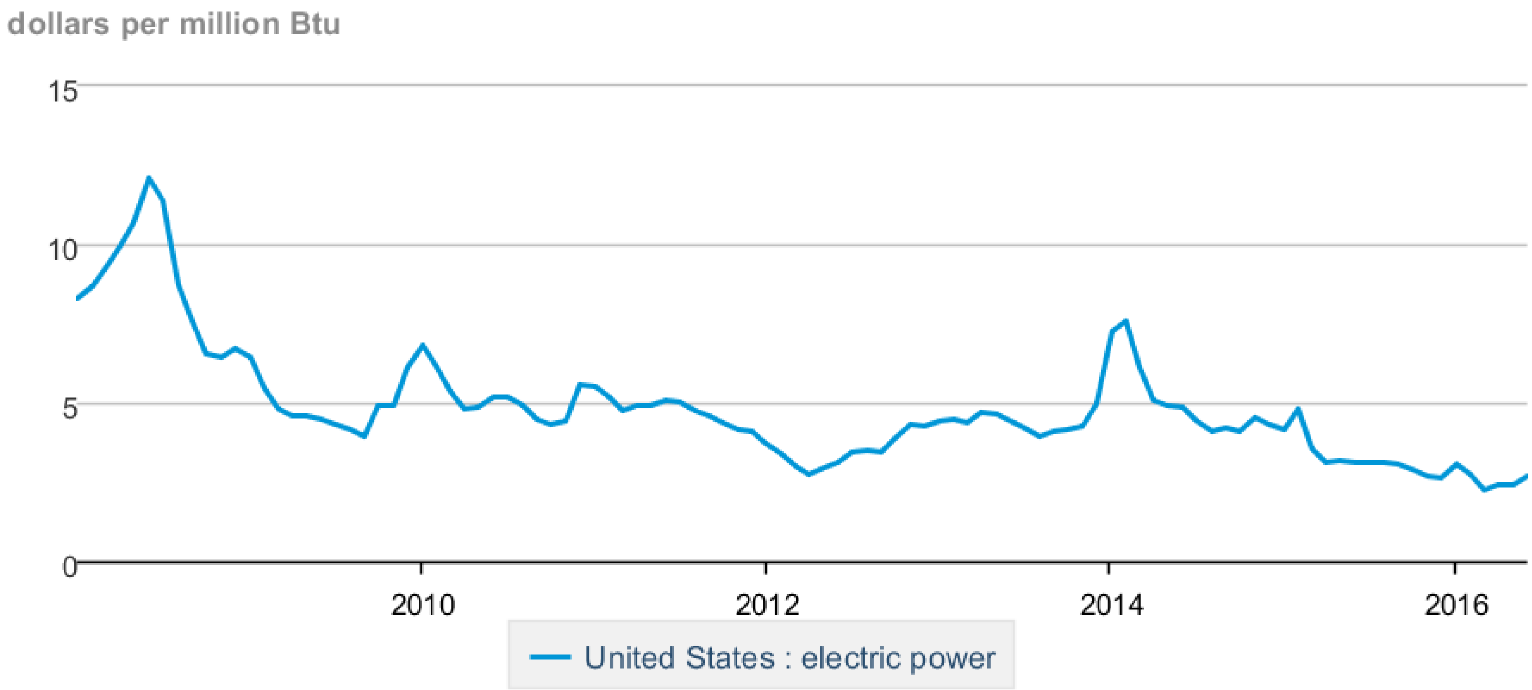
Market clearing price (wholesale price) decline since 2008

Margin Squeeze



Natural Gas Price for Electricity Generation

Average cost of fossil fuels for electricity generation (per Btu) for natural gas, monthly



Source: U.S. Energy Information Administration

Gregory Jaczko Chair NRC 2009 - 2012

"I've never seen a movie that's set 200 years in the future and the planet is being powered by fission reactors—that's nobody's vision of the future. This is not a future technology."

Transportation

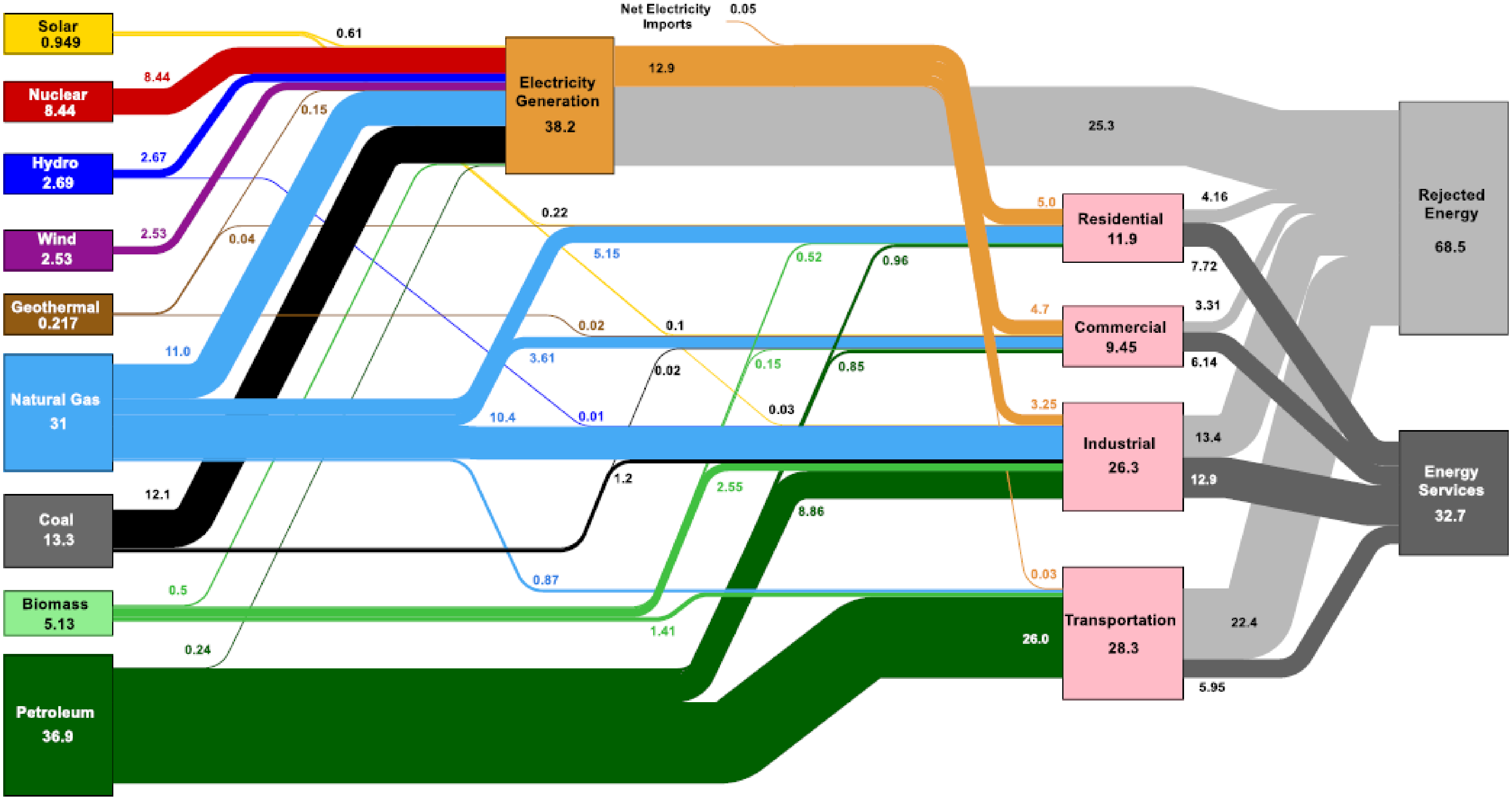
Transportation Outline

- Energy consumption in transportation sector
- Efficiency in transportation
- MPG of EV
- Current production
- Consumer choices
- Fuel of the 21st century

Energy Consumption of Transportation Sector

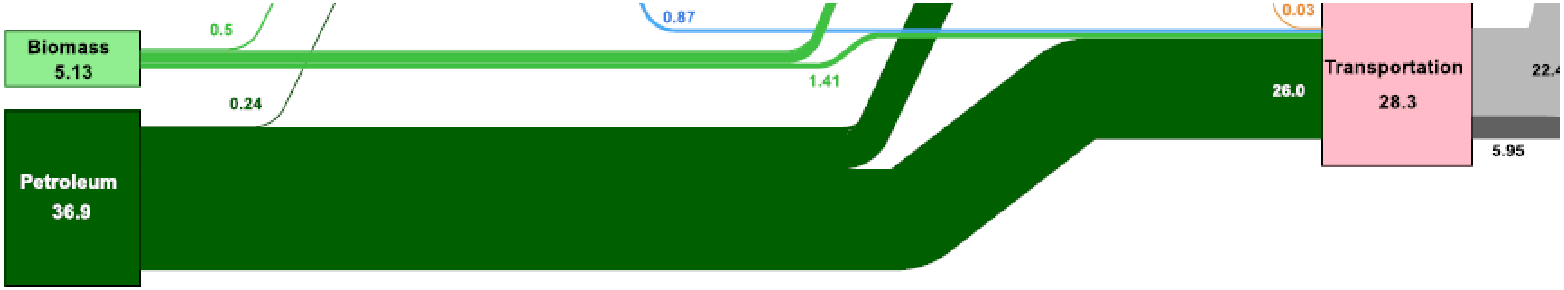
Estimated U.S. Energy Consumption in 2018: 101.2 Quads

Lawrence Livermore National Laboratory



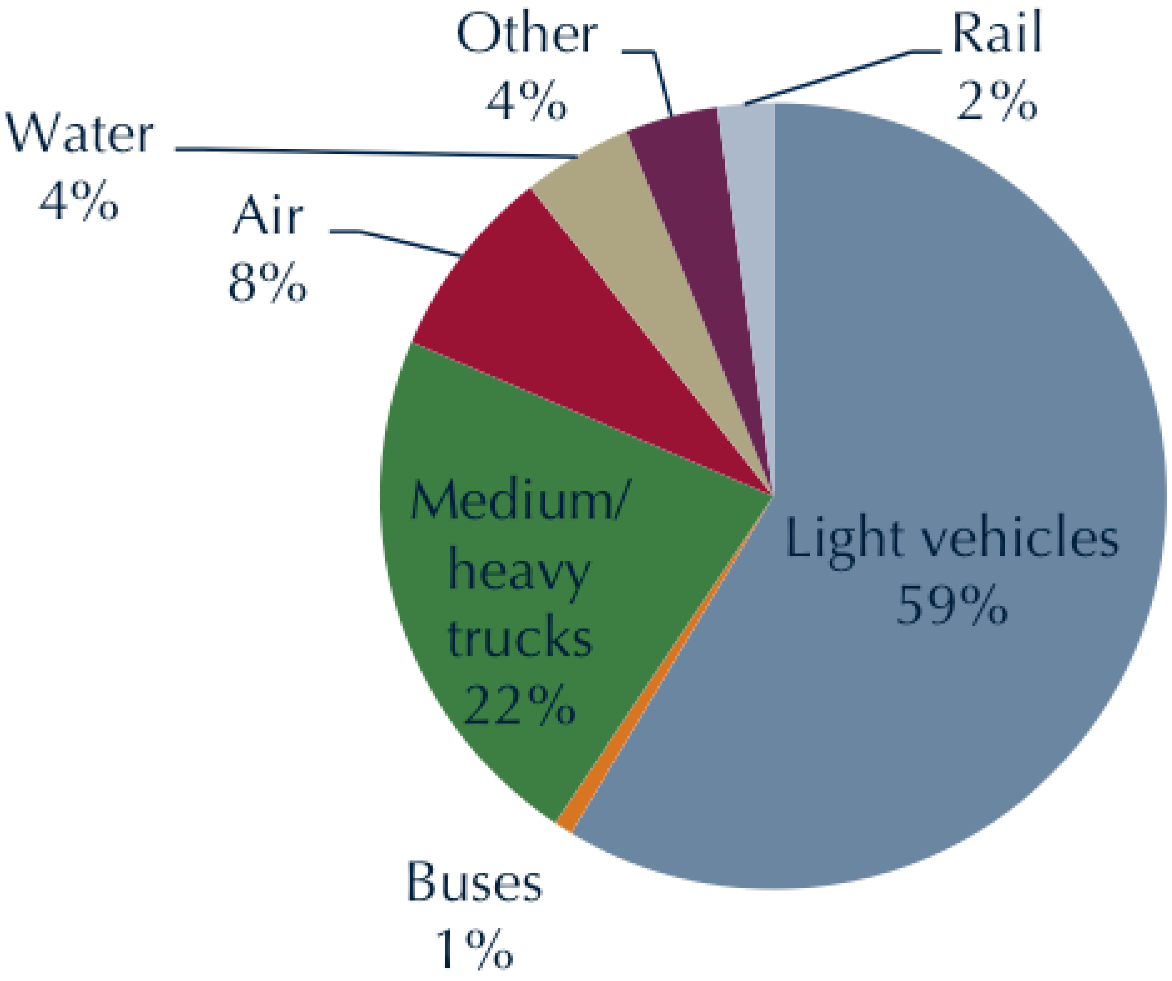
Focus on Transportation

Fuel	fraction
oil	91.8%
biofuels	5.0%
NG	3.1%
EV	0.1%



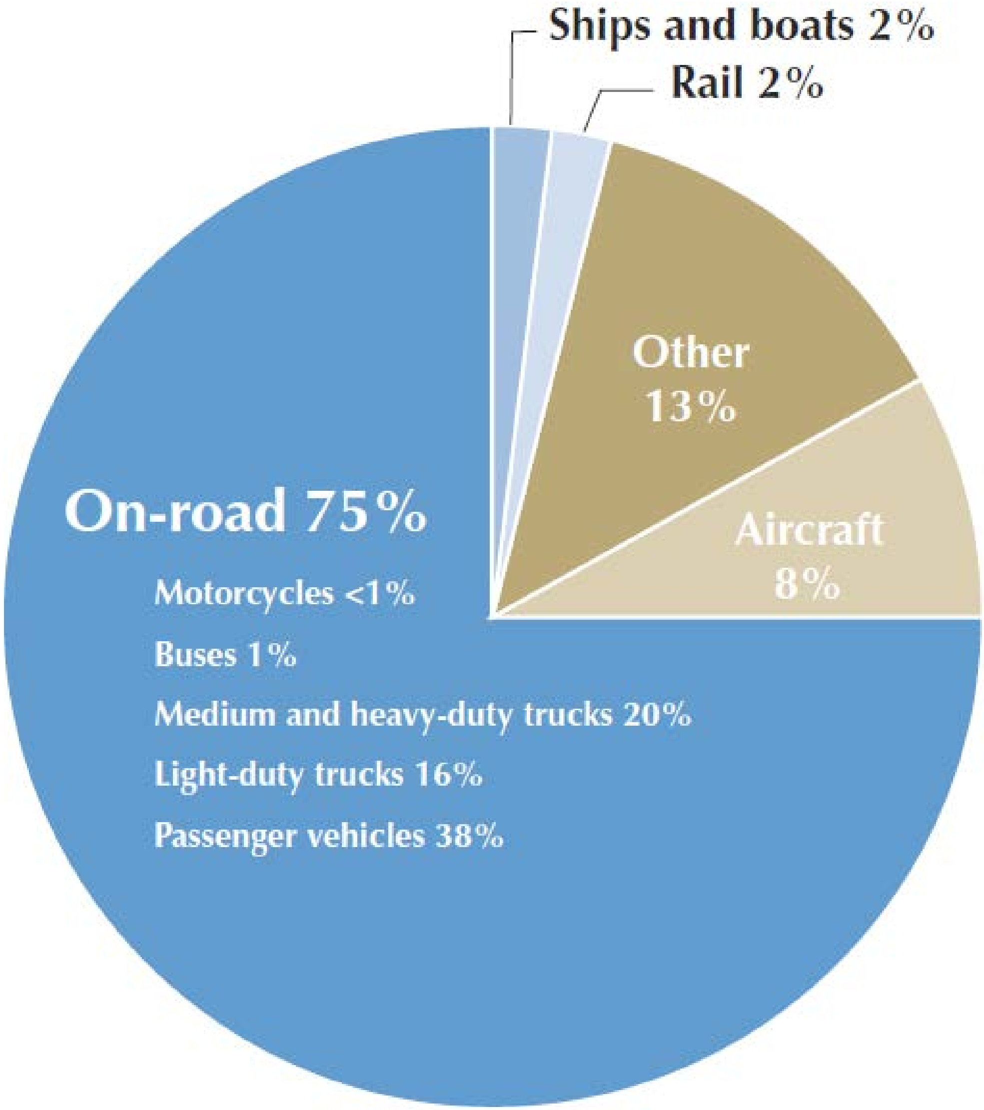
Transportation 28% of primary energy.

U.S. Transportation Energy Use by Mode



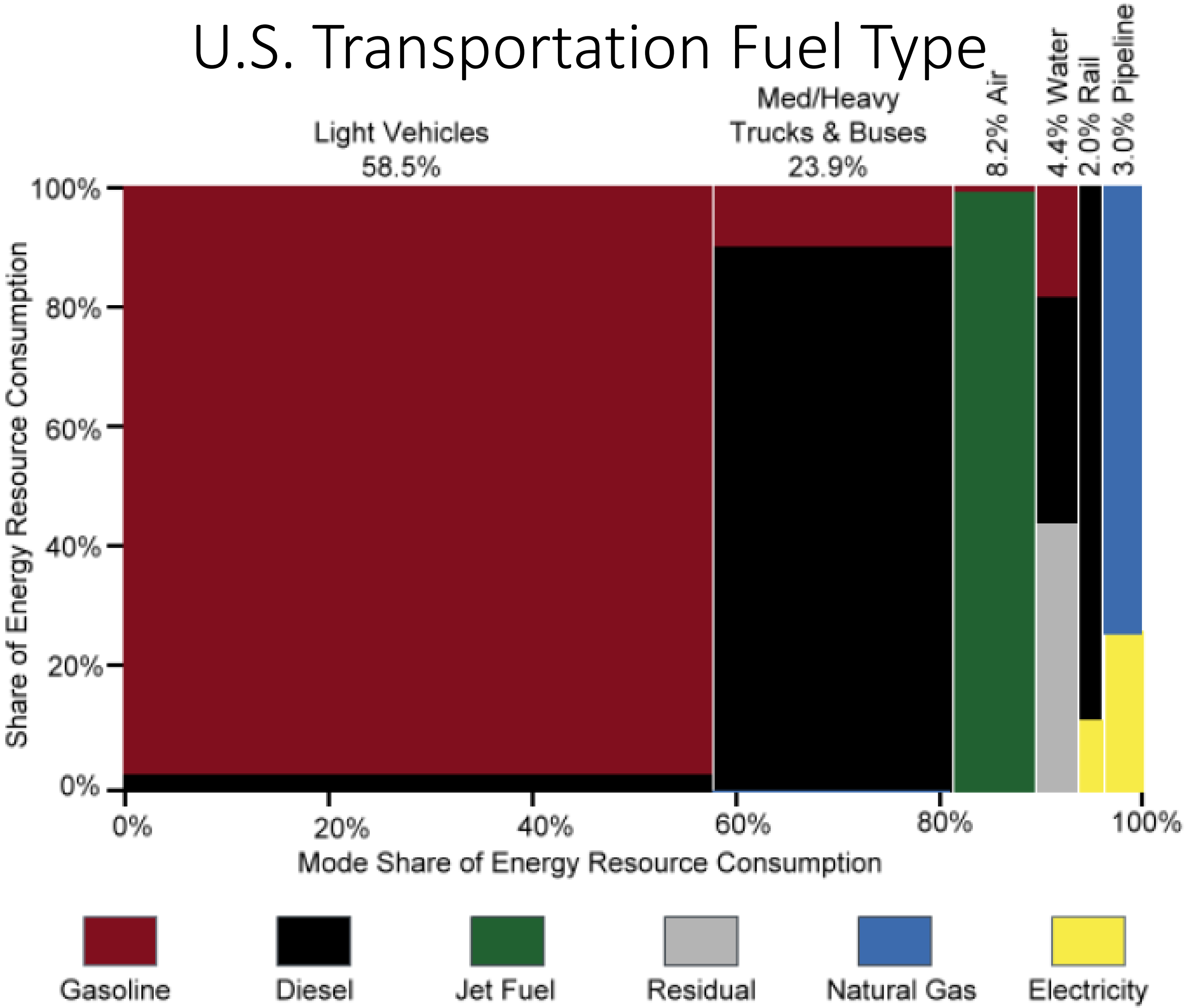
Cars, light duty trucks, buses, medium and heavy duty trucks 82% of energy use.

Transportation Emissions by Mode

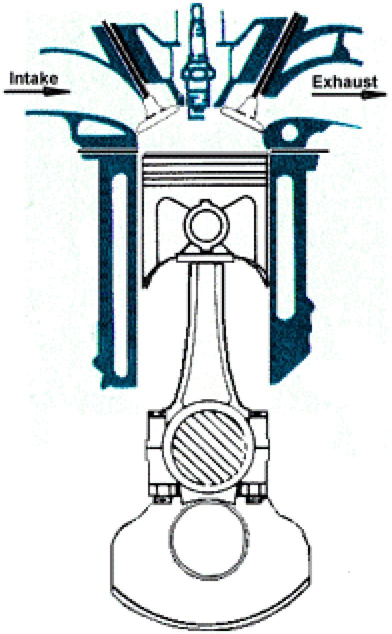


Emissions from pipelines, lubricants, and non-transportation mobile sources are shown collectively as ‘Other.’

U.S. Transportation Fuel Type

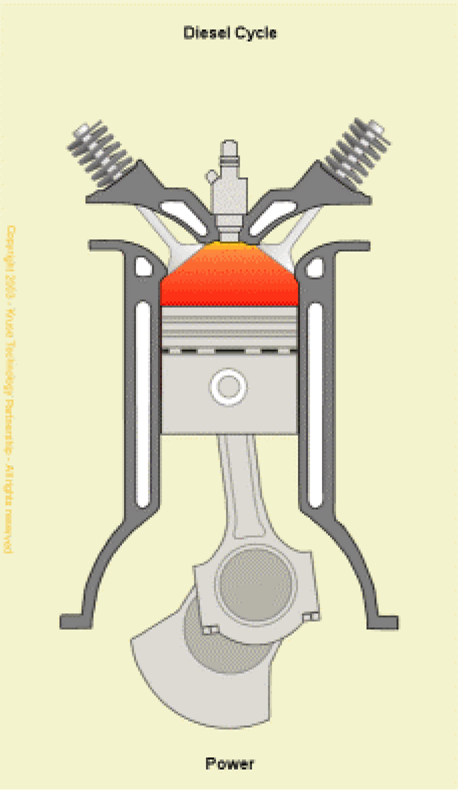


Animation Gasoline Engine

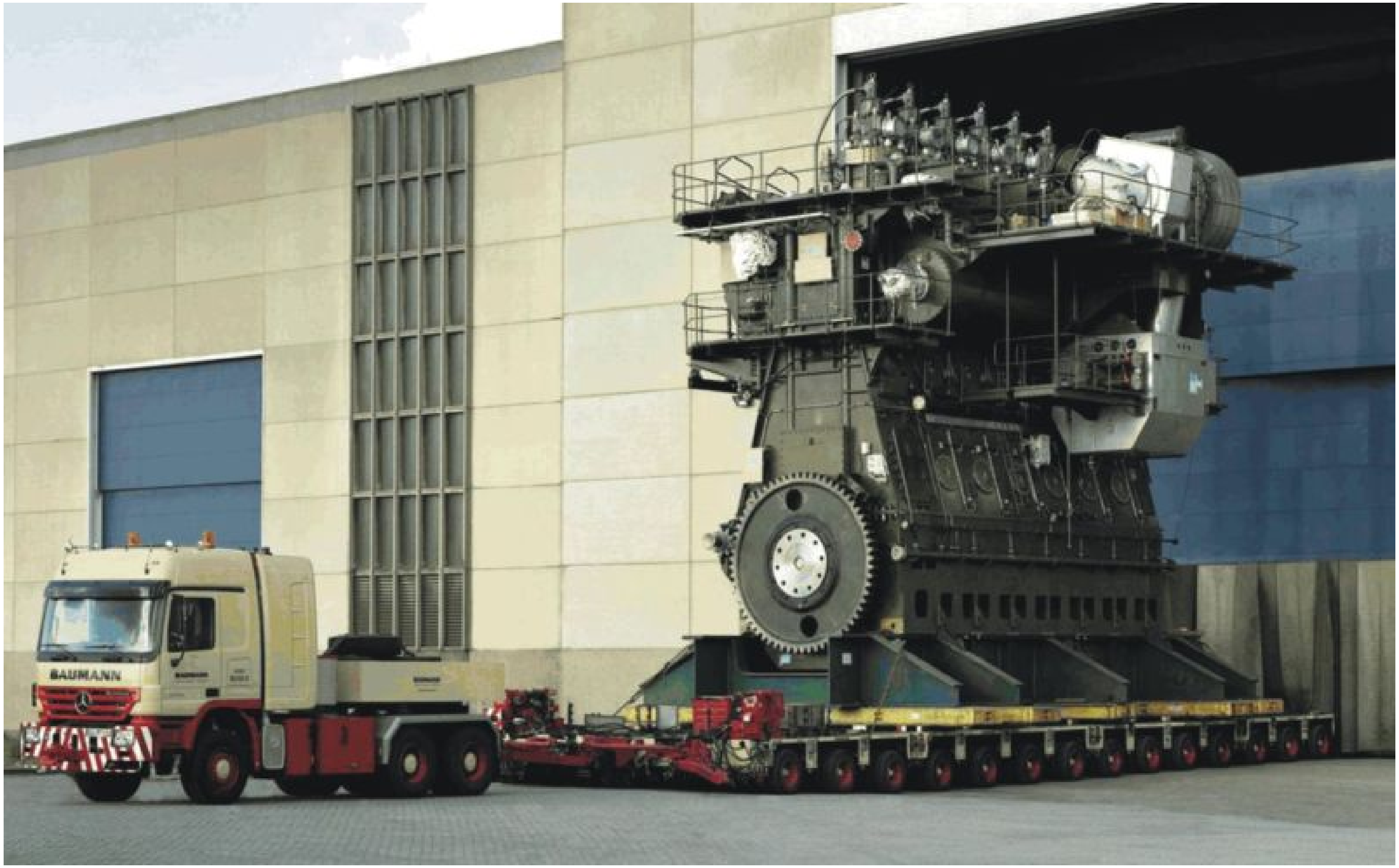


INTAKE

Animation Diesel Engine



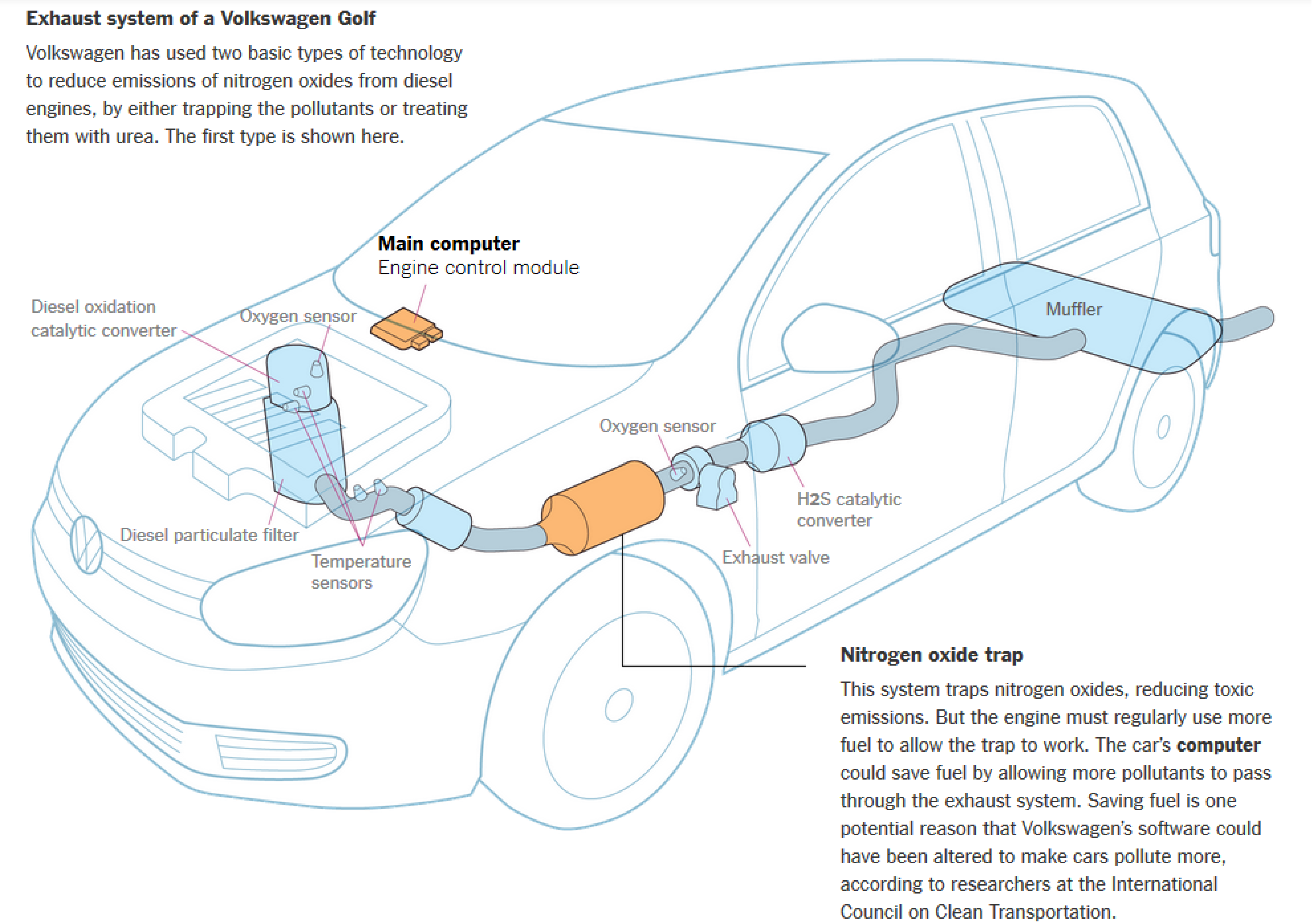
Wärtsilä-Sulzer RTA96-C



The New York Times

September 12, 2016

Explaining Volkswagen’s Emissions Scandal



Exhaust system of a Volkswagen Golf

Volkswagen has used two basic types of technology to reduce emissions of nitrogen oxides from diesel engines, by either trapping the pollutants or treating them with urea. The first type is shown here.

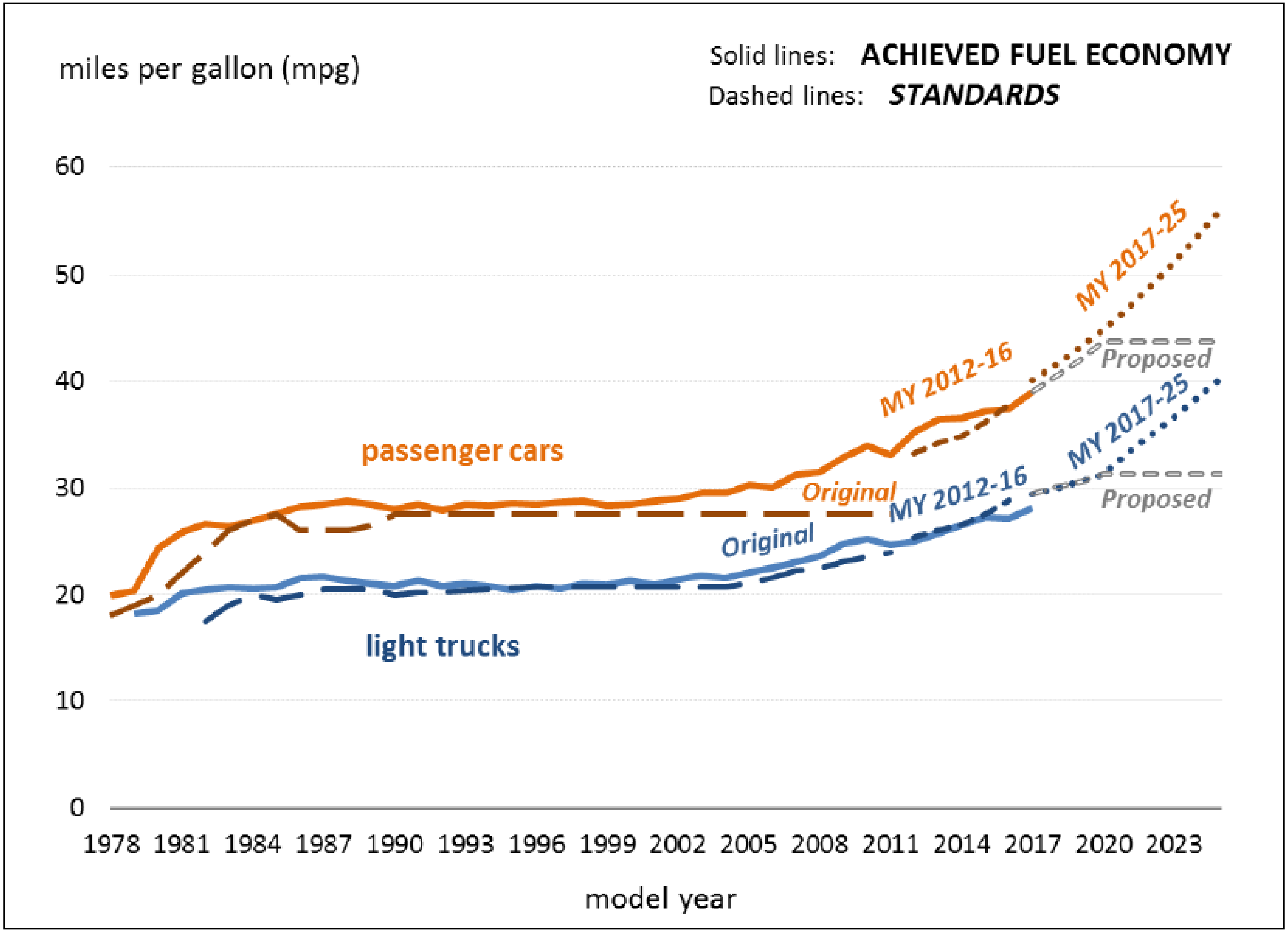
Main computer
Engine control module

Nitrogen oxide trap

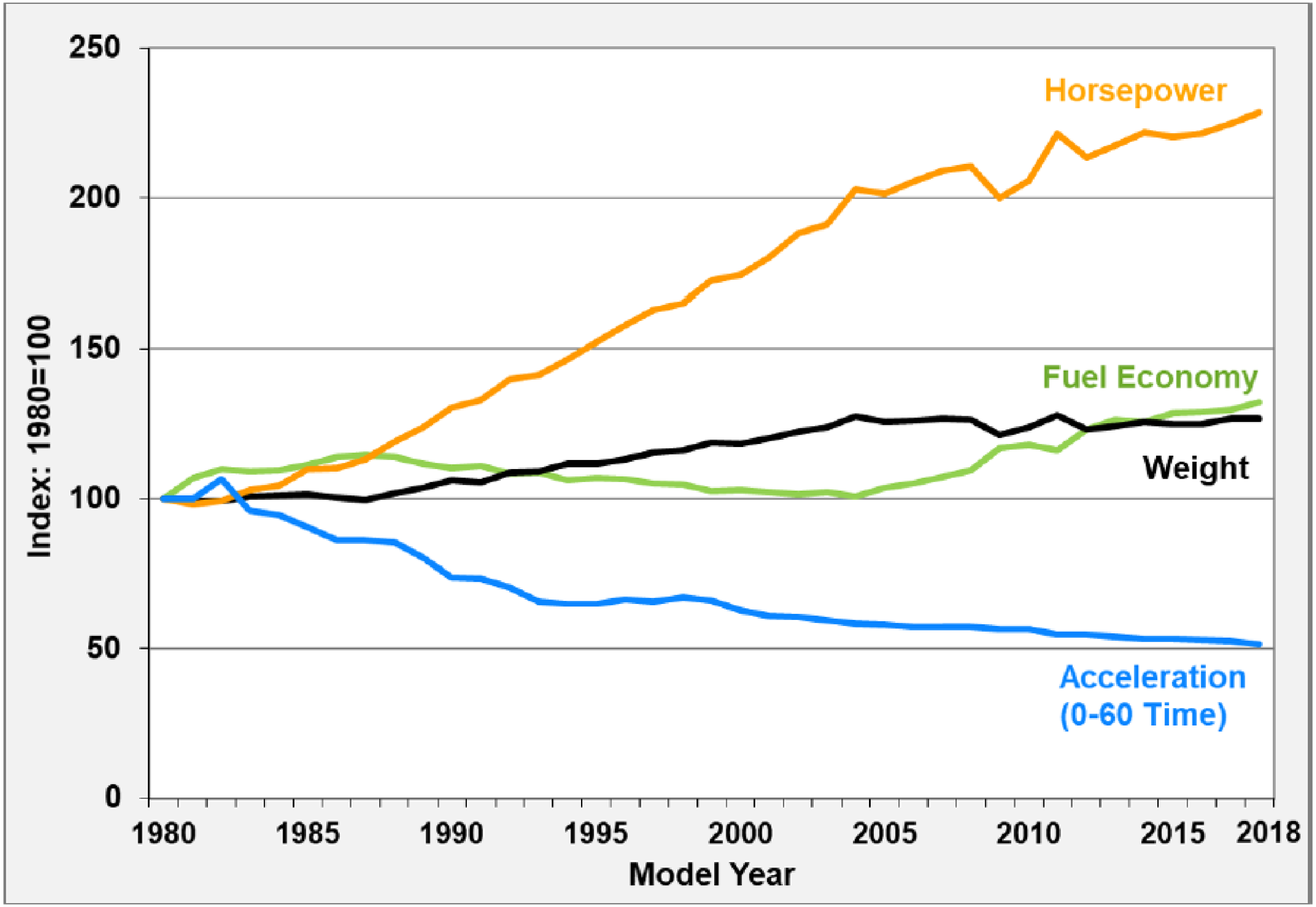
This system traps nitrogen oxides, reducing toxic emissions. But the engine must regularly use more fuel to allow the trap to work. The car’s **computer** could save fuel by allowing more pollutants to pass through the exhaust system. Saving fuel is one potential reason that Volkswagen’s software could have been altered to make cars pollute more, according to researchers at the International Council on Clean Transportation.

Efficiency in Transportation

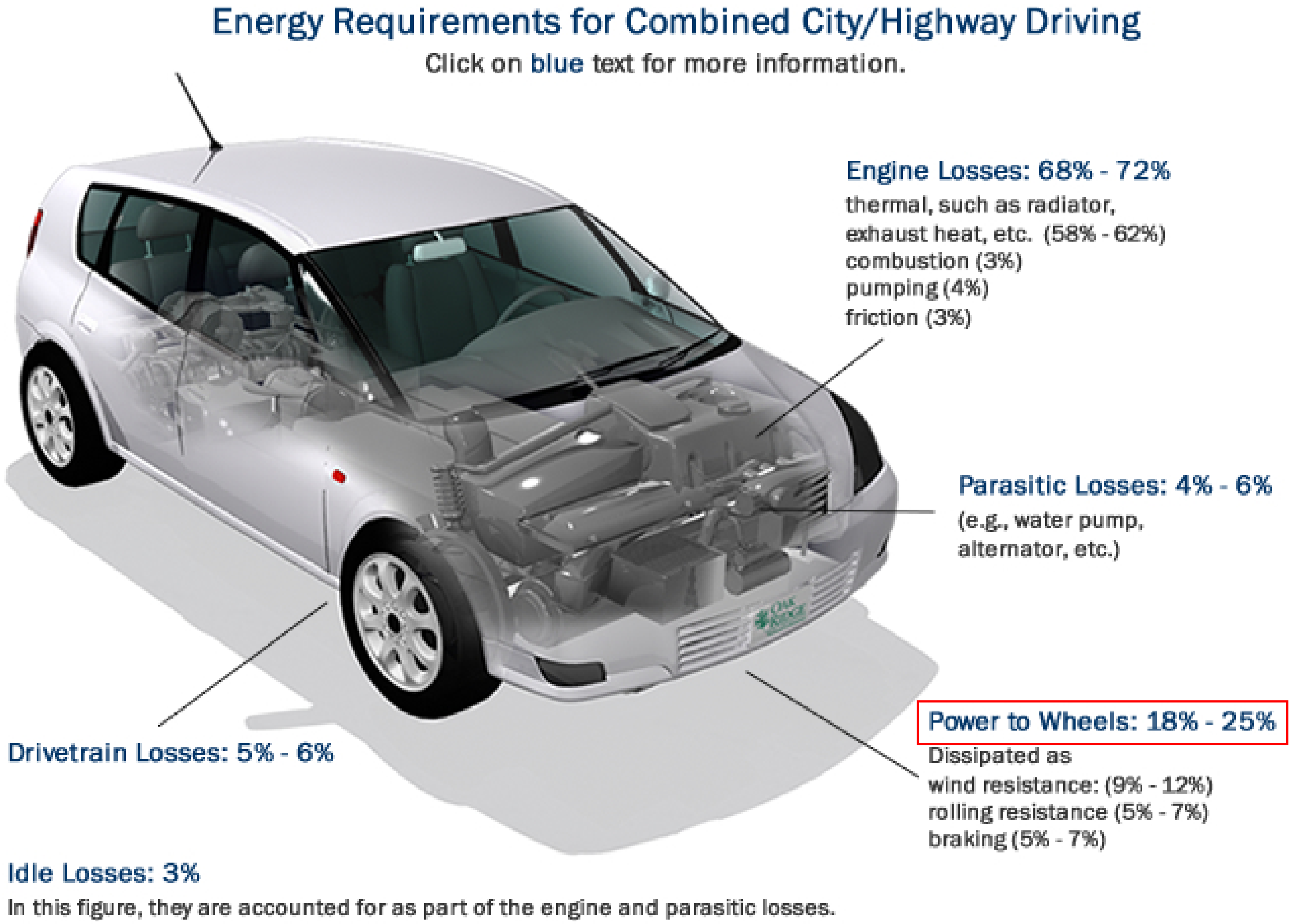
CAFE Standards and Achieved Fuel Economy, MYs 1978-2026



New Light Vehicles Performance Model Years 1980-2018 (Updated April 2019)



Gasoline Vehicle: Where does the energy go?



Energy Requirements for Combined City/Highway Driving

Click on blue text for more information.

Engine Losses: 68% - 72%
thermal, such as radiator,
exhaust heat, etc. (58% - 62%)
combustion (3%)
pumping (4%)
friction (3%)

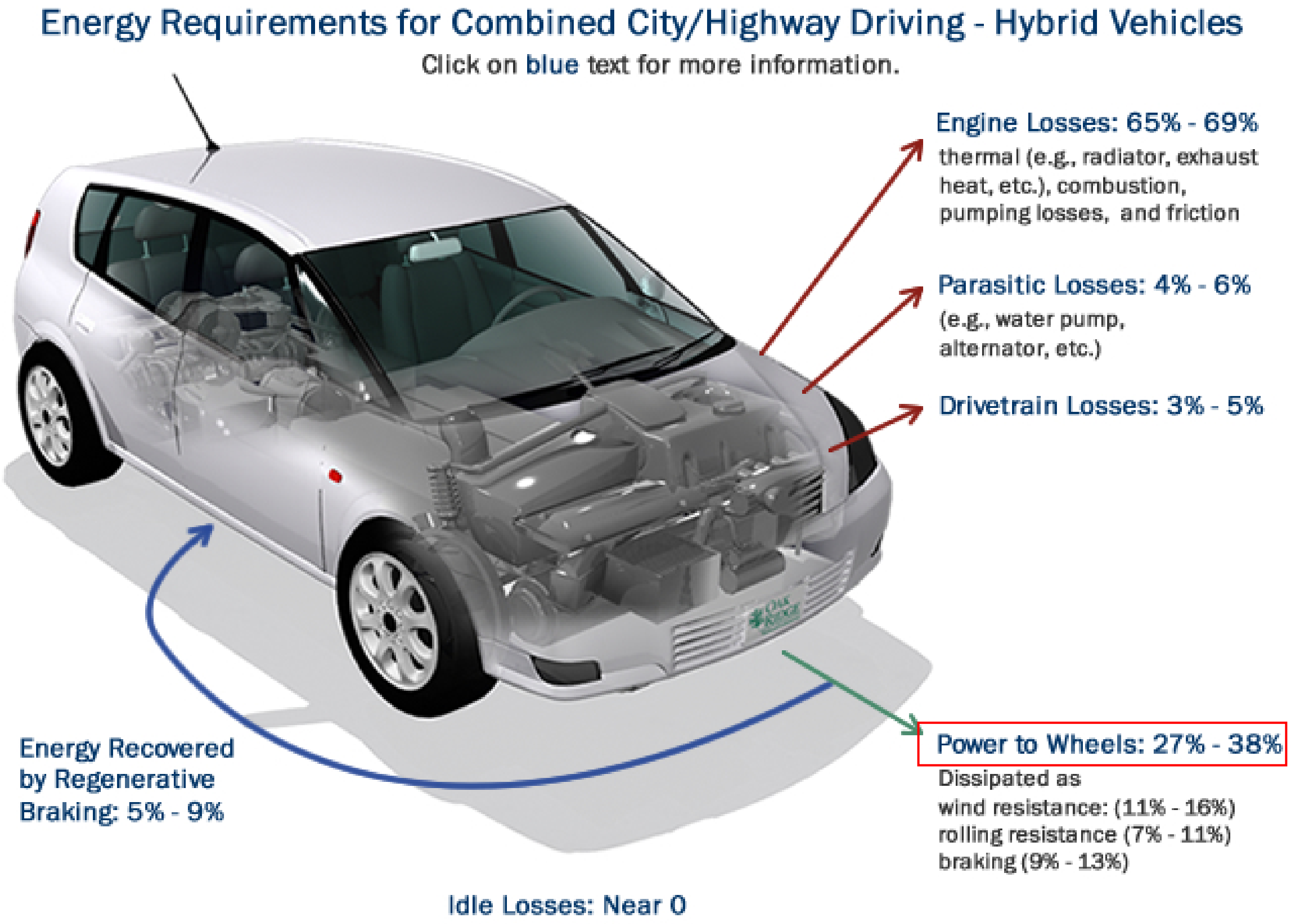
Parasitic Losses: 4% - 6%
(e.g., water pump,
alternator, etc.)

Power to Wheels: 18% - 25%
Dissipated as
wind resistance: (9% - 12%)
rolling resistance (5% - 7%)
braking (5% - 7%)

Drivetrain Losses: 5% - 6%

Idle Losses: 3%
In this figure, they are accounted for as part of the engine and parasitic losses.

Hybrid Vehicle: Where does the energy go?



Energy Requirements for Combined City/Highway Driving - Hybrid Vehicles

Click on blue text for more information.

Engine Losses: 65% - 69%
thermal (e.g., radiator, exhaust heat, etc.), combustion, pumping losses, and friction

Parasitic Losses: 4% - 6%
(e.g., water pump, alternator, etc.)

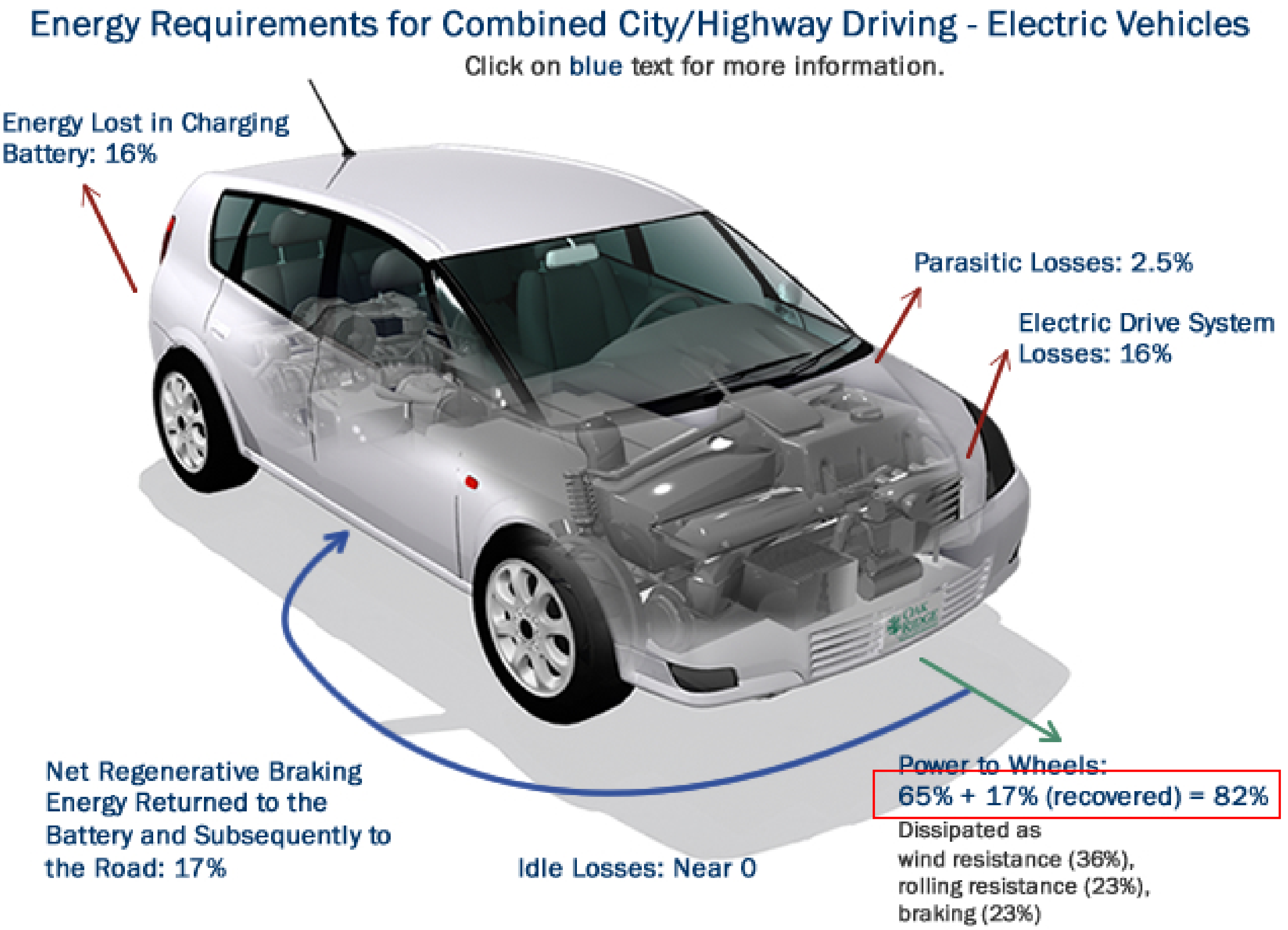
Drivetrain Losses: 3% - 5%

Power to Wheels: 27% - 38%
Dissipated as
wind resistance: (11% - 16%)
rolling resistance (7% - 11%)
braking (9% - 13%)

Energy Recovered by Regenerative Braking: 5% - 9%

Idle Losses: Near 0

Electric Vehicle: Where does the energy go?



Energy Requirements for Combined City/Highway Driving - Electric Vehicles

Click on blue text for more information.

Energy Lost in Charging Battery: 16%

Parasitic Losses: 2.5%

Electric Drive System Losses: 16%

Net Regenerative Braking Energy Returned to the Battery and Subsequently to the Road: 17%

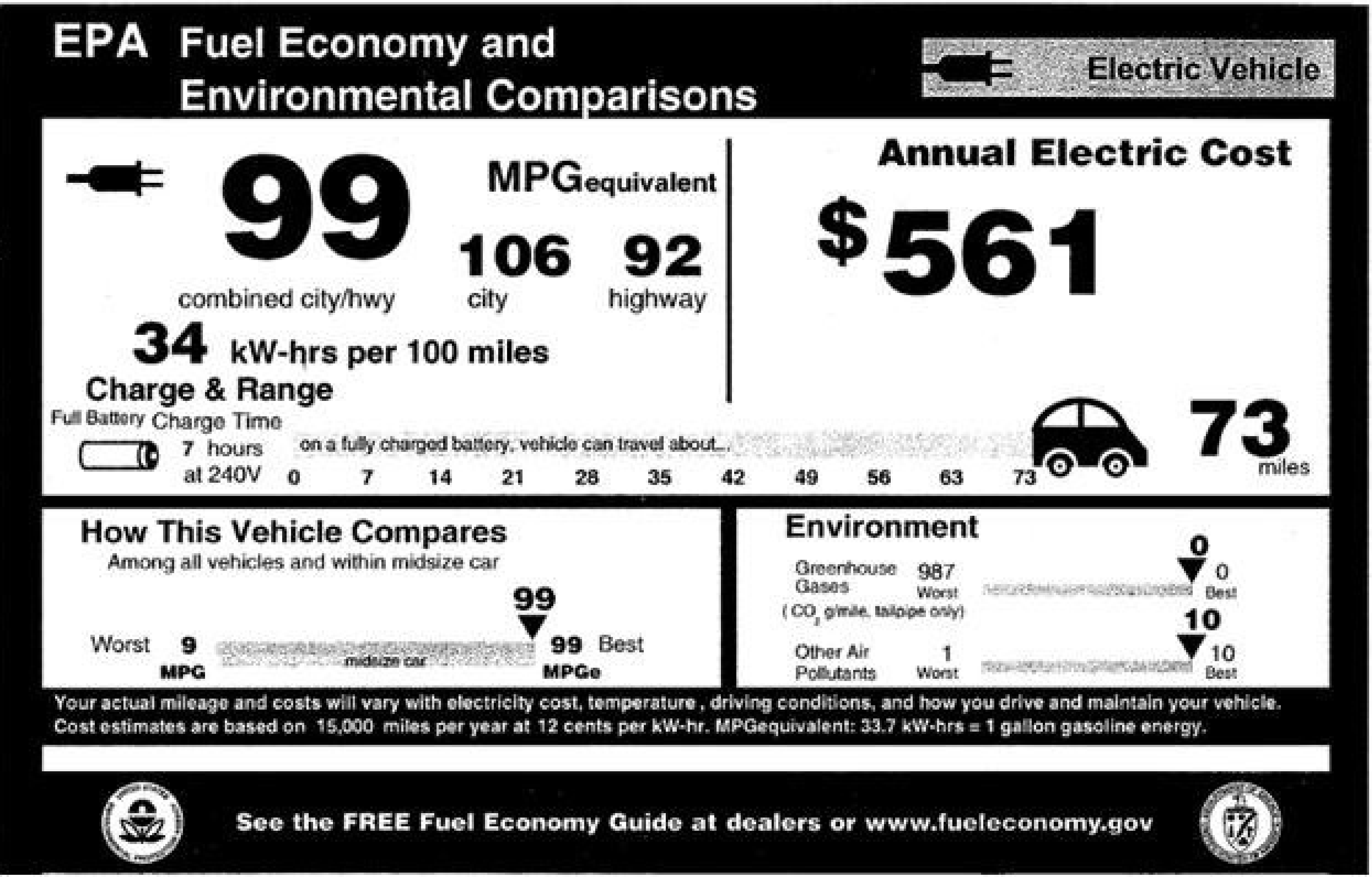
Idle Losses: Near 0

Power to Wheels:
65% + 17% (recovered) = 82%
Dissipated as
wind resistance (36%),
rolling resistance (23%),
braking (23%)

MPG for an Electric Vehicle

Nissan Leaf

Nissan Leaf Monroney Sticker



EPA Fuel Economy and Environmental Comparisons

Electric Vehicle

99 **MPGequivalent**

combined city/hwy

106 city

92 highway

34 kW-hrs per 100 miles

Annual Electric Cost

$561

Charge & Range

Full Battery Charge Time

7 hours at 240V

on a fully charged battery, vehicle can travel about...

0 7 14 21 28 35 42 49 56 63 73

73 miles

How This Vehicle Compares

Among all vehicles and within midsize car

Worst 9 MPG — midsize car — **99** — 99 MPGe Best

Environment

Greenhouse Gases (CO_2 g/mile, tailpipe only) 987 Worst — **0** — 0 Best

Other Air Pollutants 1 Worst — **10** — 10 Best

Your actual mileage and costs will vary with electricity cost, temperature , driving conditions, and how you drive and maintain your vehicle. Cost estimates are based on 15,000 miles per year at 12 cents per kW-hr. MPGequivalent: 33.7 kW-hrs = 1 gallon gasoline energy.

See the FREE Fuel Economy Guide at dealers or www.fueleconomy.gov

Electric Vehicle Fuel Economy Calculation, I
e: equivalent

$$MPGe_{battery-to-wheel} = \frac{1}{[Wh/mi]} \times U_{gasoline}$$

$$U_{gasoline} = 33.7\,kWh/gal = 8.90\,kWh/l$$

$$MPGe_{battery-to-wheel} = \frac{100\,miles}{34\,kWh} \times \frac{33.7\,kWh}{gal}$$

$$= 99\,mpg$$

Electric Vehicle Fuel Economy Calculation, II

e: equivalent

ε: efficiency

$$MPGe_{fuel-to-wheel} = MPGe_{battery-to-wheel} \times \varepsilon_{electricity}$$

$$= \frac{1}{[Wh/mi]} \times U_{gasoline} \times \varepsilon_{electricity}$$

$$\varepsilon_{electricity} = \varepsilon_{generation} \times \varepsilon_{transmission}$$

$$= 0.328 \times 0.924 = 0.303$$

Fuel-to-wheel = fuel-to-battery × battery-to-wheel.

Conventional Vehicle Fuel Economy Calculation
e: equivalent
ε: efficiency

$$MPGe_{fuel-to-wheel} = MPGe_{tank-to-wheel} \times \varepsilon_{gasoline}$$

$$\varepsilon_{gasoline} = \varepsilon_{refining} \times \varepsilon_{distribution} = 0.830$$

Fuel-to-wheel = fuel-to-tank × tank-to-wheel.

Compare EV to CV

$$MPGe_{fuel-to-wheel} = \frac{1}{[Wh/mi]} \times U_{gasoline} \times \varepsilon_{electricity}$$

$$= \frac{100\,mi}{34\,kWh} \times \frac{33.7}{gal} \times 0.303$$

$$= 99\,mpg \times 0.303 = 30\ mpg$$ (EV)

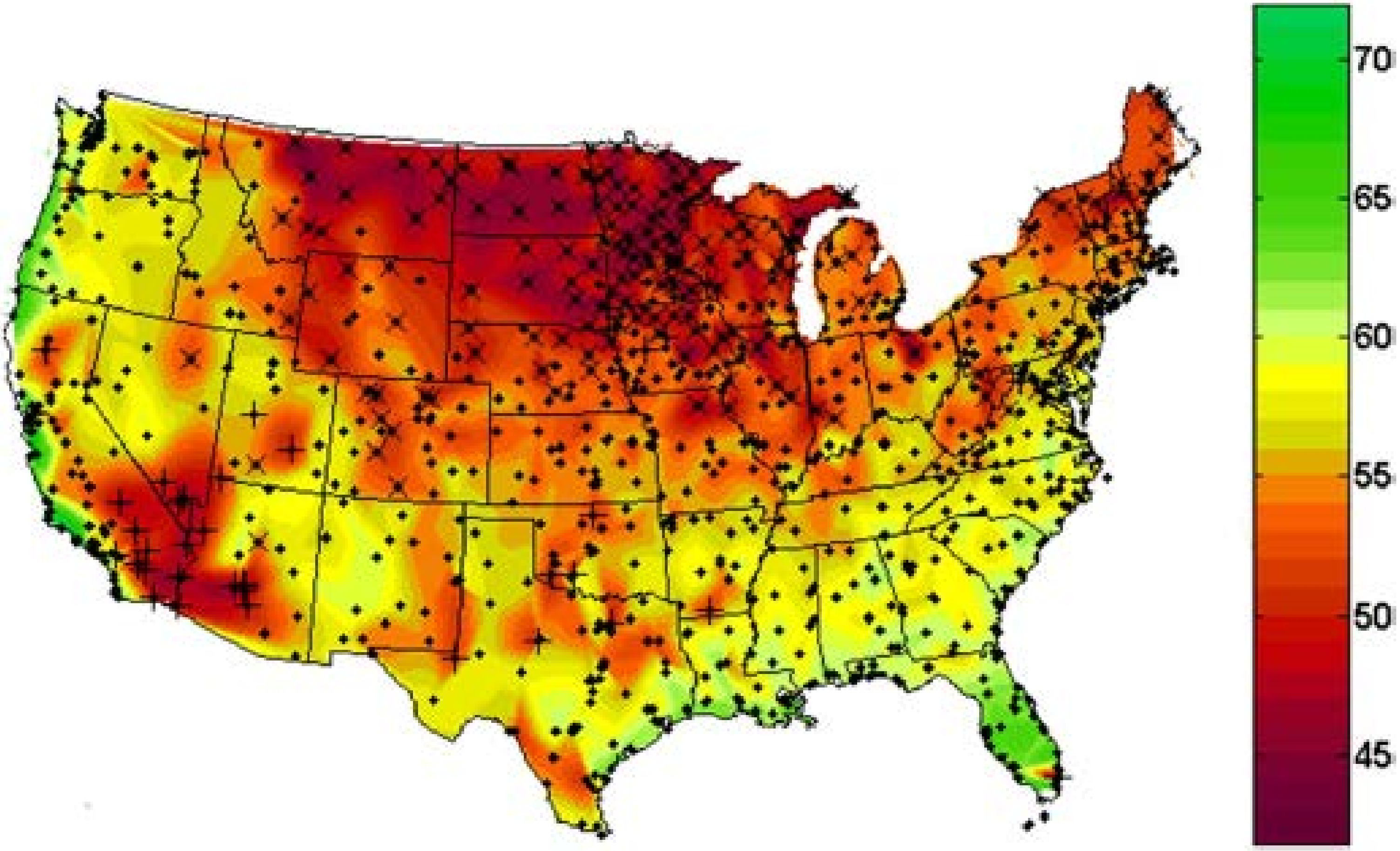
$$MPGe_{fuel-to-wheel} = MPGe_{tank-to-wheel} \times \varepsilon_{gasoline}$$

$$= 30\,mpg \times 0.830 = 25\,mpg$$ (CV)

Nissan Leaf Battery and Price

- Li Ion 86 MJ (24 kWh)
- Mass 300 kg (0.29 MJ/kg)
  - Compare to gasoline 46.4 MJ/kg
- Cost of 6kWh battery cost for additional 23 mile range $5,190 ($865/kWh)
- MSRP (U.S.) $29,860
  - Compare to MSRP (Japan) $36,000)
- U.S. Federal tax credit $7,500
  - Net cost $22,260

Nissan Leaf Range on Worst Day of the Year



Nissan Sentra

Payback Period and Oil Savings, I

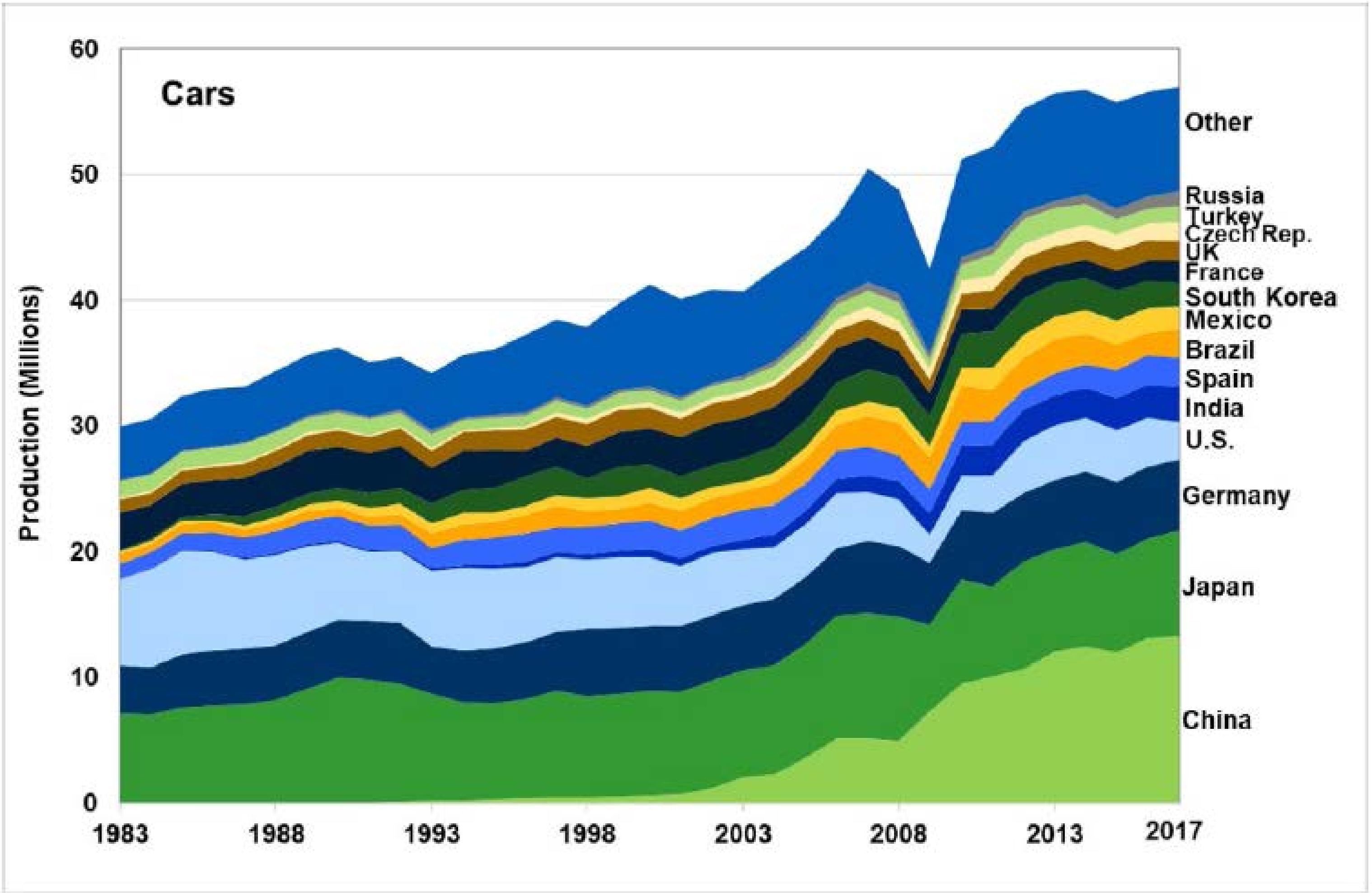
- Assume 12,000 miles/year
  - Conventional vehicle at 30 mpg → 400 gal
  - 400 gal gasoline at $2.50/gal = $1,000/year
  - Assume 19/42 bbl to gasoline → 21 bbl/year
  - Assume 10 year lifetime → 210 bbl
  - Rebate then $7,500/210 bbl = $36/bbl
  - (see below for a different calculation of cost of the rebate)

Payback Period and Oil Savings, II

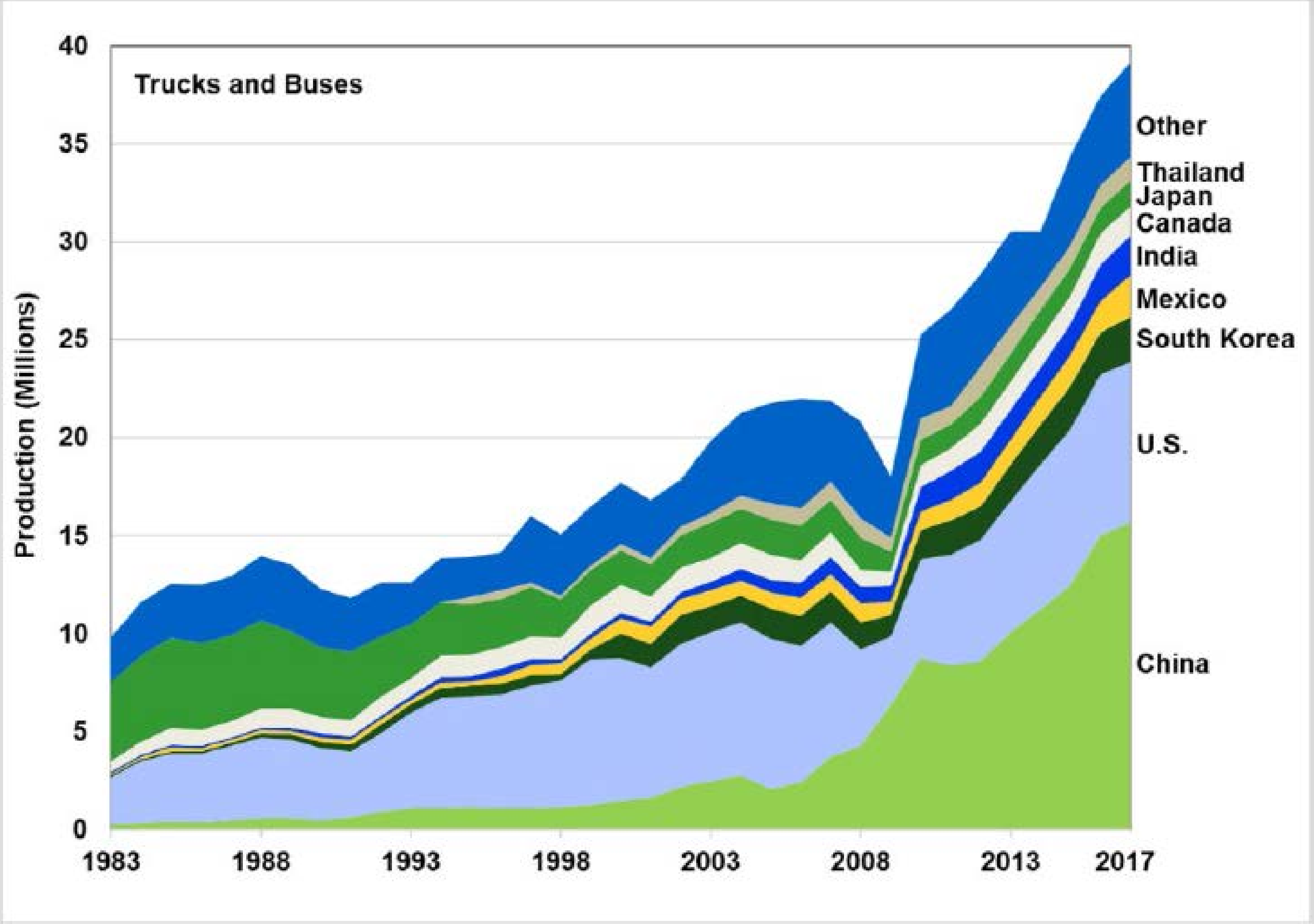
- Assume 12,000 miles/year
  - EV at 34 kWh/100 miles → 4,080 kWh/year
  - Assume Ameren IP 2010 13¢/kWh
  - 4,080 kWh → $530/year electricity
  - Fuel cost savings $1,000 - $530 = $470/year
  - Extra cost of EV Leaf over CV Sentra $12,870
  - Payback in $12,870/($470/year) = 27 years
  - With gasoline at $3.50 per gallon, in 15 years
  - With no rebate payback in 47 years for $2.50 gasoline and 23 years with $3.50 gasoline

Current Production

World Car Production, 1983–2017a (Updated August 2019)

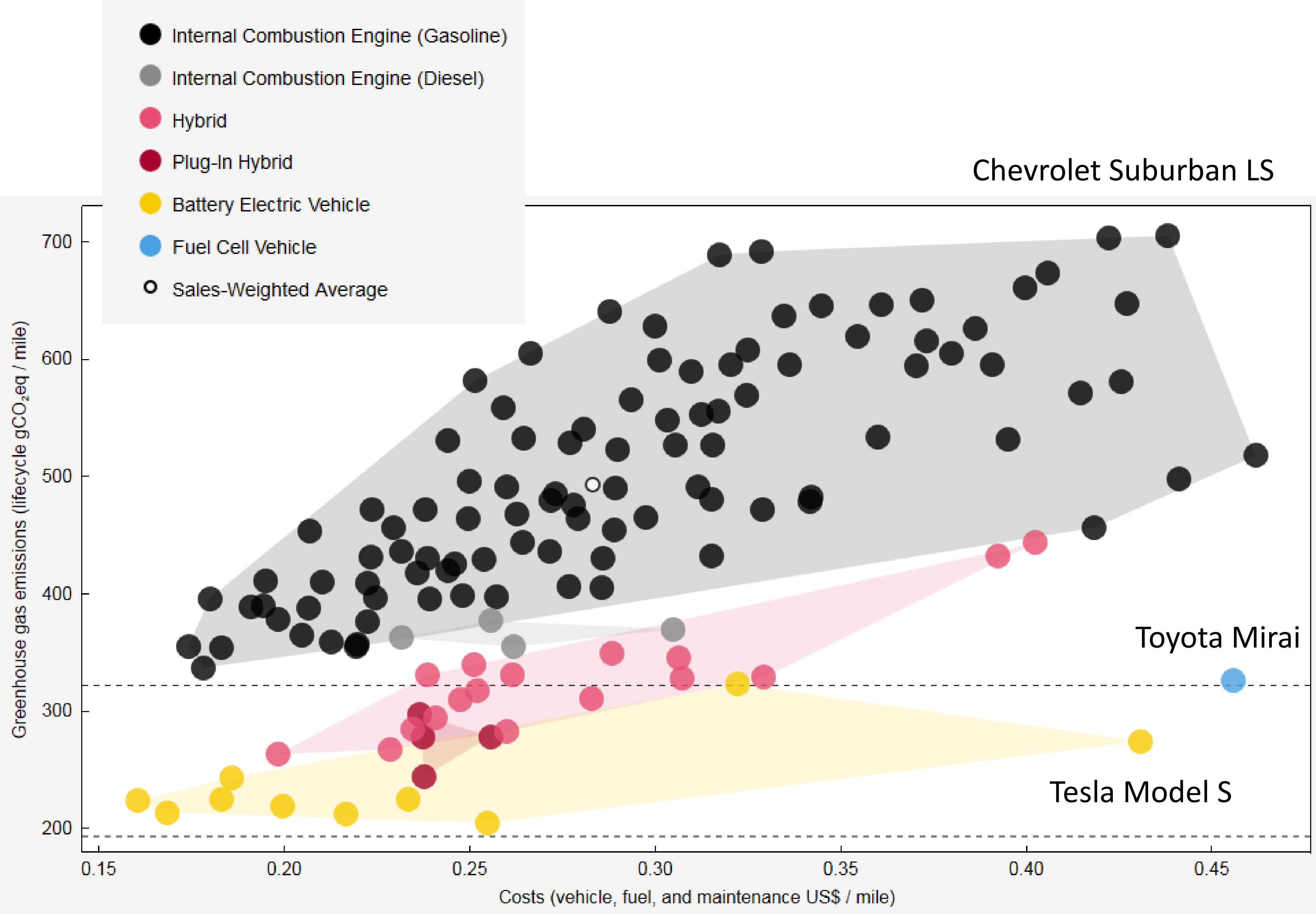


World Truck Production, 1983–2017a (Updated August 2019)



Consumer Choice

Conventional Gasoline Vehicle (CV)
Conventional Diesel Vehicle (CV)
Hybrid electric Vehicle (HEV)
Plug-in Hybrid Electric Vehicle (PHEV)
Battery Electric Vehicle (BEV)
Fuel Cell Electric Vehicle (FCEV)
Compressed Air Vehicle (CAV)
Solar Electric Vehicle



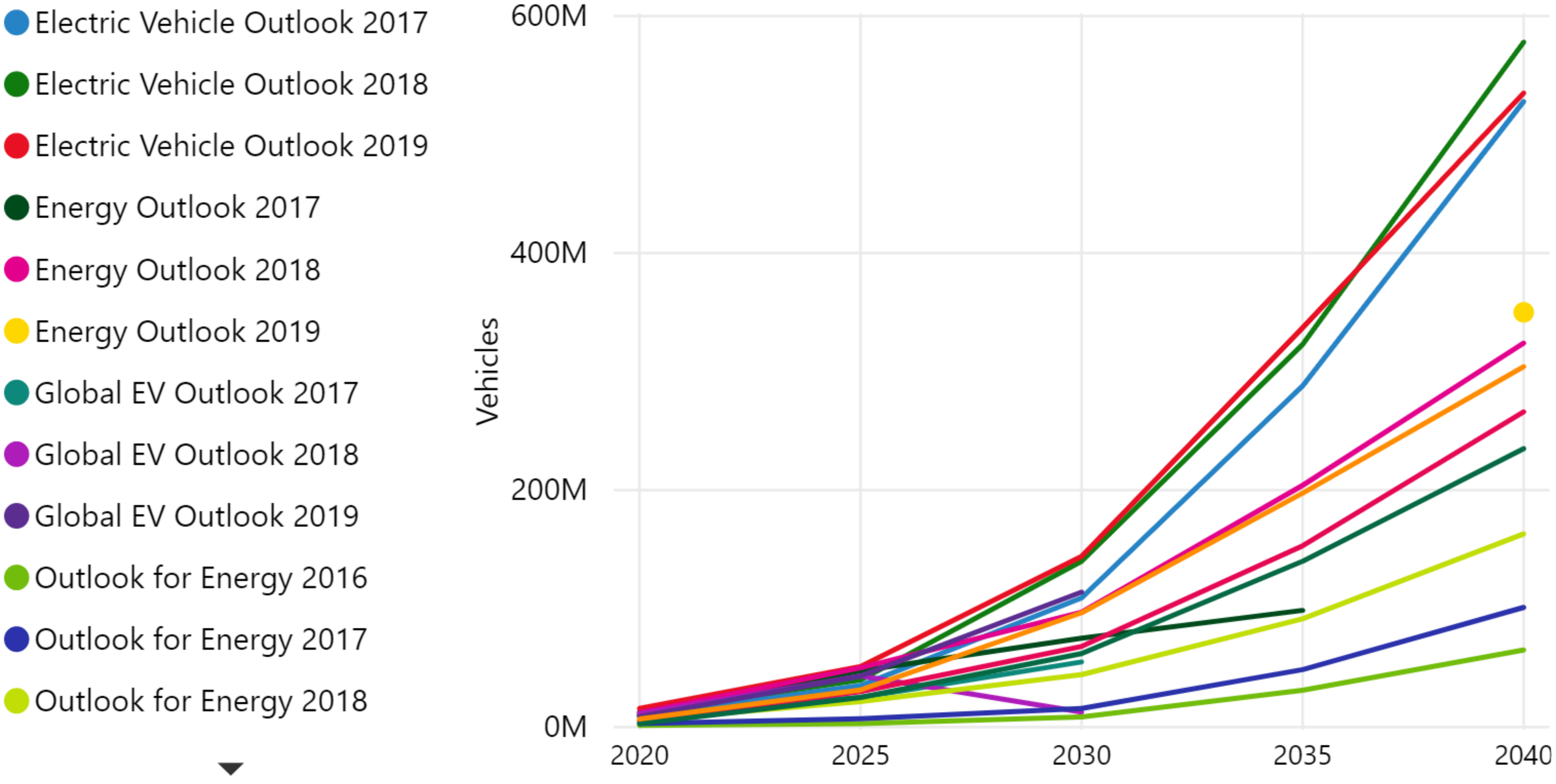
Chevrolet Suburban LS

Toyota Mirai

Tesla Model S

http://carboncounter.com/

EV Market Forecasts



The Fuel of the 21st Century?

- Gasoline and diesel
- Natural gas
- Battery
- Hydrogen with fuel cells
- Biofuels

REUTERS

February 3, 2020

Electric future: Britain to ban new petrol and hybrid cars from 2035

Victoria Embankment in London

The New York Times

February 27, 2018

In Germany’s Car Capital, the Unthinkable: The Right to Ban Cars

The New York Times

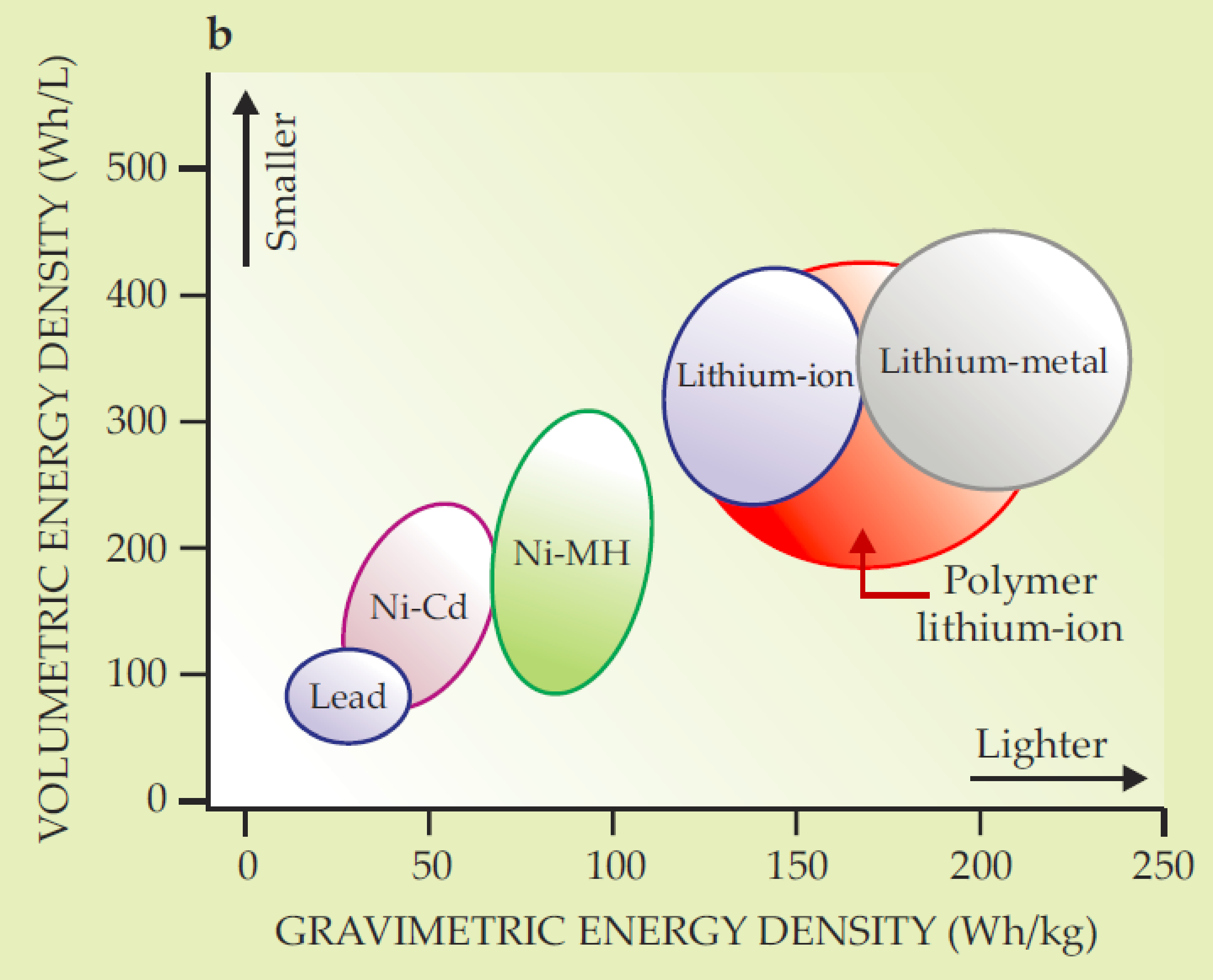
July 6, 2017

France Plans to End Sales of Gas and Diesel Cars by 2040

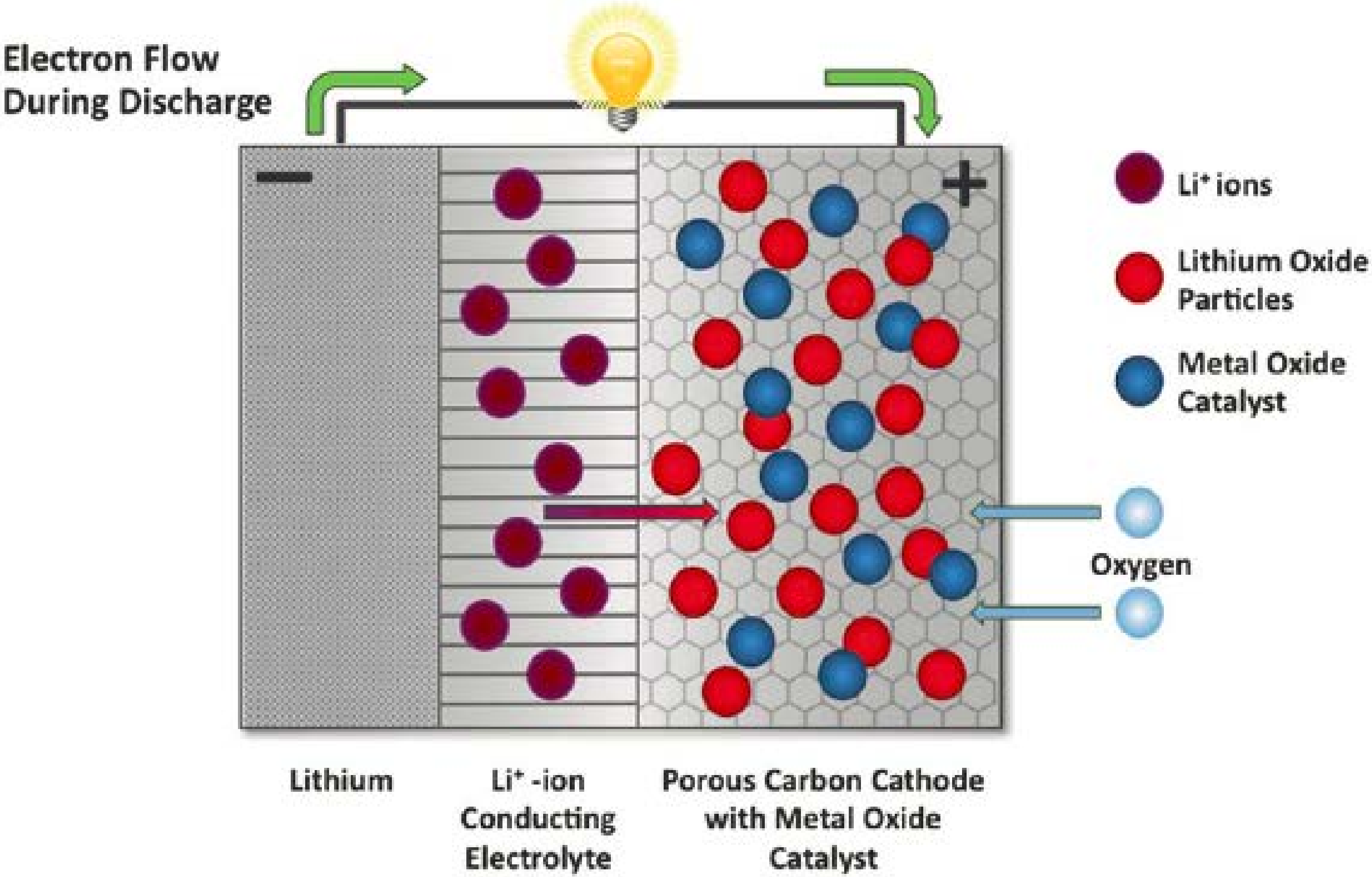
Batteries

Lithium-Ion Battery

Tesla Lithium-Ion Battery Pack

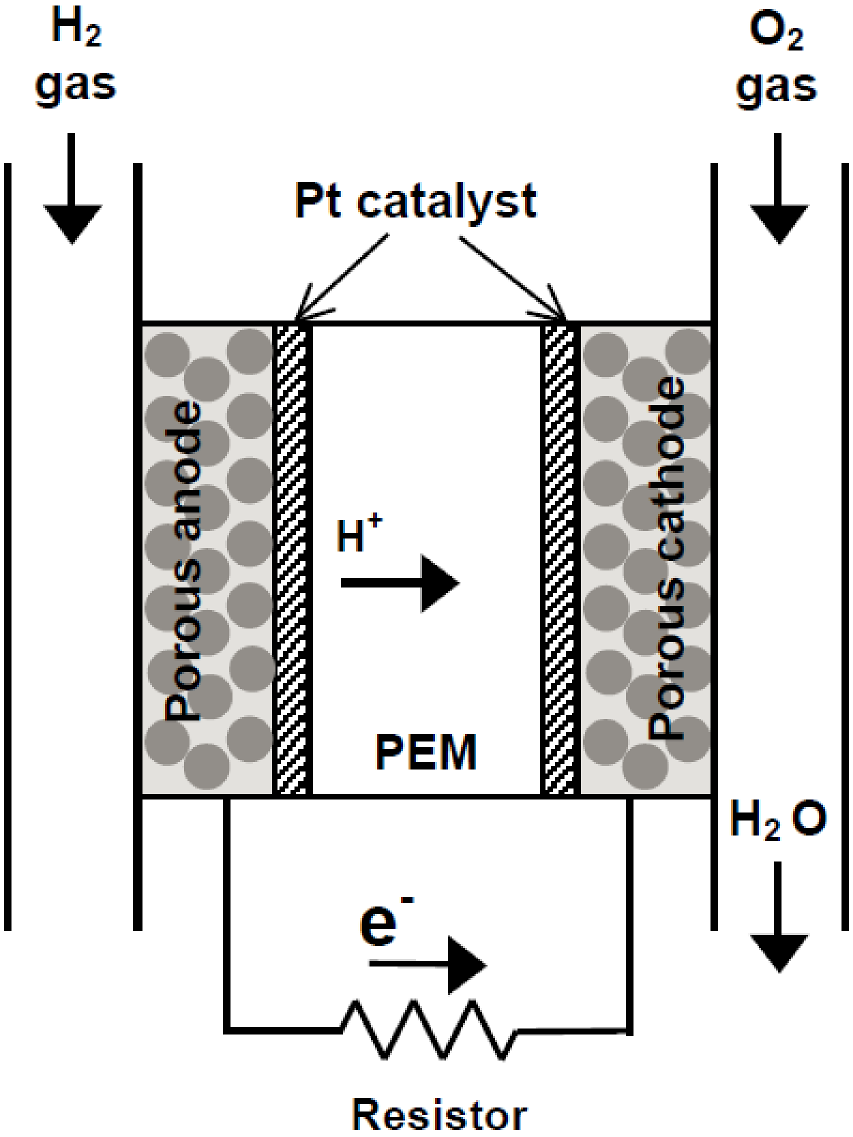

b
VOLUMETRIC ENERGY DENSITY (Wh/L)
500
400
300
200
100
0
Smaller
Lithium-ion
Lithium-metal
Ni-MH
Ni-Cd
Lead
Polymer lithium-ion
Lighter
0
50
100
150
200
250
GRAVIMETRIC ENERGY DENSITY (Wh/kg)

Beyond Lithium-Ion: Li-O_2?



Hydrogen with Fuel Cell

Proton Exchange Membrane Fuel Cell Basic



Proton Exchange Membrane Fuel Cell Chemistry

Anode (oxidation reaction, produces electrons):

$$H_{2(g)} \rightarrow 2H^{+} + 2e^{-}$$

Cathode (reduction reaction, consumes electrons):

$$\frac{1}{2}O_{2(g)} + 2H^{+} + 2e^{-} \rightarrow H_2O_{(l)}$$

Net reaction:

$$H_{2(g)} + \frac{1}{2}O_{2(g)} \rightarrow H_2O_{(l)}$$

Toyota Mirai Fuel Cell Vehicle

Available for Commercial Sale

- **$57,500 MSRP**
- 67 mi/gge
- 312 mi range, ~5 min refuel
- 114 kW stack
- US:200 2015, 3000 by 2017

Hyundai Tucson Fuel Cell SUV

Available for Lease

- **$499/month lease**
- 50 mi/gge
- 265 mi range
- 100 kW stack
- US: 70 thru May ‘15 (237 overall)

Honda Clarity Fuel Cell Vehicle

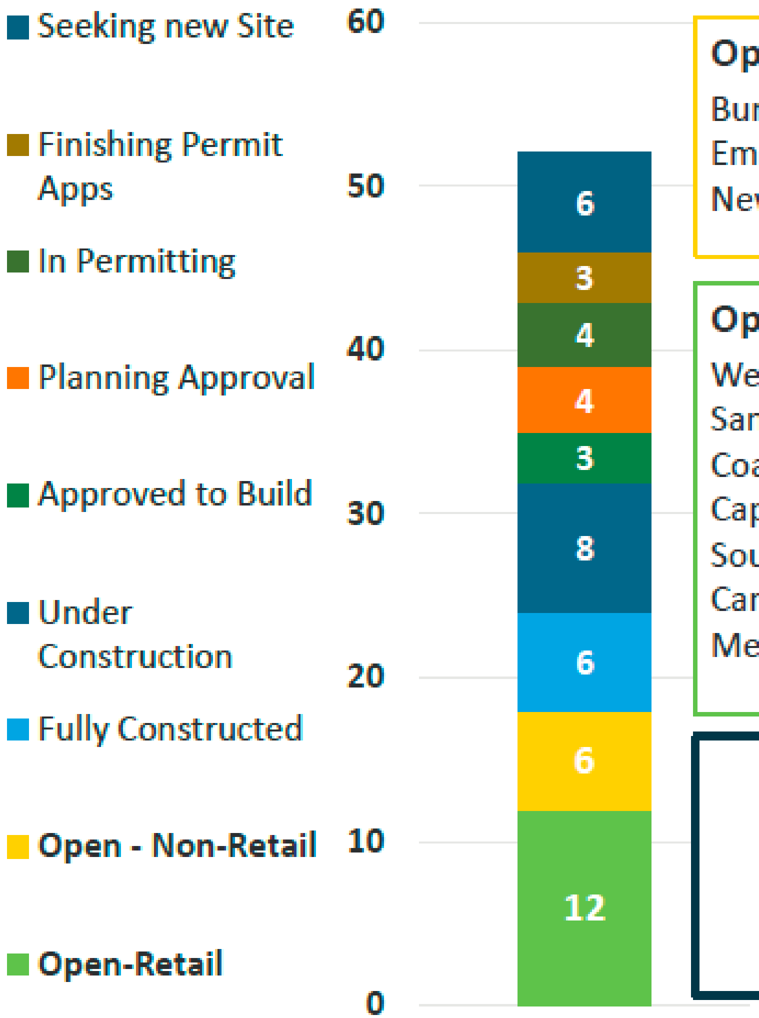
Just Announced at Auto Shows

- **$60,000 MSRP**
- **$500/month lease** for initial launch
- +300 mi range*
- 100 kW stack
- Initial launch planned for late 2016

*Preliminary range estimate dete

Example: California- H_2 Station Status

Snapshot of Status



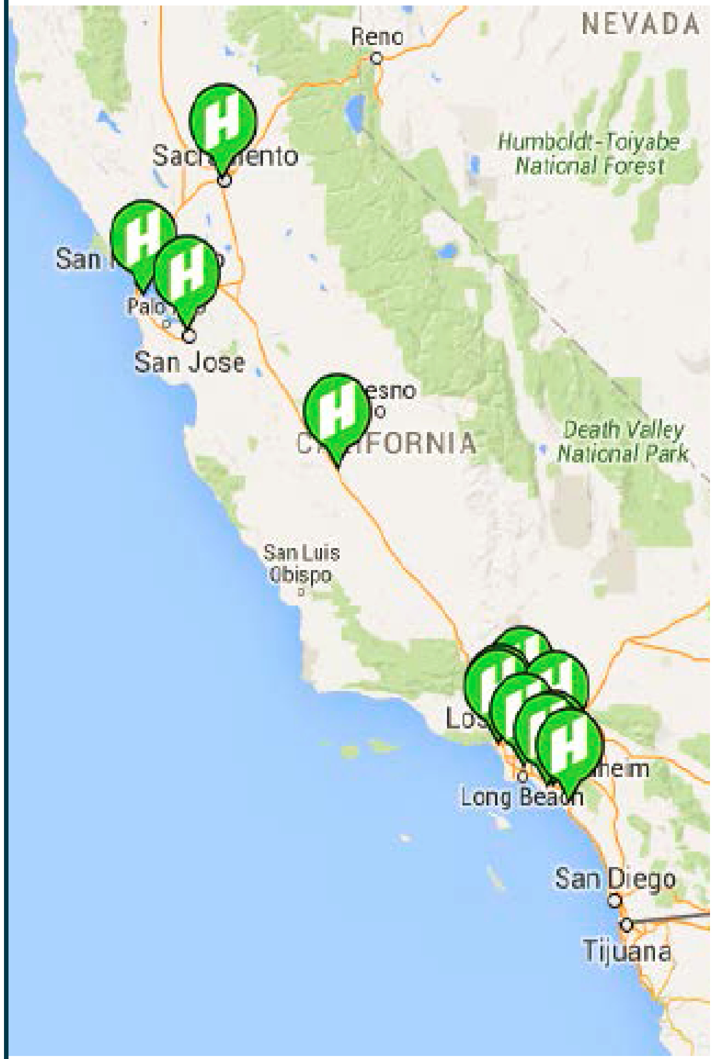
Open – Non-Retail:
Burbank, Torrance#, Emeryville*, Harbor City*, Newport Beach*, OCSD*#

Open – Retail:
West Sac, Diamond Bar, LA Santa Monica Blvd#, UCI, Coalinga, San Juan Capistrano#, Long Beach, South SF, San Jose, La Canada Flintridge, Costa Mesa, Santa Monica

Total:
52
H_2 Stations

As of February 25, 2016 (Data from CARB). * Stations in need of extension or upgrade
Currently Torrance (H70 only), Santa Monica, San Juan Capistrano, and OCSD are offline (01/15/16 CaFCP SOSS)

Locations



Green icons indicate
Open Retail Stations

Fuel Cell cars lined up for fueling in Sacramento, Aug 26, 2016

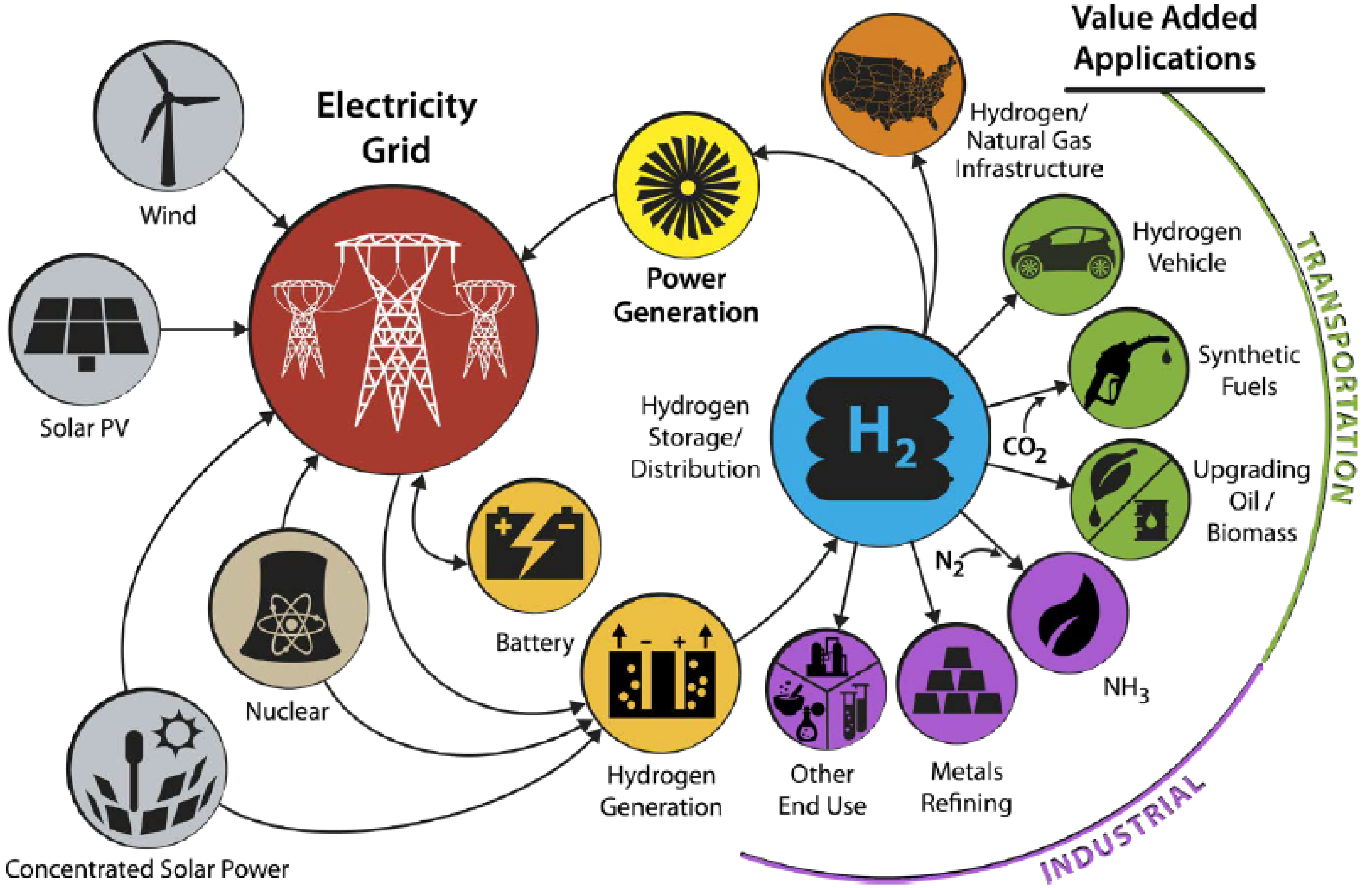
General Motors Hummer H2H

H2
VIEW

February 26, 2020

New Flyer of America to supply Illinois with hydrogen buses

Conceptual H_2 at Scale Energy System*



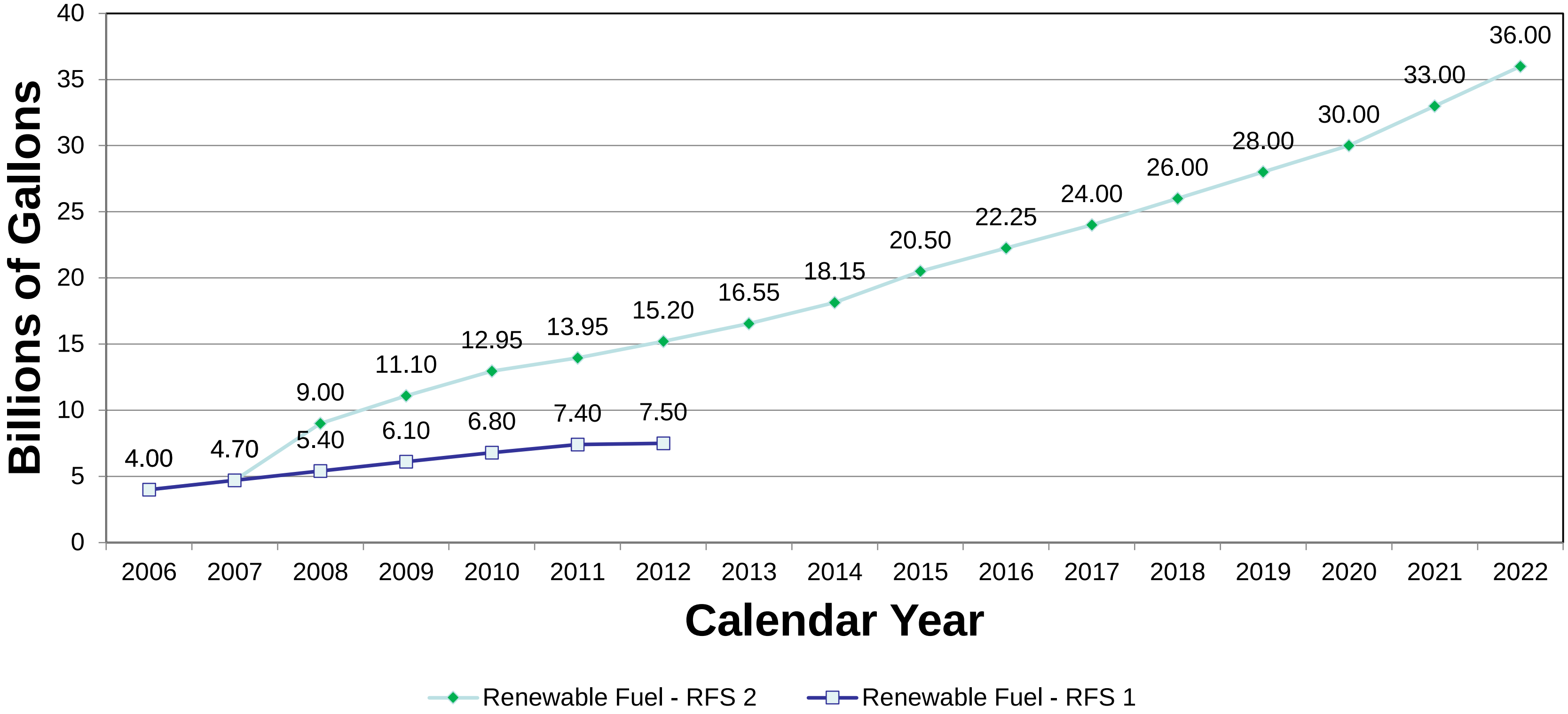
*Illustrative example, not comprehensive

H2@Scale Challenges

- Economic generation of hydrogen
- Distribution of hydrogen
- Storage of hydrogen
- Cost of fuel cells
- End use of hydrogen beyond fuel cells

Biofuels

Volumetric Requirements of RFS1(2005) and RFS2(2007)

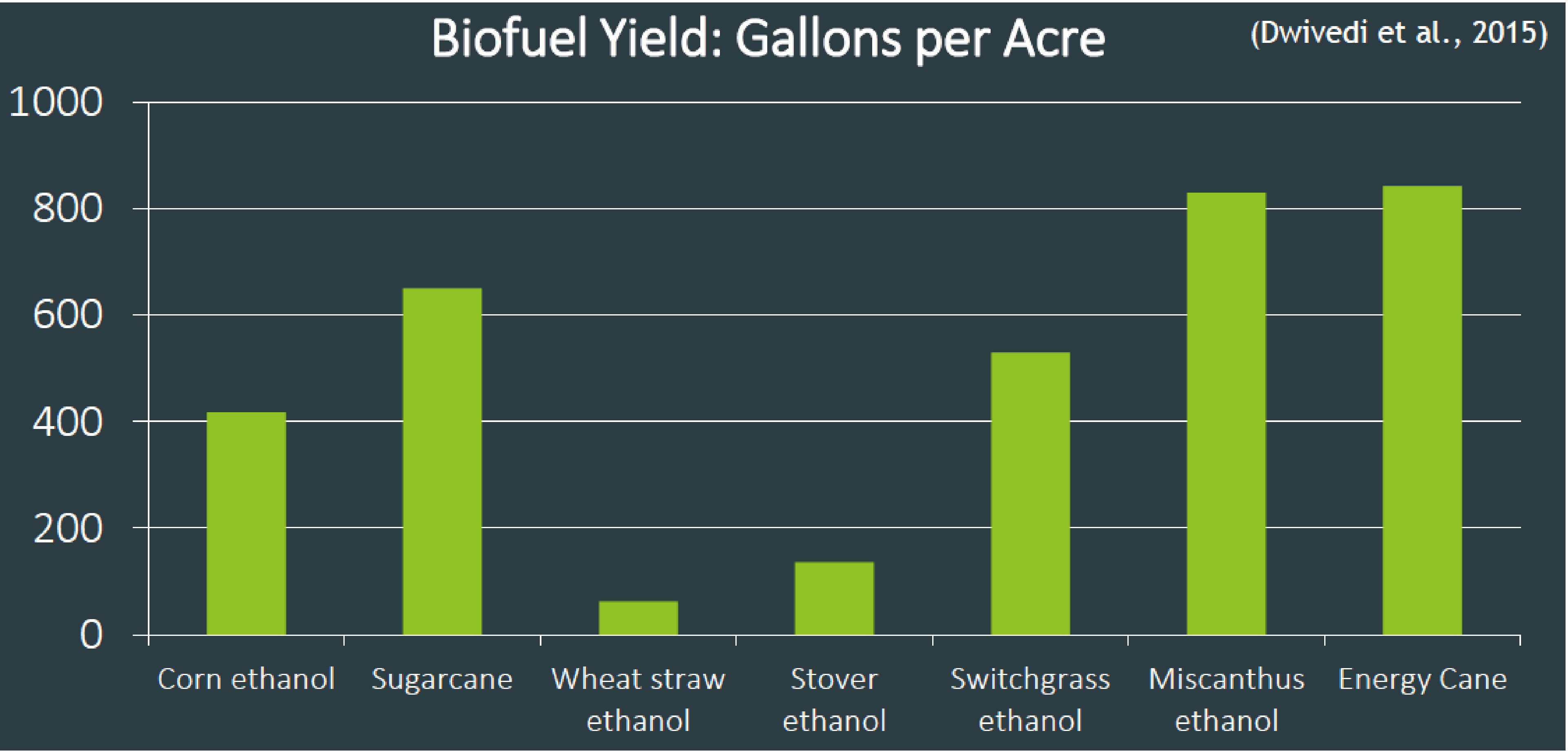


RFS 1 v. RFS 2
(Applicable Volumes of Renewable Fuel)

2015 U.S. gasoline consumption 140 billion gallons

Miscanthus at University of Illinois Experimental Plot

From D. MacKay Sustainable Energy without the Hot Air, Figure 6.10



To replace 10% of U.S. gasoline 55 million acres of corn out of 330 million acres of cropland.
For miscanthus 27 million acres of miscanthus out of 330 million acres of cropland.

Mostly Transportation Summary

- Transportation represents approximately 30% of U.S. primary energy consumption and almost 30% of U.S. GHG emissions.
- Largest component light duty vehicles
- There will be many more vehicles in the world
- Electric vehicle sales rising, but still expensive
- Battery technology needs a breakthrough
- Hydrogen may be in the future
- Ethanol of limited value, biodiesel could become important for heavy-duty vehicles

Lecture 6

- Energy storage: technology mostly available; issues with costs and markets
- Nuclear power: in a few decades, it may disappear
- Transportation: light and medium duty vehicles have a viable non-fossil fuel options