MICHIGAN STATE UNIVERSITY

# The Future of Batteries for Transportation

Wolfgang Bauer

Michigan State University

The Physical, Chemical and Technological Aspects of the Fundamental Transition in Energy Supply from Fossil to Renewable Sources – Key Aspect: Energy Storage

**791. WE-Heraeus-Seminar**

# $CO_2$ Emission from Transportation: USA

- Gasoline consumption per day: 350 million gallons (1.35 billion liters)
- Diesel fuel consumption per day: 120 million gallons (460 million liters)
- Contributes 1.6 giga-tons of $CO_2$ emission per year
  - ¼ of total US emissions
  - 10% of annual global net addition of $CO_2$ to Earth's atmosphere

Conversion to battery-powered electric vehicles is imperative

# Battery Performance Characteristics

- Volumetric energy density  [Wh/L]
- Gravimetric energy density [Wh/kg]
- Cycle efficiency
- Battery life
  - Number of charge cycles
  - Degradation per charge cycle
- Maximum charging power
- Temperature dependence
- Price
- Raw materials
  - Recyclability
  - Availability

# Side note: Supercapacitors are batteries, too!

- > 10 kF capacitors now available commercially
- Can be used for transportation
- Main advantage: very rapid recharging
- Main disadvantage: very frequent recharging needed


**FIGURE 24.33** Supercapacitor-powered bus recharging at a bus stop in Shanghai, China.

W. Bauer and G. D. Westfall

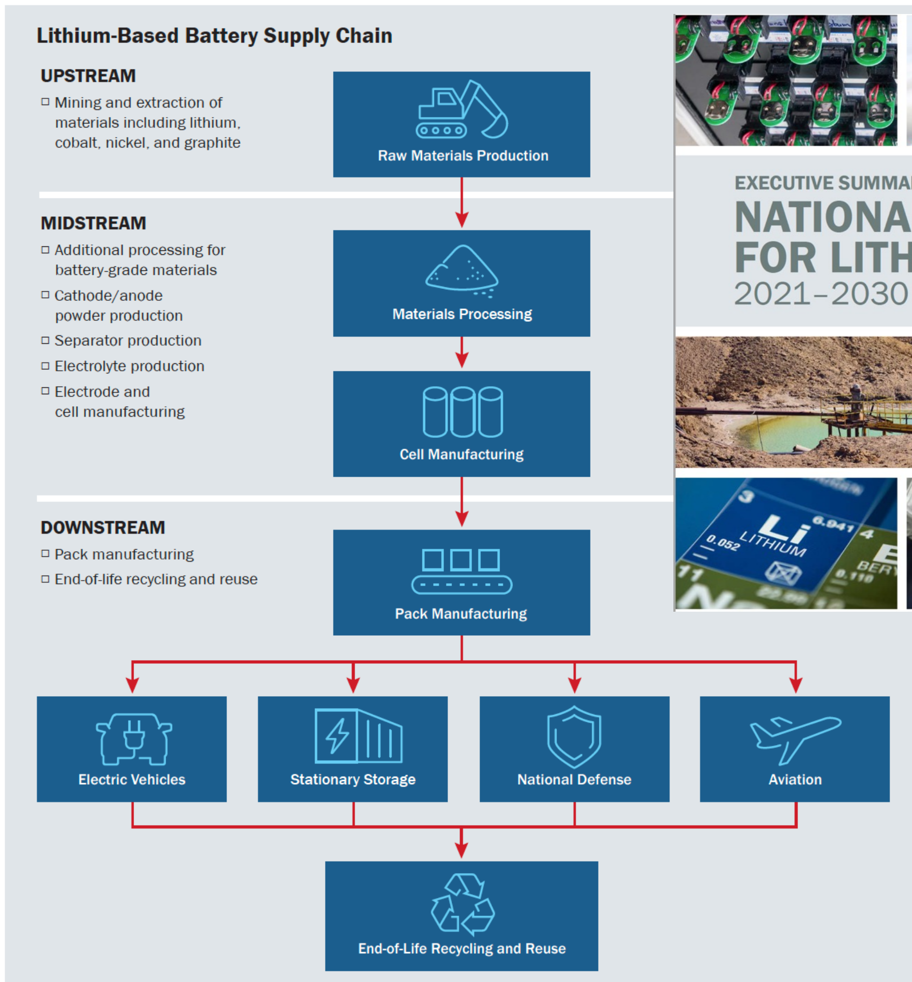




FIGURE 5. Steps in the lithium-battery material supply chain.

# Availability of battery raw materials

| Element | U.S. Reserves (1000 Metric tons) | World Reserves (1000 Metric tons) | Total Manufacturing Capacity with U.S. reserves (GWh) | Total Manufacturing Capacity with world reserves (GWh) |
|---|---|---|---|---|
| **Lithium** | 750 | 21,000 | 7470 | 209,163 |
| **Cobalt** | 53 | 7100 | 703 | 94,164 |
| **Nickel** | 100 | 94,000 | 167 | 156,510 |
| **Manganese** | 230,000 | 1,300,000 | 3,271,693 | 18,492,176 |

Source: Argonne National Laboratory derived from USGS mineral commodities summaries (2021) and simulations using BatPaC 4.0 for Li-ion batteries with $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ cathode.

# Recyclability

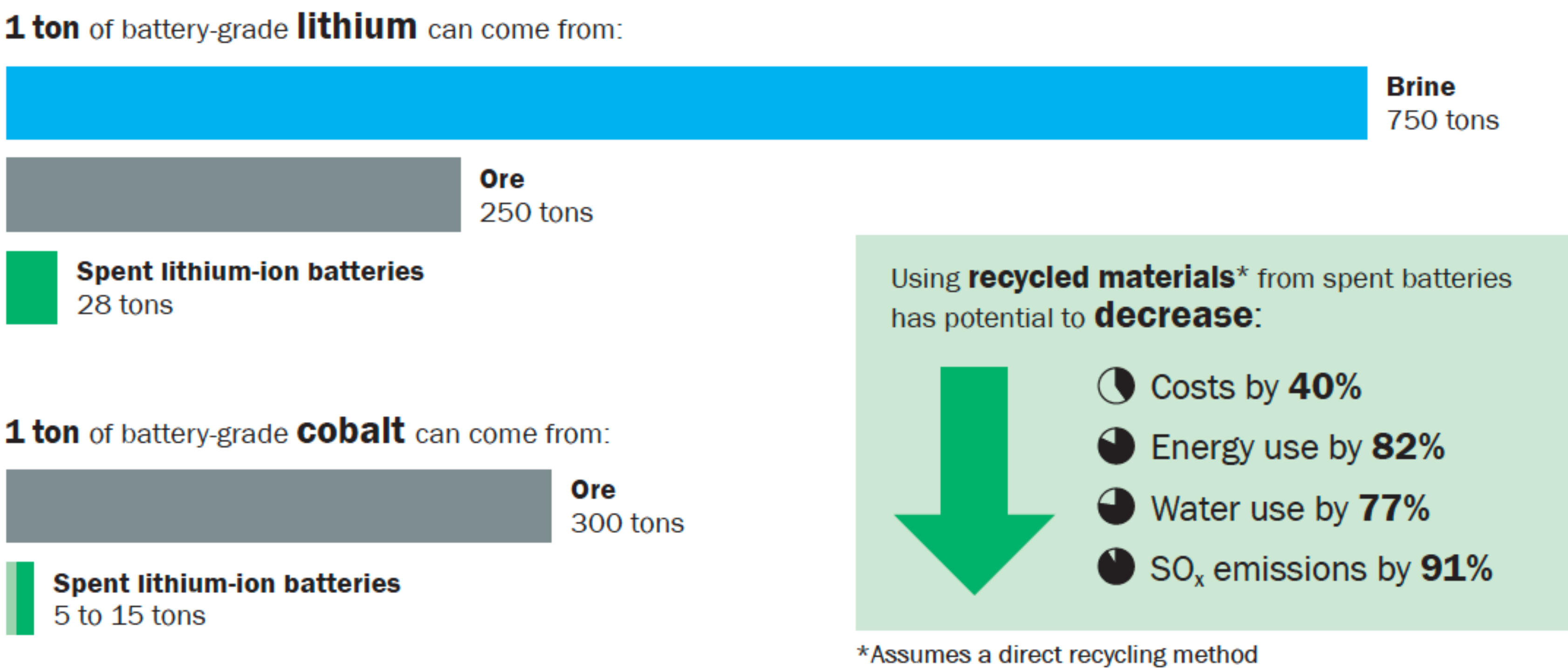
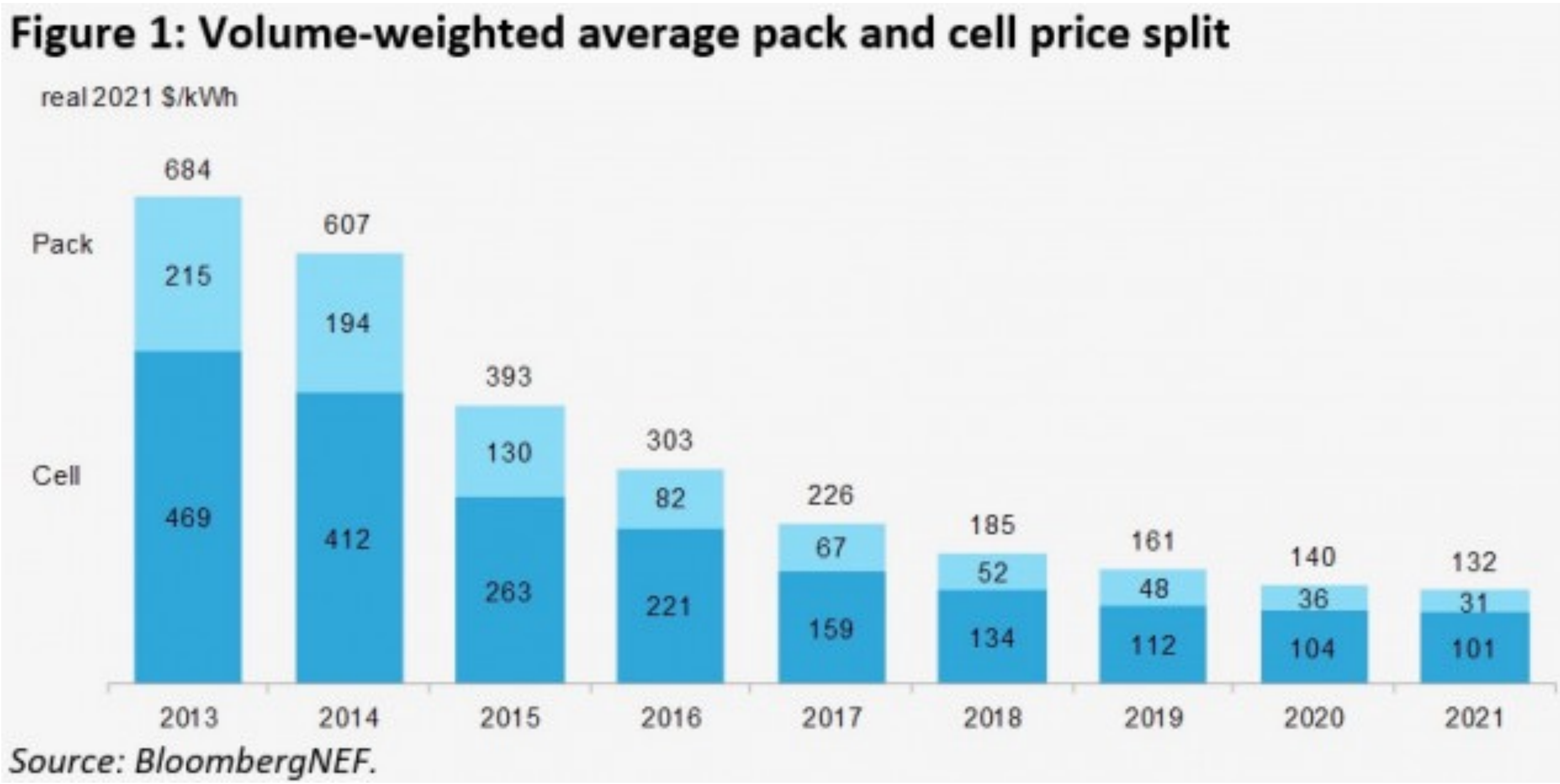
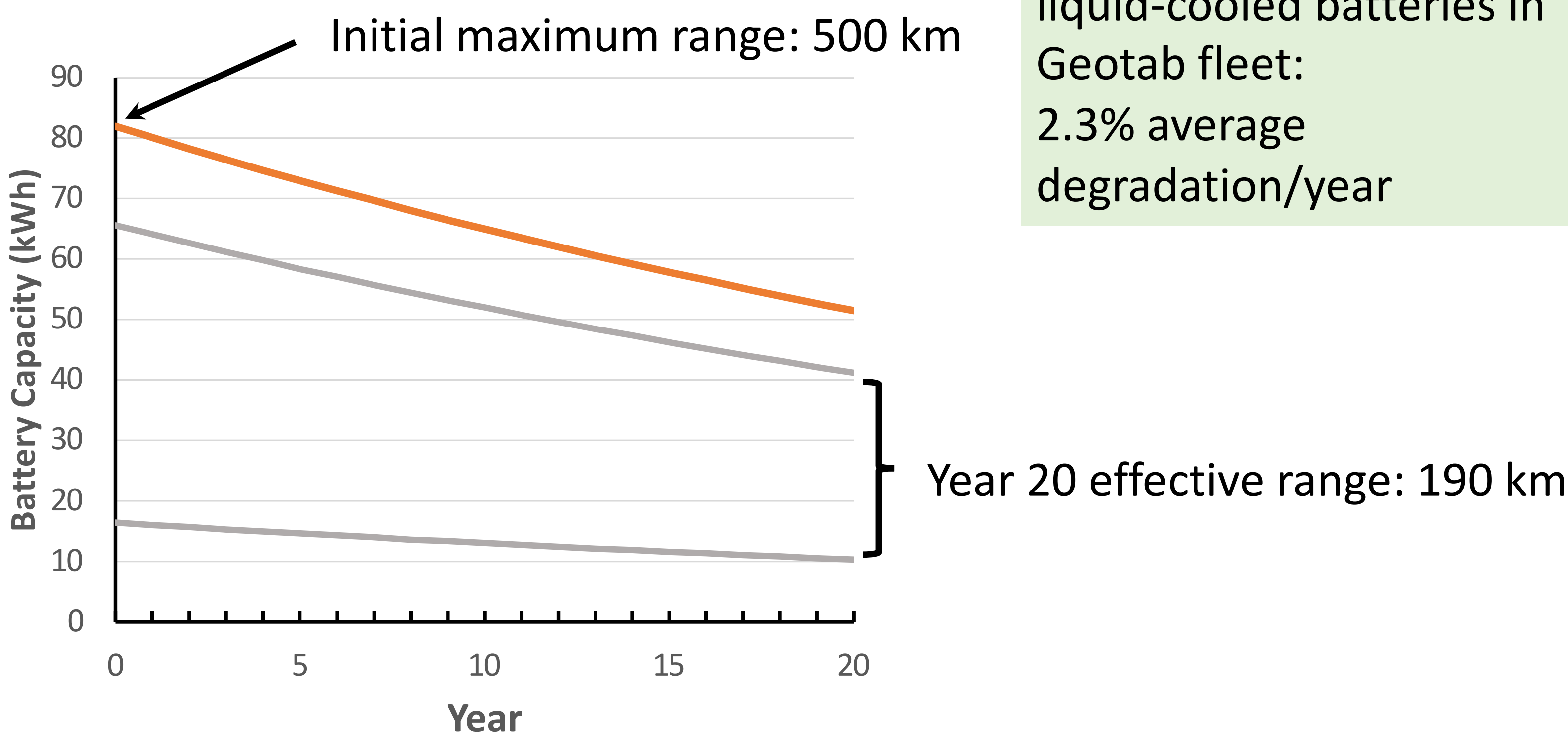



**FIGURE 7. Benefits of recycling for lithium-ion batteries. Data from Argonne National Laboratory's ReCell Center, 2019.[33]**

# Battery price: Getting gradually lower

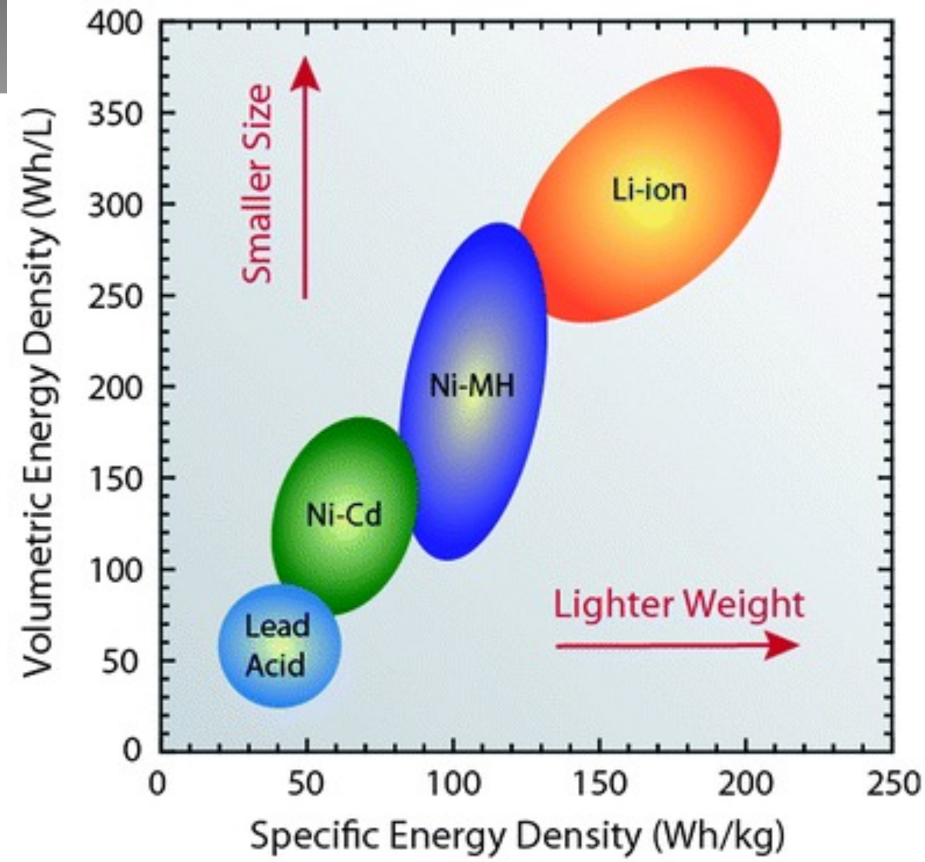


# Battery Degradation




Data from 6,300 EVs with liquid-cooled batteries in Geotab fleet:
2.3% average degradation/year

# Battery Energy Density

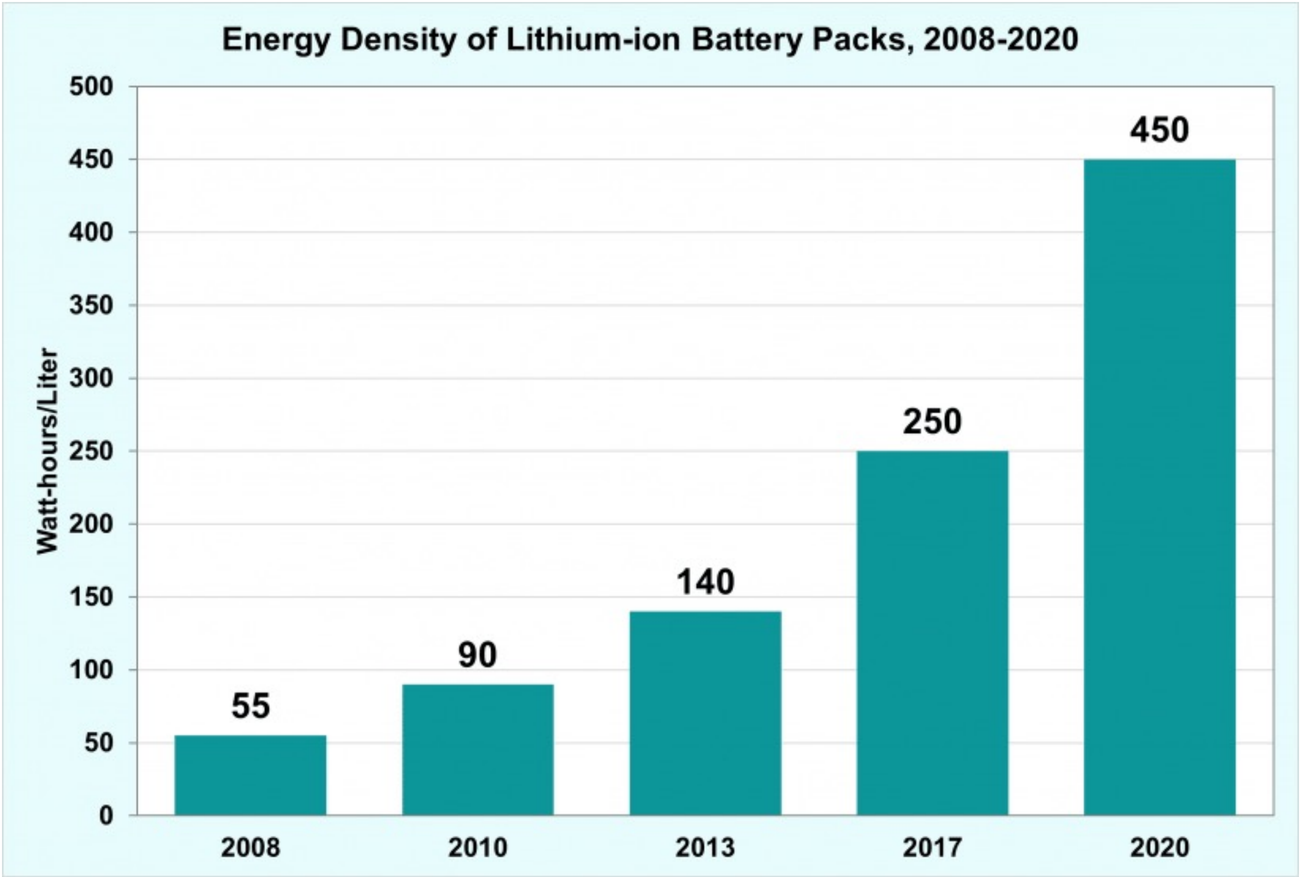



Roberta DiLeo, RIT Ph.D. Thesis, 2012 (Fig 1a)

**For comparison**

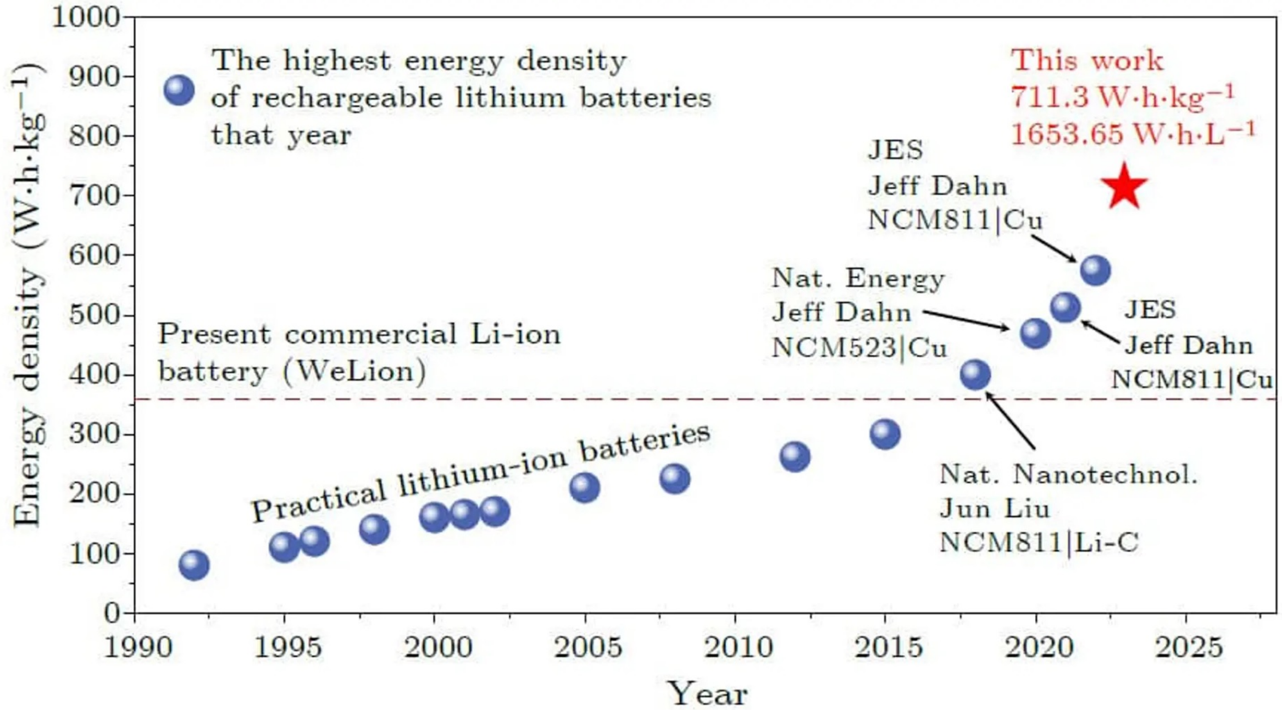
Gasoline:

- 12200 Wh/kg
- 9700 Wh/L



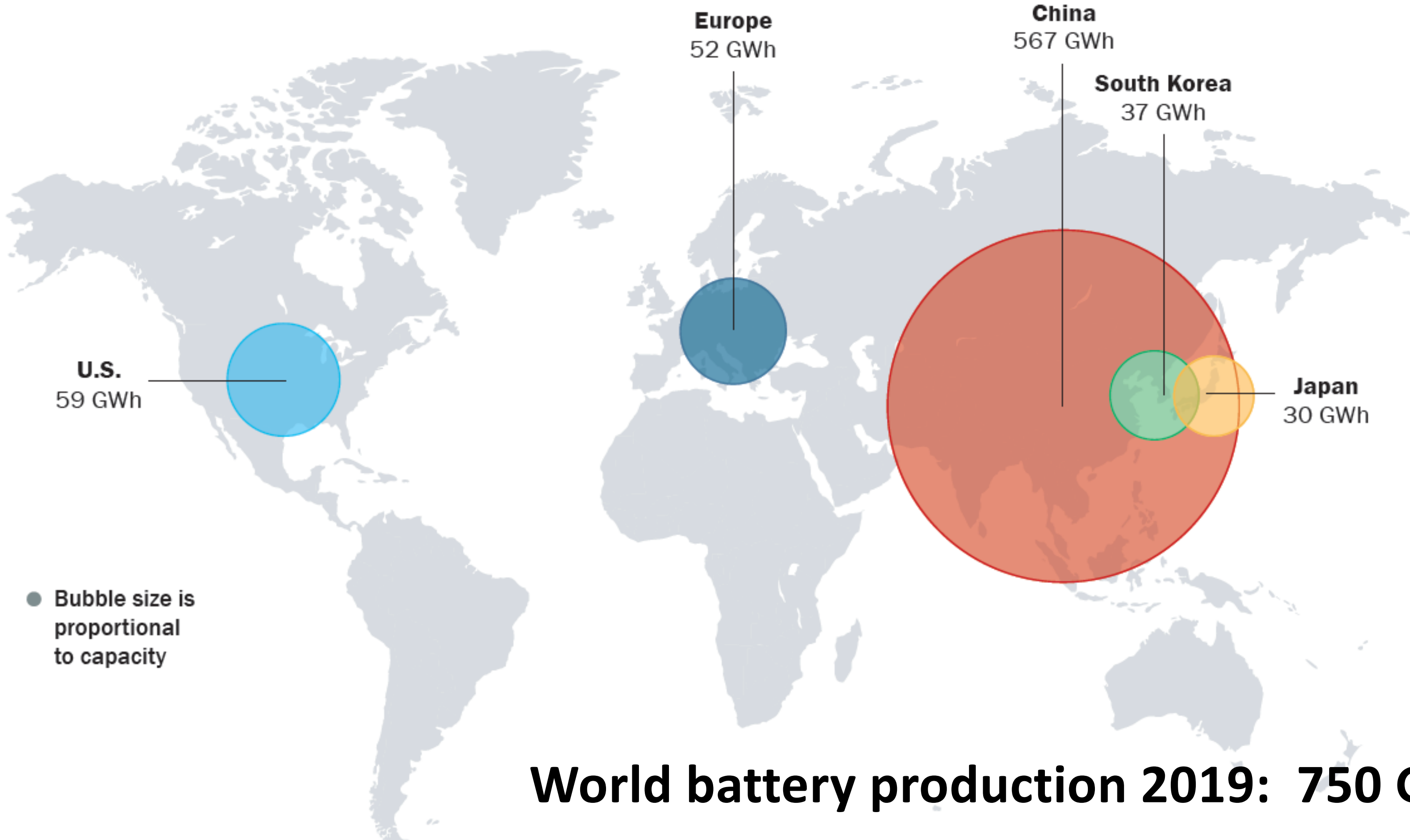

https://www.energy.gov/eere/vehicles/articles/fotw-1234-april-18-2022-volumetric-energy-density-lithium-ion-batteries

# Current world record battery lab modules




**= 1/6 of gasoline !!!**

Quan Li *et al* 2023 *Chinese Phys. Lett.* **40** 048201




**World battery production 2019: 750 GWh**

FIGURE 6. Cell manufacturing capacity by country or region.
Source: “Lithium-Ion Battery Megafactory Assessment”, Benchmark Mineral Intelligence, March 2021.[32]

# World Battery Production: Near Future

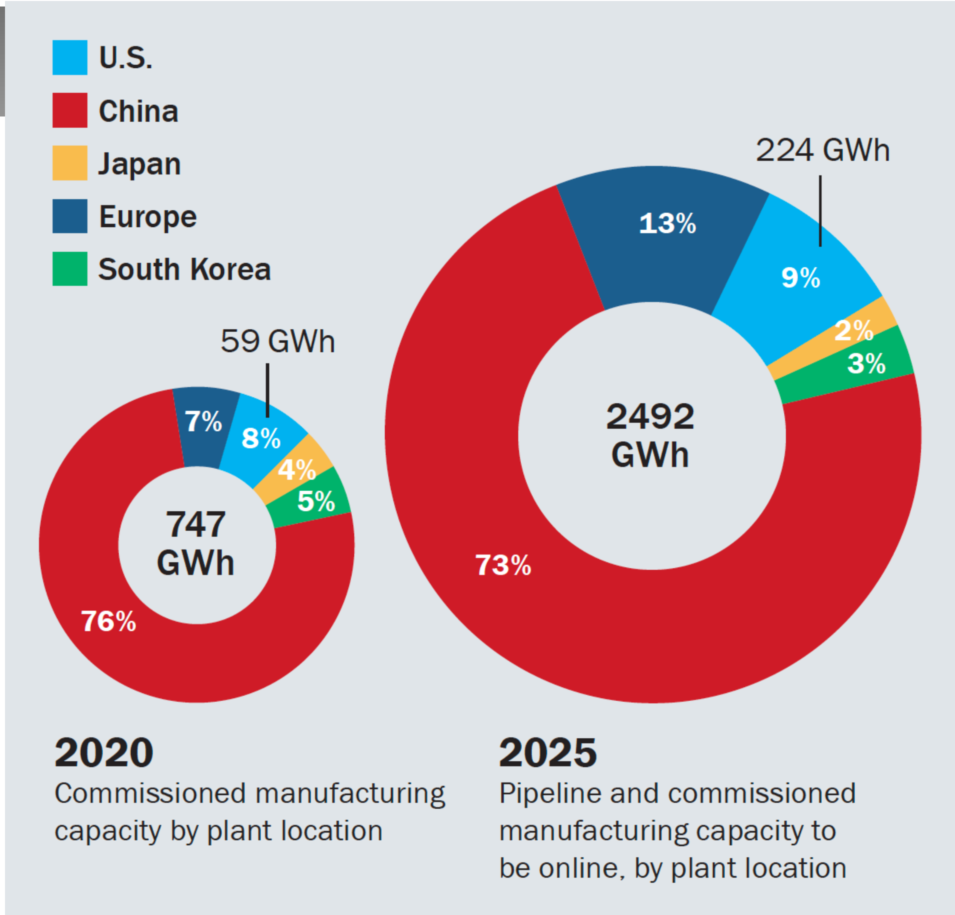



**FIGURE 3. Cell manufacturing capacities.**
**Source: "Lithium-Ion Battery Megafactory Assessment", Benchmark Mineral Intelligence, March 2021.**

# Worldwide EV sales (millions)

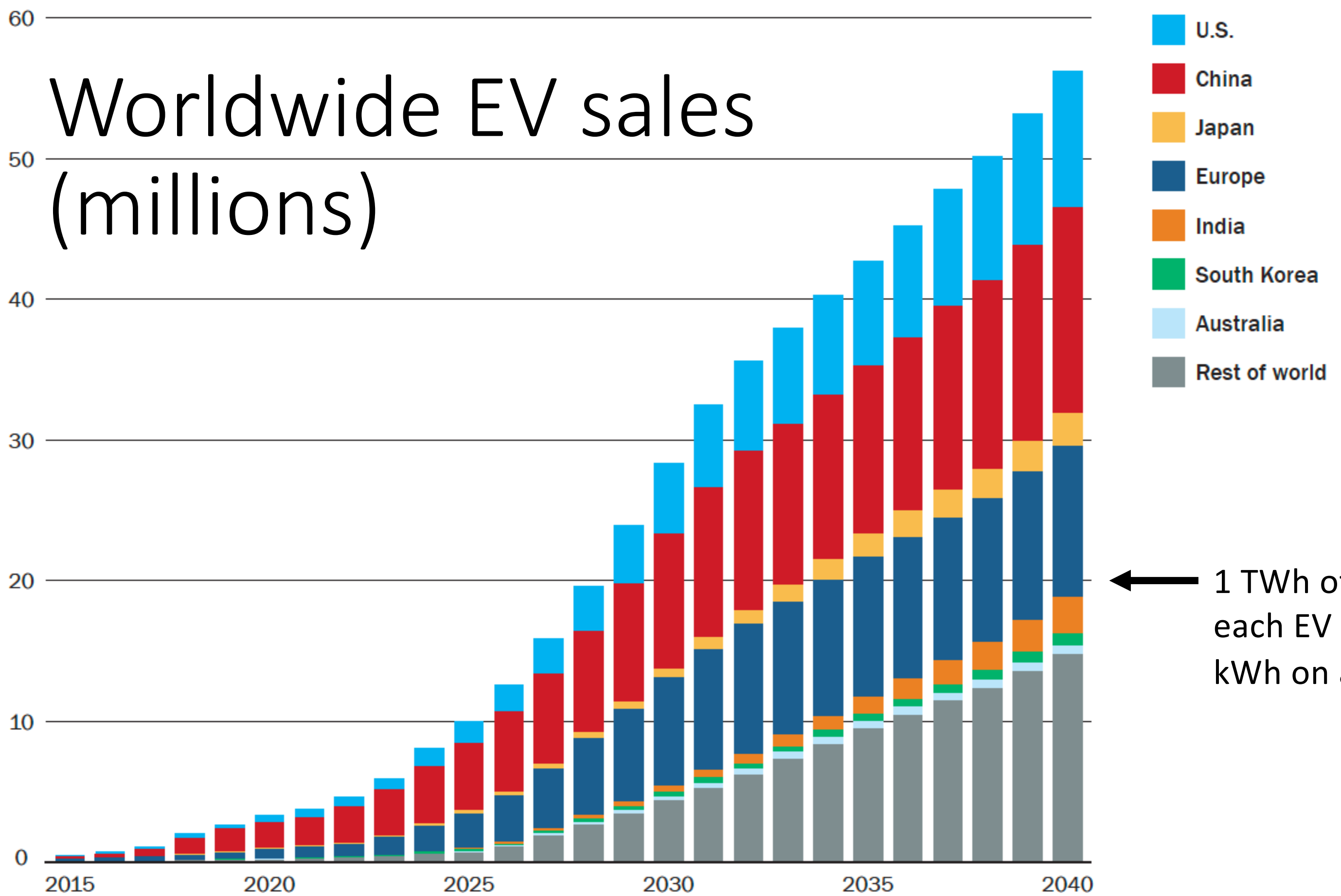
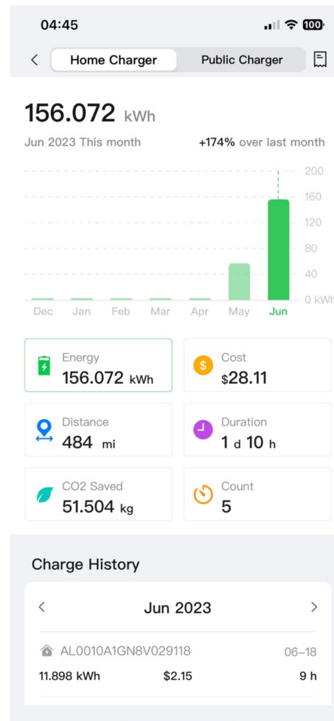



FIGURE 1. Annual Sales of Passenger EVs (Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs)). Source: BloombergNEF Long-Term Electric Vehicle Outlook 2019.[16]

1 TWh of batteries, if each EV carries 50 kWh on average

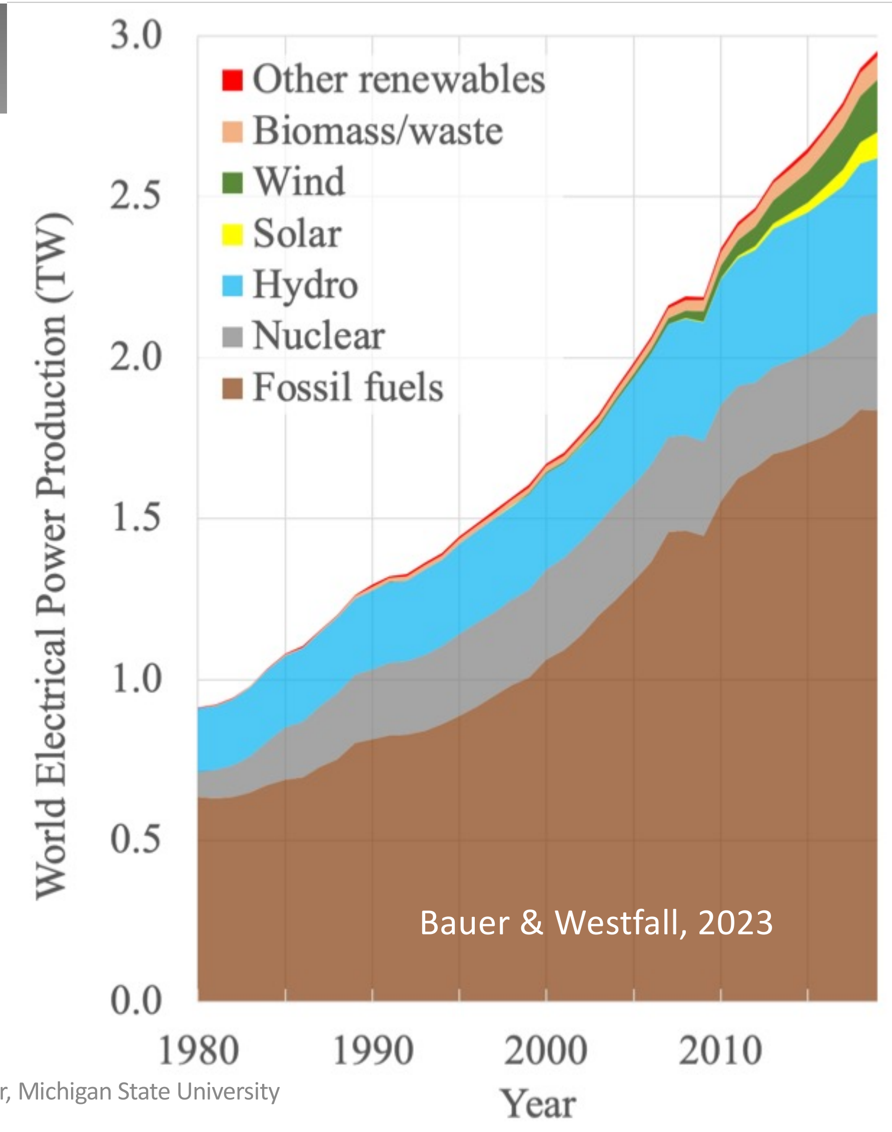
# How will we recharge the EV batteries, and when?




Passenger cars are (usually) manageable:

- Connect to your home charger
- Set schedule for low demand times and/or high availability of renewable power
- Save money & help out the grid

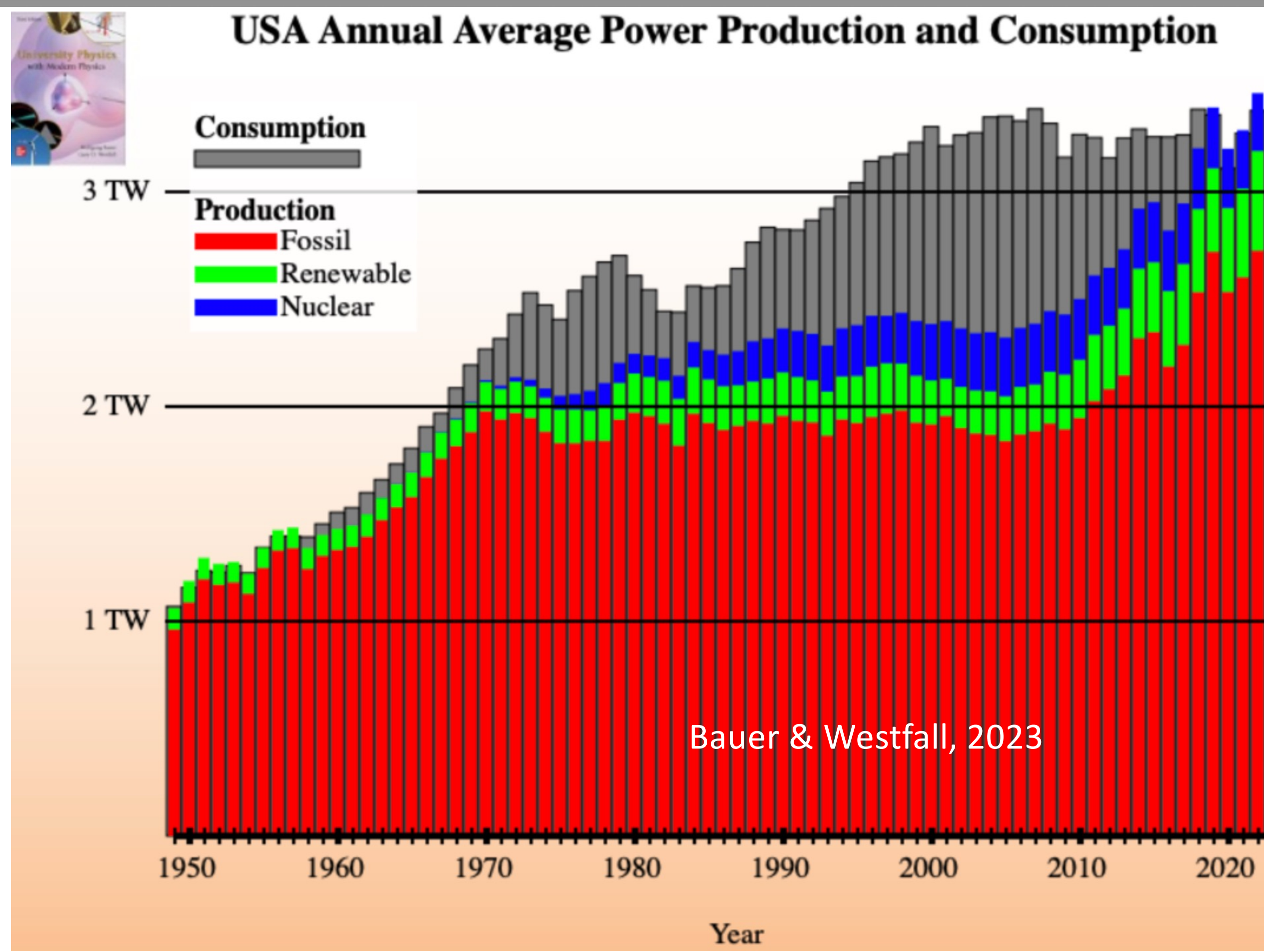
# World Electricity Production

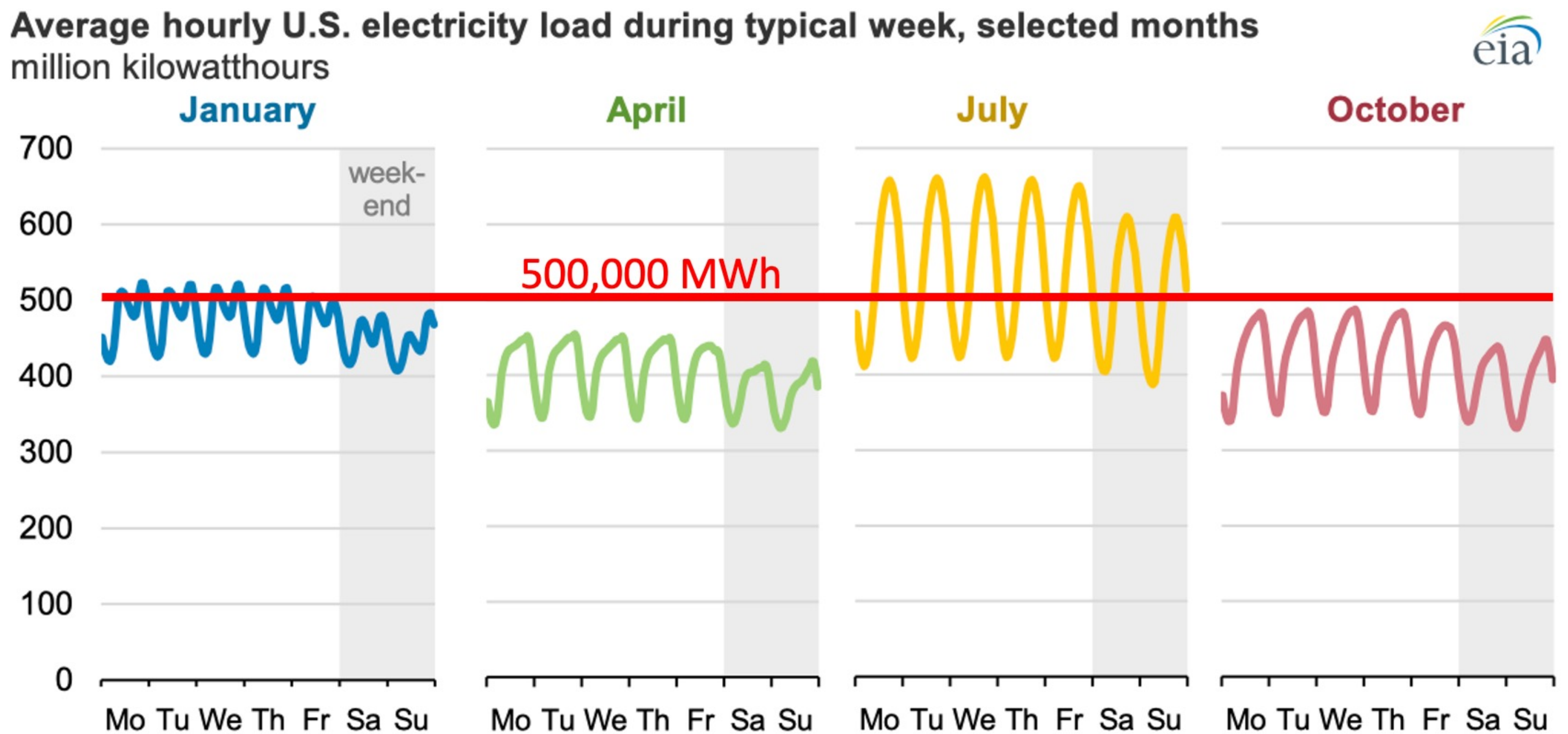


# USA

All sources:

- Electricity
- Heating
- Industrial production
- Transportation






**Source:** U.S. Energy Information Administration, *U.S. Hourly Electric Grid Monitor*
**Note:** Data shown represent the average aggregate U.S. hourly load (Eastern Standard Time) by day of the week for the months indicated between 2015 and 2019.

# EV charging: commercial vehicles

Creator: Ava_Marie | Credit: Getty Images/iStockphoto

**4 million** heavy duty (class 8) trucks in the USA (3.4 M truck drivers)

**Numerical example:**
**Assume only 20% electrification**

- 500 kWh of batteries on average truck
- ~ 250 miles of range (= ½ of daily driving)
- 800 GWh/day needed to recharge trucks
- Charging overnight at truck stops ✅
- Recharging at lunch time (1 hour)
  - Need 500 kW ultra-fast chargers
  - Additional load of 400 GW on grid during 1 hour ❌

# Implications for Grid

- 400 GW new capacity required
- Peaker plants with rapid ramp rate:
  - Most likely reciprocal internal combustion engines burning natural gas

MSU’s new 30 MW RICE plant: **need 13000 of these**

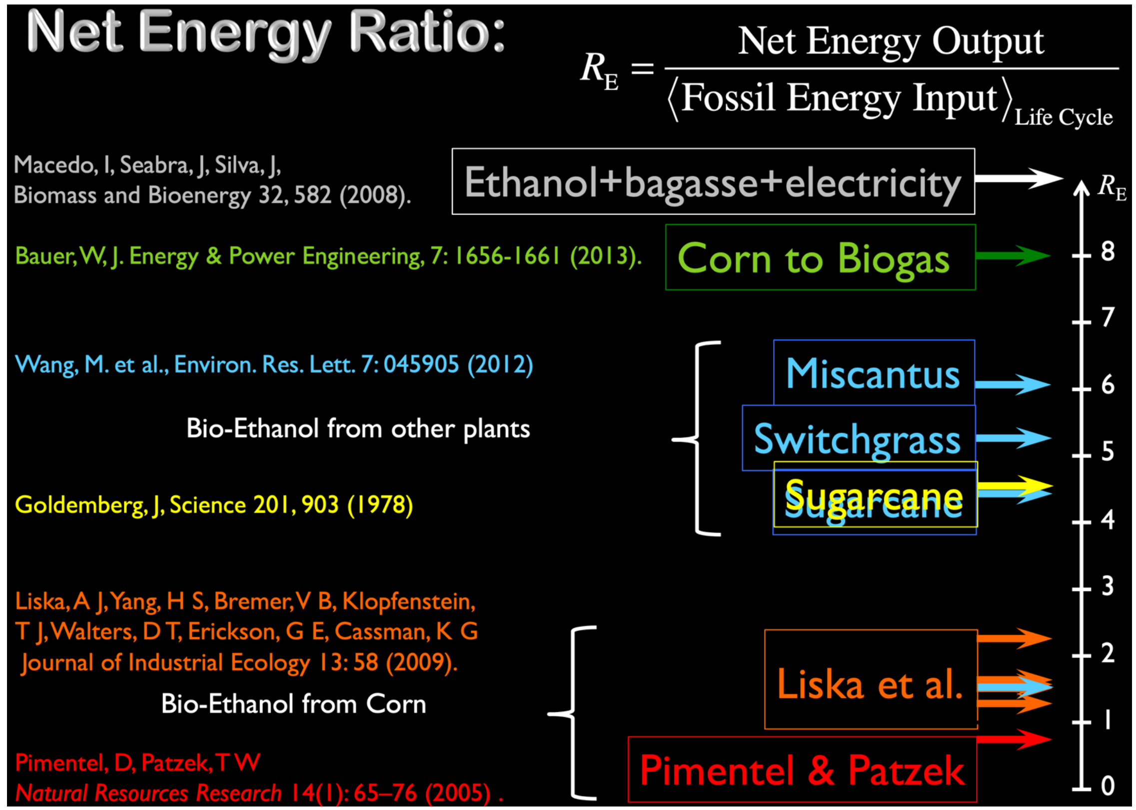
# Implications for Grid

- 400 GW new capacity required
- Peaker plants with rapid ramp rate:
  - Most likely reciprocal internal combustion engines burning natural gas
  - Could be biogas


Our German 1 MW biogas plant: **need 400000 of these**

# Implications for Grid

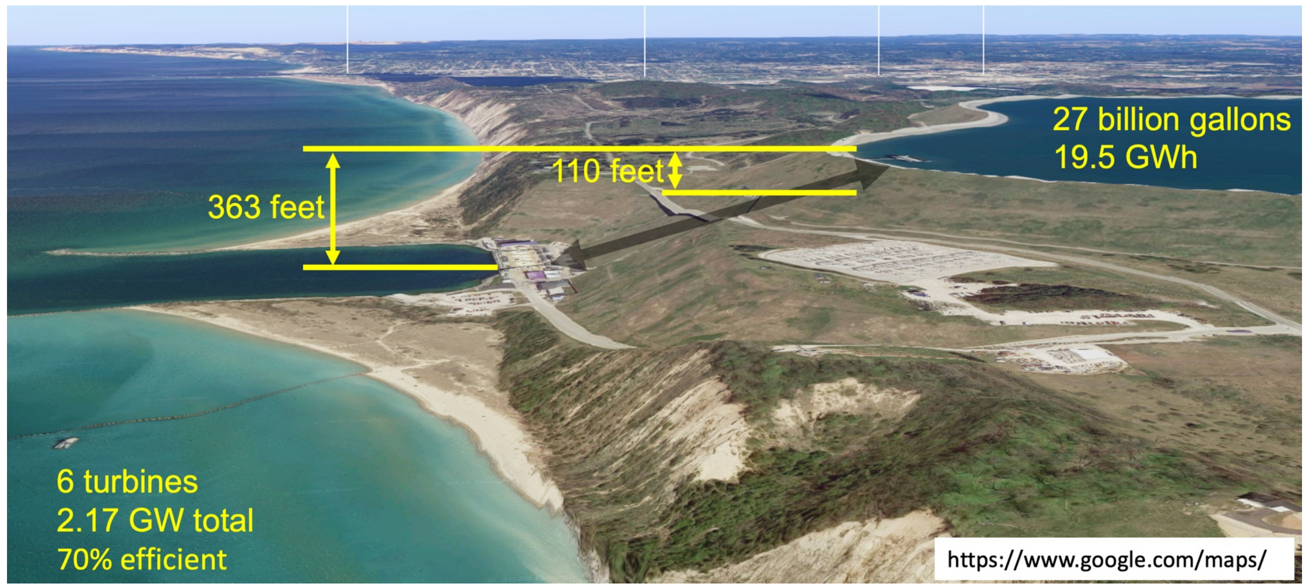
- 400 GW new capacity required
- Peaker plants with rapid ramp rate:
  - Most likely reciprocal internal combustion engines burning natural gas
  - Could be biogas




Warning: even biofuels are not free of fossil fuels!!!

# Implications for Grid

- 400 GW new capacity required
- Peaker plants with rapid ramp rate:
  - Most likely reciprocal internal combustion engines burning natural gas
  - Could be biogas
- Alternatively: storage




Ludington pump storage plant: **Need 200 of these**

# Implications for Grid

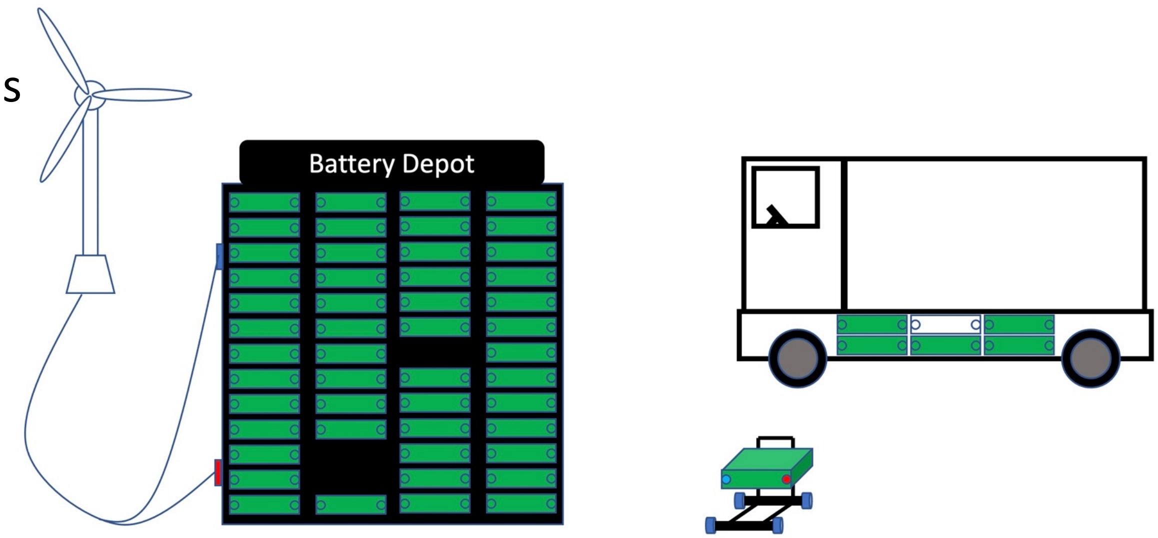
- 400 GW new capacity required
- Peaker plants with rapid ramp rate:
  - Most likely reciprocal internal combustion engines burning natural gas
  - Could be biogas
- Alternatively: storage

https://www.energyvault.com/project-cn-rudong

25 MW Energy Vault in Rudong, China: **Need 16000 of these**

# Better approach: charge batteries outside of EVs

**Advantages**:
- Extremely rapid recharge of vehicles
  - A few minutes
  - Comparable to filling tank with gas
- Easy replacement of degrading batteries over time
- Perfect utilization of renewable power sources
  - Batteries can be recharged when the wind blows or sun shines
  - Mitigates intermittency in renewable power production




Swappable individual battery modules
Similar to power tool recharging

# GM Ultium Platform

https://www.chevrolet.com/new-roads/electric/next-gen-ultium-platform

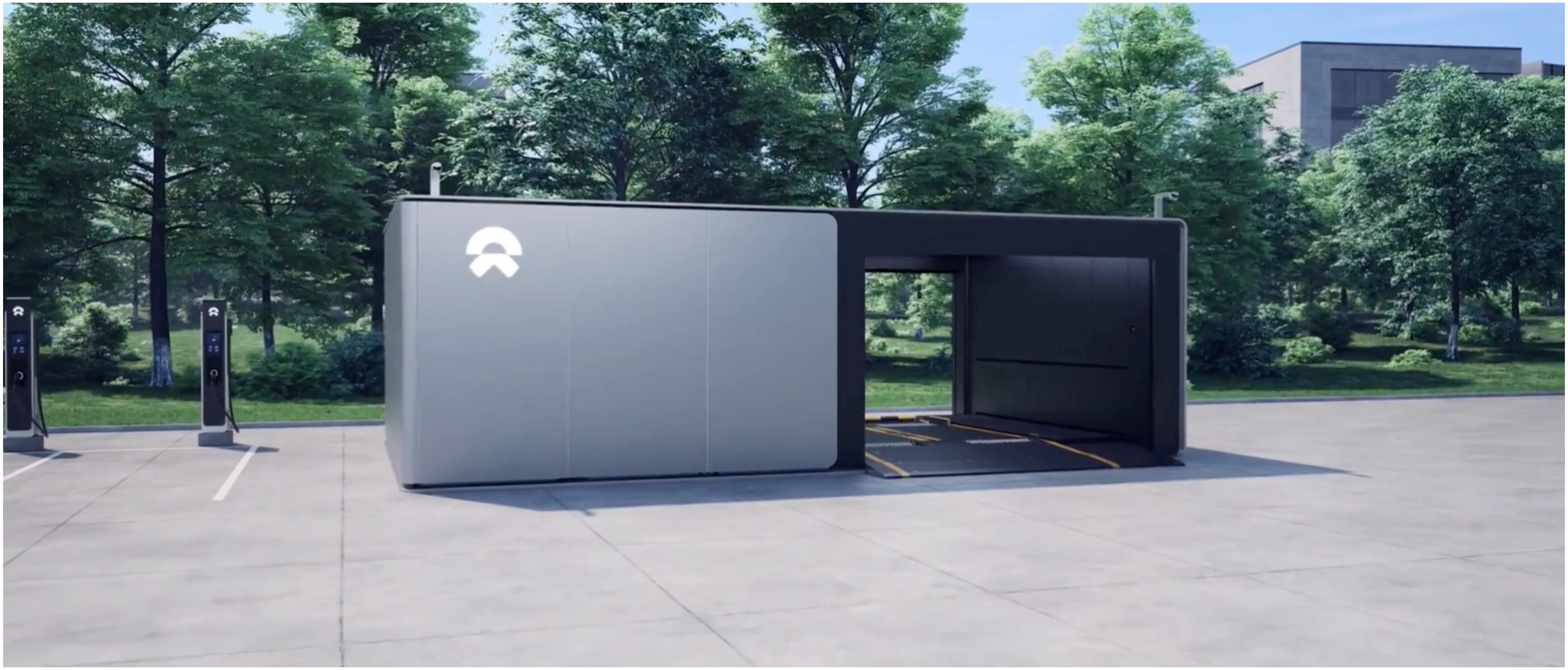
**Ultium Module:**
8.88 kWh
32.7 kg
14.5 L
270 Wh/kg
610 Wh/L

**Challenge:**
Make individual battery pouches swappable

# Nio: Swap out entire battery pack

- Nio offers > 1300 swapping stations
    - Now has 16 battery swap stations in Europe
- Also offer conventional battery chargers
- 60% of users opt for swapping


https://electrek.co/2023/05/16/nio-and-shell-open-first-ev-battery-swap-station-in-europe



https://www.nio.com/nio-power

# Current project at MSU

- Design new electric vehicle with swappable batteries
- 30 kg modules, which can be swapped rapidly by a single person
- First prototype ready by end of 2023

# Conclusions: Battery Swapping

- Eliminates range anxiety
- Minimizes recharging time
- Gradually modernizes all batteries
  - New battery performance increases 5%-10% per year
  - Year 20 EV range > than initial advertised range
- Battery depots provide giant energy storage reservoir for grid
  - 1 TWh to 10 TWh
  - Avoids losses from intermediate energy storage in other forms (pumped hydro, gravity, fixed battery)
  - Avoids the need for peaker plants
- Eliminates the need for intermittency mitigation of renewables

# Thank you

Contact: bauerw@msu.edu