# ECE 398GG – ELECTRIC VEHICLES

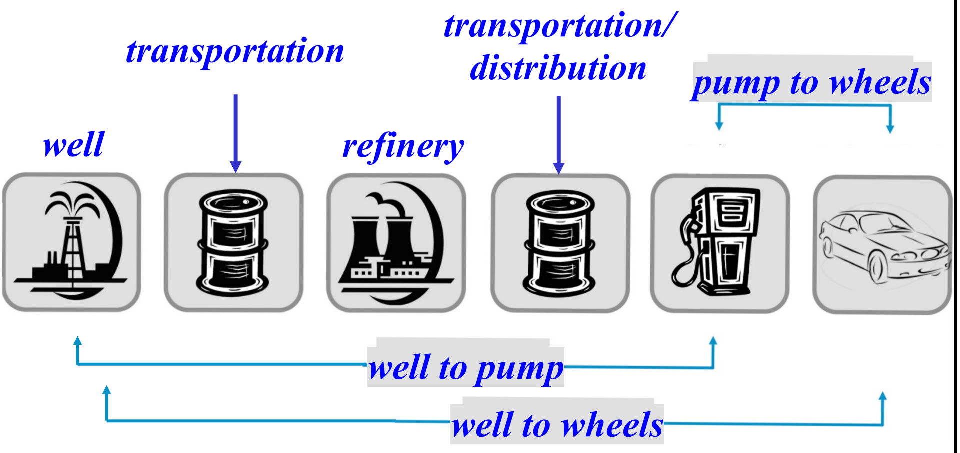
# 7. *EV* Efficiency and Emission Analysis

**George Gross**
**Department of Electrical and Computer Engineering**
**University of Illinois at Urbana–Champaign**

## TOPICAL OUTLINE

- ❑ The *well-to-wheel* process
- ❑ *EV* efficiency analysis
- ❑ Information and data sources
- ❑ *GHG* emission assessment
- ❑ Significance of *EV* efficiency & emission metrics
- ❑ The role of *EVs* in decarbonization

# THE *WELL–TO–WHEELS* PROCESS



*transportation*

*transportation/ distribution*

*pump to wheels*

*well*

*refinery*

*well to pump*

*well to wheels*

*Source: https://ars.els-cdn.com/content/image/1-s2.0-S0360544214008573-gr1_lrg.jpg*

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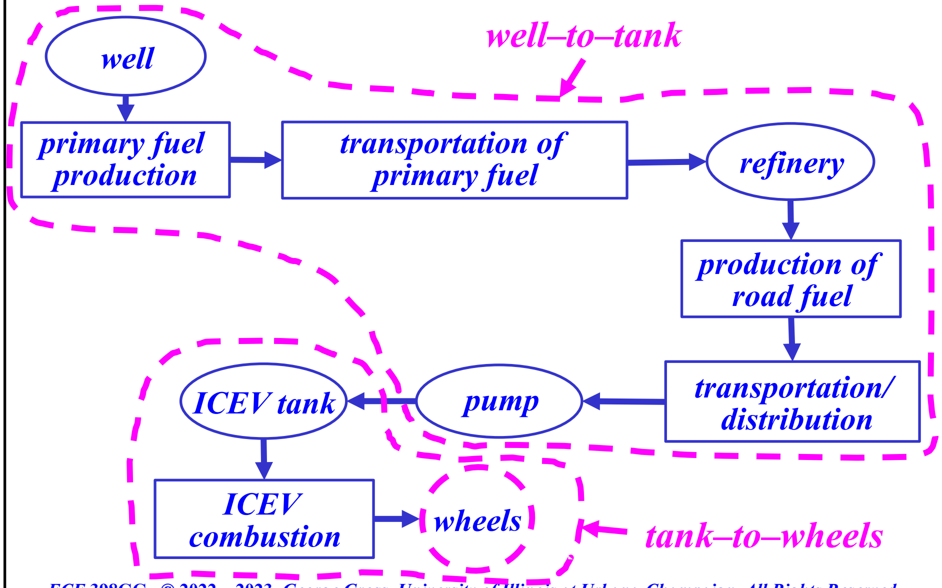
# THE *ICEV WELL–TO–WHEELS* PROCESS



*well–to–tank*

*well*

*primary fuel production*

*transportation of primary fuel*

*refinery*

*production of road fuel*

*transportation/ distribution*

*pump*

*ICEV tank*

*ICEV combustion*

*wheels*

*tank–to–wheels*

# THE *EV* EFFICIENCY ANALYSIS

- ❑ The *well-to-wheels* or *w-t-w* process comprises a sequence of subprocesses, each of which incurs a loss of energy and consequently impacts the overall efficiency of the process
- ❑ The *w-t-w* structure is typically decomposed into the two components
  - ❍ *well-to-tank* subsystem
  - ❍ *tank-to-wheels* subsystem

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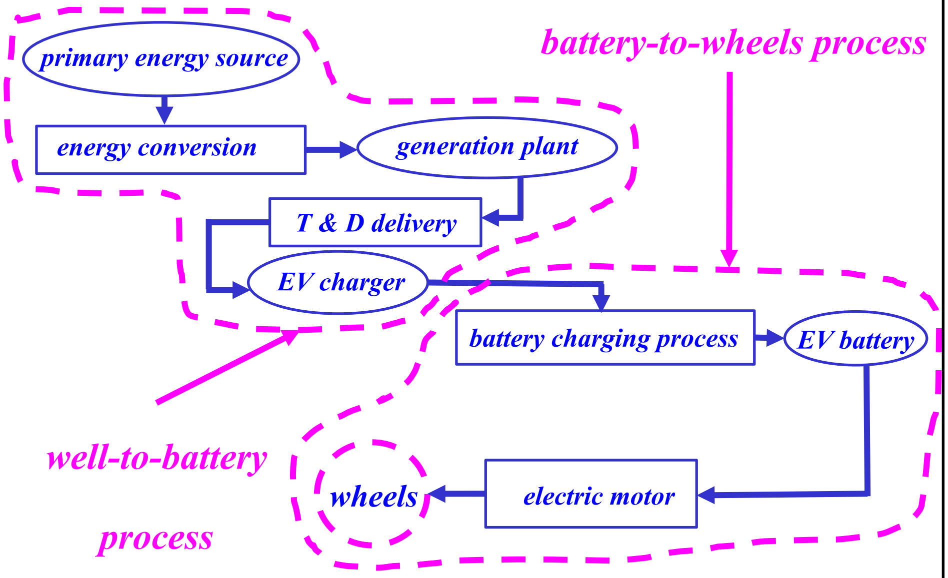
# THE *EV WELL–TO–WHEELS* PROCESS



*primary energy source*

*energy conversion*

*generation plant*

*T & D delivery*

*EV charger*

*battery charging process*

*EV battery*

*electric motor*

*wheels*

*battery-to-wheels process*

*well-to-battery process*

# THE *EV* EFFICIENCY ANALYSIS

- ❑ The *w-t-w* structure was originally introduced to assess *ICEV* efficiency; the process is applied, with small modifications, to study *EV* efficiency
- ❑ For the *EV* evaluation, the *w-t-w* decomposition results in the 2 components
  - ❍ *well-to-charger* subsystem
  - ❍ *charger-to-wheels* subsystem

# INFORMATION SOURCES AND ASSUMPTIONS

- ❑ We make detailed use of data on the energy and transportation sectors of two *US* agencies – *EPA*, the *Environmental Protection Agency* and *EIA*, the *Energy Information Administration*
- ❑ Specifically, we make use of the *EPA fuel economy* ratings of vehicles and their emissions and use the *EIA* data for the *US* generation resource mix

## INFORMATION SOURCES AND ASSUMPTIONS

for electricity production and their associated *GHG* emissions

- ☐ We use *EPA fuel efficiency* or *FE* ratings for *US*–sold *EV*s in "*The* 2022 *EPA Automotive Trends Report*"
- ☐ Our assumptions for efficiency analysis are:
  - ❍ the losses in the battery *charging – discharging cycle* due to process inefficiencies are 15 %, *i.e.*, the efficiency is 85 %

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## INFORMATION SOURCES AND ASSUMPTIONS

- ❍ losses in grids are, typically, under 8 % and we use 5 % for the combined transmission/ distribution grid losses incurred to deliver the electricity from a power plant to a charger
- ❍ the conversion of the primary energy source to electricity varies widely – depends both on the primary energy source and the specific generation technology

# MANUFACTURERS AND VEHICLES WITH THE HIGHEST / LOWEST *FE*: 2015 – 2022

| *model year* | *highest FE (mpg) manufactural model* | *lowest FE (mpg) manufacture* | *highest FE* | | *highest FE gasoline* | |
|---|---|---|---|---|---|---|
| | | | *vehicle* | *real- world FE in mpge* | *vehicle* | *real- world FE in mpg* |
| **2016** | ***Mazda*** | ***Stellantis*** | ***BMW i3*** | **121.3** | ***Mazda 2*** | **37** |
| **2017** | ***Honda*** | ***Stellantis*** | ***Hyundai Ioniq*** | **132.6** | ***Mitsubishi Mirage*** | **41** |
| **2018** | ***Tesla*** | ***Stellantis*** | ***Hyundai Ioniq*** | **132.6** | ***Mitsubishi Mirage*** | **41** |
| **2019** | ***Tesla*** | ***Stellantis*** | ***Hyundai Ioniq*** | **132.6** | ***Mitsubishi Mirage*** | **41** |
| **2020** | ***Tesla*** | ***Stellantis*** | ***Tesla 3 SR+*** | **138.6** | ***Mitsubishi Mirage*** | **41** |
| **2021** | ***Tesla*** | ***Stellantis*** | ***Tesla 3 SR+*** | **139.1** | ***Mitsubishi Mirage*** | **40** |
| **2022*** | ***Tesla*** | ***Stellantis*** | ***Lucid Air*** | **131.4** | ***Mitsubishi Mirage*** | **40** |

** preliminary data subject to change*

*Source: EPA, "The 2022 EPA Automotive Trends Report," EPA-420-S-2s-001, p. 12, issued December 2022; available online at https://www.epa.gov/system/files/documents/2022-12/420r22029.pdf*

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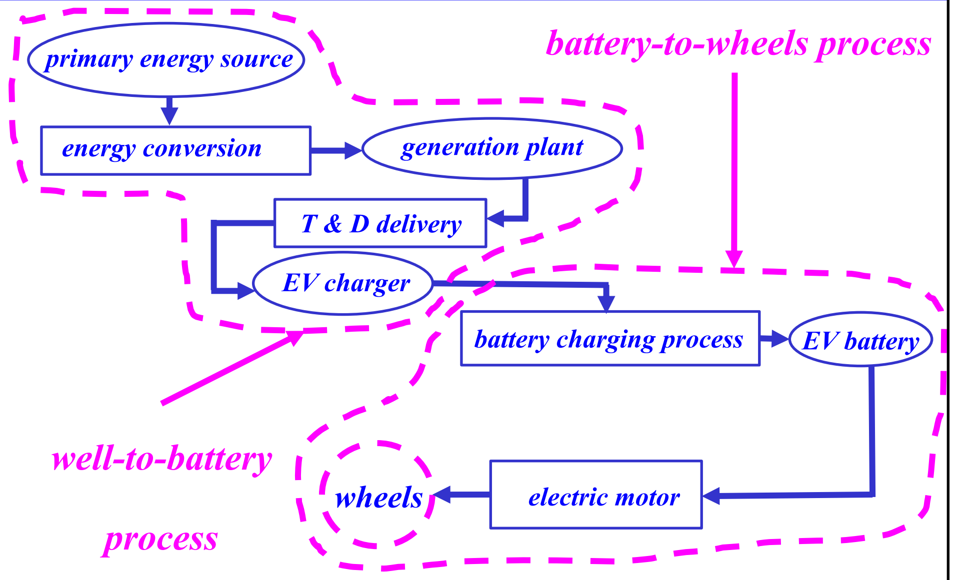
# *EPA* MODEL YEAR 2022 *EV* FUEL ECONOMY METRICS

| *manufacturer* | *model* | *electricity consumption in kWh/100mi* | *FE in mpge* |
|---|---|---|---|
| *GM* | *Bolt* | 28 | 120 |
| *Nissan* | *Leaf 62 kWh* | 31 | 108 |
| *Tesla* | *Model 3 LR* | 26 | 131 |

*Source: EPA, "The 2022 EPA Automotive Trends Report," EPA-420-S-2s-001, p. E-3, issued December 2022; available online at https://www.epa.gov/system/files/documents/2022-12/420r22029.pdf*

# THE *EV WELL–TO–WHEELS* PROCESS



*battery-to-wheels process*

*primary energy source*

*energy conversion*

*generation plant*

*T & D delivery*

*EV charger*

*battery charging process*

*EV battery*

*electric motor*

*wheels*

*well-to-battery process*

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# EFFICIENCY NOTIONS

- The engineering notion of efficiency is focused on the measure of two quantities
  - input
  - output
- For a given system with an input and an output

*input* → *system* → *output*

# EFFICIENCY NOTIONS

we define efficiency, denoted by $\eta$, as

$$\eta \triangleq \frac{output}{input}$$

where both input and output are measured in the same units and so $\eta$ is *unitless*

- Many engineers prefer to express efficiency in *%* and so

$$\eta_{\%} = \eta \times 100 \ \%$$

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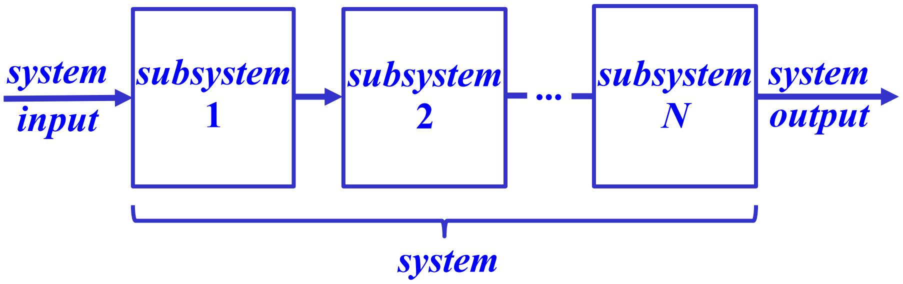
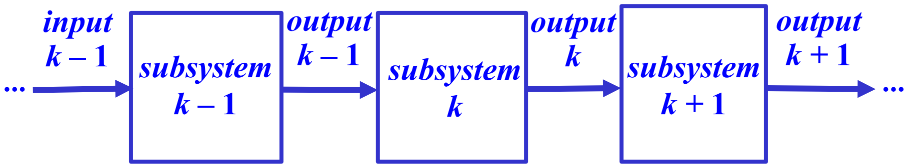
# EFFICIENCY NOTIONS

- Systems may be complex and comprise of multiple subsystems: for example, consider a string of $N$ subsystems connected in series



# EFFICIENCY NOTIONS

- ☐ The relationships between two sequential subsystems $k-1$ and $k$ in this system we are



readily apparent; in particular,

$$output\ k = input\ k+1 \qquad k = 0, 1, \ldots, N-1$$

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# EFFICIENCY NOTIONS

or, equivalently

$$input\ k = output\ k-1 \qquad k = 1, 2, \ldots, N$$

with

$$input\ 1 = system\ input$$

$$output\ N = system\ output$$

- ☐ The efficiency $\eta_k$ of each subsystem $k$ is given by

$$\eta_k = \frac{output\ k}{input\ k} \qquad k = 1, 2, \cdots, N$$

# EFFICIENCY NOTIONS

- The overall system efficiency is obtained by the application of the relations above

$$
\begin{aligned}
\eta_{system} &= \frac{system\ output}{system\ input} \\
&= \frac{output\ N}{input\ 1} \\
&= \frac{output\ N}{input\ N} \times \frac{output\ N-1}{input\ N-1} \times \cdots \times \frac{output\ 1}{input\ 1} \\
&= \eta_1 \times \eta_2 \times \cdots \times \eta_N
\end{aligned}
$$

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# *WELL – TO – WHEELS* *EV* EFFICIENCY ANALYSIS

- Let us consider the case of electricity supply generation by a *combined cycle natural gas* (*CCNG*) plant – a widely-used plant technology in the *US*
- At the well, the energy for drilling and extraction incurs losses, of say, 8.5 % of its energy content; the highly-efficient gas transport via pipelines incurs about 1.5 % loss of gas
- Therefore, the efficiency from the well to the

## *WELL – TO – WHEELS*
## *EV* EFFICIENCY ANALYSIS

*CCNG* generation plant is

$$91.5\,\% \times 98.5\,\% = 0.90$$

- ❑ A typical efficiency of a *CCNG* plant is 60 % – *i.e.,* the conversion of the caloric contents of *NG* into electricity incurs a loss of 40 %
- ❑ The electricity output by the *CCNG* is injected into the transmission grid and, subsequently, the

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## *WELL – TO – WHEELS*
## *EV* EFFICIENCY ANALYSIS

distribution grid to supply the electricity to the charger

- ❑ The overall efficiency of the *CCNG* plant and the electricity delivery to the charger is

$$\underbrace{60\,\%}_{\text{CCNG plant}} \times \underbrace{95\,\%}_{T\,\&\,D} = 0.57$$

# *WELL – TO – WHEELS*
# *EV* EFFICIENCY ANALYSIS

- ❑ **Thus, a unit of energy extracted from the well is reduced upon arrival at the charger to**

$$\underset{\textit{conversion \& delivery}}{57\,\%} \times \underset{\textit{well-to-CCNG}}{90\,\%} = 0.513,$$

**i.e., the *well-to-pump* process efficiency is 51.3 %**

- ❑ **Next, we examine the analogue of the *tank-to-wheels* process in the consumption of electricity**

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# *WELL – TO – WHEELS*
# *EV* EFFICIENCY ANALYSIS

**to charge the *EV* batteries for its use to move the wheels of the *EV* through the deployment of the electric motors & drives without a transmission system or any moving parts – a far-more simple mechanism than the engine of an *ICEV***

- ❑ **The highly-efficient electric motor uses the *DC* electricity from the battery, which an inverter**

# *WELL – TO – WHEELS*
# *EV* EFFICIENCY ANALYSIS

**transforms into *AC* to convert it into kinetic energy to result in the motion of the *EV*: we assume that the *AC–DC* and the *DC–AC* transformations are done by 95–% efficient inverters; we further assume that the motor and drivetrain efficiency is 95 %**

- ❑ **Therefore, the overall efficiency of the *charger-to-wheels* process is**

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# *WELL – TO – WHEELS*
# *EV* EFFICIENCY ANALYSIS

$$\underset{\textit{AC–DC conversion}}{95\,\%} \times \underset{\substack{\uparrow \\ \textit{DC–AC conversion}}}{95\,\%} \times \underset{\textit{charging}}{85\,\%} \times \underset{\substack{\uparrow \\ \textit{drivetrain-motor}}}{95\,\%} = 0.729$$

- ❑ **The 72.9 % efficiency is consistent with *Tesla*'s estimate of 75–% efficiency for the *charger-to-wheels* process and is far higher than the average**

# *WELL – TO – WHEELS*
# *EV* EFFICIENCY ANALYSIS

*tank-to-wheel ICEV* **efficiency of about** 16 %

- **We conclude that the overall** *EV well-to-wheels* **efficiency is**

$$51.3\ \% \quad \times \quad 72.9\ \% \quad = \quad 0.374$$

*well-to-charger*

*well-to-wheels*

*charger-to-wheels*

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# *EV* EFFICIENCY METRICS

- **The widely–used metric** *mpge* **–** *miles per gallon equivalent* **– measures the distance in** *mi* **an** *EV* **can travel on the energy stored in a** *gallon* **of gasoline**
- **We use** *EPA*’**s** 33.705 *kWh/gal of gasoline* **for the equivalence value and determine the** *EV* **energy consumption to obtain the** *FE* **metric expressed in** *kWh*/100 *mi* **and then compute the** *mpge* **metric**

## *EV* EFFICIENCY METRICS

- ❑ For example, for the *Nissan Leaf* 62 *kWh* model, the *mpge* metric value is

$$\frac{33.705\ kWh\,/\,gal}{31\ kWh\,/\,100\ mi} \quad = \quad 108.7\ mpge\,,$$

and we can compare that to the most efficient gasoline vehicle in 2021 – *Mitsubishi Mirage* at 40.1 *mpg* – to conclude that the *Nissan Leaf* is over 2.5 times more efficient!

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## *EV* EFFICIENCY METRICS

- ❑ The *Tesla* 3 *LR* electricity consumption metric of 26 *kWh*/100 *mi* may be restated as 3.85 *mi*/*kWh*, *i.e.*, each *kWh* withdrawn from the battery results in the displacement of the *EV* a distance of 3.85 *mi*
- ❑ While many engineers are less than enthusiastic about the *FE* metric in *kWh*/100 *mi* units, the *EPA* is not ready to relinquish that metric

# *OEM* REAL–WORLD FUEL ECONOMY AND $CO_2$ EMISSION ESTIMATES: *my* 2020 – 2022

| *manufacturer* | *my* 2020 *final* | | *my* 2021 *final* | | *my* 2022 *preliminary* | |
|---|---|---|---|---|---|---|
| | *real-world FE (mpg)* | *real-world $CO_2$ (g/mi)* | *real-world FE (mpg)* | *real-world $CO_2$ (g/mi)* | *real-world FE (mpg)* | *real-world $CO_2$ (g/mi)* |
| *BMW* | 25.5 | 347 | 25.8 | 339 | 25.7 | 341 |
| *Ford* | 23.0 | 386 | 22.9 | 385 | 23.0 | 382 |
| *GM* | 23.0 | 386 | 21.6 | 414 | 22.2 | 400 |
| *Honda* | 29.1 | 305 | 28.5 | 312 | 28.3 | 315 |
| *Hyundai* | 28.4 | 312 | 28.5 | 310 | 29.1 | 302 |
| *Kia* | 27.7 | 320 | 28.7 | 310 | 28.7 | 305 |
| *Mazda* | 27.9 | 319 | 27.4 | 324 | 26.5 | 335 |
| *Mercedes* | 23.4 | 379 | 23.6 | 376 | 24.6 | 359 |
| *Nissan* | 27.9 | 317 | 28.6 | 311 | 28.0 | 316 |
| *Stellantis* | 21.3 | 418 | 21.3 | 417 | 21.6 | 410 |
| *Subaru* | 28.5 | 312 | 28.8 | 309 | 28.0 | 317 |
| *Tesla* | 119.1 | 0 | 123.9 | 0 | 121.5 | 0 |
| *Toyota* | 27.0 | 329 | 27.1 | 327 | 28.0 | 316 |
| *VW* | 24.9 | 354 | 24.7 | 352 | 27.7 | 306 |
| *all OEMs* | 25.4 | 349 | 25.4 | 347 | 26.4 | 331 |

*Source: The 2022 EPA Automotive Trends Report; available on-line at https://www.epa.gov/system/files/documents/2022-12/420r22029.pdf*

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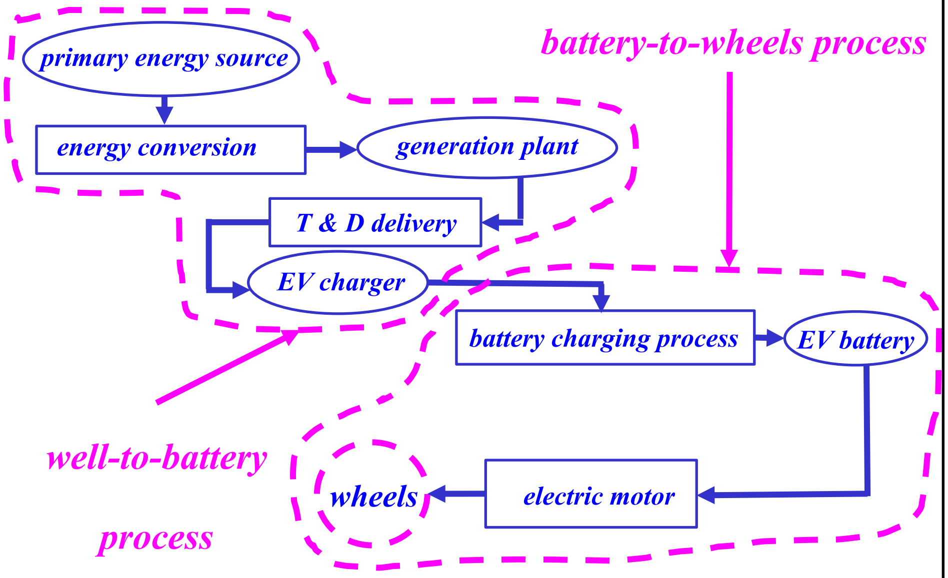
# THE *EV WELL–TO–WHEELS* PROCESS



*battery-to-wheels process*

*primary energy source*

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*T & D delivery*

*EV charger*

*battery charging process*

*EV battery*

*well-to-battery process*

*wheels*

*electric motor*

## *EV GHG* EMISSION ANALYSIS

- ❑ We have established the fact that *EV*s are very efficient means to use primary energy resources to convert them into transportation miles; next, we focus on the *EV* environmental impacts
- ❑ Unlike *ICEV*s that run on gasoline and diesel fuels and release tailpipe emissions that include $CO_2$ produced by fuel combustion, *EV*s do not produce such emissions; but, the electricity generation required for *EV* operations is accompanied

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## *EV GHG* EMISSION ANALYSIS

by smokestack emissions at the polluting generation plants

- ❑ We refer to the emissions associated with the *EV* electricity consumption as *EV* tailpipe emissions
- ❑ *EPA*'s *eGRID* data indicate that the 2021 *average US* $CO_2$ total output emission rate was 852.30 *lb/MWh*; we restate this value in metric units as 384 *g/kWh*

# *EPA* IS A KEY DATA SOURCE

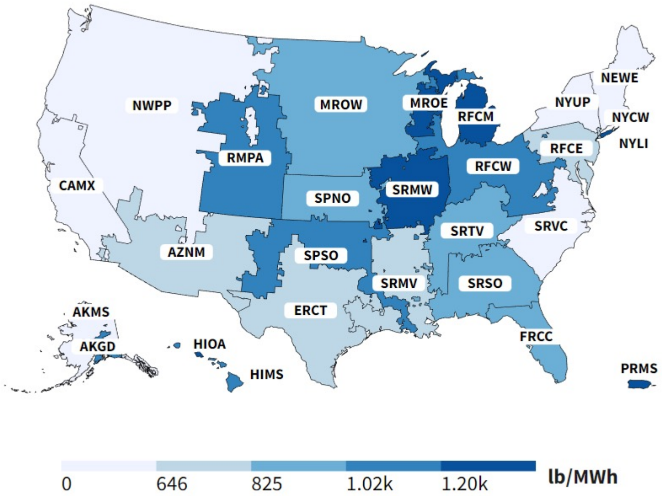
- *EPA* has collected data on every new light-duty vehicle (*LDV*) model sold in the *US* since 1975
- The data are obtained from either the tests performed by *EPA* at its *National Vehicle and Fuel Emissions Laboratory* in *Ann Arbor*, *MI*, or directly from the manufacturers as the results of the deployment of official *EPA* test procedures

# *EPA* IS A KEY DATA SOURCE

- The collected data support several significant national programs: the *EPA* criteria pollutant and *GHG* standards; the *Department of Transportation National Highway Traffic Safety Administration* (*NHTSA*); the *Corporate Average Fuel Economy* (*CAFE*) standards; and vehicle *Fuel Economy & Environment* labels
- These collected annual data sets allow *EPA* to provide a *comprehensive analysis* of the automotive industry since 1975

# 2021 *$CO_2$* TOTAL OUTPUT EMISSION RATE IN *lb/MWh* BY *eGRID* SUBREGIONS

***US average*: 852.30 *lb/MWh***



*Source: EPA Data Explorer; https://www.epa.gov/egrid/data-explorer*

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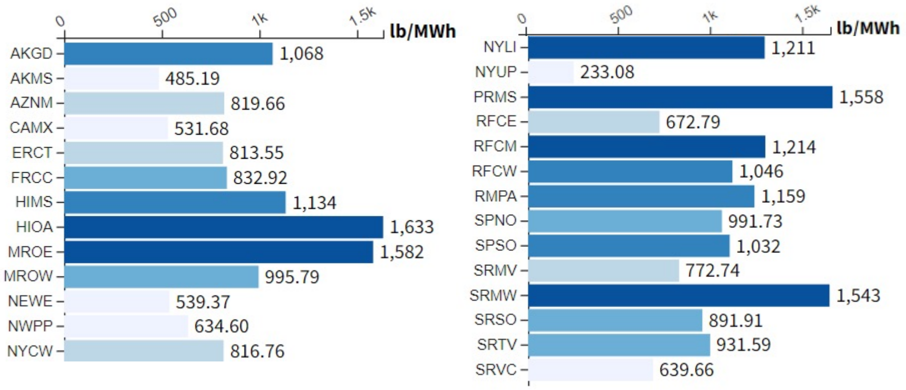
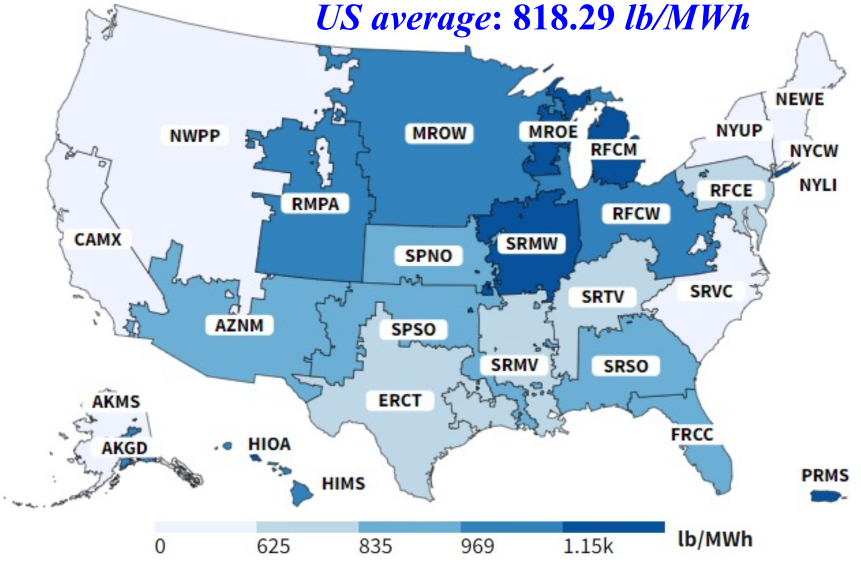
# 2021 *$CO_2$* TOTAL OUTPUT EMISSION RATE IN *lb/MWh* BY *eGRID* SUBREGION



## 2020 $CO_2$ TOTAL OUTPUT EMISSION RATE IN *lb/MWh* BY *eGRID* SUBREGIONS

***US average*: 818.29 *lb/MWh***



*Source: EPA Data Explorer; https://www.epa.gov/egrid/data-explorer*

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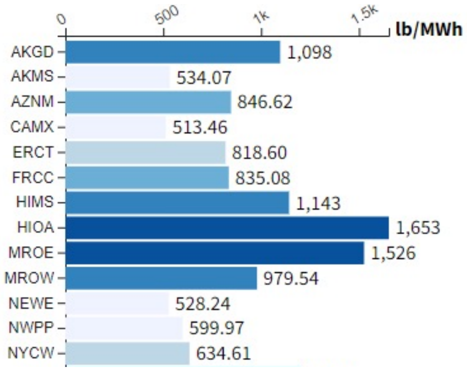
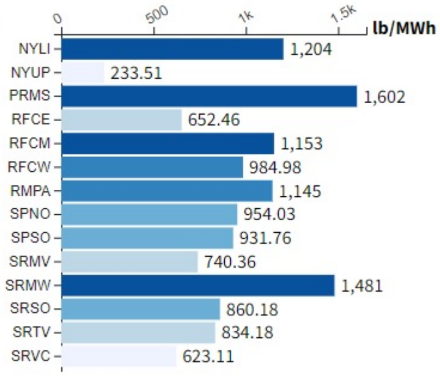
## 2020 $CO_2$ TOTAL OUTPUT EMISSION RATE IN *lb/MWh* BY *eGRID* SUBREGION





## *EV GHG* EMISSION ANALYSIS

- ☐ We carry out the emission evaluation on a few illustrative examples to give the students a better sense of what is involved in the analysis
- ☐ The 2021 *Tesla Model* 3 *LR FE* is 3.85 *mi/kWh*; at the *average US* $CO_2$ electricity emission rate, it emits

$$(384\ g/kWh)\ \ x\ \ [(1\ kWh)/(3.85\ mi)]\ \ =\ \ 99.7\ g/mi$$

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## *EV GHG* EMISSION ANALYSIS

- ☐ The *EPA* website *epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle#burning* states that "every gallon of gasoline creates about 8,887 grams of $CO_2$"
- ☐ We illustrate the impacts of an *ICEV* with a 25 *mpg FE* with emissions given by

$$8{,}887\ g/gal\ \ x\ \ 1\ gal/25\ mi\ \ =\ \ 355\ g/mi$$

## *EV GHG* EMISSION ANALYSIS

and it is evident that the *Tesla* emissions are considerably lower for the same distance

- ☐ The highest *FE* for gasoline vehicles in 2021 was the *Mitsubishi Mirage* at 40 *mpg* with the emissions given by

$$8{,}887 \ g/gal \ \times \ 1 \ gal/40 \ mi \ = \ 222 \ g/mi,$$

which are still above twice the *Tesla* emissions

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## *EV GHG* EMISSION ANALYSIS

- ☐ We can determine the *FE* of an *ICEV* that equals *Tesla* 3 *LR*'s 99.7 *g/mi* emissions using the equation

$$8{,}887 \ g/gal \ \times \ 1 \ gal/x \ mi \ = \ 99.7 \ g/mi$$

so that

$$x \ = \ 89 \ mpg,$$

a value above the efficiency of any gasoline *ICEV* that ever existed

# *EV GHG* EMISSION ANALYSIS

- ❑ We note that the *Tesla* “pipeline emissions” value is for the average *US* – which, in fact, need not correspond to any actual *US* location
- ❑ The *eGRID* data also provide more “local” or regional values, as do the *EIA* state profiles for each *US* state; moreover, each utility publishes the $CO_2$ data for its service territory

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# *EV* LIFECYCLE EMISSIONS

- ❑ In addition to the *EV* “tailpipe” emissions, there are the emissions incurred in the manufacture of both the *EV* and of the *EV* battery pack
- ❑ We may reasonably assume that the energy requirements to manufacture an *EV* and those for an *ICEV* are rather comparable
- ❑ However, the manufacture of the *EV* battery pack requires sizeable amount of energy and entails

# *EV* LIFECYCLE EMISSIONS

the associated emissions to supply this energy

- ☐ A reasonable estimate of the $CO_2$ emissions in the manufacture *per kWh* of an *EV* battery pack is 150 *kg* of $CO_2$; such emissions are non-recurring since the battery lasts over the *EV* lifecycle
- ☐ Consider the *Tesla Model* 3 *SR* battery pack with a storage capability of 54 *kWh*; the manufacture of

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# *EV* LIFECYCLE EMISSIONS

this battery pack entails $CO_2$ emissions may be estimated to amount to

$$54\ kWh \times 150\ kg\ CO_2 / kWh = 8{,}100\ kg\ CO_2$$

- ☐ The advertised battery life of *Tesla EV*s is 300,000 *mi*; the implication is that the $CO_2$ emissions *per mi* are

$$8{,}100\ kg\ CO_2 \div 300{,}000\ mi = 27\ g\ CO_2 / mi$$

# *EV* LIFECYCLE EMISSIONS

- The incorporation of the battery manufacture emissions results in the total $CO_2$ emissions of

$$99.7\ g\ CO_2\ /\ mi\ +\ 27\ g\ CO_2\ /\ mi\ =\ 126.7\ g\ CO_2\ /\ mi$$

- We conclude that even with the lifecycle emissions explicitly considered, there exists no gasoline fueled *ICEV* with $CO_2$ emissions as low as those of the *Tesla Model* 3 *SR*

# THE SIGNIFICANCE OF *EV* $CO_2$ EMISSIONS

- The *EV* $CO_2$ emissions including those in the battery pack manufacture are considerably below those of any *ICEV* that is manufactured today
- An *ICEV* 's fuel efficiency is set in stone once the car is manufactured and therefore, so are its $CO_2$ emissions; an *EV* may take advantage of renewable resources to lower its $CO_2$ emissions

# THE SIGNIFICANCE OF *EV* *CO2* EMISSIONS

- ☐ As the integration of *renewable energy resources* into today's grids continues with the objective to attain deeper penetrations of those resources, the decarbonization of the electricity sector progresses in the desired direction; moreover, the incentives for solar installations are enticing more consumers to become *prosumers*

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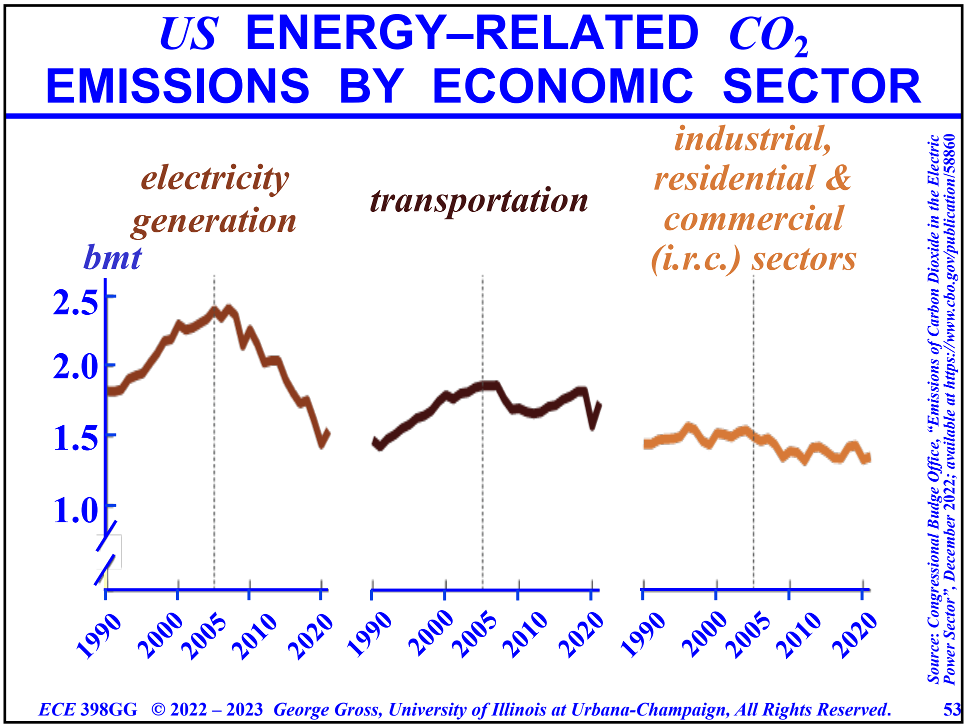
# THE SIGNIFICANCE OF *EV* $CO_2$ EMISSIONS

- ☐ *EV* charging with 100 % *renewable electricity* implies $0\ g\ CO_2/mi$ emissions by such *EV*s; moreover, the use of 100 % renewable electricity to produce the battery packs also results in 0 $CO_2$ emissions
- ☐ The broader deployment of renewable resources can therefore further reduce the *EV* $CO_2$ footprint; the *ICEV*s' inherent reliance on fossil fuels cannot provide such environmental improvements



# *US* ENERGY–RELATED *$CO_2$* EMISSIONS BY ECONOMIC SECTOR

*Source: Congressional Budge Office, "Emissions of Carbon Dioxide in the Electric Power Sector", December 2022; available at https://www.cbo.gov/publication/58860*

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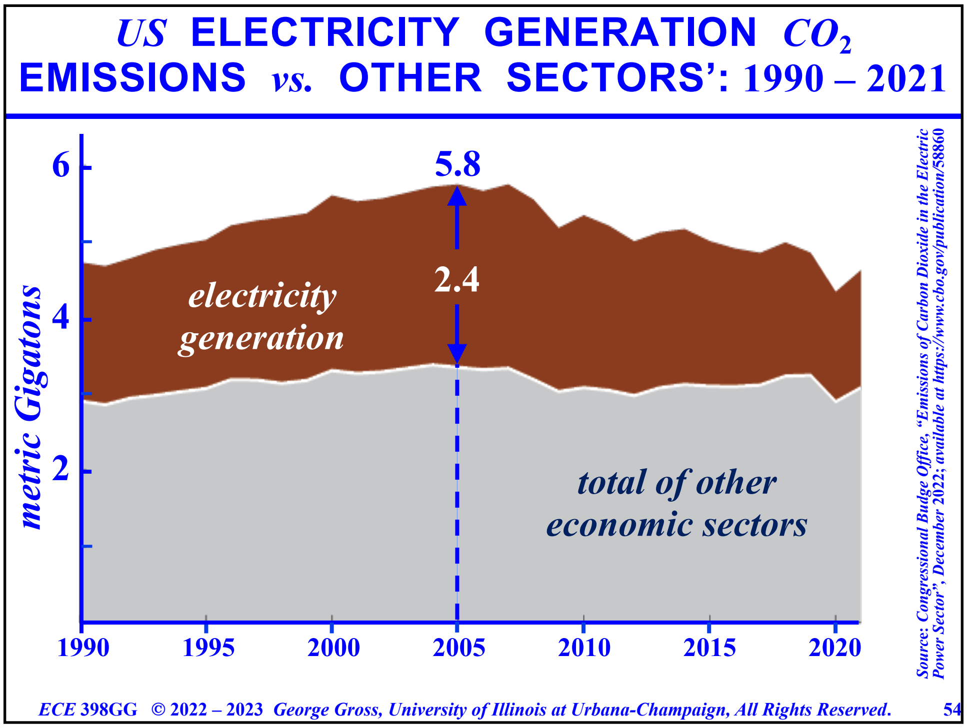

# *US* ELECTRICITY GENERATION *$CO_2$* EMISSIONS *vs.* OTHER SECTORS': 1990 – 2021

*Source: Congressional Budge Office, "Emissions of Carbon Dioxide in the Electric Power Sector", December 2022; available at https://www.cbo.gov/publication/58860*

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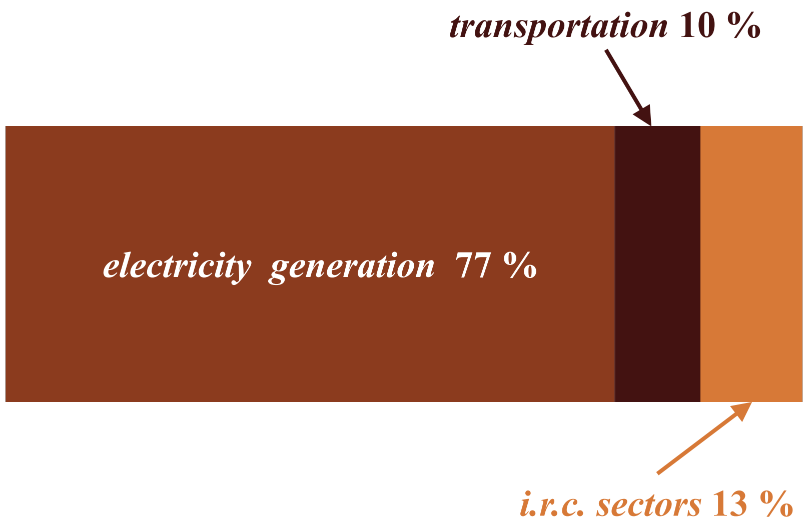
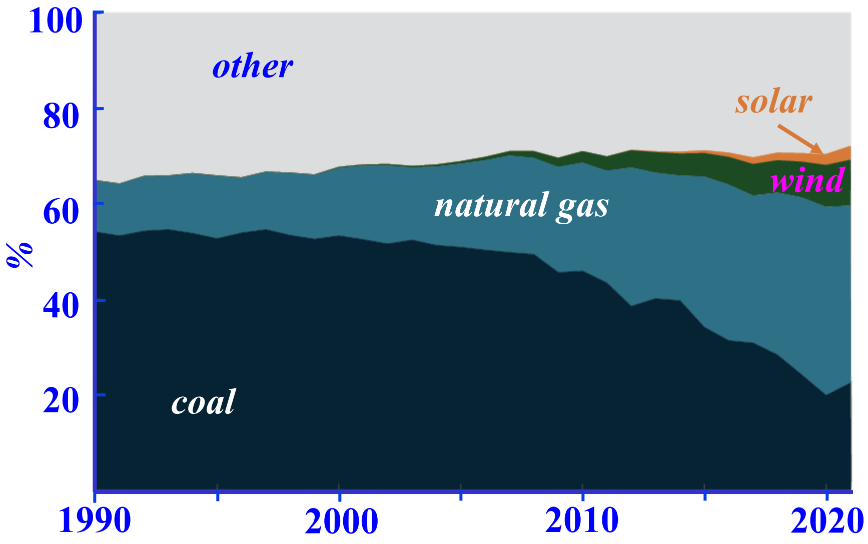
# *US* $CO_2$ EMISSION REDUCTION SINCE 2005 BY SECTOR



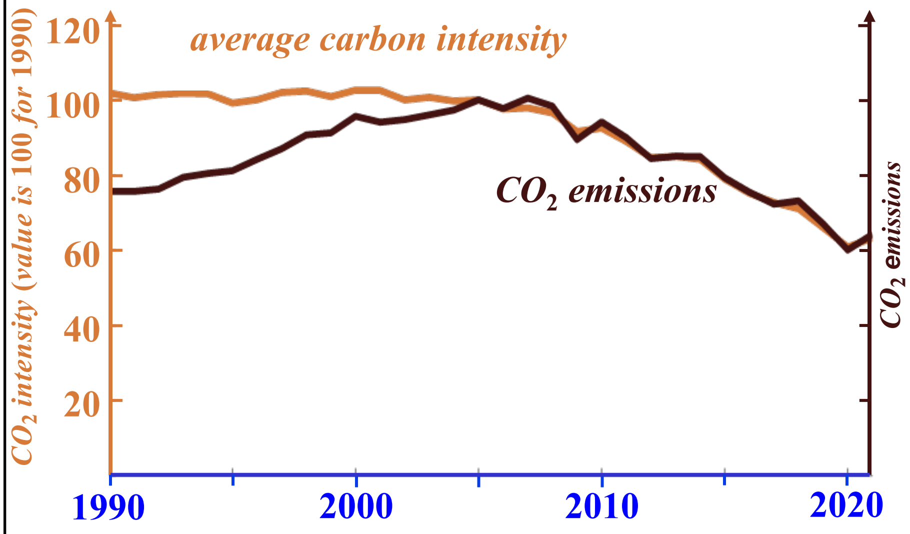
*Source: Congressional Budge Office, "Emissions of Carbon Dioxide in the Electric Power Sector", December 2022; available at https://www.cbo.gov/publication/58860*

# *US* ELECTRICITY GENERATION PRIMARY SOURCES: 1990 – 2021



*Source: Congressional Budge Office, "Emissions of Carbon Dioxide in the Electric Power Sector", December 2022; available at https://www.cbo.gov/publication/58860*

# *US* ELECTRICITY GENERATION *$CO_2$* EMISSIONS AND *CARBON INTENSITY*



*Source: Congressional Budge Office, "Emissions of Carbon Dioxide in the Electric Power Sector", December 2022; available at https://www.cbo.gov/publication/58860*

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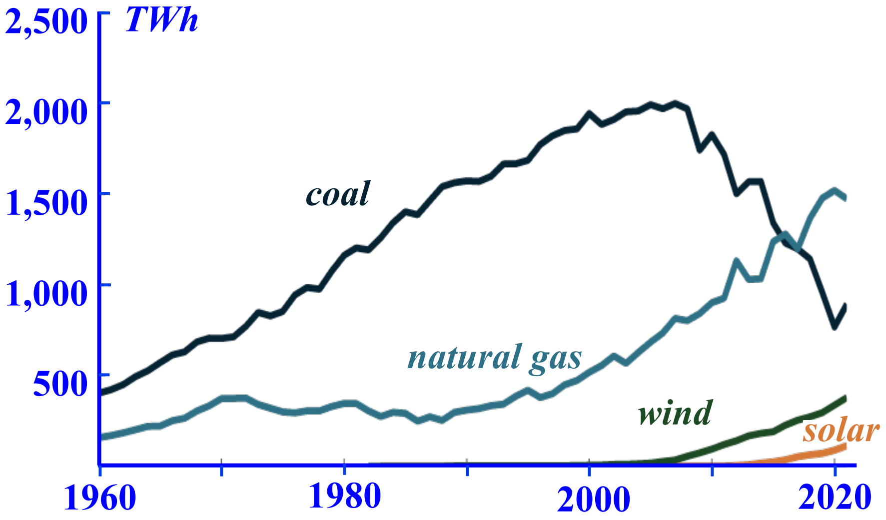
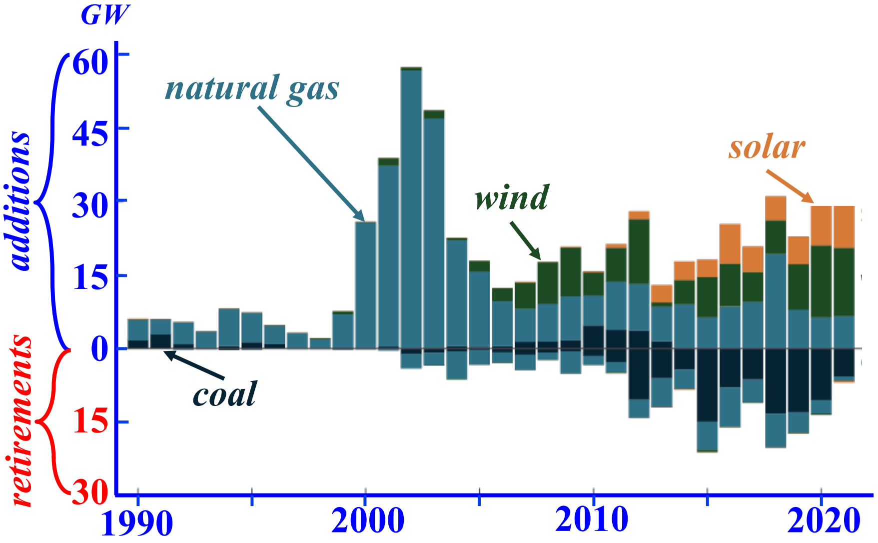
# *US* ELECTRICITY GENERATION BY PRIMARY ENERGY SOURCES: 1990 – 2021



*Source: Congressional Budge Office, "Emissions of Carbon Dioxide in the Electric Power Sector", December 2022; available at https://www.cbo.gov/publication/58860*

# *US* ELECTRIC GENERATION CAPACITY ADDITIONS / RETIREMENTS: 1990 – 2021



Source: Congressional Budge Office, "Emissions of Carbon Dioxide in the Electric Power Sector", December 2022; available at https://www.cbo.gov/publication/58860

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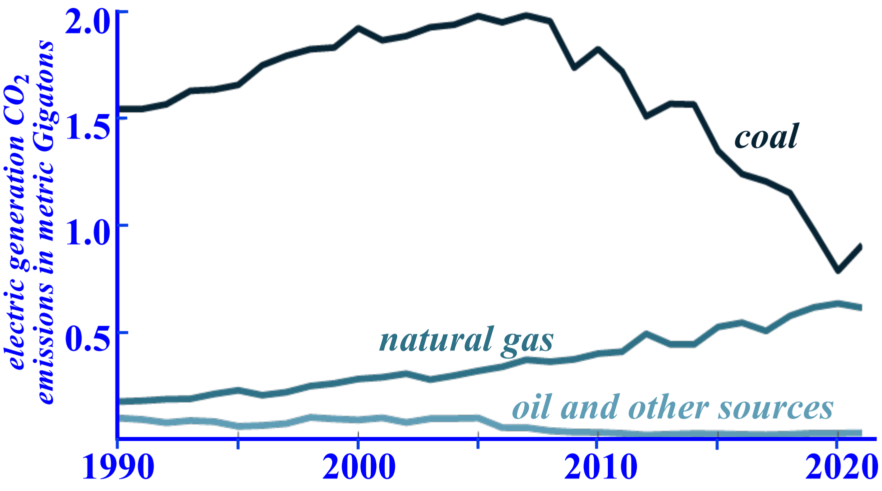
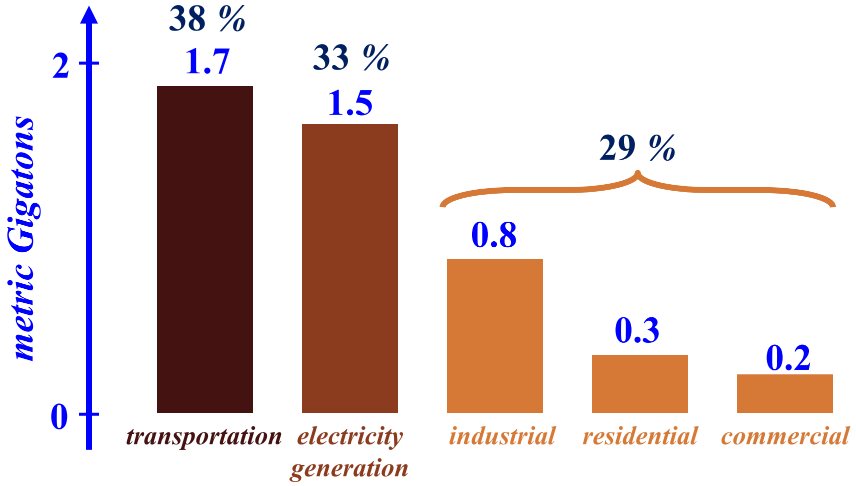
# *US* ELECTRIC GENERATION EMISSIONS FROM FOSSIL RESOURCES: 1990 – 2021



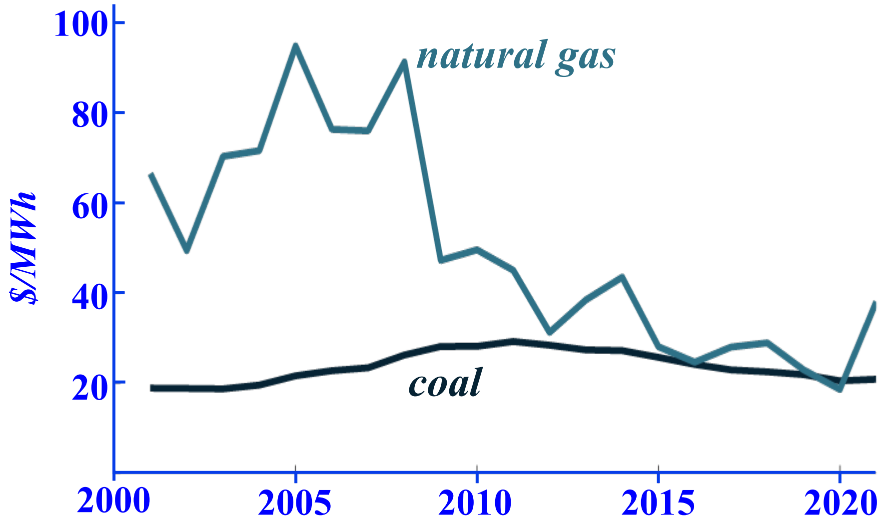
Source: Congressional Budge Office, "Emissions of Carbon Dioxide in the Electric Power Sector", December 2022; available at https://www.cbo.gov/publication/58860

# 2021 *US* *$CO_2$* EMISSIONS BY SECTOR



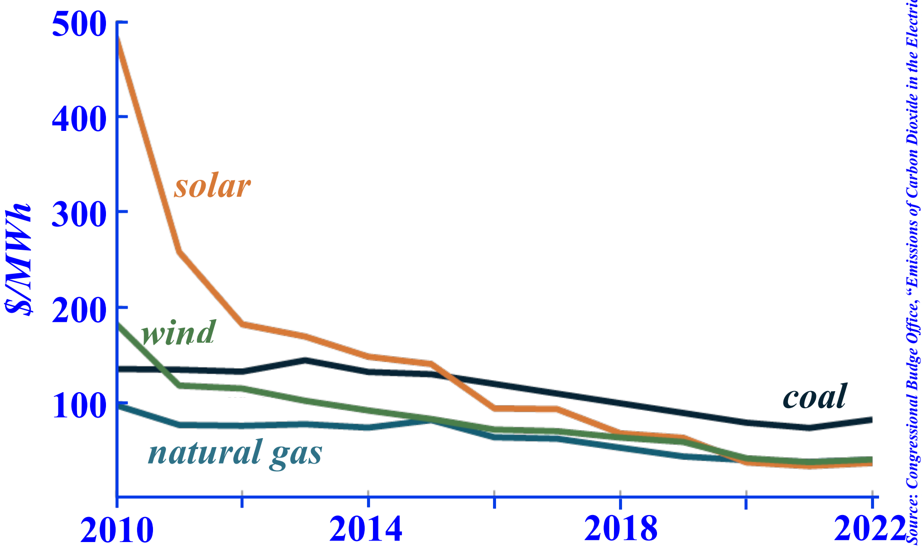
*Source: Congressional Budget Office, "Emissions of Carbon Dioxide in the Electric Power Sector", December 2022; available at https://www.cbo.gov/publication/58860*

# AVERAGE COSTS OF GAS– & COAL– GENERATED ELECTRICITY



*Source: Congressional Budget Office, "Emissions of Carbon Dioxide in the Electric Power Sector", December 2022; available at https://www.cbo.gov/publication/58860*

# LEVELIZED COSTS OF ELECTRICITY BY ENERGY SOURCE: 2010 – 2022



*Source: Congressional Budge Office, "Emissions of Carbon Dioxide in the Electric Power Sector", December 2022; available at https://www.cbo.gov/publication/58860*

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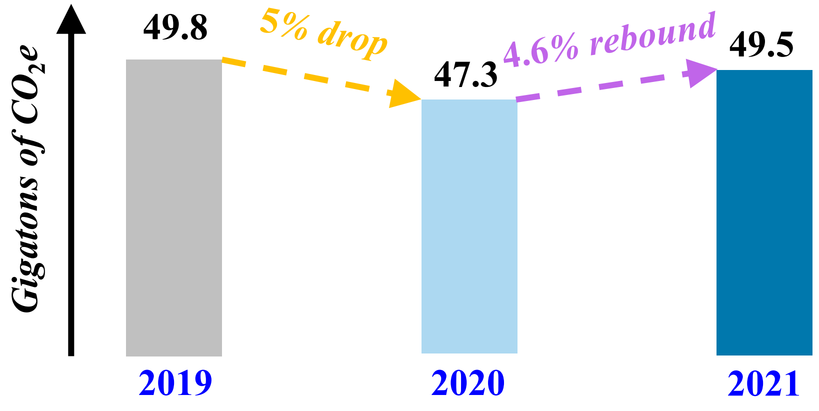
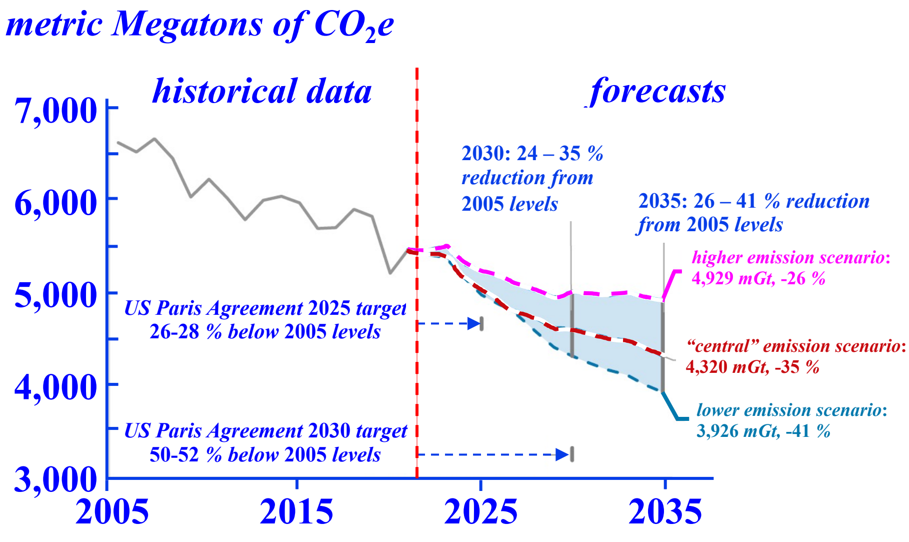
# 2021 ESTIMATED GLOBAL *$CO_2e$* EMISSIONS



*Source: Rhodium Group, "Global Greenhouse Gas Emissions: 1990-2020 and Preliminary 2021 Estimates," December 19, 2022; available online at https://rhg.com/research/global-greenhouse-gas-emissions-2021/*

# *US GHG* EMISSIONS FORECASTS



2030: 24 – 35 % reduction from 2005 levels

2035: 26 – 41 % reduction from 2005 levels

higher emission scenario: 4,929 *mGt*, -26 %

"central" emission scenario: 4,320 *mGt*, -35 %

lower emission scenario: 3,926 *mGt*, -41 %

US Paris Agreement 2025 target 26-28 % below 2005 levels

US Paris Agreement 2030 target 50-52 % below 2005 levels

*Source: Rhodium Group, "Taking Stock 2022: US Greenhouse Gas Emissions Outlook in an Uncertain World," July 14, 2022; available online at https://rhg.com/wp-content/uploads/2022/07/Taking-Stock-2022_US-Emissions-Outlook.pdf*

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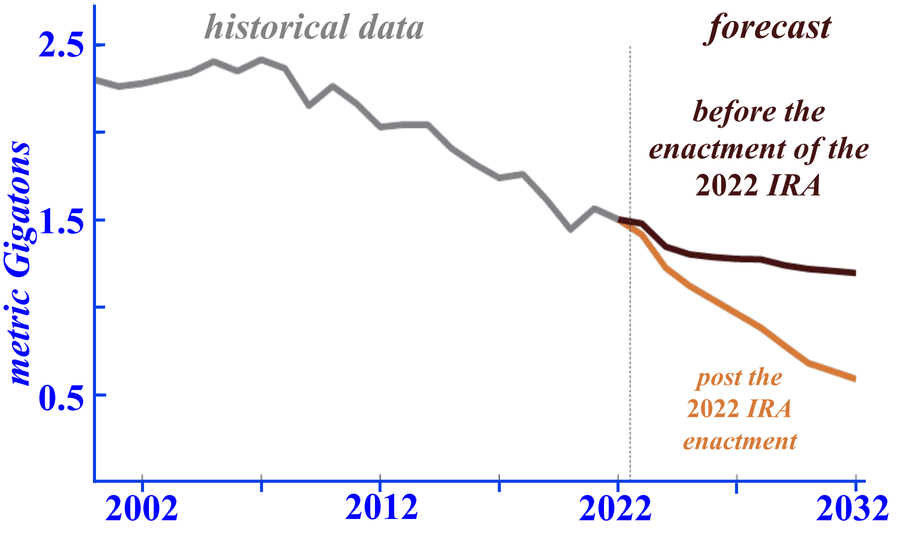
# FORECASTED EMISSIONS OF $CO_2$ FROM *US* ELECTRICITY GENERATION

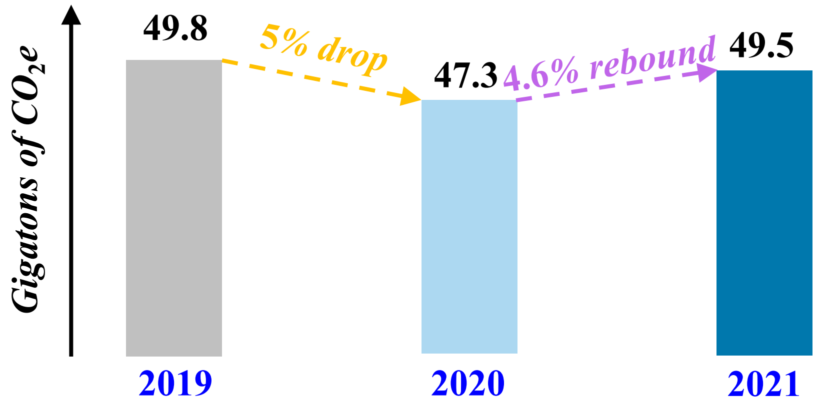


before the enactment of the 2022 *IRA*

post the 2022 *IRA* enactment

*Source: Congressional Budge Office, "Emissions of Carbon Dioxide in the Electric Power Sector", December 2022; available at https://www.cbo.gov/publication/58860*

# 2021 ESTIMATED GLOBAL $CO_2e$ EMISSIONS



*Source: Rhodium Group, "Global Greenhouse Gas Emissions: 1990-2020 and Preliminary 2021 Estimates," December 19, 2022; available online at https://rhg.com/research/global-greenhouse-gas-emissions-2021/*

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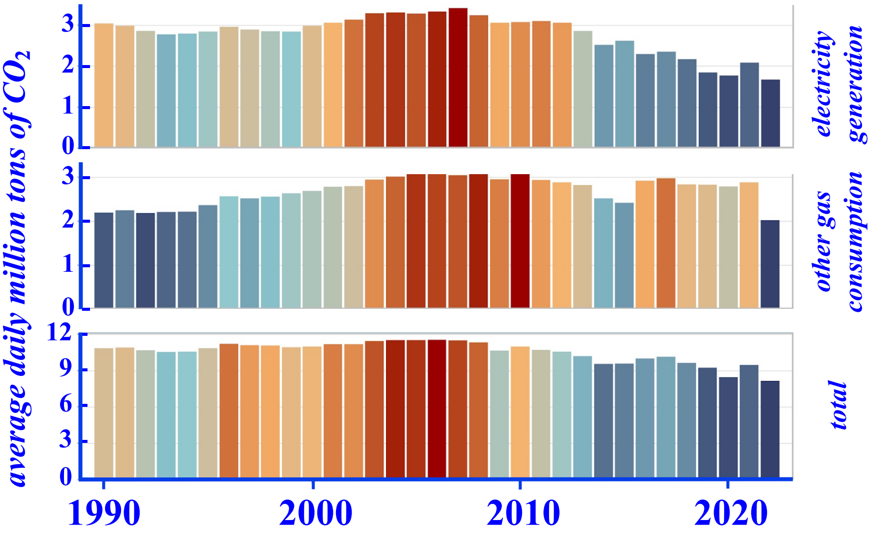
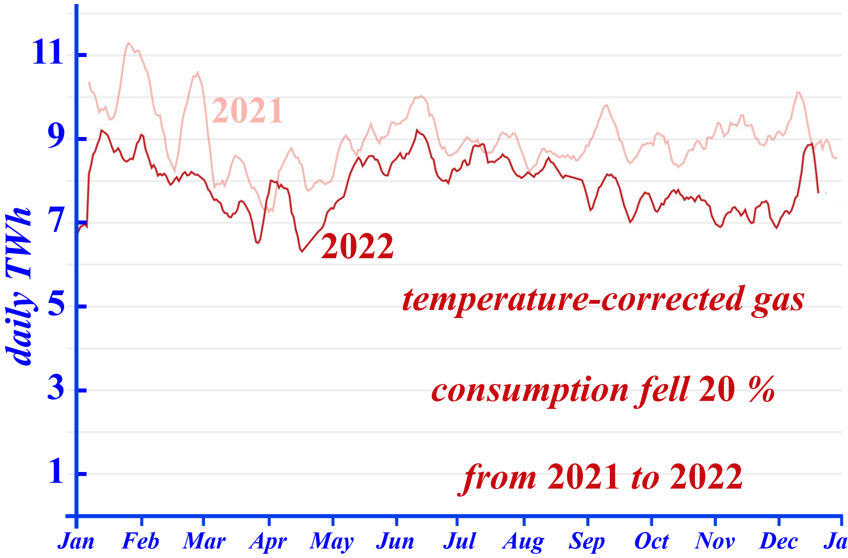
# *EU* $CO_2$ EMISSIONS



*Source: CREA, "EU CO2 emissions reached a 30-year low in November 2022", December 2022, available at https://energyandcleanair.org/eu-co2-emissions-reach-a-30-year-low-in-november/*

# GAS CONSUMPTION FOR NON–ELECTRICITY USE: 2021 *vs.* 2022



*temperature-corrected gas consumption fell 20 % from 2021 to 2022*

*Source: CREA, "EU CO2 emissions reached a 30-year low in November 2022", December 2022, available at https://energyandcleanair.org/eu-co2-emissions-reach-a-30-year-low-in-november/*

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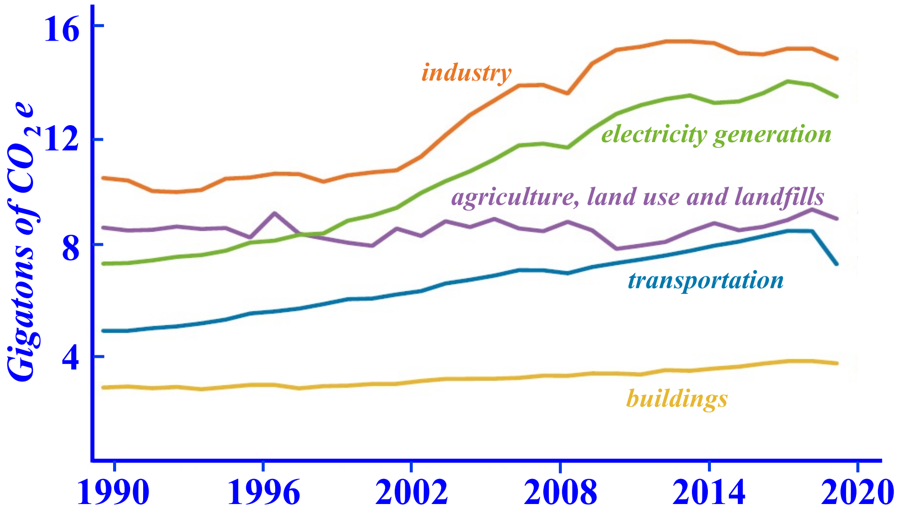
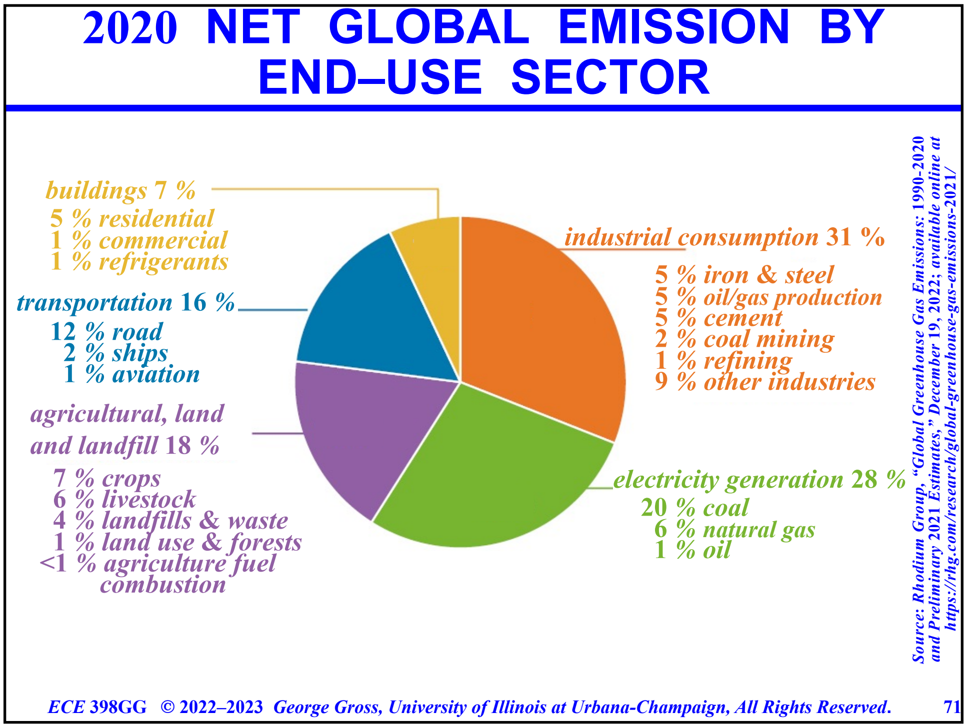
# GLOBAL *GHG* EMISSIONS BY SECTOR: 1990 – 2020



*Source: Rhodium Group, "Global Greenhouse Gas Emissions: 1990-2020 and Preliminary 2021 Estimates," December 19, 2022; available online at https://rhg.com/research/global-greenhouse-gas-emissions-2021/*



# 2020 NET GLOBAL EMISSION BY END–USE SECTOR

buildings 7 %
- 5 % residential
- 1 % commercial
- 1 % refrigerants

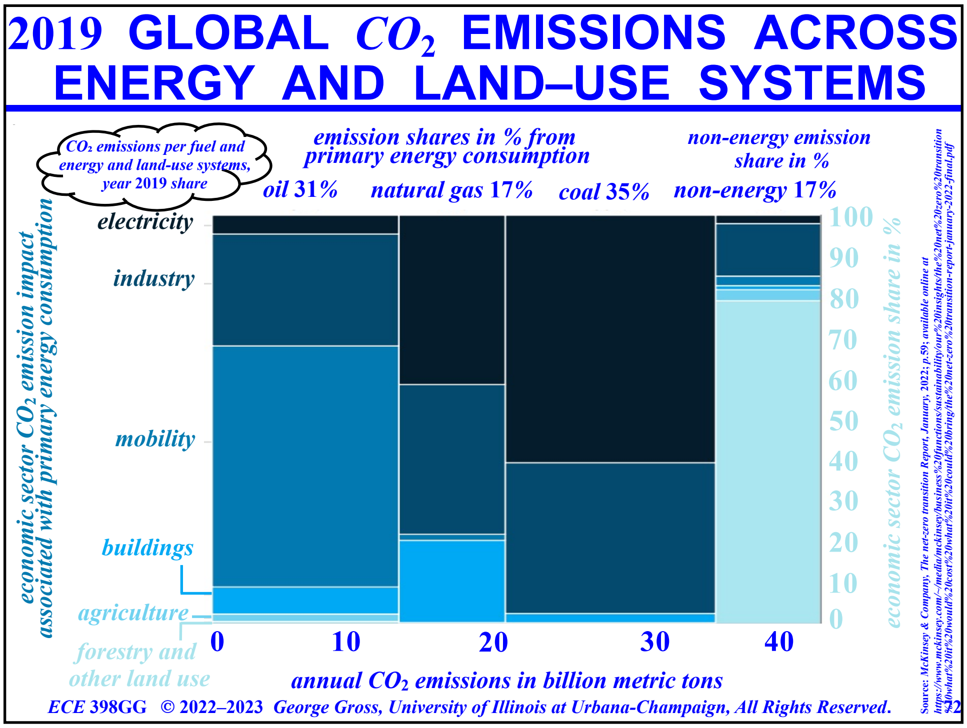
transportation 16 %
- 12 % road
- 2 % ships
- 1 % aviation

agricultural, land and landfill 18 %
- 7 % crops
- 6 % livestock
- 4 % landfills & waste
- 1 % land use & forests
- <1 % agriculture fuel combustion

industrial consumption 31 %
- 5 % iron & steel
- 5 % oil/gas production
- 5 % cement
- 2 % coal mining
- 1 % refining
- 9 % other industries

electricity generation 28 %
- 20 % coal
- 6 % natural gas
- 1 % oil

Source: Rhodium Group, "Global Greenhouse Gas Emissions: 1990-2020 and Preliminary 2021 Estimates," December 19, 2022; available online at https://rhg.com/research/global-greenhouse-gas-emissions-2021/



# 2019 GLOBAL $CO_2$ EMISSIONS ACROSS ENERGY AND LAND–USE SYSTEMS

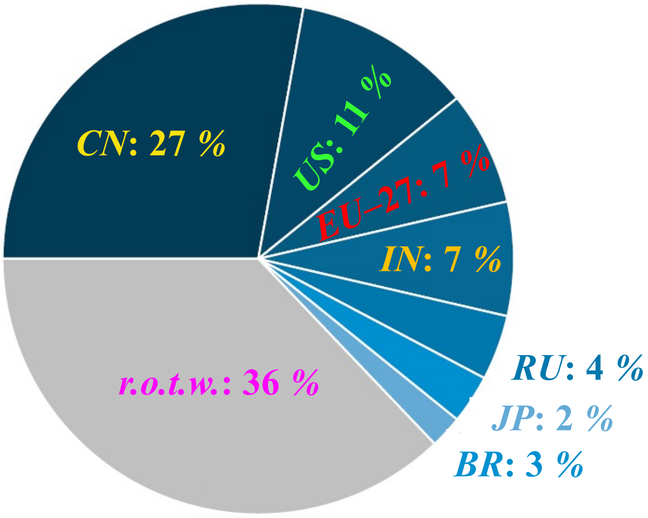
$CO_2$ emissions per fuel and energy and land-use systems, year 2019 share

emission shares in % from primary energy consumption

non-energy emission share in %

Source: McKinsey & Company, The net-zero transition Report, January, 2022; p.59; available online at https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/the%20net%20zero%20transition%20what%20it%20would%20cost%20what%20it%20could%20bring/the%20net-zero%20transition-report-january-2022-final.pdf

# 2021 NET *GHG* EMISSIONS SHARES BY COUNTRIES



*Source: Rhodium Group, “Global Greenhouse Gas Emissions: 1990-2020 and Preliminary 2021 Estimates,” December 19, 2022; available online at https://rhg.com/research/global-greenhouse-gas-emissions-2021/*

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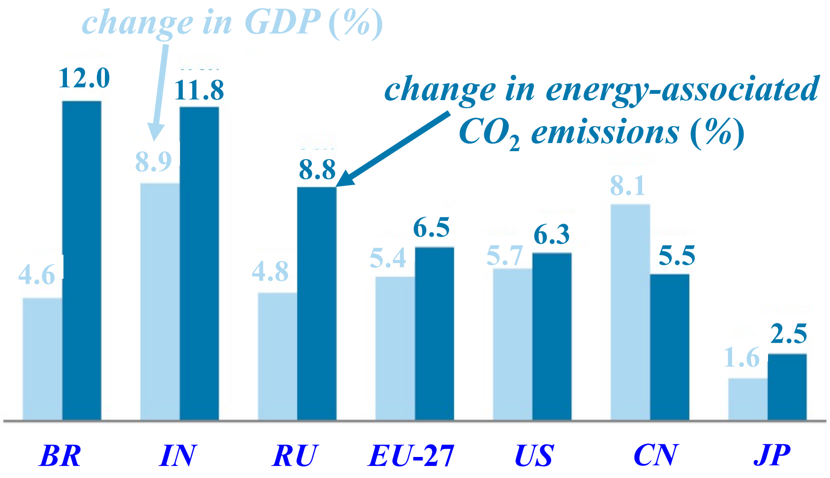
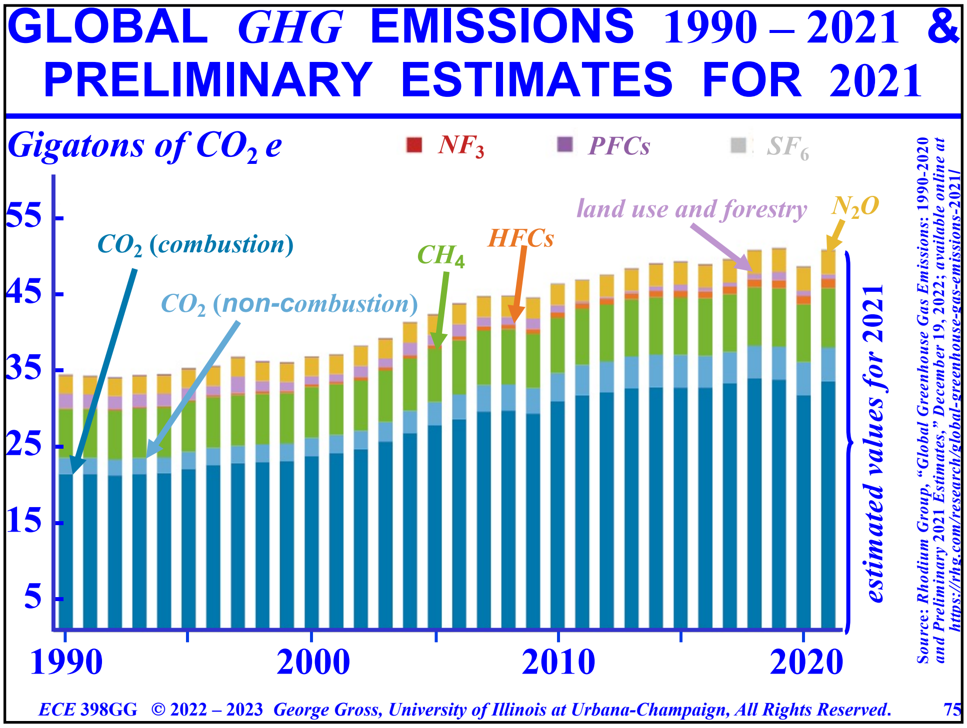
# GROWTH IN 2021 ENERGY $CO_2$ EMISSIONS AND *GDP* BY COUNTRY

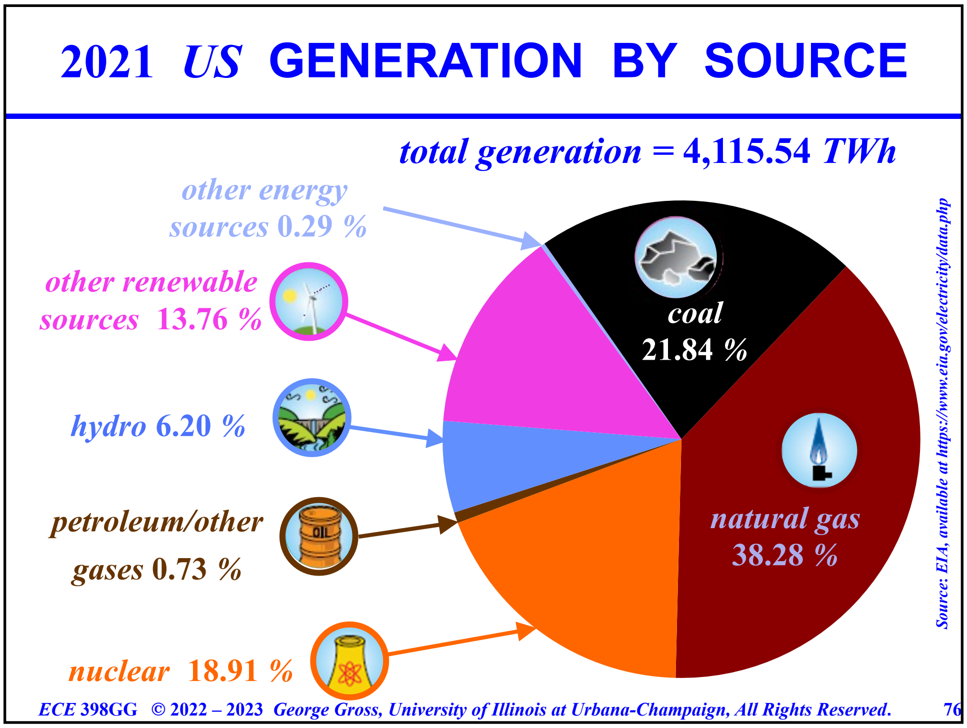


*Source: Rhodium Group, “Global Greenhouse Gas Emissions: 1990-2020 and Preliminary 2021 Estimates,” December 19, 2022; available online at https://rhg.com/research/global-greenhouse-gas-emissions-2021/*



## GLOBAL *GHG* EMISSIONS 1990 – 2021 & PRELIMINARY ESTIMATES FOR 2021

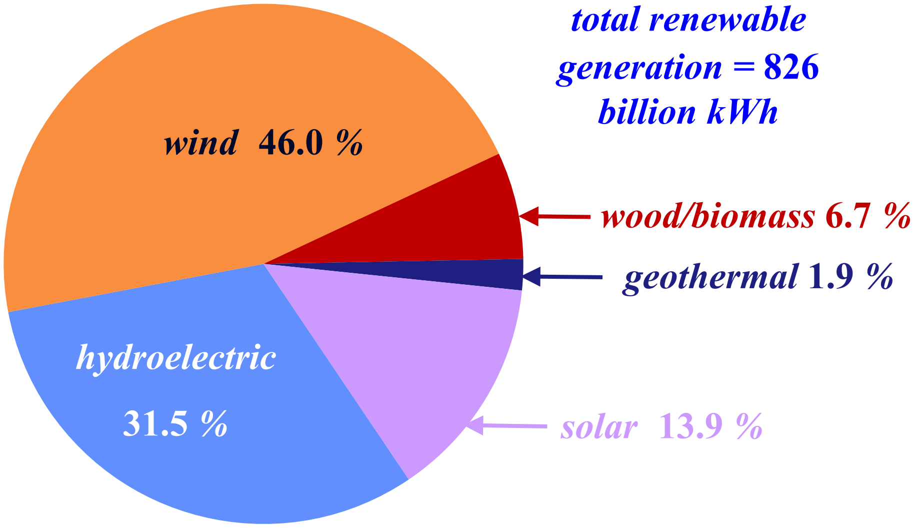
Source: Rhodium Group, "Global Greenhouse Gas Emissions: 1990-2020 and Preliminary 2021 Estimates," December 19, 2022; available online at https://rhg.com/research/global-greenhouse-gas-emissions-2021/



## 2021 *US* GENERATION BY SOURCE

Source: EIA, available at https://www.eia.gov/electricity/data.php

# 2021 NET GENERATION OF RENEWABLE ENERGY SOURCES

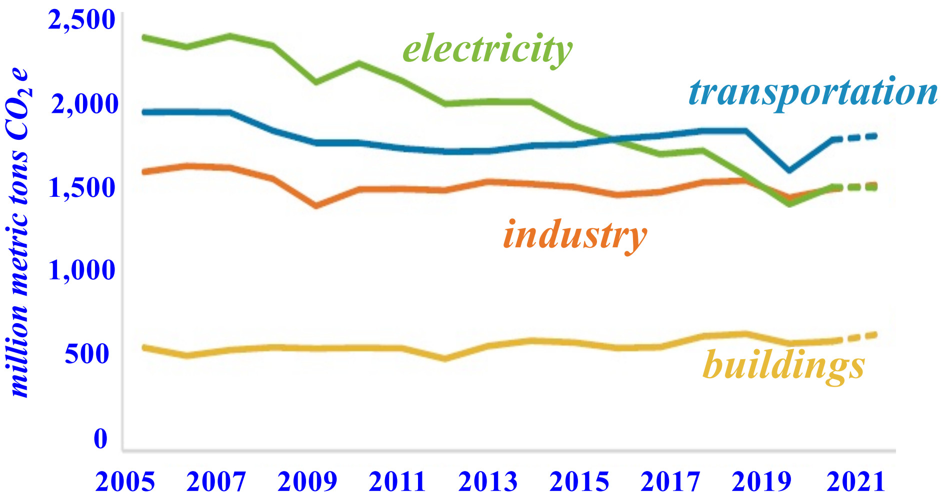


*total renewable generation = 826 billion kWh*

*Source: EIA, June 2021, https://www.eia.gov/tools/faqs/faq.php?id=427&t=3*

# *US GHG* EMISSIONS BY SECTOR: 2005 - 2022

*source: Rhodium Group, available at https://rhg.com/research/us-greenhouse-gas-emissions-2022/*



# *US GHG* EMISSIONS AND ANNUAL CHANGES: 2019 – 2022

*source: Rhodium Group, available at https://rhg.com/research/us-greenhouse-gas-emissions-2022/*