7. EV Efficiency and Emission Analysis

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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

![Diagram of the well-to-wheels process]

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

THE *ICEV WELL–TO–WHEELS* PROCESS

![Diagram of the ICEV well-to-wheels process]

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

THE EV WELL–TO–WHEELS 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 EVs 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 %

- 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

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Highest FE (mpg) Manufacturer</th>
<th>Lowest FE (mpg) Manufacturer</th>
<th>Highest FE Real-world FE in mpge</th>
<th>Highest FE Gasoline Real-world FE in mpge</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>Mazda Stellantis</td>
<td>BMW i3</td>
<td>121.3</td>
<td>Mazda 2</td>
</tr>
<tr>
<td>2017</td>
<td>Honda Stellantis</td>
<td>Hyundai Ioniq</td>
<td>132.6</td>
<td>Mitsubishi Mirage</td>
</tr>
<tr>
<td>2018</td>
<td>Tesla Stellantis</td>
<td>Hyundai Ioniq</td>
<td>132.6</td>
<td>Mitsubishi Mirage</td>
</tr>
<tr>
<td>2019</td>
<td>Tesla Stellantis</td>
<td>Hyundai Ioniq</td>
<td>132.6</td>
<td>Mitsubishi Mirage</td>
</tr>
<tr>
<td>2020</td>
<td>Tesla Stellantis</td>
<td>Tesla 3 SR+</td>
<td>138.6</td>
<td>Mitsubishi Mirage</td>
</tr>
<tr>
<td>2021</td>
<td>Tesla Stellantis</td>
<td>Tesla 3 SR+</td>
<td>139.1</td>
<td>Mitsubishi Mirage</td>
</tr>
<tr>
<td>2022*</td>
<td>Tesla Stellantis</td>
<td>Lucid Air</td>
<td>131.4</td>
<td>Mitsubishi Mirage</td>
</tr>
</tbody>
</table>

* Preliminary data subject to change.


### EPA MODEL YEAR 2022 EV FUEL ECONOMY METRICS

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Electricity Consumption in kWh/100mi</th>
<th>FE in mpge</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM</td>
<td>Bolt</td>
<td>28</td>
<td>120</td>
</tr>
<tr>
<td>Nissan</td>
<td>Leaf 62 kWh</td>
<td>31</td>
<td>108</td>
</tr>
<tr>
<td>Tesla</td>
<td>Model 3 LR</td>
<td>26</td>
<td>131</td>
</tr>
</tbody>
</table>

THE **EV WELL–TO–WHEELS PROCESS**

- **primary energy source** → energy conversion → generation plant → T & D delivery → EV charger → battery charging process → EV battery
- well-to-battery process
- wheels → electric motor → EV battery

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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:

  ![Diagram](https://via.placeholder.com/150)

  ```plaintext
  input → system → output
  ```
**EFFICIENCY NOTIONS**

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

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

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

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

---

**EFFICIENCY NOTIONS**

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

```plaintext
system input -> subsystem 1 -> subsystem 2 -> ... -> subsystem N -> system output
```

- $N$ 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,

$$\text{output } k = \text{input } k + 1 \quad k = 0, 1, \ldots, N-1$$

or, equivalently

$$\text{input } k = \text{output } k - 1 \quad k = 1, 2, \ldots, N$$

with

$$\text{input } 1 = \text{system input}$$
$$\text{output } N = \text{system output}$$

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

$$\eta_k = \frac{\text{output } k}{\text{input } k} \quad k = 1, 2, \ldots, N$$
EFFICIENCY NOTIONS

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

\[
\eta_{\text{system}} = \frac{\text{system output}}{\text{system input}}
= \frac{\text{output } N}{\text{input } 1}
= \frac{\text{output } N}{\text{input } N} \times \frac{\text{output } N - 1}{\text{input } N - 1} \times \cdots \times \frac{\text{output } 1}{\text{input } 1}
= \eta_1 \times \eta_2 \times \cdots \times \eta_N
\]

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
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 distribution grid to supply the electricity to the charger

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

\[ 60\% \times 95\% = 0.57 \]

CCNG plant  T & D
Thus, a unit of energy extracted from the well is reduced upon arrival at the charger to

\[ 57\% \times 90\% = 0.513, \]

\[ \text{conversion well-to-} \]
\[ \text{& delivery CCNG} \]

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 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
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

\[
0.729 = 95\% \times 95\% \times 85\% \times 95\%
\]

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

\[ 51.3\% \times 72.9\% = 0.374 \]

well-to-charger \hspace{1cm} well-to-wheels

charger-to-wheels

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

\[
\frac{33.705 \text{ kWh/gal}}{31 \text{ kWh/100 mi}} = 108.7 \text{ mpge,}
\]

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!

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 CO₂ EMISSION ESTIMATES: my 2020 – 2022

<table>
<thead>
<tr>
<th>manufacturer</th>
<th>my 2020 final real-world FE (mpg)</th>
<th>my 2020 final real-world CO₂ (g/mi)</th>
<th>my 2021 final real-world FE (mpg)</th>
<th>my 2021 final real-world CO₂ (g/mi)</th>
<th>my 2022 preliminary real-world FE (mpg)</th>
<th>my 2022 preliminary real-world CO₂ (g/mi)</th>
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<tbody>
<tr>
<td>BMW</td>
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<td>347</td>
<td>25.8</td>
<td>339</td>
<td>25.7</td>
<td>341</td>
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<tr>
<td>Ford</td>
<td>23.0</td>
<td>386</td>
<td>22.9</td>
<td>385</td>
<td>23.0</td>
<td>382</td>
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<tr>
<td>GM</td>
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<td>400</td>
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<td>315</td>
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<td>335</td>
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<td>376</td>
<td>24.6</td>
<td>359</td>
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<td>317</td>
<td>28.6</td>
<td>311</td>
<td>28.0</td>
<td>316</td>
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<td>418</td>
<td>21.3</td>
<td>417</td>
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<td>410</td>
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<tr>
<td>Subaru</td>
<td>28.5</td>
<td>312</td>
<td>28.8</td>
<td>309</td>
<td>28.0</td>
<td>317</td>
</tr>
<tr>
<td>Tesla</td>
<td>119.1</td>
<td>0</td>
<td>123.9</td>
<td>0</td>
<td>121.5</td>
<td>0</td>
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<td>27.0</td>
<td>329</td>
<td>27.1</td>
<td>327</td>
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<td>316</td>
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<tr>
<td>VW</td>
<td>24.9</td>
<td>354</td>
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<td>306</td>
</tr>
<tr>
<td>all OEMs</td>
<td>25.4</td>
<td>349</td>
<td>25.4</td>
<td>347</td>
<td>26.4</td>
<td>331</td>
</tr>
</tbody>
</table>


### THE EV WELL–TO–WHEELS PROCESS

- **primary energy source**
- **energy conversion**
- **generation plant**
- **T & D delivery**
- **EV charger**
- **battery charging process**
- **EV battery**
- **well-to-battery process**
- **wheels**
- **electric motor**
- **battery-to-wheels process**
**EV GHG EMISSION ANALYSIS**

- We have established the fact that EVs are very efficient means to use primary energy resources to convert them into transportation miles; next, we focus on the EV environmental impacts.
- Unlike ICEVs that run on gasoline and diesel fuels and release tailpipe emissions that include CO\(_2\), EVs do not produce such emissions; but, the electricity generation required for EV operations is accompanied 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 CO₂ 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
2020 CO₂ 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-

2020 CO₂ TOTAL OUTPUT EMISSION RATE IN lb/MWh BY eGRID SUBREGION
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

\[(384 \text{ g/kWh}) \times [(1 \text{ kWh})/(3.85 \text{ mi})] = 99.7 \text{ g/mi}\]

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

\[8,887 \text{ g/gal} \times 1 \text{ gal/25 mi} = 355 \text{ g/mi}\]
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

\[
8,887 \text{ g/gal} \times 1 \text{ gal/40 mi} = 222 \text{ g/mi},
\]

which are still above twice the *Tesla* emissions.

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

\[
8,887 \text{ g/gal} \times 1 \text{ gal/x mi} = 99.7 \text{ g/mi}
\]

so that

\[
x = 89 \text{ mpg},
\]

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 *CO₂* data for its service territory.

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 this battery pack entails \( CO_2 \) emissions may be estimated to amount to

\[
54 \text{ kWh} \times 150 \text{ kg} \ CO_2 / \text{kWh} = 8,100 \text{ kg} \ CO_2
\]

- The advertised battery life of Tesla EVs is 300,000 mi; the implication is that the \( CO_2 \) emissions per mi are

\[
8,100 \text{ kg} \ CO_2 \div 300,000 \text{ mi} = 27 \text{ g} \ CO_2 / \text{mi}
\]
**EV LIFECYCLE EMISSIONS**

- The incorporation of the battery manufacture emissions results in the total $CO_2$ emissions of
  
  \[ 99.7 \text{ g } CO_2 / \text{mi} + 27 \text{ g } CO_2 / \text{mi} = 126.7 \text{ g } CO_2 / \text{mi} \]

- 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*

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**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 CO\textsubscript{2} 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.

- EV charging with 100% renewable electricity implies 0 g CO\textsubscript{2}/mi emissions by such EVs; moreover, the use of 100% renewable electricity to produce the battery packs also results in 0 CO\textsubscript{2} emissions.

- The broader deployment of renewable resources can therefore further reduce the EV CO\textsubscript{2} footprint; the ICEVs’ inherent reliance on fossil fuels cannot provide such environmental improvements.
US ENERGY-RELATED CO₂ EMISSIONS BY ECONOMIC SECTOR

- electricity generation
- transportation
- industrial, residential & commercial (i.r.c.) sectors


US ELECTRICITY GENERATION CO₂ EMISSIONS vs. OTHER SECTORS': 1990 – 2021

- electricity generation
- total of other economic sectors

**US CO₂ EMISSION REDUCTION SINCE 2005 BY SECTOR**

- **electricity generation**: 77%
- **transportation**: 10%
- **i.r.c. sectors**: 13%


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

- **coal**: 20%
- **natural gas**: 60%
- **solar**: 10%
- **wind**: 10%
- **other**: 20%

US ELECTRICITY GENERATION \( \text{CO}_2 \) EMISSIONS AND CARBON INTENSITY

\[ \text{average carbon intensity} \]

\[ \text{CO}_2 \text{ emissions} \]


US ELECTRICITY GENERATION BY PRIMARY ENERGY SOURCES: 1990 – 2021

\[ TWh \]

coal

natural gas

wind

solar


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

**US Electric Generation Emissions from Fossil Resources: 1990 – 2021**

- **Source:** Congressional Budget Office, "Emissions of Carbon Dioxide in the Electric Power Sector", December 2022; available at https://www.cbo.gov/publication/58860
2021 US CO₂ EMISSIONS BY SECTOR

- Transportation: 38%, 1.7 metric Gigatons
- Electricity generation: 33%, 1.5 metric Gigatons
- Industrial: 29%, 0.8 metric Gigatons
- Residential: 0.3 metric Gigatons
- Commercial: 0.2 metric Gigatons


AVERAGE COSTS OF GAS- & COAL- GENERATED ELECTRICITY

- Natural gas
- Coal

LEVELIZED COSTS OF ELECTRICITY BY ENERGY SOURCE: 2010 – 2022

$/MWh

wind
color
natural gas

c coal

2010 2014 2018 2022


2021 ESTIMATED GLOBAL CO₂e EMISSIONS

Gigatons of CO₂e

49.8 47.3 49.5

5% drop 4.6% rebound

2019 2020 2021

US GHG EMISSIONS FORECASTS

metric Megatons of CO$_2$e

<table>
<thead>
<tr>
<th>Year</th>
<th>Target</th>
<th>Reduction from 2005 Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>2025</td>
<td>26-28%</td>
<td></td>
</tr>
<tr>
<td>2030</td>
<td>24-35%</td>
<td></td>
</tr>
<tr>
<td>2035</td>
<td>26-41%</td>
<td></td>
</tr>
</tbody>
</table>

**Historical Data**
- 3,000 mGt to 5,000 mGt
- 2005: 3,000 mGt, 50-52% below 2005 levels
- 2015: 4,000 mGt, 26-28% below 2005 levels
- 2025: 5,000 mGt, 26-35% below 2005 levels

**Forecasts**
- Higher emission scenario: 4,929 mGt, 26%
- "Central" emission scenario: 4,320 mGt, 35%
- Lower emission scenario: 3,926 mGt, 41%


FORECASTED EMISSIONS OF CO$_2$ FROM US ELECTRICITY GENERATION

<table>
<thead>
<tr>
<th>Year</th>
<th>Historical Data</th>
<th>Forecast</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>2.5</td>
<td>before the enactment of the 2022 IRA</td>
</tr>
<tr>
<td>2012</td>
<td>1.5</td>
<td>post the 2022 IRA enactment</td>
</tr>
<tr>
<td>2022</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

### 2021 ESTIMATED GLOBAL $CO_2e$ EMISSIONS

<table>
<thead>
<tr>
<th>Year</th>
<th>Gigatons of $CO_2e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>49.8</td>
</tr>
<tr>
<td>2020</td>
<td>47.3</td>
</tr>
<tr>
<td>2021</td>
<td>49.5</td>
</tr>
</tbody>
</table>

5% drop

4.6% rebound


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### EU $CO_2$ EMISSIONS

- **Electricity generation**
- **Other gas consumption**
- **Total**

<table>
<thead>
<tr>
<th>Year</th>
<th>average daily million tons of CO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>2.5</td>
</tr>
<tr>
<td>2000</td>
<td>2.2</td>
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<tr>
<td>2010</td>
<td>2.0</td>
</tr>
<tr>
<td>2020</td>
<td>1.8</td>
</tr>
</tbody>
</table>

GAS CONSUMPTION FOR NON-ELECTRICITY USE: 2021 vs. 2022

Temperature-corrected gas consumption fell 20% from 2021 to 2022.

GLOBAL GHG EMISSIONS BY SECTOR: 1990 – 2020

### 2020 NET GLOBAL EMISSION BY END-USE SECTOR

- **buildings**: 7%
- **transportation**: 16%
- **agricultural, land, and landfill**: 18%
- **industrial consumption**: 31%
- **electricity generation**: 28%
- **5% iron & steel**
- **5% oil/gas production**
- **5% cement**
- **2% coal mining**
- **1% refining**
- **9% other industries**


### 2019 GLOBAL CO₂ EMISSIONS ACROSS ENERGY AND LAND-USE SYSTEMS

- **electricity**: oil 31%, natural gas 17%, coal 35%
- **industry**: non-energy 17%
- **mobility**: 0% non-energy
- **buildings**: 0% non-energy
- **agriculture, forestry, and other land use**: 0% non-energy

### 2021 NET GHG EMISSIONS SHARES BY COUNTRIES

- **CN**: 27%
- **US**: 11%
- **RU**: 4%
- **JP**: 2%
- **IN**: 7%
- **BR**: 3%
- **r.o.t.w.**: 36%
- **EU**: 27%


### GROWTH IN 2021 ENERGY CO₂ EMISSIONS AND GDP BY COUNTRY

<table>
<thead>
<tr>
<th>Country</th>
<th>Change in Energy-Associated CO₂ Emissions (%)</th>
<th>Change in GDP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR</td>
<td>4.6</td>
<td>12.0</td>
</tr>
<tr>
<td>IN</td>
<td>4.8</td>
<td>8.9</td>
</tr>
<tr>
<td>RU</td>
<td>5.4</td>
<td>8.8</td>
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<tr>
<td>EU-27</td>
<td>5.7</td>
<td>6.5</td>
</tr>
<tr>
<td>US</td>
<td>6.3</td>
<td>5.7</td>
</tr>
<tr>
<td>CN</td>
<td>5.5</td>
<td>8.1</td>
</tr>
<tr>
<td>JP</td>
<td>2.5</td>
<td>1.6</td>
</tr>
</tbody>
</table>

GLOBAL GHG EMISSIONS 1990 – 2021 & PRELIMINARY ESTIMATES FOR 2021

Gigatons of CO₂ e


2021 US GENERATION BY SOURCE

total generation = 4,115.54 TWh

coal 21.84 %
natural gas 38.28 %
hydro 6.20 %
other renewable sources 13.76 %
other energy sources 0.29 %
petroleum/other gases 0.73 %
nuclear 18.91 %

Source: EIA available at https://www.eia.gov/electricity/data.php
2021 NET GENERATION OF RENEWABLE ENERGY SOURCES

- **wind** 46.0%
- **hydroelectric** 31.5%
- **solar** 13.9%
- **wood/biomass** 6.7%
- **geothermal** 1.9%


Total renewable generation = 826 billion kWh

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US GHG EMISSIONS BY SECTOR: 2005 - 2022


- **electricity**
- **transportation**
- **industry**
- **buildings**
US GHG EMISSIONS AND ANNUAL CHANGES: 2019 – 2022