CO_2 Impact of Energy Sources

A practical framework for comparing off-grid power systems

*This analysis has been developed by **INERGIO**, a Swiss cleantech company specializing in solid oxide fuel cell technology for reliable off-grid power generation. It aims to provide a structured and transparent comparison of energy systems based on publicly available data and standardized assumptions.*

Introduction

Energy systems are often evaluated based on simplified assumptions. For example, internal combustion engines are commonly associated with high emissions, while electric systems are perceived as low-impact solutions.

In practice, the comparison is more complex.

The environmental impact of an energy system cannot be assessed based on operation alone. It depends on multiple factors, including how the system is produced, how energy is generated, and how the system is used over time.

This article provides a structured overview of the Global Warming Potential (GWP) of different energy sources and power generation technologies. The objective is to present comparable data using consistent assumptions, supported by referenced sources.

The analysis is simplified to focus on key drivers of emissions and to support practical comparison across technologies.

How greenhouse gas impact is measured and compared

Greenhouse gas emissions are often assessed based on the operational phase alone. This includes emissions generated when fuel is consumed or when a system is actively producing energy.

This approach does not reflect the full environmental impact.

A complete evaluation requires considering the entire lifecycle of the energy system, including production, operation, and end-of-life.

Total greenhouse gas emissions are therefore analyzed across three phases:

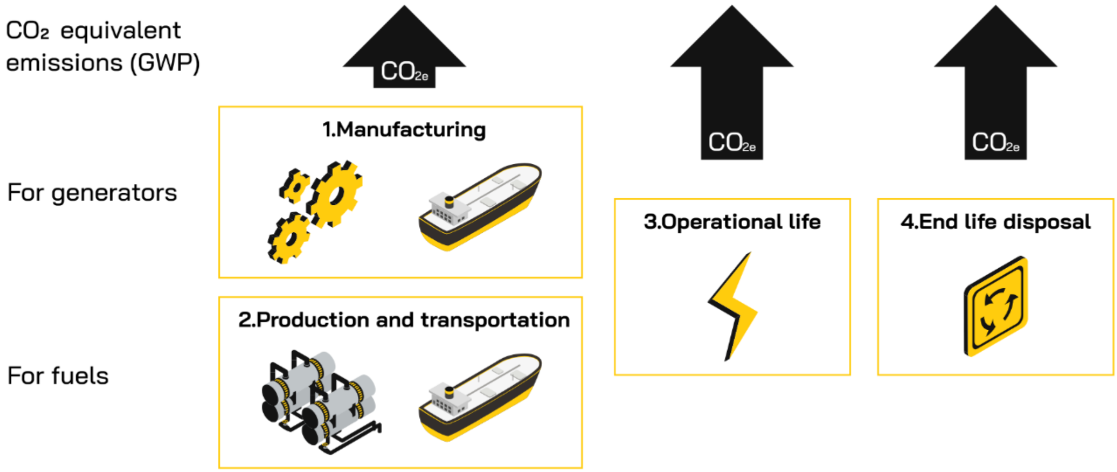
Production
Includes the extraction of raw materials, manufacturing processes, and system installation. This covers the energy and resources required to produce both the generator and the fuel, as well as transport and on-site deployment.

Operation
Includes emissions generated during energy production and fuel consumption. This phase is typically the dominant contributor in continuous-use applications.

End-of-life
Includes decommissioning, recycling, and disposal. The impact varies depending on the technology.

For example, systems with complex material compositions may require energy-intensive or limited recycling processes.

Evaluating all three phases provides a consistent basis for comparing different energy sources and power generation technologies.



What drives CO_2 emissions across the energy lifecycle

Global Warning Potential and comparison metric

Global Warming Potential (GWP) is used to quantify the impact of greenhouse gas emissions. It is expressed in CO_2-equivalent (CO_2-eq), which converts the effect of different gases into a common reference unit.

Non-CO_2 gases are weighted based on their relative impact on climate. For example:

- Methane has a global warming impact approximately 28 times higher than CO_2
- Nitrous oxide has an impact close to 300 times higher than CO_2

Expressing emissions in CO_2-equivalent allows different sources of greenhouse gases to be compared on a consistent basis.

To evaluate energy systems, emissions are normalized per unit of energy produced:

grams of CO_2-equivalent per kilowatt-hour (g CO_2-eq per kWh)

This metric provides a standardized way to compare the environmental impact of different energy sources and power generation technologies.

This analysis focuses primarily on:

- Production impact
- Operational (consumption) impact

Maintenance, disposal, and end-of-life are addressed qualitatively. While a full lifecycle assessment (LCA) includes additional parameters, this document focuses specifically on Global Warming Potential as the primary comparison metric.

1. Generator manufacturing and transport impact

The environmental impact associated with the production and installation of a power generator depends on several factors:

- Material requirements, such as metals, ceramics, or composites
- Energy consumption during manufacturing processes, including thermal treatment and machining
- Transport and on-site installation

These contributions are aggregated to estimate the total emissions associated with bringing a generator into operation.

To enable comparison across technologies**, this impact is distributed over the total energy expected to be produced during the system's lifetime**. The result is expressed in grams of CO_2-equivalent per kilowatt-hour of energy generated. This normalization allows production-related emissions to be directly compared with operational emissions.

For example, the production of a 1 kWp photovoltaic system (approximately 5.6 m^2) results in an impact of around 1,400 kg CO_2-eq. If the system produces approximately 29,750 kWh over its lifetime, the resulting production-related impact is: **~47 g CO_2-eq per kWh**

This illustrates how lifetime energy output directly influences the effective emissions per unit of energy.

***Table 1:** Global Warming Potential associated with the production and installation of different types of power generators.*

Type of generator	Manufacturing and transport impact	Energy production during lifetime	Impact per kWh [g CO_2-eq / kWh]
Solar panel	1350-1450 kg CO_2-eq per kWp	29'750 kWh per kWp	**45 to 50**
Wind turbine	600-700 kg CO_2-eq per kW	60'000 kWh per kW	**9 to 13**
Diesel generator	360 kg CO_2-eq per kW	8'000 kWh per kW	**45**
Solid Oxide Fuel Cell (SOFC) small-scale **	525 kg CO_2-eq per kW	15'000 kWh per kW	**35**
Solid Oxide Fuel Cell (SOFC) large-scale **	375 kg CO_2-eq per kW	15'000 kWh per kW	**25**
Proton Exchange Membrane Fuel Cell (PEMFC)	200 kg CO_2-eq per kW	15'000 kWh per kW	**13**
Lithium batteries	140 kg CO_2-eq per kWh of capacity	800 kWh per kWh of capacity*	**175**

* Lithium batteries are considered here as energy systems using electricity as input.

** Based on representative values derived from published literature and internal reference systems. For comparability, production-related emissions are approximated as ~35 g CO_2-eq/kWh for small-scale SOFC systems and ~25 g CO_2-eq/kWh for large-scale systems. These are not single-source measurements but normalized benchmark values consistent with typical operating lifetimes.

Proton exchange membrane fuel cells (PEMFC) are commonly used in automotive applications and typically require high-purity hydrogen. Solid oxide fuel cells (SOFC) operate at higher temperatures and can use a wider range of fuels.

Utilization has a direct impact on emissions. The values presented assume typical operating conditions over the system lifetime. When utilization is lower, emissions per kWh increase, as production impact is distributed over less energy. For example, a photovoltaic system operating at 20 percent of expected conditions can reach approximately ~235 g CO_2-eq per kWh.

This highlights the importance of considering real operating conditions when comparing technologies.

2. Fuel production and transport impact

Fuel-related emissions include all processes required to produce and deliver the fuel to the point of use. This is commonly referred to as the **well-to-tank** impact.

For fossil fuels, this includes extraction, processing, and transport. For hydrogen, the impact depends primarily on the production pathway, such as steam methane reforming or electrolysis.

Table 2: *Emission impact of 1kg production of different fuels.*

Fuel	Equivalent storage volume	Production related emissions	Fuel’s specific energy (energetic potential)
1 kg Methane (natural gas)	250 bar, 6 liters	**1’800 g CO_2-eq**	14,9 kWh
1 kg Propane	7 bar, 2 liters	**400 g CO_2-eq**	13,8 kWh
1 kg Bio-Propane	7 bar, 2 liters	**1’300 g CO_2-eq**	13,8 kWh
1 kg Diesel	Liquid, 1.2 liter	**700 g CO_2-eq**	12,7 kWh
1 kg Petrol (gasoline)	Liquid, 1.4 liter	**640 g CO_2-eq**	12,9 kWh
1 kg Methanol	Liquid, 1.3 liter	**500 g CO_2-eq**	5,5 kWh
1 kg Hydrogen – produced by natural Gas steam Reforming	200 bar, 60 liters	**7’300 g CO_2-eq**	33,4 kWh
1 kg Hydrogen – produced with green energy		**1’840 g CO_2-eq**	
1 kg Hydrogen - produced with average EU grid		**13’535 g CO_2-eq**	

Fuel properties vary significantly in terms of storage, energy density, and production impact.

Methane and hydrogen require high-pressure storage. Due to its low density, hydrogen requires large storage volumes even at high pressure. For example, 1 kg of hydrogen occupies approximately 60 liters at 200 bars.

Hydrogen production shows a high level of variability in emissions:

- Steam methane reforming results in high CO_2 emissions
- Electrolysis can result in low emissions when powered by renewable electricity
- When powered by carbon-intensive grids, electrolysis can result in higher emissions than fossil fuels

Currently, a large share of hydrogen production relies on natural gas reforming, which increases its overall carbon footprint.

These differences highlight the importance of considering fuel production pathways when evaluating total system emissions.

3. Operational lifetime impact

During operation, energy systems convert a primary energy source into usable electricity. The associated emissions depend on both the type of energy source and the efficiency of the conversion process.

Energy sources can be broadly categorized as:

- Non-emitting at point of use, such as solar, wind, or hydrogen
- Emitting during operation, such as fossil fuels

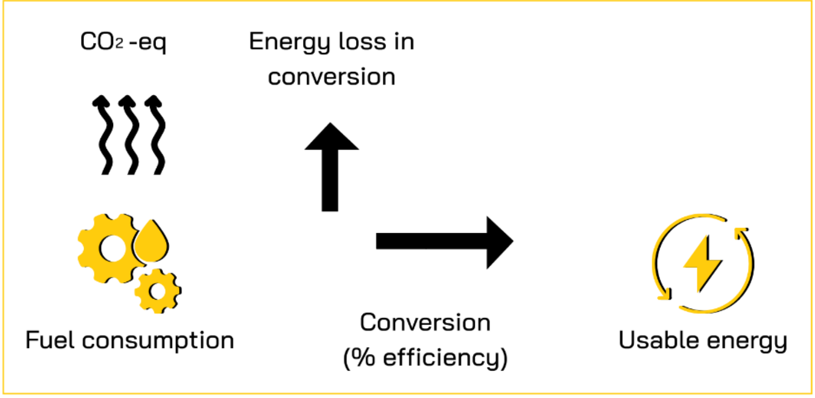
However, point-of-use emissions alone do not determine total impact. The full contribution of the fuel, including its production, must be considered.

All energy conversion processes involve losses. Only a portion of the fuel's energy is converted into usable output, while the remaining energy is typically dissipated as heat. The efficiency of this conversion directly affects total emissions per unit of energy delivered.

The operational impact is therefore expressed as:

grams of CO_2-equivalent per kWh of usable energy

Maintenance-related emissions can vary significantly depending on the deployment context. For example, access constraints in remote locations may require transport-intensive interventions. Due to this variability, maintenance is not quantified in detail, and the analysis focuses primarily on fuel-related emissions.



Conversion in a generator

Table 3: *Total emissions per unit of fuel and per unit of energy*

Fuel	Total emission*	Fuel’s specific energy (energy per kg)	Total emission per kWh of energy potential
1 kg Methane (natural gas)	**4’600 g CO_2-eq**	14,9 kWh	310 g CO_2-eq
1 kg Propane	**3’350 g CO_2-eq**	13,8 kWh	244 g CO_2-eq
1 kg Bio-Propane	**1’270 g CO_2-eq**	13,8 kWh	92 g CO_2-eq
1 kg Diesel	**3’850 g CO_2-eq**	12,7 kWh	304 g CO_2-eq
1 kg Petrol (gasoline)	**3’940 g CO_2-eq**	12,9 kWh	306 g CO_2-eq
1 kg Methanol	**1’860 g CO_2-eq**	5,5 kWh	340 g CO_2-eq
1 kg Hydrogen – Natural Gas steam Reforming	**7’300 g CO_2-eq**	33,4 kWh	219 g CO_2-eq
1 kg Hydrogen – produced with green energy	**1’840 g CO_2-eq**	33,4 kWh	55 g CO_2-eq
1 kg Hydrogen – produced with average EU grid	**13’535 g CO_2-eq**	33,4 kWh	405 g CO_2-eq

*Includes emissions from both production and combustion of the fuel.

The final impact of a power system is determined by combining fuel-related emissions with the conversion efficiency of the generator.

Fuel emissions are typically expressed per unit of energy content. However, only a fraction of this energy is converted into usable electricity. The remaining energy is lost during the conversion process.

As a result, lower efficiency leads to higher fuel consumption per unit of useful energy, increasing total emissions.

For example:

- Gasoline has an impact of approximately **306 g CO_2-eq per kWh** of energy potential
- When used in a small generator with **16 percent efficiency**, the resulting impact becomes:

  ~1956 g CO_2-eq per kWh of usable energy

This illustrates how conversion efficiency directly amplifies the emissions associated with a given fuel.

In continuous operation scenarios, this effect becomes the dominant driver of total system emissions.

The total emissions of a power system result from the combination of fuel-related emissions and conversion efficiency.

To reflect typical use cases, a distinction is made between:

- **Off-grid power generation**, characterized by smaller systems, lower efficiencies, and continuous operation
- **Utility-scale power generation**, characterized by larger systems, higher efficiencies, and optimized operating conditions

Table 4: *Final emissions per generation type in off-grid operating conditions*

Off-grid power generation			
Generator	**Fuel**	**Conversion efficiency**	**Final emission per kWh of usable energy**
Small generator	Gasoline	16%	**1956 g CO_2-eq**
Direct methanol Fuel Cell	Methanol	26%	**1342 g CO_2-eq**
Solid Oxide Fuel Cell (SOFC) – INERGIO Mini	Propane	35%	**737 g CO_2-eq**
Solid Oxide Fuel Cell (SOFC) – INERGIO Mini	Bio-propane	35%	**239 g CO_2-eq**
Small solar installation 20% energy usage*	Sun	NA	**250 g CO_2-eq**
Solid Oxide Fuel Cell (SOFC) – INERGIO Mini	Green Hydrogen	45%	**157 g CO_2-eq**

*In off-grid setups, solar systems are often oversized to ensure availability during low production periods, resulting in reduced utilization and higher effective emissions per kWh.

Table 5: *Final emissions per generation type in utility-scale operating conditions*

Utility scale power generation			
Generator	**Fuel**	**Conversion efficiency (average values)**	**Final emission per kWh of usable energy**
Large generator	Diesel	40%	**805 g CO_2-eq**
Gas turbine	Natural gas	60%	**431 g CO_2-eq**
Fuel Cell	Natural gas	60%	**406 g CO_2-eq**
Li-batteries power	EU grid power	90% charge-discharge eff.	**522 g CO_2-eq**
Average grid power EU (reference value)	Various	N/A	**295 g CO_2-eq per kWh**
Fuel Cell	Green Hydrogen	60%	**112 g CO_2-eq**
Large solar installation	Sun	N/A	**40 g CO_2-eq**
Wind turbine	Wind	N/A	**12 g CO_2-eq**
Nuclear power plant	Uranium	N/A	**5 g CO_2-eq**

4. End-of-life and disposal

End-of-life and disposal are not the primary focus of this analysis. In most cases, their contribution to total emissions is lower than production and operational phases when evaluated in terms of Global Warming Potential (GWP).

However, end-of-life considerations remain relevant due to differences in recyclability, material composition, and long-term environmental impact across technologies.

Table 6: *End-of-life considerations by generation type*

Generator type	**End-of-life impact**
Diesel generators	Most structural materials can be recycled. Electronic components require more complex treatment, but established recycling processes are available and continue to improve.
Fuel Cells	The majority of materials are recyclable. Electronic components present similar challenges to other systems. Ceramic components are more difficult to recycle but are chemically stable and do not pose significant environmental risks.
Lithium batteries	End-of-life management is a key constraint. Cathode materials represent 30 to 40 percent of total weight and contain substances with environmental impact. Recycling rates remain low, with current estimates around 5 percent. Recycling processes are developing but are expected to remain energy-intensive and cost-sensitive.

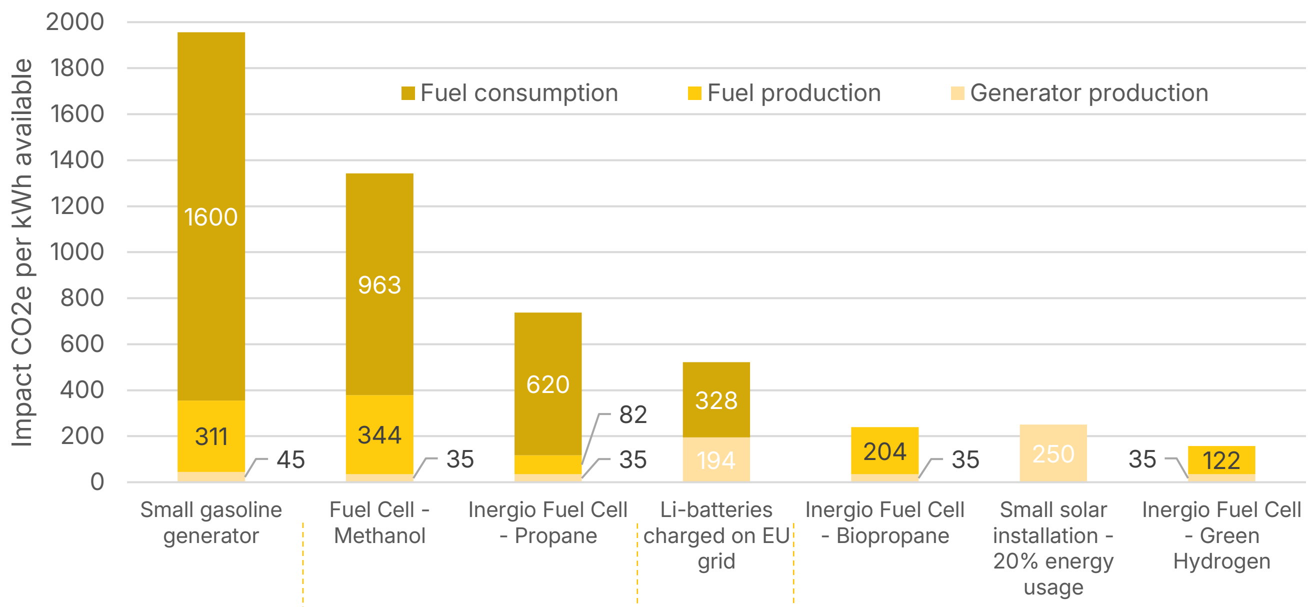
Wind turbines	Metallic components are generally recyclable. Electronic components follow standard recycling processes. Composite materials used in blades are more challenging to recycle and currently represent the main limitation.
Solar panels	Photovoltaic systems are primarily composed of glass, aluminum, silicon, and polymers. A large share of materials, typically 80 to 95 percent depending on panel type, can be recovered. Recycling processes exist but require further scaling and optimization.
Nuclear power plant	End-of-life management is complex due to plant scale and the presence of radioactive materials. Decommissioning requires controlled dismantling and long-term waste management. Nuclear waste remains hazardous over extended timescales and is currently managed through secure geological storage.

Sources for further reading:

- https://www.wired.co.uk/article/lithium-batteries-environment-impact
- https://batteryuniversity.com/learn/article/battery_recycling_as_a_business
- https://www.sciencedirect.com/science/article/pii/S0921344913002541
- https://www.rolandberger.com/en/Insights/Publications/Battery-recycling-is-a-key-market-of-the-future-Is-it-also-an-opportunity-for.html

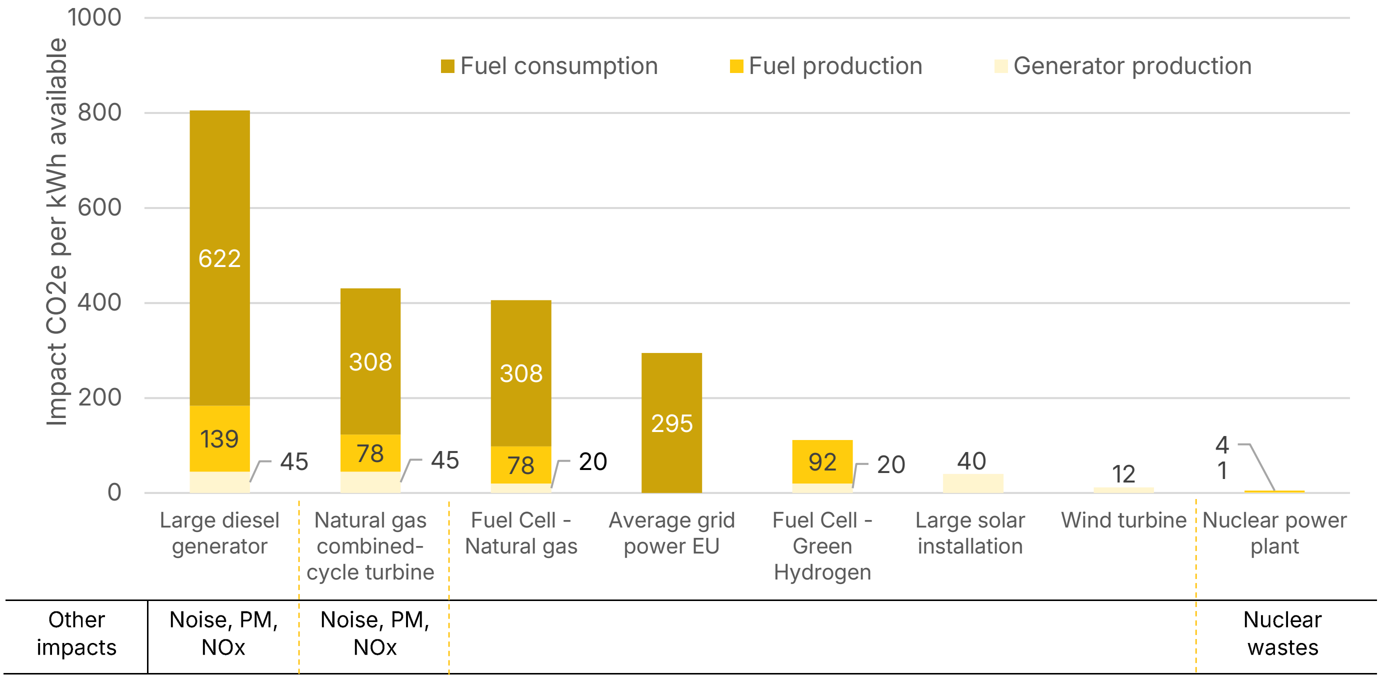
Conclusions

Graph 1: *Total greenhouse gas impact per generator and fuel combination for off-grid power systems*



Other impacts	Noise, particle matter, NOx		Polluting mining and recycling	

***Graph 2:** Total greenhouse gas impact per generator and fuel combination for utility-scale power systems*



Annex A: Units and definitions

The following units are used throughout this analysis:

- **Kilogram of CO_2-equivalent (kg CO_2-eq)** A unit used to express the global warming impact of greenhouse gas emissions. It aggregates the effect of different gases into a single metric based on their relative climate impact.
- **Kilowatt (kW)** A unit of power representing the rate at which energy is generated or consumed. 1 kW = 1,000 watts.
- **Kilowatt-hour (kWh)** A unit of energy representing the amount of energy produced or consumed over time.
  1 kWh corresponds to the energy delivered by a power output of 1 kW over one hour.
- **Kilowatt-peak (kWp)** A unit used to describe the maximum power output of photovoltaic systems under standardized test conditions. These conditions typically include solar irradiance of 1,000 W/m^2 and a cell temperature of 25°C.

Annex B: Manufacturing and installation impact of power generation technologies

Table B1: *Production-related emissions and lifetime energy output*

Type of generator	Manufacturing and transport impact per unit of power installed	Lifetime energy production under standard conditions	Impact per kWh [g CO_2-eq / kWh]	Notes
Solar panel	1350-1450 kg CO_2-eq per kWp	29'750 kWh per kWp	**45 to 50**	Standard conditions for photovoltaic systems are defined in Annex A
Wind turbine (onshore)	600-700 kg CO_2-eq per kW	52'560 kWh per kW	**11 to 13**	Values correspond to utility-scale onshore installations
Wind turbine (offshore)	600-700 kg CO_2-eq per kW	70'560 kWh per kW	**9 to 10**	Higher lifetime output reflects offshore operating conditions
Diesel generator	360 kg CO_2-eq per kW	8'000 kWh per kW	**45**	Based on typical operating lifetime assumptions
Solid Oxide Fuel Cell (SOFC) – INERGIO Mini 200W	525 kg CO_2-eq per kW	15'000 kWh per kW	**35**	Operating lifetime: 15,000 hours
Fuel Cell PEMFC	200 kg CO_2-eq per kW	15'000 kWh per kW	**13**	Assumed operating lifetime: 15,000 to 20,000 hours

➢ Photovoltaic systems (solar panels)

Table B2: *Assumptions for photovoltaic system impact*

Description [unit]	Value
Harmonized PV production [kWh] on lifetime per m2	5355
[m2] for 1kWp PV	5.6
Average impact of PV power [g CO_2-eq / kWh]	45-50
Resulting production GWP [Kg CO_2-eq] per kWp of installed power	**1350-1450**

Standard operating assumptions

The values above are based on the following standardized conditions:

- Annual solar irradiation: 1,700 kWh/m²/year
- System lifetime: 30 years
- Module efficiency: 13.2 to 14.0 percent, depending on module type
- Performance ratio: 0.75 to 0.80

Note: These assumptions represent typical operating conditions used for comparative analysis. Actual performance may vary depending on geographic location, system design, and utilization.

Sources for further reading:
- https://onlinelibrary.wiley.com/doi/full/10.1111/j.1530-9290.2011.00439.x
- https://www.nrel.gov/docs/fy13osti/56487.pdf

➢ Wind turbines

In the absence of directly reported values for production-related emissions per unit of installed power, a reverse calculation approach is applied.

Production impact is derived from:

- Reported average lifecycle emissions (g CO_2-eq per kWh)
- Estimated lifetime energy production per unit of installed capacity

This allows the total production-related emissions per kW of installed power to be estimated.

Table B3: *Assumptions for wind turbine impact*

	Onshore	Offshore
Normalized lifetime (years)	20	20
Average capacity factor	30%	40%
Average impact of wind turbine power [g CO_2-eq / kWh]	15	13
Energy production during lifetime [kWh] per kW of power installed	52’560	70’080
Total [Kg CO_2-eq / kW]	788.4	911.04
Impact production and installation	90%	70%
Production impact [Kg CO_2-eq / kW]	**710**	**638**

The **capacity factor** represents the ratio between actual energy production and the theoretical maximum output under continuous operation.

It is a key parameter in determining emissions per kWh, as it directly affects the total energy produced over the system's lifetime. Lower capacity factors result in higher emissions per unit of energy, as fixed impacts are distributed over a smaller output.

The calculation of CO_2-equivalent emissions per kWh can be expressed as:

$$\frac{CO_2 + \left(CH_4 * 25 \frac{g\ CO_2-eq}{g\ CH_4}\right) + \left(N_2O * 298 \frac{g\ CO_2-eq}{N_2O}\right)}{Capacity\ factor * 8760 \frac{hours}{year} * Lifetime * Nameplate\ capacity}.$$

Where:

- **CH_4** and **N_2O** are weighted by their respective global warming potentials
- **Capacity factor** reflects actual system utilization
- **8760 hours/year** represents total hours in a year
- **Lifetime** is the operational duration of the system
- **Nameplate capacity** is the rated power of the installation

This formulation highlights the direct relationship between utilization, lifetime energy production, and emissions per unit of energy.

Sources for further reading:

- https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1530-9290.2012.00464.x
- https://www.climatexchange.org.uk/media/1459/life_cycle_wind_-_executive_summary_.pdf

➢ Diesel and gasoline generators

Limited data is available on the manufacturing impact of small diesel and gasoline generators. This is primarily because their total lifecycle emissions are dominated by the operational phase.

Based on available estimates, the production and installation impact can be approximated as follows:

Table B4: *Manufacturing and installation impact of small generators*

Description	Value
Power	10 kVA
Manufacturing	3300 kg CO_2-eq
Transport / installation	260 kg CO_2-eq
Total (prod + install)	**3560 kg CO_2-eq**
Impact per power unit	356 kg CO_2-eq per kVA
Energy produced over lifetime	80'000 kWh
Impact on final energy production (prod + install)	**45 g CO_2-eq per kWh**

Assumptions

- Lifetime operation is based on approximately **8,000 hours at nominal power**

Note: Although production-related emissions are measurable, they remain relatively small compared to operational emissions, particularly in continuous-use scenarios where fuel consumption dominates total impact.

Sources for further reading:

- https://www.diva-portal.org/smash/get/diva2:471380/FULLTEXT02.pdf

Solid oxide fuel cells (SOFC)

Solid oxide fuel cell (SOFC) technology shows a wide range of values for production-related emissions. This variability is primarily driven by system size, design complexity, and manufacturing processes.

***Table B5:** Production-related emissions of solid oxide fuel cell (SOFC) systems*

Description	Production impact [kg CO_2-eq]	Lifetime energy production (kWh)	Production-related impact (g CO_2-eq/kWh)	Notes
Micro-tubular SOFC (100 W)	363	2000	**181**	Based on ~20,000 operating hours
SOFC stack (100 kW system)	2404	4’000’000	**0.6**	Based on ~40,000 operating hours
SOFC with gas turbine (3 kW)	1673	60000	**28**	Based on ~20,000 operating hours
INERGIO Mini (200 W)	105	3,000	**35**	Based on ~15,000 operating hours

Notes

Production-related emissions for SOFC systems vary significantly depending on system scale.

- Smaller systems typically show higher emissions per kWh due to lower total lifetime energy output and higher relative manufacturing complexity
- Larger systems benefit from scale effects, resulting in lower emissions per unit of energy produced

Hybrid configurations, such as SOFC systems combined with gas turbines, can achieve intermediate values depending on system design and operating conditions.

For comparative purposes, representative benchmark values are defined based on the range of results observed in the literature and internal reference systems:

- Small-scale SOFC systems are approximated at ~35 g CO_2-eq/kWh, reflecting higher relative manufacturing impact and lower lifetime energy output
- Large-scale SOFC systems are approximated at ~25 g CO_2-eq/kWh, reflecting scale effects and higher lifetime energy production

For comparability, large-scale SOFC values are normalized to a common lifetime basis of 15,000 operating hours, consistent with small-scale systems, although actual operating lifetimes may be higher.

Sources for further reading:

1. Life Cycle Assessment of microtubular Solid Oxide Fuel Cell based Auxiliary Power Unit systems for recreational vehicles, 2017
2. Comparative environmental profile assessments of commercial and novel material structures for solid oxide fuel cells, 2019
3. Environomic design for electric vehicles with an integrated solid oxide fuel cell (SOFC) unit as a range extender, 2017

➢ Proton exchange membrane fuel cells (PEMFC)

Proton exchange membrane fuel cell (PEMFC) systems have been assessed across different scales. Reported values show variability depending on system size, application, and operating assumptions.

Table B6: *Production impact of PEMFC systems*

Description	Production impact [kg CO_2-eq]	Lifetime energy production (kWh)	Production-related impact (g CO_2-eq/kWh)	Notes
PEMFC system (1 kW)	112	20’000	**6**	Based on ~20,000 operating hours
PEMFC system (80 kW, automotive application)	16’000	1’200’000	**13**	Based on ~15,000 operating hours

Notes

Reported values for small-scale PEMFC systems show lower production-related emissions per kWh compared to larger systems. This may reflect differences in system boundaries, assumptions, or data sources.

For consistency in this analysis, a representative value of: **~13 g CO_2-eq per kWh**

is used for PEMFC systems, based on values reported for larger-scale applications.

This value represents production and installation impacts only and is aligned with typical operating lifetimes.

Sources for further reading:

1. Critical materials in PEMFC systems and a LCA analysis for the potential reduction of environmental impacts with EoL strategies, 2019
2. Life cycle assessment of a polymer electrolyte membrane fuel cell system for passenger vehicles, 2017

Annex C: Fuel production and consumption impact

Before use, fuels must be produced or extracted and transported to the point of consumption. These stages contribute to the overall greenhouse gas impact of the energy system.

Two components are considered:

- **Production impact (well-to-tank):** emissions from extraction, processing, and transport, expressed in kg CO_2-eq per kg of fuel

- **Consumption impact:** emissions generated during use, expressed in kg CO_2-eq per kg of fuel

Each fuel is also characterized by its **specific energy**, defined as the chemical energy per unit of mass (Wh/kg or kWh/kg). This allows emissions to be normalized per unit of energy and compared across fuels.

Table C1: *Fuel properties and associated emissions*

Fuel	**Equivalent storage**	**Emission for production**	**Emission when consumed**	**Specific energy in (energetic potential)**
1 kg Methane (natural gas)	250 bar, 6 liters	**1’800 g CO_2-eq**	**2’750 g CO_2-eq**	14,9 kWh
1 kg Propane	7 bar, 2 liters	**400 g CO_2-eq**	**3’000 g CO_2-eq**	13,8 kWh
1 kg Bio-Propane	7 bar, 2 liters	**1’270 g CO_2-eq**	**0 g CO_2-eq***	13,8 kWh
1 kg Diesel	Liquid, 1.2 liter	**700 g CO_2-eq**	**3’150 g CO_2-eq**	12,7 kWh
1 kg Petrol (gasoline)	Liquid, 1.4 liter	**640 g CO_2-eq**	**3’300 g CO_2-eq**	12,9 kWh
1 kg Methanol	Liquid, 1.3 liter	**500 g CO_2-eq**	**1’370 g CO_2-eq**	5,5 kWh
1 kg Hydrogen - natural gas steam reforming	200 bar, 60 liter	**7’300 g CO_2-eq**	**0 g CO_2-eq**	33,4 kWh
1 kg Hydrogen – produced with green energy		**1’840 g CO_2-eq**	**0 g CO_2-eq**	
1 kg Hydrogen - produced with average EU grid		**13’535 g CO_2-eq**	**0 g CO_2-eq**	

*Emissions from bio-propane combustion are considered carbon-neutral, as they originate from biogenic sources.

- **Bio-propane** results in CO_2 emissions during combustion; however, these are considered biogenic and are typically accounted as carbon-neutral. Production-related emissions remain higher than for fossil propane.

- **Methane and hydrogen** require high-pressure storage. Due to its low density, hydrogen requires significantly larger storage volumes. For example, 1 kg of hydrogen occupies approximately 60 liters at 200 bars.

- **Hydrogen production pathways** show significant variability in emissions. Steam methane reforming results in high CO_2 emissions, while electrolysis can result in lower emissions when powered by renewable electricity. When powered by carbon-intensive grids, electrolysis can result in higher emissions than fossil fuels.

- **Current hydrogen production** is predominantly based on natural gas reforming, which contributes to its overall carbon footprint.

- **Propane storage** is facilitated by its ability to liquefy at moderate pressure (approximately 7 bar), making it easier to handle compared to other gaseous fuels.

- **Liquid fuels** such as diesel and gasoline offer high energy density and established storage and transport infrastructure, which contributes to their widespread use.

Annex D: Sources for fuel impact and end-of-life analysis

Sources for fuel properties and emissions

- CO2 emission per fuel: https://www.engineeringtoolbox.com/co2-emission-fuels-d_1085.html
- Impact of lead batteries: https://download.schneider-electric.com/files?p_enDocType=White+Paper&p_File_Name=VAVR-9KZQVW_R0_EN.pdf&p_Doc_Ref=SPD_VAVR-9KZQVW_EN
- Impact of lead batteries: https://en.wikipedia.org/wiki/Lead%E2%80%93acid_battery
- Co2 impact of EU grid: https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-6
- LPG impact: https://auto-gas.net/wp-content/uploads/2019/11/2017-WLPGA-Literature-Review.pdf
- Hydrogen production impact : https://www.epa.gov/sites/production/files/2015-02/documents/subpartp-tsd_hydrogenproduction.pdf
- GHG impact of different energy sources: https://en.wikipedia.org/wiki/Life-cycle_greenhouse_gas_emissions_of_energy_sources
- Fuel production impact : https://www.mizuho-ir.co.jp/english/knowledge/report/pdf/wtwghg041130.pdf
- Bio propane impact: https://onlinelibrary.wiley.com/doi/full/10.1002/bbb.1796
- Bio propane cost and impact: https://www.eua.org.uk/uploads/57304E46AB047.pdf
- Efficient Operation of Diesel Generator Sets in Remote Environments, Kaitlyn R. Wheeler
- Renewable and Nuclear energy impact: https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1911_web.pdf

Sources for end-of-life considerations

- Wind turbine end-of-life: characterization of waste material, University of Gävle, 2015
- An investigation into end-of-life management of solid oxide fuel cells, Loughborough University, 2007
- https://cen.acs.org/materials/energy-storage/time-serious-recycling-lithium/97/i28
- https://www.greenmatch.co.uk/blog/2017/10/the-opportunities-of-solar-panel-recycling

For questions regarding the analysis or to discuss specific off-grid applications, contact INERGIO at info@inergio.com or visit inergio.com.