EEB
European Environmental Bureau

RESET

Reference Environmental Standards for Energy Techniques

GUIDANCE

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Who we are

The European Environmental Bureau (EEB) is the largest network of environmental citizens' organisations in Europe. It currently consists of around 150 member organisations in more than 30 countries, including a growing number of European networks, and representing some 30 million individual members and supporters.

The RESET project is at the core of the EEB missions by providing a comprehensive assessment at the crossroad of sustainable development, environmental protection, climate change mitigation and clean energy deployment.

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Table of contents

Executive summary

The Reference Environmental Standards for Energy Techniques (RESET) project is a tool to assess environmental impacts of energy generation technologies on equal footing, from mining to recycling, and to provide recommendations of Best Available Techniques (BAT). Impacts on land, soil, air, climate and energy payback time have been assessed for eight technologies: biogas, coal, fossil gas, geothermal energy, hydropower, solar PV, solid biomass and wind.

On **land use**, rooftop solar PV could be the least surface-demanding technology, together with biogas and closely followed by fossil fuels, with hard coal and gas. When integrating the need for mining however, lignite can show highest impacts on disruptive land use. Expectedly, bioenergy with dedicated crops shows among the highest impacts, only exceeded by some hydropower dams.

On **water use**, renewables such as solar PV, geothermal, biogas and wind show the lowest impact, while technologies with combustion of solid fuels such as lignite/coal and biomass, and fossil gas show medium to high impacts. Due to cooling requirements, also geothermal could show moderate impacts. Expectedly, hydropower shows the highest impact, with however important site-specific variations.

The picture is more complex on **air pollution**. If coal/lignite, fossil gas and solid biomass are the worst polluters, some renewable technologies might show substantial emissions, too. This is the case for solar PV, of which manufacturing process could generate SOx and PM emissions due to fossil fuel use for extraction and manufacturing. Biogas from energy crops can also show high emissions. Among all technologies, geothermal, hydropower and wind show the lowest impact.

On **climate**, the picture is clearer: renewables always rank better than fossil fuels, with sometimes 100 times lower emissions and sometimes even negative emissions for waste derived biogas. This remains true when including the whole life cycle assessment of technologies. In the context of climate emergency that threatens all environmental areas, this is a pivotal point to be considered.

On **Energy Payback Time**, renewables also perform much better than their fossil competitors, with sometimes less than one year to generate back the whole energy consumed during their lifetime. This is true for wind, hydropower and some geothermal and solar PV.

The results of the RESET project clearly confirms that no energy source is 100% clean, but that renewables are part of the most cost-effective solution towards a net zero energy system and zero pollution transition. Since the greatest impacts of renewables occur during the extraction and construction phase, progress can be made through efficiency gains and a clean local energy mix during construction. On the contrary, fossil fuels emit during their entire lifecycle and thus do not meet the environmental requirements of our future energy system.

Introduction

The RESET project aims to assess the environmental impacts of different energy supply options at installation level comparatively to their energy output. It is a tool aimed at supporting civil society and policy makers in their delivery of national and local solutions for better understanding the impacts of energy generation and move towards a cleaner energy mix.

The RESET project is inspired by the approach to define best available techniques (BAT) and best environmental practices for industrial activities but adapted to NGO focus as to intended outcomes. It aims to provide insights as to what constitutes BAT when considering the various options.

The following guidance includes a selected list of technologies under scrutiny, a detailed description of the methodology behind the RESET project, data sources as well as an assessment of technologies. Based on the identified results essential recommendations and conclusions are drawn.

Background

The RESET project (Reference Environmental Standards for Energy Techniques) has been initiated by the EEB to provide a simple tool to assess the environmental impacts of energy generation (in this case electricity generation) and identify best available techniques to mitigate these impacts. The project originates from four elements.

1. The Industrial Emissions Directive (IED) is currently the main tool to define what constitutes best available techniques (BAT) as to various options on how to conduct an industrial activity. BAT constitutes the most effective and advanced stage in the development of activities and their methods of operation designed to prevent, and where not practicable, to reduce negative impacts on the environment. The IED follows the so-called integrated approach on pollution prevention and control, aiming to achieve a high general level of environmental and human health protection. The term “techniques” includes both technology but also the way in which the activity is designed, built, maintained, and operated. The environmental aspects to be considered include both emissions to all various media (e.g. air, soil, water, accidents) but also the resource inputs and outputs (resource type and amount, waste etc.) Whilst the BAT criteria also provide for a circular economy approach the fundamental limitations of the current

framework are limited as to the scope design. Whilst energy activities are listed in Annex I of the IED, it only covers a sub-set of energy industries that are by scale and type very polluting (e.g. thermal power plants with boiler size >50MWth), therefore the framework does not yet enable a fuller assessment of the identification of best methods of all type of solutions available to deliver the desired outputs. The most relevant BREF for energy generation are the Large Combustion plants BREF, Refineries BREF, Iron and Steel BREF (see full list of EU BREFs). The RESET project takes inspirations from the BREF information exchange and BAT determination method as to the topical issues to be addressed, the consideration of cross-media impacts, the integrated and fact-driven approach of the BREF information exchange. However, we derived the best in class with a much broader range of techniques to deliver the intended outputs (beyond combustion techniques only), and we include several missing impacts, such as land use or climate change.

2. The Paris Agreement Compatible (PAC) scenario, presented in 2020 by the European Environmental Bureau (EEB) and Climate Action Network (CAN) Europe. This energy scenario has shown that a fully renewable energy system is not only technically feasible by 2040, but also indispensable to reach our commitments under the Paris Agreement. While the climate benefits of renewable energy vs. fossil fuels are evident, wider benefits and potential impacts of renewables need to be considered.

3. The Environmental Impact Assessment (EIA) Directive, revised in 2014, provides a complete methodology to assess the environmental impacts of projects (including energy generation). It provides tools to analyze environmental areas and their sensitivities. However, the impact assessment process is not connected to the value of the project for the energy system. The RESET approach proposes to extract representative impacts on selected environmental areas from the impact assessment methodology.

4. The Life Cycle Assessment (LCA) methodology assesses the impact of products along their whole value chain, from the extraction to the end-of-life. This is extremely relevant for the energy sector, where impacts might happen beyond the operational phase. The RESET project proposes, where available, an analysis of the impact on the whole value chain of energy projects.

The RESET project brings together these approaches via an objective and an operational tool to identify the environmental impacts of energy generation from mining to recycling and provides recommendations of Best Available Techniques (BAT) to our zero pollution and zero emissions objectives.

The project also adapts the BAT structure used in the EU BREFs with the objective to present, for each environmental area, the performance of a unit versus the best performers of the same technology and the best available techniques (BAT) to improve the performance of that unit.

The section “results by environmental area” presents the methodology applied for the analysis of the impact on that specific area as well as a summary of different technologies' performance on the applicable Key Environmental indicators.

The “results by technology” summarizes energy technologies’ performance in the different environmental areas (soil pollution, land use, water pollution, water use, air pollution, greenhouse gases, material use) and pairs them with the energy value. The section also highlights data completeness and identifies the degree to which further research is needed.

Scope

The aim of the guidance is to provide a detailed description to inform interested parties about the objectives of the project, its methodology and findings.

Where data is available, the RESET project focuses on an analysis of **environmental impacts of energy technologies at installation level**.

The RESET project is not meant to become a substitute to the official BREFs such as the Large Combustion Plants or Energy Efficiency BREF, or a substitute for environmental impact assessment or life cycle assessment at project level. It is designed as an evolutive tool to accompany assessment and decision making based on a solid and reproductible methodology.

The project focuses on the environmental impacts of energy supply technologies (mostly electricity and for geothermal heat) at project level. The assessment includes a list of major environmental impacts occurring at the full life cycle of the energy projects, e.g. pollutants and disturbances such as resource consumption and impacts on the following environmental areas: air, water, soil, land, climate, and materials where available.

Where available, the RESET project uses a formula to propose a generic ranking (from -5 to 5 - see Methodology chapter for more details), and identifies a margin of progress and best available techniques for each environmental area (air, water, soil, climate and materials where available) applied to each energy technology, considering all relevant impacts and applicability considerations such as technology readiness levels or feasibility.

The graph below summarizes the inputs and deliverables associated with the RESET project.

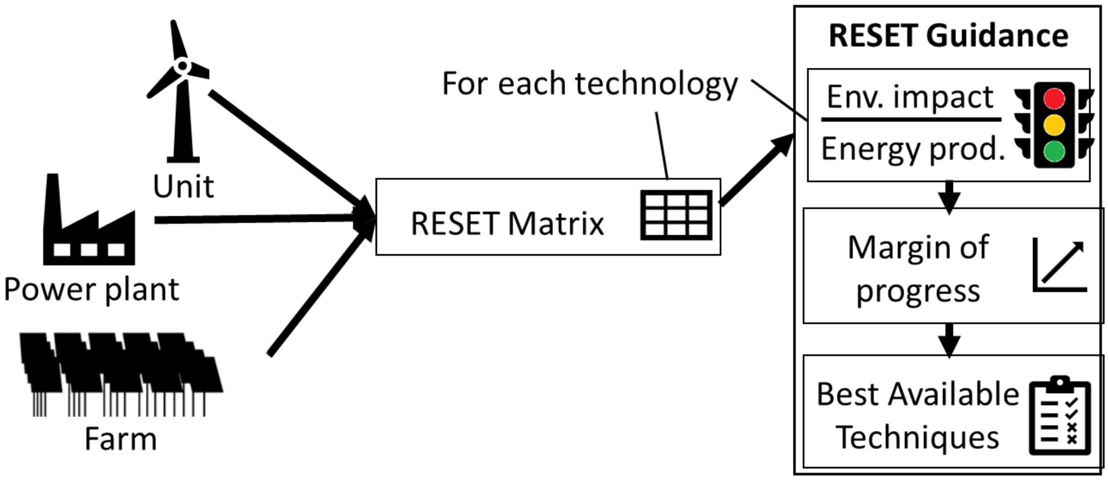


Figure 1: Scope and deliverables of the RESET project

List of technologies

The RESET analysis focuses on major technologies from the Paris Agreement Compatible (PAC) scenario. Among these technologies, it has selected the most relevant ones, considering their share in final energy demand and the availability of data. The list of representative technologies can be consulted in the table below and its selection criteria can be found in the *Data source* chapter.

Due to the timeframe and availability of data, the RESET assessment includes mostly electricity-generation technologies. For operational reasons and comparability, energy technologies for transport are not considered.

	Share in primary supply			Included in RESET ?
	2020	**2040**	**2050**	
Non-renewables	82%	5%	0%	
Coal (including with CCS)	12%	0%	0%	YES
Fossil oil products (including with CCS)	26%	0%	0%	NO
Fossil gas	25%	0%	0%	YES
Municipal waste (non-renewable)	1%	0%	0%	NO
Nuclear	18%	5%	0%	NO
Renewables	18%	95%	100%	
Bioenergy	10%	8%	7%	
Solid biomass	6%	5%	5%	YES
Liquid biofuels	2%	1%	0%	NO
Biogas	1%	1%	1%	YES
Biomethane	0%	1%	1%	YES
Municipal solid waste (renewable)	1%	0%	0%	NO
Renewable electricity	7%	74%	81%	
Wind (onshore + offshore)	4%	41%	46%	YES
Solar PV (individual + ground-mounted)	1%	29%	31%	YES
Hydropower	2%	4%	4%	YES
Ocean energy	0%	0%	0%	NO
Geothermal energy				YES
Concentrated solar power (CSP)				NO
Renewable heat	1%	13%	13%	
Ambient heat captured by heat pumps	0%	10%	9%	NO
Geothermal energy	0%	2%	2%	PARTIALLY
Solar thermal heat	0%	1%	1%	NO

Table 1: List of energy technologies and their share in primary energy supply

Methodology

Identification of environmental areas

As set out in the Environmental Impact Directive 2014/52/EU, when carrying out an impact assessment the following environmental areas (and potential cumulated effects) need to be taken into consideration:

- Population and human health
- Biodiversity[1]
- Land, soil, water, air and climate[2] and fitness for zero pollution ambition (e.g. resource availability)
- Material assets, cultural heritage and landscape
- The vulnerability of the project to climate change
- The interaction between the factors above

For the RESET project and considering the availability of data, only impacts on land, soil, air, and climate have been assessed. Materials have been assessed for technologies where data was available.

This RESET analysis assesses releases (emissions) or other negative impacts (disturbances) on air, water, soil and climate and provides an understanding of the scale of those impacts per unit of energy generated, with metrics such as kg of CO2 per MWh of electricity generated - over the whole lifetime of the installation. It also provides, where available, an analysis of material consumption and waste generation. A full-fledged analysis of the environmental impacts on human health or the environment lies beyond the scope of the RESET project.

Definition of environmental impact

The **environmental impact** is determined by a measurable **effect**, usually expressed as pollutant output, crossed with the environment's **sensitivity** which comprises aspects of tolerance and resilience[3] (see formula below). Impacts are strongly related to the specific features of the local environment where the project is developed.

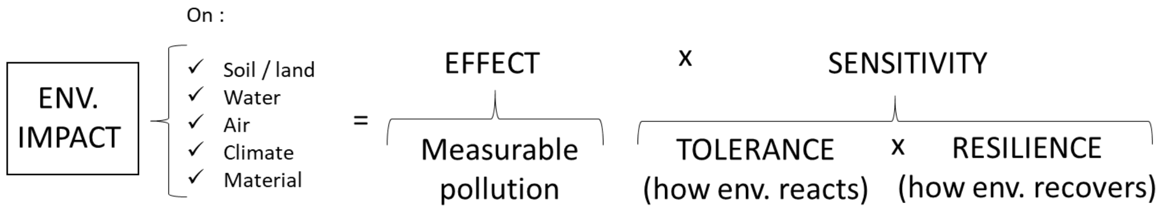


Figure 2: Definition of environmental impact

By analysing the environmental impacts of an existing project, successive adjustments can be suggested based on the information gathered to eliminate or, if not possible, to mitigate certain negative effects at the source. Following the determination of the effects, the impacts are prioritized based on an appreciation of the sensitivity of the affected environmental components.

The **effect** can be described as the consequence of the project's interaction with the surrounding environment, whilst the **impact** is the transposition of this consequence to the different environmental areas according to a sensitivity scale.

Sensitivity is understood as the potential of the environmental receptor to be affected. This includes the reaction of the ecosystem's species to the changes brought by the project (the tolerance) and the receptor's capacity to recover from the changes brought by the project (the resilience).

The RESET project assesses effects in the format of Key Environmental Indicators (see below for more details). The sensitivity analysis is excluded from the RESET impact assessment considering the availability of data and the focus of the project on pollutant output per unit of energy. It is (where relevant) part of the best available techniques and recommendations.

Selection of Key Environmental Indicators (KEI)

To evaluate the environmental **effects**, the RESET project identifies and focuses on a list of major pollutants and disturbances for the five environmental areas identified above: land / soil, water, air, climate, and materials. All effects are analyzed throughout the project life cycle (from material extraction to end-of-life), via the following four life-cycle phases:

- Manufacturing (including extraction and transport to the site)
- Construction
- Operation
- End of life (including decommissioning and recycling)

The RESET methodology is generic and proposes a set of **key environmental indicators** (KEI) that applies – where data is available - to each technology. The list of key environmental indicators is presented in Annex I. These KEI are selected as the most relevant pollutants and disturbances that can occur from energy generation – and have been summed for each phase of the lifecycle where available.

To select a short list of pollutants and disturbances that are significant for energy technologies, the RESET matrix selected the KEI in order of priority as determined during the Kick-off meeting – see *Data Source* chapter.

DISCLAIMER: As far as possible, the RESET project tried to streamline data collection and to analyse the impacts for all relevant phases of life cycle for each energy technology with comparable methodology. The RESET project has paid particular attention to collect comparable data for each technology and to perform ex-post data correction to make it consistent between different sources. Despite these corrections, it remains possible that the scope of the life cycle analysis differs between two energy technologies, making it sometimes challenging to compare. In these cases, the RESET Project specifies these discrepancies and limitations in the chapter *Results by technology*.

Final assessment: Environmental Score (Escore)

To facilitate the interpretation of the results and to put all generating assets on equal footing, all Key Environmental Indicators (KEI) have been translated in a relative scale of impacts ranging from -5 to 5: the **Environmental Score (Escore)**. For each environmental area, this scale would follow the same rule, and the technology would score:

- Below 0 if it shows "negative" impacts (e.g. biogas showing GHG credits by avoiding methane emissions)
- 0 if it shows virtually no impact in the concerned environmental area (e.g. rooftop solar PV having no impact on land use)
- 1 if it shows the lowest impact among all technologies (e.g. geothermal power on air emissions)
- 5 if it shows the highest impact among all technologies (e.g. coal on air emissions)

Due to high deviations between the values of Key Environmental Indicators, a logarithmic scale has been used for the extrapolation between 1 and 5. With these rules, the formula used for the calculation of Escore is the following:

$$If\ KEI = 0\ then\ Escore = 0$$
$$Else$$
$$Escore = sign(KEI) * (1 + LOG\left(\frac{ABS(KEI)}{KEImin+}\right) * \frac{4}{LOG\left(\frac{KEImax}{KEImin+}\right)})$$

Where:

- KEI is the value of the Key Environmental Indicator for the technology considered
- KEImin+ is the lowest positive value for this KEI among all technologies
- KEImax is the highest absolute value for the KEI among all technologies

When taking the example of **climate impacts for solar rooftop technology**, the formula above would provide:

- KEI (solar PV_rooftop) = 10 kgCO2eq/MWh
- KEImin+ = 2 kgCO2eq/MWh (corresponding to the best hydropower)
- KEImax = 1300 kgCO2eq/MWh (corresponding to the worst fossil gas)

$$Escore = sign(10) * (1 + LOG\left(\frac{ABS(10)}{2}\right) * \frac{4}{LOG\left(\frac{1300}{2}\right)})$$

$$Escore = 1 * (1 + 0.70 * \frac{4}{2.81})$$

$$Escore = 1.99/5$$

These results are presented in the chapter *Results by technology*. Where several KEI enter into account for the calculation of the Escore of a specific environmental area (ex: SO2eq and PM for air pollution), the result is the average of Escores for each pollutant.

Assessment of Data Completeness

For each technology, the RESET report presents an overview of data completeness for the following environmental areas:

- Land use
- Water pollution
- Water use
- Air pollution
- Climate
- Material use (where available)
- Energy

The data completeness score reflects in a simplified approach the following dimensions:

- Data consistency, i.e. the availability of data from the same source and with the same collection methodology
- Data representativeness, i.e. the availability of at least two different case studies with sufficient differences reflecting the reality of the technology
- Data comprehensiveness, i.e. the availability of information for each sub-area and each pollutant considered.

For example, when analyzing the data completeness of Solar PV for Water Pollution, the following data was available:

Data availability / pollutant	Metal emissions	Mercury emissions	WFD substances	Groundwater pollution
Solar PV – min. value	NO	YES (utility)	NO	NO
Solar PV – max. value	NO	YES (rooftop)	NO	NO

In this case, both data on Mercury emission is considered complete, with a range of examples available. The data on other pollutants is however missing, making the final calculation of Escore based only on Mercury and therefore less representative. In this example, data completeness for water pollution would be 2/8 = **25%**.

Identification of Best Available Techniques and margin of progress

The BAT assessment is a simplified and policy-oriented adaptation of the 10 heading BAT structure used in the EU BREFs, such as the BAT Reference Document (BREF) for Large Combustion Plants, adapted to all energy generation technologies. It presents, for each environmental area:

- The performance of the unit vs. the best performers of the same technology

- The best available techniques (BAT) to improve the performance of the unit

The definition of Best Available Techniques encompasses all most relevant life cycle phases and propose, inter alia:

- Technical upgrades to prevent/mitigate the negative environmental impact
- Techniques to reduce pollutant(s) output and/or reduce environmental footprint of the activity (e.g. resource inputs)
- Construction techniques to mitigate the environmental impact
- Recycling and circular economy processes to limit raw material consumption
- Siting and on-site mitigation measures
- Potential cross-media issues to consider
- In the last resort, compensation measures

For each Key Environmental Area, the margin of progress to mitigate adverse impacts with Best Available Techniques has been transposed in the following indicative scale:

- **Low** if most techniques to limit emissions are already implemented and the remaining emissions cannot be easily abated (e.g. Climate impacts for coal)
- **Moderate** if the current learning curve of technologies could lead to some emission reduction in the future (e.g. evolution of PV efficiency leading to lower land use)
- **High** if most of the improvements are not implemented yet but available on the market and will be implemented in the future (e.g. higher recycling rates for wind leading to substantially lower material impacts)

REMINDER: Original BAT 10 heading structure should include, for each technique:

- Description
- Technical description
- Achieved environmental benefits
- Environmental performance and operational data
- Cross-media effects
- Technical considerations relevant to applicability
- Economics
- Driving force of implementation
- Example plants
- Reference literature

Data source

Stakeholders' participation

The participation and contribution of various stakeholders was central to the elaboration and improvement of the RESET methodology and matrix. From the early stages of the project, various organizations and institutions provided input on the soundness and validity of the identified methodology as well as peer-reviewed and scientific literature. During the RESET kick-off meeting, attendees provided inputs through **participatory polls** concerning the list of representative technologies, pollutants and disturbances, Key Energy and Key Environmental Indicators. Participants provided qualitative inputs and estimates on pollutants and disturbances as well as an assessment of which process of the value chain was most concerned. Furthermore, a rough analysis of the margin of progress on various pollutants and Best Available Techniques was carried out. Throughout their assessment, energy experts also tried to indicate at which process of the value chain the impact occurs. If the impact occurs at multiple stages of the value chain, they were asked to identify where the highest impact occurs.

Close-knit collaboration with industry, NGOs and other stakeholders continued throughout the next stages of the project.

Poll results

Criteria for **choosing the list of technologies** presented in order of priority as determined during the Kick-off meeting:

1. The share in final energy demand by 2040 (based on the PAC scenario[4])
2. The availability of environmental and energy data
3. The relative increase of the share from 2020 to 2040 in %
4. The share in final energy demand in 2020

Criteria for **choosing the list of pollutants and disturbances** presented in order of priority as determined during the Kick-off meeting:

1. The contribution of the energy sector to the overall pollutant output (%)
2. The identification of the pollutant as major public health[5] or environmental concern[6]
3. The number of environmental areas potentially affected by the pollutant

Criteria for **choosing the list of material consumption** presented in order of priority as determined during the Kick-off meeting:

1. The "circulability" of material (technical/financial feasibility)
2. The environmental impact/risk attached to the extraction process
3. The strategic importance for the industry, i.e. the contribution of the energy sector to the overall material consumption (%)
4. The substitutability of the material in mid/long short-term
5. The security of supply (diversity of sources + geographical distribution)

List of data used for input

List of literature used for the RESET analysis can be found in Annex IV.

Results by environmental area

This chapter presents the range of potential impacts for a selection of energy technologies depending on data availability. The detailed results from the RESET Matrix can be found in Annex II and the detailed results for each technology under the chapter *Results by technology*.

Soil

Methodology

The analysis of the soil compartment has been performed for most power generating technologies. The selected KEI (Key Environmental Indicator) for soil is land use (in km^2/TWh). The analysis of chemical soil pollution has not been performed due to data scarcity. Land use corresponds to the surface necessary to produce a given quantity of energy (here, one terawatt-hour). For solar PV, wind and hydropower, the result corresponds to the land area occupied or modified on-site by specific projects. The land area used for mining the fuel has been added for coal, using average value for lignite extraction. For biogas and solid biomass, the results have been calculated also by using the surface necessary to produce the feedstock, using the highest value for energy crops. For hydropower, the whole catchment area has been taken into consideration for the maximum value. When it comes to pump-storage (i.e. artificial reservoirs with no run-of-river dam), only the surface of the reservoirs has been taken into account. For solar PV and wind, an indicator of total artificialized land has been added to calculate the Escore for land use. This indicator has not been presented in this section and is available under Annex II.

For each technology displayed below, a range of impacts – including minimal and maximal land use for each technology - has been extracted from the literature and from impact assessments at installation level. When only one value is available, the range corresponds to the order of magnitude of the value for land use. Given the broad range of results for the technologies considered, the graph below displays results on a logarithmic scale, ranging from 0.001 to 1000 km^2/TWh. Please note that the positions of the technologies on the scale are to be considered indicative. Only the numerical values as described in the section "results" should prevail. Details of the sources are included for each technology under the chapter "results by technology".

Results

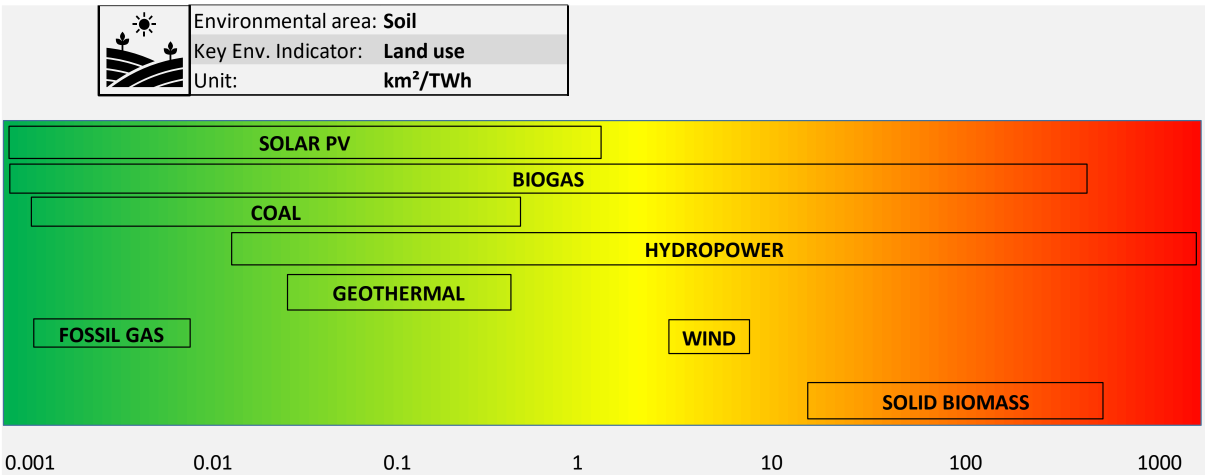


Figure 3: Land use of different energy technologies (indicative position)

Solar PV presents the lowest impact on land use, with virtually no impact for residential and commercial installations. In these cases, PV panels are installed on the top of existing roofs, hence not creating any pressure on land. For utility-scale solar PV, a moderate impact could exist, with around 1km²/TWh[7] of land-use for ground-mounted projects. This surface remains however limited compared with other renewables due to the high power density of solar PV. This figure will also gradually lower due to the improvements of PV panels efficiency and could be reduced via better energy conversion efficiency of solar PV panels, such as sun tracking techniques. To be also noted that the share of artificialized land by PV farms remains therefore limited, with around 2.5% of total land use actually occupied by PV installation and equipment[8].

Biogas also shows an excellent score when using only waste and residues, and no dedicated energy crops. If digesters using only energy crops can show very high land use (up to 349 km²/TWh[9]), they do not constitute the majority of biogas plants today. When taking an average feedstock mix with 30% energy crops[10], the impact would drop to around 77 km²/TWh[11].

Expectedly, **fossil fuels** also perform rather well in term of land use. The limited surfaces of the power plants compared with their total production allows them to rank at the lowest environmental impact, with around 0.005 km²/TWh for both fossil gas[12] and coal[13]. However, when considering the area used for lignite mining, the impact of a lignite power plant is around 100 times higher than a gas power plant. In Germany for instance, the surface used for lignite mining can go up to 0.8 km²/TWh[14], 40 times higher than the surface used for hydropower reservoir.

One of the technologies with the broadest range of impacts on land use is **hydropower.** With the lowest value of around 0,024 km²/TWh[15], this technology could be among the best performing ones when using the technique of artificial reservoir storage only. However, when considering the whole water catchment area of run-of-river hydropower, the impact of hydropower could be very high, with up to 2750 km²/TWh[16]. This means that, when building a dam on a river, the impact on land use could range way beyond the reservoir surface and affect the whole river basin. This could be marginally mitigated by upgrading the hydro power plant with more efficient turbines or only building artificial pumped storage facilities. However, the potential for large-scale hydropower deployment remains limited, and, for the reasons above, the tendency would be rather a status-quo for hydropower in the future, as shown in the Paris-Agreement Compatible (PAC) scenario[17].

Geothermal energy directly follows hydropower in the lowest value for land use impact. Geothermal power is a surface-efficient-technology. With a range from 0.04 to 0.4 km²/TWh[18], geothermal power is comparable with coal in terms of impacts on land use. With most energy collection happening underground, the limited surface of the power plant compared with a high electrical capacity makes a high areal density compared with other energy technologies. Geothermal heating and cooling projects show even better scores.

Following geothermal power and with a capacity density of 3.8 MW/km² for onshore[19] and 5.4 MW/km² for offshore[20], **wind** shows a moderate land use compared with other renewable energy sources.

The offshore technology shows the lowest impact on surface with a land use around 3 km²/TWh, while onshore wind uses around twice this surface for the same energy produced[21]. The better ranking of offshore technology is due to the combination of larger turbines and higher load factors (due to more regular wind) for offshore wind parks.

It is important to note that, contrary to fossil fuels, a limited share of the land is actually artificialized by wind turbines foundations and installations (typically below 1% of total land use[22]). The rest of the land or seabed remains untouched and can be used for agriculture or even be converted into nature conservation or aquaculture areas for offshore wind parks[23].

When using **solid biomass** from energy crops, biomass shows high to very high impacts on land use, with land use ranging from 20[24] to 623[25] km²/TWh, making it the technology of highest impact together with hydropower.

This is mostly due to the use of dedicated energy crops. In the absence of data, the impact of solid biomass from agricultural or forest residues has not been measured and could be substantially lower than from energy crops. For instance, with an average biomass mix including 30% energy crops and the rest covered by waste and residues, the impact would range from 6 to 187 km²/TWh, which lower range would be comparable with wind.

Water

Methodology

The impacts on water were researched for all major power generating technologies. The selected KEI for water are physical disturbances represented by the water consumption and chemical pollution indicated by metals and their compounds such as mercury, other substances that negatively affect the good chemical/ecological status (set under the EQS-Directive) and substances that are subject to limits for groundwater (e.g. sulphates). Water use corresponds to the quantity of water necessary to produce a given quantity of energy (m^3/kWh). Due to lack of data for comparison, the indicator on water pollution has not been elaborated here.

For each technology displayed below, a range of impact – including, where available, minimal and maximal water use for each technology - has been extracted from the literature and from impact assessments at installation level (see sources for more details). Due to a limited amount of data, chemical pollution for all technologies could not be fully assessed. When only one value is available, the range corresponds to the order of magnitude of the value for water use. Given the broad range of results for the technologies considered, the graph below displays results on a logarithmic scale, ranging from 0.01 to 1000 m^3/MWh. Please note that the positions of the technologies on the scale are to be considered indicative. Only the numerical values as described in the section "results" should prevail. Details of the sources are included for each technology under the chapter "Results by technology".

Results

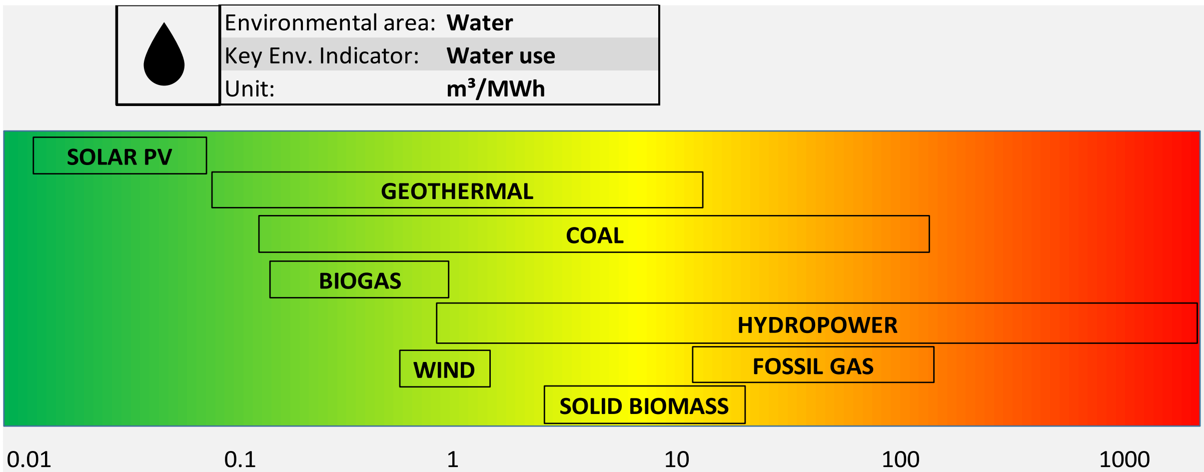


Figure 4: Water use of different energy technologies (indicative position)

Solar PV is the best performing technology with regards to water use. The manufacturing of solar PV can consume up to 0.05L/kWh[26], which remains several orders of magnitude below what a coal power plant would consume during its operational phase only.

On the downside, solar PV can show important heavy metals emissions (up to 0.05 mg/kWh) during its manufacturing phase, with however lower impacts for utility-scale system[27]. This pollution is particularly important since solar PV panels manufacturing often occurs outside of the EU. An important notice however: the value has been calculated using Mercury Hg/20 equivalent, i.e. including not only mercury emissions, but all heavy metals with specific characterization factors[28].

Geothermal is the second best-performing technology in terms of water use, at least for the most efficient techniques. For geothermal electricity, flash power plants (i.e. power plants that directly use geothermal fluid to drive a generator and re-inject it) do not consume potable water for cooling. Binary power plants (i.e. power plants that use a heat exchanger) can minimize their water use with air cooling. The use of water during operation phase is highly dependent on the cooling technology used, with a high variability between technologies. With a range from close to 0 to up to 14 m^3/MWh[29], geothermal energy performs well in term of water consumption, close to solar PV for the best performing plants[30].

Beyond operation, water consumption during drilling and construction is related to underground operations. Water is mainly used to produce drill mud (bentonite and water) and to cement the casing during well drilling, with a water use ranging from 5 to 30 m^3 of water per meter drilled[31].

Coal also uses water for turbine cooling and steam generation. Here as well, the lignite power plant shows by far the poorest performance, with a water consumption around 120 m^3/MWh[32], one of the highest of all energy technologies considered here. The hard coal power plant shows a lower water use, with around 0.2 m^3/MWh[33]. Beyond the use of water, it must also be reminded that the release of warm water into the environment can severely harm aquatic life, esp. when the temperature differential between intake and output is high.

Biogas shows a narrower range of impacts on water use. With a range from 0.23 to 0.96 m^3 of water per MWh of electricity produced[34], biogas is a water-sparse technology. This is because most biogas units studied in the literature are small CHP units which require less water cooling for the turbine, contrary to large coal or gas power plants.

Most of the water used for these units comes from the production of the feedstock itself. In this example, the plants using slurry combined with maize silage shows higher water consumption than the plants using maize silage only, due to the indirect water use of livestock.

In terms of water pollution, the use of pesticides and fertilisers for energy crops and their run-off from the soil into the water could lead to substantial soil and water pollution when the biogas production process relies highly on energy crops.

Wind scores rather well with a consumption of 1.7m³/MWh[35], positioning the technology on the lower end of impacts. To be noted that, in this case as well, most of the water consumption (94%) occurs during the extraction and manufacturing phase.

For **hydropower**, the blue water footprint (corresponding to water sourced from surface or groundwater resources) of electricity for hydropower plants presents a large variation from 1 to 3000 m³/MWh[36]. In all cases around the world, the facilities with large hydro reservoirs located in warm climate show the highest water footprint, due to water evaporation from the reservoir.

With 22 m³ of water used for each MWh of electricity generated[37], **biomass** combustion shows impact comparable with fossil fuels such as gas and coal. This relatively high water consumption is caused by the cooling requirements of the combustion process.

In this case, the water used for the cultivation of energy crops (if any) has not been included. The choice of such fuel could therefore considerably increase the water consumption of solid biomass.

Fossil gas shows relatively high values too, similar to other large combustion plants such as coal or solid biomass. In these examples, the values range from 19 m³/MWh for open cycle to 127 m³/MWh for combined cycle.

Air

Methodology

Air pollutants a are of major concern for human health and ecosystem toxicity. Some of the can also be precursors of climate change. Air emissions could be analysed for most technologies, using not only academic literature but also real-life examples of emission monitoring from large combustion plants firing coal or gas. The KEIs (Key Environmental Indicators) identified are (in mg/kWh):

- Sulphur dioxide and other Sulphur compounds (SOx)
- Oxides of Nitrogen and other Nitrogen Compounds (NOx)
- Mercury (Hg)
- Fine particulate matter, if possible, differentiated to PM 10 and 2.5 ultrafine PM

For this example and due to data availability, only SOx and NOx emissions have been developed, and converted in acidification potential in SO2-equivalent with the following formula[38]: $SO_2eq = SO_2 + 0.7\ NO_2 + 1.88\ NH_3$

For each technology displayed below, a range of impact – including, where available, minimal and maximal air pollution for each technology - has been extracted from the literature and from impact assessments or annual monitoring reports at installation level (see sources for more details). When only one value is available, the range corresponds to the order of magnitude of the value for the given air pollutant. Given the broad range of results for the technologies considered, the graphs below display results on a logarithmic scale for ranging from 0.1 to 10000 mg/kWh. Please note that the positions of the technologies on the scale are to be considered indicative. Only the numerical values as described in the section “results” should prevail. Details of the sources are included for each technology under the chapter “results by technology”.

Results

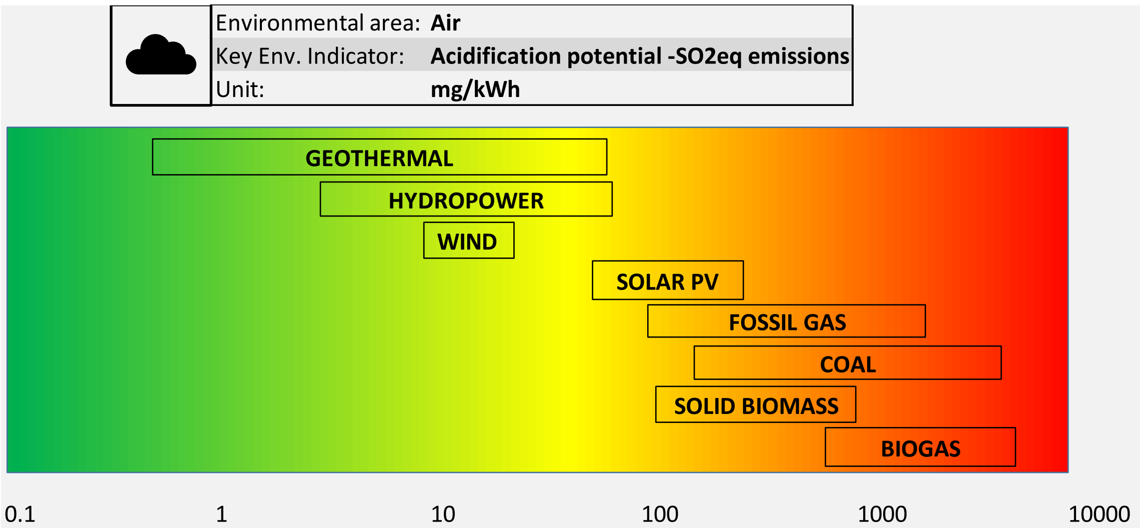


Figure 5: SO2eq emissions of different energy technologies (indicative position)

With regards to emissions occurring during the life cycle of the different technologies, large differences lie in the quantities but also the phases in which air pollution is relevant for each technology. For instance, for combustion-based technologies, a big share of emissions occurs during the operational phase, while during the same phase they are close to zero for their renewable counterparts such as solar and wind.

Geothermal energy shows low to moderate impacts, ranging from 0.35 to 64 mg/kWh[39]. The absence of combustion process, the limited use of chemicals and the limited land degradation guarantees low impact for this technology. To be noted that, in this case study, the power plant with the highest emissions is located in a region where the heat source presents a faction of non-condensable gases, including potentially SO2 or NO2.

Hydropower also shows moderate emissions of SOx and NOx compared with other energy sources. Ranging from 4 to 30 mg/kWh for SOx and 4 to 60 mg/kWh for NOx[40], hydropower compares well with other renewable technologies and show substantially lower air pollution than fossil fuel and large combustion plants.

For this technology, the emissions of NOx and SOx are closely related with the hydropower dam, for which construction and provision of materials leads to increased air emissions (mainly related to concrete / steel production).

When it comes to air pollution, **wind** scores intermediately compared with other technologies, with emissions reaching resp. 14 mg/KWh and 21 mg/KWh[41], mostly occurring during the manufacturing phase. These emissions are in the same order of magnitude than hydropower.

The impact of **solar PV** is however more important when it comes to air pollution. Here as well, most of the impact occurs during the manufacturing phase, esp. when burning hard coal in the supply chain of the electricity production[42]. With sulfur dioxides and particulate matters emissions reaching up to respectively 376mgSO2eq/kWh and 97 mg/kWh[43], solar PV comes close to coal emissions. This however depends largely on the technology chosen, where CdTe panels show almost 4 times lower emissions than multi crystalline Silicon (multi-Si) technology[44].

Contrary to other technologies using combustion processes such as coal, **fossil gas** shows acceptable SOx and PM emissions, due to the very nature of the gaseous fuel. However, for NOx emissions, fossil gas shows a broad range of impacts, with values reaching from 200 to 3800 mg/kWh for worst-performing plants[45]. In this case, fuel provision plays an important role as a consequence of the energy used for extraction of fossil gas. Also, lower efficiency of single cycle power plants leads to higher emissions compared with combined cycle.

Coal is one of the most polluting energy sources when it comes to air. If abatement techniques used in the hard coal power plant can help reduce SOx emissions to 240 mg/kWh[46], this remains above most other energy sources, and 100 times higher than the worst-performing gas power plant. To be also noted that, in this case, SOx emissions during mining and extraction represent 22% of total emissions[47]. On the upper range of emission, the lignite power plant reaches around 3400 mg/kWh[48], making it the second most polluting technology after biogas. To be noted that, on this latter case, also acidification and entrophication emissions from cultivation have been included.

Coal is also the worst performing technology when it comes to air pollution via nitrous oxideoxides (NOx), with up to 719 mg/kWh of emissions[49].

On particulate matter (PM), coal shows emissions 10 times higher than gas and comparable with biomass. To be noted that for the lignite example, PM and coarse dust emitted during the extraction phase represent 42% of total dust emissions[50].

With SOx emissions reaching 277 mg/kWh, NOx emissions of 287 mg/kWh and PM emissions of 15 mg/kWh[51], **solid biomass** ranks among the worst energy generation technologies, showing even higher particulate matter emissions than coal.

With a range of around 900 to over 5000 mg of SO2eq emissions per kWh of electricity produced[52], **biogas** also ranks among the most emitting technologies of all energy sources considered.

However, these figures must be considered cautiously, since they include not only SOx emissions during the combustion process, but total contribution to acidification potential - including maize cultivation and ammonia emitted during digestion.

In this context and expectedly, the biogas units using maize silage as a feedstock show by far the highest impact on acidification, while the plants using cow or pig slurry show five-time lower figures – comparable with a coal power plant. To be noted that the use of digestate as fertilizer vs. synthetic fertilizer can substantially reduce the impact on air pollution for fertilizing.

Climate

Methodology

A climate impact analysis has been carried out for all technologies. To capture the climate impact of different energy generation technologies throughout their lifecycle (manufacturing, construction, operation and end of life) the following KEIs (Key Environmental Indicators) have been identified (in kg/MWh):

- Carbon dioxide (CO2)
- Methane (CH4)
- Nitrous oxide (N2O)
- Hydrofluorocarbon (HFCs)
- Perfluorinated hydrocarbon (PFCs)
- Sulphur hexafluoride (SF6)

The selection of Key Environmental Indicators for climate was based on their relevance for the selected energy technologies and were identified through scientific literature (IPCC report) and stakeholder exchanges.

In many of the underlying studies used for the RESET project, most GHG emissions tend to be reported in the format of CO2 equivalent, including de facto non-CO2 emissions. When applicable, emissions of other GHG have been converted in CO2eq using averaged values of the Global Warming Potential metrics (GWP 100) of the 4^{th} IPCC report (AR4).

For each technology displayed below, a range of impacts – including, where available, minimal and maximal impact based on CO2 equivalent - has been extracted from the literature and from impact assessments at installation level (see sources for more details). When only one value is available, the range corresponds to the order of magnitude of the value for CO2 equivalent. Given the broad range of results for the technologies considered, the graph below displays results on an adjusted logarithmic scale, ranging from -1.000 to 1.000 kg of CO2 equivalent per MWh. The below logarithmic scale is an artificial scale created for the purpose of GHG analysis. Some technologies display negative values (i.e. GHG credits). Since mathematically it is impossible to extract a logarithm of a negative number, the scale below zero corresponds to the logarithmic function of the absolute emissions, multiplied by –1.

Please also note that the positions of the technologies on the scale are to be considered indicative. Only the numerical values as described in the section “results” should prevail. Details of the sources are included for each technology under the chapter “results by technology”.

Results

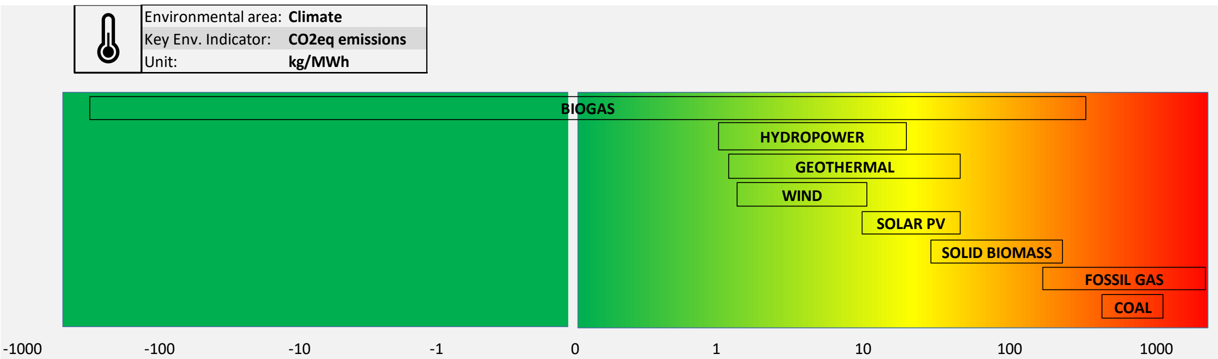


Figure 6: GHG emissions of different energy technologies (indicative position)

Biogas shows by far the broadest range of impacts of all technologies, with values ranging from −395 to 408 kg CO2eq per MWh of electricity generated[53]. Biogas is a particular example since most of the Greenhouse Gas (GHG) emissions are due to methane emitted by the digestate during its storage and from the feedstock. In these examples, carbon dioxide emissions from biogas combustion in the CHP plant are not considered as they are biogenic in nature.

On the upper range, biogas unit can emit up to 408 kg CO2eq per MWh of electricity produced, a result comparable with gas power plants. This case corresponds to biogas unit using only maize silage, where high emissions occur during cultivation and storage[54].

On the lower range, biogas can even show negative emission when the digestate is used as a fertilizer on the farm and when anaerobic digestion avoids traditional agricultural waste management (hence methane emissions from this waste). This is the case for digesters using pig or cow slurry as an input. These techniques could generate methane credits, leading to negative emissions, able to offset (in absolute value) the emissions of a fossil gas power plant.

Hydropower also performs rather well compared with other energy sources, with CO2eq emissions ranging from 2 to 20 kg/MWh. Only (some) biogas plants show less GHG emissions per energy produced.

For this area too, most emission are linked to the infrastructure. Life cycle emissions of GHG were reported in the range of 2-5 kg CO2-eq/MWh for run-of-river systems and 11-20 kg CO2-eq/MWh for dam-reservoirs[55]. An important aspect of hydropower with dam-reservoirs is methane emissions from the anaerobic decomposition of flooded organic matter. These emissions depend on the local climate, reservoir size, water depth, type and amount of flooded vegetation and soil type; thus, large variations in emission factors can be seen.

Most of GHG emission by **geothermal** operation is CO2, carried by geothermal fluids from the reservoir rocks. There is therefore an important variability in GHG emissions due to the geological conditions, hence the need to distinguish projects in volcanic and in non-volcanic areas. In volcanic areas, natural GHG emissions can occur, leading to sometimes high GHG footprint.

When integrating the whole life cycle of the plant (including construction and decommissioning), GHG emissions range from 5 to 80 kgCO2eq/MWh[56], with flash steam technology showing on average the best performance[57]. This makes geothermal energy a relatively low-GHG impact technology, with a score comparable with solar PV.

When considering the whole life cycle of **wind** technology, climate impacts were also found relatively low, with a range from 7.3 to 10.6 kgCO2eq/MWh[58]. In this case, the main contributions were related to material extraction and construction of the wind turbines. Hence, the local energy mix on the site of production has a significant influence on the results.

These results make wind a GHG-efficient technology, with only some hydropower plants and certain biogas installation being less emitting. Expectedly, wind shows better results that all combustion technologies.

Solar PV also ranks as one of the best performing renewable technologies in terms of climate impacts. The biggest percentage of GHG emissions happen -by far- during the extraction and manufacturing phases, hence the high variability of emissions depending on the production site. If low-performing Chinese PV panels operating under low radiation level can show emissions above 80 kgCO2eq/MWh, the best available technology[59] would emits around 10 kgCO2eq/MWh, with an average around 30 kgCO2eq/MWh[60]. This makes solar PV comparable with the best performing technologies such as wind or hydropower, and up to 100 lower than coal. It should also be noted that the best available technologies offer a twice faster energy payback time than the average PV module[61].

The climate performance of **solid biomass** depends largely on the type of fuel used. Following the life cycle assessment methodology based on direct GHG emissions, woodchips produced from forest systems show the lowest GHG content, with a minimal value of 51 kgCO2eq/MWh[62]. This lower range corresponds to woodchips produced with forest and wood industry residues at a low transport distance (below 500 km) of the combustion site. When the distance increases (above 10000km), the climate impact could increase by six-fold. This pattern is similar for biomass from agriculture, where agricultural residues show the lowest impact.

In general, the climate impact of wood pellets or briquettes is higher than chips, while pellets from wood industry residues compare well with woodchips from the same source. Short rotation coppice and stemwood show high impact with 230 kgCO2eq/MWh, but long-distance woodchips would show the highest impact with up to 353 kgCO2eq/MWh[63].

As for biomass and coal, climate is one of the highest concerns for **fossil gas**. With emissions ranging from 380 to 400 kgCO2eq/MWh only during operation phase, fossil gas is the second highest emitter of all energy technologies. These figures get even higher when integrating methane emissions from gas production and transport. This is particularly true for unconventional gas sources such as shale gas that show high methane leakage. Is this case, fossil gas emissions could raise above 1-ton CO2eq/MWh, making fossil gas even more polluting than coal, in the same order or even worse than lignite[64].

Even the best performing fossil gas power plant emits more than the worst performing biomass plant. These high emissions are directly connected to the thermal efficiency of the gas combustion and would be therefore extremely difficult to abate beyond a certain threshold.

Climate also one of the highest concerns for **coal** energy. With emissions ranging from 874[65] to 1145[66] kgCO2eq/MWh, coal is the highest emitter of all energy technologies together with fossil gas.

Even the best performing coal power plant emits above two times more than the worst performing biomass plant. These high emissions are directly connected to the thermal efficiency of the coal combustion and would be therefore extremely difficult to abate beyond a certain threshold.

Energy

Methodology

An analysis of energy payback time (EPBT) has been carried out for all technologies. The energy payback time is defined as the required period in which the energy technology can produce the same amount of energy (most often electricity converted into equivalent primary energy) than the energy consumed over its life cycle. The energy consumed during life cycle corresponds to the total amount of energy required to procure the fuel or extract the materials, build, operate, and decommission the facility.

To be noted that, for gas and coal, the fossil fuel used in the power plant to produce electricity has been excluded. If it were included, the EPBT would be higher than the total lifetime of the plant.

For each technology displayed below, a range of impacts – including, where available, minimal and maximal impact - has been extracted from the literature and from impact assessments at installation level (see sources for more details). When only one value is available, the range corresponds to the order of magnitude of the value.

Contrary to other technologies, a linear scale has been used since the gap between results was less important than other key indicators.

Please also note that the positions of the technologies on the scale are to be considered indicative. Only the numerical values as described in the section “results” should prevail. Details of the sources are included for each technology under the chapter “results by technology”.

Results

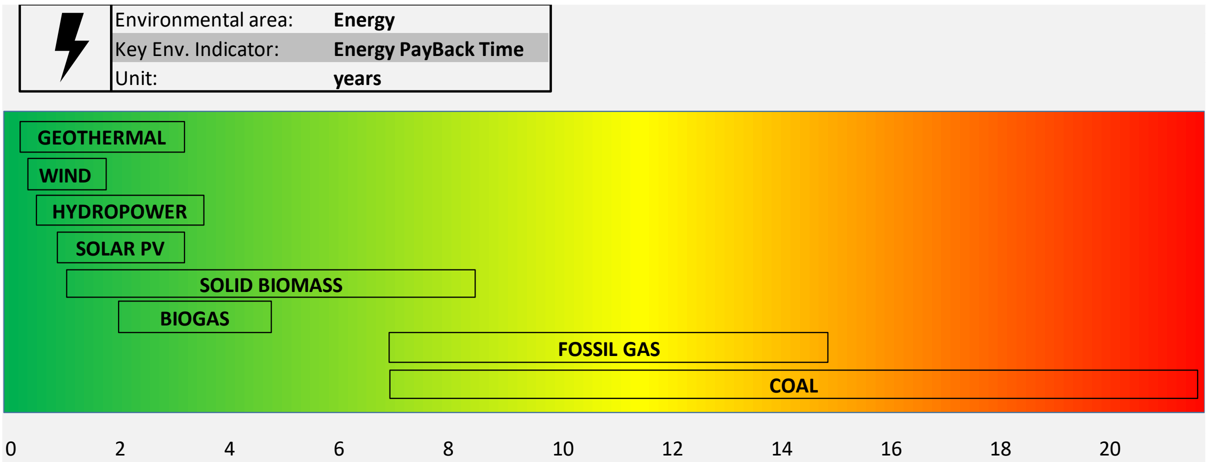


Figure 7: Energy PayBack Time of different energy technologies (indicative position)

For **geothermal energy**, the main source of energy consumption beyond electricity during operation comes from well drilling, power plants and pipes construction. When considering the total fossil fuel use during construction, operation and dismantling, the EPBT of geothermal would range from around 2 months to 3.5 years[67]. This makes geothermal a very efficient technology in terms of Energy Payback Time. These figures however do not consider the energy consumed by the products (pipes, etc.) during the extraction of raw materials and manufacturing.

With an Energy Payback Time (EPBT) ranging from 4 to 6 months[68], **wind** is also among the best performing technologies together with hydropower. Onshore wind technology shows slightly better results but new offshore wind turbines are rapidly catching up.

Hydropower often presents high power capacity and high renewable energy production; therefore, it can quickly return the energy used for its construction. With an EPBT ranging from 4 to 7 months[69], hydropower is one of the best performing technologies of all the examples studied here, with a slightly better score for run-of-river projects.

With an Energy Payback Time ranging from 6 months for the best-in-class CdTe panels up to 2.8 years for monocrystalline silicon panels[70], **solar PV** shows good performance on energy use. Since the energy production of the panel depends a lot on the irradiation, the EPBT will also significantly vary depending on the location.

The picture is more contrasted when it comes to **solid biomass.** With an energy payback time between 1 and 8 years[71], biomass compares well with fossil fuel generation but performs rather poorly compared with its renewable competitors. Biomass from waste and residues shows by far the shortest energy payback time, while biomass from energy crops shows higher values, esp. when the power plant is located long-distance from the biomass production site. This is due to the energy necessary for the production and transport of the biomass.

With an energy payback time ranging from around 2 to 5 years, **biogas** shows average performance compared with its competitors[72]. With no surprise, larger digestors show better performance than small-scale. The study used in this example presents small-scale biogas installation, it is therefore likely that EPBT would be lower for large-scale biogas plants.

Fossil gas performs poorly on energy payback time, with a range from 5 to 17 years[73]. This number is affected by the amount of energy spent in processing and transporting the gas. As for coal, these numbers would be even higher (and exceeding the total lifetime of the plant) when adding the gas necessary for the electricity production.

Coal ranks as the worst-performer of all energy supply, with 5 up to 22 years EPBT[74][75]. Especially high EPBT are found where coal is transported on long-distances, where additional resources such as lime are required, or where processes such as CCS are added. To be noted that these numbers would be even higher (and exceeding the total lifetime of the plant) when adding the coal necessary for the electricity production. Liability costs for lignite mine remediation are not accounted for. For hard coal mines, perpetual obligations in regards to water management measures have not been accounted for.

Results by technology

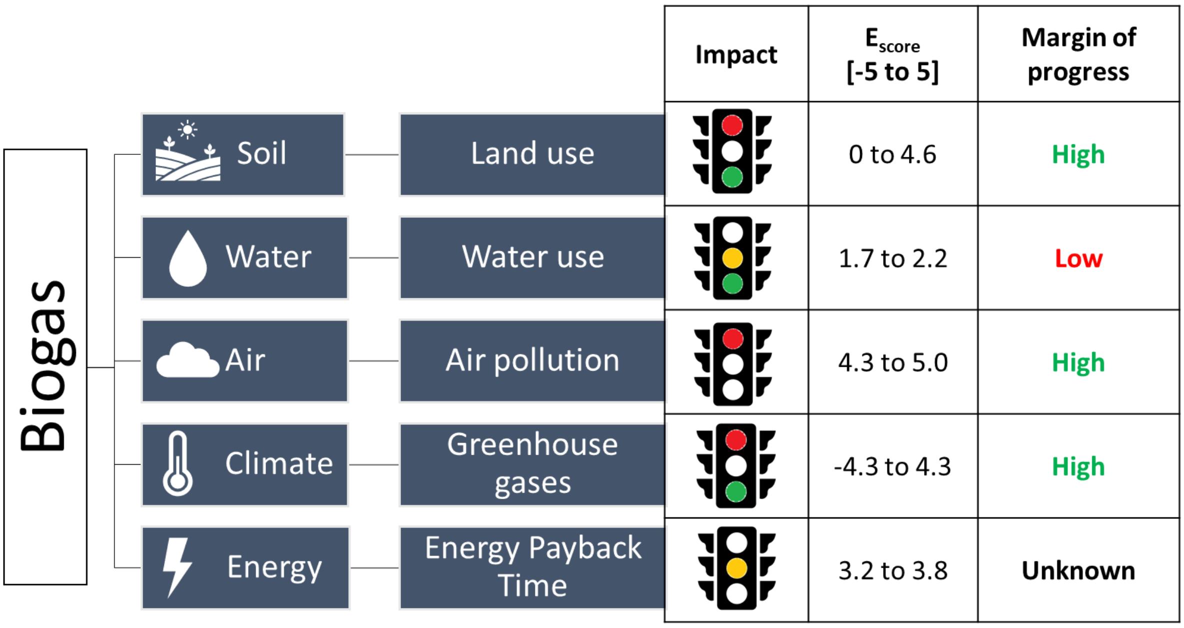
Biogas

Summary

While biogas supply is expected to decrease in the future under the PAC scenario, the upgrade of biogas into biomethane will play a prominent role to balance the energy system and substitute fossil gas in distinct industry sectors' processes that require methane.

The production of biomethane could also help reduce agricultural waste stream and cut greenhouse gas emissions when integrated into circular economy. Even though the amount of fermentable material does not allow biomethane to become a substitute for the whole fossil gas consumption in the EU, this energy carrier will still be indispensable in a clean energy transition.

The graph below summarizes the main impacts of biogas (for electricity production) and the margin of progress connected to the Best Available Techniques.



Biogas		Impact	E_{score} [-5 to 5]	Margin of progress
Soil	Land use		0 to 4.6	High
Water	Water use		1.7 to 2.2	Low
Air	Air pollution		4.3 to 5.0	High
Climate	Greenhouse gases		-4.3 to 4.3	High
Energy	Energy Payback Time		3.2 to 3.8	Unknown

Figure 8: Environmental score of Biogas technology

Soil

The impacts on land use of biogas depend largely on the amount of energy crops (mostly maize or sorghum silage) used in the digester. If digesters using only energy crops can show very high land use (up to 349 km²/TWh[76]), they do not constitute the majority of biogas plants today. When taking an average feedstock mix with 30% energy crops[77], the impact would drop to around 77 km²/TWh[78].

Today, almost no new biogas plant running on energy crops only is being built, and the percentage of energy crops allowed in most EU countries is capped[79]. The future of biomethane production will be based on valorizing waste streams, recycling nutrients, improving soil quality via cover crops, and will therefore divert from the energy-crops based model[80].

If the feedstock used for biomethane production will need to be carefully monitored in the future, the most virtuous biogas plants running on sequential crops, waste and residues could show almost no additional land use, making biogas a very land-efficient technology such as rooftop PV or geothermal.

Like other renewable and non-renewable technologies based on combustion, the use of Combined Heat and Power or the direct injection of biomethane into the gas network would deliver more energy per unit of land used than electricity-only plants (up to twice more). In this case, the impact on land use will be reduced accordingly.

Water

Due to the absence of relevant data on water pollution, only water use has been considered for biogas. With a range from 0.23 to 0.96 m³ of water per MWh of electricity produced[81], biogas is a water-sparing technology. This is because most biogas units studied in the literature small CHP units that do not require water cooling of turbine, contrary to large coal or gas power plants.

Most of the water used for these units comes from the production of the feedstock itself. In this example, the plants using slurry combined with maize silage shows higher water consumption than the plants using maize silage only, due to the indirect water use of livestock.

In terms of water pollution, the use of pesticides for energy crops and their run-off from the soil into the water could lead to substantial soil pollution when the biogas production process relies highly on energy crops.

Air

With a range of around 900 to over 5000 mg of SO2eq emissions per kWh of electricity produced[82], biogas ranks among the most emitting technologies of all energy sources considered.

However, these figures must be considered cautiously, since they include not only SOx emissions during the combustion process, but total contribution to acidification potential - including maize cultivation and ammonia emitted during digestion.

In this context and expectedly, the biogas units using maize silage as a feedstock show by far the highest impact on acidification, while the plants using cow or pig slurry show five-time lower figures – comparable with a coal power plant.

To be noted that the use of digestate as fertilizer vs. synthetic fertilizer can substantially reduce the impact on air pollution for fertilizing.

Climate

When it comes to climate change, biogas shows by far the broadest range of impacts of all technologies, with values ranging from −395 to 408 kg CO2eq per MWh of electricity generated[83]. Biogas is a particular example since most of the Greenhouse Gas (GHG) emissions are due to methane emitted by the digestate during its storage and from the feedstock. In these examples, carbon dioxide emissions from biogas combustion in the CHP plant are not considered as they are biogenic in nature.

On the upper range, biogas unit can emit up to 408 kg CO2eq per MWh of electricity produced, a result comparable with power plants. This case corresponds to biogas unit using only maize silage, where high emissions occur during cultivation and storage[84].

On the lower range, biogas can even show negative emission when the digestate is used as a fertilizer on the farm and when anaerobic digestion avoids traditional agricultural waste management (hence methane emissions from this waste). This is the case for digesters using pig or cow slurry as an input. These techniques could generate methane credits, leading to negative emissions which could offset the emissions of a fossil gas power plant.

Materials

Due to a lack of relevant data, no analysis on raw material use for construction has been performed for biogas technology. However, it is important to note that biogas could have positive impacts on key resources used for fertilizers production. The use of digestate as a fertilizer can reduce the need for phosphorus and potassium from mineral origin (from rock ores) or nitrogen from fossil origin (produced with fossil gas).

Energy

With an energy payback time ranging from around 2 to 5 years, biogas shows average performance compared with its competitors[85]. With no surprise, larger digestors show better performance than small-scale. The study used in this example presents small-scale biogas installation, it is therefore likely that EPBT would be lower for large-scale biogas plants.

Selection of Best Available Techniques

For most of the environmental areas identified above, one of the major improvements to biogas generation comes from the selection of the input. According to the studies used (see endnotes for more details), moving from energy crops (e.g. maize silage) to agricultural waste and residues could substantially lower the impact on land use, water pollution, air pollution and greenhouse gas emissions.

Soil

On land use, moving from energy crops to agricultural residues could substantially reduce the impact of biogas production. The margin of progress in this area is therefore deemed large.

On soil quality, soil in Europe is characterized by progressive loss of soil organic carbon due to the high intensity of the farming practices and overly focusing on the use of chemical fertilizers over recent decades. Biogas is a technology that allows to channel organic carbon from waste streams (food industry, agriculture, municipal waste) back to the soil in a safe and sustainable manner, hence contributing to better soil quality.

Water

Water use is the only element where energy crops show better results (up to 4 times lower consumption) than agricultural waste and residues for biogas production. However, the use of waste and residues could substantially release the pressure on arable land and the pesticide pollution of water. If the margin of progress exists, it remains limited, esp. in the future where energy crops should be progressively abandoned.

Air

The use of agricultural waste and residues rather than maize silage can divide by 6 the impact of biogas electricity production on acidification potential[86]. The margin of progress is therefore high in this area.

Climate

The anaerobic digestion of agricultural waste and residues could generate methane credits – sufficiently high to offset the emissions of the worst performing maize-silage-biogas[87]. On the top of it, the use of covered tanks to store the digestate avoid methane emission can also substantially contribute to lower methane emissions from biogas. The margin of progress is therefore very high – and best available techniques could even lead to benefits in this area.

Data completion and further research needed

Like most energy sources of this report, the analysis of soil and water pollution, and material use would require further research.The table below summarizes the data completeness on biogas use and shows fields of potential further research.

Soil	Water		Air	Climate	Material	Energy
Land use	Water pollution	Water use	Air pollution	CO2eq	Material use	EPBT
100%	0%	100%	50%	100%	0%	100%

List of data needed for further research:

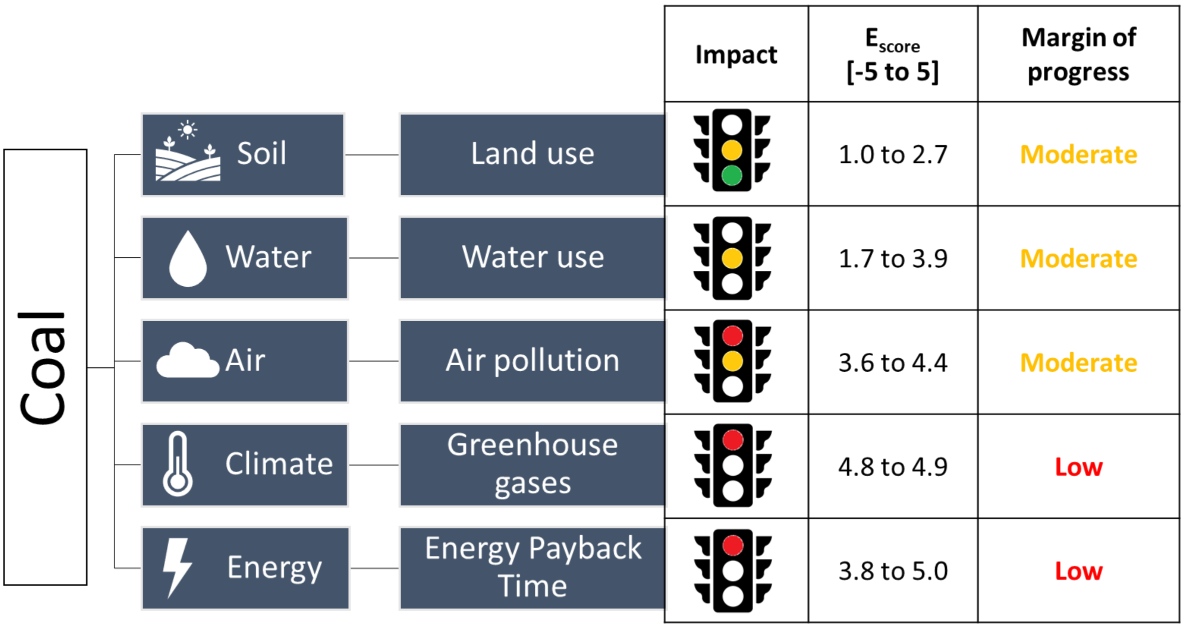
- Water pollution \ Metal emissions
- Water pollution \ Mercury emissions
- Water pollution \ WFD substances
- Water pollution \ Groundwater pollution
- Air pollution \ PM
- Material use \ Metals
- Material use \ Rare Earth
- Material use \ Others

Coal

Summary

Under the Paris Agreement Compatible (PAC) Energy Scenario, coal will be the first fossil fuel to be phased out by 2030, driven by policy, high carbon prices and low economic attractiveness. By 2030, only Czech Republic, Poland and Germany will keep coal in their energy mix. However, the picture today is different: coal would still represent in 2020 around 12% of total energy supply and 18% of electricity generation[88]. Several countries heavily rely on coal for their electricity production. With well-documented impacts on air, water, soil and greenhouse gases emissions, coal will be under scrutiny for a phase-out in the next ten years.

For this study, two specific coal power plants were considered: one lignite power plant in Bulgaria and one state-of-the-art hard coal power plant in Italy. These examples have been completed by meta studies on coal life cycle assessment. The graph below summarizes the main impacts of coal (for electricity production) and the margin of progress connected to the Best Available Techniques.



Coal		Impact	E_{score} [-5 to 5]	Margin of progress
Soil	Land use		1.0 to 2.7	Moderate
Water	Water use		1.7 to 3.9	Moderate
Air	Air pollution		3.6 to 4.4	Moderate
Climate	Greenhouse gases		4.8 to 4.9	Low
Energy	Energy Payback Time		3.8 to 5.0	Low

Figure 9: Environmental score of coal technology

Soil

With a minimal score of 1 out of 5 (corresponding to a land use of 0.0024 km^2/TWh[89]), coal would rank at the top of energy technologies in terms of land use. The limited surface of the considered power plant compared with a high electrical capacity makes a very high areal density compared with alternative energy solutions.

This is however only true for hard coal underground mining. When considering the area used for surface lignite mining, the impact of a lignite power plant is around 100 times higher than a gas power plant. In Germany for instance, the surface used for lignite mining can go up to 0.8 km^2/TWh[90], 40 times higher than the surface used for hydropower reservoir – for the same energy generated. Also to be noted that, contrary to renewable generation such as wind and solar, the land use for coal production and combustion will be heavily altered and artificialized, with no possibility use it for agriculture or nature conservation.

Water

When it comes to water pollution by heavy metals, the hard coal power plant performs a lot better than the lignite power plant. With a minimum around 0.05 mg of metal emission per kWh[91], the best-in-class hard coal power plant shows emissions comparable with fossil gas.

For the lignite power plant, the absence of efficient emission abatement techniques leads to metal emissions 20 times higher than the hard coal power plant[92], corresponding to a total score of 2.6 out of 5. All these emissions also include emissions due to extraction and mining of coal.

The emission of mercury into water, also specific to coal, rises at 0.040 mg/kWh[93], 100 times higher than biomass. Coal is also responsible for emission affecting groundwater such as sulphates. With a total emission up to 94 mg/kWh[94], coal ranks at a comparable level with fossil gas on this dimension.

Coal also uses water for turbine cooling and steam generation. Here as well, the lignite power plant shows by far the poorest performance, with a water consumption around 120 m^3/MWh[95], one of the highest of all energy technologies considered here. The hard coal power plant studied here shows a lower water use, with around 0.2 m^3/MWh[96], this is not however connected to the type of combustible. Beyond the use of water, it must also be reminded that the release of warm water into the environment can severely harm aquatic life, esp. when the temperature differential between intake and output is high.

Air

Coal is one of the most polluting energy sources when it comes to air. If abatement techniques used in the hard coal power plant can help reduce SOx emissions to 240 mg/kWh[97], this remains above most other energy sources, and 100 times higher than the worst-performing gas power plant. To be also noted that, in this case, SOx emissions during mining and extraction represent 22% of total emissions[98]. On the upper range of emission, the lignite power plant reaches around 3400 mg/kWh[99], making it the most polluting technology on SO2 only.

Coal is also the worst performing technology when it comes to air pollution via nitrous oxideoxide (NOx), with up to 719 mg/kWh of emissions[100].

On particulate matter (PM) and dust, coal shows emissions 10 times higher than gas and comparable with biomass. To be noted that for the lignite example, PM and dust emitted during the extraction phase represent 42% of total dust emissions[101].
Coal combustion is also the top anthropogenic emissions source of mercury emissions in Europe (see precited EEB briefing and IPDV).

Climate

Climate is legitimately one of the highest concerns for coal energy. With emissions ranging from 874[102] to 1145[103] kgCO2eq/MWh, coal is the highest emitter of all energy technologies, together with fossil gas.

Even the best performing coal power plant emits above two times more than the worst performing biomass plant. These high emissions are directly connected to the thermal efficiency of the coal combustion and would be therefore extremely difficult to abate beyond a certain threshold. As detailed in the PAC scenario, the introduction of CCS at large scale is not considered realistic.

Materials

Due to a lack of relevant data, no analysis on materials has been performed for biogas technology.

Energy

When it comes to Energy Payback Time (EPBT), coal ranks as the worst-performer of all energy supply, with 5 up to 22 years EPBT[104][105]. Especially high EPBT are found where coal is transported on long-distances, where additional resources such as lime are required, or where processes such as CCS are added. To be noted that these numbers would be even higher (and exceeding the total lifetime of the plant) when adding the coal necessary for the electricity production.
Liability costs for lignite mine remediation are not accounted for. For hard coal mines, perpetual obligations in regard to water management measures have not been accounted for.

Selection of Best Available Techniques[106]

For most of the environmental areas identified above, it has been demonstrated that, everything being kept equal, the hard coal examples shows lower environmental impacts than the lignite one. This assessment is amplified by the presence of better abatement techniques within the hard coal power plant, as detailed below.

Soil

On land use, moving from surface mining (lignite) to underground mining could divide by more than 200 the area necessary to produce energy. The area of the power plant itself has a limited influence on the total land use. However, the soil remains altered for years due to coal mining, making this technology very impactful in the long-term.

Water

Hybrid cooling towers (which contain wet and dry cooling elements) can account for a 20–60% reduction in water consumption compared to evaporative wet cooling systems[107].

Another method to relieve pressure on water resources is the use of dry cooling systems (using air instead of water as the cooling medium).

With regards to SO2 removal in exhaust fumes, coal power plant also uses wet flue-gas desulfurization (FGD) systems which consume water. For this technique, plants with regenerative heat exchangers can reduce water usage by cooling the flue gas before it enters the desulfurization process (40–50% reduction in water consumption). Another method to reduce water usage is to upgrade the air heater by extending the heat transfer surface and inject a sodium-based solution to prevent sulfuric acid condensation[108].

Air

For this area as well, the hard coal power plant shows lower air pollution than the lignite plant. A part of this discrepancy is due to the combustible itself, where lignite typically produces higher emissions and shows lower energy conversion efficiency than hard coal. Another explanation lies in the use of state-of-the-art abatement techniques such as the ones used in the Torrevaldaliga Nord power plant for NOx abatement, such as low NOx burners and Selective Catalytic Reduction. Secondary De-NOx abatement such as Secondary Catalytic Reduction (SCR) could reduce the pollution load by -85% also for lignite combustion. The potential for cutting air pollution are significant if operators would comply with the strict BAT-AEL set for new plants of the LCP BREF, see notably the EEB LCP BREF Briefing[109]. This scenario is however unlikely and residual emissions will remain still too high compared to other options.

Other BAT for coal combustion are: the reduction of SOx emissions through fuel choice, better combustion techniques such as fluidized bed combustion (FBC) boiler, and rigorous application of wet flue-gas desulfurization (FGD).
the reduction of the particulate matter through electrostatic precipitator (ESP), bag filters or cyclones for dust emissions, for mercury carbon sorbent injection, fuel pretreatment halogenated additives; the reduction of the amount of ash through recycling of dry ash (to be used in the cement industry) [110], dedicated Hg control or heat buffer storage tanks. The application of BAT (1µg/Nm^3) on mercury could bring the mercury intensity to a maximum of 3kg/TWh output, calculated on the basis of the German hard coal Moorburg plant (considered as close to BAT performer[111]).

The margin of progress is therefore deemed moderate in this area in comparison to other options[112].

Climate

In this specific environmental area, the margin of progress remains limited. With an average energy conversion efficiency ranging from 33% to 37%[113] or up to 46% for state of the art boilers (EU LCP BREF), GHG emission reductions are limited by the very characteristics of the fuel and the combustion cycle. Even though hard coal performs slightly better than lignite, the overall GHG emission of coal per kWh will not show substantial progress in the future.

Data completeness and further research needed

The coal assessment shows relatively complete data on emissions during operation and whole life cycle assessment. Some data is however missing on water pollution for the lignite example. Like most energy sources of this report, the analysis of soil pollution and material use would require further research.

The table below summarizes the data completeness on coal and shows fields of potential further research.

List of data needed for further research:

- Water pollution \ WFD substances
- Material use \ Metals
- Material use \ Rare Earth
- Material use \ Others

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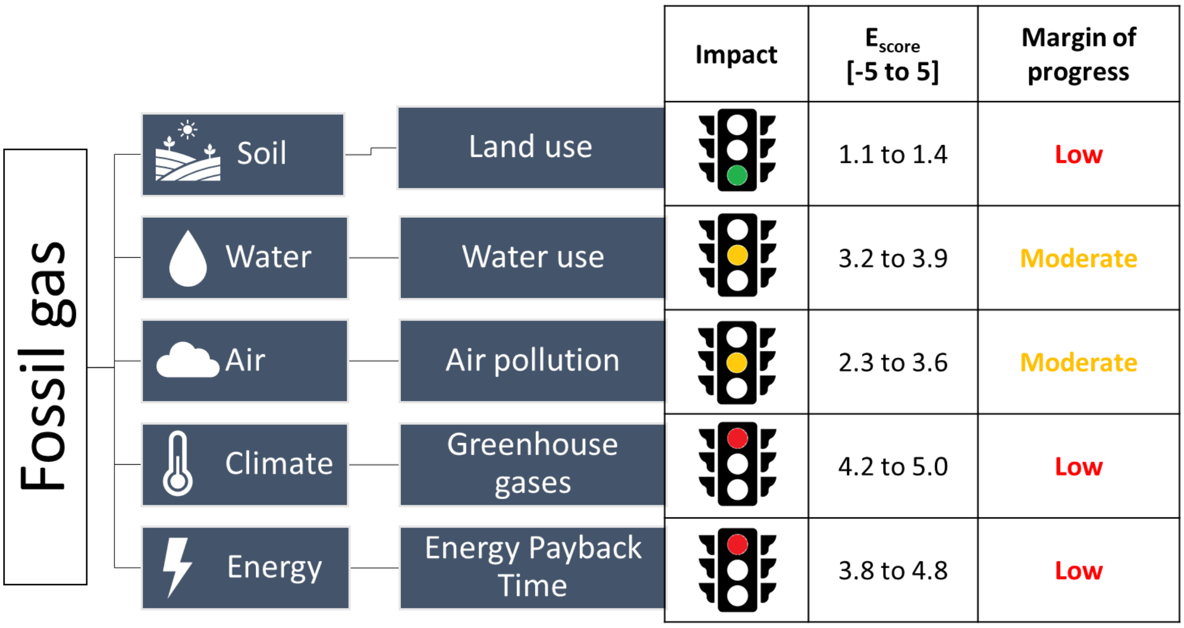
Fossil gas

Summary

Under the Paris Agreement Compatible (PAC) Energy Scenario, fossil gas should be the second fossil fuel to be phased out by 2035.

However, the picture today is different: fossil gas would still represent in 2020 around 25% of total energy supply and 17% of electricity generation[114]. The EU heating sector still heavily relies on gas. Even though fossil gas shows lower impacts than coal on air and water, it is far from being the cleanest energy source on these environmental areas. Above all, fossil gas shows among the highest greenhouse gas emissions of all technologies, hence the necessity for a swift phase-out in the next 15 years.

For this study, one combined cycle gas turbine (CCGT) in Italy[115] and one open cycle gas turbine (OCGT) in Romania[116] have been considered. This data has been completed by meta studies on gas life cycle analysis. The graph below summarizes the main impacts of gas (for electricity production) and the margin of progress connected to the Best Available Techniques.



Fossil gas		Impact	E_{score} [-5 to 5]	Margin of progress
Soil	Land use		1.1 to 1.4	Low
Water	Water use		3.2 to 3.9	Moderate
Air	Air pollution		2.3 to 3.6	Moderate
Climate	Greenhouse gases		4.2 to 5.0	Low
Energy	Energy Payback Time		3.8 to 4.8	Low

Figure 10: Environmental score of fossil gas technology

Soil

With an average score close to 1 (corresponding to a land use between 0.03 and 0.08 km^2/TWh[117]), fossil gas ranks at the top of energy technologies in terms of land use. The limited surface of the power plant compared with a high electrical capacity makes a very high areal density compared with alternative energy solutions.

This is however only true for conventional fossil gas sources such as vertical gas drilling. When it comes to unconventional gas sources such as shale gas with horizontal drilling and fracking, the impact on soil and underground could be notably higher. If imported gas is extracted with such techniques, this could lead to land alteration and soil pollution beyond the EU.

Water[118]

If fossil gas shows relatively moderate metal emissions (around 0.05 mg/kWh) compared to coal, it can emit up to 828 mg/kWh of harmful substances falling under the Water Framework Directive Environmental Quality Standards, making it the most polluting technology in this area. Fossil gas also emits from 10 to 450 mg/kWh of groundwater affecting substances such as sulphates, which latter value makes it more polluting than coal. For all these examples, the highest values are measured for the open cycle gas turbine.

When it comes to water use, fossil gas shows relatively high values too, similar to other large combustion plants such as coal or solid biomass. In these examples, the values range from 19 m^3/MWh for open gas cycle to 127 m^3/MWh for combined cycle.

Air[119]

Contrary to other technologies using combustion processes such as coal, fossil gas shows acceptable SOx and PM emissions, due to the very nature of the combustible. However, for NOx emissions, fossil gas shows a broad range of impacts, with values reaching from 200 to 3800 mg/kWh for worst-performing plants[120]. In this case, fuel provision plays an important role as a consequence of the energy used for extraction of fossil gas. Also, lower efficiency of single cycle power plants leads to higher emissions compared with combined cycle.

For particulate matter however, with a range between 0.53 and 3.7 mg/kWh during combustion, fossil gas ranks as the best performing technologies, closer to some renewables than to other large combustion plants.

Climate

As for coal, climate is one of the highest concerns for fossil gas. With emissions ranging from 380 to 400 kgCO2eq/MWh[121][122] only during operation phase, fossil gas is the second highest emitter of all energy technologies – from the examples we studied. These figures get even higher when integrating methane emissions from gas production and transport. This is particularly true for unconventional gas sources such as shale gas that show high methane leakage. Is this case, fossil gas emissions could raise above 1-ton CO2eq/MWh, making fossil gas even more polluting than coal[123].

Even the best performing fossil gas power plant from this study() emits more than the worst performing biomass plant[124]. These high emissions are directly connected to the thermal efficiency of the gas combustion, upstream methane emissions due to gas supply and would be therefore extremely difficult to abate beyond a certain threshold. As detailed in the PAC scenario, the introduction of CCS at large scale is not considered realistic to mitigate these emissions.

Materials

Due to a lack of relevant data, no analysis on materials has been performed for fossil gas technology.

Energy

As for coal, fossil gas performs poorly on energy payback time, with a range from 5 to 17 years[125]. This number is affected by the amount of energy spent in processing and transporting the gas. As for coal, these numbers would be even higher (and exceeding the total lifetime of the plant) when adding the gas necessary for the electricity production.

Soil

For fossil gas, the area of the power plant itself has a limited influence on the total land use. As stated above, the use of non-conventional gas extraction techniques could significantly increase the impact of fossil gas generation on soil. Since most of the gas used in the EU is imported, there is no guarantee that the gas supply will come from conventional sources only.

Water

As described above, the CCGT plant shows lower impacts than the OCGT one, esp. on substances affecting groundwater such as sulphates.

In the examples showed here, water use ranges from 19 m^3/MWh for open gas cycle to 127 m^3/MWh for combined cycle. To reduce water use of gas turbines, some power plant use high-efficiency air cooled gas turbines instead of water cooling. However, air cooling negatively affects efficiency and is more expensive than the business-as-usual cooling technique.

Air

For this area, the OCGT power plant performs better than the CCGT in the field of NOx and SOx emissions.

The most common method to prevent or reduce NOx emissions is the water/steam injection. For new or retrofitted plants, dry low-NOX burners and Selective Catalytic Reduction (SCR) can be applied[126].

Climate

In this specific environmental area, the margin of progress remains limited. With an average energy conversion efficiency ranging from 40% to 44%[127] with state of the art CCGT showing an efficiency around 62,5% and slightly higher for the H class turbines[128] , GHG emission reductions are limited by the characteristics of the combustible and the combustion process. Even though best CCGT plants could show thermal conversion efficiency above 60%, the overall GHG emission of gas per kWh will not show substantial progress in the future.

Data completeness and further research needed

The fossil gas assessment shows relatively complete data on emissions during operation and life cycle assessment. Some data is however missing on water pollution. Like most energy sources of this report, the analysis of soil pollution and material use would require further research.

The table below summarizes the data completeness on fossil gas and shows fields of potential further research.

Land use	Water pollution	Water use	Air pollution	CO2eq	Material use
100%	50%	100%	100%	100%	0%

List of data needed for further research:

- Water pollution \ Mercury
- Material use \ Metals
- Material use \ Rare Earth
- Material use \ Others

Geothermal

Summary

Under the Paris Agreement Compatible (PAC) Energy Scenario, geothermal energy is expected to play an important role in the future energy system. With an expected increase from 21 TWh in 2020 to 132 TWh by 2040, geothermal energy will be one of the fast-growing renewable to supply heat and electricity at household level[129].

The role of combined heat and power will be prominent in the deployment of geothermal energy though the need for sustainably sourced European deposits of lithium hydroxide and other chemical compounds. Geothermal heating also offers direct and local substitution to fossil-based technologies, hence being one of the key technologies to decarbonize heating and cooling.

For this energy example, the focus has been put on electricity generation, even though geothermal provides heating and cooling for individual buildings and to cities through district heating systems. The graph below summarizes the main impacts of geothermal energy and the margin of progress connected to the Best Available Techniques.

			Impact	E_{score} [-5 to 5]	Margin of progress
Geothermal	Soil	Land use		1.9 to 2.6	Low
	Water	Water use		1.4 to 3.1	Moderate
	Air	Air pollution		1.0 to 3.2	Unknown
	Climate	Greenhouse gases		1.6 to 3.3	Moderate
	Energy	Energy Payback Time		1.0 to 3.5	Unknown

Figure 11: Environmental score of Geothermal technology

Detailed results

Soil

The amount of land required by a geothermal plant depends on the properties of the resource reservoir, the amount of power capacity, the type of energy conversion system, the type of cooling system, the arrangement of wells and piping systems, and the substation and auxiliary building needs.

Geothermal power is a surface-efficient-technology. With a range from 0.04 to 0.4 km^2/TWh[130], geothermal power scores between 1.8 and 2.5, making it comparable with coal. With most energy collection happening underground, the limited surface of the power plant compared with a high electrical capacity makes a high areal density compared with other energy technologies. Geothermal heating and cooling projects show even better scores.

Over the life cycle, the drilling and test phase will occupy a surface of land with drilling rigs and material a surface of 4 to 8 km^2 but just for a limited period (1 to 2 years). The operation phase lasts for a period of 20 to 40 years, and the land use is limited to the buildings of the plant(s).

Water

Due to absence of data on water pollution, only water use has been measured in this example. In general, large-scale geothermal energy uses subterranean brines as a heat transfer fluid, which does not compete with drinking water. Water remains underground in heating systems, only geothermal electricity production requires cooling towers.

During operation, water is used in small amount which depend on the cooling technology used. For geothermal electricity, flash power plants (i.e. power plants that directly use geothermal fluid to drive a generator and re-inject it) do not consume potable water for cooling. Binary power plants (i.e. power plants that use a heat exchanger) can minimize their water use with air cooling.

Most geothermal plants re-inject water into the reservoir after it has been used to prevent contamination and land subsidence. The amount of water needed depends on the size of the plant and the technology used. However, it is often not necessary to use clean water for this purpose. For example, the Geysers geothermal site in California injects non-potable treated wastewater into its geothermal reservoir.

The use of water during operation phase is highly dependent on the cooling technology used, with a high variability between technologies. With a range from close to 0 to up to 14 m^3/MWh[131], geothermal energy performs well in term of water consumption, close to solar PV for the best performing plants[132].

Beyond operation, water consumption during drilling and construction is related to underground operations. Water is mainly used to produce drill mud (bentonite and water) and to cement the casing during well drilling, with a water use ranging from 5 to 30 m^3 of water per meter drilled[133].

Air

For air pollution (identified here in SO2-eq[134]), geothermal energy shows low to moderate impacts, ranging from 0.35 to 64 mg/kWh[135]. The absence of combustion process, the limited use of chemicals and the limited land degradation guarantees low impact for this technology, with a score from 1.0 to 3.5. To be noted that, in this case study, the power plant with the highest emissions is located in a region where the heat source presents a faction of non-condensable gases.

Climate

Most of GHG emission by geothermal operation is CO2, carried by geothermal fluids from the reservoir rocks. There is therefore an important variability in GHG emissions due to the geological conditions, hence the need to distinguish projects in volcanic and in non-volcanic areas. In volcanic areas, natural GHG emissions can occur, leading to sometimes high GHG footprint.

When integrating the whole life cycle of the plant (including construction and decommissioning), GHG emissions range from 5 to 80 kgCO2eq/MWh[136], with flash steam technology showing on average the best performance[137]. This makes geothermal energy a relatively low-GHG impact technology, with a score comparable with solar PV.

Materials

Due to a lack of relevant data, no analysis on materials has been performed for geothermal technology.

Energy

For geothermal energy, the main source of energy consumption beyond electricity during operation comes from well drilling, power plants and pipes construction. When taking into account the total fossil fuel use during construction, operation and dismantling, the EPBT of geothermal would range from around 2 months to 3.5 years[138]. This makes geothermal a very efficient technology in terms of Energy Payback Time. These figures however do not take into account the energy consumed by the products (pipes, etc.) during the extraction of raw materials and manufacturing.

Selection of Best Available Techniques

Soil

The impact of deep geothermal on land use is extremely limited. Where the geothermal potential allows for it, the scaling up of the installation capacity or the extension of lifetime will guarantee even lower land use impact per kWh produced. However, the margin of progress depends largely on local conditions and potential, and remains therefore limited.

Water

The study used for this analysis shows no drinking water consumption for geothermal heating purposes. When water is used for cooling the power generator, the use of geothermal fluids (brine) rather than freshwater substantially reduces the water impact. As stated above, binary power plants can also reduce their water use with air cooling. Here as well, the choice of the technology largely depends on local conditions. If a margin of progress exists, it remains moderate.

Air

In this example, geothermal energy shows low to medium air pollution. Lower air pollution could be reached by emissions treatment system to treat non-condensable gases from the geothermal fluid.

Climate

As stated above, the GHG emissions of geothermal energy largely depend on the choice of the geothermal site and on the construction phase. The emissions during the construction phases also depend largely on the geological conditions, since more than 80% of the impacts result from the energy consumption during drilling, and from the material input for the required steel pipes for the casing of the production well[139]. The margin of progress exists in this area but remains moderate due to site constraints. The use of recycled construction material could therefore help mitigate the impacts of the construction phase. But one of the most efficient way to limit the GHG emissions per unit of energy produced would be to increase the lifetime of power plants, esp. when the highest impacts occur during the construction phase[140].

Data completeness and further research needed

The geothermal assessment is based on one case study completed by several meta-analyses on land, water and GHG. It shows gaps on water pollution, but relatively complete data on air pollution. Like most energy sources of this report, the analysis of soil pollution and material use would require further research. The table below summarizes the data completeness on geothermal energy and shows fields of potential further research.

Soil	Water		Air	Climate	Material	Energy
Land use	Water pollution	Water use	Air pollution	CO2eq	Material use	EPBT
100%	0%	100%	50%	100%	0%	100%

List of data needed for further research:

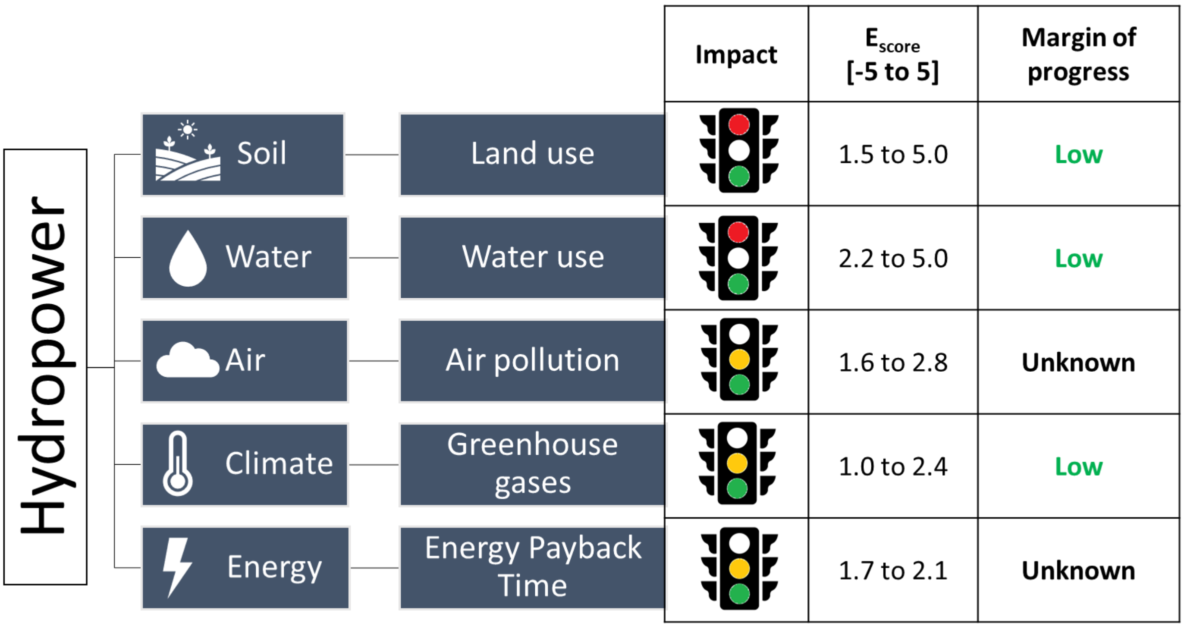
- Water pollution \ Metal emissions
- Water pollution \ Mercury emissions
- Water pollution \ WFD substances
- Water pollution \ Groundwater pollution
- Air pollution \ PM
- Material use \ Metals
- Material use \ Rare Earth
- Material use \ Others

Hydropower

Summary

Under the Paris Agreement Compatible (PAC) Energy Scenario, hydropower will continue to play an important role in the energy mix. If new capacities will be capped post-2020, existing capacities will continue to deliver electricity and services such as storage to the energy system. The role of hydropower reservoirs will be key to balance the future energy system, with an increasing share of variable renewables and a need for system flexibility[141].

For this energy source, a meta study including complete Life Cycle Assessment (LCA) of 12 hydropower systems has been used (see Annex IV for more details), including generation within and beyond the EU. This study has been completed by ad-hoc examples and studies in the EU and beyond the EU where data was missing. The graph below summarizes the main impacts of hydropower energy (for electricity generation) and the margin of progress connected to the Best Available Techniques.



Hydropower		Impact	E_{score} [-5 to 5]	Margin of progress
Soil	Land use	(red lit)	1.5 to 5.0	Low
Water	Water use	(red lit)	2.2 to 5.0	Low
Air	Air pollution	(yellow lit)	1.6 to 2.8	Unknown
Climate	Greenhouse gases	(yellow lit)	1.0 to 2.4	Low
Energy	Energy Payback Time	(yellow lit)	1.7 to 2.1	Unknown

Figure 12: Environmental score of Hydropower technology

Soil

With the lowest value of around 0,024 km²/TWh[142], hydropower can show among the lowest impact on land use of all renewables. This is esp. valid for hydropower installation using the technique of artificial reservoir storage only (opposed to dams installed on existing river).

However, when considering the whole water catchment area of a hydropower dam, the impact of this technology could be very high, with up to 2750 km²/TWh in our example[143], making it the technology of highest impact. This means that, when building a dam on a river, the impact on land use could extend beyond the reservoir surface and affect the whole river basin by modifying the natural ecological continuity. This could be marginally mitigated by upgrading the hydro power plant with more efficient turbines or building infrastructure to improve ecological continuity.

Where feasible, the choice of artificial pumped storage facilities instead of run-of-river hydropower will limit the impact on soil and surface water.

Water

Due to absence of data on water pollution, only water use has been measured in this example. For this technology, the blue water footprint (corresponding to water sourced from surface or groundwater resources) of electricity for hydropower plants presents a large variation from 1 to 3000 m³/MWh[144]. In all cases around the world, the facilities with large hydro reservoirs located in warm climate show the highest water footprint, due to water evaporation from the reservoir.

Air

Hydropower shows moderate emissions of SOx and NOx compared with other energy sources. Ranging from 4 to 30 mg/kWh for SOx and 4 to 60 mg/kWh for NOx[145], hydropower compares well with other renewable technologies and show substantially lower air pollution than fossil fuel and large combustion plants.

As for water, the emissions of NOx and SOx are closely related with the hydropower dam, for which construction and provision of materials leads to increased air emissions.

Climate

When it comes to greenhouse gas emissions, hydropower performs rather well compared with other energy sources, with CO2eq emissions ranging from 2 to 20 kg/MWh. Only (some) biogas plants show less GHG emissions per energy produced.

For this area too, most emission are linked to the infrastructure. Life cycle emissions of GHG were reported in the range of 2-5 kg CO2-eq/MWh for run-of-river systems and 11-20 kg CO2-eq/MWh for dam-reservoirs[146]. An important aspect of hydropower with dam-reservoirs is methane emissions from the anaerobic decomposition of flooded organic matter. These emissions depend on the local climate, reservoir size, water depth, type and amount of flooded vegetation and soil type; thus, large variations in emission factors can be seen.

Materials

Due to a lack of relevant data, no analysis on materials has been performed for hydropower technology.

Energy

With high electricity capacity and high renewable energy production, hydropower can quickly return the energy used for its construction. With an EPBT ranging from 4 to 7 months[147], hydropower is one of the best performing technologies of all the examples studied here, with a slightly better score for run-of-river projects.

Selection of Best Available Techniques

In most cases presented above, the infrastructure is the most influential parameter to the overall environmental impact of a hydropower facility. The presence of a hydro dam and reservoir, their size and design, will have substantial influence on soil, water, air and climate impacts.

For all these cases, the margin of progress remains limited since the design of hydropower dams depends mostly on site constraints and electricity system requirements. In Europe, most eligible sites for hydropower are already occupied. A refurbishment of the power plant to install for instance more efficient turbines could help gain a few percentages in electricity generation without increasing the environmental impact but will not be a game-changer for hydropower.

In most cases, run-of-river hydropower will show less impact per kWh of energy produced than hydro reservoir, esp. when run-of-river is coupled with ecological continuity infrastructure.

The value for the energy system of run-of-river hydropower is however lower than hydro-reservoir, and its future added value is questionable in an energy system where low-impact electricity is also available via alternative energy sources.

Data completeness and further research needed

The hydropower assessment shows relatively complete data. The absence of data on water pollution comes from the absence of chemical alteration of water during the production of hydroelectricity. Like most energy sources of this report, the analysis of soil pollution and material use would require further research.

The table below summarizes the data completeness on hydropower and shows fields of potential further research.

Soil	**Water**		**Air**	**Climate**	**Material**
Land use	Water pollution	Water use	Air pollution	CO2eq	Material use
100%	0%	100%	67%	100%	0%

List of data needed for further research:

- Air pollution \ PM
- Material use \ Metals
- Material use \ Rare Earth
- Material use \ Others

Solar PV

Summary

With a potential increase from 1% to 29% of the primary energy supply between 2020 and 2040 under the PAC Energy Scenario, solar photovoltaics (PV) is one of the most promising technologies to decarbonize our energy system and reach net-zero emissions by 2040. With such a rapid uptake, solar PV was one of technologies under highest scrutiny in the RESET project.

For this energy source, a meta study including three solar PV examples (one residential, one commercial and one utility-scale) has been used. This study has been completed with data from the industry, from public authorities and from research institutes (see Annex IV for more details). The graph below summarizes the main impacts of solar PV and the margin of progress connected to the Best Available Techniques.

Solar PV		Impact	E_{score} [-5 to 5]	Margin of progress
Soil	Land use		0 to 2.3	Moderate
Water	Water use		1.0 to 1.1	High
Air	Air pollution		3.8 to 4.3	High
Climate	Greenhouse gases		2.0 to 3.3	High
Energy	Energy Payback Time		2.0 to 3.4	High

Figure 13: Environmental score of solar PV technology

Soil

At a first glance, solar PV performs rather well compared to its renewable and non-renewable competitors. When it comes to land use, residential and commercial solar PV even score with zero impact, due to their installation on existing rooftops. With a maximum land use of 1.11 km^2/TWh[148], utility-scale solar PV still shows moderate impact in general, and rather low compared with other renewable energy sources. Utility-scale solar PV can also be mounted in heavily modified land such as industrial sites or urban areas, hence limiting the consumption of pristine land.

On the top of it, agriculture can remain possible under large-scale PV installations. The co-existence of agriculture and utility-scale solar PV (agrivoltaics) can even lead to co-benefits in terms of plant CO2 absorption and fruit production[149].

The share of artificialized land by PV farms remains therefore limited, with around 2.5% of total land use actually occupied by PV installation and equipment[150]. This result assumes best practices such as limited land sealing for foundation are already in place.

Water

When it comes to water pollution, solar PV can show important heavy metals emissions (up to 0.05 mg/kWh) during its manufacturing phase, with however lower impacts for utility-scale system[151]. This pollution is particularly important since solar PV panels manufacturing often occurs beyond the EU. An important notice however: the value has been calculated using Mercury Hg/20 equivalent, i.e. including not only mercury emissions, but all heavy metals with specific characterization factors[152].

In term of water use, the manufacturing of solar PV can consume up to 0.05L/kWh[153], which remains several orders of magnitude below what a coal power plant could consume during its operational phase only.

Air

The impact of solar PV is however more important when it comes to air pollution. Here as well, most of the impact occurs during the manufacturing phase, esp.

when burning hard coal in the supply chain of the electricity production[154]. With sulfur dioxides and particulate matters emissions reaching up to respectively 376mgSO2eq/kWh and 97 mg/kWh[155], solar PV could be an impactful technology. This however depends largely on the technology chosen, where CdTe panels show almost 4 times lower emissions than multi crystalline Silicon (multi-Si) technology[156]. If the manufacturing happens beyond the EU, the margin of progress depends on upstream due diligence and strong environmental product and manufacturing policies and uptake of best practice by the producer in that country. Good practices already exist (see “Best Available Techniques” for more details.)

Climate

Solar PV ranks as one of the best performing renewable technologies in terms of climate impacts. The biggest percentage of GHG emissions happen -by far- during the extraction and manufacturing phases, hence the high variability of emissions depending on the production site. If low-performing Chinese PV panels operating under low radiation level can show emissions above 80 kgCO2eq/MWh, the best available technology[157] would emits around 10 kgCO2eq/MWh, with an average around 30 kgCO2eq/MWh[158]. This makes solar PV comparable with the best performing technologies such as wind or hydropower, and up to 100 lower than coal. It should also be noted that the best available technologies offer a twice faster energy payback time than the average PV module[159].

During the operation phase, this technology shows almost no emissions. Most of the margin of progress lies in the improvement of the production process and esp. the reduction of the GHG content of the electricity mix of the manufacturing country. The margin of progress is therefore high.

Materials

When it comes to materials, it is important to keep in mind that most of the impacts could be mitigated via an efficient recycling process and a circular economy flow. Solar PV could show important metal, glass and plastic consumption during manufacturing processes – up to 821.5mg/kWh for metal and 246mg/kWh for plastics. This material, according to the literature, could be mostly recycled. For example, CdTe PV modules achieve >90% recovery of glass and semiconductor in commercial recycling operations[160].

The potentially high impact will therefore depend on the overall material context, and on the possibility of recycling. The margin of progress is therefore extremely high.

Also to be noted that a limited share of solar PV panels also uses cadmium telluride (CdTe) in their manufacturing[161]. Cadmium telluride presents more environmentally efficient manufacturing, but cadmium toxicity has been raised in the past as a potential concern. According to an industry study, CdTe is a stable compound that is insoluble in water and has an extremely high chemical and thermal stability[162]. These properties limit its bioavailability and potential for exposure.

In CdTe PV panels, only a thin layer of CdTe is encapsulated between two sheets of glass and sealed with an industrial laminate, resulting in a strongly bonded monolithic device which limits the potential for release into the environment[163]. In modern facilities, electro deposition and chemical deposition of Cadmium are about 90% efficient, and not more than 0.0005% of the cadmium and tellurium used in the facility would be lost in the form of very dilute liquid and waste streams. This would correspond to a residual emission of 8.5×10^{-6} mgCd/kWh, for a total use of cadmium of 2 mg/kWh[164]. Once they reach their end of life, 90% of the materials used in CdTe modules are recycled and recovered for use in new modules. This includes over 90% of the glass and semiconductor material, with the remainder consisting of glass fines that are safely disposed of.

Energy

With an Energy Payback Time (EPBT) ranging from 6 months for the best-in-class CdTe panels up to 2.8 years for monocrystalline silicon panels[165], solar PV shows good performance on energy use. Since the energy production depends a lot on the irradiation, the EPBT will also significantly vary depending on the location.

Selection of Best Available Techniques

Soil

One simple way to lower the impact of solar PV on land use is to use in priority existing rooftops from residential and commercial facilities. In locations where rooftops are not easily accessible, the priority for utility-scale solar PV should be on land with low environmental value such as industrial sites, in particular contaminated sites where removal of hazards cannot be covered by the polluter. Responsibly developed PV power plants can create new habitats and help protect endangered animal and plant species by providing refuge, particularly in areas that were previously farmed, regularly tilled and/or treated with pesticides, fertilizers or rodenticides. Studies have found that the PV plant's shading effect can create varied microclimates, resulting in greater vegetation growth and higher species diversity than surrounding Stewardship Lands and control sites[166].

Best practices to limit the impact or even have positive impact on biodiversity could include a limitation of module cover to 50-60% or the respect of minimal distance between module rows. Local consultation and biodiversity management plans will also help, as well as further integration of solar PV in EU strategies for biodiversity, and support schemes design that favors projects of best environmental impact[167].

The use of agrivoltaics (i.e. combined ground-mounted PV with agricultural systems) or floatovoltaics (i.e. PV modules attached to pontoons that float on water) can also reduce the impact of photovoltaics on land use[168].

Another technical measure to mitigate the impact of utility-scale solar PV on land use would be to use sun tracking techniques or high efficiency panels to increase the energy production per km^2.

The margin of progress of solar PV to reduce land use is high is theory but limited by available space on existing rooftops and already artificialized land. Overall, there is a moderate margin of progress to limit land use by photovoltaics.

Water

According to the case studies presented above, utility-scale solar PV is less water-intensive and less water-polluting than small-scale residential installation. This is due to economies of scale in the manufacturing process and installation process.

*Other techniques to reduce water pollution and water use would be to use optimized PERC (*Passivated Emitter and Rear Cell), which is a design feature that allows lower silicon and glass use, thus allowing reduced water use. This technique has been used esp. for residential PV in the example analyzed in this report[169]. Another choice, used for commercial and utility-scale PV, would be to choose Cadmium Telluride (CdTe) technology. The margin of progress in water consumption is high for CdTe technology, with a dramatic drop in water use compared to Multi Crystalline Si module[170].

Air

As with water pollution, utility-scale solar PV would show lower impacts on air pollution than small-scale solar PV. Cadmium Telluride (CdTe) and Copper indium gallium selenide (CIGS) technologies are also the ones showing the least air pollution. Currently, the European energy mix is less polluting on average than the world average, therefore PV panels produced in Europe tend to show lowest air impacts[171]. This confirms the importance to support use of low-carbon and clean energy in PV supply chain. The margin of progress in this area remains therefore high.

Climate

Since 99% of the emissions happen during the extraction and manufacturing process[172], one way to reduce climate impact of solar PV production would be to re-locate the production in a less GHG-intensive economy – also limiting the emissions due to transport. Another way would be to improve the GHG content of the electricity mix used for solar PV production, or to use a 100% renewable electricity mix. Such commitment has already been made by some solar PV manufacturers by joining 100% renewables companies[173]. The actual emission reduction should be carefully monitored in the future, but the margin of progress remains high in this field.

The most advanced PV modules carry less than half the carbon footprint compared to average modules. The use of sustainability requirements for PV modules and inverters, including requirements on carbon footprint under the Ecodesign Directive, can also deliver substantial improvements. As for other technologies, support schemes can also play an important role by valorizing technologies with a low carbon footprint.

Other techniques to reduce climate impact would be to limit emissions in the manufacturing process, esp. during the production of polysilicon. This includes optimized reactor and processes or closed loop operations. The reduction of carbon-intensive materials such as aluminum, glass and silicon could be achieved through reducing solar wafer thickness or promoting internal recycling and use of recycled materials[174].

Another important aspect to limit carbon footprint of PV panels would be to extend product lifetime and efficiency – which is still ongoing process for the solar PV industry.

Material

As shown in the studies presented above, the reduction of waste from material consumption is directly connected to the recycling economy of the country where the PV panels reach their end-of-life. 95 % of the materials (e.g. glass, copper, aluminium, etc.) in PV panels can be recycled[175]. For some materials such as steel, the recycling rate could be close to 100%. Solar PV does not consume rare Earth materials but uses aluminum, copper, silver, cadmium, gallium, germanium, indium, selenium, silicon metal and tellurium[176]. Standards have been adopted to promote high-value recycling for solar PV. The definition of recycling standards, as already in place under the Waste from Electrical and Electronic Equipment (WEEE) Directive plays an important role in improving the circularity of PV products.

Other techniques to reduce the impact of material use would be to integrate circularity in the early stage of the design of the panels, by choosing materials that are easier to treat and recycle compared to their alternatives, and that do not contain hazardous substances. The standardization of the collection of end-of-life panels is also important, as well as the re-using and retrofitting of solar PV panel, which is currently it the very early stage[177].

Energy

In general, Cadmium Telluride PV panels show better performance than silicon panels (above twice shorter energy payback time). As detailed in the climate section, the use of renewable electricity in the production process will considerably lower the fossil energy payback time, and hence improve the energy performance of solar PV. The margin of progress in this field in therefore high.

Data completeness and further research needed

The solar PV assessment shows relatively complete data. On water pollution however, only mercury emissions have been collected. Unlike other energy sources of this report, the solar PV case present a relatively complete analysis of material use. However, the absence of such an analysis for other energy sources makes the comparison difficult.

The table below summarizes the data completeness on solar PV and shows fields of potential further research.

Soil	Water		Air	Climate	Material	Energy
Land use	Water pollution	Water use	Air pollution	CO2eq	Material use	EPBT
100%	25%	100%	100%	100%	67%	100%

List of data needed for further research:

- Water pollution \ WFD substances
- Water pollution \ Groundwater pollution

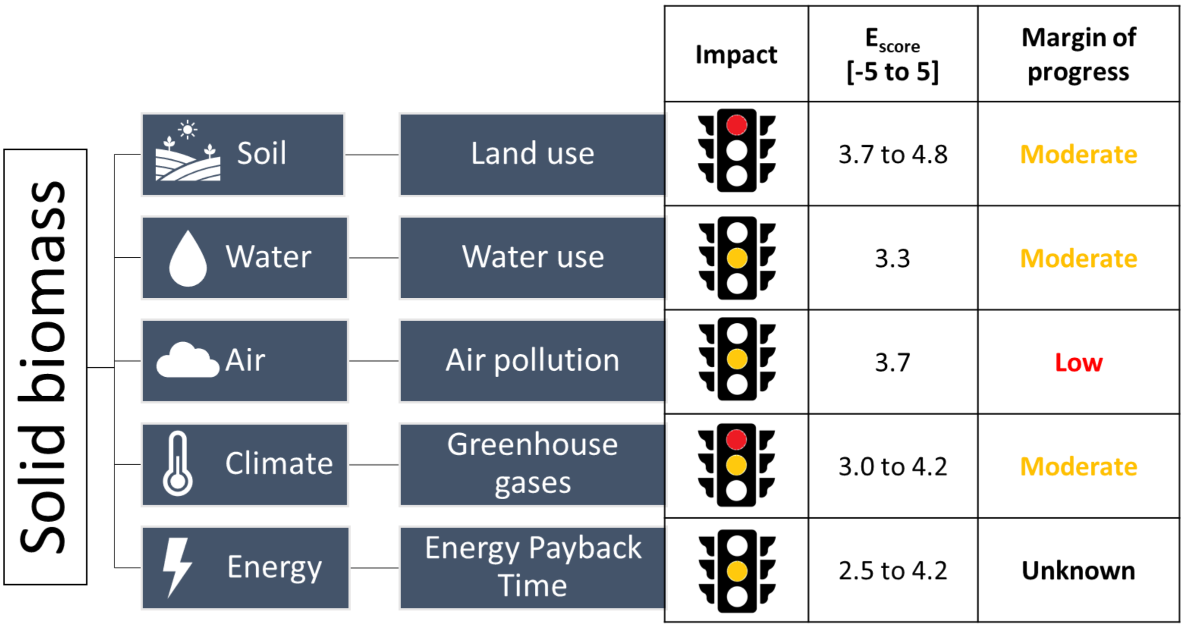
Solid Biomass

Summary

With one third of the renewable energy supply, solid biomass is currently the most important renewable energy source and by far the biggest contributor to renewable heating[178].

Biomass is an abundant resource, with however a very limited sustainable potential for energy production. Under the PAC scenario, the contribution of solid biomass to the total energy supply is expected to decrease from 1064 TWh in 2020 to 384 TWh in 2050[179], almost a division by three. The use of solid biomass for electricity generation should be phased-out and replaced – where possible – by cogeneration and alternative energy.

For this energy source, the impact assessment of a Combined Heat and Power (CHP) biomass plant from Finland has been used. This plant uses a mix of wooden biomass and peat. This case has been completed by meta studies on land use and GHG emissions. The graph below summarizes the main impacts of biomass and the margin of progress connected to the Best Available Techniques.



Solid biomass		Impact	E_{score} [-5 to 5]	Margin of progress
Soil	Land use		3.7 to 4.8	Moderate
Water	Water use		3.3	Moderate
Air	Air pollution		3.7	Low
Climate	Greenhouse gases		3.0 to 4.2	Moderate
Energy	Energy Payback Time		2.5 to 4.2	Unknown

Figure 14: Environmental score of Solid biomass technology

Soil

When using biomass coming from energy crops, biomass shows high to very high impacts on land use, with land use ranging from 20[180] to 623[181] km²/TWh, making it the technology of highest impact together with hydropower.

This is mostly due to the use of dedicated energy crops. In the absence of data, the impact of solid biomass from agricultural or forest residues has not been measured and could be substantially lower than from energy crops. For instance, with an average biomass mix including 30% energy crops and the rest covered by waste and residues, the impact would range from 6 to 187 km²/TWh, which lower range would be comparable with wind.

Water

Water pollution of biomass electricity generation has been measured via Mercury emissions and substances that negatively affect the good status of water under the Water Framework Directive. Despite the limited data availability for comparison, solid biomass performs rather well compared with its fossil competitor, with mercury emission 100 times lower than coal, and WFD substances emissions around 114 mg/kWh, 7 times lower than coal[182].

With 22 m³ of water used for each MWh of electricity generated[183], the biomass power plant shows impact comparable with fossil fuels such as gas and coal. This relatively high water consumption is caused by the cooling requirements of the combustion process.

To be noted that, in this case, the water used for the cultivation of energy crops (if any) has not been included. The choice of such a fuel could therefore considerably increase the water consumption of solid biomass.

Air

All relevant air pollutants have been measured for the solid biomass power plant. With SOx emissions reaching 277 mg/kWh, NOx emissions of 287 mg/kWh and PM emissions of 15 mg/kWh[184], solid biomass ranks among the worst energy generation technologies, showing even higher particulate matter emissions than coal.

To be noted that, in this case as well, the air pollution due to the cultivation of biomass (if any) has not been included. The choice of such a combustible could therefore increase the air pollution of solid biomass.

Climate

The climate performance of electricity generated by solid biomass depends largely on the type of combustible used. Following the life cycle assessment methodology based on direct GHG emissions, woodchips produced from forest systems show the lowest GHG content, with a minimal value of 51 kgCO2eq/MWh[185]. This lower range corresponds to woodchips produced with forest and wood industry residues at a low transport distance (below 500 km) of the combustion site. When the distance increases (above 10000km), the climate impact could increase by six-fold. This pattern is similar for biomass from agriculture, where agricultural residues show the lowest impact.

In general, the climate impact of wood pellets or briquettes is higher than chips, while pellets from wood industry residues compare well with woodchips from the same source. Short rotation coppice and stemwood show high impact with 230 kgCO2eq/MWh, but long-distance woodchips would show the highest impact with up to 353 kgCO2eq/MWh[186].

Materials

Due to a lack of relevant data, no analysis on materials has been performed for solid biomass technology.

Energy

With an energy payback time between 1 and 8 years[187], biomass compares well with fossil fuel generation but performs rather poorly compared with its renewable competitors. Biomass from waste and residues shows by far the shortest energy payback time, while biomass from energy crops shows higher values, esp. when the power plant is located long-distance from the biomass production site. This is due to the energy necessary for the production and transport of the biomass.

Selection of Best Available Techniques [188]

Soil

The origin of the combustible is the main driver to limit the land use associated with solid biomass. Where available, the choice of forest and wood industry residues will considerably lower the pressure on arable land caused by biomass cultivation.

However, and as shown in the PAC scenario, the availability of forest and wood industry residues will be limited in the future, where competing uses such as biomass for material will enter the market.

Water

For this area as well, the origin of the combustible is determinant in the impact on water. Where available, the choice of forest and wood industry residues will considerably lower the pressure on irrigation needs caused by biomass cultivation.

Pollutant emissions to water have not been identified as a major concern for biomass and/or peat combustion plants.

Air

To reduce NOx emissions, primary techniques (i.e. techniques used before or during the combustion process) such as staged air supply systems can be used also in combination with Selective Catalytic Reduction. For dust abatement, electrostatic precipitators and bag filters can be applied.

Climate

As for soil and water, the choice of the combustible is pivotal to limit GHG emission of biomass. Biomass of short-distance origin should be privileged and residues from forest, agriculture and wood industry should be prioritized. Such a choice could divide by up to six the carbon content of the combustible.

Data completeness and further research needed

The solid biomass assessment has been mostly derived from one case study on a large combined-heat and power plant. The addition of a small-scale plant could complete the analysis. Like most energy sources of this report, the analysis of soil pollution and material use would require further research.

The table below summarizes the data completeness on solid biomass and shows fields of potential further research.

Soil	Water		Air	Climate	Material	Energy
Land use	Water pollution	Water use	Air pollution	CO2eq	Material use	EPBT
100%	33%	50%	75%	100%	0%	100%

List of data needed for further research:

- Water pollution \ Metal emissions
- Water pollution \ Groundwater pollution
- Material use \ Metals
- Material use \ Rare Earth
- Material use \ Others

Wind

Summary

With an expected increase from 652 TWh in 2020 to 3576 TWh in 2050, wind power is one of the pivotal energy sources in the clean energy transition. In 2050, wind energy will represent over a half of renewable electricity generation, making it the most important renewable energy source, ahead of solar PV. Although wind onshore will still represent the highest share, wind offshore will show the highest increase – seven-fold between 2020 and 2050. By 2050 wind onshore will represent 77% of total wind electricity generation[189], wind offshore will represent the remaining 23%.

For this energy source, life cycle assessment of a 100 MW onshore wind park has been used. This case has been completed by meta studies on environmental impact of onshore and offshore wind parks (see Annex IV for more details). The graph below summarizes the main impacts of wind power (including onshore and offshore technologies) and the margin of progress connected to the Best Available Techniques.

Wind		Impact	E_{score} [-5 to 5]	Margin of progress
Soil	Land use		2.6 to 2.7	Moderate
Water	Water use		2.4	High
Air	Air pollution		3.4 to 4.0	High
Climate	Greenhouse gases		1.8 to 2.0	High
Energy	Energy Payback Time		1.6 to 2.0	Unknown

Figure 15: Environmental score of Wind technology

Soil

With a capacity density of 3.8 MW/km² for onshore[190] and 5.4 MW/km² for offshore[191], wind shows a moderate land use compared with other renewable energy sources.

The offshore technology shows the lowest impact on surface with a land use around 3 km²/TWh, while onshore wind uses around twice this surface for the same energy produced[192]. The better ranking of offshore technology is due to the combination of larger turbines and higher load factors (due to more regular wind) for offshore wind parks.

In general, wind parks allow existence of other activities such as grazing or agriculture for onshore wind, or some fisheries and navigation for offshore. It is important to note that, contrary to fossil fuels, a limited share of the land is actually artificialized by wind turbines foundations and installations (typically below 1% of total land use[193]). The rest of the land or seabed remains untouched and can be used for agriculture or even be converted into nature conservation or aquaculture areas for offshore wind parks[194].

Water

Among all energy technologies, wind shows high emissions of metal into water, with around 1.5 mg/kWh[195]. However, most of these metal emissions are iron emissions, which shows lower ecotoxicity than other heavy metals. As for other renewable technologies, most of the impact (95%) occurs during the extraction and manufacturing phase.

These high emissions are balanced by relatively moderate emissions of substances regulated under the Water Framework Directive. Despite the limited data availability, these emissions compare rather well with other technologies, comparable with solid biomass and 5 times lower than fossil gas.

When it comes to water use, wind scores rather well with a consumption of 1.7m³/MWh[196], positioning the technology on the lower end of impacts. To be noted that, in this case as well, most of the water consumption (94%) occurs during the extraction and manufacturing phase.

Air

When it comes to sulphur oxideoxides (SOx) and nitrogen oxideoxides (NOx), wind scores intermediately compared with other technologies, with emissions reaching resp. 14 mg/KWh and 21 mg/KWh[197], mostly occurring during the manufacturing phase.

These emissions are in the same order of magnitude than hydropower, for instance.

For particulate matter however, with emissions ranging from 27 to 48 mg/kWh[198], wind is positioned on the upper range of the impact scale, with emissions comparable with solid biomass.

Climate

When considering the whole life cycle of a wind turbine, climate impacts were found relatively low, with a range from 7.3 to 10.6 kgCO2eq/MWh[199]. In this case, the main contributions were related to material extraction and construction of the wind turbines. Hence, the local energy mix on the site of production has a significant influence on the results.

These results make wind a GHG-efficient technology, with only some hydropower plants and certain biogas installation being less emitting. Expectedly, wind shows better results that all combustion technologies.

Materials

Due to a lack of relevant data, it is difficult to compare the material use of different energy technologies. Is this report, only solar PV and wind have benefitted from detailed results.

When comparing the use of metals and esp. steel, wind shows the highest consumption compared with solar PV, with up to 337 mg/kWh[200]. However, with current best available techniques, this figure can drop to 108 mg/kWh[201], hence the importance to further integrate wind industry into circular economy and recycling.

Energy

With an Energy Payback Time (EPBT) ranging from 4 to 6 months[202], wind is among the best performing technologies together with hydropower. Onshore wind technology shows slightly better results but new offshore wind turbines are rapidly catching up.

Selection of Best Available Techniques

As elaborated above, most of the impacts of wind technology occurs during material extraction, processing and manufacturing phase. On GHG for instance, materials are responsible for 71% of the emissions, while manufacturing only accounts for 6%. Therefore, the emissions are closely linked to the extraction and processing techniques on the production site and the waste management policy of the country of disposal.

Soil

One of the most efficient way of reducing the impact of a wind park on land use is to increase the production capacity of wind turbines. If blades design could contribute to higher turbine efficiency, the most common technique to increase the MW of a wind turbine is to increase the diameter of the rotor.

In 2020, the average power rating of turbines ordered by the industry was 4.2MW for onshore and 10,4MW for offshore, an increase of almost 50% compared with 2015[203]. This means a higher efficiency and a lower land use per energy generated. If there is still a moderate margin of progress in this area, this could lead to cross-media effects with landscape, i.e. when a positive effect in one area has a negative impact on another area. This could ultimately lead to a diminished public acceptance and should therefore be taken into consideration when planning future wind capacities.

Water

Water consumption is mainly driven by the manufacturing of different elements of the wind turbine, esp. by the production of iron, steel and aluminum. Among all components, the production of blades is the most water intensive, representing almost half of blue water consumption[204].

One of the solutions to mitigate the impacts on water is to use recycled water in the production process. This recycling water could originate from internal treatment facilities or external sources. Current figures from the industry show relatively low share of recycling water (around 4% of total water consumption[205]), which implies a high room for maneuver in this field.

Another impactful measure to limit water use would be to select most virtuous metal production facilities in the very early life cycle of wind power. The margin of progress in this area has not been assessed, however the leverage is important.

Air

As with other impact categories, the extraction and manufacturing phases dominate the overall life cycle. Iron, steel and glass fiber production are responsible for most SOx and NOx and PM emissions. Air pollution reduction can therefore be achieved by rigorous implementation of BAT in the supply chain.

As for water, an efficient technique to mitigate air pollution would be to select most virtuous production facilities in the very early life cycle of wind power. The margin of progress in this area is deemed high.

Climate

As elaborated above, the carbon content of the material production, electricity, and transport mix of the country of production has the highest impact of the overall GHG emissions of wind parks. The location of the production in less GHG-intensive countries, the choice of most virtuous material providers or the use of renewable electricity could be a solution to mitigate the climate impact of wind turbines production.

Some companies are already using a 100% renewable electricity supply for their manufacturing, leading to more than 50% reduction in emissions intensity[206]. The margin of progress to reduce GHG emissions in the manufacturing process is therefore high.

Another way to reduce GHG emissions during material extraction and manufacturing would be to use recycled materials. This could also have positive impacts on other environmental areas. Additionally, wind turbines manufacturers can also optimize material use in production, working with suppliers to source materials more directly to the sizes needed to reduce waste in production and develop ways to recycle more of this waste stream.

Materials

The use of alternative, circular and renewable materials could provide benefits not only in raw material use but also in the areas above. For instance, the use of wood instead of steel for the wind tower is now under development by wind companies[207]. The use of superconductors for power transmission and generation allows for lower material use, while the use of rare Earth-free permanent magnet generator can release the pressure on rare Earth materials.

Currently, 85% to 90% of wind turbine can be recycled[208], and demonstrations have been made of their recyclability[209]. The wind technology has therefore a high margin of progress in terms of circularity, greenhouse gas emissions and material use.

Data completeness and further research needed

The wind assessment shows relatively complete data on environmental areas but could benefit from additional data on offshore technology. Like other energy sources, data would need to be completed on water and soil pollution. Unlike other energy sources of this report, the analysis of material has brought some results, esp. on the use of metals. The table below summarizes the data completeness on wind and shows fields of potential further research.

Soil	Water		Air	Climate	Material	Energy
Land use	Water pollution	Water use	Air pollution	CO2eq	Material use	EPBT
100%	25%	50%	75%	100%	33%	100%

List of data needed for further research:

- Water pollution \ Mercury emissions
- Water pollution \ Groundwater pollution
- Material use \ Rare Earth
- Material use \ Others

Conclusion

No energy is 100% clean…

Producing energy is a process of transformation by nature: transforming the flow of a river into electricity, transforming coal into heat and power, or harnessing the power of the sun. This transformation requires technology, which requires materials, transport, and manufacturing. It also sometimes requires fuel and combustion process. All these phases of the lifecycle of energy supply produce effects on the environment: pressure on land, resource use and waste, water, greenhouse gases… that have impacts on local or even the global environment.

Through this analysis, the RESET project has shown that no energy supply could be considered 100% clean, and that all energy sources would have negative impacts on their environment. It has revealed that most of the impacts of renewables occurs during the extraction and manufacturing phase, while fossil fuels installations pollute during their entire lifetime.

The RESET project has also demonstrated the importance of complete life cycle analysis and comprehensive environmental impact assessment when it comes to measuring the impact of energy technologies. If it did not select any environmental area as more relevant than another, it gives the possibility to perform weighted average of technologies and to adapt weighting to the environmental areas deemed more relevant.

The RESET project has also shown that the magnitude of impacts can considerably vary between the different energy sources, with sometime several orders of magnitude of discrepancy between the most polluting technology and the most virtuous one (defined as Best Available Techniques). It has also highlighted that some technologies such as biogas can even have positive impacts on the climate, by avoiding harmful methane emissions.

…but renewables are part of the solution

Under the RESET project, six renewable technologies have been studied: biogas, geothermal, hydropower, solar PV, solid biomass, and wind. Among all environmental effects analysed, one of the most salient compared with fossil fuels is greenhouse gases emissions. When it comes to climate change mitigation, most renewable technologies are by far best placed than their fossil competitors. In particular, non-combustion technologies such as wind and solar show emissions several times lower than coal or gas. This is particularly relevant in a context where the EU should reach **net-zero emissions by 2040** if it wants to be in line with its Paris-Agreement commitments, as shown in the PAC scenario as well as achieving the **Zero pollution ambition** by 2050 in regard to other pollutants and resource related impacts.

For almost all renewable technologies, another clear pattern emerges: if emissions of pollutants can still occur (for instance air pollutants for solar PV), most of this pollution happens during extraction, manufacturing, and transport phases. This means that most of the emissions depend on processes happening in the first phases of the production, and from the electricity mix of the country of production. With the evolution of manufacturing techniques and the move towards greener electricity mixes, there is a substantial margin of progress for renewable technologies. For the most impactful bio-based solution such as biogas or solid biomass, an important margin of progress lies within the choice of input – where the choice of waste and residues could even lead to net environmental benefits.

Another important dimension under scrutiny is the impact of renewables on land use. Here, some major technologies such as solar PV show relatively low impacts, with similar scores on average than fossil technologies. When considering the average land use of solar PV (with a combination of 50% rooftop and 50% utility-scale), the surface necessary to fulfil the energy supply by solar PV in the EU by 2040[210] would be around 990 km², the equivalent of the area of Berlin – for the whole EU. Particular care should be taken to avoid potential land use conflicts, including approaches within the AgriVoltaics concept that will mitigate potential risks of displacement of soil for arable purposes. Further improvement in technology efficiency will also lead to reducing the surface needed for installing renewable technologies.

In the next years, most of the focus to reduce the impact of renewable energy deployment would therefore be on the **reduction of the pollutant output during the production phase** – including the CO2 content of the electricity mix. The integration of renewable energy into a circular value chain and the recycling of end-of-life installations would be indispensable if the EU wants to move towards a cleaner and safer energy supply.

Limitations and room for improvement

The RESET project has analysed 8 different energy sources and their environmental impacts for 6 different environmental areas. The present report is the result of a nine-month data compilation and desk research on these energy technologies. As described in the sub-chapters *Data completeness and further research needed* under the technology analyses; the RESET project could benefit from deeper research on impact on soil pollution, water pollution and material use, where most data is currently missing and does not allow a comparative assessment.

In general, the RESET project has shown that it is difficult to obtain easily comparable data from different sources. Where several sources were available, the RESET analysis has checked consistency between the different figures and selected the most relevant source based on data completeness and accuracy. Despite these data checks, some Key Environmental Indicators and Environmental scores might diverge in scope from one technology to another, due to different approaches regarding system boundaries of the LCA concerned. Data on greenhouse gas emissions or air pollution for instance might sometimes include different phases of the life cycle assessment and different pollutants. Where relevant, precisions have been added on the scope of each technology assessment.

For certain technologies such as solid biomass, only one single impact assessment of an installation has been found. This low data availability could sometimes hamper the representativity of the results. The RESET analysis could therefore be completed by alternative examples of installations to provide a more representative range of impacts.

Next steps

The RESET methodology and Matrix are generic and could be easily transposed to other energy sources and energy services. The list below presents a series of suggestions of potential continuation of the RESET project to provide a comprehensive picture of the impacts of the energy system. For each item suggested below, an analysis of data availability and completeness will have to be performed to determine the most relevant field of investigation. Potential further investigations for the RESET project could be:

- Expand to major electricity supply technologies, including:
  - Fossil oil
  - Nuclear
  - Ocean energy
- Expand to heat generation, with the following technologies:
  - Heat pumps
  - Geothermal heat
  - Solar thermal
- Include an analysis of hydrogen, ammonia and liquid synthetic fuels
- Expand the analysis to energy services, including:
  - Energy storage
  - Energy efficiency
  - Demand-side management

Annexes

Annex I: Key Environmental Indicators

(Where available: impact over the lifetime of the installation, else: extrapolated from annual data)

SOIL

Chemical pollution	**Unit**
BTEX (Benzene, toluene, ethylbenzene, and xylene)	mg/kWh
Chlorinated aliphatics	mg/kWh
Heavy metals	mg/kWh
MTBE (methyl tertiary-butyl ether)	mg/kWh
PAH (Poly-Aromatic Hydrocarbons)	mg/kWh
Nitroaromatics	mg/kWh
Others: phenols, pesticides, NSO-compounds, PCBs, cyanide, arsenic, and a number of emerging contaminants (estrogens, antibiotics, etc.)	mg/kWh
Physical disturbances	
Total land / seabed area use for the project (grid connection included)	km^2/TWh
Land / seabed actually artificialized or heavily modified by the project	km^2/TWh

WATER

Chemical pollution	**Unit**
Metals and their compounds (Mercury excluded)	mg/kWh
Mercury	mg/kWh
Substances that negatively affect the good chemical/ecological status (Env. Quality Standards - Water Framework Directive)	mg/kWh
Substances that are subject to limits under groundwater (affecting groundwater) e.g. Sulphates	mg/kWh
Physical disturbances	
Water use	m^3/kWh

AIR

Chemical pollution	**Unit**
Sulphur dioxide and other sulphur compounds (SOx)	mg/kWh
Oxides of nitrogen and other nitrogen compounds (NOx)	mg/kWh
Mercury (Hg)	mg/kWh
Fine particulate matter, if possible differentiated to PM 10, 2.5 ultrafine PM	mg/kWh

CLIMATE

Direct and indirect emissions	Unit
Carbon dioxide (CO2)	kg/MWh
Methane (CH4)	kg/MWh
Nitrous oxide (N2O)	kg/MWh
Hydrofluorocarbon (HFCs)	kg/MWh
Perfluorinated hydrocarbon (PFCs)	kg/MWh
Sulphur hexafluoride (SF6)	kg/MWh

MATERIALS

Metals	Unit
Copper	mg/kWh
Magnesium	mg/kWh
Manganese	mg/kWh
Cromium	mg/kWh
Nickel	mg/kWh
Cobalt	mg/kWh
Lithium	mg/kWh
Gold	mg/kWh
Zinc	mg/kWh
Aluminium	mg/kWh
Steel (Only Iron)	mg/kWh
Rare Earth	
Neodymium	mg/kWh
Indium	mg/kWh
Dysprosium	mg/kWh
Praseodymium	mg/kWh
Lanthanum	mg/kWh
Cerium	mg/kWh
Promethium	mg/kWh
Samarium	mg/kWh
Europium	mg/kWh
Gadolinium	mg/kWh
Others	
Plastics	mg/kWh
Glass	mg/kWh
Silicone	mg/kWh
Share of secondary raw materials	mg/kWh
Concrete	mg/kWh

Annex II: Detailed results

	Soil		Water pollution				Water use	Air pollution				Climate	Material			Energy
Technology	Land use	Land artificialized	Metal	Mercury	WFD substances	Groundwater pollution	Water use	SOx	NOx	SO2eq	PM	CO2eq	Metals	Rare Earth	Others	EPBT
BIOGAS_ELEC_Max	349.71	349.714286					0.0009569	5450		5450		408				4.7
BIOGAS_ELEC_Min	0	0					0.0002341	920		920		-395				2.22
COAL_ELEC_Max	0.6241	0.62414408	0.1038	0.04		94.03058	0.117241	3392.52	719.719	3896.32	27.6711	1144.9				21.875
COAL_ELEC_Min	0.0024	0.00240568	0.0455				0.0002001	240.366	255.282	419.064	13.7822	874.3				5
FOSSIL_GAS_ELEC_Max	0.008	0.00796468	0.0544		828.30666	449.89815	0.1265185	320	3800	2980	3.6785	1300				16.667
FOSSIL_GAS_ELEC_Min	0.0035	0.00347548				10.660981	0.0187146	10	200	150	0.52772	380.01				5
GEOTHERMAL_ELEC_Max	0.4	0.4					0.014	64		64		80				3.2499
GEOTHERMAL_ELEC_Min	0.04	0.04					0.0001	0.352		0.352		5				0.1417
HYDROPOWER_Max	2750.5						3.0541516	30	60	72		20				0.5882
HYDROPOWER_Min	0.012	0.012					0.001083	4	4	6.8		2				0.3571
SOLAR_PV_Max	1.1129	0.02782218		0.0542			4.484E-05	376.32		376.32	96.884	80	79.285		246	2.8
SOLAR_PV_Min	0	0		0.0282			2.942E-05	96.2332		96.2332	58.4382	10	33.5		151.16	0.5
SOLID_BIOMASS_ELEC_Max	622.81	622.806814		0.0006	114.18488		0.0226115	277.158	287.019	478.071	15.0516	352.52				8.3333
SOLID_BIOMASS_ELEC_Min	20	20										51.387				0.9259
WIND_Max	7	0.03564349	0.1003		175.72		0.0017266	14.033	21.34	28.971	48	10.6	336.66			0.5
WIND_Min	3.4118	0.14257397									26.9	7.3	108.14			0.3
	[km^2/TW	[km^2/TWh]	[mg/kWh	[mg/kWh	[mg/kWh]	[mg/kWh]	[m^3/kWh]	[mg/kWh]	[mg/kWh	[mg/kWh]	[mg/kWh]	[kg/MWh	[mg/kWh	[mg/kWh	[mg/kWh	Years

Annex III: List of consulted organisations (in alphabetical order)

- Agora-EnergieWende
- ECF
- ECOS
- Energy Watch Group
- European Biogas Association (EBA)
- European Heat Pumps Association (EHPA)
- European Renewable Energy Council (EUREC)
- SmartEn
- Solar Heat Europe
- SolarPower Europe
- Wind Europe

Annex IV: References

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