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Life cycle assessment of electricity from wind, photovoltaic and biogas from maize in combination with area-specific energy yields – a case study for Germany

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Abstract

Due to the massive expansion of renewable energy-based production capacity, the benefits and drawbacks of wind turbines, ground-mounted photovoltaic (PV) and biogas plants are currently being discussed in Germany and elsewhere. The expansion of renewable energy-based plants is competing with other uses for land area. In addition to area-specific energy yields, the environmental impact of renewables is increasingly gaining awareness. Existing research on the area-specific energy yields and environmental impact for wind, PV and biogas lacks comparability due to factors including time, location, and scale. This study addresses this research gap by combining life cycle assessment (LCA) to compare potential environmental impacts with an area-specific energy yield assessment of wind, ground-mounted PV and biogas from maize in Germany. The LCA includes an assessment of eleven midpoint and three endpoint impact indicators, while the area-specific energy yield is assessed on the basis of both gross and net area-specific energy yield. The LCA results indicate the lowest impact for wind, followed by PV and biogas. This ranking is consistent across all three endpoint and nine out of eleven midpoint categories. The same ranking also applies to the area-specific energy yield, with wind producing the most and biogas the least gross and net energy per area. These results indicate that the current political support in Germany for biogas from maize for electricity generation should be thoroughly re-evaluated in view of the more favourable alternatives, wind and PV. The findings also provide relevant insights for other regions with similar boundary conditions.

1. Introduction

With the aim of reducing greenhouse gas (GHG) emissions and ending dependence on fossil energy sources, the expansion of renewable energies for electricity production is being strongly promoted in Germany. The ambitious politically driven expansion goals set in the *Renewable Energy Sources Act* (‘*Erneuerbare-Energien-Gesetz*’, *EEG*) aim to reach 80% of renewable electricity in the electricity mix by 2030 (Federal Ministry of Justice (Germany) 2023).

Various technologies are available to meet this goal. Of those technologies, wind turbines (referred to as ‘wind’ from here on) and ground-mounted photovoltaic systems (‘PV’) are considered to be the most relevant technologies for future electricity systems powered by renewables (Metzger *et al* 2021, Reinert *et al* 2021). This assessment is underlined by the ambitious expansion goal of up to 10 GW per year for each wind and PV in the *Renewable Energy Sources Act* (Federal Ministry of Justice (Germany) 2023).

However, the expansion goals for renewable electricity production options is in most cases in Germany in direct competition with agricultural land use, as indicated by Böhm *et al* (2022). The amount of agricultural land in Germany is limited and declining (Haß *et al* 2022), while being needed for food and feed production. At the same time, new uses are emerging, e.g., the production of fibres and raw materials for bio-based plastics. Furthermore, a large area share of agricultural land is currently used to grow energy crops. The land use conflict between electricity generation and agriculture is therefore expected to intensify in the future (Haß *et al* 2022, Osterburg *et al* 2023).

Currently, PV occupies only 0.1% of agricultural land in Germany (Böhm *et al* 2022). This share is expected to grow to 2% until 2040 (Böhm and Tietz 2022). Meanwhile, 75% of existing and new wind energy installations in 2018 were built on agricultural land (Berkhout *et al* 2019). Biogas production for electricity is very extensive in Germany and requires a large amount of agricultural land, occupying approximately 9% of it (Jankowski *et al* 2020, Böhm 2023, Ignatowicz *et al* 2023, Fachagentur Nachwachsende Rohstoffe e.V. 2023a). This large share of agricultural land for biogas and subsequent electricity production is mainly subsidy driven by the political introduced electricity feed-in tariff in the EEG (Theuerl *et al* 2019, Federal Ministry of Justice (Germany) 2023). This leads to a share of 4.5% of electricity in the German grid produced from biogas (Lebuhn *et al* 2014). Maize cultivation for biogas plants makes up one third (0.89 M ha out of 2.48 M ha) of the total cultivated maize area in Germany (Fachagentur Nachwachsende Rohstoffe e.V. 2023a, 2023b).

In order to use finite land resources for electricity production efficiently, the area-specific energy yield for each of the production options needs to be evaluated. In this context, area-specific energy yield is defined as the amount of energy provided divided by the land area occupied by the energy-producing plant (Prochnow *et al* 2009, Fuksa *et al* 2012, Grassini and Cassman 2012). For example, in the case of a common ground-mounted PV system, the area taken into account for the area-specific energy yield is the area occupied by the mounted PV-modules and the inverter. However, the land required to house the factories that produce all necessary parts of the PV system, e.g., the PV modules, is not counted towards the area-specific energy yield. This regional focus of the area-specific energy yield allows regional comparisons of land-use options. In Germany, the renewable electricity production options wind, PV and biogas from maize silage are often built on the finite resource of agricultural land, which can then no longer be used for intensive farming, therefore ensuring that this occupied land is used as efficiently as possible with the concept of area-specific energy yield is essential.

A previous study evaluated the area-specific gross energy yields for Germany for the electricity, heat, and transport sector (Böhm 2023). The results indicate that wind turbines have the highest area-specific energy yield, followed by ground-mounted PV, and biogas from maize (Böhm 2023). Currently, environmental impacts associated with the expansion of renewable energies are also becoming increasingly important. Especially the contribution to GHG emissions is of highest importance, underlined by one of the goals of the European Green Deal (Costa *et al* 2021). The question of whether the results of the area-specific energy yields are still valid if the cumulative energy demand of the entire supply chain and other environmental impacts are taken into account is still unanswered. Furthermore, it is conceivable that the high energy yields are achieved at the expense of other environmental impacts. Therefore, a comprehensive assessment of electricity production options should compare both area-specific energy yields and potential environmental impacts. This differentiation makes it possible to observe the local environmental impacts independent from area requirements elsewhere.

The environmental impact assessment should not only cover one impact category, e.g., climate change/global warming potential (GWP). Instead, an assessment which covers a wide range of possible impact categories would highlight potential conflict of objectives between production options, and would avoid burden shifting between impact categories. A methodology that allows for such an assessment of multiple environmental impact categories is Life Cycle Assessment (LCA).

Several studies have already conducted LCAs on renewable energy-based production options, though none had explicitly considered the area-specific energy yield. These LCAs compare the land-use of these systems over the whole production chain, regardless the location of production. Especially for comparing land-use options in one country it is necessary to look at the environmental impacts per area used at the facility location.

For the results of these studies to be comparable, they have to be based on a similar set of assumptions and parameters. More specifically, they should refer to the same location while using state-of-the art Life Cycle Inventories, and include all three production options (wind, PV, biogas from maize) in the same study. The region of the production site is important because of variations of the energy production potential. Using current data is important because the energy production systems have seen strong efficiency gains during the past years. The temporal influence on technological progress can therefore lead to a distortion of the results. To compare all options within the same study is beneficial since, e.g., the goal and scope of an LCA, but also methodological aspects such as the treatment of multi-output processes and end-of-life treatments, can have a major impact on the results. Typically, these aspects vary between LCA studies, which is why the results of separate studies are in many cases hardly comparable. Our review of the literature indicates that no previous study meets all criteria outlined above. No study compares all three options with a consistent set of assumptions and data, while also comparing the area-specific energy yields.

Mahmud and Farjana (2022) and Gao *et al* (2021) compare wind turbines, PV, and biomass, but consider very different locations and plant sizes. Piotrowska *et al* (2022) examine equal plant sizes for PV and wind in Poland but the biogas production is not considered. Hengstler *et al* (2021) evaluate the environmental impacts of wind and PV for different locations in Germany and Oğuz and Şentürk (2019) for a location in Turkey, but neither study considers biogas plants. Gao *et al* (2019) examine biomass systems and wind farms in China, but make no reference to ground-mounted PV systems.

Various other studies focus on one technology only. The difference between miscellaneous PV technologies is pointed out by Leccisi *et al* (2016). The effect of varying locations for PV systems in the US is analysed by Grant *et al* (2020). Neither study assesses wind or biogas. Fusi *et al* (2016) focus on different biogas plants in Italy.

This study addresses this gap in the literature. It contains an LCA to evaluate potential environmental impacts of three renewable energy-based electricity production options (wind, PV, biogas from maize), based on a consistent set of assumptions and parameters, and for multiple impact categories. The LCA results are combined with an assessment of the area-specific energy yields for each production option. This integrated assessment highlights two highly relevant target dimensions and indicates potential goal conflicts between them. The study parameters and assumptions refer to the context of Germany.

2. Method

The study consists of three sections: an assessment of the area specific productivity (area-specific energy yields), an assessment of the environmental impacts using LCA, and an integrated assessment to combine results of the former two parts. Each of the three parts of the study covers the three production options of interest for Germany: wind turbines, ground-mounted PV, and biogas from maize. In Germany, the operation of agricultural biogas plants is subsidised by the feed-in tariff for the electricity generated from biogas (Theuerl *et al* 2019). For this reason, only electricity produced from biogas from maize is covered. The co-produced heat is only considered for fermenter heating of the biogas plant, but no further heat use concept.

The overall goal of the LCA is to compare the environmental impacts of the three production options. The comparison relies on the LCA modelling software Umberto version 11 and is conducted according to ISO standards 14040 and 14044 (ISO 2006, ISO 2006). The Ecoinvent v3.9.1 cut-off data base is used for background data (Wernet *et al* 2016, Ecoinvent 2022). The functional unit, the quantitative reference to which all results refer to, is set to 1 kWh_{el} fed into the grid.

LCA results can be provided both at the midpoint and at the endpoint level. Midpoint indicators are closer to the source, and less prone to value judgements. An example is the global warming potential, used to characterize impact on the climate change impact category. The benchmark here is the 2020 German electricity mix with a GWP of 471 g $CO_{2eq.}$ kWh^{-1} (Ecoinvent 2022). Endpoint indicators are used to communicate results to a wider audience and integrate multiple midpoint indicators into one single endpoint indicator. Reliance on both midpoint and endpoint indicators when conducting an LCA are recommended, which is why this study also relies on both indicators.

To identify the individual environmental impacts on the midpoint level, the CML 4.8 2016 method for the European context is used, which was first presented by de Haes (1992). The following eleven midpoint indicators are assessed in this study:

- Acidification potential (AP)
- Global warming potential (GWP)
- Freshwater aquatic ecotoxicity potential (FAETP)
- Marine aquatic ecotoxicity potential (MAETP)
- Terrestrial ecotoxicity potential (TETP)
- Abiotic depletion potential (fossil fuels) (ADP-FF)
- Eutrophication potential (EP)
- Human toxicity potential (HTP)
- Abiotic depletion potential (ultimate reserves/elements) (ADP-UR)
- Ozone layer depletion (ODP)
- Photochemical oxidants formation (POF)

All midpoint indicators refer to the environmental impacts over a time-period of 100 years.

For the assessment of environmental impacts at endpoint level, the ReCiPe 2016 Endpoint (Hierarchical, H) impact assessment method with focus on human health, ecosystems, and resources is used (Huijbregts *et al* 2017, Rashedi and Khanam 2020).

This study does not assess the LCA impact category *'land use'*, as this would result in the land use of the whole upstream chain of each production option being considered. The focus instead is on land use required for the use phase of electricity production options. Hence, assumptions specific to Germany are used. In order to differentiate the wording, the term *'area requirement'* is used instead.

The system boundaries are set in such a way that the entire life cycles of the plants are analysed, including raw material extraction, manufacturing, the construction with all upstream activities, use and maintenance phase up to the dismantling of the plants. Recycling of individual materials is also taken into account, but not their further use, as the cut-off approach is applied (Wernet *et al* 2016). All assessed systems consider plant components up to the grid connection. Grid or storage capacities, and changes of soil carbon, are not within the system boundaries and therefore not modelled.

As there are many possible plant design options, and other factors, such as the exact location, also have an impact on electricity production, three different scenarios are considered for each electricity production option: *conservative*, *baseline* and *optimistic*. The parameter range covered by the scenarios is defined by previous LCA studies and expert interviews. They cover the range that can be realistically expected for a current installation in Germany, considering different locations and system configurations. The baseline scenario represents a typical scenario. The *conservative/optimistic* scenarios reflect realistic but more adverse respective beneficial parameters with relatively high/low area requirements. The assumptions are explained in more detail in the following sections. In addition to these scenario assumptions, which apply to various facilities in Germany, a sensitivity analysis is performed focusing on the methodological approach.

2.1. Wind turbines

Different area requirements can be considered for wind turbines: *sealed area requirement* or *wind area requirement*. The former describes the area that is sealed by crane sites, foundations and access roads, while the latter refers to the area defined by a radius around the wind turbine in which no other wind turbine may be built (Ciliberti *et al* 2016, Böhm 2023). This study relies on the sealed area requirement, because only this perspective makes it possible to compare it with PV and biogas looking at the loss of agricultural land.

The main components of a wind turbine are the foundation, the tower, the nacelle with the generator, and three rotor blades. The electricity yield and the environmental impact of a wind turbine can vary greatly depending on the assumptions made. Table 1 shows the scenario assumptions for wind turbines.

The life cycle inventory for wind turbines is mainly based on Ozsahin *et al* (2022), Schreiber *et al* (2019), and Rashedi *et al* (2013). It is updated with more recent literature. A full list of references used can be found in the supplementary material, tables S1–S11.

2.2. Ground-mounted photovoltaics

Photovoltaic systems can be installed on various surfaces. In addition to roof surfaces, open spaces are often used. Due to the current market growth rates and scalability this study focuses on ground-mounted PV systems.

All components required to operate the system are considered: these are the PV modules, the inverter, the mounting structure and the cabling of the system. Due to the very high market share of over 84%, monocrystalline silicon modules are assumed for this analysis. As 75% of all silicon cells are produced in China, this study considers only Chinese production (Philipps and Warmuth 2023).

The activities during the use phase are limited to the cleaning of the panels, maintenance of the grassland below the panels and inspection and repair of the system. More detailed assumptions for the PV scenario assumptions are shown in table 2.

As a basis, the production, use, maintenance, and recycling processes from the Ecoinvent database and Müller *et al* (2021) are used. In addition, the life cycle inventory is supplemented with data from Szilágyi and Gróf (2020). A full list of references can be found in the supplementary material tables S12–S29.

2.3. Biogas from maize silage

Various substrates can be used for biogas production. In Germany, maize silage is very often used as a renewable substrate in combination with manure. In Germany 55% of the energy supply for biogas comes from maize (Daniel-Gromke *et al* 2018). For this study it is assumed that maize silage is the only substrate used in the biogas plant (Jankowski *et al* 2020). The direct and indirect field emissions such as nitrous oxide, ammonia, nitrate, and heavy metals were calculated with a wide range of emission calculation models (e.g., Intergovernmental Panel on

Table 1. Scenario assumptions for wind turbines.

	Conservative	Baseline	Optimistic
Plant size [kWp]	2,500	3,000	5,000
Wind yields [full load hours $year^{-1}$]	1,800	2,500	3,200
Sealed area requirement per system [ha $system^{-1}$]	0.6	0.4	0.24
Wind area requirement per system [ha $system^{-1}$]	25	20.1	14.3
Service life [years]	20	25	30
Part replacement of gearbox [% over lifetime]	0.95	0.95	0.95
Part replacement of generator [% over lifetime]	0.19	0.19	0.19
Rotor diameter [m]	100	112	126
Tower height [m]	100	119	120
Losses due to the energy grid capacity [%]	3	1	0
Distance from the factory to the wind turbine location [km]	900	450	100
Inspections per year (100 km distance each)	6	6	6
Leakage of insulator gas SF6 during use [%]	0.10	0.10	0.10
Leakage of insulator gas SF6 during dismantling [%]	5	5	5

Table 2. Scenario assumptions for ground-mounted photovoltaic.

	Conservative	Baseline	Optimistic
Plant size [kWp]	750	5,000	100,000
PV yields [kWh kWp^{-1} $year^{-1}$]	982	1,058	1,150
PV area requirement [ha MWp^{-1}]	2	1.2	0.9
Annual power degradation [%]	0.3	0.25	0.2
Service life of inverter [years]	15	15	15
Service life of entire system [years]	20	25	30
Interception losses due to grid capacity [%]	3	1	0
Mowing per year	2	1	0
Efficiency of the modules [%]	21	21	21
Losses due to the energy grid capacity [%]	3	1	0
Replacement of modules in the entire system over whole life time [%]	3	3	3

Climate Change (IPCC), Swiss Agricultural Life Cycle Assessment (SALCA)). The procedure for calculating field emissions is based on the approach of Herzog *et al* (2021) and Krexner *et al* (2023).

In addition to the electricity production, the biogas plant produces heat. It is assumed that the heat is used for the heating of the fermenter, but no further heat use concept is considered. To study the degree to which this assumption affects results, we conduct a sensitivity analysis (see section 4). It contains a comparison of the reference case (no heat use) to two cases in which the environmental impacts are allocated to both electricity and heat by a) energy (calorific method) and b) exergy (Carnot method).

The assessment only considers the area required for maize cultivation, but neither the area required for the biogas plant itself nor for the storage silos. The silo area and the fermenter area differ greatly between the plants, but only take up a small proportion of the area compared to the area under cultivation.

In biogas plants, both the maize yields and the efficiencies of the fermenters and engines can show considerable fluctuations. A possible range of fluctuations in Germany is shown with the scenario assumptions in table 3 and examined in more detail below.

In addition to the Ecoinvent database, the life cycle inventory for biogas plants are supplemented by data from Kral *et al* (2016), Fusi *et al* (2016), Böhm (2023) and Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (2023). Details and a full list of references can be found in the supplementary material tables S30–S34.

3. Results

The result section first lists the area-specific energy yields, followed by environmental impacts for both midpoint and endpoint indicators. It concludes with an integrated assessment that combines energy yields and environmental impacts.

Table 3. Scenario assumptions for biogas from maize silage.

	Conservative	Baseline	Optimistic
Maize yields [t fresh matter (FM) ha^{-1} $year^{-1}$]	35	42.25	65
Nitrous oxide field emissions [kg ha^{-1}]	2.63	2.63	2.63
Field to biogas plant distance [km]	20	10	2
Energy storage losses of maize [%]	12	12	12
Service life [year]	20	20	20
Maize dry matter (DM) [%]	34	34	34
Organic dry matter content [%]	95	95	95
Biogas yield per fresh matter of maize [m^3 t^{-1} FM^{-1}]	216	216	216
Methane emissions of the biogas plant [%]	1.5	1.5	1.5
Methane yield per organic dry matter	330	330	330
Methane content in biogas [%]	52	52	52
Own power consumption [%]	12.6	9.3	7.5
Own power consumption [kWh t^{-1} FM^{-1}]	36.7	36.7	36.7
Own heat consumption [%]	19.5	23.5	28.1
Own heat consumption [kWh_{th} t^{-1} FM^{-1}]	155	155	155
Electric efficiency of combined heat and power (CHP) plant [%]	28	38	47

Table 4. Gross and net area-specific energy yields of all assessed scenarios.

Area-specific energy yields [kWh ha^{-1} $year^{-1}$]	Scenario	Wind turbines (sealed area requirement)	Ground-mounted photovoltaic	Biogas from maize
Gross	conservative	7,275,000	462,696	9,165
	baseline	18,562,500	846,665	15,014
	optimistic	66,666,667	1,240,722	28,570
Net	conservative	6,672,167	375,340	142
	baseline	15,760,892	728,595	5,775
	optimistic	59,513,632	1,108,802	17,653

3.1. Area-specific energy yields

The energy yield per hectare varies substantially between production options. The results of the area-specific energy yields are listed in table 4. A distinction can be made between gross and net area-specific energy yields.

NAEY = GAEY * (1-CED)

NAEY = Net area-specific energy yield [kWh ha^{-1} $year^{-1}$]

GAEY = Gross area energy-specific yield [kWh ha^{-1} $year^{-1}$]

CED = Cumulative Energy Demand

The difference between gross and net values ranges from 8.3%–15.1% for wind, followed by 10.6%–18.9% for PV and 38.2%–98.4% for biogas. Energy Pay Back Time (EPBT), i.e., the time required until an installation has generated the amount of energy required to produce it, is 0.4 (0.3–0.6) years for wind, 1.4 (1.3–1.5) years for PV, and 4,8 (3.0–7,8) years for biogas.

If the wind area requirement instead of the sealed area requirement is considered, the values for the wind baseline scenario are reduced to 369,403 kWh ha^{-1} $year^{-1}$ and 353,916 kWh ha^{-1} $year^{-1}$ for the gross and net electricity yields, respectively, and thus lower than for PV.

3.2. Environmental impacts—midpoint indicators

The environmental impacts of the considered renewable energies vary strongly depending on the scenario. Figure 1 compares the relative environmental impacts across impact categories, scenarios, and production options. 100% represents the impact per category for the baseline scenario of the production option with the absolute highest impact of all three options (biogas in most cases). The coloured bars represent the impact for the baseline scenario, while the 'whiskers' extending above and below the bars represent the optimistic and conservative scenario.

The results are consistent across almost all impact categories. Wind has the lowest impacts per kWh, followed by PV and biogas from maize. Biogas has the highest impacts in 10 of 11 assessed impact categories. Only for ADP-UR, PV has the highest impact. This is due to the high demand of abiotic resources, especially for

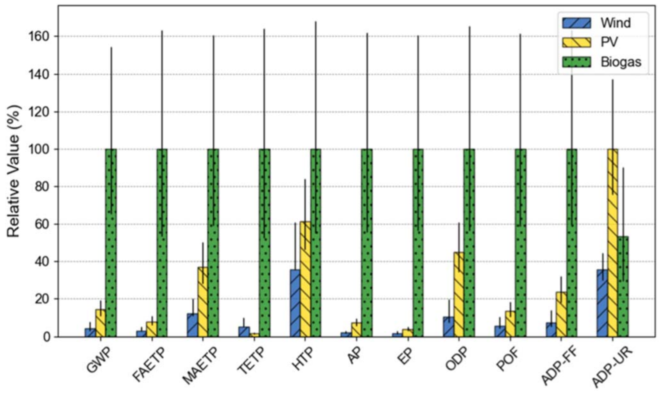

Figure 1. Relative environmental impacts on midpoint level of the three assessed renewable electricity production options (wind, PV, biogas from maize) for the baseline scenarios, respectively. Whiskers represent the deviation for the conservative and optimistic scenarios for each electricity production method.

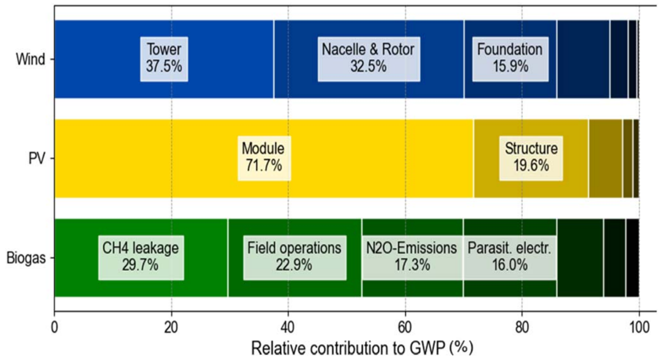

Figure 2. Contribution of different processes and parts for the renewable energies on the GWP emissions (baseline scenario).

the PV module production. In contrast, wind has the lowest environmental impacts in 10 of 11 assessed impact categories.

For GHG emissions, the total amount of GWP is important. In the baseline scenario, biogas from maize has a GWP of 268 g CO_2eq kWh^{-1}, ground-mounted PV 39 g CO_2eq kWh^{-1}, and wind turbines 11 g CO_2eq kWh^{-1}.

For each production option, the contribution of individual components and aspects to the total environmental impact differs. A contribution analysis, shown in figure 2, illustrates this for the GWP impact category and the baseline scenario. For wind, the main contributors are the production of the tower with 37.5%, followed by 32.5% for nacelle and rotor. In the case of ground-mounted PV, the highest share of GWP (71.7%) comes from the module production, which is mainly due to the high electricity demand. In the case of biogas from maize, the methane leakage (29.7%) contributes the most to the GWP. When considering the absolute values in combination with the contribution analysis, it is apparent that only the N_2O emissions from the nitrogen fertiliser result in a higher GWP than the overall GWP for either wind or PV.

3.3. Environmental impacts—endpoint indicators

The endpoint indicators according to the ReCiPe 2016 Endpoint (H) impact assessment method show that biogas production has the highest environmental impacts for all three areas of protection: human health, ecosystems, and resources. The baseline scenario shows clear advantages of wind compared to PV, but depending on the scenarios, difference can appear whether wind or PV has lower endpoint impacts (see figure 3).

3.4. Integrated assessment—combination of area-specific energy yields and environmental impacts

An integrated assessment of environmental impacts and land area requirements can reveal potential goal conflicts. The results of the area-specific energy yields and environmental impacts per kWh show a consistent ranking, with wind being the most preferable option, followed by PV and biogas. One exception is TETP, depicted in figure 4. The central goal conflict exists between wind and PV: wind has a higher energy yield, and

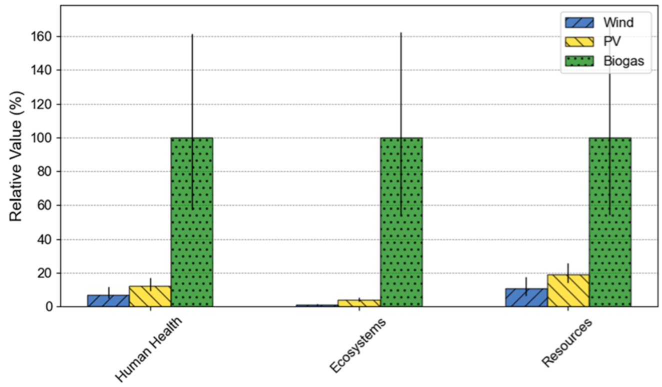

Figure 3. Relative environmental impacts on endpoint level of the three assessed renewable electricity production options (wind, PV, biogas from maize) for the baseline scenarios, respectively. Whiskers represent the deviation for the conservative and optimistic scenarios for each electricity production method.

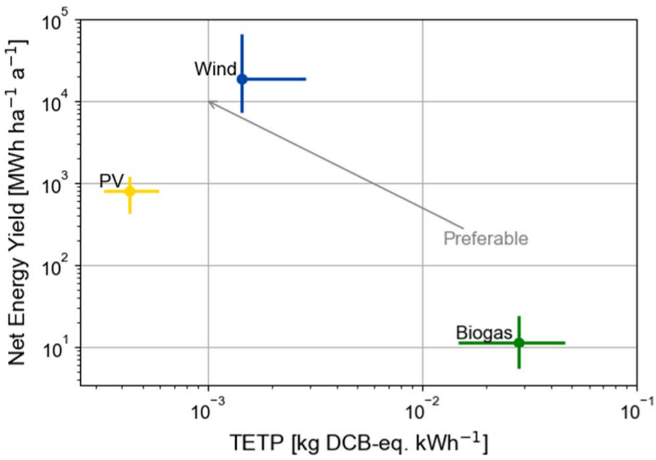

Figure 4. TETP per kWh in contrast to the net energy yield. Preferable is higher yield (up) and lower environmental impact (left).

thus a lower land requirement, but PV has a lower environmental impact with respect to TETP. Biogas performs worst with respect to both target dimensions, even when considering the optimistic scenario. Similar plots for GWP and ADP-UR are included in the supplementary material, Figures S5 & S6.

4. Sensitivity analysis - midpoint indicators

Besides the scenario assumptions, looking at the range of different system parameter in Germany, some methodological assumptions can have a major impact on the results. Therefore, sensitivity analyses are performed, to identify the effect of assumptions for the modelling approaches on the results and therefore their robustness. We conduct three different types of sensitivity analyses: 1) end-of-life modelling, 2) heat allocation, and 3) manufacturing location. Detailed results for the sensitivity analysis can be found in supplementary material section S6.

4.1. End-of-life modelling

The methodological use of the cut-off procedure and the avoided burdens approach can strongly influence the results, which is also mentioned by McAuliffe *et al* (2023). As Schreiber *et al* (2019) state, the cut-off method tends to overestimate and the 'avoided burden approach' tends to underestimate the actual environmental impacts. With respect to end-of-life-modelling, if the Avoided Burden Approach according to Frischknecht (2010) is used, the results change significantly. This approach awards credits for the reuse of recyclable materials and can be used instead of the cut-off method for modelling the end-of-life phase. Recycling processes of PV show a strong effect, reducing environmental impacts by up to 62%. Also, recycling of wind turbines results in a high reduction of environmental impacts of up to 50%, depending on the impact category. Biogas is not affected by the avoided burden approach, since this production option offers no substantial amount of material available for recycling. Applying the avoided burdens approach does not change outcome of the comparison between renewable energy production options. With the avoided burden approach as opposed to the cut-off approach, the relative environmental impact for the biogas option is even higher compared to wind and PV.

4.2. Heat allocation

To test how results change when a heat use concept is available at the biogas plant, the methodological approach of allocation is used to distribute environmental impacts between the two outputs electricity and heat. Two allocation factors based on exergy and energy are taken into account. Results show that with allocation based on exergy (Carnot method), the environmental impacts for biogas are reduced in all categories by 19% to 34% of the original impact (without heat use concept). For allocation based on energy (calorific method), the impacts decrease by 40% to 60%. Due to the big difference to PV and wind, even this reduction for biogas still means that biogas has the highest impact of all three production options. Three exceptions exist: the impact categories ADP-UR, HTP, and ODP show slightly lower impacts compared to PV in the optimistic biogas scenario.

4.3. Manufacturing location

Due to the practical relevance, the manufacturing location is highly important for PV systems. In the sensitivity analysis of the results of ground-mounted PV systems, it becomes clear that the location of the manufacturing of the modules has a major influence on the results of PV. A total of eight out of 11 environmental impacts (except FAETP, EP, ODP) are lower for PV production in Germany compared to China. However, the impacts for PV are still higher than for wind, and lower than for biogas from maize.

5. Discussion

When comparing the results to the values given in the literature, it is evident that most results from this study are comparable to those from previous studies. In the case of wind, the literature shows similar gross electricity yields per hectare when the values for the energy yield of the plant are converted to area-specific yields (Garrett and Rønde 2013, Al-Behadili and El-Osta 2015, Ozoemena *et al* 2018, Alsaleh and Sattler 2019, Wang *et al* 2019, Hengstler *et al* 2021, Vélez-Henao and Vivanco 2021, Ozsahin *et al* 2022, Verma *et al* 2022, Böhm 2023). The optimistic wind scenario shows higher gross energy area yields compared to the literature due to technology development with larger wind turbines. The cumulative energy demand is within the range of the literature studies with Al-Behadili and El-Osta (2015) showing the lowest and Teffera *et al* (2021) showing the highest numbers. Same is true for the GWP of wind with Ozsahin *et al* (2022) showing the lowest GWP with 0.0052 kg CO_{2eq} kWh^{-1} and Alsaleh and Sattler (2019) with the highest figures of 0.053 kg CO_{2eq} kWh^{-1}. Because of the broad range of the scenario assumptions, some results are lower compared to the literature, as for example for FAETP, MAETP, TETP, and HTP. The optimistic scenario is within the range of the literature, but the conservative scenario shows higher numbers as compared with highest figures presented in the literature by Xu *et al* (2018).

The results of the gross energy area yield of PV is within the range of the literature, but also show larger number in the optimistic scenario (Oğuz and Şentürk 2019, Raugei *et al* 2020, Szilágyi and Gróf 2020). The environmental impact most frequently observed in the literature is the GWP. The study results are within the fluctuation ranges of the values (Fu *et al* 2015, Leccisi *et al* 2016, Oğuz and Şentürk 2019, Raugei *et al* 2020, Hengstler *et al* 2021, Mahmud and Farjana 2022, Urbina 2022). Regarding ODP, the optimistic scenario shows lower numbers than the literature, and the conservative scenario shows higher numbers (Fu *et al* 2015, Leccisi *et al* 2016). This range is reflected in the scenario assumptions.

The biogas from maize results shows higher energy area yields in the optimistic scenario, lower in the conservative and are within the range of the literature with the baseline scenario (Dressler *et al* 2012, Fusi *et al* 2016, Valli *et al* 2017, Tamburini *et al* 2020). The GWP of the conservative scenario is with 0.413 kg CO_{2eq} kWh^{-1} slightly higher than 0.408 kg CO_{2eq} kWh^{-1} from Fusi *et al* (2016). The optimistic and baseline scenario is within range of the literature results. Simultaneous to the gross energy area yields, the AP results are within the range of the literature, but show more extreme values (Dressler *et al* 2012, Whiting and Azapagic 2014, Fusi *et al* 2016). The literature comparison shows that the study results can be reproduced by other studies. The LCA results in the literature vary to some extent due to the different methodologies, time points and locations. The focus on the area-specific energy yields and the standardised assumptions is a unique feature of this study and shows the possible trade-off.

In the case of wind, it makes a big difference whether the environmental impact is related to the sealed area or the wind area requirement. Due to the significantly larger area of the wind area requirement, the electricity yields are similar to those of ground-mounted PV systems. The environmental impact per hectare is significantly lower because less energy is generated on the area.

A combined consideration of the area-specific energy yields and the environmental impacts is necessary, as the impacts per area could lead to misleading results. This can be shown in the example of wind and biogas from maize in the baseline scenario. Wind emits 0.011 kg CO_{2eq} kWh^{-1} whereas biogas emits 0.27 kg CO_{2eq} kWh^{-1}, which is 23-times higher. Because of the high area-specific energy yield of wind, the GWP per area is 213,168 kg CO_{2eq} ha^{-1} in contrast to 4,022 kg CO_{2eq} ha^{-1} of biogas. Wind has better characteristics in terms of both impact and area-specific energy yields, but this results in higher emissions from the area. This shows that perspective can make a big difference when considering environmental impacts.

For assessing the impact of additional electricity production from a specific supply option, one has to compare the impact from that option to the impact of the electricity mix displaced within the grid. To do that, we compare the GHG emissions from each of the three production options with the average grid emissions for Germany in 2020 using the data of Ecoinvent. This is a conservative estimate, since using marginal grid emissions (e.g. as demonstrated by the German Federal Environmental Agency/Umweltbundesamt in a report for the year 2020 which relies on energy systems modelling) instead of average emissions would result in displaced emissions that are even higher. For wind turbines and the German grid, this results in emission reductions of 2,999-27,587 t CO_{2eq} ha^{-1} $year^{-1}$ (GHG avoidance potential). The value range is explained by the wide range of parameter variations of the three different scenarios. The respective values are 157-489 t CO_{2eq} ha^{-1} $year^{-1}$ for ground-mounted PV and 0-5 t CO_{2eq} ha^{-1} $year^{-1}$ for biogas from maize.

The contribution analysis shows which components or factors have the greatest impact on the GWP. It becomes clear that individual components have a very large share, for example steel production for the tower in wind turbines. It can be deduced that the environmental impact can be reduced effectively by, e.g., lowering the impact from steel production. The electricity mix used in the production process also has a major influence. For example, it makes a significant difference whether the PV modules are manufactured in China or Germany. This means that production in Germany would reduce the environmental footprint for PV.

In order to utilise the study results for policy advice, the following characteristics should also be taken into account: When comparing electricity from wind, PV and biogas in the actual application in the energy system, the timing of electricity production plays also an important role. Here, the advantage of the storability and flexible use of biogas is often mentioned in the case of biogas plants. The flexible use of biogas requires a large gas storage capacity and a large overbuilding of the engine capacity. This leads to very high costs. Even for non-flexible biogas plants, the LCOE (8.5–17.3 €cent kWh^{-1}) is higher than that of ground-mounted PV plants with battery storage (5.2–9.9 €cent kWh^{-1}) (Kost *et al* 2021). This shows that even from an economic point of view, wind and PV show an advantage over biogas. Although electricity generation from biogas plants cannot compete with wind and PV in terms of economics and environmental impact, it has other strengths. A focus on the production of biomethane, for example, and thus the replacement of fossil natural gas could be a possibility. Biomethane can also be used ideally for industrial processes such as high-temperature applications in steel and iron production, as these are difficult to replace with other forms of energy.

The LCA results of the study can be scaled up with an bottom-up approach, as in the study of Arvesen and Hertwich (2011), to analyse environmental impacts of different energy systems of the future. In particular, the necessary battery storage, storage losses, and the necessary power grid expansion could have a major impact. For a clear policy recommendation, costs should also be considered in more detail. For example, CO_2 abatement costs can be used as an indicator to compare social costs. Consequently, the abatement should be considered in more detail in future studies.

6. Conclusion

The results of the area-specific energy yields make it clear that the wind turbines supply significantly more electricity than ground-mounted PV systems per hectare. Both options produce significantly more than the conversion of biogas from maize into electricity. If the energy demand for production is included in the net energy yields per unit area, the results are even clearer. For the conservative biogas scenario, the net energy area yield is close to zero.

The comparison of the individual environmental impacts also shows clear advantages of wind and PV over biogas for most indicators. Only for one of the observed midpoint indicators biogas does not have the highest environmental impacts (ADP-UR). From an endpoint-indicator perspective biogas has higher environmental impacts than wind turbines or ground-mounted PV. In a comparison of emissions per area, it becomes clear that due to the low area-specific energy yields of biogas, the emissions per area are lower compared to wind and PV, even though the environmental impacts per kWh are higher. Compared to the German average grid emissions, wind provides the largest emission reduction potential, followed by PV and biogas.

The results of the study illustrate the advantages of technology-based systems (wind and PV) over plant-based systems (biogas from maize) for generating electricity in Germany when considering environmental impacts and area-specific energy yields. Legislation such as feed-in tariffs should reflect this assessment.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflicts of interest/competing interests

The authors have no relevant financial or non-financial interests to disclose.

Authors' contribution

All authors contributed to the study's conception, design, material preparation and data collection. The LCA analysis was mainly done by Fabian Holzheid. The first draft of the manuscript was written by Jonas Böhm and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Ethics approval

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