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Which environmental impacts are captured by the life cycle assessments of low-emission energy technologies – are we closer to comprehensive assessments?

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ABSTRACT

Achieving net-zero emissions requires rapid deployment of renewable and low-carbon energy technologies. Although these systems emit fewer greenhouse gases than fossil fuels, their broader environmental impacts are less well understood. Life cycle assessment (LCA) is applied to evaluate multiple environmental impact categories and increasingly supports sustainability assessment of energy production. This review examines LCA studies (2015–2024) on wind, solar, geothermal, hydropower, e-fuels, and nuclear energy in Europe, following the PRISMA 2020 methodology. Studies reporting quantitative results per kWh were included. Nearly 90% ($n = 94$) of studies assessed climate impacts, while acidification (56%), resource use (minerals and metals, 51%), and freshwater eutrophication (43%) were analysed less consistently. Climate findings aligned with previous literature, but other impacts showed substantial variability due to methodological differences and data gaps. Key gaps persist in toxicity, biodiversity, and local environmental assessments. More standardised, comprehensive LCA approaches are needed to capture these effects and guide sustainable energy transitions.

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Introduction

The European Union (EU) has set a greenhouse gas reduction target of 55% by 2030 and aims to achieve net-zero emissions by 2050. The revised Renewable Energy Directive (RED III, EU/2023/2413) establishes a binding target of at least 42.5% renewable energy by 2030. In addition to renewable energy sources, nuclear power plants are among the key measures for achieving global net-zero carbon emissions (Baig et al. 2025). In most cases, renewable and low-carbon energy technologies are considered to impose a smaller environmental burden than conventional fossil fuel-based systems (Holma et al. 2018). However, while the expansion of renewable and other low-carbon energy technologies is central to meeting the climate targets, their broader environmental implications beyond greenhouse gas reductions require careful consideration.

When aiming for a rapid energy transition and the expansion of energy production of zero-carbon technologies, the full life-cycle impacts of these technologies, including all relevant environmental impacts. Renewable energy systems such as solar and wind power are highly mineral-intensive (Carr-Wilson, Pattanayak, and Weinthal 2024). In addition, solar and wind power production require large areas of land, potentially leading to biodiversity impacts (Bennun et al. 2021).

Life cycle assessment (LCA) is a widely used tool for evaluating the environmental aspects of a product or system throughout its entire life cycle (e.g. de Haes and Heijungs 2007; Turconi, Boldrin, and Astrup 2013). Sokka et al. (2016) and Holma et al. (2018) reported the results of a comprehensive quantitative and qualitative study conducted in Finland in 2014. In the study, a review of the potential life cycle impacts of different renewable energy sources was conducted (Sokka et al. 2016). This was followed by a qualitative

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study engaging a panel of experts to evaluate the severity of potential risks associated with the energy strategy (Holma et al. 2018). The experts concluded that although the risks in 2014 were generally moderate, certain areas of concern could be identified—particularly those related to resource depletion caused by the use of solar, wind, and geothermal energy. The aim of the present study is to examine the state of LCA research on renewable and low-carbon energy sources in 2025 and to assess how comprehensively current studies address relevant life cycle environmental impacts.

Finland has one of Europe's most ambitious carbon neutrality targets—achieving net carbon neutrality as early as 2035. A rapid transition to a low-carbon energy system is one of the key prerequisites for reaching this goal. In this paper, low-carbon energy technologies are evaluated particularly from the perspective of Finland, and Northern Europe, to inform the national energy transition. However, the findings on life cycle assessment (LCA) methodologies are also relevant to other regions in Northern Europe.

The aims of this systematic review are to:

- Assess the current state of LCA use in the scientific literature focusing on renewable energy technologies
- Identify the most frequently considered environmental impacts
- Determine the ranges of the most frequently reported environmental impacts of low-emission energy technologies, and thereby identify the most important environmental impacts of these technologies.

Material and methods

LCA data accumulation

The analysis is primarily based on a scoping review following the PRISMA guidelines¹⁴ (see Supplementary material 1 for the PRISMA Checklist). The collection of LCA datasets was based on scientific, peer-reviewed articles written in English and published between 2015 and 2024. The search was conducted in the Web of Science database Core Collection). As solar irradiation in Europe—particularly in Northern Europe—is significantly lower than in many other regions, only European solar power studies were included to maintain comparability.

In the review, the following energy production technologies were studied: 1) Hydropower, 2) wind power, 3) solar power, 4) E-fuels production from CO₂ and hydrogen, 5) geothermal energy, and 6) nuclear power. Wood-based energy systems are excluded from this analysis, as their LCA has been extensively covered in previous research (e.g. D'Amato, Gaio, and Semenzin 2020; Wolf et al. 2015). If the impact category was quantitatively assessed and the scores were provided, these scores were used in a framework to assess the comprehensiveness of energy LCA studies and to aggregate descriptive statistics.

The functional unit provides a reference point for all input and output data (materials, energy, emissions, etc.) in an LCA, ensuring that comparisons between systems are meaningful. The functional unit in this review was set to kWh of produced energy. If the LCA scores were aggregated using other energy units (e.g. MJ or MWh), they were converted to kWh. Many studies did not clearly indicate whether the reported results referred to thermal or electrical output; therefore, the review does not distinguish between heat and electricity. If applicable, we calculated averages, ranges, and 95% confidence intervals (using the Student's t-distribution) for LCA impacts per kWh.

System boundaries define what is included and excluded in the LCA. The reviewed LCA studies applied different system boundaries. For instance, the cradle-to-gate approach includes resource extraction but excludes the use phase and end-of-life stages, whereas the cradle-to-grave approach includes the full life cycle. Depending on the energy system, the choice of which life cycle phases are included can have a substantial effect on the impact scores of the LCA: the majority of environmental burden from fuel provision accounts for 71% and 60% of the GHG emissions of nuclear power plants, respectively, whereas infrastructure represents nearly the entire burden (97–99% of total emissions) for hydropower and wind systems (Turconi, Boldrin, and Astrup 2013). Geothermal energy GHG emissions and energy use are also generated by infrastructure (Sullivan and Clark 2013). This is also true for solar power as well (Bošnjaković et al. 2023). Thus, although system boundaries in the reviewed studies differed in terms of which life-cycle stages were included, this has a minimal effect on the LCA results of wind and solar systems, as the

majority of environmental load is caused during the construction phase. Emissions related to infrastructure in nuclear power production were found to be relevant for GHGs (20–30% of the total), while being almost insignificant for both NO_x and SO₂ (Turconi, Boldrin, and Astrup 2013). Thus, the environmental burden of nuclear power is caused by several sources during its life cycle, not only from the infrastructure. Because of this, no average values were aggregated for nuclear power as it is likely that a substantial share of variation is caused by system boundaries.

The environmental impacts in the reviewed LCA studies were assessed using various life cycle impact assessment (LCIA) methods. Consequently, the impact category scores are not necessarily expressed in the same units. Even when the units are consistent, differences in how the methods aggregate impact assessment scores may occur (Abdallah et al. 2024). Therefore, impact category results based on different LCIA methods are not comparable. Disparities were observed when three alternative LCIA methods—ReCiPe 2016, ILCD 2011, and CML-IA baseline (with IMPACT 2002+)—were compared for ozone formation/respiratory organics, particulate matter/respiratory inorganics, ecotoxicity, and water consumption, whereas climate change impacts showed minimal differences (Rybaczewska-Błażejowska and Jezierski 2024). Additionally, freshwater eutrophication and acidification scores were generally consistent across methods, with IMPACT 2002+ being an exception (Rybaczewska-Błażejowska and Jezierski 2024). Following this reasoning, the average values and ranges of environmental impacts were aggregated from the reviewed studies only when a sufficient number of comparable datasets were available i.e. studies where LCA scores of energy systems were reported using the same unit and a similar impact assessment method, and where the system boundaries would only have a minimal effect on the scores.

Results

As a result of a systematic data collection, 630 scientific articles and book chapters were identified for further review. After detailed examination, 29 articles on hydropower, 15 on wind power, 14 on solar power, 9 on e-fuels, 23 on geothermal energy, and 5 on nuclear energy were included (Figure 1) (see the included articles and LCA scores in supplementary material 2).

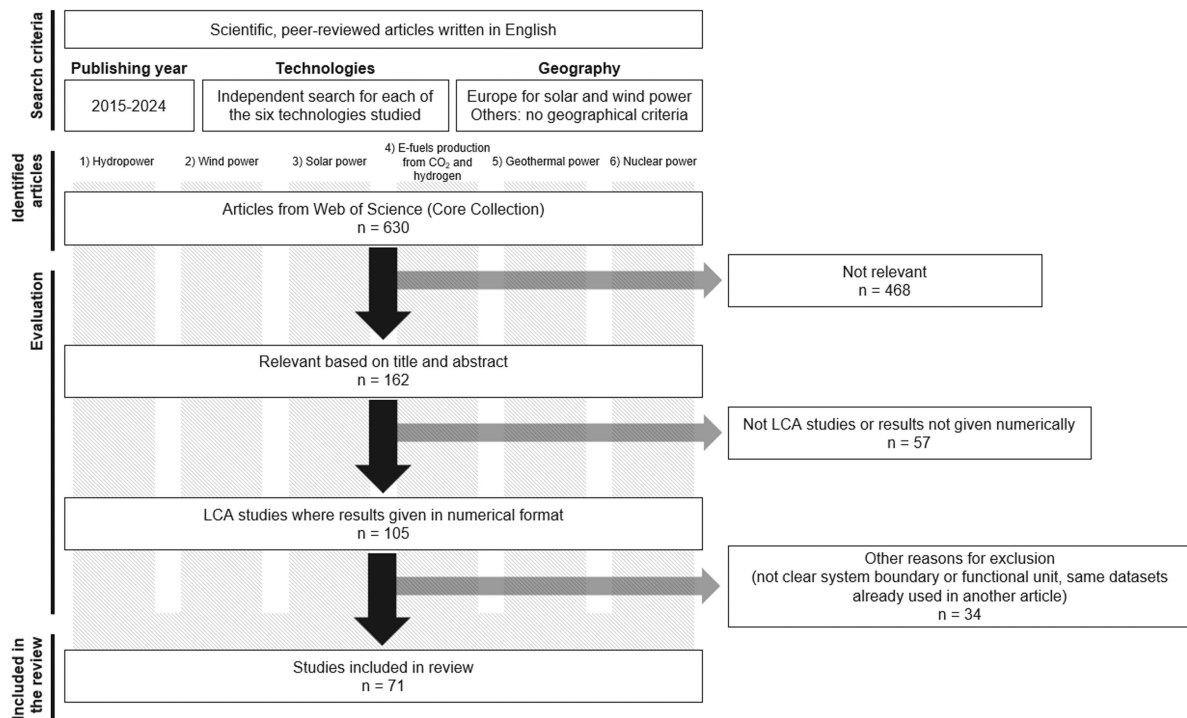


Figure 1. PRISMA flow chart of record retrieval and selection.

Based on the literature review, the vast majority of LCA studies focused primarily on climate change. Even when several other impact categories were included, the interpretation of results and discussion on their relevance was on climate change. In studies where, for example, human and ecosystem toxicity scores were calculated, these scores were rarely discussed, and their relevance was not evaluated. In many cases, the results of other impact categories were only presented in a table or in supplementary material and were not discussed in the article.

The variation in human and ecosystem toxicity impact scores between studies was substantially higher than the variation in e.g. climate change scores. Some variation in impact assessment results is expected, as the scores depend on differences in system boundaries, regional contexts, and datasets. However, the markedly higher variation observed in e.g. human and ecosystem toxicity scores—and not in climate change scores—cannot be explained solely by differences in system boundaries, as such factors would be expected to affect all impact categories. An example of such a case is pharmaceuticals: a substantial share of toxicity effects is caused by pharmaceuticals (Khan, Rehman, and Malik 2020). Pharmaceutical residues in water bodies can create toxic effects on nature and human health (Khan, Rehman, and Malik 2020). Based on a review by Emara et al. (2019), variation in the results of modelling and characterisation of pharmaceutical ingredients could be explained by incomplete modelling, limited active pharmaceutical ingredients coverage in existing LCIA toxicity models, and missing pharma-specific impact pathways in existing LCIA models. The differences are often difficult to reconcile, causing the exclusion of chemical emissions (Hauschild et al. 2008). Similar reasons could also be behind the findings of this review.

Wind power

Shading and shadow flicker caused by wind turbines have been considered significant impacts, while GHG emissions from material acquisition and decommissioning, as well as aesthetic impacts and biodiversity effects, have been considered moderately significant by experts (Holma et al. 2018). However, these aspects were not addressed in the reviewed LCA case studies (Table 1). Climate change was considered in 54% of the studies, making it the second most frequently included impact category, with acidification being the most assessed (Table 1). Resource consumption (metals and minerals) was the third most frequently included impact category (38%).

Until recently, most wind power projects have been constructed onshore, but many nations are now adjusting policies to encourage offshore wind power development (Enevoldsen and Valentine 2016). In the current review, the majority of the studies focused on assessment of onshore wind energy, and offshore wind energy was far less commonly considered (with exceptions by Bonou, Laurent, and Olsen 2016; Nayak et al. 2023; Piasecka 2019; Wang et al. 2019). The climate change effects of onshore and offshore wind energy appear somewhat similar, although the variation in both systems is high (e.g. Li et al. 2020).

Table 1. Impact categories included in the reviewed wind power LCA studies.

Impact category	Inclusion rate
Acidification	67 %
Climate change	54 %
Human toxicity, cancer	15 %
Human toxicity, non-cancer	15 %
Eutrophication, freshwater	25 %
Eutrophication, marine	21 %
Ionising radiation, human	13 %
Ionising radiation, other	4 %
Land use	19 %
Particulate matter	25 %
Ozone formation, other	4 %
Photochemical ozone formation, human	7 %
Ecotoxicity, terrestrial	19 %
Ecotoxicity, freshwater	29 %
Ecotoxicity, marine	21 %
Resources, fossil	25 %
Resources, metals and minerals	38 %
Water use	27 %
Ozone depletion	31 %

The average GHG emissions of wind energy, according to this review, are 54 g CO₂ eq./kWh (95% confidence interval from 15 to 94 g CO₂ eq./kWh). There were outlier values by Lombardi, Mendecka, and Carnevale (2018) and Wang et al. (2019). Lombardi, Mendecka, and Carnevale (2018) examined micro wind turbines (1–3 kWh). Also, the data from Wang et al. (2019) provided emission intensities significantly higher than other studies. For climate impacts, the values were 295 g CO₂ eq./kWh for onshore and 468 g CO₂ eq./kWh for offshore wind. As noted also in their paper, the numbers are significantly higher than those of other studies. However, no discussion nor explanation on why their values differ so significantly from other results is given. Only high impact from transport emissions is highlighted. If these outlier values by Wang et al. (2019) and Lombardi, Mendecka, and Carnevale (2018) are excluded, the average value is 17 g CO₂ eq./kWh, which is similar to emissions factors in IPCC (8 to 20 g CO₂ eq./kWh) (Wiser et al. 2011). Mendecka and Lombardi (2019) reviewed 109 LCA studies for onshore and 30 for offshore wind power plants. Their results show that the median climate impact of large wind power plants (of 1000–5000 kW) varied around 7–10 g CO₂ eq./kWh, whereas for the smaller wind power plants of 100–500 kW the median result varied around 30 g CO₂ eq./kWh and for 500–1000 kW plants around 14 g CO₂ eq./kWh. Emissions from infrastructure materials such as aluminium, steel, and concrete are the main contributors to climate change. Therefore, reducing the use of these raw materials can effectively reduce the GHG intensities (Zhu et al. 2022).

The average acidification emissions were 0.0013 kg SO₂ eq./kWh (Table 2). The highest emission factors were reported by Kouloumpis and Azapagic (2022). When the two articles by Lombardi, Mendecka, and Carnevale (2018) were omitted, the average SO₂ emissions were decreased to 7.31208×10^{-5} kg SO₂ eq./kWh. Lombardi, Mendecka, and Carnevale (2018) also reported that average wind speed had a substantial effect on all impact category scores. For example, acidification emissions are highly influenced by wind speed. An appropriate analysis of the wind speed profile and the selection of sites that exceed the cut-in speed are necessary to achieve optimal performance (Kouloumpis and Azapagic 2022).

The average freshwater eutrophication impact was 0.07 g P eq./kWh (0.0023–0.413 g P eq./kWh). This is higher than the average emission factor suggested by UNECE (2021), which ranges from 0.014 to 0.0284 g P eq./kWh. When the maximum values reported by Prévost (2025) are excluded, the average emission factor decreases to 0.012 g P eq./kWh. As only six LCA studies included eutrophication, the resulting average emission factor is highly sensitive to extreme values. Wind power has been identified as one of the most metal-intensive renewable energy technologies (e.g. Kabayo et al. 2019). The mineral resource use associated with wind energy was considered in the majority of the LCA case studies. Reported estimates of mineral and metal use from wind energy range from 0.0187 to 0.021 kg Fe eq./kWh (Danthurebandara & Rajapaksha, 2019).

Solar power

The environmental impacts of solar collectors and photovoltaic (PV) panels are primarily associated with the manufacturing phase, particularly during the production and procurement of raw materials (Holma et al. 2018). Assumed lifespans, energy yield, and module efficiency are key factors influencing the outcomes of life-cycle assessment (LCA) studies (Ferrara et al. 2024; Tsang, Sonnemann, and Bassani 2016). The use of non-renewable raw materials was considered in the majority of reviewed LCA studies (78%) and acidification in most of the studies (76%) (Table 3).

The climate change impacts of solar energy were, with a 95% confidence interval: 0.039–0.047 kg CO₂ eq./kWh, which corresponds closely to the emission factor reported by the Intergovernmental Panel on Climate Change (IPCC 2014) (0.041 kg CO₂ eq./kWh) (Table 4). The variation in GHG emissions from solar power was considerably smaller than that observed for other renewable technologies, likely as there is

Table 2. Climate change, acidification, and eutrophication effects of reviewed wind power LCA case studies.

	Climate change (kg CO ₂ eq./kWh)	Freshwater eutrophication (kg P eq./kWh)	Acidification (kg SO ₂ eq./kWh)
Mean	1.72E-02	7.31E-05	1.32E-03
Lower bound of the 95% confidence interval	1.41E-02	1.30E-04	3.72E-03
Upper bound of the 95% confidence interval	5.80E-03	9.33E-05	1.65E-03

Table 3. Impact categories included in the reviewed solar power LCA studies.

Impact category	Inclusion rate
Acidification	76 %
Climate change	75 %
Human toxicity, cancer	11 %
Human toxicity, non-cancer	11 %
Eutrophication, freshwater	86 %
Eutrophication, marine	42 %
Ionising radiation, human	61 %
Ionising radiation, other	4 %
Land use	42 %
Particulate matter	64 %
Ozone formation, other	4 %
Photochemical ozone formation, human	7 %
Ecotoxicity, terrestrial	13 %
Ecotoxicity, freshwater	44 %
Ecotoxicity, marine	13 %
Resources, fossil	33 %
Resources, metals and minerals	78 %
Water use	18 %
Ozone depletion	40 %

Table 4. Impact categories included in the reviewed geothermal energy LCA studies.

Impact category	Inclusion rate
Acidification	32 %
Climate change	92 %
Human toxicity, cancer	17 %
Human toxicity, non-cancer	17 %
Eutrophication, freshwater	25 %
Eutrophication, marine	19 %
Ionising radiation, human	25 %
Ionising radiation, other	4 %
Land use	26 %
Particulate matter	26 %
Ozone formation, other	13 %
Photochemical ozone formation, human	7 %
Ecotoxicity, terrestrial	25 %
Ecotoxicity, freshwater	30 %
Ecotoxicity, marine	23 %
Resources, fossil	36 %
Resources, metals and minerals	32 %
Water use	25 %
Ozone depletion	26 %

little variation in solar panel types and a substantial share of panels is produced in China, where GHG emissions of electricity are coal-dominated, contributing to overall GHG emissions of solar power (Gan et al. 2023).

The average acidification effects are 0.258 g SO₂ eq./kWh. This aligns closely with the range reported by Turconi, Boldrin, and Astrup (2013) 0.12–0.29 g SO₂ eq./kWh. For freshwater eutrophication, the average emission factor was 0.069 g P eq./kWh (0.013–0.125 g P eq./kWh). Emissions of coal are 0.6–0.8 g P eq./kWh (UNECE (2021)). Thus, solar energy would provide a substantial reduction in eutrophication emissions when used instead of coal. The material consumption was assessed in the majority of the reviewed LCA studies; however, the results were not directly comparable due to differences in the reported units.

Geothermal

Geothermal energy sources vary; for example, geothermal power stations can produce electricity in suitable geological locations, while a more widely accessible application are ground-source heat pumps. Most of the reviewed geothermal LCA studies included climate change, but other impact categories were also often included (Table 4). The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation reported emissions ranging from 6 to 79 g CO₂ eq./kWh for geothermal power (IPCC,

2011a). whereas in the current study the average is 53 g CO₂ eq./kWh (95% CI 11–91 g CO₂ eq./kWh), and the range 22 to 103 g CO₂ eq./kWh. In Strojny et al. (2024), the reported GHG emissions were substantially higher than those in Li et al. (2020). This indicates that results are highly variable, even when the same LCIA methodology is applied. Overall, the average emissions from geothermal power are much lower than those of fossil energy systems, but higher than those of other renewable energy sources.

Abiotic resource depletion associated with heat pumps was considered a moderately significant impact (Holma et al. 2018), largely due to the use of many rare metals, and abiotic resource depletion associated with geothermal energy. Metal depletion was assessed in 36% of the studies, but an average metal consumption value could not be defined due to the use of different methods and units. When looking at the individual studies, in Sevindik et al. (2021) the life cycle metal depletion was 0.01 kg Fe eq./kWh for domestic applications, while it was only 0.004 kg for a natural gas-based heating system. Furthermore, Martínez-Corona et al. (2017) reported 0.417 kg Fe eq./kWh for heat pumps. An expert panel in Holma et al. (2018) also highlighted local impacts such as noise, aesthetic effects, and impacts on the surrounding landscape; however, none of the reviewed LCA studies accounted for these impacts.

Metal depletion has been identified as an important environmental impact when assessing geothermal energy, as the generation of geothermal electricity involves large volumes of geothermal fluids that can be enriched in high-value metals such as lithium, caesium, and rubidium (Lo et al. 2014). Despite this, only approximately 30% of LCA case studies of geothermal energy include an assessment of metal depletion.

Hydropower

The climate change impact of hydropower was considered significant by experts (Holma et al. 2018). In the hydropower LCA studies reviewed here, climate change was the most frequently included impact category (78%), followed by acidification (58%) and resource use (54%) (Table 5). Other categories, including eutrophication, biodiversity, erosion, and water use, were also regarded significant; however, they were seldom assessed (with exceptions, e.g. Bidoglio, Berger, and Finkbeiner 2019). Freshwater eutrophication was included in 29% of LCA case studies, while only 10% considered marine eutrophication. Water use was assessed in 25% of studies. However, the studies applied different methodologies, or the cases were so different, that it was impossible to present any ranges for these impacts. Land use was generally considered a ‘significant’ impact category. Additionally, local noise pollution, aesthetic impacts, scenic depletion, and negative effects on recreational uses were recognised as ‘to some extent significant,’ but these impacts were not included in the reviewed LCA studies.

Reservoir dams cover large areas and can generate considerable CH₄ emissions as organic matter decomposes underwater (dos Santos 2023). CH₄ can generate the majority (87%) of power plant GHG emissions due to degradation of biomass submerged in the water. The operation phase is the single most

Table 5. Impact categories included in the reviewed hydro power LCA studies.

Impact category	Inclusion rate
Acidification	58 %
Climate change	78 %
Human toxicity, cancer	10 %
Human toxicity, non-cancer	10 %
Eutrophication, freshwater	29 %
Eutrophication, marine	10 %
Ionising radiation, human	8 %
Ionising radiation, other	4 %
Land use	22 %
Particulate matter	19 %
Ozone formation, other	10 %
Photochemical ozone formation, human	7 %
Ecotoxicity, terrestrial	36 %
Ecotoxicity, freshwater	42 %
Ecotoxicity, marine	25 %
Resources, fossil	54 %
Resources, metals and minerals	49 %
Water use	22 %
Ozone depletion	39 %

impactful phase, accounting for 91.1% of the total impact. This is mainly associated with biotic CH₄ release (74.4%) from land-use change from the reservoir and CO₂ (16.7%) from land-use changes (Bidoglio, Berger, and Finkbeiner 2019). The inclusion of these estimates represents a crucial point in reconsidering hydropower as a green low-carbon technology, as reservoir gross CH₄ emissions and emissions from reservoir sediments contributed to 48.0% and 28.8% of the variance in life cycle GHG emissions, respectively. Lower GHG emissions of e.g. Geller and Meneses (2016) do not include emissions from flooded areas.

E-fuels

LCA studies of E-fuels have been predominantly focused on climate change, while other environmental impact categories were rarely assessed (Table 6). Even though only 9 LCA studies were available on E-fuels, the uncertainties are reduced due to the fact that the impacts largely result from electricity production.

The reported GHG emissions ranged from 2.2 to 101 g CO₂-eq./kWh. The GHG emissions of e-fuels are mainly dependent on the assumption about the electricity used for the electrolysis, producing hydrogen for the e-fuel process (Figure 2). As this study focuses on renewable energy, only renewable electricity sources for hydrogen (wind and solar) were considered, resulting in low GHG impact for the e-fuels. The maximum value of 101 g CO₂-eq./kWh also assumed solar power as the electricity source, but the particular OME3–5 synthesis showed an additional considerable impact due to the supply of high-pressure steam, assumed as fossil. Also, the other environmental impacts highly depend on the electricity production method. If fossil electricity was used for e-fuels production, the GHG impact would be considerably higher. If average grid electricity was used for e-fuel production, the GHG impact would depend on the emission profile of the electricity in each region (Figure 2).

Nuclear power

Nuclear power LCA case studies remain limited, with only 15 studies reporting comprehensive life cycle assessment results. The majority (87%) assessed climate change impacts (Table 7), with reported values ranging from 11 to 51 g CO₂ eq./kWh. A surprising finding is that, despite radiation being one of the most relevant environmental concerns associated with nuclear energy, only three LCA studies explicitly included this impact category (Sokka, Kirppu, and Leppänen 2024; Treyer and Bauer 2016). In the reviewed LCA studies, the main life cycle phases causing the impacts were uranium mining and plant construction; Ashley et al. 2015; Sokka, Kirppu, and Leppänen 2024). Among the three studies that included ionising radiation as an impact category, reported values ranged between 0.01 and 1.80 kBq U-235 eq/kWh. For freshwater eutrophication, the scores were 0.72, 5.6, and 44.6 mg PO₄³⁻ eq./kWh, as

Table 6. Impact categories included in the reviewed E-fuel LCA studies.

Impact category	Inclusion rate
Acidification	29 %
Climate change	100 %
Human toxicity, cancer	3 %
Human toxicity, non-cancer	3 %
Eutrophication, freshwater	4 %
Eutrophication, marine	4 %
Ionising radiation, human	0 %
Ionising radiation, other	4 %
Land use	8 %
Particulate matter	3 %
Ozone formation, other	14 %
Photochemical ozone formation, human	7 %
Ecotoxicity, terrestrial	3 %
Ecotoxicity, freshwater	4 %
Ecotoxicity, marine	3 %
Resources, fossil	14 %
Resources, metals and minerals	14 %
Water use	14 %
Ozone depletion	3 %

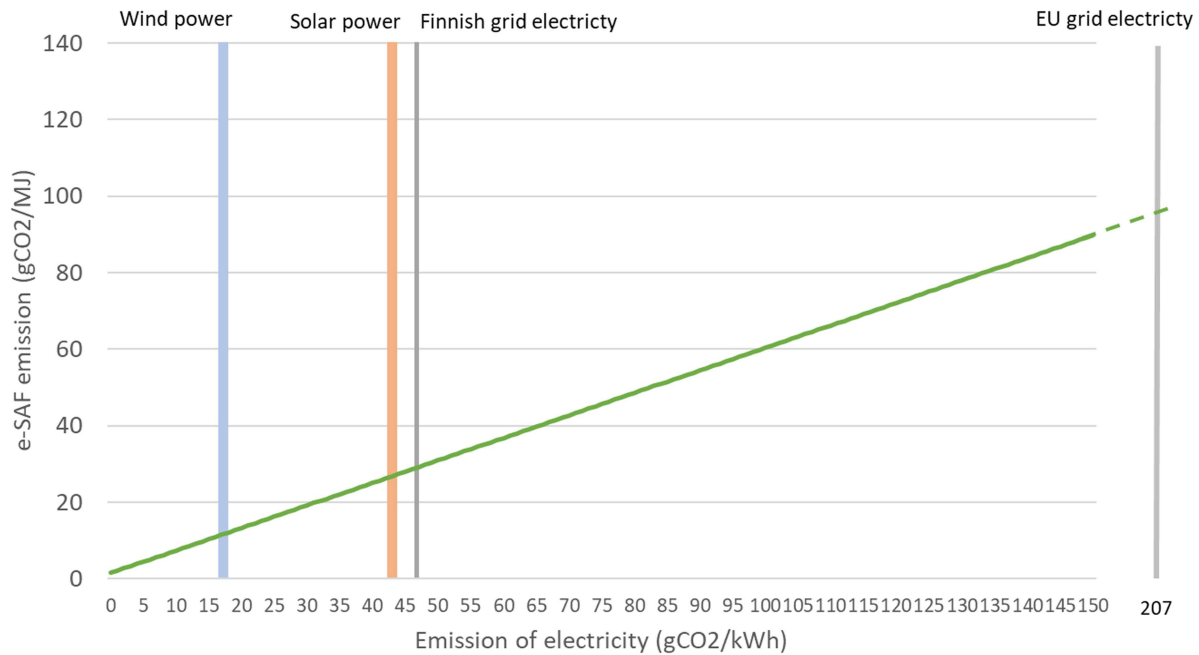


Figure 2. E-fuel GHG impact depends on the emissions of electricity used for electrolysis. (adapted from VTT 2024, electricity emissions for Finland Energy Authority Finland (2024), for Europe European Environment Agency (2025)). Emissions for wind and solar are average values from this review.

Table 7. Impact categories included in the reviewed nuclear LCA studies.

Impact category	Inclusion rate
Acidification	38 %
Climate change	87 %
Human toxicity, cancer	0 %
Human toxicity, non-cancer	0 %
Eutrophication, freshwater	38 %
Eutrophication, marine	6 %
Ionising radiation, human	6 %
Ionising radiation, other	4 %
Land use	13 %
Particulate matter	6 %
Ozone formation, other	0 %
Photochemical ozone formation, human	7 %
Ecotoxicity, terrestrial	38 %
Ecotoxicity, freshwater	38 %
Ecotoxicity, marine	31 %
Resources, fossil	19 %
Resources, metals and minerals	6 %
Water use	0 %
Ozone depletion	31 %

presented by Sokka, Kirppu, and Leppänen (2024) and Ashley et al. (2015), respectively. However, because Sokka, Kirppu, and Leppänen (2024) analysed heat production rather than electricity generation—and therefore assumed higher conversion efficiency—their results are not directly comparable with those of the other studies.

In the study of Sokka, Kirppu, and Leppänen (2024), the overall production efficiency was considerably higher than that of a conventional nuclear power plant (95% and 34%, respectively). On the other hand, the fuel burnup (utilisation rate), i.e. the amount of fission energy produced per enriched uranium mass, is 18.5 MWd/kgU for the LDR-50 while it is 40–50 MWd/kgU in conventional power reactors (Sokka, Kirppu, and Leppänen 2024). On the other hand, power plant data used in Sokka, Kirppu, and Leppänen (2024) were based on conventional nuclear power plants, which are large production units with massive concrete structures, while the LDR plants are presently planned to be produced underground

with less heavy structures. Thus, it is likely that a part of the life cycle emissions is overestimated for the LDR-50 (Sokka, Kirppu, and Leppänen 2024).

Discussion

The primary focus of most LCA studies is on climate change

Based on the findings of this review, the volume of LCA literature on low-carbon energy sources has increased substantially over the past decade. Despite this growth, notable data gaps remain. The current research remains strongly focused on climate change, with GHG emissions assessed in nearly 90% of the reviewed LCA studies while other categories were often relegated to supplementary tables without substantive interpretation. The most frequently considered impact categories beyond climate change were acidification, metal depletion, and eutrophication. According to the experts, however, these were not regarded as significant impact categories when evaluating the environmental risks associated with renewable energy systems (Holma et al. 2018). Thus, LCA studies are not consistently focused on the most relevant impacts. Furthermore, the results of less well-established impact categories were often overlooked or omitted from the main discussion, limiting the comprehensiveness of environmental impact evaluations in current LCA literature.

However, LCAs are sometimes designed to answer specific research questions rather than provide generalised estimates of environmental impacts. Thus, variation in LCA results does not necessarily indicate bias but often reflects real differences among the case studies assessed. Climate change is widely recognised as a critical impact category, and most LCA studies focus on greenhouse gas emissions. Yet, to improve the comprehensiveness of LCA, greater emphasis should be placed on underrepresented categories such as biodiversity, metal depletion and toxicity. As pointed out in the results section, particularly biodiversity and toxicity are impact categories where more methodology development is needed. Furthermore, as biodiversity is a very local impact, its analysis with LCA is particularly challenging, and local characterisation factors are increasingly needed.

LCA has become relatively easy to conduct using commercial software tools that provide ready-to-use life cycle inventory databases, predefined impact assessment methods, and user-friendly interfaces. Thus, it is likely that environmental impact categories are included but little effort is given to collecting input data or analysing the results. This is a fundamental challenge as it appears that comprehensive LCAs are available on various energy systems, but the effort put into less-established environmental impact categories is limited, and the reliability of the generated results may be biased. Consequently, the results of less well-established impact categories were often overlooked or omitted from the main discussion, limiting the comprehensiveness of environmental impact evaluations in current LCA literature.

Furthermore, it is evident that the variation in impact scores for less-established categories was much higher than for climate change. While this variation could be explained by differences in system boundaries, such differences would be expected to affect all impact categories. However, it is possible that system boundaries have a more fundamental effect on less-established impact category scores. A more plausible explanation is that studies employed highly divergent approaches to assessing less well-established impact categories, whereas climate change was assessed with more coherent approaches. In some studies, considerable effort was invested in collecting data on these impacts, whereas in others, much less effort was invested. Therefore, some of the observed variation in scores may be attributable to differences in data collection effort. Additionally, errors are likely more common for less well-established impact categories, as assessing them is more challenging due to the limited number of published scores available for benchmarking.

Trade-offs and methodological developments in LCA

A well-established method for assessing biodiversity impacts within the LCA framework is still lacking (Holma et al. 2018). In recent years, several quantitative LCA models have been proposed to address biodiversity effects, particularly in the context of renewable energy technologies. Most of these methods focus on biodiversity impacts related to land use and land-use change, while quantitative assessment

methods for aquatic ecosystem biodiversity remain underdeveloped. For example, onshore wind farms can cause both direct and indirect disturbances to nature and biodiversity. Documented effects include collisions of birds and bats with turbines, resulting in injury or mortality (Gaultier et al. 2020). Similarly, hydropower can substantially reduce species richness through habitat conversion and fragmentation. However, it remains highly challenging to quantitatively estimate biodiversity damage per functional unit within the LCA framework. Although recent methodological advances have improved this area, current approaches do not capture all dimensions of biodiversity (Damiani et al. 2023). Thus, technical and methodological challenges continue to limit the full potential of LCA.

Other possibly relevant but seldom included impact categories were noise and flickering effects of wind energy. Reliable methods to assess noise are not abundantly available, but the DALY (Disability Adjusted Life Year) is supported as the best unit to measure the negative impacts of noise upon human health (Kawahara et al. 2025). Shadow flicker effects caused by wind energy systems are not currently considered in any well-established LCIA methods. The flickering effect can be barely noticeable, but a persistent flicker can be highly disconcerting (Tabassum-Abbasi, Premalatha, and Abbasi 2014). However, tools to integrate this effect into LCA are missing.

Even in cases where several environmental impacts of renewable energy technologies are included in an LCA, it is challenging to assess what the trade-offs between the environmental impacts are. When different impact assessment methods have been used or the LCA scores are expressed in different units, results cannot be compared between different studies. Studied the impact of methodological choices on the variability of LCA results, looking at two different aspects: the allocation approach and the LCIA method. Based on their findings, acidification, eutrophication, and freshwater ecotoxicity were the most sensitive to the LCIA method used.

In LCA, substantial effort has been made over the past 15 years to improve the comparability and harmonisation of studies, through developments in methodology, databases, and impact assessment frameworks (European Commission JRC 2010; Hauschild et al. 2013; Wernet et al. 2016). Yet, as also highlighted in a recent study by Smurthwaite, Jiang, and Williams (2024), weighing and normalisation are still often used without detailing the normalisation and weighting factors or the inventory data in the paper. If they are not given, it is impossible to scientifically analyse those results, nor compare them to other studies. The findings of the present paper support this as well. Thus, as the present review also shows, more unified practices are needed to make the studies more comparable with one another. One important development within this area has been the Environmental Footprint guidelines developed within the EU. While their development has been ongoing for past 15 years, the final recommendation was only accepted in 2021. This may be one reason why guidelines are not yet applied in scientific literature more comprehensively. Furthermore, except for battery technologies and solar panels, the product environmental footprint category rules (PEFCRs) do not focus on energy production. In addition, the EU has given separate regulations on the calculation of life cycle climate impacts of different energy technologies, including the Renewable Energy Directive ((EU) 2023/2413), Delegated Regulations concerning CCUS ((EU)2023/1184 and (EU)2023/1185), Regulation on Batteries ((EU) 2023/1542) and the Directive 2009/30/EC including a mechanism for monitoring and reducing greenhouse gas emissions of petrol, diesel and gas-oil.

Finally, there have been significant reductions in electricity production emissions in recent years, which could decrease the emissions from manufacturing renewable energy technologies and thus affect the LCA emission results. However, this change is not yet prominent in this review. The transition to a low-emission energy system is essential to stop fossil fuel use and to reach the national and international climate change mitigation targets. As shown in this review, the renewable and low-emissions options to replace fossil fuel use clearly reduce the climate impacts, but also trade-offs with other environmental impacts may also occur. Compromises between various impacts on the environment will inevitably be made. Here, LCA studies play a crucial role in identifying these trade-offs, pointing out the local vulnerabilities, and supporting the finding of solutions with minimal harm to the environment and locals. Thus, developing the use and interpretation of the results for impact categories other than climate change is necessary.

Implications for LCA practice

This review demonstrates that LCAs must evolve to better capture the full environmental profile of renewable and low-carbon energy systems. Most studies still focus primarily on climate change, while

other relevant impact categories are either excluded or their assessment remains at a cursory level. Broadening the scope of LCAs is essential to identify trade-offs between the impact categories. High variability in results often reflects limited primary data and the lack of mature characterisation models, particularly for biodiversity. Finally, rapidly decarbonising electricity systems mean that background datasets used in LCAs can quickly become outdated, requiring more up-to-date electricity mixes. Strengthening these areas will enhance the ability of LCA to guide sustainable energy transitions and support decision-making that minimises environmental harm.

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Data availability statement

The datasets openly available in the supplementary material 1.

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