Article:

Shamoushaki, M. and Koh, S.C.L. (2024) Comparative life cycle assessment of integrated renewable energy-based power systems. Science of The Total Environment, 946. 174239. ISSN 0048-9697

https://doi.org/10.1016/j.scitotenv.2024.174239

Science of the Total Environment 946 (2024) 174239

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Comparative life cycle assessment of integrated renewable energy-based power systems

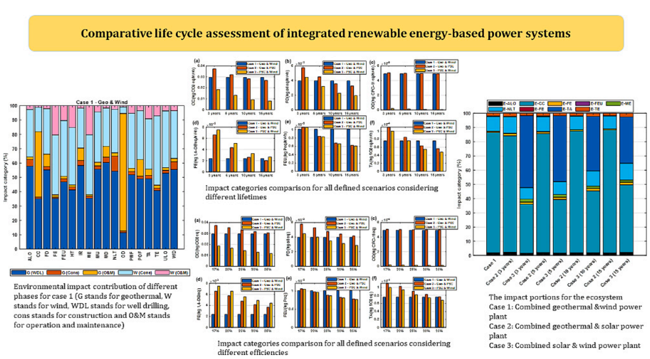
Moein Shamoushaki *, S.C. Lenny Koh *

Sheffield University Management School, The University of Sheffield, Sheffield S10 1FL, United Kingdom
Energy Institute, The University of Sheffield, Sheffield S10 2TN, United Kingdom

HIGHLIGHTS

- Comparative life cycle assessment of three renewable-based power plants is done.
- Cases 1, 2 &3 indicate combined geothermal & wind, geothermal & solar, wind & solar.
- Rising perovskite solar cell (PSC) lifetime reduced the environmental impact.
- Considering PSC in an integrated power plant is the main novelty of this work.
- Climate change and ozone depletion in wind & solar cases are lower than in others.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jacopo Bacenetti

Keywords:
Life cycle assessment
Environmental impact
Combined power plant
Renewable energy
Perovskite solar cell

ABSTRACT

Integrated renewable-based power cycles should be employed to produce more sustainable electricity. This is a comparative life cycle assessment (LCA) of three combined power plants, encompassing: case 1 involving combined geothermal and wind, case 2 featuring combined geothermal and solar, and case 3 integrating wind and solar systems. The base case perovskite solar cell (PSC) modelling assumes a 3-year lifespan and a power conversion efficiency of 17 %. However, diverse scenarios are evaluated through a sensitivity assessment involving enhancements in lifetime and efficiency. The base case evaluation emphasizes that the phases with the most significant negative environmental effects which includes the drilling of geothermal wells, construction of wind plants, and manufacturing and installation of PSCs. The midpoint findings indicate that boosting the power conversion efficiency of PSC from 17 % to 35 % yields a notable decrease in environmental impact. Moreover, extending the lifetime from 3 to 15 years led to reduction in CO_2 emissions from 0.0373 and 0.0185 kg CO_2 eq/kWh to 0.026 and 0.0079 kg CO_2 eq/kWh in cases 2 and 3, respectively. Assessing worst and best-case scenarios highlights significant declines in certain impact categories. In case 3, terrestrial ecotoxicity (TE), photochemical oxidant formation (POF), human toxicity (HT), marine ecotoxicity (ME), and marine eutrophication (MU) saw reductions exceeding 88 % compared to worst-case results. The environmental effects observed in cases 2 and 3 stem from toxicity and metal depletion, mainly linked to the PSC. Endpoint results revealed that when considering a PSC lifespan of 10 years or more, the detrimental ecosystem impacts of cases 2 and 3 become less severe than those of case 1. Uncertainty assessment has been done for different cases and impact categories. The study's

* Corresponding authors at: Sheffield University Management School, The University of Sheffield, Sheffield S10 1FL, United Kingdom.
E-mail addresses: m.shamoushaki@sheffield.ac.uk (M. Shamoushaki), s.c.l.koh@sheffield.ac.uk (S.C.L. Koh).

https://doi.org/10.1016/j.scitotenv.2024.174239
Received 19 December 2023; Received in revised form 31 May 2024; Accepted 21 June 2024
Available online 25 June 2024

results are also novel in which it evaluated the innovative PSC technology when integrated with other renewable resources, contrasting it with other integrated plants.

Nomenclature

A	area, (m^2)
ALO	agricultural land occupation
CC	climate change
CCS	carbon capture and storage
CHP	combined heat and power
Cons	construction
CPGS	coal-fired power generation system
Eco	ecosystem
FD	fossil depletion
FE	freshwater ecotoxicity
FEU	freshwater eutrophication
HH	human health
HT	human toxicity
i	insolation, ($kWh/m^2/year$)
IC	impact category
IR	ionising radiation
ITO	indium tin oxide
LCA	life cycle assessment
M&I	mounting and installation
ME	marine ecotoxicity
MU	marine eutrophication
MD	metal depletion
NLT	natural land transformation
OD	ozone depletion
O&M	operation and maintenance
PMF	particulate matter formation
POF	photochemical oxidant formation
PR	performance ratio
PV	photovoltaic
PSC	perovskite solar cell
Res	resources
SOFC	solid oxide fuel cell
TA	terrestrial acidification
TE	terrestrial ecotoxicity
ULO	urban land occupation
y	lifetime, (year)
WD	water depletion
WDL	well drilling

Greek signs

ε	energy produced, (kWh)
η	efficiency, (%)

1. Introduction

Global warming and climate change have become one of the most challenging issues in recent years and greenhouse gas emission (GHG) is predicted to increase by 50 % by 2050 (Cao et al., 2022). Despite the increasing influence of renewable technologies in the energy portfolios of nations, fossil resources continue to play a predominant role in the current energy landscape (Martín-Gamboa et al., 2018). Many researchers, research institutes, companies, governments, and stakeholders are working on clean fuel and systems to provide decarbonised energy for different sectors. However, reaching to net-zero goal needs more effort and there are many remained steps to do. One of the most significant parts that play a remarkable role in reaching net-zero goals is power generator systems. Then applying renewable energies to provide low-carbon energy would be one promising solution instead of using fossil fuels (Cucchiella et al., 2015). Besides, designing combined power plants using renewable energy as an energy source has been under attention in recent decades.

Different renewable-based power cycles have been analysed from energy and economic aspects by researchers in recent decades (Afshari et al., 2022; Ancona et al., 2015; Ehyaei et al., 2019; Jiang et al., 2023; Łukasiewicz and Shamoushaki, 2022; Shamoushaki et al., 2022; Wang et al., 2016; Yilmaz et al., 2020). However, sustainable energy production should be assessed by environmental sustainability evaluation. Life Cycle Assessment (LCA) is a useful methodology for the environmental sustainability assessment of different processes and technologies (Famiglietti et al., 2021). This study seeks to the environmental impact of three integrated renewable-based power plants comprising geothermal, wind, and solar photovoltaic (PV) systems. There is a large number of research that has been conducted on renewable technologies' environmental impact assessment. LCA analysis of stand-alone geothermal power plants (Cook et al., 2022; Fiaschi et al., 2021; Kjeld et al., 2022; McCay et al., 2019; Parisi et al., 2019), wind turbine power cycle (Das and Nandi, 2022; Demir and Taşkın, 2013; Mello et al., 2020; Vélez-Henao and Vivanco, 2021; Wang and Sun, 2012; Xu et al., 2018), and solar PV power generators (Ansanelli et al., 2021; Backes et al., 2021; Fan et al., 2021; Gasa et al., 2022; Guillén-Lambea et al., 2023; Martin-Gorriz et al., 2021; Piemonte et al., 2011; Rabaia et al., 2021; Ye et al., 2023) have been done by some researchers. These evaluated solar PV systems are mostly conventional solar PV systems which are known as the first and second generations. However, in this study, we have considered a third-generation solar cell called perovskite solar cell (PSC) which is a newly emerged technology and is in the early stage of its development. Besides, it showed a huge potential for efficiency improvement in the short term. However, the use of lead in the manufacturing process of PSC technology can pose a significant challenge due to its toxicity (Babayigit et al., 2016). Lead exposure, whether in water or air, can severely impact human health, leading to chronic poisoning (Ding et al., 2022; Yue et al., 2023). Manufacturing different solar cell technologies have amalgamated some GHGs and environmental impacts (Menoufi et al., 2013). That is why in recent years some researchers have focused on the environmental impact investigation of this novel technology (Ibn-Mohammed et al., 2017; Li et al., 2022; Okoroafor et al., 2022; Ramamurthy Rao et al., 2021). Besides, recent reports projected that the production cost of this system is considerably lower than previous conventional solar cells which makes it a more competitive option (Cannavale et al., 2017).

Besides studies done on stand-alone renewable-based power cycles, the benefits of combined power cycles have attracted scholars to study the LCA analysis of integrated power plants using a renewable energy source. Ameri and Mohammadzadeh (Ameri and Mohammadzadeh, 2018) conducted a comparative LCA of a combined cycle originating from natural gas and solar energy using OpenLCA. Their assessment showed that the environmental impact of the integrated solar PV combined cycle in two indicators, human health, and resources damage categories, were lower compared with natural gas-based units, in contrast, ecosystem damage was lower in the natural gas combined cycle. LCA study of a combined heat and power cycle in a small size unit considering different biomass products to use instead of gas as fuel is done by Havukainen et al. (Havukainen et al., 2018). They aimed to evaluate the environmental performance of the district heating system by applying a Combined Heat and Power (CHP) system instead of using gas. Besides, they were looking for the environmental consequences of using various biomass in CHP units. Karlsdottir et al. (Karlsdottir et al., 2020) performed geothermal (CHP) plant LCA evaluation to deeply understand its environmental impacts. Their analysis proved that geothermal systems have great potential to provide clean energy. Zahid Gill et al. (Zahid Gill et al., 2021) did an LCA and exergo-environmental assessment of a solar-based multi-production system to find the environmental effects. They investigated the environmental behaviour of different components of the power plant from exergo-environmental point of view.

LCA of different geothermal case studies compared with other technologies has been done by Zuffi et al. (Zuffi et al., 2022). They calculated a single score value for all geothermal cases to compare with other technologies. Results illustrated that for some geothermal systems, environmental impacts were higher than solar and wind; however, in others, it was in line with other renewable cycles. Alhaj et al. (Alhaj et al., 2022) carried out an environmental LCA analysis of a solar-based system coupled with a multi-effect desalination unit. Results presented that a majority of environmental impact was related to the operation phase. Also, using solar energy caused a carbon footprint decline compared with conventional systems. A solar PV system application to link with a hydrogen production unit has been studied from the environmental point of view by Zhang et al. (Zhang et al., 2022). Four impact categories (ICs) were calculated for three different hydrogen production methods. Results revealed that among the considered systems, solar photothermal integrating with thermochemical water had the lowest environmental impacts. Besides, the highest impact was related to the construction of a combined system.

In addition, some comparative LCA evaluation on different power generator system has been done in recent years. Kimming et al. (Kimming et al., 2011) conducted a comparison of two biomass-based CHP power cycle based LCA methodologies. They assessed the system based on four different scenarios based on applying biomass on a small scale and fossil fuel on a large scale. A comparative LCA study on coal-fired power for two different types of cycles to find their performance from an environmental viewpoint has been carried out by Schakel et al. (Schakel et al., 2014). They investigated the variables which cause the variation in needed fuel, such as system efficiency, which is the most sensitive parameter. Nease and A. Adams II (Nease and Adams, 2015) performed a comparative LCA analysis of a coal-based intergrade solid oxide fuel cell (SOFC) with a combined supercritical pulverized coal and gasification power system. They applied midpoint and endpoint methods and systems with and without carbon capture units. Smith et al. (Smith et al., 2019) carried out a comparative study of SOFC technology environmental consequences based on a new and commercial configuration. They examined three different structures: one that is commercially available, and two others with intermediate temperature capabilities. These intermediate temperature structures include one utilizing erbia-stabilized bismuth oxide electrolytes and a suggested structure incorporating strontium-doped sodium bismuth titanate electrolytes. The results show a transition towards lowering the operational temperatures of SOFCs by employing innovative material designs.

Wang et al. (Wang et al., 2019) conducted a comparative LCA assessment of three stand-alone technologies (wind, hydropower, and nuclear) in China. They considered a cradle-to-grave boundary considering several ICs to compare. Two types of combined SOFC and CHP cycles coupled with thermal storage units have been compared from an environmental point of view by Di Florio et al. (Di Florio et al., 2021). They evaluate the uncertainty based on the input data of the system using the Monte Carlo method. Costa et al. (Costa et al., 2022) did an LCA and supply chain evaluation of a CHP cycle using biomass as a heat resource. They presented that half of the total damaging impact is related to the combustion and gasification phases. A comparative LCA assessment of three coal-fired power plants has been conducted by Dong et al. (Dong et al., 2022). The first system was base case coal-fired, the second was coupled with a carbon capture system, and the second was with solar PV and organic Rankine cycle (ORC). The results showed that based on the LCA viewpoint, a coal-fired power generation system - carbon capture and storage (CPGS-CCS) is the most desirable configuration.

This research aims to conduct a cradle-to-operation LCA impact assessment of various renewable energy-based power cycles using the OpenLCA application (OpenLCA, n.d.). The three power systems evaluated are: a combination of geothermal and wind (case 1), a combination of geothermal and PSC (case 2), and a combination of PSC and wind power plants (case 3). All relevant data regarding material and energy inputs and outputs for these cases were obtained from literature and the ecoinvent v3.6 database (Frischknecht et al., 2005; Steubing et al., 2016; Wernet et al., 2016). The base case environmental impact calculations for all three considered power cycles have been conducted. These calculations are based on the current short lifetime and efficiency of the PSC system. However, a sensitivity assessment is conducted to evaluate the environmental impact variations of the PSC unit, considering a longer lifetime and higher efficiency using a prospective LCA approach. Several scenarios were developed based on different lifetimes and efficiencies of the PSC. Additionally, two new scenarios were defined to explore the highest assumed efficiency and lifetime, contrasting the environmental improvements of the integrated case 2 and case 3 against the base case assessment.

The assessments conducted in the present study, combined with the performed literature reviews, highlight the novelty of this research. The literature review reveals that most previous LCA studies on renewable power plants have focused solely on standalone systems. Additionally, prior studies on integrated power cycles typically examined the coupling of a renewable resource with a fossil fuel-based power cycle, thereby maintaining a dependency on fossil fuels for the base load. However, there is a significant gap in research on LCA evaluations of integrated power cycles that combine two renewable-based power plants without involving any fossil fuel-based plants. The idea of considering combined power plants is due to the potential of integrating different technologies to increase the efficiency of the system by using the excess remaining heat of one system in running another one (DeLovato et al., 2019). To the best of our knowledge, no prior research has undertaken a comparative analysis of the three integrated systems examined here. Another novel aspect of this research is the technological-environmental assessment of integrating a PSC system with another power cycle, as previous studies have primarily conducted LCAs on standalone PSC systems. Additionally, this study introduces an innovative element by performing a sensitivity analysis on the lifespan and efficiency of PSC in an integrated system. Given the pressing issues of global warming, climate change, and fluctuations in fossil fuel prices, adopting renewable and clean technologies is crucial for providing low-carbon energy solutions across various sectors. Therefore, environmental evaluation of these technologies is essential. The worst and best scenarios are delineated through prospective LCA assessment, aiming to facilitate a comparative environmental evaluation of cases involving PSC which has not been assessed in previous studies. Additionally, a heatmap table ranking all considered scenarios based on sustainability results, using all 18 midpoint and 3 endpoint results, was conducted, representing another novel aspect of this research.

This study's findings address the existing gaps in environmental assessments of combined renewable power cycles, an area that has not received widespread attention from other researchers. Shifting towards integrated renewable-based power plants aligns with government priorities aimed at reducing the carbon footprint in the electricity generation sector and diminishing reliance on polluting fuels. Moreover, this study pioneers the evaluation of an innovative solar-based unit combined with wind and geothermal systems from an environmental perspective, assessing its potential for future commercialization.

Additionally, this study marks the first instance of evaluating the prospective technological advancements of this system and their environmental impacts.

2. Methodology

2.1. Life cycle assessment

LCA is an applicable and popular approach to specify the environmental impacts of different processes, products, and systems. The implementation of LCA addresses essential ecological sustainability issues that are crucial for the subsequent development and expansion (Shamoushaki and Koh, 2023). This methodology helps identify the best technology from environmental criteria and performance (Arvanitoyannis, 2008; Finkbeiner et al., 2006; Nguyen et al., 2020; Standardization, 2006). The raw material and resource consumption, relevant production process, consumed energy, and substances emissions into water, air, or soil result in adverse environmental impacts of processes.

2.2. Goal and scope definition

The main objective of this research is to conduct a comparative assessment of the environmental impact throughout the life cycle of three integrated power generation systems based on renewable energy sources. It is worth noting that while the geothermal and wind technologies under consideration are more established and widely used, the solar cell technology being evaluated is not yet widely commercialized and is primarily in the developmental stages, mainly in laboratory settings. Another primary purpose of this study is to assess the sensitivity of different lifetimes and efficiency impacts of the PSC system on the environmental impacts of the combined systems.

The main aim of this research is to examine the materials used and energy consumed across different phases of a power plant's lifespan (manufacturing, operation, and maintenance (O&M)) to ascertain the feasibility of integration for more efficient power generation with reduced environmental impacts. Therefore, this study does not take into account variations and technical factors that can impact electricity generation, leading to fluctuations in its performance, in which this aspect is considered to be out of scope in this LCA. Due to variations in the operational lifetimes of each cycle, the assumption is made that maintenance and replacement activities are conducted over the entire lifespan of the integrated system.

Also, transportation has been excluded from this study because this assessment focused mainly on the energy technologies aspect. Moreover, the installation and assembly of components are omitted from this study because there is insufficient data available to mitigate the uncertainty associated with a comparative assessment. Besides, the end-of-life phase is not considered because it increases the assessment uncertainty specifically for perovskite technology due to the lack of sufficient data since it is still far from scalable manufacturing (Kumar et al., 2024). The applied data in modelling and assessing all studied cases are considered based on the European average data. The base case modelling for PSCs is modelled based on 3 years of lifetime. However, other scenarios are considered based on higher lifetime to have a deeper insight into its effect on the environmental impacts. That is why the calculations for cases 2 and 3 have been done based on lifetimes of 5 which is named scenario 2, 10 which is named scenario 3, and 15 years named scenario 4. Besides, as PSC has shown a significant enhancement in its efficiency in just a short period, the calculation for cases 2 and 3 are done according to different efficiency of PSCs assuming the enhancing efficiency from 17 % to 35 %.

Additionally, a comprehensive comparison of all cases is conducted, taking into account both the worst and best-case scenarios to gauge the potential reduction in environmental impact achievable through the advancement of PSC technology. The worst-case scenario is characterized by a 3-year lifespan and an efficiency of 17 %, while the best scenario is based on a 15-year lifespan and 35 % efficiency. Due to a lack of data for O&M of PSCs, this phase has been excluded from results to prevent the uncertainty increment. However, the mounting and installation (M&I) of the solar PV system on the structure have been considered in this analysis. The summary of considered cases and scenarios are presented in Table 1.

2.3. Functional unit

In accordance with the relevant ISO standards, any product system within the realm of LCA must conform to a function that signifies the performance characteristics of the system (Mayer et al., 2019). Functional unit precisely determines the product's size and type, the life cycle of which is being analysed by the function quantitative definition that it delivers (Smith et al., 2018). The functional unit for all considered combined power systems is 1 kWh of electricity generated. The supposed lifetime of each technology is different. The expected lifespans for the geothermal, wind, and solar PV systems are set at 30, 25, and 3 years, respectively. In order to conduct a meaningful comparison of these three power cycles, the environmental impact is assessed per 1 kWh of electricity generated from each combined system. The functional unit for solar system is based on alternating current (AC) electricity. The contribution portion of each combined cycle is considered based on each single power system's capacity. Because the capacity of a power plant has a direct impact on applied material and used energy for its operation as well as the O&M phase.

2.4. Data inventory

Data inventory is one of the most important stages of the LCA assessment of different systems. Gathering reliable and accurate data would be a challenging part of the study. In this research, the input and output of raw material, energy, and emission within the system boundary have been collected from available literature reviews (for geothermal systems (Gkousis et al., 2022; Zuffi et al., 2022), solar (Gong et al., 2015; Rao et al., 2021) and for wind (Angelakoglou et al., 2014)) and the ecoinvent v3.6 database. An inventory of data related to all considered cases has been included in Tables S1–S3 in the Supplementary Information.

2.4.1. Configuration description and assumptions

In this study, three combined power plants have been analysed from

Table 1
Summary of considered cases and scenarios.

Case study	Configuration	Lifetime (year)			PSC efficiency
		Geo	Wind	PSC	
Case 1	Combined geothermal & wind	30	25	–	17 %
Case 2	Combined geothermal & PSC	30	–	3	17 %
Case 3	Combined PSC & wind	–	25	3	17 %
Case 2 - scenario 1	Combined geothermal & PSC	30	–	3	17 %
Case 2 - scenario 2	Combined geothermal & PSC	30	–	5	17 %
Case 2 - scenario 3	Combined geothermal & PSC	30	–	10	17 %
Case 2 - scenario 4	Combined geothermal & PSC	30	–	15	17 %
Case 3 - scenario 1	Combined PSC & wind	–	25	3	17 %
Case 3 - scenario 2	Combined PSC & wind	–	25	5	17 %
Case 3 - scenario 3	Combined PSC & wind	–	25	10	17 %
Case 3 - scenario 4	Combined PSC & wind	–	25	15	17 %

an environmental point of view. The first power cycle which is named case 1 is an integration of geothermal and wind power systems. Cases 2 and 3 are combined geothermal and solar PV and wind and solar PV power cycles, respectively. This research aims to evaluate the environmental viability of combining two renewable sources for the production of low-carbon electricity, with a focus on examining their environmental implications throughout their operational lifespan. The study does not address challenges related to intermittency or other factors impacting the performance of solar and wind units. Instead, the primary focus of this research revolves around examining the environmental impact of integrated plants throughout their lifespan. Nevertheless, the assessment takes into account the capacity factor of each technology, recognizing that the potential of individual stand-alone systems varies based on their specific features. The storage system has not been considered for these systems. The specific details of each power cycle are outlined below.

Geothermal power plants commonly produce surplus heat, which can be harnessed in a secondary cycle to enhance overall energy effectiveness (DeLovato et al., 2019). Employing this excess heat not only boosts the efficiency of geothermal power plants but also aligns with environmental considerations by optimizing energy extraction from geothermal resources. Typically, the recovery and reutilization of this heat involve the installation of a heat exchanger in the reinjection stream before reinjection well. The heat exchanger has the capability to transfer heat, thereby elevating the enthalpy of another fluid for application in another coupled cycle (Shamoushaki et al., 2021). In our study, two scenarios (Case 1 and Case 2) focus on a geothermal cycle as the primary system, utilizing its excess heat in another interconnected cycle. In contrast, solar and wind turbine systems generally do not produce significant excess heat, but integrating them has unique benefits as their power generation is complementary, functioning efficiently at different times (Wu et al., 2022a). These combined technologies could be located on the same site or different sites depending on the geological and specific features of the region. However, as combined systems could generate more efficient energy, they are a great option to generate more power with higher productivity.

There are some limitations in the defined scenarios, as the selected lifespans and efficiencies might not encompass the full spectrum of potential future advancements in PSC technology. The environmental evaluation focuses on specific combinations of renewable sources, which may neglect other possible configurations or regional variations in resource availability and technological integration. Furthermore, the study does not consider economic factors, potential technological advancements, or policy shifts that might influence the viability and uptake of these renewable energy systems.

2.4.2. Geothermal system

Geothermal energy is one of the most promising renewable resources which has outstanding features compared with other clean resources. The considered geothermal power cycle in this study is a binary power cycle which is a simplified configuration and related energy, mass, and emission data are collected from the literature. The data related to power plant construction is gathered from ref. (Zuffi et al., 2022). The geothermal system data is supposed to be based on average data from European geothermal case study. Then the data applied for environmental assessment in both equipment construction and well drilling are based on collected data from geothermal cases in European countries (Zuffi et al., 2022). The main components of considered geothermal power plants are steam turbine, condenser, pump, regenerative heat exchanger, and evaporator. The geofluid flows into the primary heat exchanger at a temperature of 180 degrees Celsius and under atmospheric pressure. The high enthalpy vapor powers the turbine, producing electricity. The ORC fluid then passes through a regenerator to warm it before reaching the primary heat exchanger. Next, it moves into the condenser, where it cools and transitions into a saturated liquid state. Maximizing efficiency involves integrating other cycles with a geothermal plant, enabling the capture of residual heat before reinjection and ensuring the most effective use of available resources. It has been assumed that this power plant produces 10 MW of electricity. It is assumed that pressure losses in cycle components and piping are negligible. Besides, the data of well drilling, operation and maintenance (O&M), building construction, and direct emissions has been applied from ref. (Gkousis et al., 2022; Heberle et al., 2016). For the O&M stage, some consuming materials such as lubricating oil and working fluid leakage have been considered. The considered working fluid for the organic Rankine cycle is R134a. Two production wells and one reinjection well are supposed for this plant. The wells are designed to have 3000 m depth.

2.4.3. Wind turbine system

Wind power plant is asserted as one of the most environmentally friendly power generator technologies as wind turbine does not have any direct emission during the operation, however, they have some environmental impact during the construction and O&M (Wang and Sun, 2012). The Vestas 3 MW wind turbine served as the benchmark in this study due to its widespread utilization and accessibility of data. The considered wind power system is comprised of a rotor, nacelle, tower, and foundation. The rotor comprises two to three blades and a central hub that connects the blades to the rotational shaft. The specification of the studied wind turbine is brought in Table 2 (Angelakoglou et al., 2014). This wind turbine is designed for land installation or onshore application. For life cycle modelling, power plant construction and operation and maintenance of power plants have been considered. The data relating to energy and material applied in modelling and turbine specification have been gathered from ref. (Angelakoglou et al., 2014). The power mentioned in this table is based on nominal power.[1]

2.4.4. Perovskite solar system

PSC shows great promise in meeting energy demands more affordably and efficiently compared to other solar technologies. PSC utilizes a light-harvesting active layer that consists of a perovskite-structured compound, which can be based on tin halides or organic-inorganic lead. There are two primary designs for PSCs, namely mesoscopic and planar architectures (Ibn-Mohammed et al., 2017). This new system has not been commercialized as it needs to be improved from different aspects such as short lifetime. The power conversion efficiency of this system has had significant development in a short period, from 3.8 % up to 25 % only after a decade (Ahmed et al., 2023). It is crucial to conduct assessments of the environmental impact and sustainability of any new technology prior to its commercialization. In this study, we have

Table 2
Specification of studied wind turbine (Angelakoglou et al., 2014).

Parameter	Unit	Value
Nominal power	MW	3
Average wind speed	m/s	6
Tower height	m	85
Working voltage	kV	10–35
Frequency	Hz	50/60
Working speed	m/s	3.5–25
Rotor diameter	M	90

[1] Nominal capacity, often referred to as nameplate capacity, signifies the theoretical maximum power output that a power cycle is designed to achieve under ideal conditions. It serves as a crucial parameter in the initial design and engineering stages, providing a standardized reference point for the system's potential. On the other hand, average capacity represents the observed power output over a specified operational period, accounting for real-world factors such as variations in operating conditions, maintenance downtime, and other practical constraints.

evaluated zinc oxide (ZnO) perovskite, a material characterized by its straightforward synthesis and remarkable electrical properties, including high charge mobility. ZnO-based perovskite solar cells can achieve up to 20.6 % efficiency by using self-assembled monolayers to enhance energy alignment, film quality, and reduce defects (Wu et al., 2022b). ZnO demonstrates high transparency within the visible light spectrum and possesses a refractive index of roughly 2.1. ZnO showcases electron mobility ranging from 205 to 300 $cm^2 \cdot V \cdot s^{-1}$ and an electron diffusion coefficient of 1.7×10^{-4} $cm^2 \cdot s^{-1}$, significantly surpassing those of TiO_2. It possesses advantageous characteristics for PSCs. ZnO exhibits a conducive energy level arrangement, with its conduction band minimum (CBM) situated approximately at −4.17 eV, accompanied by a bandgap of 3.2 eV (Qiu et al., 2022).

The data related to material and energy applied in zinc oxide perovskite cells and data related to the mounting system on the structures have been collected from refs. (Gong et al., 2015; Rao et al., 2021).

The applied formula to calculate the area for considered functional unit is as follows:

$$A = \frac{\varepsilon}{\eta . I . y . PR} \quad (1)$$

In the above correlation, A, ε, η, I, y and PR are cell area (m^2), energy produced (kWh), cell efficiency (%), insolation value ($kWh/m^2/year$), cell lifetime (year) and performance ratio, respectively. Insolation value may vary from region to region according to sunlight value and angle. In this study, insolation is supposed to be 1100 $kWh/m^2/year$ which is typical value related to central Europe (Monteiro Lunardi et al., 2017). Also, efficiency of the cell and performance ratio are assumed to be 17 % and 0.75, respectively (Monteiro Lunardi et al., 2017). Furthermore, the active area ratio is 70.0 %, and the module efficiency is 11 % (Gong et al., 2015).

2.5. Life cycle impact assessment

In the present study, both midpoint and endpoint methods have been applied using OpenLCA 1.11.0 (OpenLCA, n.d.). The midpoint-level characterisation factors happen along with the impact pathway, however, the endpoint-level characterisation factors are relevant to the quality of the ecosystem, resource shortage, and human health (Smith et al., 2023). The ReCiPe midpoint has been selected to calculate 18 ICs, and the ReCiPe endpoint has been chosen to obtain three main impacts such as ecosystem, human health, and resources.

2.6. Data assessment

Data quality assessment which is a vital procedure is conducted to ensure the data's accuracy, reliability, and relevance in this study. The collected data is assessed against key criteria such as reliability, completeness, temporal relevance, geographical relevance, and technological relevance. It is essential to ensure that the collected data is consistent across various life cycle stages and between different data points to guarantee that comparisons and aggregations are meaningful and reliable. This thorough evaluation enhances the transparency and robustness of the LCA. A summary of the implemented methodology is presented in Table 3.

3. Results and discussion

This study undertakes a comparative LCA to explore the environmental implications of three integrated renewable power generation systems. This section presents both midpoint and endpoint results. Examining both midpoint and endpoint results is crucial as it offers a holistic perspective on the environmental performance of the integrated systems. Midpoint assessments track the systems' ongoing progress and performance, offering insights into their alignment with objectives. On the other hand, endpoint evaluations provide a glimpse into the ultimate outcomes and success of the systems.

Table 3
Summary of applied methodology.

Item	Information
Goal and scope	• A comparative assessment of the environmental impact throughout the life cycle of three integrated power generation systems based on renewable energy sources • Sensitivity assessment of different lifetimes and efficiency impacts of the PSC system on the environmental impacts of the combined systems
Studied technologies	• Combined geothermal & wind power plant • Combined geothermal & PSC power plant • Combined PSC & wind power plant
Functional unit	1 kWh of electricity generated
System boundary	Cradle-to-operation
Software	OpenLCA v1.11.0
Gathered data	Secondary data (literature and ecoinvent)
Chosen impact categories	18 midpoints, 3 endpoints
Life cycle impact assessment method	ReCiPe (midpoint and endpoint)
Uncertainty assessment	Monte Carlo

3.1. Midpoint impact results

3.1.1. Comparison by phases contribution

Fig. 1 illustrates the environmental impact of various stages in case 1 using the midpoint method. The results indicate that, in most ICs, geothermal well drilling has the most significant negative influence when compared to other stages, with the exception of two impacts: climate change (CC) and ozone depletion (OD). The primary factor contributing to the adverse effects of well drilling is the consumption of diesel fuel to power the machinery (Xia et al., 2021). In the case of CC and OD impacts, the O&M related to the geothermal cycle are responsible for the most substantial negative impact, accounting for approximately 46 % and 82 % of the total impacts, respectively. The climate change impact primarily arises from direct emissions occurring during the operation of the power plant, specifically from the binary system. OD is primarily caused by the organic working fluid used and potential leakage in the ORC cycle over the power plant's lifespan. For the wind

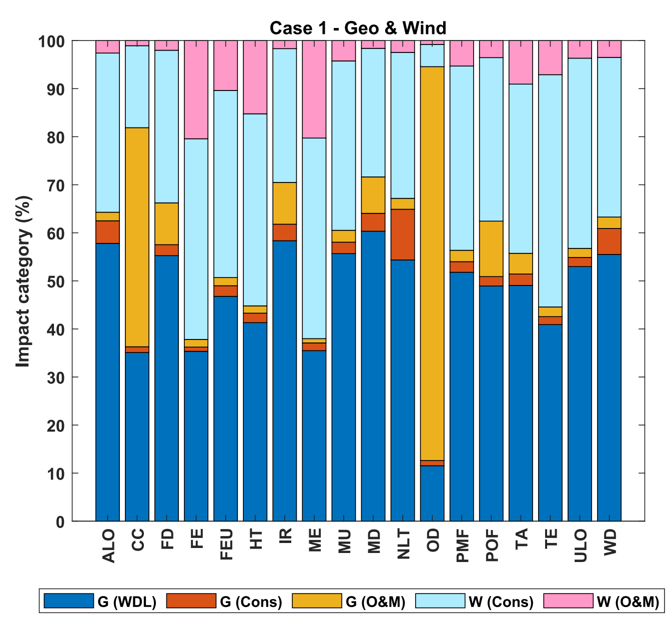


Fig. 1. Environmental impact contribution of different phases for case 1, (G refers to geothermal, WDL refers to well drilling, W refers to wind, Cons refers to construction and O&M stands for operation and maintenance).

power cycle, the O&M phase has a greater adverse impact in four categories when compared to other phases: freshwater ecotoxicity (FE), freshwater eutrophication (FEU), human toxicity (HT), and marine ecotoxicity (ME). These impacts are primarily linked to the use of copper, steel, and aluminium, which are the main materials employed in this phase.

Besides, the construction of wind power units has the highest impact after geothermal well drilling in most impact categories. The primary driver of this adverse effect during the construction of wind units can be attributed to the manufacturing of nacelles and towers, primarily due to the use of copper and steel. It's important to note that the utilization of copper also results in negative impacts, particularly in terms of freshwater and marine resource toxicity (Demir and Taşkın, 2013). However, the construction of a geothermal power cycle has a minor environmental impact on all ICs. In general, it can be found that most environmental consequences of case 1 in all categories are relevant to geothermal well drilling and wind power cycle construction.

Fig. 2 illustrates the environmental impact portion for each phase of case 2 which is a combined geothermal and solar PV power cycle based on 3 years of PSC lifetime. Results proved that the geothermal construction phase has an insignificant impact compared with other phases. The highest geothermal plant construction impact is related to metal depletion which is around 5 % of the total impact and mainly due to consumed metals for equipment manufacturing. Based on the displayed plot, it is visible that the phases with considerable impacts are geothermal well drilling, PSC manufacturing, and M&I parts. PSC manufacturing has a huge adverse environmental impact in five categories (marine eutrophication (MU), metal depletion (MD), particulate matter formation (PMF), photochemical oxidant formation (POF), and terrestrial ecotoxicity (TE)) which proves the toxicity problem of this system. Besides, MD impact is another major consequence of the PSC system which is mainly related to zinc applied in the electron-transport layer, silver in the back electrode and indium tin oxide (ITO) applied in the substrate. Silver used in cathode has a significant impact on freshwater ecotoxicity (FE), and ME (Gong et al., 2015). PSC manufacturing's least impact is in CC (around 13 %) and OD (less than 2 %).

However, the M&I phase also plays a significant role in the damaging impact of the solar PV power cycle, in which the highest impact of this phase is ME which is approximately 58 % of the total impact and mainly due to aluminium and steel applied. In addition, well drilling is one of the main factors of environmental damage for all ICs. Besides, the O&M phase of the geothermal unit has a huge impact on OD and another considerable impact of this phase is clear in the CC category which is caused by non-condensable gases in brine and relevant emissions during plant operation (Zuffi et al., 2022).

Fig. 3 displays the percentage of environmental impacts of case 3 based on three years of PSC lifetime. From this bar graph, it can be found that the environmental impact of the solar unit in all ICs is higher than the wind turbine power cycle. The values of six ICs, HT, ME, MU, PMF, POF, and TE, together account for approximately 90 % of the total impact attributed to the PSC manufacturing process. POF is primarily induced using ITO, while PMF is chiefly driven by the electron-transport layer (58 %) and certain materials like zinc, in addition to the substrate (25 %). Besides, silver has negative impacts on ME and MU (Gong et al., 2015). In these six categories, the impact of wind units is negligible. Among all four shown phases in this graph, the O&M of the wind turbine system has the lowest negative environmental impacts. The M&I phase of PSC is another main cause of environmental degradation. This phase has a significant influence on CC and other ICs which is mainly due to the implementation of heavy metals such as steel and aluminium (Rao et al., 2021). The M&I is the source of 50 % of environmental problems. The highest M&I effect is on water depletion (WD) which is the reason for more than 50 % of total impacts. Also, the least impact caused by PSC manufacturing is for WD.

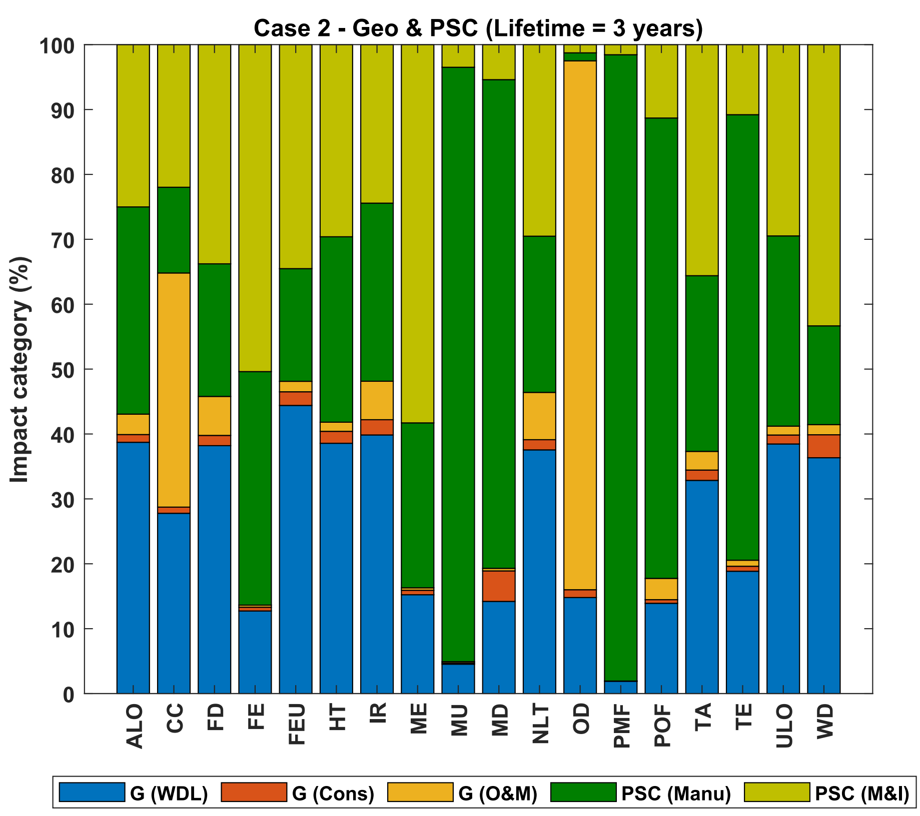


Fig. 2. Environmental impact contribution of different phases of case 2 (based on 3 years of PSC lifetime), (G refers to geothermal, WDL refers to well drilling, PSC refers to perovskite solar cell, Cons refer to construction, Manu refers to manufacturing, O&M stands for operation and maintenance and M&I refers to mounting and installation).

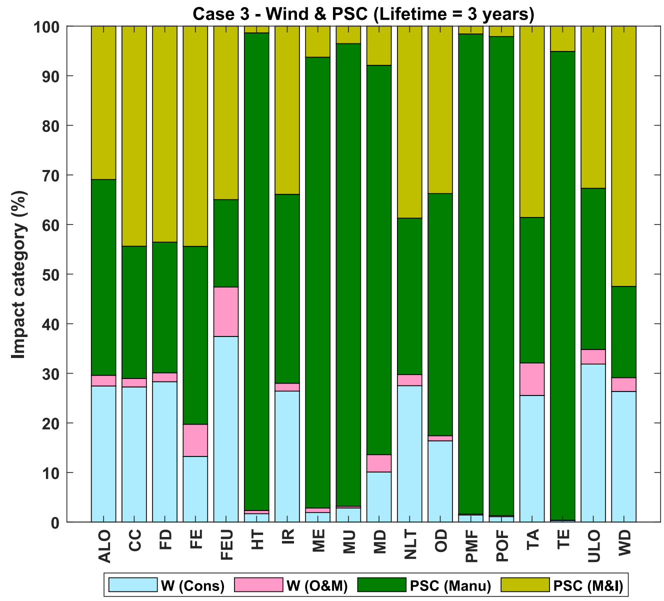


Fig. 3. Environmental impact contribution of different phases of case 3 (based on 3 years of PSC lifetime), (W refer to wind, PSC refers to perovskite solar cell, Cons refer to construction, Manu refers to manufacturing, O&M stands for operation and maintenance and M&I refers to mounting and installation).

3.1.2. Comparison by cases and scenarios: sensitivity analysis

As it has been mentioned before, different scenarios based on a different lifetime of the PSC system are considered in this study. The environmental adverse percentage of different scenarios of case 2 has been presented in Fig. 4. Considering longer lifetime for the PSC system results in decreasing the environmental damages of the PSC and generally in the entire combined power plant. However, the reduction of the consequences for the two considered phases of the PSC power cycle is different. Results showed that considering a longer lifetime for PSC higher than 10 years will have a remarkable effect on the ecological impacts of this system. However, the lowest diminish occurred for MU and PMF which are around 10 and 8 % which shows other interventions such as material replacement should be considered to reduce these impacts. An illustrative case of this modest reduction is seen in the use of zinc in the electron-transport layer and ITO in the substrate, which are the primary contributors to PMT. However, the extension of the PSC's lifetime could not fully offset the negative impacts of these elements. The findings indicate a significant reduction in the environmental damage associated with PSC manufacturing when a longer lifetime is considered. For instance, in twelve out of eighteen impact categories, the adverse effects of PSC manufacturing account for less than 15 % of the total detrimental impacts of the combined cycle. This underscores the substantial environmental potential of PSC systems when technology and lifespan are enhanced.

According to the illustrated results in Fig. 5, the damaging consequences of the PSC unit have had a significant decline in some ICs by developing its lifetime from 3 to 15 years. This plot is showing the environmental impacts of different phases of the case 3. In this combined plant, HT is a challenging problem arising from the PSC manufacturing process which is mainly due to applying some toxic materials like lead (Ren et al., 2022). The portion of PSC manufacturing just has had an 8 % decrease in HT from the first scenario to the fourth. Besides, some other categories such as ME, MU, MD, PMF, POF, and TE still have a high portion despite increasing the lifetime. A majority part of toxicity issues and formation challenges come from direct emissions (19 %), hole transport layer deposition, and specifically Spiro-MeOTAD (29 %), ITO (14 %), and electricity (6 %) (Ibn-Mohammed et al., 2017). It should not be overlooked that some other ICs have a slight portion in longer lifetime scenarios such as agricultural land occupation (ALO), CC, fossil depletion (FD), FE, FEU, ionising radiation (IR), natural land transformation (NLT), TA, ULO, and WD. The most significant IC decline is achieved in CC, FD, NLT, terrestrial acidification (TA), WD, OD, FE, FEU, and ULO with around 35 to 40 %. However, toxicity, metal depletion, and particulate and photochemical matter formations are the main causes of environmental impacts of PSC units. The proportion of impacts attributable to the wind turbine cycle in this integrated system has increased as the PSC lifetime has been extended. Overall, in this combined cycle, in scenario 1, less than 36 % of the total impacts across all categories are associated with the wind unit. However, with the improvement in the

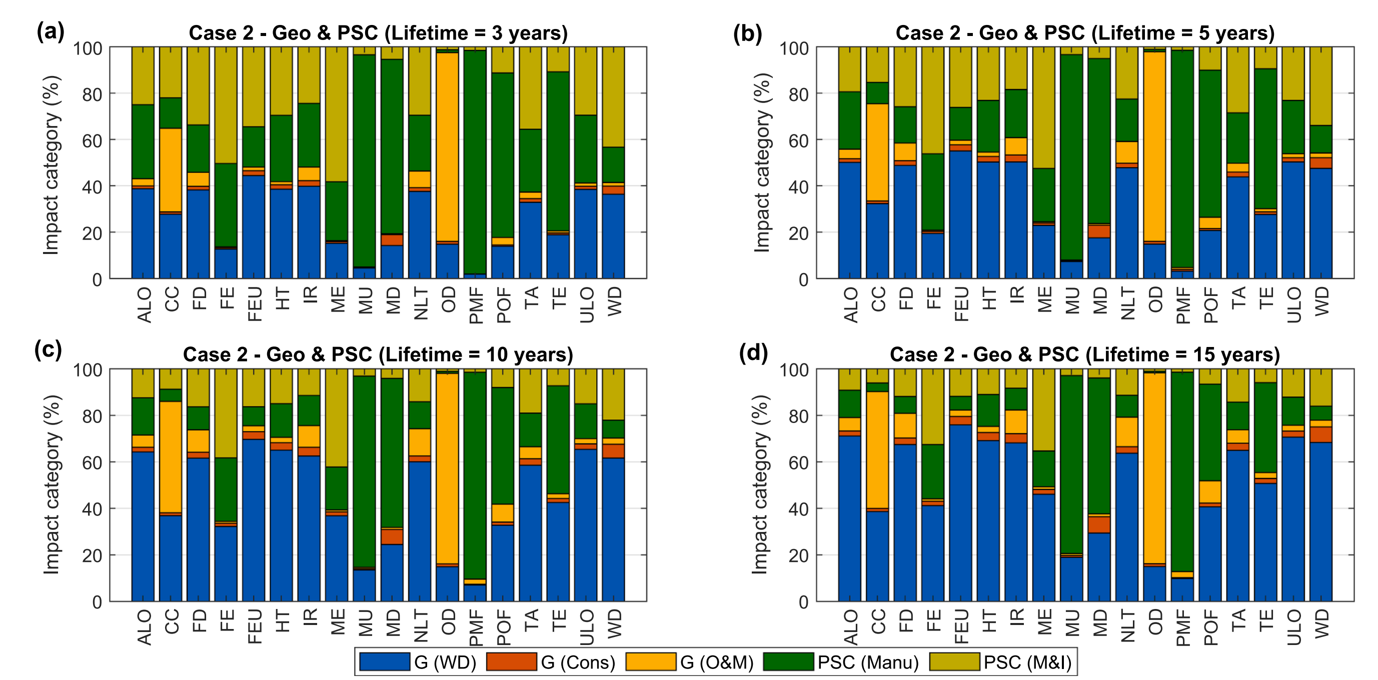


Fig. 4. Environmental adverse percentage of case 2 for all scenarios (a) scenario 1 (PSC lifetime of 3 years), (b) scenario 2 (PSC lifetime of 5 years), (c) scenario 3 (PSC lifetime of 10 years), (d) scenario 4 (PSC lifetime of 15 years).

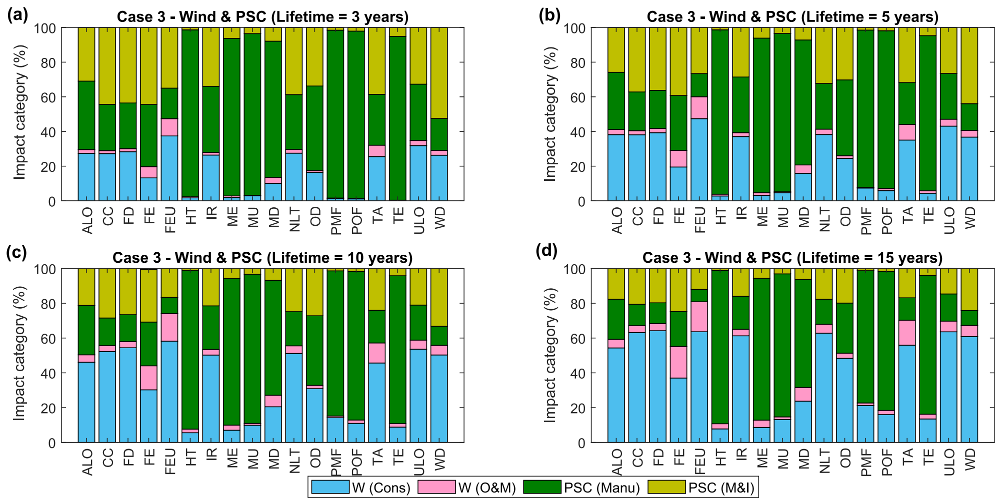


Fig. 5. Environmental adverse percentage of case 3 for all scenarios (a) scenario 1 (PSC lifetime of 3 years), (b) scenario 2 (PSC lifetime of 5 years), (c) scenario 3 (PSC lifetime of 10 years), (d) scenario 4 (PSC lifetime of 15 years).

PSC lifetime, extending up to 15 years, in half of the impact categories, the wind unit contributes to over 50 % of the total detrimental impacts. It's important to note that the impact of the wind turbine on two categories, namely HT and ME, has remained insignificant, accounting for less than 8 % of the total impacts in all scenarios.

3.1.2.1. PSC lifetime. Fig. 6 compares various ICs of all three cases based on different scenarios. According to these bar graphs, it is visible that developing the PSC technology results in diminishing the environmental impacts of cases 2 and 3 which include PSC system, however, the decrement amount varies for different ICs, so that in some ICs it has a remarkable reduction, and in some others lower diminish. Besides, these graphs give a comparable holistic view of each case's effect on ICs variations. In some cases, the amount of a specific IC even for scenarios 3 and 4 is still higher than in case 1, for instance, however, in some others, both or one of them has lower impacts.

One noteworthy distinction lies in the category of OD, where the value for case 3 (1.9×10^{-9} kg CFC-11 eq/kWh) is considerably lower than the other two cases which are 4.93×10^{-8} and 5.1×10^{-8} kg CFC-11 eq/kWh for case 1 and 2, respectively. It's important to highlight that the reduction in case 2 remained insubstantial, primarily due to the impact of the geothermal plant, specifically in its O&M phase, and the utilization of organic working fluids. In cases 1 and 2, the primary dominant factors contributing to OD are direct emissions from the geothermal plant and the impact of organic working fluids. Conversely, in some ICs, such as HT, ME, POF, and TE, the impact of case 3 is much higher than in two other cases. As has been mentioned before, due to the toxicity issue of PSC and relevant applied material in its manufacturing. Nonetheless, it's worth noting that in scenario 4, these values have decreased to less than a third compared to the base case (scenario 1), indicating a significant reduction. The underlying reasons for these differences vary for each impact category. For ME, the electron and hole-transport layers play a significant role, while the substrate and its associated emissions are the primary drivers of POF. In the case of TE, in PSC, and in case 3, the hole-transport layer and substrate are the most dominant factors. For case 3, the TE value in the base case assessment is 0.00143 kg 1,4-dB eq/kWh. When the lifetime is extended to 15 years, this value decreases to 0.00029 kg 1,4-dB eq/kWh. Despite this improvement, it remains significantly higher than the TE values for cases 1 and 2. In general, some key elements, such as CC and OD, exhibit lower values for cases 2 and 3 in scenarios 3 and 4 compared to the other cases. Conversely, they have notable implications in terms of toxicity and metal depletion. More details are elaborated in Figs. S1–S2 in the supplementary information.

3.1.2.2. PSC efficiency. To have a wider insight regarding the influence of PSC technological improvement, the effect of enhancing the efficiency of this system has been compared for all cases in Fig. 7. Here, the idea of this analysis is to see how much positive impact can be achieved with efficiency improvement of the PSC from 17 % up to 35 %. The efficiency of geothermal and wind systems has been considered constant in this assessment because the considered technologies for these two systems in this research have been studied for decades and maybe a significant increase may not occur in the near future, however, as the PSC system is under the development and in a short period showed huge potential in efficiency improvement, the possibility of its development considered in this evaluation. The achieved results showed that enhancing the efficiency to 35 % could have a considerable positive effect on reducing the environmental impacts. The most significant reduction is observed in MD for cases 2 and 3, where it decreases from 1.794 and 1.802 kg Fe eq/kWh at 17 % efficiency to 0.489 and 0.491 kg Fe eq/kWh at 35 % efficiency, respectively. These results are compatible with the obtained consequences from other research which showed the dependency of the environmental impact of PSC on the efficiency of conversion (Zhang et al., 2017). Normalised environmental impacts for all ICs and cases can be found in Fig. S3 in the supplementary information. Nevertheless, based on these charts, it becomes evident that the increase in lifetime has a more significant effect on the rise in environmental impact compared to the development of efficiency. A more influential intervention is considering enhancement in both lifetime and efficiency.

3.1.3. Best and worst-case results

To gain a more insightful understanding of how technological advancements impact PSC technology, we have established both a best-case and worst-case scenario. The worst-case scenario is determined by assuming an efficiency of 17 % and a PSC system lifetime of 3 years. This calculation represents our base case, rooted in the typical available lab-scale capacity for PSC technology. In the best-case scenario, we simultaneously consider improvements in both the efficiency and the lifetime of PSC technology to assess their combined effect on the environmental performance of this system. In the best scenario, we anticipate an efficiency of 35 % and a lifespan of 15 years. Fig. 8 illustrates the decline in environmental impacts for cases 2 and 3 under both the worst and best-case scenarios, as depicted by the endpoint results. These findings demonstrate that the reduction in impact is greater in case 2 compared to case 3, with the most substantial difference observed in the ecosystem impact, amounting to 42 %, while the smallest variation concerns resources, with only a 1 % decrease. The main reason for the lesser reduction in ecosystem impact in case 3 is the detrimental impact

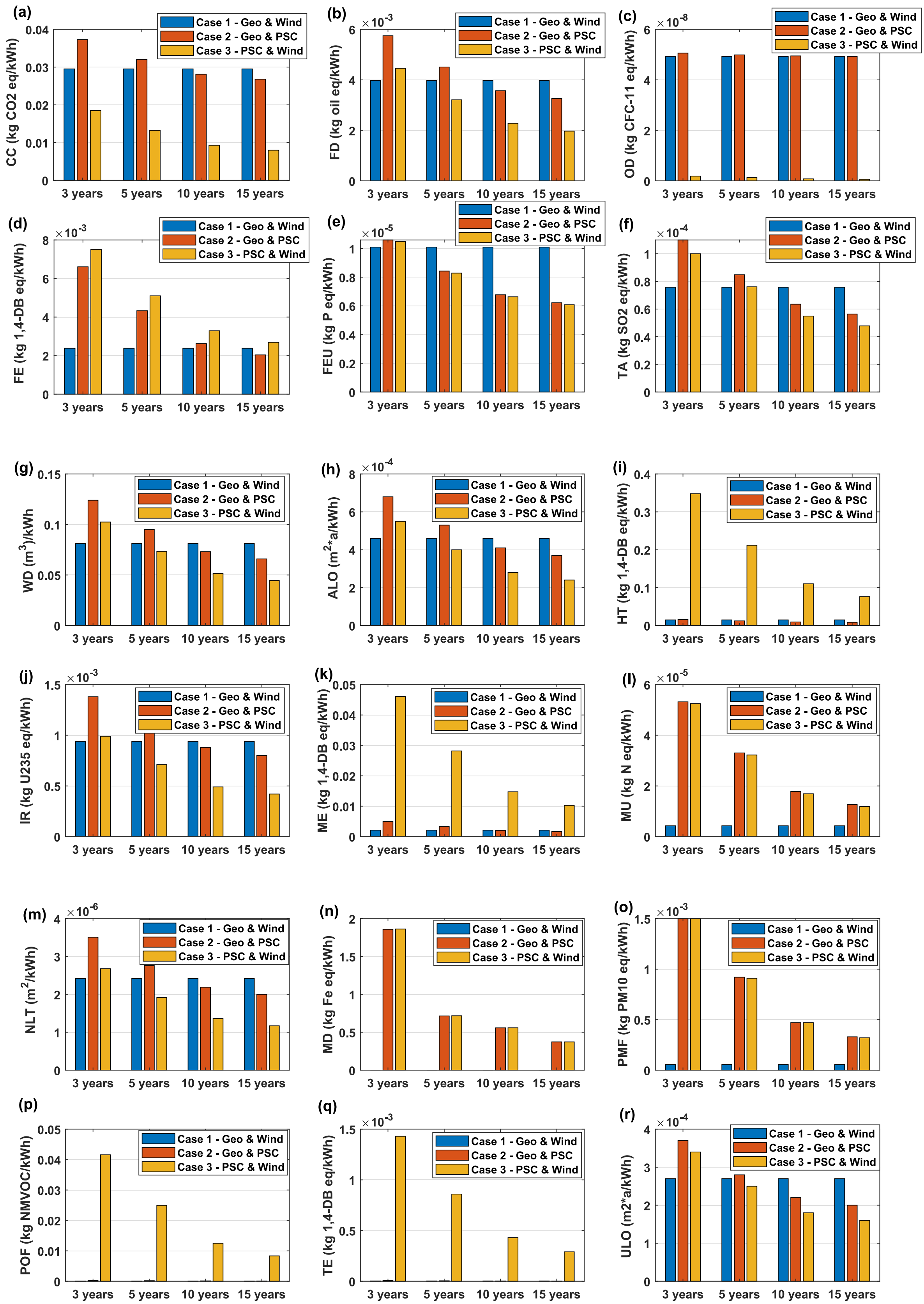


Fig. 6. Impact categories comparison for all cases and scenarios, (a) climate change, (b) fossil depletion, (c) ozone depletion, (d) freshwater ecotoxicity, (e) freshwater eutrophication, (f) terrestrial acidification, (g) water depletion, (h) agricultural land occupation, (i) human toxicity, (j) ionising radiation, (k) marine ecotoxicity, (l) marine eutrophication, (m) natural land transformation, (n) metal depletion, (o) particulate matter formation, (p) photochemical oxidant formation, (q) terrestrial ecotoxicity, (r) urban land occupation.

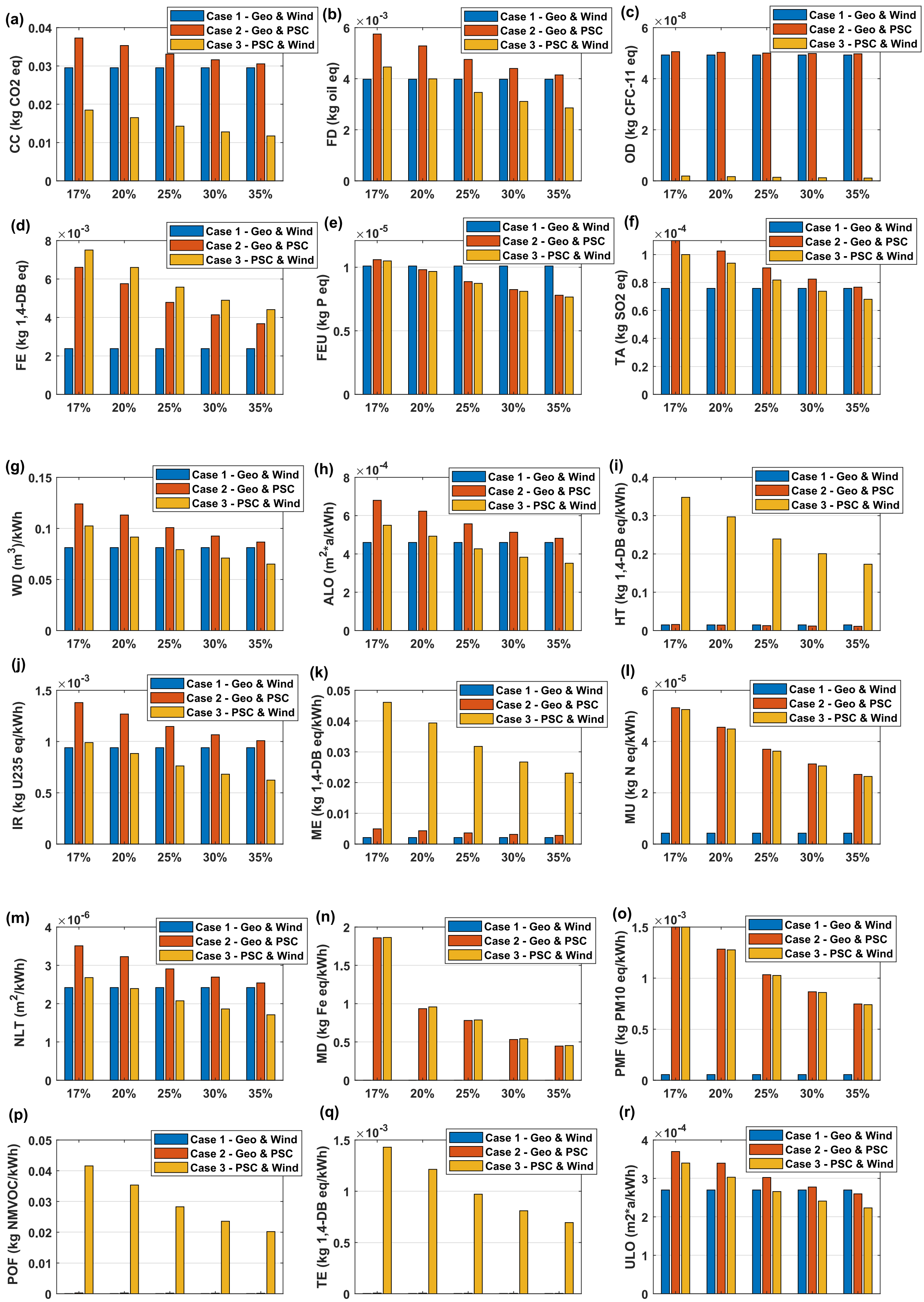


Fig. 7. Impact categories comparison for all cases based on different PSC efficiencies, (a) climate change, (b) fossil depletion, (c) ozone depletion, (d) freshwater ecotoxicity, (e) freshwater eutrophication, (f) terrestrial acidification, (g) water depletion, (h) agricultural land occupation, (i) human toxicity, (j) ionising radiation, (k) marine ecotoxicity, (l) marine eutrophication, (m) natural land transformation, (n) metal depletion, (o) particulate matter formation, (p) photochemical oxidant formation, (q) terrestrial ecotoxicity, (r) urban land occupation.

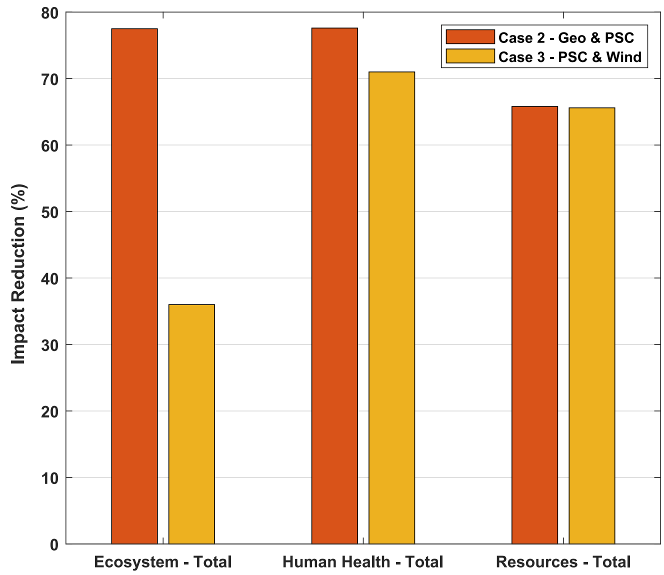


Fig. 8. Damaging environmental impact reduction based on the best and worst-case scenarios according to the endpoint method (Case 1 is not represented in these graphs due to the absence of a PSC unit. Consequently, there was no observed reduction resulting from enhancements in the lifetime or efficiency of PSCs.)

of the PSC system, primarily due to the use of toxic materials such as lead. Additionally, the impact of the various phases of the PSC system takes precedence over the wind turbine plants in this integrated power cycle. Nevertheless, the results underscore the significant environmental impact of developing PSC technology and its capacity, both as a stand-alone system and within an integrated system. The harmful environmental impact decrement considering the best-case scenario based on the midpoint method is presented in the supplementary information (see Fig. S4).

3.2. Endpoint impact results

Fig. 9 depicts the environmental impacts of all considered cases according to different scenarios and endpoint methods. The obtained results showed that increasing the PSC lifespan has had a positive impact on cases 2 and 3 combined cycles' environmental performance. Base case results illustrate that for all three ICs, case 1 has lower impacts compared to the two others. The most significant difference is in resources, so the case 1 value (0.00066 \$/kWh) is insignificant compared with the two other cases (0.11987 for case 2 and 0.11998 \$/kWh). Enhancing the lifetime significantly reduces the impact in cases 2 and 3. For a 15-year lifetime, case 2 has a resource impact of 0.044397 \$/kWh, and case 3 has 0.04408 \$/kWh. However, these values are still notably higher than those for case 1. The findings reveal that when considering a PSC lifetime of 10 years or more, the detrimental ecosystem impacts of cases 2 and 3 become less severe than those in case 1 (2.606×10^{-10} for case 2 and 1.7×10^{-10} for case 3 for the lifetime of 10 years and 2.462×10^{-10} species.yr/kWh for case 2 and 1.33×10^{-10} species.yr/kWh for case 3 for the lifetime of 15 years). In fact, for cases 2 and 3, assuming a 15-year PSC lifetime, the ecosystem impact is reduced to less than a quarter and a third, respectively, in comparison to the base case value. The main drivers behind the reduction in environmental impacts for cases 2 and 3 are the decrease in the M&I phase by approximately 50 % and encapsulation by 11 % in the fourth scenario, compared to the base case. Significantly, the most notable decrease is observed in the PMF impact for case 3 when assuming a 15-year PSC lifetime, which registers approximately an 80 % decrease compared to the base case. This considerable reduction primarily stems from decreases in the electron-transport layer (44 %) and substrate (28 %). Furthermore, in the fourth scenario, the HH impact for case 2 is approximately 72 % lower than in the base case (which reduced to 1.283×10^{-7} species.yr/kWh). However, the reduction in HT is comparatively minor in contrast to the decline in PMF. Nevertheless, it is noteworthy that the values for the fourth scenario remain higher than those observed in case 1.

The percentage of each ecosystem IC based on endpoint results has been displayed in Fig. 10. Based on the obtained results, CC is the main cause of ecosystem damaging impact in cases 1 and 2. However, in case 3, in addition to CC, TA is another main contributor to ecosystem problems. Expanding the PSC lifetime in case 3 causes an increase in the CC portion and a decrease in TA. It should be mentioned that the portion of TE, FE, FEU, ALO, and ME ICs is negligible compared with others. The impact portions for human health and resources are presented in the supplementary information (see Figs. S5–S6).

Both midpoint and endpoint results are presented in this study due to several reasons. Firstly, from the goal domain, midpoint results concentrate on granular environmental indicators (mentioned 18 ICs), whereas endpoint results offer a more cumulative and interconnected perspective. Midpoint results are geared towards a technical audience, such as experts and researchers, whereas endpoint results are commonly employed in communication with non-experts, policymakers, and the public which means the different audiences of these two methods.

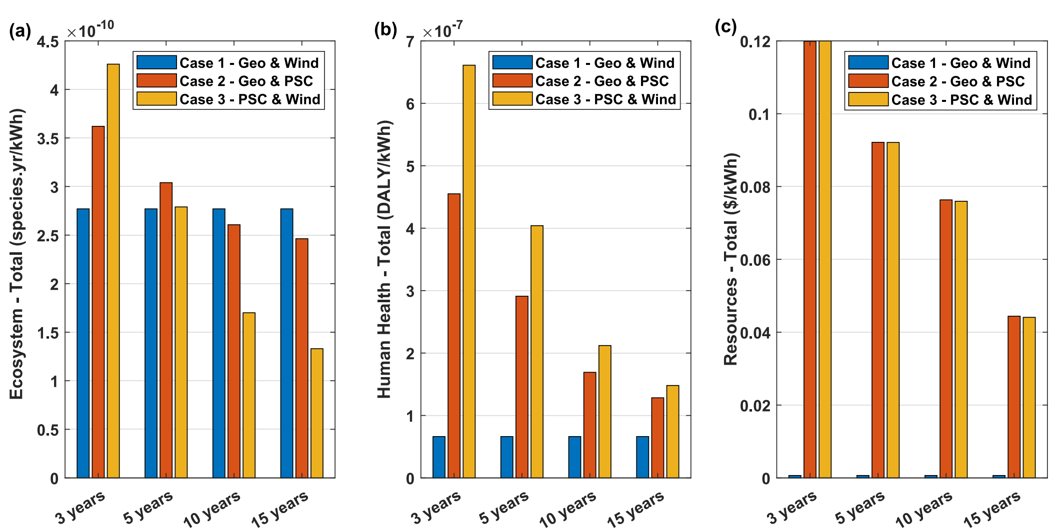


Fig. 9. (a) Ecosystem, (b) human health, and (c) resources impacts values for all cases and scenarios based on endpoint results.

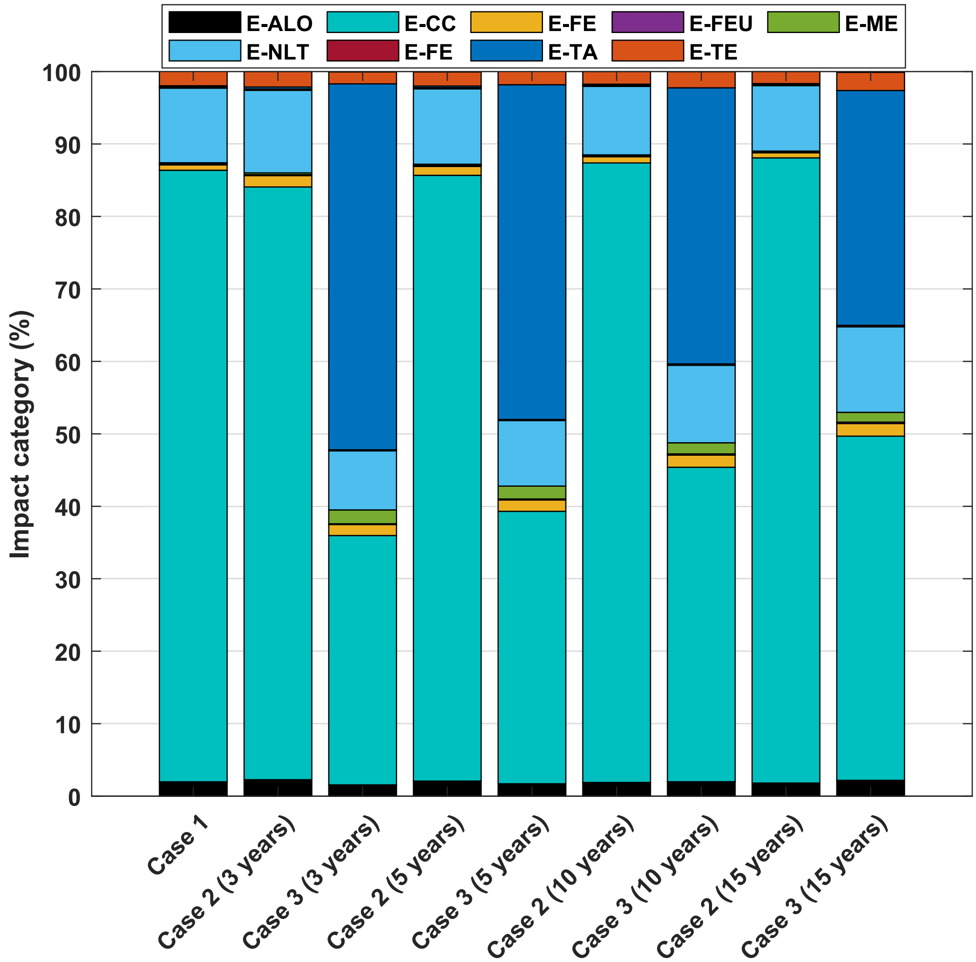


Fig. 10. The impact portions for the ecosystem.

Midpoint results aid in pinpointing environmental stressors, whereas endpoint results provide an understanding of the comprehensive impact on human and ecological systems. Endpoint results convert midpoint indicators into potential consequences for human health, ecosystems, and resources, offering a closer alignment with actual effects and implications for quality of life. It should be considered while midpoint results furnish detailed information regarding environmental categories, endpoint results provide a more encompassing comprehension of the power plant's impact by translating these indicators into potential effects on both people and the environment. This added layer of information enhances the understanding of the real-world implications and provides a more holistic assessment of the power plant's overall impact, making the analysis more meaningful. Besides, the decision to opt for either power plant endpoint or midpoint methods carries significant consequences for decision-makers. Midpoint methods provide a more detailed insight into the environmental impacts linked to power generation, allowing for precise interventions at the source. Conversely, endpoint methods offer a more inclusive perspective, enabling a holistic evaluation of a product or process. The choice between these methods should be guided by the assessment's goals and the desired level of detail necessary for informed decision-making. Both sets of results contribute significantly to a comprehensive LCA which comprises a wider range of decision makers.

Tables 4 and 5 present the heatmap of obtained results for all cases and scenarios based on midpoint and endpoint methods respectively. These tables use a color-coded system, with varying shades of green and corresponding numbers ranging from 1 to 5. In this scheme, dark green (labelled as 5) represents the most environmentally sustainable option, while light green (labelled as 1) signifies a less environmentally friendly option. Therefore, as the number decreases from 5 to 1 and the color shifts from darker to lighter green, the environmental impact increases. These tables offer a quick and easily interpretable overview of the environmental performance of all the systems under consideration. Table 4 shows that on the left-hand side of the table, which is related to longer PSC lifetimes, the table is darker which proves their sustainability. In Table 5, case 1 exhibits a better sustainability scenario in terms of human health and resource impacts. In scenarios 3 and 4, where longer system lifetimes are considered, cases 3 and 2 emerge as more sustainable choices in comparison to case 1.

3.3. Uncertainty assessment

Monte Carlo simulation is utilized to evaluate uncertainty within this study. The analysis considers various uncertainty parameters, such as material and energy data (variations in raw material and energy quantities and sources across different phases), emission factors (uncertainties in factors related to emissions from various processes), and operational aspects (variations in operational conditions and maintenance needs). Rather than using fixed values, probability distributions are employed to define input data for the LCA, accommodating these uncertainties and yielding a spectrum of potential outcomes. Fig. 11 displays the uncertainty of ICs based on the midpoint method. The magnitude of the error varies across different cases and impact categories, but, in general, it remains below 15 %. The error bars for different cases based on the endpoint results are presented in the supplementary information (see Fig. S7). The results from these

Table 4
Heatmap table for all cases and scenarios based on the midpoint method.

IC	Case 1	Case 2 (3 years)	Case 3 (3 years)	Case 1	Case 2 (5 years)	Case 3 (5 years)	Case 1	Case 2 (10 years)	Case 3 (10 years)	Case 1	Case 2 (15 years)	Case 3 (15 years)
ALO	3	1	2	3	2	4	3	4	5	3	4	5
CC	2	1	4	2	1	4	2	3	5	2	3	5
FD	3	1	2	3	2	4	3	3	5	3	4	5
FE	4	2	1	4	3	2	4	5	4	4	5	4
FEU	1	1	1	1	2	3	1	4	4	1	4	5
HT	4	4	1	4	4	2	4	5	3	4	5	3
IR	2	1	2	2	1	4	2	3	5	2	3	5
ME	4	1	2	4	2	2	4	5	2	4	5	3
MU	5	1	1	5	2	2	5	2	2	5	2	3
MD	5	1	1	5	1	1	5	2	1	5	1	2
NLT	3	1	3	3	3	5	3	4	5	3	4	5
OD	2	1	4	2	2	4	2	2	5	2	2	5
PMF	5	1	1	5	2	2	5	2	2	5	2	3
POF	5	2	1	5	2	1	5	3	1	5	4	3
TA	3	1	2	3	2	3	3	3	4	3	4	5
TE	4	2	1	4	3	1	4	5	1	4	5	2
ULO	3	1	2	3	2	3	3	4	5	3	4	5
WD	3	1	2	3	2	4	3	4	5	3	4	5

Keys: Number 1 represents the least sustainable option with the highest impact value →
Number 2 represents it is far from sustainability criteria →
Number 3 represents the third option from sustainability aspect →
Number 4 represents the second suitable option from environmental view →
Number 5 represents the most sustainable option with the lowest impact value →

Table 5
Heatmap table for all cases and scenarios based on the endpoint method.

IC	Case 1	Case 2 (3 years)	Case 3 (3 years)	Case 1	Case 2 (5 years)	Case 3 (5 years)	Case 1	Case 2 (10 years)	Case 3 (10 years)	Case 1	Case 2 (15 years)	Case 3 (15 years)
Eco	5	4	3	5	3	4	3	4	5	3	4	5
HH	5	3	2	5	3	2	5	3	2	5	4	3
Res	5	2	1	5	2	1	5	2	1	5	2	1

Keys: Number 1 represents the least sustainable option with the highest impact value →
Number 2 represents it is far from sustainability criteria →
Number 3 represents the third option from sustainability aspect →
Number 4 represents the second suitable option from environmental view →
Number 5 represents the most sustainable option with the lowest impact value →

uncertainties demonstrate that the level of uncertainty for all cases falls within an acceptable range, staying under 12 %. It's also worth noting that the uncertainty results for resource-related impacts are slightly higher compared to other categories.

3.4. Comparing integrated cycles with stand-alone power cycles

The study compares the environmental impacts of integrated renewable power cycles with other LCA studies on stand-alone renewable power cycles. The combined power cycles have the benefit of enhancing the power capacity production compared with stand-alone systems. This heightened power capacity in combined renewable-based power cycles, in contrast to standalone cycles, arises from the synergistic integration of diverse renewable sources, and incorporation of the optimized utilization of resources. Combined power cycles frequently incorporate various renewable sources like solar and wind, capitalizing on their complementary attributes. This enables a more effective utilization of resources, thereby reducing the environmental impact linked to an excessive dependence on a single renewable technology. However, the applied material or consumed energy in the combined system may be higher than the stand-alone cycle which can increase the environmental impact of implemented material. However, it should be considered that the efficiency of the combined cycle is higher than a single system with less heat loss and more efficient performance. The enhanced efficiency leads to the generation of more energy using an equivalent amount of renewable resources, leading to a reduced environmental impact for each unit of electricity produced. In a combined cycle, where the workload on each component may be more uniformly distributed, it is possible to mitigate wear and tear on individual components. This has the potential to prolong their lifespan, thereby diminishing the environmental impact linked to various stages of the life cycle. Assessing whether a binary geothermal power plant or a flash geothermal power plant has a reduced environmental footprint requires an evaluation of multiple factors. While both types of

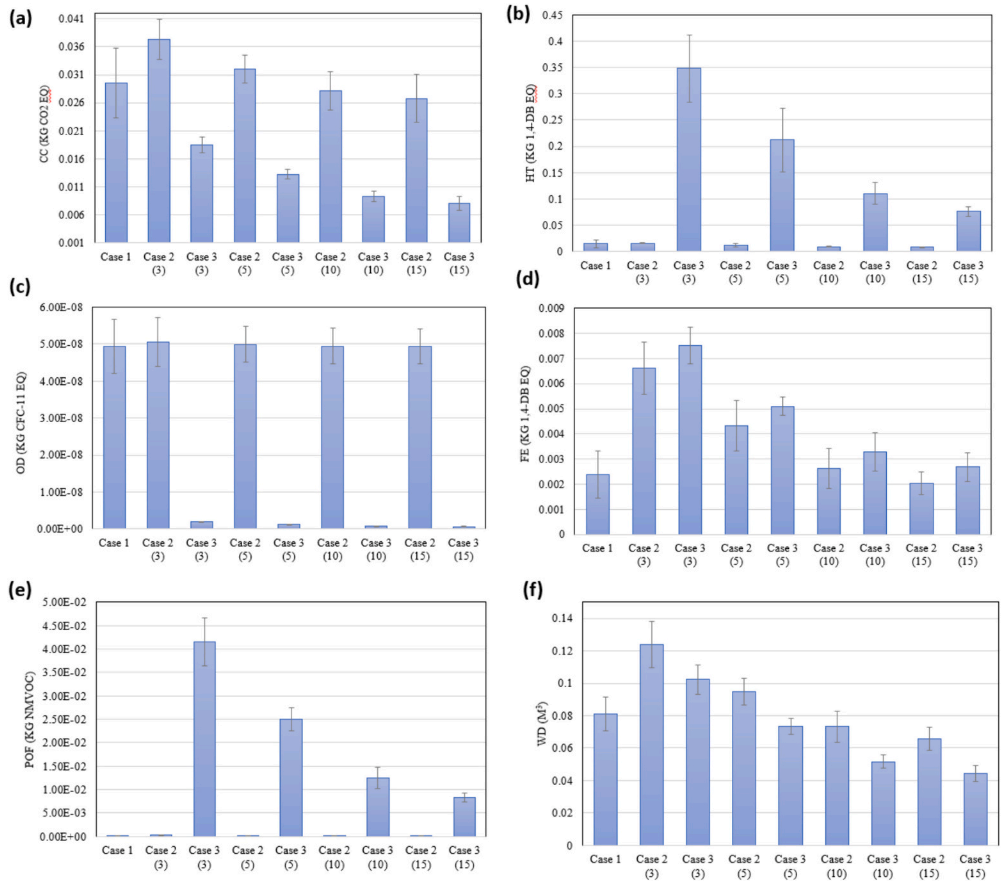


Fig. 11. Error bars for all cases and scenarios based on the midpoint method, (a) climate change, (b) human toxicity, (c) ozone depletion, (d) freshwater ecotoxicity, (e) photochemical oxidant formation, (f) water depletion.

geothermal power plants utilize Earth's heat for electricity generation, their operational processes vary. The environmental impact is contingent on aspects like resource utilization, water consumption, and emissions. That is why different geothermal technologies are compared with the studied one. It's important to emphasize that technological advancements and continuous research have the potential to impact the environmental efficiency of various geothermal power plant types. Furthermore, thorough environmental impact assessments should be carried out for each individual project, considering site-specific conditions and potential fluctuations in environmental effects. The results are presented in Table 6 and reveal that, in all scenarios, the CO_2 emissions per kilowatt-hour from a stand-alone geothermal power cycle are higher than those in both case 1 (combined geothermal-wind system) and case 2 (geothermal-PSC combined system). This study evaluates various geothermal technologies in comparison with the system under consideration, and the combined system demonstrates significant potential in terms of reducing environmental impacts. For solar PV systems, it becomes evident that by extending the PSC's lifetime up to 5 years, case 2 exhibits lower environmental impacts than two distinct stand-alone solar PV power systems. Among these stand-alone renewable power cycles, wind power units have the least impact compared to geothermal and solar PV. Consequently, the climate change impact of case 1 and case 3 (for over a 3-year lifetime) is higher than that of the aforementioned stand-alone wind turbine power cycle. However, with an extended PSC lifetime in case 3, reaching 10 years or more, its CO_2 emissions become significantly lower than those of a stand-alone wind power plant. Nevertheless, it's important to take into account that integrating more sustainable materials, advancing the incorporation of renewable energy into the energy mix, and adopting innovative technologies are key factors that can diminish the environmental impacts associated with each power cycle throughout its lifespan.

4. Discussion

Analysis indicated that geothermal well drilling is a significant contributor to environmental impacts across most categories. However, the O&M phase of geothermal plants primarily drives CC and OD impacts. The manufacturing phase of the PSC system is a major source of toxicity impacts due to materials such as lead. Additionally, the construction of wind power plants and the M&I phase of PSCs also significantly contribute to pollution. The base case analysis, based on a PSC lifetime of 3 years and an efficiency of 17 %, revealed that the environmental performance of the three cases varies across different impact categories. Case 3 has the lowest impact in the two critical categories (CC and OD), but higher impacts in other categories compared to the other two cases. Extending the PSC lifetime improves the environmental competitiveness of cases 2 and 3, resulting in lower negative impacts in many categories at a 15-year lifetime compared to case 1. However, toxicity impacts remain a contentious issue for cases 2 and 3. Using more sustainable materials instead of toxic ones like lead in PSC construction would significantly reduce impacts. The results demonstrated that increasing the PSC system's lifetime and efficiency substantially reduces impacts in most midpoint and endpoint categories. The reduction trend is more pronounced with lifetime extension than with efficiency improvement. Enhancing efficiency from 17 % to 35 % notably reduces environmental impacts, though the trend is less pronounced compared to lifetime extension. Nevertheless, efficiency remains a key factor in mitigating negative impacts in cases 2 and 3.

Optimal scenarios (with a 15-year lifetime and 35 % efficiency) and worst-case scenarios (with a 3-year lifetime and 17 % efficiency)

Table 6
Comparing the integrated cycle considered in this study with other power plant (both renewable and fossil fuels).

CC (kg CO2 eq/ kWh)	Parameter	CC (kg CO2 eq/ kWh)	Parameter	CC (kg CO2 eq/ kWh)	Parameter
0.02953	Case 1	0.0373	Case 2	0.02953	Case 1
0.01848	Case 3 (3 years)	0.01848	Case 3 (3 years)	0.0373	Case 2 (3 years)
0.01323	Case 3 (5 years)	0.03205	Case 2 (5 years)	0.03205	Case 2 (5 years)
0.00929	Case 3 (10 years)	0.00929	Case 3 (10 years)	0.02811	Case 2 (10 years)
0.00798	Case 3 (15 years)	0.0268	Case 2 (15 years)	0.0268	Case 2 (15 years)
0.0286	Wind (Demir and Taşkın, 2013)	0.0312	Solar PV (Gasa et al., 2022)	0.48	Geo (Basosi et al., 2020)
0.012	Wind (Basosi et al., 2020)	0.025	Solar PV (Basosi et al., 2020)	0.248	Geo (Buonocore et al., 2015)
0.459	Natural gas combined cycle power plant (Singh et al., 2011)	0.459	Natural gas combined cycle power plant (Singh et al., 2011)	0.053	Geo (Frick et al., 2010)
0.167	Natural gas combined cycle power plant with carbon capture (Singh et al., 2011)	0.167		0.459	Natural gas combined cycle power plant (Singh et al., 2011)
0.09	Solar based combined thermal and gas plant (Ozturk and Dincer, 2019)	0.09	Natural gas combined cycle power plant with carbon capture (Singh et al., 2011)	0.167	Natural gas combined cycle power plant with carbon capture (Singh et al., 2011)
			Solar based combined thermal and gas plant (Ozturk and Dincer, 2019)	0.09	Solar based combined thermal and gas plant (Ozturk and Dincer, 2019)

exhibited significant differences in endpoint impact categories. The greatest reductions were observed in ecosystem and human health impacts, with around a 78 % reduction in the best-case scenario for case 2 compared to the worst case. Similar significant reductions were noted for case 3. The assessments underscored the importance of the materials used in ICs. Additionally, the efficiency and lifetime of PSC technology significantly affect the reduction of most impact categories, except for those related to toxicity. For categories where material usage is the primary source of pollution, improving efficiency and lifetime is less effective in reducing ecological impacts.

5. Conclusion

This study considers various cases and scenarios to comprehensively examine how the advancement of technologies might impact the environmental performance of the cycles under investigation. The considered cases are case 1: combined geothermal & wind, case 2: combined geothermal & solar, case 3: combined wind & solar; and the scenarios modelled are PSC lifespan (3 years, 5 years, 10 years, 15 years), PSC efficiency (17 %, 20 %, 25 %, 30 %, 35 %), best and worst-case scenarios, and comparison between integrated vs. stand-alone systems. Base case evaluation results showed that geothermal well drilling and wind plant construction are the most significant contributors in most ICs in case 1, respectively. Also, the impact of constructing geothermal plants is considerably lower compared to others. In the context of case 2, the findings revealed that the phases with significant impacts are geothermal well drilling, PSC manufacturing, and the production of M&I parts. Particularly, PSC manufacturing has a substantial adverse environmental effect in five categories (MU, MD, PMF, POF, and TE), underscoring the system's toxicity issue. Additionally, the MD is another significant outcome of the PSC system, primarily associated with the use of zinc in the electron-transport layer, silver in the back electrode, and ITO in the substrate. Nonetheless, the M&I phase is also a notable contributor to the detrimental effects of the PSC power cycle, with the largest proportion of this impact being attributed to ME, accounting for roughly 58 % of the total impact and mainly due to aluminium and steel applied. Case 3 results showed that the environmental impact of the solar PV unit in all ICs is higher than the wind turbine power cycle. The values of six ICs (HT, ME, MU, PMF, PO, and TE) caused around 90 % of the total impact arising from the PSC manufacturing process.

Increasing both the lifetime and efficiency of PSCs significantly reduces environmental impact in cases 2 and 3. However, efficiency increment is not as effective as lifetime development. Evaluating the worst and best-case scenarios illustrates a huge decline in ICs values in both midpoint and endpoint results for both integrated systems including PSC. The highest impact decline for case 3 happened in TE, POF, HT, ME, and MU in order which showed a more than 88 % reduction compared with worst-case results. Also, the least diminish of case 3 is in FEU which is 48 % and after that, the lowest decrement is related to ULO and TA which are around 59 %. However, in case 2, the highest and lowest impact reduction occurred in PMF and OD respectively. The highest difference in impact diminish is relevant to OD which is around 71 %. The OD impact in case 2 is mainly because of the geothermal system.

The findings from this study suggest that PSC technology has the capability to enhance the environmental sustainability of integrated renewable power plants. Further technical enhancements, such as improving system longevity and efficiency, could amplify the benefits of this technology upon commercialization. An encouraging potential action might involve substituting the existing pollutants employed in PSC manufacturing with materials characterized by reduced carbon emissions, lower toxicity, and fewer resource scarcity concerns. There are some limitations in doing this kind of prospective LCA. The main obstacle lies in the limited availability of comprehensive data for all systems, particularly for PSC due to the scarcity of data from literature and laboratory studies, which often pertain to small-scale projects. The environmental effects of renewable energy technologies depend on geographical location, but obtaining comprehensive data for a specific area is challenging. Future research can explore the technological feasibility of integrating systems and their environmental impacts on combined system performance geo-spatially.

CRediT authorship contribution statement

Moein Shamoushaki: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **S.C. Lenny Koh:** Writing – review & editing, Visualization, Supervision, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We have shared applied data in supplementary file.

Acknowledgements

The authors acknowledge support from UKRI, Research England, Energy Institute and AREC on the Supply Chain Innovation research in the South Yorkshire Sustainability Centre.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.174239.

References

Afshari, H., Ehyaei, M.A., Esmaeilion, F., Shamoushaki, M., Farhadnia, M., Rosen, M.A., 2022. Assessment of a novel geothermal powered polygeneration system with zero liquid discharge. Energy Sci. Eng. 10, 3819–3838.
Ahmed, S.F., Islam, N., Kumar, P.S., Hoang, A.T., Mofijur, M., Inayat, A., et al., 2023. Perovskite solar cells: thermal and chemical stability improvement, and economic analysis. Mater. Today Chem. 27, 101284.
Alhaj, M., Tahir, F., Al-Ghamdi, S.G., 2022. Life-cycle environmental assessment of solar-driven Multi-Effect Desalination (MED) plant. Desalination 524, 115451.
Ameri, M., Mohammadzadeh, M., 2018. Thermodynamic, thermoeconomic and life cycle assessment of a novel integrated solar combined cycle (ISCC) power plant. Sustain. Energy Technol. Assess. 27, 192–205.
Ancona, M.A., Bianchi, M., Branchini, L., De Pascale, A., Melino, F., Peretto, A., 2015. Thermodynamic evaluation of repowering options for a small-size combined cycle with concentrating solar power technology. Energy Procedia 82, 584–590.
Angelakoglou, K., Botsaris, P.N., Gaidajis, G., 2014. Issues regarding wind turbines positioning: a benchmark study with the application of the life cycle assessment approach. Sustain. Energy Technol. Assess. 5, 7–18.
Ansanelli, G., Fiorentino, G., Tammaro, M., Zucaro, A., 2021. A life cycle assessment of a recovery process from end-of-life photovoltaic panels. Appl. Energy 290, 116727.
Arvanitoyannis, I.S., 2008. ISO 14040: life cycle assessment (LCA)–principles and guidelines. In: Waste Management for the Food Industries, pp. 97–132.
Babayigit, A., Ethirajan, A., Muller, M., Conings, B., 2016. Toxicity of organometal halide perovskite solar cells. Nat. Mater. 15, 247–251.
Backes, J.G., D'Amico, A., Pauliks, N., Guarino, S., Traverso, M., Lo Brano, V., 2021. Life cycle sustainability assessment of a dish-stirling concentrating solar power plant in the Mediterranean area. Sustain. Energy Technol. Assess. 47, 101444.
Basosi, R., Bonciani, R., Frosali, D., Manfrida, G., Parisi, M.L., Sansone, F., 2020. Life cycle analysis of a geothermal power plant: comparison of the environmental performance with other renewable energy systems. Sustainability 12, 2786.
Buonocore, E., Vanoli, L., Carotenuto, A., Ulgiati, S., 2015. Integrating life cycle assessment and emergy synthesis for the evaluation of a dry steam geothermal power plant in Italy. Energy 86, 476–487.
Cannavale, A., Ierardi, L., Hörantner, M., Eperon, G.E., Snaith, H.J., Ayr, U., et al., 2017. Improving energy and visual performance in offices using building integrated perovskite-based solar cells: a case study in Southern Italy. Appl. Energy 205, 834–846.
Cao, Y., Kasaeian, M., Abbasspoor, H., Shamoushaki, M., Ehyaei, M.A., Abanades, S., 2022. Energy, exergy, and economic analyses of a novel biomass-based multigeneration system integrated with multi-effect distillation, electrodialysis, and LNG tank. Desalination 526, 115550.
Cook, D., Sigurjónsson, H.Æ., Davíðsdóttir, B., Bogason, S.G., 2022. An environmental life cycle cost assessment of the costs of deep enhanced geothermal systems – the case studies of Reykjanes, Iceland and Vendenheim, France. Geothermics 103, 102425.
Costa, M., Piazzullo, D., Di Battista, D., De Vita, A., 2022. Sustainability assessment of the whole biomass-to-energy chain of a combined heat and power plant based on biomass gasification: biomass supply chain management and life cycle assessment. J. Environ. Manag. 317, 115434.
Cucchiella, F., D'Adamo, I., Lenny Koh, S.C., 2015. Environmental and economic analysis of building integrated photovoltaic systems in Italian regions. J. Clean. Prod. 98, 241–252.
Das, U., Nandi, C., 2022. Life cycle assessment on onshore wind farm: an evaluation of wind generators in India. Sustain. Energy Technol. Assess. 53, 102647.
DeLovato, N., Sundarnath, K., Cvijovic, L., Kota, K., Kuravi, S., 2019. A review of heat recovery applications for solar and geothermal power plants. Renew. Sust. Energ. Rev. 114, 109329.
Demir, N., Taşkın, A., 2013. Life cycle assessment of wind turbines in Pınarbaşı-Kayseri. J. Clean. Prod. 54, 253–263.
Di Florio, G., Macchi, E.G., Mongibello, L., Baratto, M.C., Basosi, R., Busi, E., et al., 2021. Comparative life cycle assessment of two different SOFC-based cogeneration systems with thermal energy storage integrated into a single-family house nanogrid. Appl. Energy 285, 116378.
Ding, G., Zheng, Y., Xiao, X., Cheng, H., Zhang, G., Shi, Y., et al., 2022. Sustainable development of perovskite solar cells: keeping a balance between toxicity and efficiency. J. Mater. Chem. A 10, 8159–8171.
Dong, Z., Ye, X., Jiang, J., Li, C., 2022. Life cycle assessment of coal-fired solar-assisted carbon capture power generation system integrated with organic Rankine cycle. J. Clean. Prod. 356, 131888.
Ehyaei, M.A., Ahmadi, A., Rosen, M.A., 2019. Energy, exergy, economic and advanced and extended exergy analyses of a wind turbine. Energy Convers. Manag. 183, 369–381.
Famiglietti, J., Toppi, T., Pistocchini, L., Scoccia, R., Motta, M., 2021. A comparative environmental life cycle assessment between a condensing boiler and a gas driven absorption heat pump. Sci. Total Environ. 762, 144392.
Fan, Y., Meng, J., Ye, H., Wang, P., Wang, Y., Wang, Y., 2021. Sustainability and ecological efficiency of low-carbon power system: a concentrating solar power plant in China. J. Environ. Manag. 290, 112659.
Fiaschi, D., Manfrida, G., Mendecka, B., Shamoushaki, M., Talluri, L., 2021. Exergy and Exergo-Environmental analysis of an ORC for a geothermal application. In: E3S Web of Conferences. 238. EDP Sciences, p. 01011.
Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., Klüppel, H.-J., 2006. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. Int. J. Life Cycle Assess. 11, 80–85.
Frick, S., Kaltschmitt, M., Schröder, G., 2010. Life cycle assessment of geothermal binary power plants using enhanced low-temperature reservoirs. Energy 35, 2281–2294.
Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Dones, R., Heck, T., et al., 2005. The ecoinvent database: overview and methodological framework (7 pp). Int. J. Life Cycle Assess. 10, 3–9.
Gasa, G., Prieto, C., Lopez-Roman, A., Cabeza, L.F., 2022. Life cycle assessment (LCA) of a concentrating solar power (CSP) plant in tower configuration with different storage capacity in molten salts. J. Energy Storage 53, 105219.
Gkousis, S., Thomassen, G., Welkenhuysen, K., Compernolle, T., 2022. Dynamic life cycle assessment of geothermal heat production from medium enthalpy hydrothermal resources. Appl. Energy 328, 120176.
Gong, J., Darling, S.B., You, F., 2015. Perovskite photovoltaics: life-cycle assessment of energy and environmental impacts. Energy Environ. Sci. 8, 1953–1968.
Guillén-Lambea, S., Sierra-Pérez, J., García-Pérez, S., Montealegre, A., Monzón-Chavarrías, M., 2023. Energy Self-Sufficiency Urban Module (ESSUM): GIS-LCA-based multi-criteria methodology to analyze the urban potential of solar energy generation and its environmental implications. Sci. Total Environ. 879, 163077.
Havukainen, J., Nguyen, M.T., Väisänen, S., Horttanainen, M., 2018. Life cycle assessment of small-scale combined heat and power plant: environmental impacts of different forest biofuels and replacing district heat produced from natural gas. J. Clean. Prod. 172, 837–846.
Heberle, F., Schifflechner, C., Brüggemann, D., 2016. Life cycle assessment of Organic Rankine Cycles for geothermal power generation considering low-GWP working fluids. Geothermics 64, 392–400.
Ibn-Mohammed, T., Koh, S.C.L., Reaney, I.M., Acquaye, A., Schileo, G., Mustapha, K.B., et al., 2017. Perovskite solar cells: an integrated hybrid lifecycle assessment and review in comparison with other photovoltaic technologies. Renew. Sust. Energ. Rev. 80, 1321–1344.
Jiang, P., Bai, H., Xu, Q., Arsalanloo, A., 2023. Thermodynamic, exergoeconomic, and economic analyses with multi-objective optimization of a novel liquid air energy storage coupled with an off-shore wind farm. Sustain. Cities Soc. 90, 104353.
Karlsdottir, M.R., Heinonen, J., Palsson, H., Palsson, O.P., 2020. Life cycle assessment of a geothermal combined heat and power plant based on high temperature utilization. Geothermics 84, 101727.
Kimming, M., Sundberg, C., Nordberg, Å., Baky, A., Bernesson, S., Norén, O., et al., 2011. Biomass from agriculture in small-scale combined heat and power plants – a comparative life cycle assessment. Biomass Bioenergy 35, 1572–1581.
Kjeld, A., Bjarnadottir, H.J., Olafsdottir, R., 2022. Life cycle assessment of the Theistareykir geothermal power plant in Iceland. Geothermics 105, 102530.
Kumar, M., Khan, S.Y., Liu, S., Ji, W., Shen, Y., Sohrabi, A., et al., 2024. Scientific mapping and data analysis of the research landscape in perovskite solar cell technology. Sol. Energy 273, 112509.
Li, Q., Monticelli, C., Zanelli, A., 2022. Life cycle assessment of organic solar cells and perovskite solar cells with graphene transparent electrodes. Renew. Energy 195, 906–917.
Łukasiewicz, E., Shamoushaki, M., 2022. Heating potential of undeveloped geothermal water intakes in Poland in the context of sustainable development and air protection. Water Resour. Ind. 27, 100175.
Martín-Gamboa, M., Iribarren, D., Dufour, J., 2018. Environmental impact efficiency of natural gas combined cycle power plants: a combined life cycle assessment and dynamic data envelopment analysis approach. Sci. Total Environ. 615, 29–37.
Martin-Gorriz, B., Maestre-Valero, J.F., Gallego-Elvira, B., Marín-Membrive, P., Terrero, P., Martínez-Alvarez, V., 2021. Recycling drainage effluents using reverse osmosis powered by photovoltaic solar energy in hydroponic tomato production: environmental footprint analysis. J. Environ. Manag. 297, 113326.
Mayer, F., Bhandari, R., Gäth, S., 2019. Critical review on life cycle assessment of conventional and innovative waste-to-energy technologies. Sci. Total Environ. 672, 708–721.
McCay, A.T., Feliks, M.E.J., Roberts, J.J., 2019. Life cycle assessment of the carbon intensity of deep geothermal heat systems: a case study from Scotland. Sci. Total Environ. 685, 208–219.
Mello, G., Ferreira Dias, M., Robaina, M., 2020. Wind farms life cycle assessment review: CO2 emissions and climate change. Energy Rep. 6, 214–219.
Menoufi, K., Chemisana, D., Rosell, J.I., 2013. Life cycle assessment of a building integrated concentrated photovoltaic scheme. Appl. Energy 111, 505–514.

Monteiro Lunardi, M., Wing Yi Ho-Baillie, A., Alvarez-Gaitan, J.P., Moore, S., Corkish, R., 2017. A life cycle assessment of perovskite/silicon tandem solar cells. Prog. Photovolt. Res. Appl. 25, 679–695.

Nease, J., Adams, T.A., 2015. Comparative life cycle analyses of bulk-scale coal-fueled solid oxide fuel cell power plants. Appl. Energy 150, 161–175.

Nguyen, T.K.L., Ngo, H.H., Guo, W.S., Chang, S.W., Nguyen, D.D., Nghiem, L.D., et al., 2020. A critical review on life cycle assessment and plant-wide models towards emission control strategies for greenhouse gas from wastewater treatment plants. J. Environ. Manag. 264, 110440.

Okoroafor, T., Maalouf, A., Oez, S., Babu, V., Wilk, B., Resalati, S., 2022. Life cycle assessment of inkjet printed perovskite solar cells. J. Clean. Prod. 373, 133665.

OpenLCA. https://www.openlca.org/. GreenDelta, GmbH, Berlin, Germany.

Ozturk, M., Dincer, I., 2019. Comparative environmental impact assessment of various fuels and solar heat for a combined cycle. Int. J. Hydrog. Energy 44, 5043–5053.

Parisi, M.L., Ferrara, N., Torsello, L., Basosi, R., 2019. Life cycle assessment of atmospheric emission profiles of the Italian geothermal power plants. J. Clean. Prod. 234, 881–894.

Piemonte, V., Falco, M.D., Tarquini, P., Giaconia, A., 2011. Life Cycle Assessment of a high temperature molten salt concentrated solar power plant. Sol. Energy 85, 1101–1108.

Qiu, C., Wu, Y., Song, J., Wang, W., Li, Z., 2022. Efficient planar perovskite solar cells with ZnO electron transport layer. Coatings 12, 1981.

Rabaia, M.K.H., Abdelkareem, M.A., Sayed, E.T., Elsaid, K., Chae, K.-J., Wilberforce, T., et al., 2021. Environmental impacts of solar energy systems: a review. Sci. Total Environ. 754, 141989.

Ramamurthy Rao, H.K., Gemechu, E., Thakur, U., Shankar, K., Kumar, A., 2021. Life cycle assessment of high-performance monocrystalline titanium dioxide nanorod-based perovskite solar cells. Sol. Energy Mater. Sol. Cells 230, 111288.

Rao, H.K.R., Gemechu, E., Thakur, U., Shankar, K., Kumar, A., 2021. Life cycle assessment of high-performance monocrystalline titanium dioxide nanorod-based perovskite solar cells. Sol. Energy Mater. Sol. Cells 230, 111288.

Ren, M., Qian, X., Chen, Y., Wang, T., Zhao, Y., 2022. Potential lead toxicity and leakage issues on lead halide perovskite photovoltaics. J. Hazard. Mater. 426, 127848.

Schakel, W., Meerman, H., Talaei, A., Ramírez, A., Faaij, A., 2014. Comparative life cycle assessment of biomass co-firing plants with carbon capture and storage. Appl. Energy 131, 441–467.

Shamoushaki, M., Koh, S.L., 2023. Heat pump supply chain environmental impact reduction to improve the UK energy sustainability, resiliency and security. Sci. Rep. 13, 20633.

Shamoushaki, M., Aliehyaei, M., Taghizadeh-Hesary, F., 2021. Energy, exergy, exergoeconomic, and exergoenvironmental assessment of flash-binary geothermal combined cooling, heating and power cycle. Energies 14, 4464.

Shamoushaki, M., Fiaschi, D., Manfrida, G., Talluri, L., 2022. Energy, exergy, economic and environmental (4E) analyses of a geothermal power plant with NCGs reinjection. Energy 244, 122678.

Singh, B., Strømman, A.H., Hertwich, E., 2011. Life cycle assessment of natural gas combined cycle power plant with post-combustion carbon capture, transport and storage. Int. J. Greenh. Gas Control 5, 457–466.

Smith, L., Ibn-Mohammed, T., Koh, S.C.L., Reaney, I.M., 2018. Life cycle assessment and environmental profile evaluations of high volumetric efficiency capacitors. Appl. Energy 220, 496–513.

Smith, L., Ibn-Mohammed, T., Yang, F., Reaney, I.M., Sinclair, D.C., Koh, S.C.L., 2019. Comparative environmental profile assessments of commercial and novel material structures for solid oxide fuel cells. Appl. Energy 235, 1300–1313.

Smith, L., Ali, M., Agrissais, M., Mulligan, S., Koh, L., Martin, N., 2023. A comparative life cycle assessment of dental restorative materials. Dent. Mater. 39, 13–24.

Standardization IOf, 2006. Environmental Management: Life Cycle Assessment; Principles and Framework: ISO.

Steubing, B., Wernet, G., Reinhard, J., Bauer, C., Moreno-Ruiz, E., 2016. The ecoinvent database version 3 (part II): analyzing LCA results and comparison to version 2. Int. J. Life Cycle Assess. 21, 1269–1281.

Vélez-Henao, J.-A., Vivanco, D.F., 2021. Hybrid life cycle assessment of an onshore wind farm including direct and indirect services: a case study in Guajira, Colombia. J. Environ. Manag. 284, 112058.

Wang, Y., Sun, T., 2012. Life cycle assessment of CO2 emissions from wind power plants: methodology and case studies. Renew. Energy 43, 30–36.

Wang, J., Lu, Y., Yang, Y., Mao, T., 2016. Thermodynamic performance analysis and optimization of a solar-assisted combined cooling, heating and power system. Energy 115, 49–59.

Wang, L., Wang, Y., Du, H., Zuo, J., Yi Man Li, R., Zhou, Z., et al., 2019. A comparative life-cycle assessment of hydro-, nuclear and wind power: a China study. Appl. Energy 249, 37–45.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230.

Wu, C., Zhang, X.-P., Sterling, M., 2022a. Solar power generation intermittency and aggregation. Sci. Rep. 12, 1363.

Wu, Y., Song, J., Wu, X., Qiu, C., Yin, X., Hu, L., et al., 2022b. Highly efficient and stable ZnO-based perovskite solar cells enabled by a self-assembled monolayer as the interface linker. Chem. Commun. 58, 9266–9269.

Xia, Z.H., Jia, G.S., Ma, Z.D., Wang, J.W., Zhang, Y.P., Jin, L.W., 2021. Analysis of economy, thermal efficiency and environmental impact of geothermal heating system based on life cycle assessments. Appl. Energy 303, 117671.

Xu, L., Pang, M., Zhang, L., Poganietz, W.-R., Marathe, S.D., 2018. Life cycle assessment of onshore wind power systems in China. Resour. Conserv. Recycl. 132, 361–368.

Ye, H., Peng, H., Li, C., Li, Y., Li, Z., Yang, Q., et al., 2023. A demonstration concentrating solar power plant in China: carbon neutrality, energy renewability and policy perspectives. J. Environ. Manag. 328, 117003.

Yilmaz, F., Ozturk, M., Selbas, R., 2020. Thermodynamic investigation of a concentrating solar collector based combined plant for poly-generation. Int. J. Hydrog. Energy 45, 26138–26155.

Yue, Z., Guo, H., Cheng, Y., 2023. Toxicity of perovskite solar cells. Energies 16, 4007.

Zahid Gill, E., Abdul Hussain Ratlamwala, T., Waseem, S., Hussain, G., Alkahtani, M., Altaf, K., 2021. Life cycle assessment and feasibility study of solar based multi-generation system. Sustain. Energy Technol. Assess. 47, 101321.

Zhang, J., Gao, X., Deng, Y., Zha, Y., Yuan, C., 2017. Comparison of life cycle environmental impacts of different perovskite solar cell systems. Sol. Energy Mater. Sol. Cells 166, 9–17.

Zhang, J., Ling, B., He, Y., Zhu, Y., Wang, Z., 2022. Life cycle assessment of three types of hydrogen production methods using solar energy. Int. J. Hydrog. Energy 47, 14158–14168.

Zuffi, C., Manfrida, G., Asdrubali, F., Talluri, L., 2022. Life cycle assessment of geothermal power plants: a comparison with other energy conversion technologies. Geothermics 104, 102434.