Article:

Shamoushaki, M. orcid.org/0000-0002-4176-9639 and Koh, S.C.L. (2024) Solar cells combined with geothermal or wind power systems reduces climate and environmental impact. Communications Earth & Environment, 5 (1). 572. ISSN 2662-4435

https://doi.org/10.1038/s43247-024-01739-3 communications earth & environment | Article

https://doi.org/10.1038/s43247-024-01739-3

Solar cells combined with geothermal or wind power systems reduces climate and environmental impact

Check for updates

Moein Shamoushaki[1,2] ✉ & S. C. Lenny Koh[1,2] ✉

This research investigates the environmental sustainability of three integrated power cycles: combined geothermal-wind, combined solar-geothermal, and combined solar-wind. Here, a promising solar technology, the perovskite solar cell, is considered and analysed in conjunction with another renewable-based cycle, evaluating 17 scenarios focusing on improving the efficiency and lifespan. Among the base cases, combined solar-wind had the lowest ozone depletion impact, while combined geothermal-wind had the lowest freshwater ecotoxicity and marine ecotoxicity impacts. The study shows that extending the perovskite solar cell lifespan from 3 to 15 years reduces CO_2 emissions by 28% for the combined solar-geothermal and 56% for the combined solar-wind scenario. The most sustainable cases in ozone depletion, marine ecotoxicity, freshwater ecotoxicity, and climate change impacts are combined solar-wind, combined solar-geothermal, and combined geothermal-wind, respectively, among all evaluated scenarios. This research suggests investing in the best mix of integrated power cycles using established and emerging renewable technologies for maximum environmental sustainability.

On a worldwide scale, the growing body of evidence and broader international awareness regarding the impact of climate change highlight the imperative to address and reduce atmospheric CO_2 levels[1]. According to recent research, there is a projected 50% increase in the release of greenhouse gases (GHGs) by 2050, making it the predominant contributing factor to climate change[2]. As the population grows, both the demand for energy and its consumption will rise in tandem, necessitating a focus on electricity provision and the transition to decarbonized heating and cooling systems[3]. In 2010, greenhouse gas emissions from the production of electricity and heat made up 25% of the total global emissions[4], and by 2019, this proportion had increased to around 34%[5]. Of the multiple factors contributing to climate change, the overabundant release of greenhouse gases poses notable threats to both environmental equilibrium and human well-being[6]. To meet global targets for diminishing emissions, policymakers and stakeholders are exploring measures beyond simply avoiding carbon dioxide emissions. Aside from GHGs, sustainability assessments should also consider other forms of pollution, such as toxicity, ecotoxicity, ozone depletion, acidification, ionizing radiation and more, which can arise from energy generation and warrant thorough evaluation[7]. These multi-criteria effects may stem from the materials used in the manufacturing and operating the technologies which should be considered in the assessments. These measures include the substitution of fossil fuels with renewable alternatives and the implementation of efficiency enhancements[8]. By integrating various criteria into our analysis, our goal is to offer a comprehensive grasp of the environmental impacts of energy generation, aiding informed decision-making and the formulation of sustainable energy strategies. The heightened demand for advancements in environmental indices (e.g. carbon footprint and air quality index), increased energy efficiency, and the promotion of energy security has drawn considerable focus towards emerging technologies[9]. Creating applications for renewable energy sources is valuable and strategically important in achieving various energy goals in Europe, such as ensuring a secure energy supply and mitigating greenhouse gas emissions[10]. Meeting the global goal of achieving net-zero carbon emissions by 2050 necessitates notable expansion of renewable energy production[11]. To date, limited studies consider the environmental sustainability of integrated renewable power plants, despite concerted efforts to improve and innovate the energy production technology individually. The integration of various renewable resources into a cohesive system of power generation signifies a promising advancement in energy innovation. This approach, combining multiple renewable sources within a unified structure, enhances the dependability (ensuring a reliable and consistent power supply), effectiveness, and adaptability of the energy grid.

This study evaluates three integrated renewable-based power plants from environmental impact consequences. The implemented renewable

[1]Sheffield University Management School, The University of Sheffield, Sheffield, S10 1FL, United Kingdom. [2]Energy Institute, The University of Sheffield, Sheffield, S10 2TN, United Kingdom. ✉e-mail: m.shamoushaki@sheffield.ac.uk; s.c.l.koh@sheffield.ac.uk

resources are geothermal, solar and wind. Three considered case studies are: (Case I) combined geothermal-wind (CGW), (Case II) combined solar-geothermal (CSG), and (Case III) combined solar-wind (CSW) cycles. These combined systems provide numerous remarkable advantages. Initially, they improve the dependability and steadiness of energy generation by capitalising on the complementary characteristics of different renewable sources. For example, if one source encounters fluctuations or downtime, others can compensate, ensuring a more uniform power supply. Secondly, the integration of multiple sources can optimise land usage and infrastructure, enhancing efficiency and cutting overall expenses. Furthermore, such integration promotes energy diversification, lessening dependence on any single energy source and bolstering energy security. Lastly, from a service standpoint, integrated renewable power plants offer flexibility in meeting diverse energy demands and grid requirements, thereby delivering more customised and dependable services to consumers. Additionally, the investigation includes the evaluation of a recently introduced solar technology called perovskite solar cell (PSC), which is currently in its early developmental stages and undergoing laboratory-scale experiments. This system is being considered for its remarkable efficiency enhancement within a brief timeframe, experiencing a surge from 3.8% to 25% in a decade[12]. Enhancing the stability of the system stands out as the paramount factor for achieving successful commercialisation of PSC technology in the foreseeable future which directly influences the environmental evaluations. Moreover, certain elements utilised in PSCs manufacturing, like lead, prompt worries regarding their potential environmental and health repercussions[13]. PSCs can be manufactured on flexible substrates, enabling the creation of lightweight and bendable solar panels ideal for curved surfaces or mobile devices. Conversely, conventional silicon-based solar panels are inflexible and not as versatile for diverse installation requirements. However shorter lifetime of PSC system compared to conventional solar panels may cause some challenges. From an economic standpoint, the necessity for more frequent replacements or maintenance could raise ownership expenses and influence the appeal of PSCs for investors and consumers. Moreover, shortened lifespans might disrupt the energy payback time of PSCs, diminishing overall energy efficiency and sustainability.

Some thermodynamic and economic studies are done on standalone geothermal[14,15], solar[16,17] and wind[18,19] power plants. Many researchers have focused on technical and thermodynamic assessments of combined geothermal[20,21], solar[22,23], and wind[24,25] power cycles. Other researchers have done Life Cycle Assessment (LCA) evaluation of standalone geothermal[26–28], solar (including concentrated-solar power, photovoltaics and PSCs)[29–33], and wind[34,35]. Research on the environmental effects of combining two renewable power cycles is limited. Assessing each technology's sustainability before commercialization is crucial. This study emphasizes the importance of exploring synergies between renewable technologies and offers insights into how integrated systems can mitigate climate change and reduce fossil fuel use.

Our primary goal in focusing on PSC technology is to explore the environmental impacts of emerging renewable energy technologies, particularly perovskite solar cells, which are a rapidly advancing field. We aim to thoroughly evaluate their potential environmental effects and compare them with those of existing renewable energy systems. Moreover, considering the dynamic nature of perovskite research and its potential to transform the solar industry, we deemed it essential to evaluate its environmental performance within the framework of integrated renewable power plants. Nonetheless, we recognize the significance of including a wider array of technologies in future studies to offer a more comprehensive understanding of the environmental implications associated with renewable energy systems.

Unlike previous studies that focus on individual renewable technologies or their integration with fossil fuels, this research explores the environmental impacts of combining two renewable energy systems using a life cycle assessment approach. This study addresses the lack of detailed evaluations on the environmental viability of systems integrating two renewable energy sources, a gap noted in previous research. By analysing three configurations, it provides a thorough assessment of the benefits and trade-offs of combining multiple renewables, offering insights into optimizing energy generation and reducing environmental impacts through strategic technology integration. Furthermore, by including perovskite solar cells, an emerging and rapidly evolving technology, the study contributes to the growing body of knowledge on the environmental sustainability of cutting-edge renewable energy solutions. To the best of our knowledge, this study represents a novel exploration as it investigates the environmental impact of integrating PSCs with another renewable-based power plant, an aspect that has not been previously examined. Overall, the study represents a considerable step towards understanding the complex interactions between different renewable energy technologies and their implications for achieving sustainable energy systems. The study includes a sensitivity analysis to evaluate how extending the PSC system's lifespan and improving efficiency impact its integration with other power cycles. Initial calculations use a 3-year PSC lifespan, with further analysis comparing the effects of a longer lifespan and other technologies. A scoring method is used to visually compare the environmental performance of all scenarios, as shown in Fig. 1.

The study reveals that the B3 scenario shows the lowest CC and OD impacts, while B1 demonstrates the lowest FE and ME impacts among the base scenarios. Enhancing the lifespan of PSCs greatly minimizes environmental impacts, with the most significant reductions occurring with lifespan extensions. For example, extending the PSC lifespan from 3 to 15 years in the CSW scenario results in a 56% decrease in greenhouse gas emissions. Furthermore, improving PSC efficiency yields significant emissions reductions, with a 37% decrease observed in the CSW scenario when efficiency is increased from 17% to 35%. Combining renewable energy technologies such as solar and wind in a single power plant presents technical difficulties, mainly because of the intermittency and variability of these energy sources, which can cause grid instability. Furthermore, the dependence on critical materials and minerals for these technologies introduces risks associated with supply chain vulnerabilities, environmental sustainability, and geopolitical issues.

Considered cases and scenarios

Three base scenarios, denoted as B1, B2, and B3, depict integrated systems with a PSC lifespan of 3 years and an efficiency of 17%. These base cases evaluate CSG and CSW power plants based on the current state of PSC technology. Conversely, scenarios labelled with the letter 'L' are envisioned to reflect the future development of the PSC lifespan, representing a forecasting assessment with an assumed extension of the lifespan from 3 to 15 years. The study's assumptions hinge on anticipated technological advancements in the future. A reduced lifespan of PSC systems may contribute to an increase in environmental impact. Continued technological progress in this area is expected to enhance the competitiveness of these systems relative to conventional solar systems in the years ahead. In addition, eight scenarios labelled with the letter 'E' explore the potential impact of PSC technological advancement by increasing its efficiency from 17% to 35%. These 17 scenarios are developed and compared to assess the corresponding environmental impacts over the integrated systems' lifespan. The geothermal system is assumed to be a binary plant, with data derived from an average European geothermal case study. The geothermal unit being evaluated possesses a power capacity of 5 MW, while the PSC unit is designed to produce 0.42 kW of power. The Vestas 3 MW wind turbine is chosen as the benchmark in this study due to its widespread use and the availability of data. It should be mentioned that the optimal application of 3 MW wind turbines is typically within onshore wind power systems. The lower capacity of the PSC unit is intentional and reflects its role in the energy system. PSCs are designed for space-constrained or modular applications, often in distributed systems or integrated into buildings, which limits their scale compared to larger geothermal plants and wind farms. The PSC unit complements these larger sources, contributing to a more flexible and resilient energy system by operating at an optimal scale for its intended use. Because the PSC unit has a lower capacity, directly comparing it with the significantly larger capacities of wind and geothermal units may result in an

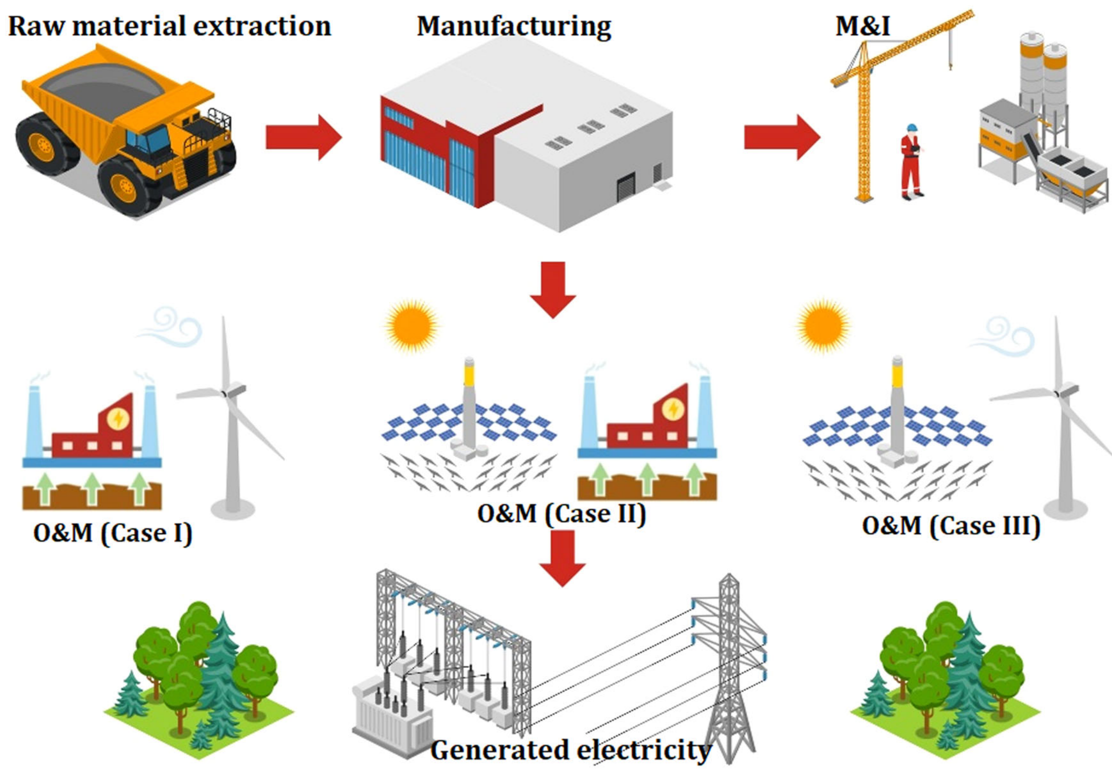

Fig. 1 | Considered life cycle phases of studied integrated cycles. This chart shows different life cycle phases of three combined renewable-based power cycles. Case I is combined geothermal-wind, Case II is combined solar-geothermal cycle and Case III is combined solar-wind power plant. This chart displays different assessed phases of these integrated plants which includes raw material extraction, manufacturing of component, installation and assembly of equipment and operation and maintenance (O&M) over plants lifespan to generate low-carbon electricity.

overestimation of the environmental impacts associated with PSCs. However, we utilised an allocation method in the LCA assessment that accounts for the power generation capacity of each unit. This method enables a more accurate comparison and provides clearer insights into the PSC unit's contributions and impacts compared to the larger systems. Supplementary Table 1 presents all investigated cases and scenarios in this research.

Results

This research aims to conduct a comparative life cycle environmental assessment of three integrated power plants that utilise geothermal, solar, and wind resources as their energy sources. A notable aspect of this study is the consideration of the PSC system, a promising and recently developed solar cell technology. This technology has not been previously studied as part of an integrated system in a power plant coupled with another renewable power cycle. Furthermore, the study explores various scenarios based on assumptions about the technological development of the PSC system to identify the most sustainable solutions. All results are presented for the four impact categories (Climate Change (CC), Freshwater Ecotoxicity (FE), Ozone Depletion (OD), Marine Ecotoxicity (ME)) over the system's lifespan, representing the most dominant environmental damages with the highest influence. These impact categories are chosen because they showcase the greatest levels of influence as indicated by the normalised results assessments in comparison with all other midpoint results.

Figure 2 shows the contribution of each phase to the CC impact for the three base case power cycles (B1, B2, B3). In subplot (2a), the CGW cycle's CC impact is primarily due to the O&M phase, which accounts for 46% of emissions, mainly from direct emissions and maintenance materials. Well drilling in geothermal plants and wind plant construction also significantly contribute to CC impact, with drilling involving high energy and material use and construction emissions from steel, copper, and concrete. O&M of the wind plant and geothermal cycle construction have relatively lower impacts.

Subplot (2b) illustrates the CC-related contributors for the CSG plant. The three main causes of greenhouse gas emissions are O&M (36%), well drilling in the geothermal cycle (28%), and Manufacturing and Installation (M&I) of the PSC unit (22%). Materials used in the M&I stage, such as aluminium and steel, contribute significantly to the impact category of CC. The construction of the geothermal plant has a negligible impact compared to other phases.

In subplot (2c), the CC-related contributors for the CSW plant are presented. M&I emerge as the most dominant phase in the impact category of CC, while the manufacturing of the PSC and the construction of the wind power cycle contribute equally (27%). The main impact of PSC manufacturing is attributed to adhesive application in the encapsulation process, and the production of Indium Tin Oxide (ITO) glass also contributes to carbon dioxide emissions. O&M of the wind power cycle has a relatively insignificant CC impact compared to other phases. The main contributors to the impact of constructing the wind plant are the tower, foundation, and nacelle construction processes, respectively.

Figure 3 displays the main contributions of FE impact category of base scenarios of studied combined cycles. In subplot (3a), the most dominant causes of FE impact in the CGW cycle are highlighted. The major contributor is the construction of the wind power cycle, accounting for 42% of total impacts. This impact is primarily attributed to the use of copper in generator construction and the frame construction of the nacelle. Additionally, steel used (both reinforcing and low alloyed) in the tower construction process contributes to the impact. Geothermal well drilling is the second most significant phase, contributing 35% to the total impact, mainly due to the use of steel and activated bentonite in both production and reinjection wells. The O&M phase of the wind turbine cycle also causes a notable impact, primarily due to the use of copper.

Subplot (3b) showcases the most dominant causes of the FE impact category in the CSG cycle. Approximately half of the total impacts arise from the M&I phase of the PSC unit, mainly due to the use of aluminium in the manufacturing process. The deposition of the hole-transport layer is a main

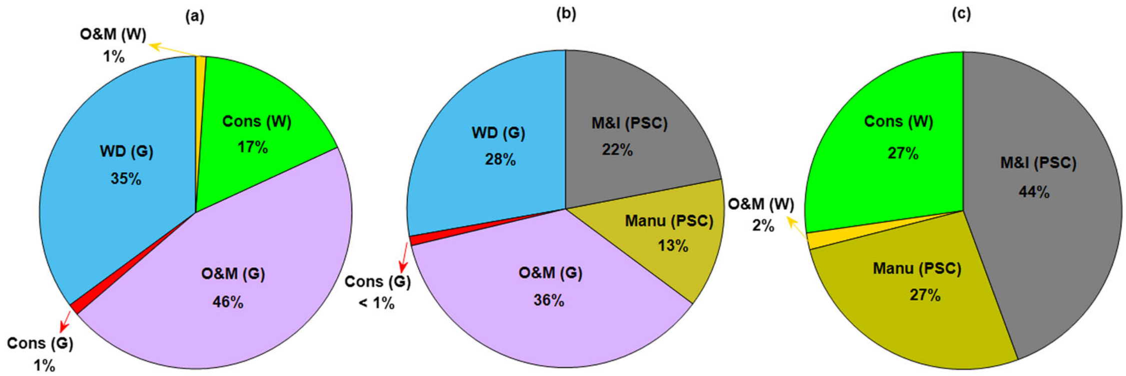

Fig. 2 | CC impact contribution of base scenarios of integrated power cycles, highlighting the contribution of different phases. These pie plots display the percentage of CC influence of studied based scenarios for all three combined power systems, (**a**) the CC portion for B1, (**b**) the CC portion for B2, and (**c**) the CC portion for B3. G stands for geothermal, W stands for wind and S stands for solar systems. Also, WD refers to well drilling, Cons refers to construction, Manu refers to manufacturing, O&M refers to operations and maintenance, M&I refers to manufacturing and installation.

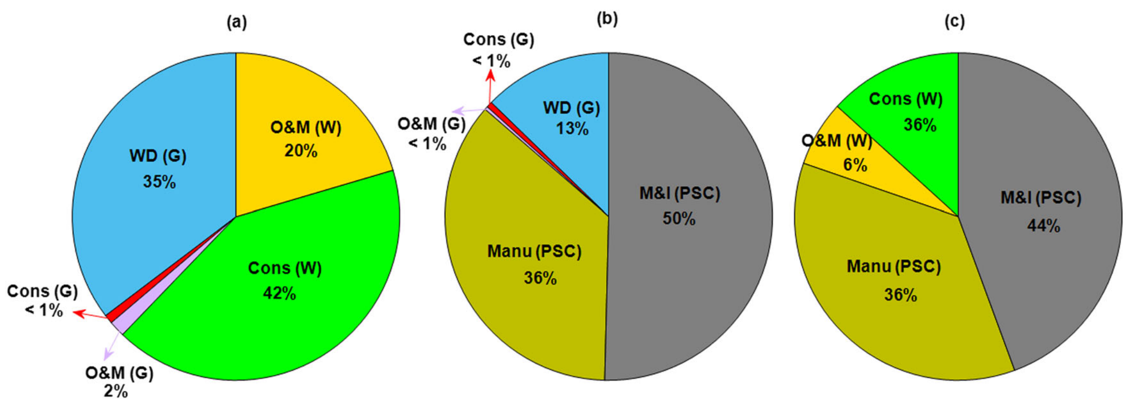

Fig. 3 | FE impact contribution of base scenarios of integrated power cycles, highlighting the contribution of different phases. These pie plots depict the percentage of FE influence of studied base scenarios for all three combined power systems, (**a**) the FE portion for B1, (**b**) the FE portion for B2, and (**c**) the FE portion for B3. G stands for geothermal, W stands for wind and S stands for solar systems. Also, WD refers to well drilling, Cons refers to construction, Manu refers to manufacturing, O&M refers to operations and maintenance, M&I refers to manufacturing and installation.

contributor to the FE impact of PSC manufacturing, primarily due to the application of chlorobenzene. The construction and O&M of the geothermal cycle have minimal FE impact (less than 1% of the total impact) compared to other phases. Geothermal well drilling contributes only 13% to the total FE pollution, highlighting the noteworthy toxicity impact of the PSC system that requires attention for further development. As mentioned in previous study[36] it is a principal barrier for its commercialisation.

The most dominant of causes of FE category in CSW cycle is shown in subplot (3c). According to the graph, the M&I and manufacturing of the PSC unit have the most considerable impacts, accounting for 44% and 36% of the total FE consequences, respectively. The main pollutants originate from aluminium and steel used in the M&I stage. However, the deposition of the hole-transport layer is the primary cause of the FE effect in PSC manufacturing, mainly stemming from chlorobenzene production. Additionally, the construction of the wind cycle is the third-highest contributor to FE pollution after M&I and manufacturing of the PSC. The graphs and results interpretation of OD and ME impact categories are presented in Supplementary Figs. 1 and 2.

Figure 4 shows how four impact categories change with the PSC system's lifetime. The green line, representing the CGW power cycle (which includes geothermal and wind but not solar), remains flat and serves as a reference for other scenarios. In subplot (4a), the variation in the CC impact category is visible. The CC impact calculations for the base cases (B1, B2, and B3) - related to a 3-year PSC lifetime - show the highest value for the CSG scenario, whereas the lowest is associated with the CSW scenario. The higher CC impact in CGW is due to significant emissions from geothermal well drilling, wind cycle construction, and the use of materials like steel and cement. Key contributors include O&M of the geothermal cycle and the construction of wind cycle infrastructure, with steel used in wind plant towers being a major source of CC-related pollution. In the CSG power cycle, in addition to well drilling and O&M phases of the geothermal unit, the M&I phase is another major contributor to carbon dioxide emissions. However, as the CC-related pollution impact of the solar system with a 3-year lifetime is higher than that of the wind plant, the carbon footprint of CSG is higher than CGW. The calculations indicate a substantial decrease in the carbon footprint of CSG and CSW with an increase in the PSC lifespan. The results demonstrate a 28% and 56% reduction in greenhouse gas emissions for CSG and CSW, respectively, by extending the PSC lifespan from 3 years to 15 years. Based on the results for the CSW cycle, a mere 7-year increase in PSC lifetime could result in around a 49% reduction in the carbon footprint of the integrated system. The similar trend is observed for three other considered impact categories (FE, OD, and ME). In all plotted trends, a notable reduction in environmental impact is evident with the improvement in the PSC system's lifetime. Subplot (4b) illustrates the variation of FE impact against PSC lifetime enhancement for all base scenarios. The FE value for CGW is lower than other scenarios up to a PSC lifetime of 10; however, considering a lifetime of 15 years for the PSC, CSG's FE impact becomes lower than CGW. As OD and FE values for CSW have much difference compared to the values of the two other cases, they are shown based on the right-axis values in subplots (4c) and (4d). The OD

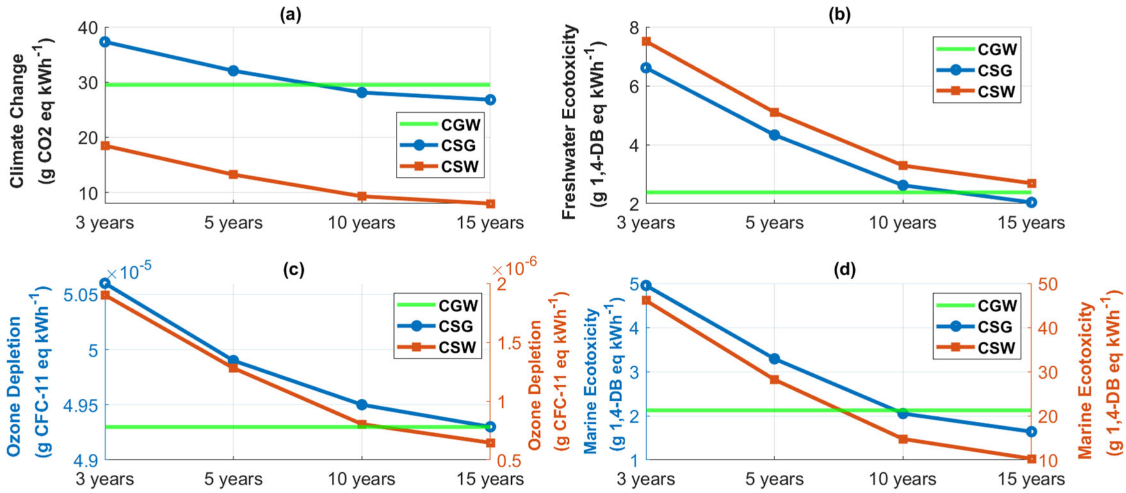

Fig. 4 | The variation of environmental impacts of four main impact categories for all scenarios and technologies assuming lifetime increment of PSC. These graphs illustrate the reduction in environmental damages of impact categories considering technological improvement supposing promoting the PSC lifetime, (**a**) CC impact reduction, (**b**) FE impact reduction, (**c**) OD impact reduction, (**d**) ME impact reduction. The three integrated power cycles considered are combined geothermal-wind (CGW), combined solar-geothermal (CSG) and combined solar-wind (CSW).

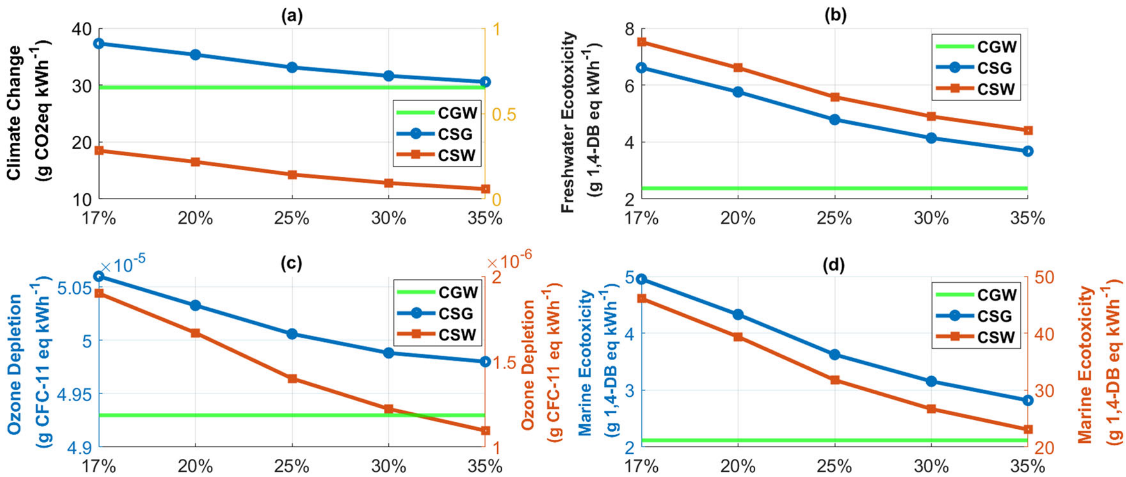

Fig. 5 | The variation of environmental impacts of four main impact categories for all scenarios and technologies assuming efficiency enhancement of PSC. These graphs illustrate the reduction in environmental impacts of impact categories considering technological improvement supposing promoting the PSC efficiency, (**a**) CC impact reduction, (**b**) FE impact reduction, (**c**) OD impact reduction, (**d**) ME impact reduction. The three integrated power cycles considered are combined geothermal-wind (CGW), combined solar-geothermal (CSG) and combined solar-wind (CSW).

impact for the CSG power cycle shows a remarkable decline with an increase in the PSC lifespan, and at a lifetime of 15 years, the values of OD impact for CSG are approximately the same as CGW. For all impact categories, the influential effect of environmental reductions by incrementing the PSC lifetime is evident.

Figure 5 (a to d) illustrates the changes in the environmental impact of the considered base scenarios, assuming technological development of the PSC system through efficiency enhancement from 17% to 35%. As it is shown in Fig. 5a, the increases in PSC efficiency from 17% to 35% resulted in an 18% reduction in greenhouse gas emissions for the CSG scenario and a 37% reduction for the CSW scenario. While there is a notable decline in the carbon footprint of CSG and CSW, it is important to note that this reduction is lower than the impact observed with the extension of the PSC lifetime. These findings underscore the greater influence of lifetime improvement compared to system efficiency. It's worth mentioning that the carbon footprint of the CSW power plant is significantly lower than the other two power systems. Based on Fig. 5b, the FE values attributed to CSW are notably lower than the other plants, so even with the development of PSC unit efficiency up to 35%, the FE impacts of CSG and CSW cycles remain higher. As the OD and ME values for CSW differ significantly from the values of the other cases, they are displayed based on right-axis values in subplots (5c) and (5d). Both OD and ME impact categories of CSG and CGW power plants have decreased assuming the efficiency improvement of the PSC cycle. However, for all the mentioned impact categories, the amount of impact reduction for efficiency increment is lower than for lifetime enhancement.

Figure 6 presents the scoring of different considered case studies and scenarios based on four impact categories to compare their environmental sustainability. The scoring is conducted for all cases, including base systems and defined scenarios, with scores ranging from 1 to 9 in subplot (6a). A score of 1 implies the least environmentally sustainable case, while a score of 9 indicates the most environmentally sustainable technology. Higher scoring numbers represent systems causing less pollution.

Results reveal that the CSW cycles have the least CC impact, and with an increase in the lifespan of the PSC unit, the damaging impact decreases. Scenario L6 is identified as the most sustainable solution from a CC

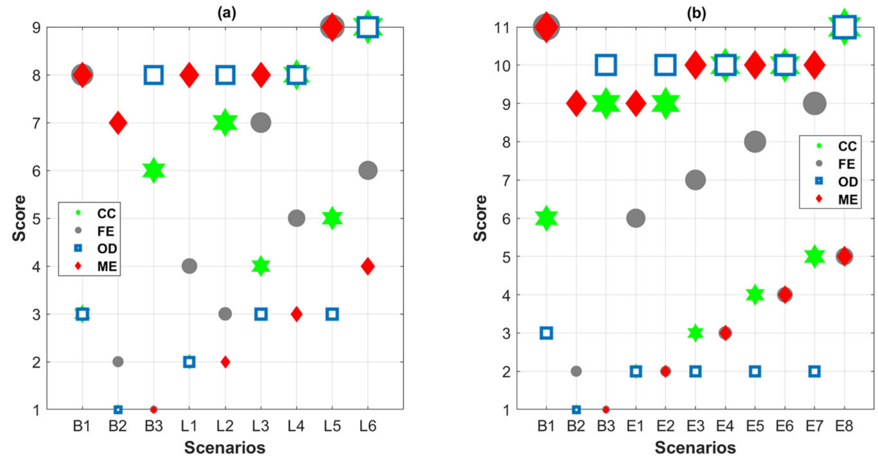

Fig. 6 | The scoring of all considered scenarios (17 scenarios in total) and technologies (3 integrated technologies) based on environmental sustainability impacts. These graphs illustrate the sustainability scoring based on the environmental performance of all studied systems and scenarios based on four main impact categories which are the main impact contribution of these technologies over their lifespan. **a** The scoring results for base (B1 to B3) and lifetime scenarios which are related to PSC system (L1 to L6) for all considered impact categories. **b** The scoring outcomes of base (B1 to B3) and efficiency scenarios (E1 to E8). CC stands for climate change impact, FE stands for freshwater ecotoxicity impact, OD stands for ozone depletion impact, ME stands for marine ecotoxicity impact.

indicator perspective. On the other hand, the least sustainable case is B2, which corresponds to the base case of CSG. The scoring based on OD criteria is more or less similar to CC, with L6 being the most environmentally sustainable and B2 being the most pollutant. The least pollutant cycle from the FE perspective is L5, related to CSG with a PSC lifespan of 15 years. Following this scenario, B1, related to CGW, is a more sustainable plant with a score of 8. After them, L3 and L6 have lower FE pollution than other scenarios. However, the most pollutant power cycle belongs to B3, the base case scenario of CSW. ME-related pollution is lower in CSG cases (L1, L3, and L5) compared to CSW cases. However, B1 scenario is scored 8, indicating low ME pollution as well. The scores of other cases are notably lower due to their considerably higher pollution amounts.

Subplot (6b) on the right represents the scoring of base cases and efficiency-related scenarios, ranging from 1 to 11. A score of 1 represents the least environmentally sustainable power plant, and 11 indicates the most sustainable one. The scoring approach shows that scenarios involving CSW cycles have lower carbon dioxide emissions. With an increase in PSC efficiency, the CC impact decreases, resulting in the highest score for scenario E8. B2 is identified as the most pollutant case. Scenarios B1 have the highest score in FE impact, indicating the notable role of the PSC system in FE pollution. Scenarios related to CSG have the highest score from FE impact criteria, and with an enhancement in the effectiveness of PSC performance, relevant scores have increased, with the highest score being related to scenario E7, the second environmentally sustainable solution. OD-related scoring has the same highest and lowest scores as CC. However, there is a considerable difference between CSG and CSW cases, with CSG scenarios being more pollutant, mainly due to the geothermal system and the application of refrigerant, which has a notable impact on the ozone layer. Regarding ME impact, B1 has the highest score, followed by CSG scenarios having higher scores compared to CSW scenarios.

While previous research has focused on individual renewable technologies or their integration with fossil fuels, our study explores the environmental effects of combining two distinct renewable-based power systems. This approach highlights the importance of advancing sustainable energy systems through the collaboration of various renewable sources to enhance energy production and minimize environmental harm. By analysing three configurations, our study reveals that integrating renewable energy sources significantly reduces environmental damage compared to fossil fuels. However, advancing technology and infrastructure is crucial to improve the reliability and cost-effectiveness of clean energy solutions. Our research provides new insights into the environmental impacts of multiple renewable sources, offering valuable information for policymakers, investors, and stakeholders.

The findings of this research demonstrate the sustainability performance of integrating three renewable resources throughout the lifespan of systems. Substantial environmental benefits are evident through the replacement of fossil fuel-based power plants with renewable alternatives. By diversifying energy sources, integrated systems reduce dependence on environmentally detrimental technologies like fossil fuels. This transition leads to broader environmental benefits such as reducing air and water pollution, preserving natural habitats, and mitigating climate change. Furthermore, the study reveals the feasibility of reducing the environmental footprint of individual renewable power plants by integrating additional renewable units. This integration capitalizes on the complementary generation patterns of diverse renewable technologies. By combining multiple renewable sources, reliance on any single energy generation method diminishes, bolstering grid stability and resilience against weather fluctuations, thus ensuring a reliable power supply. In contrast, standalone renewable power plants, while effective in displacing fossil fuels and curbing emissions, may encounter limitations due to intermittency or resource availability. This could pose challenges in maintaining grid stability and optimizing environmental advantages. Such plants exclusively rely on a singular renewable resource, potentially resulting in underutilization of available resources and inefficient land usage.

Furthermore, the calculated results, contingent upon the assumptions made, underscore the significance and pivotal influence of technological advancements in mitigating environmental impacts. This highlights that enhancements in lifetime and efficiency render CSG and CSW more competitive for future commercialisation, potentially positioning them as promising alternatives to traditional solar technologies. Moreover, it suggests the potential interoperability of this system with other renewable units such as geothermal and wind, or other clean energy resources, offering integrated solutions for sustainable energy generation in the future.

The findings of this research could boost the motivation to utilise exclusively renewable resources for power generation, potentially enhancing energy resilience and security in nations by reducing reliance on imported fossil fuels. Furthermore, integrating renewable energy sources diminishes susceptibility to geopolitical tensions and interruptions in fossil fuel supply chains, commonly linked with their extraction and transportation processes. Broadening the energy mix with renewables additionally enhances energy security by lessening reliance on finite and geopolitically sensitive resources. Moreover, the adoption of renewables can enhance the robustness of supply chains by encouraging local production of renewable technologies, thus decreasing dependency on imports and vulnerabilities to fluctuations in the global market. This shift requires policymakers to revise regulatory frameworks and advocate for sustainable practices, creating an environment conducive to the deployment of renewable energy. In essence, mitigating the environmental impact of renewable-based power generation not only combats climate change but also strengthens energy resilience, security, and supply chains, while guiding policymakers toward sustainable energy pathways.

A comparative assessment of the climate change impact of the studied cases is provided alongside other similar previous power cycle studies, including both fossil fuel-based and renewable power generation, in the Supplementary Information file (Supplementary Table 3). The values compared in this table are derived from the base case results, which represent the worst-case scenarios. However, considering PSC systems' enhanced efficiency and extended lifetime, it resulted in a lower carbon footprint impact for cases 2 (CSG) and 3 (CSW).

Discussion

Developing and expanding combined renewable energy power plants can lead to a robust and sustainable energy infrastructure. This infrastructure helps reduce greenhouse gas emissions while promoting energy security and environmental conservation. The study reveals that the B3 scenario has the lowest CC and OD impacts among the three base scenarios (B1, B2, and B3). Additionally, B1 has the lowest FE and ME impacts compared to the other two base scenarios. However, the study also emphasizes that enhancing the efficiency and lifespan of PSC substantially reduces the environmental impact of combined cycles. The reduction is more pronounced for lifespan development, underscoring the importance and influence of improving the system's lifespan compared to its efficiency. The results indicate that the lowest and highest carbon footprint and OD impacts are associated with the L6 and B2 scenarios, respectively. Similarly, the lowest and highest FE and ME impacts are linked to the L5 and B3 scenarios, respectively. The study further reveals a noteworthy 28% and 56% reduction in greenhouse gas emissions for the CSG and CSW scenarios, respectively, by extending the PSC lifespan from 3 years to 15 years. In the case of the CSW cycle, even a 7-year increase in the PSC lifespan could result in around a 49% reduction in the carbon footprint of the integrated system. Moreover, an increase in PSC efficiency from 17% to 35% led to an 18% reduction in greenhouse gas emissions for the CSG scenario and a 37% reduction for the CSW scenario. The scoring approach is applied to rank all considered scenarios, providing a visual representation of their sustainability potential.

Integrating various renewable energy technologies, such as solar and wind, into a single power plant brings technical challenges and potential risks. Managing the coordination of these diverse technologies to optimize overall performance can be complex. Since renewable energy sources like solar and wind are intermittent and weather-dependent, they can cause fluctuations in power output, making it difficult to maintain a stable and reliable power supply. These fluctuations may lead to grid instability, particularly as the proportion of variable renewable energy sources increases, making grid stability harder to maintain. Addressing these challenges requires effective energy storage solutions, though the availability and cost-effectiveness of these technologies remain hurdles. Additionally, optimal renewable resources are often located far from population centres, necessitating significant investments in transmission and distribution infrastructure to efficiently deliver energy. The deployment of renewable technologies also depends on the resilience of supply chains for critical materials and minerals, which introduces risks in the manufacturing of technologies like perovskites, wind turbines, and geothermal systems. Challenges related to the availability, extraction, and processing of these materials impact their environmental sustainability, while limited global supplies, geopolitical concerns, and environmental issues associated with mining pose further risks. Strategies such as circular economy initiatives, material substitution, supply chain diversification, and the development of alternative technologies can help mitigate these risks. Overall, the main challenges of integrating renewable-based power plants include resource scarcity, price volatility, supply chain vulnerabilities, energy-intensive manufacturing, and technological dependencies. Overcoming these challenges requires a coordinated approach involving technological innovation, policy development, and careful planning in the design and implementation of combined renewable energy power plants.

Grasping the global energy landscape relies on understanding the energy consumption, production, and policy strategies of nations with high energy demands[37]. Over time, the United States (USA) has shifted towards cleaner energy alternatives and bolstered domestic production, while the European Union (EU) has spearheaded the adoption of renewable energy, set ambitious targets, and promoting sustainable practices and innovation. Despite facing challenges, rapidly expanding economies such as India and China have shown advancement by investing in renewable energy infrastructure and enacting measures to alleviate emissions, albeit grappling with the reconciliation of energy demand and environmental conservation. In countries like Vietnam, governmental efforts to promote renewable energy involve tailored policy actions and initiatives adapted to unique conditions, including setting adoption targets, providing fiscal incentives like feed-in tariffs or tax breaks to spur investment, establishing regulatory frameworks to facilitate integration, and fostering technology transfer and local capacity building.

The inclusion of renewable power plants in a country's energy mix carries substantial policy implications across multiple realms. Environmentally, investment in renewables offers a means to mitigate GHG emissions and diminish reliance on fossil fuels, in line with international climate objectives and obligations. On an economic front, policies that bolster renewable energy development have the potential to stimulate innovation, generate employment opportunities, and bolster energy security through diversification of the energy portfolio. Furthermore, the integration of renewables necessitates robust regulatory structures to tackle challenges related to grid integration, ensure grid stability, and foster equitable competition among energy sources. Policymakers also need to account for social factors, such as ensuring fair access to clean energy and addressing potential impacts on local communities and ecosystems.

Incorporating renewable energy sources into energy systems, especially in smart cities, fosters environmentally friendly and efficient processes. By utilizing solar, wind, and geothermal power, smart cities can reduce carbon emissions, enhance energy resilience, and stimulate economic growth. Furthermore, Explainable Artificial Intelligence (XAI) shows promise in advancing renewable energy technologies by addressing challenges like intermittency and grid stability. XAI also improves transparency in renewable energy systems, enabling informed decision-making and resource optimization. Ultimately, integrating renewable energy with XAI supports a greener and more sustainable energy landscape[38].

Evaluating the environmental impact of combined renewable power systems has limitations, particularly due to data maturity between established technologies such as geothermal and wind energy and emerging ones such as perovskite solar cells. The limited data for perovskite solar cells, especially regarding production, material use, and end-of-life management, introduces uncertainties in LCA results. These challenges, along with varying social acceptance and regulatory frameworks, may affect the implications of the results. Therefore, while LCA provides valuable insights, results must be interpreted cautiously, acknowledging these uncertainties.

To address the limitations in evaluating the environmental impact of combined renewable power systems, further research should focus on several key areas. First, there is a need for enhanced data collection to provide more reliable and up-to-date lifecycle information for perovskite solar cells, particularly concerning their large-scale applications and end-of-life management. Additionally, developing and standardizing processes for the disposal and recycling of perovskite solar cells, including the safe handling of hazardous materials such as lead, would help reduce uncertainties in LCA results. Furthermore, broader studies on social acceptance and regulatory challenges associated with different renewable technologies would improve the understanding of ways to combine them in the future to maximise sustainability. Finally, implementing rigorous sensitivity and uncertainty analyses can help quantify the impact of data variations on LCA results. These steps will lead to more robust and comprehensive environmental assessments, facilitating better-informed decisions regarding sustainability of renewable power systems.

Method

Life cycle assessment

Over the past thirty years, LCA has developed into a pivotal instrument for environmental management and decision-making support. It has notably served as the scientific foundation for the formulation of policies and plans[39]. The application of LCA in environmental policy is expanding to encompass intricate and extensive externalities[40]. It is a recognized systematic method employed to identify, quantify, and evaluate the environmental impacts associated with the entire value chain of an activity, product, or process[41,42]. The fundamental concept of LCA involves tracing a product throughout its life stages and establishing a distinction between its product system and the external environment[43]. It serves as a valuable instrument for pinpointing areas of concern in terms of environmental sustainability[44]. LCA is commonly employed to aid in decision-making for substantial strategies aimed at reducing carbon emissions in energy systems[45]. The energy and material exchanges occurring across this boundary are connected to the inputs and outputs of the system[46]. The four stages of an LCA study, include (1) defining goals and scope, (2) conducting inventory analysis, (3) performing impact assessment, and (4) interpreting the results[47].

Goal and scope definition

In this stage, which is the first step of the LCA study, the examination involves addressing questions related to what, how, and why aspects of the LCA work. This stage establishes the system boundaries and determines the functional unit[48,49]. The main objective of this research is to conduct a comparative environmental impact assessment of three integrated renewable-based power plants using a life cycle methodology. The aim is to gain insights into the sustainability implications and identify opportunities for improvement. It is crucial to note that while geothermal and wind technologies, subjects of examination in this study, are more mature and widely deployed, the evaluation of solar cell technology, particularly PSCs, is at an early stage of commercialization and predominantly in the developmental phase, primarily within laboratory settings. Furthermore, this study places emphasis on the integration of the mentioned renewable energy cycles, an aspect that has received less attention in prior research. The OpenLCA tool is utilised for modelling the systems, and the system boundary is set as cradle-to-gate for all three combined systems. The functional unit defined for the evaluated integrated power systems is the generation of 1 kWh of net energy. Each technology has a distinct anticipated lifespan, with geothermal, wind, and PSC systems expected to operate for 30, 25, and 3 years, respectively. Transportation is not considered in this study, and the end-of-life phase is excluded due to insufficient data, leading to uncertainty and compatibility concerns in the study. In our study, we merge the raw material phase with the manufacturing phase to streamline the life cycle stages and simplify the analysis. This approach provides a comprehensive evaluation of material extraction, processing, and transportation, capturing the complete range of impacts related to raw material usage.

Evaluating the environmental impact of these combined renewable-based power systems comes with certain limitations. Geothermal and wind energy systems have well-established, though geographically and technologically variable data sets, while perovskite solar cells, as a newer and rapidly evolving technology, present challenges due to limited lifecycle data, particularly for large-scale applications. This disparity in data maturity introduces uncertainties in assessing environmental impacts, with perovskite solar cells facing additional uncertainties in production processes, material use, durability, and end-of-life management, including the handling of hazardous materials such as lead. Moreover, the social acceptance and regulatory challenges differ across these technologies, potentially limiting the broader implication of the combined renewable power systems. Therefore, while LCA offers valuable insights, results should be interpreted cautiously, considering these uncertainties.

Data inventory

In the era of research driven by data, the comprehensive disclosure of life cycle inventory data holds paramount significance as a key enhancement to any study[50]. During the inventory analysis phase, data is collected on various aspects, including resource consumption, energy usage, water utilization, and emissions released into the soil, air, and water, along with waste generation. This analysis enables a comprehensive assessment of the environmental impacts of the material, helping researchers identify and understand crucial environmental hotspots[51]. The accuracy of results derived from an LCA model is directly proportional to the precision of the data sources employed in the model[52]. The applied data in this study are collected from different literatures[53–58] and ecoinvent version 3.9[59]. An inventory of data related to all considered cases has been brought in Supplementary Data 1-3.

Impact assessment approach

During this phase, effective data management of life cycle inventory is facilitated, enabling the assessment of environmental impacts arising from the materials and energy involved throughout the entire life cycle of the system[60]. The outcomes of the life cycle impact assessment provide an evaluation of a product's life cycle across various impact categories, utilizing the functional unit as a basis[61]. In this study, the environmental impacts in the life cycle impact assessment are computed using the ReCiPe 2016 (H) midpoint approach.

Results interpretation

During the interpretation stage, the findings from the preceding phases are analysed in connection with the established goal and scope to draw conclusions and make recommendations[62]. In the interpretation step of the study, findings are analysed and summarised, with suggestions for potential measures to alleviate the environmental impact[63].

Sensitivity analysis

In this comparative LCA study, Scenario Analysis is selected as the preferred method for sensitivity analysis based on several important considerations. Firstly, it provides clarity and ease of interpretation, offering a simple way to demonstrate how different assumptions or variations in inputs affect the comparative outcomes - an essential feature for stakeholders who require clear and actionable information. Secondly, Scenario Analysis facilitates a targeted examination of critical assumptions by outlining specific scenarios, such as best-case, worst-case, and typical situations, thereby highlighting the factors most likely to cause remarkable differences between the alternatives. Moreover, this method is resource-efficient, demanding fewer computational resources and less time compared to more complex approaches like Monte Carlo or Global Sensitivity Analysis, a factor that was particularly important given the scope of this study. Lastly, Scenario Analysis is highly applicable to decision-making, as it helps to clearly illustrate how outcomes may shift under different practical scenarios, simplifying the evaluation of alternatives under various conditions. By using Scenario Analysis, this study ensures that the sensitivity analysis remains both accessible and pertinent, offering valuable insights into the robustness of the comparative LCA results without resorting to overly complex methodologies.

Scoring approach

The scoring process generally entails defining a set of criteria or metrics to gauge performance. These criteria may take the form of quantitative measures like numerical scores or percentages, or qualitative assessments that involve subjective judgments and observations. Successfully implementing this methodology involves a thoughtful assessment of the relative significance of diverse criteria and the creation of a scoring system that effectively produces the ranking outcomes. The scoring methodology applied in this study is based on obtained results from LCA of all cases and scenarios based on low to high amounts for each considered impact category. The highest value shows the most sustainable power plant, and the least value presents the most pollutant cycle. All scenarios are compared with base cases to rank the position of each case among other cycles.

Data availability

Authors can confirm that all relevant data are included in the paper and its Supplementary Data 1-3 file.

Received: 26 January 2024; Accepted: 27 September 2024;
Published online: 08 October 2024

References

1. Koh, S. et al. Drivers of US toxicological footprints trajectory 1998–2013. *Sci. Rep.* **6**, 39514 (2016).
2. Cao, Y. et al. Energy, exergy, and economic analyses of a novel biomass-based multigeneration system integrated with multi-effect distillation, electrodialysis, and LNG tank. *Desalination* **526**, 115550 (2022).
3. Vargas, C. A., Caracciolo, L. & Ball, P. J. Geothermal energy as a means to decarbonize the energy mix of megacities. *Commun. Earth Environ.* **3**, 66 (2022).
4. Schomberg, A. C., Bringezu, S., Flörke, M. & Biederbick, H. Spatially explicit life cycle assessments reveal hotspots of environmental impacts from renewable electricity generation. *Commun. Earth Environ.* **3**, 197 (2022).
5. Dhakal, S. et al. *Emissions Trends and Drivers (Chapter 2)*, (2022).
6. Mi, Z. & Sun, X. Provinces with transitions in industrial structure and energy mix performed best in climate change mitigation in China. *Commun. Earth Environ.* **2**, 182 (2021).
7. Kabayo, J., Marques, P., Garcia, R. & Freire, F. Life-cycle sustainability assessment of key electricity generation systems in Portugal. *Energy* **176**, 131–142 (2019).
8. Babacan, O. et al. Assessing the feasibility of carbon dioxide mitigation options in terms of energy usage. *Nat. Energy* **5**, 720–728 (2020).
9. Shamoushaki, M., Ehyaei, M. A. & Ghanatir, F. Exergy, economic and environmental analysis and multi-objective optimization of a SOFC-GT power plant. *Energy* **134**, 515–531 (2017).
10. Cucchiella, F., D'Adamo, I., Gastaldi, M., Koh, S. C. L. & Rosa, P. A comparison of environmental and energetic performance of European countries: A sustainability index. *Renew. Sustain. Energy Rev.* **78**, 401–413 (2017).
11. Chen, S. et al. Deploying solar photovoltaic energy first in carbon-intensive regions brings gigatons more carbon mitigations to 2060. *Commun. Earth Environ.* **4**, 369 (2023).
12. Ahmed, S. F. et al. Perovskite solar cells: Thermal and chemical stability improvement, and economic analysis. *Mater. Today Chem.* **27**, 101284 (2023).
13. Urbina, A. The balance between efficiency, stability and environmental impacts in perovskite solar cells: a review. *J. Phys.: Energy* **2**, 022001 (2020).
14. Shamoushaki, M., Fiaschi, D., Manfrida, G. & Talluri, L. Energy, exergy, economic and environmental (4E) analyses of a geothermal power plant with NCGs reinjection. *Energy* **244**, 122678 (2022).
15. Shamoushaki, M., Aliehyaei, M. & Rosen, M. A. Energy, exergy, exergoeconomic and exergoenvironmental impact analyses and optimization of various geothermal power cycle configurations. *Entropy* **23**, 1483 (2021).
16. Zhang, S. et al. Thermodynamic analysis on a novel bypass steam recovery system for parabolic trough concentrated solar power plants during start-up processes. *Renew. Energy* **198**, 973–983 (2022).
17. Wang, A., Han, X., Liu, M., Yan, J. & Liu, J. Thermodynamic and economic analyses of a parabolic trough concentrating solar power plant under off-design conditions. *Appl. Therm. Eng.* **156**, 340–350 (2019).
18. Aghbashlo, M., Tabatabaei, M., Hosseini, S. S., B. Dashti, B. & Mojarab Soufiyan, M. Performance assessment of a wind power plant using standard exergy and extended exergy accounting (EEA) approaches. *J. Clean. Prod.* **171**, 127–136 (2018).
19. Redha, A. M., Dincer, I. & Gadalla, M. Thermodynamic performance assessment of wind energy systems: An application. *Energy* **36**, 4002–4010 (2011).
20. Shamoushaki, M., Aliehyaei, M. & Taghizadeh-Hesary, F. Energy, exergy, exergoeconomic, and exergoenvironmental assessment of flash-binary geothermal combined cooling, heating and power cycle. *Energies* **14**, 4464 (2021).
21. Ehyaei, M., Esmaeilion, F., Shamoushaki, M., Afshari, H. & Das, B. The feasibility study of the production of Bitcoin with geothermal energy: Case study. *Energy Sci. Eng.* **12**, 755–770 (2023).
22. Boukelia, T. E., Arslan, O. & Bouraoui, A. Thermodynamic performance assessment of a new solar tower-geothermal combined power plant compared to the conventional solar tower power plant. *Energy* **232**, 121109 (2021).
23. Alibaba, M., Pourdarbani, R., Manesh, M. H. K., Ochoa, G. V. & Forero, J. D. Thermodynamic, exergo-economic and exergo-environmental analysis of hybrid geothermal-solar power plant based on ORC cycle using emergy concept. *Heliyon* **6**, e03758 (2020).
24. Yang, Z., Wang, Z., Ran, P., Li, Z. & Ni, W. Thermodynamic analysis of a hybrid thermal-compressed air energy storage system for the integration of wind power. *Appl. Therm. Eng.* **66**, 519–527 (2014).
25. Sezer, N. & Koç, M. Development and performance assessment of a new integrated solar, wind, and osmotic power system for multigeneration, based on thermodynamic principles. *Energy Convers. Manag.* **188**, 94–111 (2019).
26. Fiaschi, D., Manfrida, G., Mendecka, B., Shamoushaki, M. & Talluri, L. Exergy and Exergo-environmental analysis of an ORC for a geothermal application. in *E3S Web of Conferences*. **238**, 01011, (EDP Sciences). https://doi.org/10.1051/e3sconf/202123801011 (2021).
27. Parisi, M. L., Ferrara, N., Torsello, L. & Basosi, R. Life cycle assessment of atmospheric emission profiles of the Italian geothermal power plants. *J. Clean. Prod.* **234**, 881–894 (2019).
28. Kjeld, A., Bjarnadottir, H. J. & Olafsdottir, R. Life cycle assessment of the Theistareykir geothermal power plant in Iceland. *Geothermics* **105**, 102530 (2022).
29. Tian, X., Stranks, S. D. & You, F. Life cycle assessment of recycling strategies for perovskite photovoltaic modules. *Nat. Sustainability* **4**, 821–829 (2021).
30. Gasa, G., Prieto, C., Lopez-Roman, A. & Cabeza, L. F. 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 (2022).
31. Ibn-Mohammed, T. et al. Perovskite solar cells: An integrated hybrid lifecycle assessment and review in comparison with other photovoltaic technologies. *Renew. Sustain. Energy Rev.* **80**, 1321–1344 (2017).
32. Soares, W. M., Athayde, D. D. & Nunes, E. H. LCA study of photovoltaic systems based on different technologies. *Int. J. Green. Energy* **15**, 577–583 (2018).
33. Rashedi, A. & Khanam, T. Life cycle assessment of most widely adopted solar photovoltaic energy technologies by mid-point and end-point indicators of ReCiPe method. *Environ. Sci. Pollut. Res.* **27**, 29075–29090 (2020).
34. Das, U. & Nandi, C. Life cycle assessment on onshore wind farm: An evaluation of wind generators in India. *Sustain. Energy Technol. Assess.* **53**, 102647 (2022).
35. Mello, G., Ferreira Dias, M. & Robaina, M. Wind farms life cycle assessment review: CO2 emissions and climate change. *Energy Rep.* **6**, 214–219 (2020).
36. Park, N.-G. Green solvent for perovskite solar cell production. *Nat. Sustainability* **4**, 192–193 (2021).
37. Eufrasio Espinosa, R. M. & Lenny Koh, S. Forecasting the ecological footprint of G20 countries in the next 30 years. *Sci. Rep.* **14**, 8298 (2024).
38. Nguyen, V. N. et al. Potential of explainable artificial intelligence in advancing renewable energy: challenges and prospects. *Energy Fuels* **38**, 1692–1712 (2024).

39. Cavalett, O., Watanabe, M. D., Fleiger, K., Hoenig, V. & Cherubini, F. LCA and negative emission potential of retrofitted cement plants under oxyfuel conditions at high biogenic fuel shares. *Sci. Rep.* **12**, 8924 (2022).
40. Gontard, N., David, G., Guilbert, A. & Sohn, J. Recognizing the long-term impacts of plastic particles for preventing distortion in decision-making. *Nat. Sustainability* **5**, 472–478 (2022).
41. Ibn-Mohammed, T. et al. Integrated hybrid life cycle assessment and supply chain environmental profile evaluations of lead-based (lead zirconate titanate) versus lead-free (potassium sodium niobate) piezoelectric ceramics. *Energy Environ. Sci.* **9**, 3495–3520 (2016).
42. Lan, K. & Yao, Y. Feasibility of gasifying mixed plastic waste for hydrogen production and carbon capture and storage. *Commun. Earth Environ.* **3**, 300 (2022).
43. Smith, L., Ibn-Mohammed, T., Koh, S. C. L. & Reaney, I. M. Life cycle assessment and environmental profile evaluations of high volumetric efficiency capacitors. *Appl. Energy* **220**, 496–513 (2018).
44. Ögmundarson, Ó., Herrgård, M. J., Forster, J., Hauschild, M. Z. & Fantke, P. Addressing environmental sustainability of biochemicals. *Nat. Sustainability* **3**, 167–174 (2020).
45. Hellweg, S., Benetto, E., Huijbregts, M. A., Verones, F. & Wood, R. Life-cycle assessment to guide solutions for the triple planetary crisis. *Nat. Rev. Earth Environ.* **4**, 471–486 (2023).
46. van der Werf, H. M., Knudsen, M. T. & Cederberg, C. Towards better representation of organic agriculture in life cycle assessment. *Nat. Sustainability* **3**, 419–425 (2020).
47. *Standardization, International Organization for "Environmental management: life cycle assessment: principles and framework." Vol. ISO* 14040 (2006).
48. Smith, L., Ibn-Mohammed, T., Koh, L. & Reaney, I. M. Life cycle assessment of functional materials and devices: Opportunities, challenges, and current and future trends. *J. Am. Ceram. Soc.* **102**, 7037–7064 (2019).
49. Eufrasio, R. M. et al. Environmental and health impacts of atmospheric CO2 removal by enhanced rock weathering depend on nations' energy mix. *Commun. Earth Environ.* **3**, 106 (2022).
50. Peters, J. F. Best practices for life cycle assessment of batteries. *Nat. Sustainability* **6**, 614–616 (2023).
51. Shamoushaki, M. & Koh, S. L. Heat pump supply chain environmental impact reduction to improve the UK energy sustainability, resiliency and security. *Sci. Rep.* **13**, 20633 (2023).
52. Goucher, L., Bruce, R., Cameron, D. D., Lenny Koh, S. & Horton, P. The environmental impact of fertilizer embodied in a wheat-to-bread supply chain. *Nat. Plants* **3**, 1–5 (2017).
53. Gkousis, S., Thomassen, G., Welkenhuysen, K. & Compernolle, T. Dynamic life cycle assessment of geothermal heat production from medium enthalpy hydrothermal resources. *Appl. Energy* **328**, 120176 (2022).
54. Zuffi, C., Manfrida, G., Asdrubali, F. & Talluri, L. Life cycle assessment of geothermal power plants: A comparison with other energy conversion technologies. *Geothermics* **104**, 102434 (2022).
55. Gong, J., Darling, S. B. & You, F. Perovskite photovoltaics: life-cycle assessment of energy and environmental impacts. *Energy Environ. Sci.* **8**, 1953–1968 (2015).
56. Ramamurthy Rao, H. K., Gemechu, E., Thakur, U., Shankar, K. & Kumar, A. Life cycle assessment of high-performance monocrystalline titanium dioxide nanorod-based perovskite solar cells. *Sol. Energy Mater. Sol. Cells* **230**, 111288 (2021).
57. Angelakoglou, K., Botsaris, P. N. & Gaidajis, G. Issues regarding wind turbines positioning: A benchmark study with the application of the life cycle assessment approach. *Sustain. Energy Technol. Assess.* **5**, 7–18 (2014).
58. Heberle, F., Schifflechner, C. & Brüggemann, D. Life cycle assessment of Organic Rankine Cycles for geothermal power generation considering low-GWP working fluids. *Geothermics* **64**, 392–400 (2016).
59. Frischknecht, R. et al. The ecoinvent database: overview and methodological framework (7 pp). *Int. J. life cycle Assess.* **10**, 3–9 (2005).
60. Ahmed, A. et al. Environmental life cycle assessment and techno-economic analysis of triboelectric nanogenerators. *Energy Environ. Sci.* **10**, 653–671 (2017).
61. Alengebawy, A. et al. Understanding the environmental impacts of biogas utilization for energy production through life cycle assessment: An action towards reducing emissions. *Environ. Res.* **213**, 113632 (2022).
62. Christensen, T. H. et al. Application of LCA modelling in integrated waste management. *Waste Manag.* **118**, 313–322 (2020).
63. Prasad, S. et al. Sustainable utilization of crop residues for energy generation: A life cycle assessment (LCA) perspective. *Bioresour. Technol.* **303**, 122964 (2020).

Acknowledgements

The authors thank Research England who funded the research work on Supply Chain Innovation as part of the South Yorkshire Sustainability Centre. The authors thank UKRI for the funding of the research projects, and Energy Institute and AREC facility for their support.

Author contributions

M.S. initiated and designed the research, gathered data, did the LCA analysis, and wrote the first draft. S.C.L.K. additional assessments, validated the results, edited the first draft and provided comments and feedback on the text.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-024-01739-3.

Correspondence and requests for materials should be addressed to Moein Shamoushaki or S. C. Lenny Koh.

Peer review information *Communications Earth & Environment* thanks Paula PEREZ-LOPEZ and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: I-Yun Lisa Hsieh and Martina Grecequet. A peer review file is available.