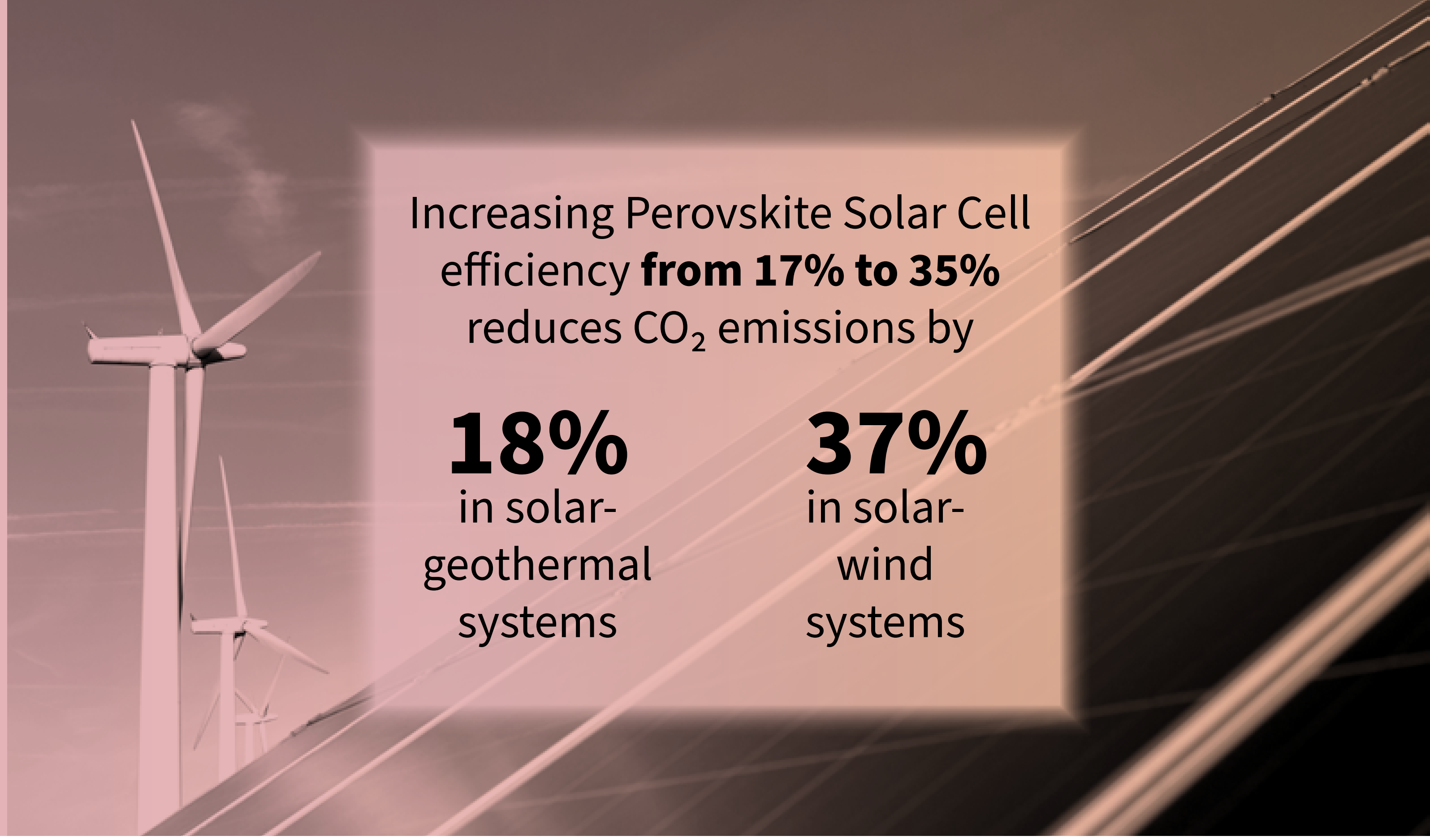
Hybrid Renewable Power Systems for Net-Zero: Life Cycle Evidence for Integrating Solar, Wind, Geothermal, and Perovskite Solar Cells

Project team:
University of Sheffield: Prof. Lenny Koh, Dr Moein Shamoushaki, Eleanor Borrill



Challenge Statement

The UK's net-zero transition relies heavily on the rapid expansion of renewable energy generation. While the deployment of renewable technologies is essential for decarbonisation, it also presents several challenges.

First, there are environmental trade-offs. Renewable technologies often carry high embedded impacts arising from manufacturing, raw materials extraction, and installation, particularly in hybrid power systems that combine multiple generation technologies.

Second, there remains a significant technology maturity gap. Perovskite solar cells (PSCs) are an emerging technology manufactured using alternative materials to conventional silicon solar cells. They offer advantages such as the capability to be manufactured on curved or flexible surfaces, along with rapid efficiency improvements over the last decade. However, they are currently constrained by short operational lifespans and toxicity concerns related to their material composition, particularly lead usage.

Additionally, the supply chains underpinning PSC deployment are vulnerable. Critical materials – including lead, silver, and indium tin oxide – face risks of scarcity, geopolitical disruption, and adverse environmental impacts from mining.

Finally, as renewable penetration increases, grid stability becomes a pressing concern. The variability of solar and wind generation introduces fluctuations in power supply that complicate integration and challenge system resilience.

Regional Relevance

Contribution of Research

Prior to this study, significant knowledge gaps existed: no comparative life cycle assessments (LCAs) had been conducted for integrated renewable-based hybrid power cycles, the integration of PSC technology into such systems had not been evaluated for sustainability trade-offs, and the effects of PSC lifespan and efficiency improvements on environmental performance were poorly understood.

This research addresses these gaps by delivering the first comparative LCA of three integrated renewable-based power cycles: combined geothermal-wind, combined solar-geothermal, and combined solar-wind. The study quantifies and compares the environmental impacts of these systems, explicitly incorporates PSC technology into solar-based configurations, and models system sensitivity to PSC lifespan (3-15 years) and efficiency (17-35%). It also identifies key environmental hotspots within hybrid systems and provides evidence to guide technology mix decisions that maximise sustainability and resilience.

Evidence and Outputs

Research Findings

In base case modelling, solar-wind systems demonstrate the lowest impacts on ozone depletion and climate change, while geothermal-wind achieves the lowest impacts in freshwater and marine ecotoxicity categories. Across all systems, improvements in PSC lifespan yield the greatest environmental benefits. Extending lifespan from 3 to 15 years reduces CO_2 emissions by 28% in solar-geothermal systems and 56% in solar-wind systems, with even a 7-year extension delivering a 49% reduction in greenhouse gas emissions in solar-wind. Efficiency improvements are also beneficial, though less significant. Increasing PSC efficiency from 17% to 35% reduces CO_2 emissions by 18% in solar-geothermal and 37% in solar-wind systems.

Environmental hotspots vary by technology. Geothermal well drilling is highly material-intensive, requiring steel, cement, and bentonite. Wind plant construction is dominated by impacts from steel, copper, and concrete. PSC manufacturing is a critical hotspot, with aluminium, chlorobenzene, and indium tin oxide glass contributing heavily to environmental burdens. Toxicity-related impacts, driven by lead, zinc, silver, and indium tin oxide, are less responsive to lifespan or efficiency improvements, underlining the need for material substitution strategies.

In best-case scenarios, certain environmental impacts - including terrestrial ecotoxicity, photochemical oxidant formation, and human toxicity - can be reduced by more than 88% relative to worst cases, demonstrating the significant potential of targeted interventions.

Published academic papers on this research project can be found here[1] and here[2].

1 Shamoushaki, M., Koh, S.C.L., Solar cells combined with geothermal or wind power systems reduces climate and environmental impact. Nature Commun Earth Environ 5, 572 (2024).
2 Shamoushaki, M., Koh, S.C. Lenny, Comparative life cycle assessment of integrated renewable energy-based power systems, Science of The Total Environment, 946, (2024).

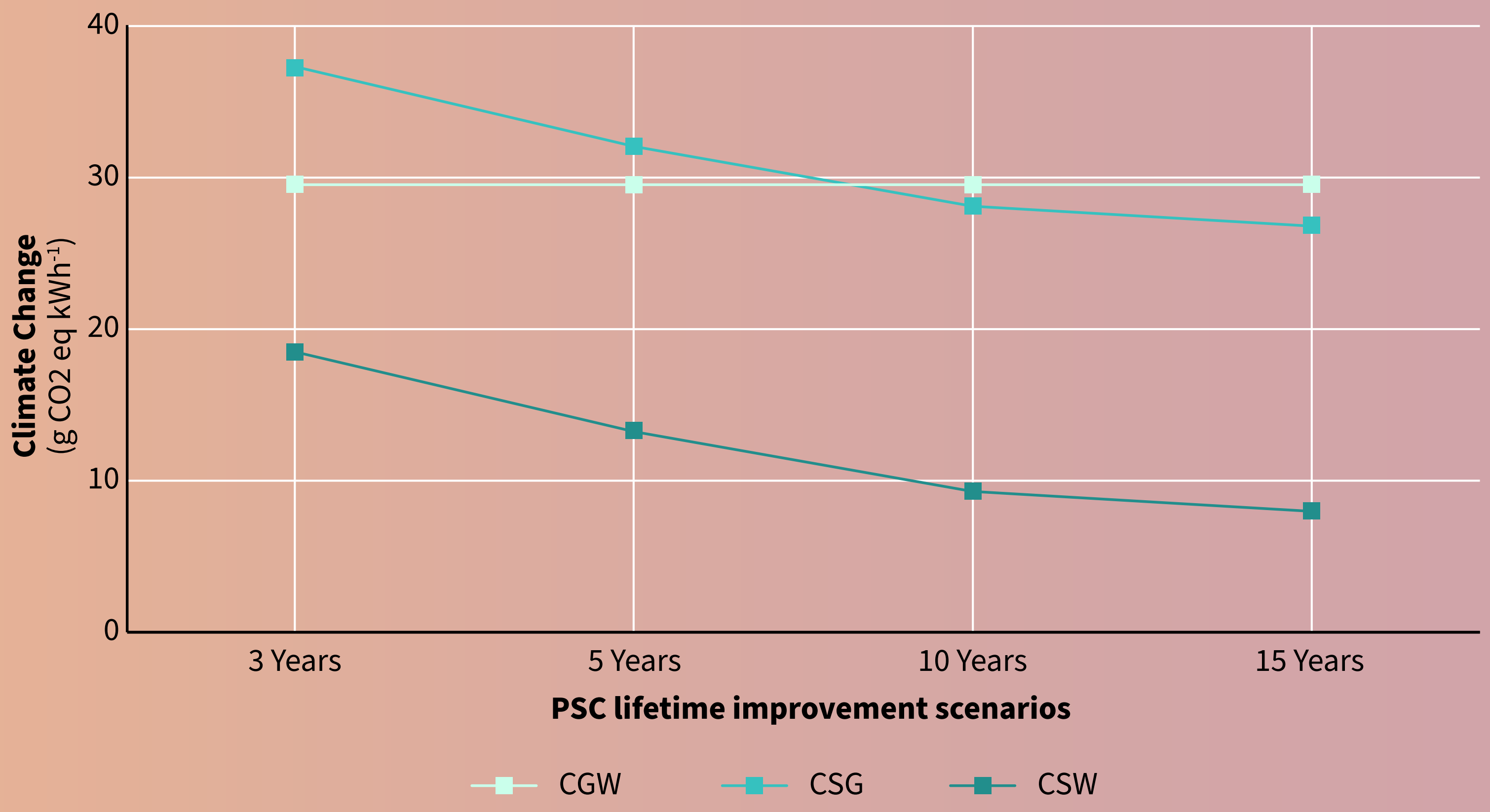


Figure 1: Variation in climate change impact per kWh electricity generated by each combined power system under scenarios of PSC lifetime improvement. Increasing the PSC lifetime from 3 to 15 years would reduce the climate change impacts of the solar-geothermal and solar-wind systems by 28% and 56%, respectively.

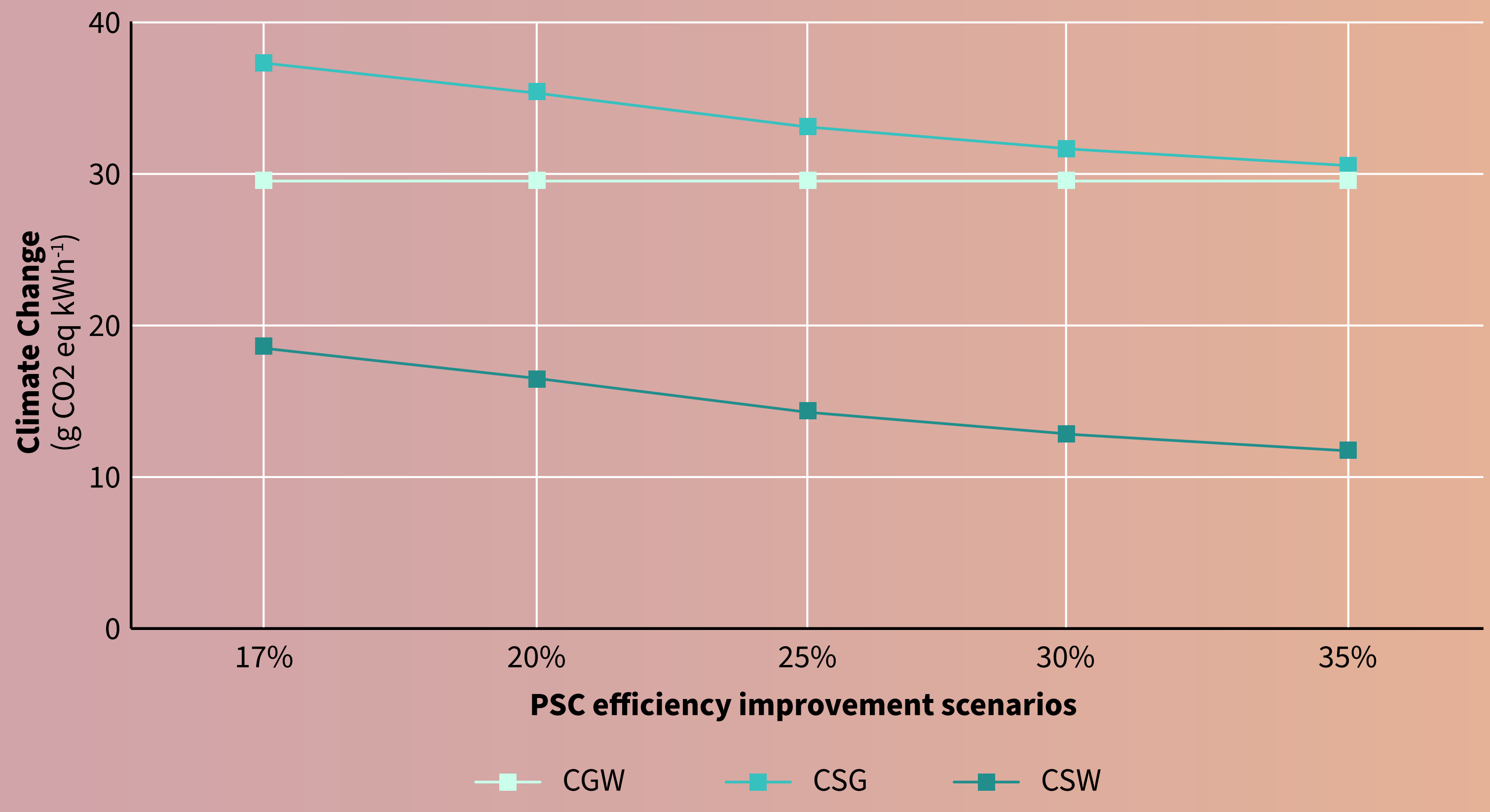


Figure 2: Variation in climate change impact per kWh electricity generated by each combined power system under scenarios of PSC efficiency enhancement. Increasing the PSC efficiency from 17% to 35% would reduce the climate change impacts of the solar-geothermal and solar-wind systems by 18% and 37%, respectively.

Scalability and Commercialisation

The study highlights global opportunities for scaling integrated renewable systems. In South Yorkshire, there is clear potential to develop local PSC component manufacturing and hybrid system assembly, drawing on the region's materials engineering expertise, established steel and advanced manufacturing base, and logistics infrastructure. Integrating this with the region's growing hydrogen and renewable energy capabilities would not only strengthen supply chain resilience and energy sovereignty but also provide the foundation for scaling deployment.

At the same time, scaling must account for the capacity requirements of both energy production and supply chains. Expanding hybrid renewable systems, particularly solar-wind and solar-geothermal, will require reliable access to critical materials, localised recycling pathways, and sufficient renewable energy generation to support manufacturing and operation.

Key Policy Insights

While the findings of this research hold global significance as renewable energy innovation and deployment accelerates worldwide, actionable recommendations can be drawn for South Yorkshire. The following section sets out key policy insights, building on the conclusions and recommendations drawn from the selected publications.

1. Continue to expand hybrid renewable energy systems.

   Build energy security and sovereignty by continuing to accelerate the transition to decarbonised energy systems using support from the UK government such as the Powering Up Britain: Net Zero Growth Plan (2023), the Powering Up Britain: Energy Security Plan (2023), the UK Renewables Deployment Supply Chain Readiness Study (2024), and the Strategy and Policy Statement for Energy Policy in Great Britain (2023).

2. Expand specialist skills training.

   The region should build on its strong academic and industrial base by working with Sheffield's universities, colleges, the AMRC Training Centre, and local industry to expand specialist skills provision. In order to ensure a skilled workforce capable of supporting large-scale deployment of hybrid renewable systems, the region should develop accredited courses and apprenticeships focused on PSC manufacturing, renewable energy integration, and sustainable construction. These initiatives will strengthen South Yorkshire's talent pipeline and position the region as a leader in advanced low-carbon technologies.

3. Develop circular supply chains

   The region should build on existing partnerships with the local steel, copper, and advanced materials industries, such as those demonstrated by Sheffield Forgemasters, Liberty Steel, and C F Booth Ltd in Rotherham, to further develop circular supply chains that recycle and repurpose key system components. In order to enhance resource efficiency and minimise waste, further regional initiatives should be established to repurpose PSC and hybrid system components at scale.

4. Position South Yorkshire as a national hub for hybrid renewable energy.

   In order to achieve net zero emissions by 2040, as outlined in the regional Energy Strategy, South Yorkshire should build on its strong engineering base, the AMRC's research infrastructure, the Energy Institute's capabilities, and the region's logistics network to pilot component production, develop PSC prototypes, and position itself as a national hub for hybrid renewable energy technologies.

5. Leverage housing retrofit and energy programmes.

   The region should continue to build on existing housing retrofit and energy efficiency programmes, such as the Home Upgrade Grant (HUG 2), Barnsley Council's Energy Efficiency Works, and the South Yorkshire Housing Association (SYHA) Retrofit Projects, to integrate locally manufactured PSC-enabled hybrid systems. This approach will stimulate local demand, support green manufacturing, and accelerate the region's transition to low-carbon housing.