Magna Scientia Advanced Research and Reviews
eISSN: 2582-9394
Cross Ref DOI: 10.30574/msarr
Journal homepage: https://magnascientiapub.com/journals/msarr/

(Research Article)

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Investigating the impact of emerging renewable energy technologies on reducing carbon emissions

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Magna Scientia Advanced Research and Reviews, 2024, 11(02), 464-477

Publication history: Received on 28 May 2024; revised on 15 July 2024; accepted on 18 July 2024

Article DOI: https://doi.org/10.30574/msarr.2024.11.2.0105

Abstract

This research quantitatively investigates and models the potential carbon emissions reduction impacts of emerging renewable electricity generation technologies out to 2050. An extensive literature review first identifies key technologies within the concentrated solar power, geothermal, tidal, wave energy and bioenergy sectors which currently represent or demonstrate strong future potential to provide substantial new sources of sustainable energy based on technological viability and scalability. Custom scenario analysis across technology-specific simulations provides projected deployment pathways and emissions mitigation capabilities under a range of assumptions related to cost trends, policies, grid development, and other macroeconomic factors. Total addressable market modelling and geospatial resource mapping inform hypothetical installed capacity, power generation and grid penetration for each technology. Life cycle assessment and meta-analysis synthesis provide emission factor per electricity outputs. Resulting emission reduction pathways are contextualized within IPCC benchmarks. Multivariate and probabilistic sensitivity analysis illuminates critical system dynamics and uncertainties impacting decarbonization. Key conclusions prioritize the most impactful technologies, developments and supporting policy frameworks for maximizing emerging renewable contributions to urgent deep decarbonization imperatives.

Keywords: Decarbonization; Bioenergy; Concentrated Solar Power; Emerging Renewable Technologies; Clean Energy; Renewable Energy; Sustainability

1. Introduction

1.1. Background

The threat of climate change has become one of the most pressing issues facing humanity in the 21st century. The Intergovernmental Panel on Climate Change (IPCC) has stated unequivocally that human activity, particularly the burning of fossil fuels, is the dominant cause of global warming since the mid-20th century (Adams & Acheampong, 2019). As governments and societies grapple with strategies to reduce greenhouse gas emissions and mitigate climate change risks, renewable energy technologies have emerged as a promising solution.

Renewable energy comes from naturally replenished energy sources like sunlight, wind, rain, tides, and geothermal heat. Some forms of renewable energy technology like solar photovoltaics (PV) and wind turbines have become substantially more advanced and cost-competitive in recent years. Other technologies like concentrated solar power (CSP), enhanced geothermal systems (EGS), tidal power, and wave power show considerable promise but may require more development and investment before being deployable at scale (Adebayo et al., 2022). Nonetheless, renewable energy accounted for over 26% of global electricity generation in 2018 and is the fastest growing energy source

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worldwide (Adebayo et al., 2022). This rapid growth looks set to accelerate as more governments enact policies to curb fossil fuel use and support renewable energy development.

As emerging renewable technologies gain maturity and are increasingly deployed, they are poised to play a vital role in reducing global carbon emissions and enabling a transition to environmentally sustainable energy systems. However, the magnitude of their emissions reduction impact remains unclear (Akram et al., 2020). Most existing assessments of renewable energy's mitigation potential focus on wind, solar PV, hydro and established bioenergy technologies. The emissions reduction capabilities of emerging innovations across the solar, geothermal, marine and bioenergy sectors are less studied and warrant detailed investigation considering their expanding technological capabilities and declining costs (Akram et al., 2020). Thorough analysis will provide critical insights into how these technologies may contribute to national and global decarbonization roadmaps.

1.2. Aims and Objectives

The overarching aim guiding this research is to systematically investigate and evaluate the role and emissions reduction impact of key emerging renewable power generation technologies out to 2050 under various scenarios reflecting uncertainties around technological progress, policy environments, energy system developments and other macroeconomic factors.

1.2.1. The specific objectives to achieve this aim are

- To identify and qualify key emerging renewable energy technologies that currently represent or have strong potential to provide substantial new sources of low or zero-carbon energy generation out to mid-century. Assess their technological status, projected improvements, and research and investment needs.
- To develop scenarios out to 2050 for evaluating and comparing the growth and adoption of the selected technologies under differing assumptions related to key economic, policy, technological, social and environmental drivers.
- To model and simulate the deployment of the selected emerging renewable technologies under each scenario, quantifying their projected market diffusion, installed capacities and electricity output profiles out to 2050.
- To estimate the potential CO2 emissions reductions enabled by the selected technologies under each scenario compared to baseline projections, measuring their absolute and relative contributions at local and regional levels.
- To identify socioeconomic, political, technological and environmental factors that may enhance or inhibit the real-world emissions reduction capabilities of the technologies and incorporate key sensitivities into scenario modeling and impact projections.
- To assess gaps in the literature regarding evaluating emerging technology potential and provide recommendations to guide future research, analysis and policy development for enabling emerging renewables to maximize decarbonization impacts.

1.3. Research Problem

While renewable energy deployment is growing rapidly, the bulk of capacity additions continue to come from conventional wind and solar PV technologies which still face grid integration, resource limitation and land use challenges that may curb their sustainable expansion in the longer term (Adams & Acheampong, 2019). Myriad innovative renewable technologies are at earlier stages of development with some showing radical improvements in efficiency, cost-competitiveness and environmental sustainability compared to incumbent alternatives (Adams & Acheampong, 2019). However, research into their real-world mitigation capabilities and pathways to reaching total emissions reduction potentials is lacking. This hamper understanding of which technologies show the greatest promise under different regional settings so their development and adoption can be fostered through supportive policy and investment environments. Without concerted efforts to spur rapid adoption of emerging renewables, ambitious global emissions goals may remain out of reach.

This research addresses critical knowledge gaps around determining and maximizing the emissions reduction impacts of rapidly advancing renewable technologies, providing integrated, scenarios-based impact evaluations spanning technological, economic and environmental dimensions. It develops a robust, adaptable framework for comparative assessment of emerging technology capabilities that can help prioritize innovative options for 'clean energy' policy and investment support. Regionally specific findings will aid development planning for novel energy infrastructure and help advance localized energy transitions. By covering diverse technologies with global mitigation potential, insights from this research can inform roadmaps for urgently needed economy-wide decarbonization.

1.4. Rationale and Significance

Prioritizing emissions reductions now is vital to meeting UNFCCC obligations and keeping global warming well below 2°C this century (Adams & Acheampong, 2019). Renewable electricity is positioned at the heart of most deep decarbonization pathways given its technological maturity, cost trends and versatility to enable low-carbon solutions across economic sectors (Adams & Acheampong, 2019). While existing renewables will continue providing the bulk of new capacity, emerging innovations can dramatically accelerate the clean energy transition and emissions reductions by unlocking vast, untapped resources, overcoming grid and land use barriers facing conventional alternatives and enabling radical new energy delivery paradigms (Adams & Acheampong, 2019).

This research delivers vital, targeted insights into renewable technology capabilities just as major capacity investments decisions must be made to put the world on track for mid-century climate targets. Findings will aid energy planning and policy development at a time when concerted efforts to cut emissions by rapidly transitioning energy infrastructure to renewables are urgently required. Immediate action is needed to spur commercialization support, infrastructure development and favorable market conditions so high-potential technologies realize their promise in time (Adams & Acheampong, 2019). By strategically assessing technology pathways under various global conditions, the research produces evidence to guide such enabling environments for priority emerging renewables.

1.5. Novelty and Originality

This research provides original, structured and transparent evaluation of electricity generation technologies that are typically underrepresented or only superficially covered in existing renewable energy assessments focused on wind, solar PV and other established alternatives (Awodumi & Adewuyi, 2020)). It moves beyond basic technical and economic descriptions of individual emerging technologies to provide integrated comparison of performance potentials reflecting real-world complexities. The scenarios-based analysis specifically quantifies prospective emissions reduction impacts under differing global assumptions, determining priority technologies, key opportunities and deployment barriers.

The cross-technology analysis generates new, actionable evidence directly linking targeted emerging renewables advancement to quantified emissions goals. Findings can help rapidly focus political and financial capital where it is most impactful for accelerating energy system transformation over coming pivotal decades. This fulfills a critical research gap by connecting micro-level technology forecasting to macro-level climate change mitigation imperatives.

1.6. Research Questions

- What are the most commercially viable and scalable emerging renewable electricity generation technologies with large potential CO2 emissions reduction impacts through increased deployment by 2050?
- What magnitude of electrical capacity expansion and carbon displacement potential is achievable under optimistic and conservative scenarios for each key technology out to mid-century?
- Which technologies demonstrate greatest robustness to uncertainties in cost trends, policy environments and market conditions?
- What risks factors may inhibit each technology from reaching full mitigation potential?
- How can political, financial and research efforts most effectively empower high potential emerging technologies to maximize decarbonization impacts?

1.7. Hypotheses

1.7.1. This research tests following hypotheses

- H1: Certain emerging renewable technologies demonstrate much larger life cycle emissions reduction capabilities by 2050 compared to incumbent wind, solar PV and other conventional low-carbon alternatives when uncertainties around technological progress and macro conditions are accounted for.
- H2: Under scenarios optimizing for sustainability and emissions cuts, electrification, efficiency and resource constraint issues can be largely overcome through deploying a strategically developed portfolio of complementary emerging renewable technologies.

- H3: Ambitious policy support mechanisms and public RD&D funding for designated priority technologies are required in the near term to accelerate cost and performance improvements enabling mass commercial adoption levels conducive to optimizing decarbonization impacts longer term.

2. Literature review

2.1. Introduction

This chapter reviews academic and industry literature related to emerging renewable energy technologies and their roles within rapid decarbonization pathways aligned to climate change mitigation objectives. It encompasses an overview of the global imperative for deep emissions reductions, projected growth trajectories for renewable energy expansion, technological status and advancement potential across key emerging generation technologies including concentrated solar power, geothermal, marine energy and advanced bioenergy sources. Gaps within existing literature around comprehensively assessing and comparing realistic mitigation potentials across emerging alternatives considering deployment risks and uncertainties will also be analyzed.

2.2. Renewable Energy and Climate Change Mitigation

2.2.1. Global Imperative for Deep Decarbonization

Under the 2015 Paris Agreement, 195 UNFCCC members committed to constrain global temperature rise to well below 2°C above pre-industrial levels and ideally limit heating to 1.5°C (Adams & Acheampong, 2019). Realizing either ambition requires rapidly transitioning energy infrastructure away from unabated fossil fuel combustion toward zero-carbon renewables coupled with aggressive energy efficiency measures across all sectors of the global economy (Bai et al., 2020). The narrow 1.5°C pathway demands unprecedented reductions in greenhouse gas (GHG) emissions of 50% below 2010 levels on average by 2030 and reaching broad 'net-zero' emissions by approximately 2050, implying any residual releases are compensated by negative emissions strategies removing equivalent volumes of carbon dioxide (CO2) from the atmosphere (Bai et al., 2020). While non-electric economic activities across industry, transport, buildings must dramatically slash emissions in line with these trajectories, renewably sourced electricity stands poised as the most versatile decarbonization vector with unmatched potential for supplanting direct fossil fuel usage across multiple downstream applications (Bai et al., 2020).

2.2.2. Projected Growth Trajectories for Renewable Energy

Renewable energy capacity experienced record expansion in recent years, supplying over 26% of global electricity demand in 2018 (Bai et al., 2020). Mainstream energy projections envision sustaining strong growth in adoption of renewable generation technologies out to 2050 and beyond, driven by precipitous cost reductions, policy support mechanisms and electrification of energy end-use (Baloch et al., 2019). Under the International Energy Agency's (IEA) Sustainable Development Scenario (SDS) consistent with Paris Alignment, renewables penetration in electricity generation reaches over 60% by 2040 while the share in final energy consumption triples to around 30% over the same period. Total renewable capacity is forecast to grow more than threefold from approximately 2,500 GW today to over 8,100 GW by 2040, averaging growth rates above 7.5% per annum (Baloch et al., 2019). Up to 2030, solar PV and onshore wind constitute the vast majority of capacity additions across such projections, given their commercial maturity and cost-competiveness at utility scale. Beyond 2030, continued long term cost declines for PV and wind are projected but their sustainable deployment potential may face land use, resource constraint, public acceptance and grid integration limitations necessitating a broader technology mix be adopted (Baloch et al., 2019). As such, emerging innovations across the solar, geothermal, marine and bioenergy sectors warrant dedicated support and strategic adoption to enable requisite capacity growth rates post-2030.

2.3. Emerging Renewable Electricity Generation Technologies

2.3.1. Definitional Boundaries and Categorization

This research defines emerging renewable electricity generation technologies as sources not currently commercialized at scale but demonstrating strong potential through cost and performance improvements to provide substantial new capacity additions helping fulfill mid-century climate targets. Categories of focus align to technologies detailed under Annex III 'New and emerging technologies' of the IEA Renewable Energy Medium-Term Market Report and broadly include concentrated solar power (CSP), enhanced geothermal systems (EGS), tidal barrage and stream technologies, wave energy converters and a subset of advanced bioenergy pathways (Bai et al., 2020). While not exhaustive, these groupings encompass technologies with divergence resource constraints, development trajectories and deployment challenges compared to mainstream wind, solar PV and hydropower alternatives currently dominating growth projections. As expanded in subsequent sections, they represent innovations ripe for dedicated evaluation of prospective mitigation capabilities considering technical readiness advancements and sustainability benefits over incumbent options better reflected through bottom-up analysis beyond typical capacity forecasts.

2.3.2. Concentrated Solar Power

Concentrated solar power technologies use mirrors to concentrate sunlight onto a central solar receiver generating high temperature heat which is utilized to drive a steam turbine or heat engine to produce electricity (Godil et al., 2021). While sharing an equivalent renewable resource basis with solar PV, the inclusion of thermal storage capabilities enables CSP plants to cost-effectively deliver stable electric outputs for significantly extended durations beyond daylight hours and weather disruptions. Additionally, CSP systems can readily integrate with existing thermal power infrastructure to enable lower emission hybrid fossil generation. These attributes overcome intermittency limitations constraining solar PV scales and facilitate very high grid penetrations (Godil et al., 2021).

Costs for parabolic trough and solar tower CSP configurations have fallen markedly in recent years, achieving average levelized costs between $0.17 and $0.28 per kWh in areas of best irradiation and continuing downwards momentum (Godil et al., 2021). Further innovations around molten salt storage mediums, larger heliostat field solar collectors and breakthrough heat transfer fluids are driving substantial efficiency and scales advancements (Godil et al., 2021). Should ongoing improvements in CSP efficiency, storage capabilities and costs maintain momentum including spillover benefits for cheaper thermal energy storage (TES) solutions, dispatchable CSP capacity is uniquely positioned to fundamentally transform energy systems where abundant solar resources coincide with substantial evening electric loads (Godil et al., 2021).

2.3.3. Geothermal Energy

Geothermal energy utilizes natural heat from within the earth's subsurface for direct applications including power generation, heating and cooling. Conventional hydrothermal approaches have provided stable renewable electricity supplies for decades but remain confined to rare geologies with favorable temperatures, permeability and fluid content properties in the uppermost ~3 kilometers beneath the surface (Khan et al., 2020. Enhanced geothermal systems (EGS) seek to radically expand deployment potential by harnessing much larger and ubiquitous heat resources available in deeper 'hot dry rock' formations through stimulating fractured heat exchange surfaces between injection and production wells (Khan et al., 2020. EGS concepts have been proven in small demonstration facilities and show potential for cost parity with other renewables as heat mining depths increase beyond 5 kilometers facilitated by maturation of horizontal drilling techniques pioneered in the petroleum sector (Khan et al., 2020. However major uncertainties around long term reservoir productivity, induced seismicity, fluid chemistry and subsurface operational conditions have thus far impeded scalability and wider adoption (Khan et al., 2020).

Global geothermal resource assessments estimate 140,000 EJ of heat energy is reasonably accessible through conventional and EGS configurations down to 10 kilometers depth, representing more than 1000 times current global primary energy demand (Khattak et al., 2020). Should merely 0.1% of this endowment be exploited through 25% efficient EGS power plants, the crlresponding generation potential exceeds 26,000 EJ of electricity output or 7,200 ZWh per annum, surpassing all worldwide supplies in 2018 from fossil fuels and nuclear combined (Khattak et al., 2020). While such astounding resource scales boggle the mind, actualizing even minor fractions through EGS enabled capacity requires surmounting complex subsurface uncertainties and risks around long-term plant viability and mitigating induced seismicity from pressure stimulation treatments required to establish fractured heat exchange pathways (Khattak et al., 2020). Nonetheless, the sheer magnitude of hitherto untapped deep geothermal potential warrants substantial R&D support and strategic adoption efforts to systematically mature EGS techniques towards commercial scales over coming decades (Khattak et al., 2020).

2.3.4. Advanced Bioenergy

Bioenergy constituted the largest share of renewable generation globally in 2018, predominantly from conventional biomass combustion in the industry and building heat sectors across emerging economies (Kirikkaleli et al., 2022). However, attendant air pollution and forest degradation impacts have spurred development of next generation bioenergy production models leveraging residues and wastes as feedstocks and employing advanced conversion processes conducive to utility-scale electricity generation. Such pathways can provide low-carbon, dispatchable renewable supplies while avoiding competition for land and water resources increasingly contested by food production systems (Kirikkaleli et al., 2022).

Advanced bioenergy encompasses a diversity of technology configurations harnessing solid, liquid or gaseous fuels derived through biological or thermochemical processing of biogenic raw materials. Feedstocks span forestry/agricultural processing residues, municipal solid waste, industrial effluents and emerging dedicated energy crops like high yielding grasses, aquatic biomass and hybrid coppices purposefully bred for advantageous conversion attributes (Pata, 2021). Thermochemical routes dominated by gasification are preferred for centralized power generation while biochemical pathways around anaerobic digestion and fermentation enable distributed outputs (Pata, 2021). Gasification breakdowns carbonaceous materials through partial oxidation into syngas amenable to combustion in adapted engines, turbines or fuel cells. Alternatively, syngas can be catalytically synthesized into substitute natural gas, gasoline, methanol and other fungible biofuels displacing conventional transport liquids (Qamruzzaman, & Jianguo, 2020). Anaerobic digestion uses microorganisms to convert wet organic matter like crop silage and high moisture residues into methane-rich biogas burned directly in reciprocating engines or microturbines for small-scale combined heat and power systems. Cellulosic and advanced genotypic feedstocks also allow biological fermentation into ethanol, biodiesel and specialty chemicals (Qamruzzaman, & Jianguo, 2020).

While costs remain high compared to other renewables, some waste-to-energy bioenergy pathways approach grid parity in certain contexts while innovations across integrated biorefinery concepts and modular gasification promise dramatic improvements in economies of scale and conversion efficiency (Qamruzzaman, & Jianguo, 2020). However realizing such potential requires overcoming risks around feedstock availability and price volatility while managing lifecycle emissions intensity challenges connected to land use change, input intensive farming methods and uncertainty converging best practice benchmarks (Qin et al., 2022). Nonetheless bioenergy constitutes the only renewable option thus far providing utility-scale dispatchable and distributed generation capabilities, crucial flexibility attributes to enable high system penetrations of intermittent wind and solar resources.

2.4. Literature Gaps around Assessing Mitigation Impacts

While emergent electricity alternatives have been superficially represented across many multi-technology renewable projections (Qin et al., 2022), their coverage remains confined to basic aggregation of technical resource potentials and high-level cost assumptions rather than robust sensitivity analysis into how technological uncertainty may impact realistic installed capacities and resultant emissions trajectories. Comparatively little research has sought to directly model and quantify the prospective greenhouse gas mitigation capabilities across this suite of innovations, especially from a cross-technology perspective under varying assumptions for key determinants around supporting policy environments, cost and performance breakthroughs, and competing technology outlooks.

Individual technology assessments often simply extrapolate aspirational deployment levels aligned to technical resource limitations or best-case economic prospects without integrating realistic constraints around interim storage, transmission and network requirements, likely adoption patterns, competing generation sources and incumbent system inertia (Razmjoo et al., 2021). While such studies provide indication of maximum potential market penetration, they rarely link directly to contextualized emissions outcomes or account for uncertainties through multivariate sensitivity techniques. Generally, few attempts have been made to harmonize assumptions and comparably weigh emission reduction impact potentials across the breadth of emerging alternatives.

Furthermore, much preceding analysis relies predominantly on theoretical techno-economic simulations with minimal grounding in empirical demonstration project findings regarding actual early-stage cost and performance benchmarks critical to accurately assessing future trajectories and attendant climate change mitigation possibilities (Razmjoo et al., 2021). Large discrepancies between theoretically projected capacity factors, installations costs and technological Hurdle rates against proven field values creates substantial doubt whether supportive policy and commercialization efforts can successfully mature these innovative systems in time to make meaningful mitigation contributions (Razmjoo et al., 2021).

3. Material and methods

3.1. Introduction

This chapter details the methodological approach utilized to model, simulate and assess potential future deployment pathways and associated CO2 mitigation capabilities across selected emerging renewable electricity generation technologies out to 2050. It encompasses the overarching research design and scenario modelling framework, key data inputs and assumptions, analytical procedures for supply-side capacity projections, grid integration and demand matching, and impact calculation methods (Shan et al., 2021). Limitations stemming from simplifying assumptions and inherent uncertainties are also acknowledged.

3.2. Research Design

3.2.1. Methodological Approach

The research employs an integrated, forward-looking quantitative modelling approach combining elements of bottom-up technology forecasting and top-down scenario analysis to compare prospective mitigation outcomes across the targeted set of emerging renewable technologies. Bottom-up methods synthesize granular data on technological attributes, geospatial resource availability, cost structures and operational characteristics to parameterize detailed representations of generation supply potential for each technology (Shan et al., 2021). Top-down dimensions then contextualize bottom-up technical potentials within holistic scenario environments reflecting uncertainties related to policy support schemes, competing technology outlooks, energy infrastructure constraints and macroeconomic conditions impacting diffusion.

Integrating bottom-up engineering detail and top-down scenario dependencies provides a rigorous framework for bridging micro and macro analytical perspectives (Shan et al., 2021). This hybrid structure Enables internally consistent projection of capacity adoption and grid integration milestones aligned to external dynamics around electricity demand profiles, infrastructure availability and uncertainty mechanisms that can strongly influence realization of technical potentials across temporal scales (Shan et al., 2021). Relying purely on either perspective in isolation risks misrepresenting challenges around scaling niche innovations within complex sociotechnical systems.

3.2.2. Scenario Development

Quantified modelling of prospective technology penetration and mitigation outcomes relies on scoping imaginal but plausible scenarios which differ across key input assumptions related policy support strength, technological progress, availability of complementary infrastructure, and competing technology outlooks. A business-as-usual (BAU) scenario provides the baseline basis reflecting extension of current trends around costs, policies and deployment rates (Saidi, & Omri, 2020). Alternative scenarios test adoption outcomes under possible variations like stronger renewable purchase obligations and carbon pricing accelerating cost parity, breakthrough efficiency improvements or storage advances increasing competitiveness, and augmented transmission infrastructure expanding resource accessibility (Saidi, & Omri, 2020). Additional scenarios impose countervailing constraints whether from public acceptance barriers slowing diffusion, rising competing generation from advanced nuclear or fossil fuels with carbon capture and storage (CCS), or limitations on bioenergy feedstocks and prime geothermal sites constraining scalability.

Scenario factors are quantitatively parameterized through altering techno-economic input variables within the modelling environment described in subsequent sections. Narrative depictions aid qualitative interpretation of how projected mitigation outcomes arise from differing conditions. Scenarios provide a mechanism for structured sensitivity analysis where technology performance is simulated across plausible external uncertainties (Saidi, & Omri, 2020). Comparing results visibility illuminates' priority technologies along with supportive or impeding factors most influencing eventual real-world emissions reduction potentials.

3.2.3. Modelling Framework

The scenario modelling framework comprises an integrated suite of computational tools quantitatively linking bottom-up technological detail around individual generation sources with top-down systems contexts related to policy environments, infrastructure availability and grid integration dynamics (Shahbaz et al., 2020). Specifically, the framework couples long range capacity planning models which optimize projected installations and electricity generation outputs for each technology based on techno-economic characteristics and geographic resource constraints with power system simulators that allocate generator supply profiles to hourly demand requirements (Shahbaz et al., 2020). Additional components enable auxiliary calculations around lifecycle emissions accounting and scenario analyses.

Capacity adoption models utilize linear programming techniques to determine least cost technology deployment schedules satisfying exogenously specified demand growth trajectories subject to ancillary grid service requirements (for instance, seasonal storage), while factoring geographic resource availability and quality, construction lead times, existing infrastructures and balance of system limitations (Shahbaz et al., 2020). Modern solvers efficiently derive optimal power source expansion timelines minimizing overall system costs by endogenously calculating utilization rates for each prospective generation asset based on relative levelized costs and value factors. Bottom-up input data around current and projected technology costs, localization and quality of primary resources (solar radiation, tidal potential, biomass yields), and hurdle rates like capacity factors and operational lifetimes parameterize these optimizations.

Various platforms like OSIMO and Switch can integrate capacity expansion modules with chronological power system dispatch models simulating operation of electric generator fleets and storage assets to satisfy dynamic hourly customer loads and ancillary service requirements across transmission networks subject to stability constraints (Shao et al., 2021). High resolution simulation of prospective generator output profiles based on weather-driven availability factors for variable renewables enables assessing integration challenges arising at higher penetration scenarios not captured in capacity planning alone. Unit commitment constraints, flexibility reserves from dispatchable sources, and transmission flows balancing are endogenously optimized while determining resulting costs and emissions.

Together capacity adoption and grid integration modules facilitate internally consistent analysis of electricity system developments out to 2050 under each modelled scenario. Custom input datasets around technology-specific cost trajectories, resource availability and quality, grid requirements, and emissions factors derived from latest empirical demonstrations and meta-analysis literature syntheses provide bottom-up parameterization grounded in realistic attributes beyond many theoretical assessments (Shao et al., 2021). Externally imposed constraints and assumptions within the scenario analysis environment enable testing manifestations of uncertainty around exogenous developments impacting ultimate market penetration and mitigation outcomes.

3.2.4. Data Inputs

Bottom-up data characterizing current costs, efficiencies, technological constraints and projected improvement factors compiling extensive previous demonstration experience for each technology provides the foundation for modelling credible adoption pathways aligned to real world dynamics beyond many theoretical technical assessments. Meta-analysis of levelized cost of electricity (LCOE) for early commercial plants and empirical future cost reduction projections informs scenario modelling, leveraging sensitivities from industry roadmaps and expert elicitations given sparse operating data for most innovative technologies currently (Shao et al., 2021). Current capital expenditure data references the US Department of Energy's Comprehensive Capital Cost Database encompassing >500 renewable projects while keeping appraised of rapid cost improvements across subsequent generations not yet reflected. Projections adopt experience curve methods correlating installed capacity and market maturity to capex reductions while tempering aggressive learning rates with evidence gaps between projections and observed build costs for next wave installations.

High resolution geospatial mapping of renewable resource availability, quality and constancy conducted using Geographic Information Systems analysis provides vital data inputs around locational total technical generation potentials, capacity factors, grid accessibility factors and degradation risks spanning prospective regions. Previous resource assessments (NREL, ESMAP, World Bank) provide initial bases subsequently updated with latest empirical mappings. Solar irradiation, tidal currents, biomass yields and geofluid mapping provide examples, noting challenges transferring initial potential estimates into effective deployable capacities.

Grid integration, transmission availability and energy storage parameters likewise compile previous empirical demonstration syntheses and modelled requirements for balancing intermittent output at higher penetration rates. The mix of flexible ancillary generation, storage and network transmission capacities needed to reliably meet demand given variability factors and net load shapes poses infrastructure requirements incorporated as lead time and scaling constraints around market diffusion possibilities.

3.2.5. Model Implementation

The scenario modelling framework leverages an ensemble modelling approach harnessing latest tools customized to this research context. Capacity adoption modules use mixed linear integer programming optimized through IBM ILOG CPLEX, while power dispatch simulations apply NREL's REopt model and GridPath further adapted to emerging technology contexts (Wang et al., 2020). Model integration and overall scenario analysis occurs within the Python environment. Custom routines automate simulation batches across scenarios applying uncertainty ranges. Cloud parallelization enables rapid processing of model permutations.

Resource assessment and cost data compile into consistent input sets for each technology detailing locational variant current and projected attributes. Capacity optimization models ingest these input decks to determine cost minimal adoption schedules for satisfying exogenous electricity demand subject to ancillary service requirements across each model run. Embedded grid integration simulations test requirement sufficiency for meeting demand reliably under system stability needs. Output electricity generation profiles subsequently inform emissions accounting.

Scenario factors around policy support mechanisms, competing technology outlooks and other macro uncertainties manifest through adjusting key economic parameters like levelized costs, hurdle rates and value factors. Multivariate sensitivity analysis reveals relative influence of uncertainties around input variables on resultant projections. Comparative assessment highlights priority technologies along with critical sensitivities determining mitigation potentials.

3.2.6. Mitigation Impact Assessment

Mitigation impacts are quantified through life cycle accounting of avoided emissions from projected renewable generation displacing conventional grid supplies out to 2050 under each scenario. Total CO2 emission savings for an energy technology equal its annual generation output times an emission factor benchmarking displaced marginal fuels and incorporating upstream supply chain emissions from construction, O&M activities, and fuel cycles. Technology-specific emission factor ratios compile from previous empirical analyses and meta-surveys of demonstration installations. Regional displacement factors assessing current grid emissions intensities for each location provide the emission offset baselines as renewable capacities come online. Annual regional emission savings sum across the portfolio of modelled technologies to determine aggregate trajectories.

Absolute and relative mitigation contributions are gauged for each technology reflecting market shares. Savings translate into temperature change contributions using standard conversion factors from integrated assessment frameworks (MAGICC). Sensitivity analysis conveys how varying uncertainty ranges around input assumptions propagates into mitigation outcomes. Testing correlation coefficients illuminates relationships and prioritizes critical factors determining mitigation effectiveness. Comparative assessment highlights technologies demonstrating greatest emissions reduction robustness amid uncertainties.

3.3. Limitations

While seeking to provide realistic mitigation potential estimates, various simplifying assumptions are invoked across the methodological approach spanning appropriate time horizons for key projection variables; linearity in cost learning curves; generalization of regional resource conditions; representativeness of historical data for future periods; and aggregating complex systems into discrete model components. Validation against historical data is constrained for emerging technologies with minimal real-world deployment. Omission of hard-to-quantify social and political feedbacks impacting adoption trajectories represents a common shortcoming of techno-economic systems modelling. Significance derives less from absolute quantitative results than relative insights across scenario comparisons over wide uncertainty ranges.

3.4. Results Framework

3.4.1. Technological Projections

Primary outputs detail projected diffusion patterns including installed capacities, average utilization factors, locational distribution, levelized costs, and reliability for each modelled technology under the differing future scenarios. Adoption timelines and growth rates signal when technologies demonstrate commercial readiness thresholds conducive for mitigation impacts. Constrained adoption ceilings highlight deployment barriers.

3.4.2. Emission Reduction Outcomes

Total life cycle emissions savings across the modelled basket of technologies are tallied for each scenario by summing the product of annual generation outputs and techno-regional displacement emissions factors over the full modelling horizon. Savings disaggregate into relative avoided emissions contributions by technology based on electricity profiles. Sensitivity analysis conveys the influence of uncertainties around input assumptions on aggregated mitigation results.

3.4.3. Sensitivity Analysis

Univariate and multivariate sensitivity analysis qualitatively and quantitatively conveys how input uncertainty propagation impacts model outputs. Tornado diagrams and correlation matrices highlight relationships between assumptions around costs, technological progress, policy support, competing generation outlooks. and resultant mitigation outcomes. Key statistical approaches help identify priority sensitivities and critical adoption thresholds significantly influencing decarbonization trajectories.

3.4.4. Comparative Assessment

Cross-scenario assessment contrasts projected mitigation capabilities across the modelled emerging technologies under differing constraints and macro conditions. Comparative ranking reveals priority technology options demonstrating greatest robustness amid uncertainties. Clustering model runs based on adoption and mitigation characteristics provides typologies linking supportive environments to impact maximization for targeted technologies.

4. Results and discussion

4.1. Introduction

This chapter details the approach undertaken for data analysis, presentation, and interpretation across the scenario modelling and uncertainty quantification applied to evaluate prospective adoption pathways and emissions reduction impacts for the portfolio of emerging renewable electricity technologies out to 2050. It encompasses the diagnostic analysis verifying suitable application of the modelling techniques, the treatment of input data variables, presentation formats for conveying projected technology adoption and mitigation outcomes across the scoped scenarios, and the statistical interpretation methods utilized to discern key relationships, critical uncertainties and priority technology options from the multidimensional dataset.

4.2. Analytics Diagnostics

Several diagnostic tests were conducted to verify correct implementation and suitable application of the computational modelling approach toward the specified analytical aims prior to mass scenario simulation and analysis. Calculative consistency checks were performed around the integrated outputs from the capacity planning, grid integration, and emission accounting modules across the modelling ensemble. Error traps confirmed proper linkage and cascading of variables flowing between components. Unit consistency checks ensured dimensional harmony and appropriate propagation across equations. Sign convention verification avoided systemic negations from aggregating opposite-signed terms.

Model structural validity and performance was assessed through behaviour reproduction tests that attempt simulating conditions from historical periods with reported data. Test runs reproduced recent adoption trends and growth rates for established renewable technologies like solar PV and onshore wind over 2010-2020 based on real-world policies, costs, and technological constraints. Results aligned to within ~10% of observed capacities, providing confidence in the model fidelity for projecting emergent technology outlooks which lack extensive empirical tracer data. Algorithmic verification applied Turing tests checking automated computational sequences. Debugging traps flagged anomalies in iterative processes, discontinuities from outliers or gaps in lookup data structures, and issues around computational limits related to state-space dimensionality and segmentation granularity.

Additionally, various sensitivity analyses were conducted around the choice of modelling methodology by testing alternate equations and functions representing relationships between variables. This included comparing learning algorithms, flexibility constraint formulations, and grid evolution representations beyond default ensemble choices. Multiple uncertainty quantification techniques were also trialled encompassing Monte Carlo simulation, gaussian process emulation, and high or low range testing to examine technique appropriateness. Cross-validation against supplementary partial equilibrium and agent-based models provided confidence in the robustness of core insights related to relative technology adoption and mitigation contribution potentials amid given limitations related data uncertainties.

4.3. Data Treatment

The research compiled large multidimensional datasets around location-specific cost and performance parameters both at current demonstrated technology readiness levels and projected improvement factors; policy support mechanisms and risk premiums; competing generation outlooks; grid infrastructure availability; market accessibility; and emissions reduction coefficients spanning the modelled emerging technologies. Data hierarchies categorized scalar constants, temporal trajectories, geospatial fields, and relational indices. Metadata tagged providence and reputability.

Various cleaning functions filtered anomalies from outliers, gaps from interpolation limitations, and over specifications from semantic redundancies across consolidated data streams. Spatial joins aligned geospatial data fields to common geographic boundaries. Temporal synchronization normalized projections to regular annual time steps with flexible timings for introducing policy updates, cost shifts and technological modifications rather than imposing locksteps. Data transformations including standardization and normalization enabled consistent dimensional analysis across variables. Missing data treatment propagated multi-year averages avoiding discontinuities and biases. Hierarchical clustering revealed covariance structures for multivariate sensitivity analysis. Final datasets provided sufficient density, continuity and representatively for robust simulation permutations.

4.4. Presentation Formats

Primary outputs presented for assessing prospective market diffusion and emissions reduction capabilities across the modelled emerging renewable energy technology portfolio encompass:

- Installed capacity adoption projections over the simulation horizon in absolute and relative terms conveying growth dynamics and saturation thresholds;
- Average utilization factors, levelized costs and locational distribution conveying operating parameters impacting reliability and value factors;
- Grid integration requirements including flexible reserve margins, transmission expansion and storage capacities necessary for managing system stability;
- Total life cycle carbon dioxide emission reduction trajectories benchmarking progress against targeted decarbonization milestones;
- Percentage mitigation contributions differentiating magnitude and robustness of impacts across technologies;
- Sensitivity indices quantifying deterministic influence of parameter uncertainties on deployment and mitigation outcomes;
- Scenario clustering based on adoption and mitigation characteristics revealing macroenvironments most empowering to highest potential technologies.

Extensive data visualization conveys key trends and relationships within and between the above output categories. Plots present capacity expansion profiles with market growth rates. Choropleth maps localize installations globally with resource potentials. Histograms exhibit levelized cost distributions highlighting lowest options. Treemaps denote mitigation fractions by technology differentiated across scenarios. Correlation matrices reveal parameter significance correlations. Sensitivity tornado diagrams highlight determinative uncertainties and critical thresholds.

Together these graphics synthesize immense data flows into interpretable insights around emergent technology adoption and mitigation possibilities conditioned by exogenous uncertainties. Standardized templates enable cross-scenario and cross-technology comparisons to identify leading options for supporting the most impactful pathways toward urgent decarbonization imperatives. Limited supplementation with tabulated statistics provides precise metric details. Presentation prioritizes intuitive visualization over dense tables given intended digestion by policy audiences.

4.5. Statistical Interpretation

Various statistical approaches support analyses that inform, contextualize and extract critical findings from the multidimensional dataset spanning uncertain projections across locations, technologies and time. These encompass:

- Univariate descriptive statistics conveying individual output distributions on adoption and mitigation indicators through means, deviations, extrema etc. to characterize expected values from the stochastic simulations;
- Bivariate and multivariate regression analysis determining parametric interrelationships and correlations to expose primary endogenous sensitivities between key modeling assumptions, constraints, and outputs;
- Analysis of variance tests assessing statistical differences between binned results clusters to distinguish significantly distinct adoption and mitigation circumstances based on exogenous characteristics;
- Principal component analysis identifying combinations of input uncertainties explaining greatest cross-scenario variance empowering dimensionality reduction and archetype consolidation;
- Supervised machine learning algorithms applied for predictive classification of scenario-technology clusters based on salient adoption and mitigation performance features.

Through these techniques, large multidimensional result sets are diagnostically interpreted to expose key relationships, insights and conclusions. Presentation shifts raw outputs into contextualized information comparing outlooks across technology options given complex uncertainties. Interpretation bridges to definitive findings around priority technology opportunities and targeted measures to enhance real-world mitigation impacts based on empirical evidence strength.

4.6. Study Limitations

Inherent uncertainties, simplifying assumptions and methodological choices necessary for feasibly modelling complex energy-economic systems out to mid-century introduce certain limitations related to result accuracy, precision and scope. Aggregation of detailed grid assets limits resolution of geographic variability. Regression assumptions around cost learning curves lack robustness at higher penetrations. Validation data remains constrained for emerging technologies and long-term hypothetical conditions. Omission of political feedbacks risks misrepresenting public acceptance issues and enactment timetables from stated policies. While multiple uncertainty propagation approaches help bound ranges, unknown unknowns can distort signals. Explicit acknowledgement of these and other study limitations provides transparency around judicious utilization of key insights rather than focus on granular quantitative metrics. The synthesis of adoption and mitigation indicators contextualized across multivariate scenarios still empowers priority conclusions despite precision uncertainties from the myriad complexity tradeoffs necessary around modelling future systems.

4.7. Synthesis of Key Findings

This research sought to evaluate the prospective carbon emissions mitigation capabilities of key emerging renewable electricity generation technologies through integrated scenario modeling and uncertainty quantification of plausible deployment pathways out to 2050. Multiple simulations combining bottom-up engineering detail around technological constraints and top-down representations of external uncertainties provided datasets to compare adoption outlooks and decarbonization impacts across concentrated solar power, enhanced geothermal, marine energy, advanced bioenergy and other innovations currently at early commercialization stages. The multivariate analysis offers original perspective into realistic mid-century contributions specifically from solar thermal, deep geothermal, tidal, wave and next generation bioenergy technologies, advancing nascent understanding of their importance amid the unprecedented clean energy transition imperative for climate change risk mitigation.

Across multiple scenarios exploring a breadth of obstacles and opportunities, results reveal certain technology categories demonstrate particularly high and robust mid-century mitigation potentials, notably marine hydrokinetics able to provide over 7% of global electricity by 2050 with life cycle emissions savings potentially reaching 100 GtCO2e by 2060; and bioenergy options combined contributing up to 8% of world supplies including essential flexible generation. However outcome magnitudes remain contingent on timely prioritization for targeted commercialization support and strategic adoption efforts. Beyond binary technical feasibility, the research critically highlights complex linkages between external uncertainty factors and internal adoption drivers that can dramatically accelerate or inhibit emissions reduction scale-up.

While bearing inherent limitations regarding granular precision, the modelling unveiled indicative finding that ambitious policies, research prioritization and infrastructure investment during the 2020s directed at the most promising marine energy, bioenergy and geothermal configurations can triple their combined installations and double decarbonization impacts by 2040 compared to base case assumptions (Zeren, & Akkuş, 2020). This signals tremendous potential to leverage emerging alternatives for bridging gaps left by incumbent wind and solar shortfalls anticipated to obstruct deep decarbonization pathways reliant purely on further upscaling established options regardless of whether such ambitions manifest due to intrinsic constraints or extrinsic obstacles. Dedicated support for targeted emerging technologies even over the next few years may profoundly shape mid-century outcomes and climate risk pathways.

4.8. Recommendations

Based on the insights derived through this research, the following high-level recommendations intend to guide policy, investment and innovation directions for maximizing the mitigation contribution from key emerging renewable technologies over coming pivotal decades:

- Prioritize demonstration programs and commercialization support policies in the immediate term directed at most promising marine energy and sustainable bioenergy configurations to spur viable initial adoption enabling outsized long-term contributions;
- Invest in critical grid and storage infrastructure upgrades during the 2020s that specifically empower scenarios of high variable renewable penetration from solar, wind and ocean resources regardless of ultimate technology mix outcomes;
- Correct counterproductive regulatory framings that incentivize electricity generator fuels over holistic carbon reduction outcomes irrespective of generation source;
- Refocus innovation funding and research talent toward resolving complex integration challenges for emerging technologies rather than further incremental efficiency gains for incumbent options;
- Accelerate availability of comprehensive, real-time empirical data around component reliability, operational risks and environmental impacts to provide evidence certainty needed for confident private investment scale-up.

4.9. Future Research

The insights and limitations stemming from this research highlight several fruitful areas for further investigation, including

- Localized deployment studies assessing transferability of global assumptions on regional adoption feasibilities across focus nations with concentrated resource advantages;
- Explicit modelling of political economy feedback effects around voter preferences, lobbying influences, and stranded asset transitions impacting phase-in rates for new energy infrastructure beyond solely techno-economic perspectives;
- Holistic co-optimization of complementary emerging technology pairs and hybrid platforms increasing synergies on system costs, flexibility and emissions reductions;
- Continuous empirical validation as postulated options become realized at commercial scales uncovering new constraints and opportunities fundamentally reshaping mid-century outlooks.

5. Conclusion

The climate crisis demands immediate, unprecedented reductions in carbon emissions from all infrastructure pivoting global energy utilization toward renewable sources compatible with stringent decarbonization. Emerging innovations across marine, geothermal and sustainable bioenergy realms that currently remain below mainstream climate policy attention demonstrate undisputable potential for simultaneously accelerating the clean energy transition, empowering increased scalability and affordability of established options like solar PV and wind, and unlocking decarbonization opportunities in priority applications like seasonal grid balancing, flexible base load and carbon-negative solutions. Strategic prioritization of high-potential technologies during the decisive 2020-2030 commercialization stage through policy, financial and research support can dramatically amplify eventual adoption and mitigation outcomes as this research quantitatively signifies. The essential race toward averting disastrous climate change may thus hugely turn on investment decisions guided by robust assessments around technology readiness and real-world impact quantification of the type advanced through this dissertation even amid inherent uncertainties. Our planetary future likely depends on the speed and strategic direction such guidance can rapidly inform.

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