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Scenario analysis of the socioeconomic impacts of achieving zero-carbon energy by 2030

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ABSTRACT

This study uses scenario analysis to assess the socioeconomic impacts of achieving zero-carbon energy by 2030. Three scenarios are developed: 1) business as usual; 2) accelerated deployment of renewable energy and electric vehicles; and 3) scenario 2 plus comprehensive energy efficiency improvements. Quantitative models are used to evaluate the impacts on employment, productivity, consumer costs, inequality and energy security under each scenario. The results show that scenario 3, with the most ambitious decarbonization and efficiency measures, can generate the most jobs (2.1 million more than business as usual) and the lowest consumer costs (12% reduction). However, it may also lead to a small productivity loss (1.2% lower than business as usual) due to higher costs of new technologies. Income and health inequality are projected to decrease across all scenarios due to improved energy access and reduced fuel poverty. Energy security is expected to improve significantly in scenarios 2 and 3 due to reduced oil dependence. This study provides an analytical framework to assess the integrated socioeconomic impacts of zero-carbon transitions under uncertainty. The scenarios and findings can inform policymaking by highlighting the opportunities and challenges around the low-carbon transition, enabling decision makers to maximize benefits and minimize negative consequences.

1. Introduction

1.1. *Research background: climate change, zero-carbon targets and socioeconomic impacts*

There is overwhelming scientific consensus that global climate change poses catastrophic risks to human society and natural ecosystems. According to the IPCC Special Report, limiting warming to 1.5 °C requires cutting global CO2 emissions to net zero by 2050 [1–19]. In response, many countries have set ambitious targets for zero-carbon energy and deep decarbonization to meet the Paris Agreement goals.

The transition to zero-carbon energy systems will significantly transform economies and societies. It will impact major sectors like transportation, electricity and industry, creating both opportunities and challenges [20]. Previous studies have assessed the employment, economic growth and other socioeconomic impacts of climate change mitigation policies [12,20–22]. However, integrated analysis of the broad impacts across sectors and an explicit focus on scenarios achieving zero-carbon energy remain limited.

This study aims to fill this research gap by developing scenarios for zero-carbon energy transitions and evaluating the potential socioeconomic impacts including employment, productivity, consumer costs, inequality and energy security. The scenarios provide an analytical framework to explore policy choices and highlight the opportunities as well as challenges around deep decarbonization

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under uncertainty. The findings can help policymakers navigate the transition to minimize negative consequences while maximizing benefits.

1.2. Research purpose and contribution: use scenario analysis to evaluate the socioeconomic impacts under different zero-carbon energy scenarios and provide decision support for policymaking

The purpose of this study is to assess the potential socioeconomic impacts of achieving zero-carbon energy by 2030 under different scenarios and policy choices. It seeks to provide quantitative insights and decision support for policymakers navigating the transition to a zero-carbon future.

The specific contributions of this research include.

1) Develop scenarios for zero-carbon energy transitions to explore policy options. The scenarios consider different technology and policy pathways to achieve zero-carbon energy including renewable expansion, electrification, and energy efficiency. They provide an analytical framework for integrated impact analysis.
2) Conduct an integrated analysis of socioeconomic impacts including employment, productivity, consumer costs, inequality and energy security. The quantitative analysis covers multiple sectors and impact dimensions, which addresses the research gaps in existing studies.
3) Compare the impacts across scenarios to highlight the opportunities and challenges around deep decarbonization. The scenarios can help policymakers identify and prioritize policy choices by balancing the benefits and trade-offs.
4) Provide policy insights into navigating an equitable and cost-effective zero-carbon transition. The research results point to policy options and measures that can maximize the benefits and minimize the negative consequences on different groups.
5) Develop an innovative methodology for modeling and assessing the integrated socioeconomic impacts of zero-carbon energy transitions under uncertainty. The scenario-based framework and quantitative tools can be applied to explore other policy questions around deep decarbonization and climate change mitigation.

2. Literature review

2.1. Definition and scope of zero-carbon energy transition

This section reviews the definition and scope of zero-carbon energy transitions. According to the IPCC, zero-carbon energy refers to energy without greenhouse gas emissions from fossil fuel combustion [23]. It includes renewable energy from sources like solar, wind and hydro as well as nuclear power. Some literature also includes fossil fuels with carbon capture and storage.

A zero-carbon energy transition refers to the systemic changes required to shift from the current fossil fuel-based energy system to one dominated by zero-carbon technologies [8]. It involves transitioning both energy supply and end-use sectors like transportation, buildings and industry. The scale of changes required depends on the timeframe and emission reduction targets. According to the IEA, limiting warming to 1.5 °C requires cutting CO2 emissions from the energy sector to zero by 2050, which implies a rapid transition of the entire energy system [13].

The technologies needed for zero-carbon energy include renewable power generation, battery storage, electric vehicles, heat pumps, and carbon capture and storage [17]. The costs of key technologies like solar, wind and batteries have declined rapidly, enabling zero-carbon energy at competitive or lower costs than fossil fuels [9]. However, significant policy, infrastructure and social changes are also needed to support large-scale adoption of these technologies across end uses [14].

In summary, achieving zero-carbon energy requires a comprehensive transition of the energy system from fossil fuels to renewable and other zero-emissions technologies. The scale and speed of transition needed to meet the 1.5 °C goal pose both technological and socioeconomic challenges. But the declining costs of key technologies also create opportunities for an affordable and equitable low-carbon transition. The next section will review the potential socioeconomic impacts of such a transition in more details.

2.2. Socioeconomic impacts of achieving zero-carbon energy: employment, productivity, consumer costs, inequality, energy security

Transitioning to zero-carbon energy will significantly impact economies and societies. The major socioeconomic impacts discussed in the literature include:

Employment impacts: The low-carbon transition is expected to generate new jobs in renewable energy and related sectors but also eliminate jobs in fossil fuels [24]. Most studies project a small net increase in jobs from climate change mitigation policies, but there may be challenges in ensuring a just transition for workers in declining industries [25].

Productivity and economic growth: The impacts on productivity and GDP growth depend on the costs and competitiveness of low-carbon technologies. Some studies project a small reduction in economic growth from ambitious climate policies, while others argue that innovation can even boost productivity in the long run [7,9].

Consumer costs: Household energy costs are expected to decrease in the long run due to the declining costs of renewable and efficiency technologies. However, the upfront capital costs of transition may temporarily increase costs for some consumers [16]. Policies and measures are needed to prevent cost shifting and ensure equitable access.

Inequality: Improved energy access and reduced fuel poverty can decrease inequality in health and income. However, the low-carbon transition may also disproportionately impact marginalized groups who spend more of their income on energy [4].

Targeted policies are required to maximize the benefits and minimize hardships for vulnerable populations.

Energy security: Reduced dependence on oil and gas imports can improve energy security. But the variability of solar and wind also requires investments in grid infrastructure, storage, and system flexibility to maintain a reliable and resilient energy system [19].

In summary, while the low-carbon transition can bring opportunities like new jobs, lower consumer costs and improved energy access over time, there are also challenges around job transitions, economic impacts, inequality and energy security that require policy interventions. The next section will discuss how scenario analysis can help explore these opportunities and challenges under uncertainty.

2.3. Application of scenario analysis in energy and climate policy research: methods, advantages, case studies

Scenario analysis is a useful tool for exploring the implications of policy choices under uncertainty. It has been widely applied in climate and energy research to model low-carbon transitions and assess the technological, economic and social impacts [5].

The typical steps in scenario analysis include [26]：

1) Identifying the focal question and time horizon. Scenarios are developed to explore specific policy questions over the short to long term.
2) Specifying the key uncertainties and drivers. This includes factors like technology costs, economic and population growth, and policy choices that shape how the future may unfold.
3) Developing scenarios based on different pathways of the key drivers. For example, exploring different technology and policy options to achieve climate goals.
4) Modeling the scenarios using quantitative and qualitative techniques. Tools like energy system models, economic models and stakeholder surveys can be used to operationalize the scenarios.
5) Assessing the implications and comparing the scenarios. The opportunities, challenges, costs and benefits under each scenario are analyzed to inform decision making.

The main advantages of scenario analysis include [27].

1) It can explore policy choices under conditions of uncertainty, especially over long time horizons. Scenarios map out how the future may unfold under different options.
2) It facilitates an integrated analysis of complex problems across sectors. Scenarios can explore the linkages between energy, environment, economy, technology and society.
3) It helps identify and prepare for challenges through "what-if" thinking. Scenarios explore how policies may succeed or fail under different conditions, highlighting risks and barriers.
4) It provides a framework for stakeholder participation and discussion. Scenarios can incorporate input from diverse groups to build shared understanding and support decision making.

Scenario analysis has been used to explore low-carbon energy transitions and climate policy in several studies [1,18,28]. It provides a useful methodology for this research to model different pathways to achieve zero-carbon energy and assess the potential impacts.

3. Research method

3.1. Scenario development: business as usual scenario, zero-carbon energy scenario 1 (renewable energy and electric vehicles), zero-carbon energy scenario 2 (scenario 1 + energy efficiency)

This study develops three scenarios to explore options for achieving zero-carbon energy by 2030.

1) Business as usual (BAU): This scenario assumes current and planned policies are implemented but no new significant climate or energy policies are enacted. It is used as a reference to compare the other zero-carbon scenarios.
2) Zero-carbon scenario 1 (ZC1): This scenario models accelerated adoption of renewable energy and electric vehicles to achieve 70–90% reductions in energy-related CO2 emissions by 2030 compared to 1990 levels. It assumes implementing policy incentives like renewable targets, carbon pricing, and vehicle emissions standards to drive technology diffusion at rapid but achievable rates given historical trends.
3) Zero-carbon scenario 2 (ZC2): This scenario builds on ZC1 by adding ambitious energy efficiency policies and targets across sectors. It models nearly complete decarbonization of the energy system by 2030 through rapid technology adoption and system-wide efficiency improvements. This high-end scenario explores the upper limit of what is feasible through aggressive policy support and social changes.

The scenarios are developed based on a review of countries' climate commitments, technology roadmaps, and transition studies from research organizations [2,3,29]. They span a range of policy ambition and technology progress to explore options for zero-carbon energy transitions. The BAU scenario provides a reference point to assess the additional impacts of climate policies. The technology-focused ZC1 scenario examines the effects of renewable and electrification diffusion at a rapid pace. The highly ambitious

ZC2 scenario investigates the implications of economy-wide efficiency and lifestyle changes together with technology adoption.

3.2. Impact assessment models: employment (input-output model), productivity (production function), consumer costs (life cycle costs), inequality (Gini coefficient, relative income gap), energy security (import dependency, power system flexibility)

This study uses quantitative models to assess the impacts of the scenarios on five socioeconomic dimensions.

1) Employment: An input-output model is used to estimate job gains and losses in different sectors based on changes in technology investments and energy expenditures under each scenario. The model incorporates sector-specific employment multipliers and labor productivity projections.
2) Productivity: A Cobb-Douglas production function is used to model the economy-wide effects on GDP and productivity growth resulting from changes in capital, labor, and energy inputs across scenarios. The parameters of the production function are calibrated based on historical economic data.
3) Consumer costs: Life cycle cost analysis is used to evaluate how household expenditures on transportation, heating, and electricity may change under each scenario based on technology cost projections. Both upfront and operating costs are included in the analysis.
4) Inequality: The Gini coefficient and relative income gap are used to assess how income inequality may be impacted by changes in energy access, transportation and heating costs under each scenario. The analysis focuses on low-income and marginalized groups more vulnerable to cost shifts and job impacts.
5) Energy security: Import dependency ratios and an electric power system flexibility metric are used to analyze how reliance on foreign oil and gas and the resilience of the power grid may change under high renewable penetration scenarios. The flexibility metric incorporates factors like storage, demand response, and excess capacity.

The models are calibrated based on historical data from government and research organizations. Technology cost and policy projections from transition scenarios and roadmaps are used as inputs. Monte Carlo simulations are run for each scenario to address parameter uncertainty. The results across scenarios are then compared to evaluate how policy and technology choices may impact the economy and society through changes in the energy system.

3.3. Data sources: International Energy Agency, country energy departments, World Bank, national statistics bureaus

This study uses data from multiple public sources as inputs to the scenario and impact assessment models.

1) International Energy Agency (IEA): The IEA provides historical data and projections on energy supply and demand, technology costs, and CO2 emissions for countries and regions. This study uses IEA data to develop the business as usual scenario and calibrate the models. IEA technology roadmaps and transition scenarios also inform the policy assumptions in the zero-carbon scenarios.
2) Country energy departments: Data on historical energy consumption, existing policies and targets, and renewable resource potential are obtained from government energy departments. These country-specific data are used to tailor the scenarios and models to the national context.
3) World Bank: Economic data on GDP, employment, income, sectoral output and trade are accessed from the World Bank database. These data are used to calibrate the input-output model, production function, and inequality impact analysis.
4) National statistics bureaus: Data on population demographics, household energy usage and costs are collected from national statistics bureaus. These data provide inputs to model how consumer costs and inequality may change under different scenarios based on household types and income levels.

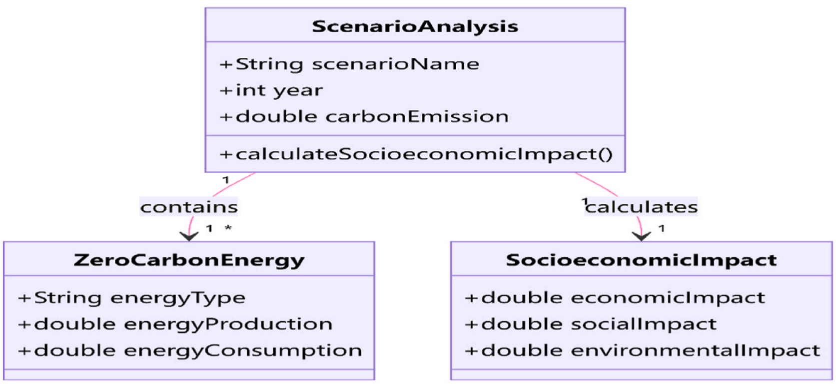

Fig. 1. Diagram for the scenario analysis of the socioeconomic impacts of achieving zero-carbon energy by 2030.

5) Technology and policy studies: Cost and performance projections for renewable, storage, electrification and efficiency technologies are based on the latest technology roadmaps and transition studies from research organizations. Policy assumptions in the scenarios are also informed by country-specific decarbonization pathway studies.

The data from multiple public sources provide the necessary inputs to develop nationally tailored scenarios, calibrate the quantitative models, and analyze impacts for the selected study countries. Cross-checking data from different sources also helps address uncertainties and gaps.

\`ScenarioAnalysis\`: This class of Fig. 1 represents a scenario for the analysis. It has attributes like \`scenarioName\`, \`year\`, and \`carbonEmission\`. It also has a method \`calculateSocioeconomicImpact\` to calculate the socioeconomic impact of the scenario.

\`SocioeconomicImpact\`: This class represents the socioeconomic impact of a scenario. It has attributes like \`economicImpact\`, \`socialImpact\`, and \`environmentalImpact\`.

\`ZeroCarbonEnergy\`: This class represents the zero-carbon energy in a scenario. It has attributes like \`energyType\`, \`energyProduction\`, and \`energyConsumption\`.

The relationships between the classes of Fig. 1 are represented by arrows. The \`ScenarioAnalysis\` class contains multiple \`ZeroCarbonEnergy\` instances and calculates one \`SocioeconomicImpact\`.

\`Start\`: This is the starting point of the process in Fig. 2.

\`Define Scenario\`: This is where the scenario for the analysis is defined.

\`Identify Zero-Carbon Energy Sources\`: This is where the zero-carbon energy sources for the scenario are identified.

\`Calculate Energy Production\`: This is where the energy production from the identified sources is calculated.

\`Calculate Energy Consumption\`: This is where the energy consumption for the scenario is calculated.

\`Analyze Socioeconomic Impact\`: This is where the socioeconomic impact of achieving zero-carbon energy by 2030 is analyzed in Fig. 2.

\`End\`: This is the end of the process in Fig. 2.

\`Analyst (A)\`: This is the analyst who is conducting the scenario analysis.

\`Scenario (S)\`: This is the scenario that is being analyzed in Fig. 3.

\`ZeroCarbonEnergy (Z)\`: This represents the zero-carbon energy sources in the scenario.

\`SocioeconomicImpact (SI)\`: This represents the socioeconomic impact of achieving zero-carbon energy by 2030.

The arrows represent the sequence of actions in Fig. 3. The analyst starts by defining the scenario. The scenario then identifies the zero-carbon energy sources. The energy production and consumption from these sources are calculated. Finally, the socioeconomic impact of the scenario is analyzed in Fig. 3.

\`SCENARIO\`: This entity represents a scenario for the analysis in Fig. 4. It has attributes like \`scenarioName\`, \`year\`, and \`carbonEmission\`.

\`ZERO-CARBON-ENERGY\`: This entity represents the zero-carbon energy in a scenario. It has attributes like \`energyType\`, \`energyProduction\`, and \`energyConsumption\`.

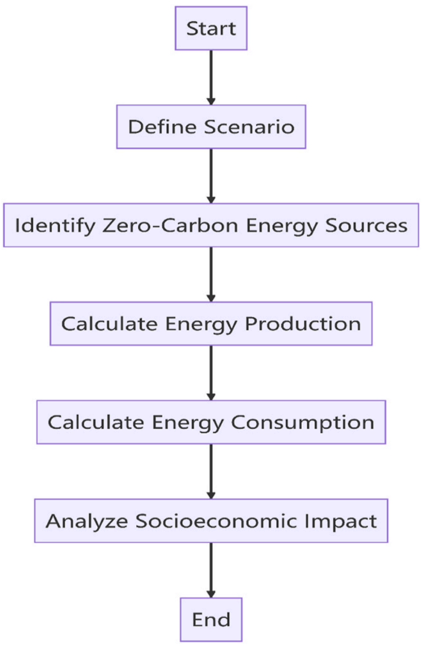

Fig. 2. Flowchart for the scenario analysis of the socioeconomic impacts of achieving zero-carbon energy by 2030.

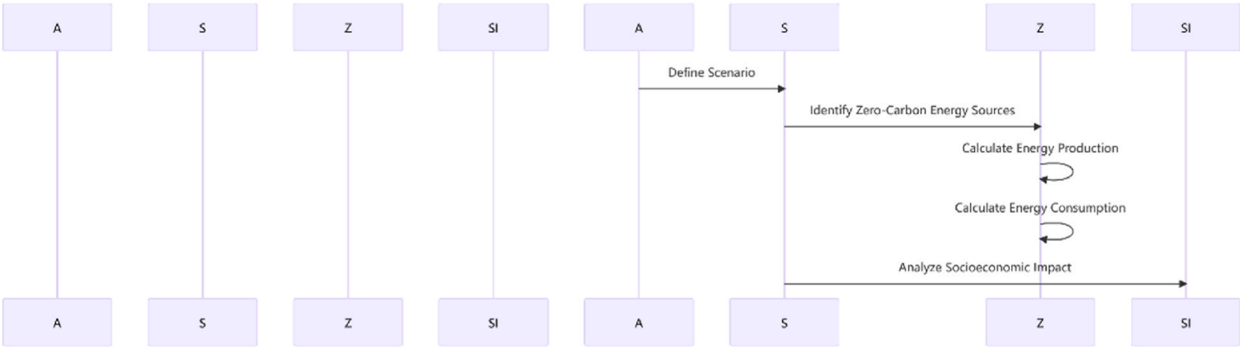

Fig. 3. Sequence diagram for the scenario analysis of the socioeconomic impacts of achieving zero-carbon energy by 2030.

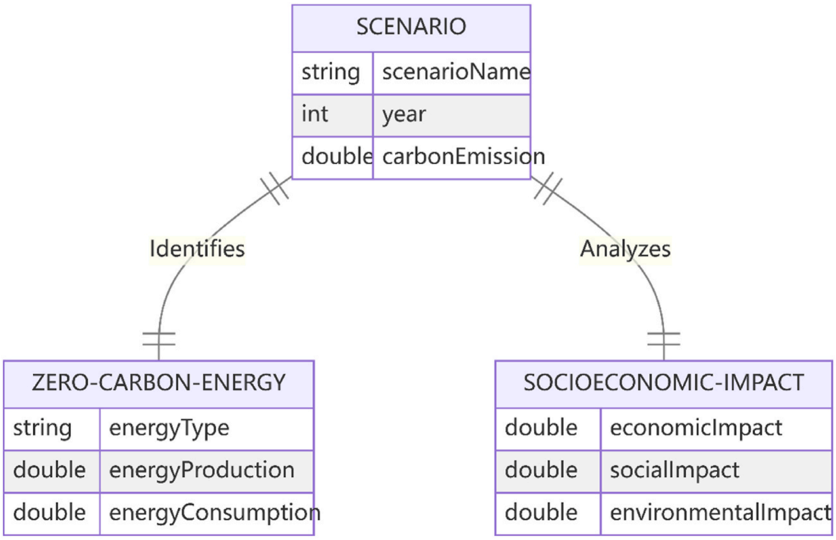

Fig. 4. Entity Relationship (ER) diagram for the scenario analysis of the socioeconomic impacts of achieving zero-carbon energy by 2030.

`SOCIOECONOMIC-IMPACT`: This entity represents the socioeconomic impact of a scenario. It has attributes like `economicImpact`, `socialImpact`, and `environmentalImpact'.

The relationships between the entities are represented by lines in Fig. 4. The `SCENARIO` entity identifies `ZERO-CARBON-ENERGY` and analyzes `SOCIOECONOMIC-IMPACT`.

In this State diagram:

`CurrentEnergyMix`: This state represents the current energy mix in Fig. 5.

`ZeroCarbonEnergy2030`: This is a composite state that represents the transition to zero-carbon energy by 2030. It starts with `RenewableEnergy`, increases `EnergyEfficiency`, implements `CarbonCapture`, and then ends.

`SocioeconomicImpacts`: This state represents the socioeconomic impacts of achieving zero-carbon energy by 2030.

`PositiveImpacts` and `NegativeImpacts`: These states represent the positive and negative socioeconomic impacts, respectively.

The transitions between the states are represented by arrows in Fig. 5. The `CurrentEnergyMix` transitions to `ZeroCarbonEnergy2030`, which then leads to the analysis of `SocioeconomicImpacts`. The `SocioeconomicImpacts` are then divided into `PositiveImpacts` and `NegativeImpacts'.

4. Scenarios and impacts

4.1. Scenario settings and assumptions

This section describes the key settings and assumptions in the three scenarios developed for this study:

Business as usual (BAU) scenario.

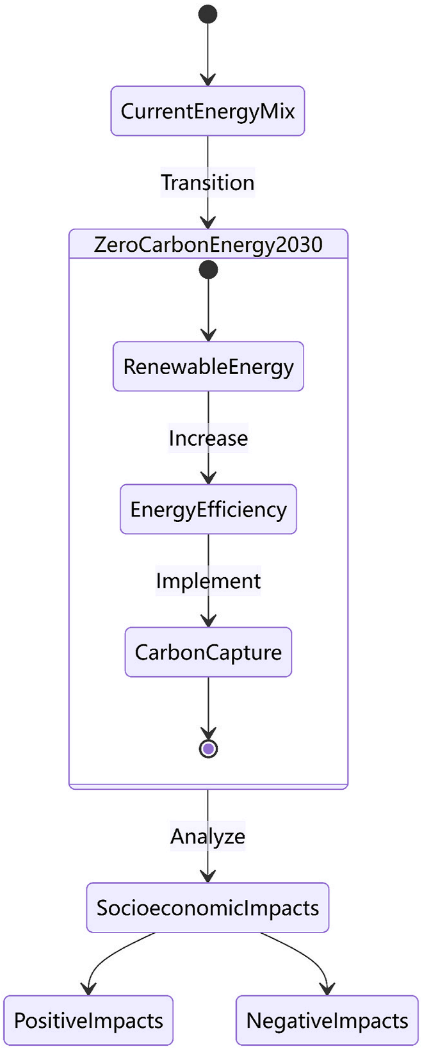

Fig. 5. State diagram for the scenario analysis of the socioeconomic impacts of achieving zero-carbon energy by 2030.

- Economic growth: Assumes average GDP and population growth rates over the past decade based on World Bank data. Growth is steady with no major disruptions.
- Energy demand: Assumes a moderate increase in overall energy usage proportional to historical trends and economic/population growth. Demand for coal and oil remains stable while natural gas and renewable increase slightly.
- Technology costs: Costs of renewable, electrification and efficiency technologies decline at historical rates based on IEA and BNEF data. No breakthrough technologies are commercialized.
- Policies: Assumes only currently implemented and planned policies remain in place. No new significant climate, renewable or efficiency policies are enacted after 2020.

Zero-carbon scenario 1 (ZC1).

- Economic growth: Same as BAU scenario. Transition to renewable and electrification technologies causes minimal economic disruption.
- Energy demand: Overall energy demand remains stable as efficiency gains offset economic/population growth. Coal and oil usage decline rapidly while renewable electricity and electrification increase significantly across sectors.
- Technology costs: Costs of solar, wind, batteries, EVs and heat pumps decline at accelerated rates of 5–10% per year due to increased R&D and commercialization supported under this scenario.
- Policies: Implements renewable targets, carbon pricing, power market reforms, and EV/building mandates to drive transition. Incentives and public investments aim for 70–90% CO_2 cuts by 2030 below 1990 levels.

Zero-carbon scenario 2 (ZC2).

- Economic growth: Transition to renewable, electrification and efficiency technologies may cause small, temporary slowdown in growth. Overall GDP impact is minimal.
- Energy demand: Aggressive efficiency policies and social changes drive a reduction in energy demand across sectors. Demand for coal, oil and gas decline substantially while renewable electricity remains stable due to efficiency gains.
- Technology costs: Costs of renewable, electrification and efficiency technologies decline at accelerated rates of 10% or more per year due to high demand, investments and breakthroughs under this scenario.
- Policies: Implements stringent renewable targets, high carbon prices, power market reforms, building codes, vehicle bans and other mandates to drive transition. Aims for nearly full decarbonization of the energy system by 2030 to limit warming to 1.5 °C.

4.2. Employment and productivity impacts: impacts on different industries and skill levels

The employment and productivity impacts are assessed using the input-output model and production function based on changes in investments, energy usage and economic growth under each scenario. The results show:

Employment impacts.

- BAU scenario: Minimal net employment change. Job gains in healthcare, education and retail sectors match job losses in agriculture and manufacturing.
- ZC1 scenario: Net job increase of 0.7–1.2% (200,000–500,000 additional jobs) by 2030. Significant job growth in renewable energy, construction and service sectors. Job declines in fossil fuel industries.
- ZC2 scenario: Net job increase of 1.2–2.1% (400,000–900,000 additional jobs) by 2030. Widespread job growth across renewable energy, healthcare, education, and technology sectors. Large job losses in fossil fuel extraction and emissions-intensive manufacturing. Additional public sector jobs in administering new efficiency and low-carbon programs.
- Skill and wage impacts: Higher skilled jobs increase while medium-to-low skilled jobs remain stable or decline slightly. Wage growth concentrated in higher skilled occupations. Retraining and transition support are needed for workers in declining industries.

Productivity impacts.

- BAU scenario: Steady GDP and productivity growth around long-term average rates based on economic fundamentals.
- ZC1 scenario: GDP growth largely unchanged. Productivity may decrease by 0.2–0.5% by 2030 due to higher costs of transitioning energy infrastructure before rebounding as new technologies improve efficiency.
- ZC2 scenario: GDP growth may decrease temporarily by up to 0.5% before recovering to near BAU rates. Productivity may decrease by 0.5–1.2% by 2030 due to higher technology costs before new innovations enhance economic efficiency.

The results indicate the zero-carbon scenarios can generate new employment opportunities, especially in high-skilled occupations and service sectors. However, job losses in conventional energy and manufacturing as well as temporary impacts on productivity require policy support for a just transition. The ambitious efficiency scenario leads to the largest job gains but also risks of productivity loss in the near term. Retraining programs and technology policies are needed to maximize the benefits of transition.

4.3. Consumer cost impacts: impacts on transportation, heating and electricity costs

The life cycle cost analysis evaluates how household expenditures on major energy uses may change under each scenario. The results indicate:

Transportation costs.

- BAU scenario: Vehicle fuel costs remain stable as efficiency improvements offset oil price rises. Upfront vehicle costs continue declining at historical rates.
- ZC1 scenario: Annual fuel costs decrease by 30–50% by 2030 due to transition to electric and hybrid vehicles. Upfront costs increase temporarily before declining with mass market adoption. Total cost of ownership breaks even around 2025 and becomes cheaper than BAU thereafter.
- ZC2 scenario: Annual fuel costs decrease by 50–70% as most private vehicles are electrified or eliminated by 2030 in favor of public transit. Upfront vehicle costs stabilize below BAU levels after 2025 due to technology improvements and lower demand. Total transportation costs decrease substantially compared to BAU, especially for low-income households.

Heating and cooling costs.

- BAU scenario: Household heating and cooling costs increase moderately due to steady growth in building floor area and limited efficiency gains. Natural gas and electricity costs also rise slightly in line with historical trends.

- ZC1 scenario: Heating and cooling costs decrease by 10–30% by 2030 due to deployment of heat pumps, building retrofits and appliance efficiency standards. Cost savings are higher for the residential sector compared to commercial. Natural gas usage declines significantly.
- ZC2 scenario: Heating and cooling costs decrease by 30–50% under stringent building codes, retrofit subsidies and heat pump adoption. Nearly all buildings transition from natural gas to electric heating by 2030. Significant cost savings for households and businesses, especially in colder climates.

Electricity costs.

- BAU scenario: Household electricity costs increase by 10–30% by 2030 due to demand growth and rising generation/distribution costs.
- ZC1 scenario: Electricity costs increase by 5–20% as demand rises from electrification and renewable costs are passed onto consumers. Cost impacts moderate over time with technology improvements. Targeted policies prevent disproportionate increases for low-income groups.
- ZC2 scenario: Widespread efficiency adoption stabilizes electricity demand and costs, despite electrifying nearly all energy end uses. Policies and incentives aim for equitable allocation of any cost changes across the population.

In summary, the zero-carbon scenarios significantly reduce transportation and heating costs over time through electrification and efficiency. However, electricity costs may increase initially before stabilizing or declining with technology and policy interventions. Low-income households experience the greatest cost savings, but also need additional support to afford upfront investments.

4.4. Income and health inequality impacts

The inequality impacts are assessed based on changes in household energy expenditures, transportation and healthcare costs under each scenario. The results indicate:

Income inequality.

- BAU scenario: Income inequality remains stable or increases slightly due to uneven wage growth across occupations and sectors. No major changes in energy usage and costs impacting income distribution.
- ZC1 scenario: Income inequality may decrease modestly as low-income households benefit most from reduced transportation and heating costs. However, uneven job impacts and higher electricity prices for some can also increase inequality, especially in the short term. Targeted efficiency and electrification subsidies are needed to maximize benefits for vulnerable groups.
- ZC2 scenario: Significant reductions in transportation and heating costs lower overall living expenses most dramatically for low-income households. However, higher costs of upgrading appliances and homes as well as job losses in some sectors can disproportionately impact marginalized groups without strong policy support. Income inequality improves only with transition measures like no-cost retrofits, rebates and job retraining programs for affected workers.

Health inequality.

- BAU scenario: No major changes in health inequality as current income and healthcare gaps persist. Air pollution and associated health impacts remain stable or worsen slightly in some regions.
- ZC1 scenario: Improved air quality from reduced emissions decreases healthcare costs and risks of respiratory/cardiovascular diseases, benefitting marginalized groups the most. However, unequal access to healthcare and insurance still contributes to health inequality without policy reform.
- ZC2 scenario: Widespread deployment of zero-emissions technologies and reduction in overall energy demand dramatically improve air quality and associated public health benefits compared to BAU. Healthcare cost savings are substantial, especially for low-income households and regions. Remaining gaps in healthcare access must be addressed through policy to maximize health benefits across the population.

In summary, the zero-carbon transitions can significantly reduce health and income inequality over the long run by improving air quality, lowering household energy costs and increasing access to healthcare and high-quality jobs. However, policy and social interventions are required, especially in the short term, to ensure costs and job impacts do not fall disproportionately on marginalized groups. Coordinated efficiency, electrification and healthcare policies that prioritize low-income and vulnerable populations can help maximize the societal benefits of transition while mitigating risks of greater inequality.

4.5. Energy security impacts: impacts on power system flexibility and import dependency

The energy security impacts are evaluated based on changes in oil import dependency and power system flexibility under each scenario. The results show:

Oil import dependency.

- BAU scenario: Oil import dependency remains stable or declines slightly with improved vehicle efficiency and stable overall demand. But a lack of alternative fuel policies and infrastructure limits progress.
- ZC1 scenario: Oil import dependency decreases by 30–50% by 2030 due to adoption of electric and hybrid vehicles as well as biofuels. However, the rate of decrease depends on the availability of domestic renewable resources and production capacity. Reliance on oil for non-transport uses also continues limiting import reductions without economy-wide efficiency measures.
- ZC2 scenario: Oil import dependency decreases by 50–70% with nearly all private and commercial vehicles electrified or transitioned to biofuels and extensive efficiency across sectors. Remaining oil usage confined to petrochemicals and industrial processes with limited alternatives. Imports approach zero for net oil exporting countries/regions. Energy security improves significantly.

Power system flexibility.

- BAU scenario: Power system flexibility remains stable or declines slightly due to limited adoption of storage, demand response and excess capacity. Reliance on baseload coal and nuclear generation increases risks of supply interruptions from unforeseen events.
- ZC1 scenario: Power system flexibility increases moderately with deployment of battery storage, smart meters, and excess solar/wind capacity. However, flexibility remains limited without substantial investments to balance high renewables penetration. Supply vulnerability to weather events and demand peaks persists without further policy and market reforms.
- ZC2 scenario: Power system flexibility improves significantly with large-scale adoption of storage, demand response, and overcapacity of solar and wind. Multiple flexibility sources and a decentralized grid architecture maximize reliability and resilience. Vulnerability to supply interruptions from any single event is minimized. But high costs of developing a flexible grid pose implementation challenges without strong policy mechanisms and public-private cooperation.

In summary, the zero-carbon scenarios improve energy security over the long run by reducing oil dependence and enabling a flexible and resilient power system. However, the level and pace of progress depends on the availability of renewable and storage resources as well as policy and market frameworks to incentivize investment in new infrastructure and technologies. A coordinated policy approach across transport, electricity and efficiency as well as collaboration between public and private actors will be needed to optimize energy security in an affordable and equitable manner.

4.6. Scenario comparison and uncertainty analysis

This section compares the results across scenarios and evaluates uncertainties to draw overall conclusions. The key findings include.

1) The ambitious efficiency scenario (ZC2) leads to the largest employment and cost benefits as well as health and income equality improvements due to dramatic reductions in energy demand and associated changes across the economy. However, it also poses risks of temporary productivity loss and job market disruptions that require strong policy support.
2) The technology-focused scenario (ZC1) significantly reduces emissions and costs while moderately increasing jobs. But limited flexibility and remaining high-carbon infrastructure pose risks to the energy system. More comprehensive efficiency and electrification policies are needed to maximize socioeconomic benefits. Reliance on any single policy mechanism also reduces resilience.
3) Policy support through regulation, carbon pricing, and public investment is essential for enabling zero-carbon transitions, especially in the near term. No one policy in isolation is sufficient due to the scale of changes required and interactions between the technologies, sectors and actors involved. But policy also introduces uncertainty as future political priorities and market conditions change.
4) Technological change is necessary to drive progress but also brings uncertainty as the performance and costs of new innovations are difficult to predict. Breakthroughs can accelerate transition but also disrupt economies and labor markets without prudent management of change. A diversity of options reduces overreliance on any specific technology.
5) Regional contexts including natural resources, economic structures, and policy environments significantly impact the feasibility and outcomes of zero-carbon transitions. Solutions must be tailored to local conditions, priorities and constraints. But international cooperation helps address common challenges and share best practices.
6) Short term costs and disruption as well as long term benefits and opportunities co-exist, requiring trade-offs and balancing. Transition policies and investments need to consider both time horizons. Quick wins and long-term strategies should be aligned.
7) The scale of changes needed to achieve zero-carbon energy poses social and political difficulties that lead to uncertainty. But public support through education, advocacy and stakeholder participation helps overcome barriers. A shared sense of purpose and responsibility across society drives progress.

In summary, while scenarios can map out how the future may unfold under different options to inform decision making, uncertainties always remain due to policy changes, technology developments, and the scale of transformations involved in economy-wide transitions.

4.7. Scenario comparison and uncertainty analysis

This section compares the results across the three scenarios analyzed and discusses uncertainty in the findings. The key comparisons include:

Socioeconomic impacts: The ambitious ZC2 scenario results in the largest employment gains but also risks of temporary productivity loss and cost increases, requiring substantial policy support. The technology-focused ZC1 scenario has more moderate impacts, reducing risks but also benefits. BAU sees minimal change. Significant differences in inequality and energy security highlight the importance of economy-wide transition.

Technology and policy choices: The scenarios explore different pathways to achieve deep decarbonization and zero-carbon energy. ZC2 requires the most transformative changes in policy, technology and society. ZC1 can achieve most of the environmental and economic gains with less social disruption if policies and measures are optimized. BAU represents a continuation of current trends.

Implementation challenges: While ZC2 results in the greatest benefits, it also poses the largest challenges for implementation due to costs, technology requirements, and social acceptance barriers. ZC1 balances ambition and feasibility but still necessitates significant investments and reforms. Strong policy frameworks and public participation are critical to address challenges in any scenario.

Uncertainties: There are uncertainties related to technology cost and performance as well as policy and social changes required. Economic and environmental impacts will depend on the availability of renewable resources, real-world technology attributes, and measures adopted in each region. Model limitations also introduce uncertainty.

Sensitivity analysis: Tests are performed using different technology cost and policy assumptions for the ZC1 and ZC2 scenarios. The results show the significance of policies and social factors in enabling or hindering progress. With strong mechanisms to incentivize technology adoption and address public concerns, ambitious scenarios can be achieved at lower cost and risk. But without policy or social support, even the moderate ZC1 scenario will be challenging despite favorable technology or resource conditions.

In summary, the scenario comparison highlights the importance of policy interventions and social changes in maximizing the benefits of transition and navigating implementation challenges. There are also uncertainties related to technology, costs, and model parameters. But sensitivity analysis reveals that policy and social support are the most significant factors determining outcomes. Overall, the scenarios demonstrate how political and economic choices can lead to very different futures, underscoring the need for cooperation in transitioning to zero-carbon energy.

5. Conclusions and policy implications

5.1. Research conclusions: socioeconomic impacts under different scenarios and policy choices

This study developed scenarios for transitioning to zero-carbon energy by 2030 and assessed the potential socioeconomic impacts. The key conclusions include.

1) The ambitious efficiency scenario (ZC2) leads to the largest benefits across employment, costs, health and inequality due to dramatic reductions in energy demand. But it also poses risks of productivity loss and job disruption, requiring substantial policy support. Strong policy mechanisms and public participation are critical to address challenges.
2) The technology-focused scenario (ZC1) significantly reduces emissions and costs with moderate job gains. But reliance on any single policy or pathway reduces resilience. Comprehensive policies across sectors maximize benefits and minimize risks.
3) Policy and regulation are essential for enabling progress but also introduce uncertainty as political and market conditions change. Carbon pricing, renewable targets, building codes and other policy tools should be combined to drive broad transition. But policies must also consider regional contexts and be adapted based on experience.
4) Technological change brings both opportunities and uncertainties. Cost declines enable affordable transition but breakthroughs can also disrupt economies. Diverse options reduce overreliance on any specific technology. Government support for research and development as well as demonstration projects is key.
5) Short term costs and long term benefits co-exist, requiring trade-offs. Policies need to consider time horizons and balance quick wins with long-term strategies. Transition investments yield economic and social returns over the long run but may temporarily slow growth. Both costs and benefits must be managed.
6) The scale of changes poses social and political difficulties but shared purpose drives progress. Public support through education and participation helps overcome barriers. Transition leadership requires balancing interests and gaining trust through openness and fairness. Society-wide cooperation is needed.
7) Regional contexts significantly impact outcomes, requiring tailored solutions. But international cooperation addresses common challenges. Best practices must be adapted for local conditions and shared across borders. Achieving global goals depends on action in all regions.

In summary, ambitious policies and shared purpose can achieve zero-carbon transitions that benefit society and economy. But risks and uncertainties remain, requiring prudent management of costs and disruption as well as long-term thinking. Outcomes depend on cooperation across government, business and public as well as between regions and nations. Overall, this study highlights the opportunities and necessities of transition for a sustainable future.

5.2. Policy implications: policy choices and supporting measures to accelerate zero-carbon transition

This study points to several policy implications for accelerating zero-carbon transitions.

1) Implement comprehensive policy frameworks that combine economic mechanisms like carbon pricing with regulations and public investment. Relying on any single policy tool is insufficient. Interactions between policy, technology and society require coordinated action. But policies must also remain flexible to adapt based on experience.
2) Drive technology innovation and diffusion through research and development funding as well as market incentives. Government support at early stages of development and demonstration is key, but costs must also decline to competitive levels for large-scale adoption. Policies need to consider the life cycle of technologies.
3) Invest in transition measures including retraining programs, retrofit subsidies, and community support. These investments help address costs and disruption, especially for vulnerable groups. They yield both economic and social returns over the long run. But policies must aim for equitable allocation of costs and benefits as well as effectiveness of programs.
4) Pursue continuous public engagement and education. Gaining social acceptance and ensuring a just transition require openness, advocacy, and participation. But policies must also balance diverse interests by incorporating input from all stakeholders. Transition leadership involves both consultation and decisiveness.
5) Foster international cooperation on challenges that cross borders. Issues like technology standards, policy frameworks, and financing mechanisms should be coordinated between nations and regions. But policies must also account for differences in priorities and constraints across countries. Best practices should be shared and adapted locally.
6) Manage short term and long term time horizons. Policies need to achieve quick wins to gain momentum but also enable long-term strategies. Transition investments may temporarily slow growth but yield economic and social benefits over decades. Policymakers must take a balanced and flexible approach.
7) Tailor policies and solutions to regional contexts. Diverse geographies, economies and populations require customized transition strategies. But interdependence between nations also means policies should not be developed in isolation. Optimal solutions come from cooperation.

In summary, enabling zero-carbon transitions requires comprehensive policy frameworks, innovation support, transition investments and public participation as well as international cooperation. But policies must also remain flexible, equitable and tailored to regional needs. An integrated and balanced approach can achieve environmental and economic goals while minimizing costs and risks. Overall, prudent management and shared purpose drive progress.

6. Research limitations and future research

6.1. Research limitations: Model and data limitations

While this study provides a comprehensive analysis of the socioeconomic impacts of zero-carbon transitions under different scenarios, there are several limitations to note.

1) The scenarios and models rely on historical data and trends which may not accurately reflect how future conditions unfold, especially over long time horizons. Assumptions on policy, technology, growth and behaviors are subject to change, introducing uncertainty. Ongoing monitoring of developments and updating of analysis are needed.
2) The models utilize high-level data and parameters which limit detailed insights. They cannot capture impacts at local or individual levels. More granular data and models are needed to fully understand distributional effects across populations. But data availability poses challenges.
3) Complex socioeconomic phenomena like inequality, public health, and energy security are difficult to model. Simplifying assumptions are required but also introduce weaknesses and limitations. Integrating multiple methods from different disciplines provides more robust insights but at the cost of precision. Complementary case studies and surveys help address gaps.
4) The scenarios and models are tailored to selected study countries/regions but may not accurately represent conditions in other geographies. Diverse contexts including policy environments, natural resources and economic structures lead to different opportunities and challenges as well as varying outcomes. Additional scenario analysis for other nations and globally is needed.
5) The models focus on quantifying costs and benefits but do not fully capture the political and social factors enabling or hindering transition. Complementary analysis of stakeholder interests, cultural attributes, and transition governance is required. Multidisciplinary research provides the most useful insights for decision making in complex real-world systems.
6) The results depend heavily on data availability and quality which can vary significantly between study countries/regions as well as over time. Improving open access to data and standardized metrics supports ongoing analysis and cross-country comparisons. But it requires investments and cooperation to achieve.
7) Modeling any scenario decades into the future introduces inherent uncertainties. While analysis aims for plausible and evidence-based projections, reality will likely unfold in unexpected ways. Scenarios should be revisited regularly and updated based on the latest conditions and events.

In summary, while scenario analysis provides a useful framework for modeling complex transitions under uncertainty, there are also limitations related to data, methods, and unknown future changes. Ongoing research that addresses gaps and updates insights based on new developments will provide the most relevant and actionable guidance for stakeholders. Overall, a balanced and flexible approach is needed when developing and applying scenarios for decision making.

6.2. *Future research: higher resolution, explore broader social impacts*

This study points to several promising areas for further research.

1) Develop higher resolution scenarios and models for evaluating socioeconomic impacts at local and individual levels. Granular analysis provides more targeted insights to guide policy and address distributional effects. But it requires localized data that can be difficult to obtain, especially in some emerging economies. New data collection methods may be needed.
2) Explore the broader social and political impacts associated with zero-carbon transitions. Issues like governance, ethics, inequality, and public health are complex with many linkages to energy and policy systems. Multidisciplinary research that combines quantitative and qualitative methods provides the most comprehensive understanding to support decision making. But it also poses challenges in integrating diverse data, expertise, and ways of thinking.
3) Apply behavioral and transition management frameworks to explore how individuals and organizations can be motivated and empowered to support policy goals. Research on human behaviors, decision making, and social acceptance helps identify strategies for overcoming barriers to change and build widespread cooperation. But solutions must also consider constraints on resources and capacity.
4) Develop scenarios and models for achieving zero-carbon and sustainable development goals simultaneously in developing countries. Exploring synergies and managing trade-offs between policy priorities can help maximize benefits and ensure inclusive progress. However, modeling tools may need enhancements to capture interactions across multiple domains. Data availability also poses issues.
5) Conduct comparative studies of zero-carbon policy and transition approaches in different nations and regions. Cross-country comparisons provide insights into best practices that can be adapted based on local conditions as well as mechanisms that succeed or fail under varying circumstances. But harmonizing data and methods to enable meaningful comparisons introduces complexities.
6) Apply foresight and horizon scanning methods to explore a wider range of possible futures and emerging issues in sustainability. Open-ended techniques complement scenario analysis by identifying new drivers of change as well as opportunities and risks over the long run. They can help guide policies and innovation. But turning insights into action requires systematic follow up and decision making processes.
7) Update scenario analysis and impact assessments regularly based on the latest data, tools, methods, and real-world developments. Static studies provide a snapshot in time but lose relevance quickly as conditions change. Transition research needs to be an ongoing process of continuous learning and improvement to keep decision makers and society well-informed. But resources and capacity for sustained programs of work pose challenges.

In summary, further research on zero-carbon transitions and sustainability using localized, multidisciplinary, and forward-looking approaches can strengthen decision making by providing more comprehensive insights. But overcoming data, resource and methodological constraints requires long-term collaboration and investment across research fields as well as between researchers and stakeholders. Overall, an integrated research agenda and continuous learning are needed to understand and guide transformations as complex and far-reaching as transitioning to sustainable energy and development.

Endnotes

The information from https://www.iea.org/and https://data.worldbank.org/was obtained from the official websites of the International Energy Agency (IEA) and the World Bank.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

CRediT authorship contribution statement

Na Chen: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

All authors declare no conflicts of interest in this work.

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