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California end-use electrification impacts on carbon neutrality and clean air

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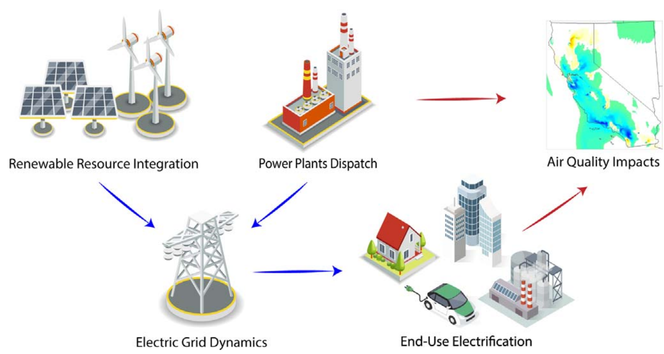
HIGHLIGHTS

- Grid and emission impacts of electrification while decarbonizing power are studied.
- Electrification can enable the integration of higher levels of renewable resources.
- Electrification yields up to 20.3% GHG emission reductions compared to 1990 levels.
- Air quality impacts show the importance of spatial and temporal variation in emissions.
- Electrification improves urban air quality, while worsening areas near generators.

GRAPHICAL ABSTRACT



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ABSTRACT

Widespread electrification, i.e., switching direct fossil fuel end-uses to electricity, coupled with renewable power use is essential to achieve aggressive greenhouse gas and criteria pollutant emission reduction targets. Few have investigated the requisite electric grid infrastructure transformation and technology path coupled with spatial and temporal resolution of criteria pollutant emissions for assessing air quality impacts. In this study, we analyze grid and emission impacts of electrifying end-use sectors while decarbonizing power generation, using detailed modeling of infrastructure stocks and economic dispatch of the electric utility grid network. Results show that decarbonizing power supply without electrifying end-use sectors can reduce total greenhouse gas emissions by only 2 percent, while partial electrification of end-use sectors alongside decarbonizing electricity generation yields up to 20.3 percent greenhouse gas emission reductions compared to 1990 levels. Spatially and temporally resolved criteria pollutant emissions portend certain scenarios that improve air quality more than others, requiring consideration of spatial and temporal emission perturbations dictated by specific electrification end-uses and power generation technology dynamics for meeting the increased electric demand.

1. Introduction

Global warming, air pollution and lack of energy security are considered serious threats to public and ecosystem health, economic growth and political stability. They will evolve the way energy is supplied and converted over the next century with substantial increases in levels of clean and secure energy while reducing energy demand in all economic sectors. Over the past decade, human activities have greatly influenced the climate system primarily through burning of fossil fuels, causing global warming and sea level rise that have resulted in climatic extremes such as heat waves, wildfires, and droughts [1].

Continued release of greenhouse gas emissions will result in further global warming, increasing the possibility of severe and irreversible impacts for humans and ecosystems. Without further mitigation policies

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beyond those in position today, global warming will lead to very high risk of extensive global disbenefits by the end of the century. Even if the concentrations of greenhouse gas (GHG) emissions are stabilized now, the effects of greenhouse-gas emissions will persist long after they are emitted due to the long time that most GHGs remain in the atmosphere, indicating the importance of immediate action on cutting GHG emissions [2,3].

There are several mitigation pathways for controlling global warming, each involving significant emissions reductions of GHG, while requiring substantial technological, economic, and social adaptations. Many of these solutions are feasible and cost-effective today, while others may be viable in the future, as technologies advance, costs shrink, and energy competitiveness evolves. There is no unique solution for addressing all energy and environmental challenges, but potential solutions will comprise a range of options that will vary geographically and with time [4]. Moreover, the energy roadmap must be established in such a way to bridge the gap between planning for shallower, near-term solutions depending entirely on commercially available technologies and deeper, long-term solutions that will be based on technologies that are not yet commercialized.

An integrated mitigation approach combining reduction measures for energy consumption and GHG emissions of end-use sectors, decarbonizing energy supply, and enhancing carbon sinks in land-based sectors can be a feasible and cost-effective solution [5]. Widespread deployment of energy-efficient technologies in buildings alone could eliminate the necessity of expanding U.S. electricity supply [6]. Although energy savings can be achieved by employing cutting-edge technologies in end-use sectors, it must be noted that deep energy efficiency improvements are not possible without government support, including regulations and tax policies, and public awareness [7].

Renewable power is the first and foremost option for decarbonizing electricity generation since it is abundant, sustainable, and can be zero-emitting. Previous studies have shown that multiple combinations of renewable resources including solar, wind, geothermal, hydropower, and biopower are capable of meeting 80% of total U.S. electricity demand in 2050 while achieving deep reductions in electric sector emissions. However, greater levels of renewable power pose new challenges to regional electrical grids due to geographical dependency, transmission constraints and, most importantly, power output variability. Therefore, increasing penetrations of renewable power must be accompanied by higher flexibility in the electricity grid through a portfolio of supply- and demand-side technologies, including energy storage, transmission and distribution expansion, higher responsive loads, and enhanced power system operation [8]. Furthermore, a medium-term approach will likely include replacement of coal power plants by state-of-the-art combined cycle natural gas plants with lower emissions and higher flexibility for balancing the grid [9]. For example, within the western grid of the United States, all existing coal power plants are planned to retire by the end of their lifetime of 30 years [5].

However, implementing energy efficiency measures and decarbonizing the electricity sector to the maximum feasible extent are not sufficient on their own to meet deep emission reduction targets, such as California's targeted reductions under Assembly Bill 32 of 80% below 1990 levels by 2050 [10]. Achieving such goals requires not only transforming the way power is generated, transmitted, and distributed, but also evolving how fuel is consumed by end-use technologies across all economic sectors. Unless extensive energy efficiency measures are employed, end-use fuel conversion and corresponding GHG emissions will continue to increase due to growing trends of population and economy. Improving end-use energy efficiency without transitioning away from fossil fuels might be an effective short-term strategy, but is not adequate for achieving long-term goals [11–13]. Current energy policies are primarily focused on decarbonizing electricity generation, while overlooking end-use energy sectors, which contribute more than 50 percent of the gross annual GHG emissions worldwide [1]. Even complete decarbonization of the power supply sector cannot lead to aggressive GHG emission reductions since only 25 percent of total global GHG emissions are attributed to electricity generation. Therefore, extensive electrification, i.e., switching direct fuel use to electricity use, is essential for meeting deep emission reduction targets [5]. Undoubtedly, electricity will have to play a much greater role in the future by contributing to decarbonization of transportation, built environment and industrial sectors. However, electrifying end-use sectors will not achieve necessary emission reductions if the electricity is supplied mainly from fossil fuel power plants [9]. Electrification is considered as a technically feasible way to boost the reduction of emissions by increasing the use of electricity in tandem with increasing renewable electricity production.

As an example, the State of California has adopted aggressive GHG emission reduction target of 40 percent below 1990 levels by 2030 and 80 percent below 1990 levels by 2050, but decarbonizing the power supply sector alone cannot lead to such deep emission reductions since only 21 percent of total statewide GHG emissions originate from power generation. Therefore, widespread electrification of otherwise fuel consuming end-uses is required.

A few studies have emphasized the importance of electrification to the future energy economy and emission reduction goals. Williams et al. [5] analyzed the infrastructure and technology path required to fulfill California's goal of an 80% GHG emission reduction below 1990 levels by 2050 using detailed modeling of infrastructure stocks, resource constraints, and electricity system operability. They concluded that practical levels of energy efficiency and clean energy supply alone are not sufficient and extensive electrification of transportation and other end uses is necessary to achieve emission targets. Wei et al. [14] conducted a detailed analysis of supply and demand alternatives to evaluate the requirements for future California energy systems that will meet the 2050 GHG emission reduction target. They highlight the importance of expanding the existing vehicle electrification policies and developing new policies for building electrification alongside the aggressive expanded use of renewable energy to fulfill the GHG emission targets. McCollum et al. [15] assessed the importance of transport electrification for energy system transformation and climate stabilization using an integrated assessment modeling framework. Their analysis emphasized the prominent role of electric vehicles to diversify primary transportation resources, which can enable the integration of higher levels of nuclear and renewable power.

Several researchers have studied the potential impacts of transport electrification on greenhouse gas emissions and climate change. Wu et al. [16] developed various scenarios for the penetration of electric vehicles in three regions of China from 2010 to 2030 and studied the impacts of these scenarios on oil consumption and GHG emissions. Their analysis emphasized the difficulty of mitigating CO_2 emissions in regions where coal is the overwhelming power source. On the other hand, their results showed more significant CO_2 emission benefits in regions with cleaner energy mix. Singh and Strømman [17] studied the environmental impacts of electrifying passenger vehicle fleet of Norway using life cycle assessments and temporally variable inventory models. They highlighted the fact that emission benefits are more prominent in Norway since hydropower is the main source of electric power. Cai and Xu [18] evaluated the life cycle GHG emissions impact of adopting plug-in hybrid electric vehicles (PHEV) in the taxi fleet of Beijing based on the characterized individual travel patterns using big data mining techniques. Their results indicated that the electrification of taxi fleet can worsen greenhouse gas emissions with the existing electric grid, however, GHG emission benefits can be achieved if the fuel cycle emission factor of electricity is reduced.

Other studies have focused on the impacts of fleet electrification on criteria pollutants and air quality. Tessum et al. [19] assessed the air quality impacts of alternative fuel technologies for light-duty transportation in the United States using a combination of life cycle emission inventories, chemical transport modeling, and health impact analysis. They found that vehicle electrification with grid average electricity