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The Importance of Developing Climate-Resilient Pathways for Energy Transition and Climate Change Adaptation

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Recently in *Joule*, Lombardi et al. developed an approach to formulating socially and politically favorable energy-system decarbonization strategies, pointing out the strong impacts of weather on the developed optimal solution. Considering climate resilience has timely importance to guarantee the climate change adaptation of energy infrastructure while improving its sustainability.

According to the Intergovernmental Panel on Climate Change report "Global Warming of 1.5°C," devastating changes will occur on the planet unless anthropogenic CO_2 emissions are halved by 2030 and reach net zero by 2050.[1] The energy sector is a key contributor to global CO_2 emissions and thus climate change and must accelerate its transition toward decarbonization through large-scale deployment of renewable energy technologies. Strong links exist between the energy sector and other sectors, such as building, production, and transportation; as such, the adopted solutions for a sustainable transition must be selected wisely if we are to avoid cascade failures.[2] Assessment of future energy solutions is challenging because of the multifaceted effects at each stage, from energy generation to user demand, especially given the complex social, economic, biophysical, and technical interactions[3] and connectivity across different scales.[4]

As recently reported in *Joule*, Lombardi et al.[5] have developed an integrated renewable energy system to derive spatially explicit, practically optimal results (SPORES) with the aim of formulating socially and politically favorable energy-system decarbonization strategies. The study moves beyond the classical approach of localized system optimization to practical optimal interconnected energy-system architecture while also considering a number of energy-generation and -storage technologies. In the study, the Italian power sector was divided into six geographical bidding zones: NORD, CNOR, CSUD, SUD, SARD, and SICI (for more information about bidding zones, refer to Table S4 in Lombardi et al.[5]). These zones present notably diverse settings concerning renewable energy potential, energy demand, etc. The study revealed that optimal design solutions are highly sensitive to climate variations. The authors found that selecting the weather year has the strongest effect on the developed optimal set because it directly influences the generation of renewable energy and the utilization of energy storage. They point out that by relying (only) on a cost-optimal energy-system configuration, the solution might suffer from "an overfitting of variable renewable generation and storage capacity to a specific weather year." This can become more problematic for future climates with stronger and more frequent extreme events, which can induce malfunctioning of the systems designed on the basis of past climates. Energy systems with a higher penetration level of renewable energy technologies that cater to multiple energy services, such as electricity, heating, and cooling, become more dependent on climate conditions. As a result of extreme weather events, such as heatwaves, the impacts of climate change at periods of peak demand can reach well beyond simple changes in net annual demand, harming the operation of the energy infrastructures and undermining their reliability.[6] Key performance indicators used for the energy-system design process, including power-supply reliability, grid integration level, net present value, emission reduction, and flexibility, can notably degrade as a result of future climate variations, leading to a significant performance gap.[7] This situation poses a great risk. Instead of win-wins between climate mitigation (i.e., reducing CO_2 emissions through renewable technologies) and adaptation (i.e., on-demand energy under future climates), in the absence of a holistic consideration, advancing one kind of climate action could compromise other future requirements (i.e., climate-adaptive renewable energy systems). To ensure reliable operation of energy systems, adequate consideration of future climate changes, including short-term extreme events, is essential in the development of energy-transition pathways.[8] However, understanding the impacts of climate variations on energy systems is extremely challenging because of the multivariate and multiscale changes of the climate system, as well as the complex workflows between climate models and energy systems.

The concept of resilience is usually used to address the performance of a system in relation to extreme conditions. Adopting the concept is surely needed for realizing reliable energy systems; however, limiting only to investigating short-term extremes is not sufficient for the long-term sustainability and reliability of energy systems. When energy systems are designed for the future, both long-term and short-term variations of climate should be taken into account because both can influence the selection of energy technologies and component sizing. Developing frameworks for assessing climate resilience as a means of addressing both short-term and long-term climate change variations and uncertainties can become useful in this regard.[8] Moreover, proper methods that can accommodate sophisticated uncertainties should be further developed and adopted given that quantifying the uncertainties introduced by future climate variations, along with other uncertainties such as energy markets and technology improvements, is a difficult task.

As discussed thoroughly in a previous work,[9] two major challenges in the impact assessment of climate change are climate uncertainties and large datasets, making energy-system optimization extremely demanding. Perera et al.[10] developed novel approaches to quantifying the impacts of climate change and extreme events on energy systems in Sweden. For the first time, they showed how neglecting future climate variations, uncertainties, and extremes can lead to a significant performance gap (up to 34% for grid integration) and a drop in power-supply reliability (up to 16%). Variations and extreme events associated with climate change can lead to low-probability, high-impact events and high-probability, low-impact events, respectively, leading to blackouts and degradation of energy-system performance (e.g., an increase in operation costs). This will retard the integration of renewable energy technologies, increase the dependence on fossil fuels, and further accelerate climate change, creating a vicious cycle. We can ensure the robustness and reliability of energy systems by appropriately quantifying the impacts of climate change through adopting climate-resilient energy-transition strategies and accounting for climate change adaptation alongside decarbonization.

Lombardi et al.[5] uncovered the hypersensitivity of the proposed SPORES renewable energy system under varying weather conditions, although they did not include a broader range of climate variables, such as temperature, wind speed, and solar radiation. On the basis of our experience of synthesizing weather datasets and conducting impact assessment of climate change on buildings and energy systems, the impacts of climate variations and the scale of extreme events can be altered significantly by the adopted future climate scenarios. For example, according to Nik[9] and Perera et al.,[10] adopting a representative concentration pathway with a higher concentration could induce warmer average temperatures and stronger extremes but slightly lower wind speeds and solar radiations. This indicates that there might be a larger need for cooling demand on average, as well as a higher risk of heatwaves, whereas the potential for renewable energy generation (based on climate conditions) is not increased and could even be decreased. This points to the importance of increasing the flexibility in the energy system on both the supply and demand sides, confirming that higher resilience of energy systems demands higher flexibility as well.[7] It is calling for a well-established scheme that can integrate sustainable energy supply, smarter demand-side management, and reliable as well as responsive energy storage.

Renewable energy infrastructure will be the backbone of future interconnected infrastructures and will play a vital role in decarbonizing multiple sectors. The methodology introduced by Lombardi et al.[5] will play a vital role in this regard to provide us with the potential to move beyond the cost-optimal solutions at the national scale. Further extension of such models to consider climate resilience would have timely importance to guarantee the climate change adaptation and resilience of energy infrastructure while improving its sustainability.

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