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From prediction to optimization: digital and hybrid approaches for sustainable energy systems



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The transition toward sustainable energy systems is no longer defined only by the deployment of renewable technologies. It is increasingly shaped by our ability to manage complexity. As renewable generation expands across power systems, buildings, and distributed energy infrastructures, the central challenge is not simply producing clean energy, but using it more intelligently, more efficiently, and more flexibly.

This shift marks an important evolution in the energy field. For many years, research and innovation focused primarily on improving individual technologies: more efficient photovoltaic modules, better wind turbines, cleaner fuels, stronger batteries, and lower-emission industrial processes. These advances remain essential. However, as renewable penetration continues to grow, the performance of the overall system depends not only on the quality of its components, but also on how effectively they interact with one another across different spatial and temporal scales.

In this context, digitalization is becoming one of the most important enablers of the energy transition. Data-driven tools, artificial intelligence, advanced sensing, predictive analytics, and digital twins are increasingly being used to support better planning, operation, and control of energy systems. They offer new opportunities to improve forecasting, optimize demand, integrate variable renewable generation, enhance grid flexibility, and reduce waste. At the same time, they can strengthen the connection between technical performance and economic decision-making, which is crucial if sustainability is to be translated into real and scalable implementation.

Among the most promising developments in this area is the growing use of hybrid approaches, which combine physics-based understanding with data-driven intelligence. Purely physical models remain fundamental because they offer interpretability, scientific consistency, and transferability across contexts. Purely data-driven methods, on the other hand, can capture complex nonlinear relationships and exploit large volumes of operational data. Yet both approaches also have limitations when used in isolation. Physical models may oversimplify real-world variability, while purely data-driven models may struggle with robustness, transparency, or generalization beyond the conditions represented in training data.

Hybrid modeling provides a compelling path forward because it seeks to combine the strengths of both worlds. In renewable energy systems, this means integrating domain knowledge with adaptive learning, using physics not as a constraint on innovation but as a foundation for more reliable prediction and optimization. This perspective is especially relevant in systems characterized by intermittency, uncertainty, and strong interactions between generation, storage, loads, and user behavior.



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The implications are broad. Forecasting is no longer only about estimating what will happen next; it is increasingly about enabling better decisions. Accurate and robust prediction supports the management of batteries, electric mobility, heat pumps, demand response, and distributed generation. It can improve self-consumption strategies, reduce operational costs, mitigate stress on the grid, and help align energy use with the availability of renewable resources. In this sense, prediction is evolving into optimization, and optimization into system intelligence.

This broader view is particularly important for buildings and local energy systems. Buildings are no longer passive consumers of energy. They are becoming dynamic nodes within a wider energy ecosystem, capable of producing, storing, shifting, and managing energy flows. Smart buildings, energy communities, and hybrid energy systems require models that are not only accurate, but also actionable. The real value of digital and hybrid approaches lies in their ability to support decisions under realistic constraints: technical, economic, environmental, and social.

At the same time, the energy community must remain attentive to the quality and meaning of the digital transition. The increasing use of AI and advanced analytics should not lead to black-box dependence or technological enthusiasm detached from practical relevance. Instead, the field should aim for methods that are scientifically grounded, transparent where possible, and validated under real operating conditions. Research should not only pursue better algorithms, but also better integration between models, measurements, applications, and decision contexts.

This is where interdisciplinary work becomes essential. The future of renewable and sustainable energy will be shaped not by isolated advances, but by the convergence of engineering, materials science, computer science, environmental assessment, economics, and policy. The most impactful contributions are likely to be those that move beyond narrow technical optimization and address how energy technologies perform within real systems, real markets, and real societies.

For journals in this field, this creates both a responsibility and an opportunity. Renewable and sustainable energy research must continue to welcome technological innovation, while also encouraging contributions that connect innovation with implementation. The next phase of progress will depend on our ability to bridge scales and disciplines: from materials to devices, from devices to systems, and from systems to societal outcomes.

As the energy transition accelerates, the need for this integrated perspective will only grow. Renewable and Sustainable Energy seeks to contribute to this discussion by providing a platform for research that is rigorous, forward-looking, and relevant to the evolving challenges of sustainable energy systems. The path ahead will require not only cleaner technologies, but smarter ways of predicting, managing, and optimizing their role in an increasingly complex energy landscape.