Autonomous Energy Systems

Building reliable, resilient, and secure electrified communities.

Abstract

Technological changes across energy systems are directing utilities and operators to reconsider their methods for managing power delivery, but few have adopted advanced controls and operational software. The challenge is that every system has particular requirements, and the available solutions are relatively new, untested, and difficult to integrate into an operational environment.

Through extensive collaboration with utilities and cooperatives, the National Renewable Energy Laboratory (NREL) has been developing solutions for autonomous and optimized management of energy resources, leading to a suite of capabilities to realize autonomous energy systems (AES), a packaged set of controls that is ready to be integrated into existing control rooms. AES solutions have been validated in applications such as voltage regulation, demand response, peak load shaving, system recovery, protection for two-way power flow, and dispatching energy resource aggregations. AES is especially effective at supplying adaptive resilience to remote communities, automated restoration during severe outages, and scalable operations for highly distributed systems. As long as utilities collect sufficient system data, AES solutions offer a ready-to-use interface for the hybrid management of energy devices and the coordination of system- and local-level objectives. This paper summarizes the purpose and value proposition of AES.

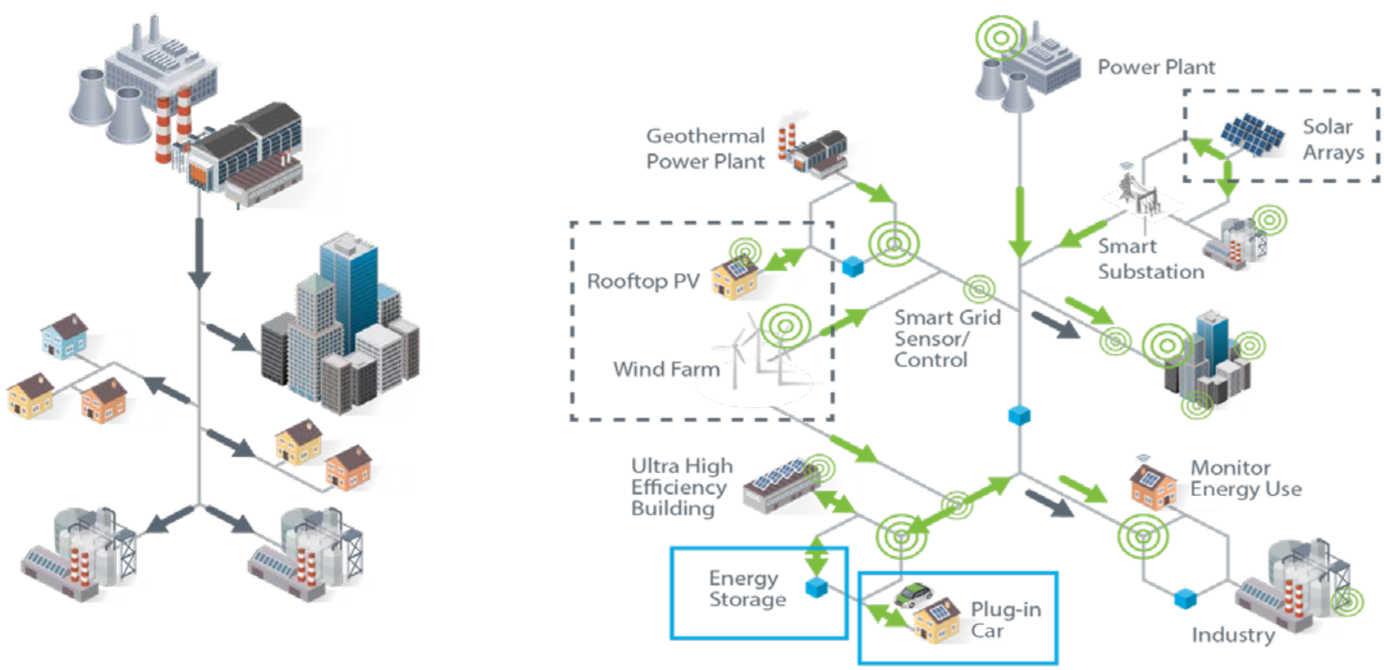

Figure 1. A comparison of current (left) and emerging (right) power systems. *Images by NREL.*

Background

Energy systems are undergoing substantial changes from the growth in distributed solar, wind, energy storage, electric vehicles (EVs), and building automation (Figure 1). Meanwhile, electrification is driving closer couplings between power system operations, buildings, and transportation networks. Communities, utilities, vendors, regulators, and energy systems broadly are in need of new approaches to communications, control, and operation to accommodate interdependences and seamlessly integrate distributed decisions, devices, and data. To address these concurrent changes, NREL has formed an AES strategy which uses intelligent and robust methods to operate highly electrified, distributed, and heterogeneous energy systems with millions of devices in real time. Through further adoption and large-scale demonstration capabilities at NREL, AES can scale up to the solve the complex challenges of future system operation.

Definition

The core research objectives of AES are to **apply distributed intelligence** over controllable devices; **integration** among the grid, buildings, transportation, renewables, and storage; and collectively **manage controllable devices** across multiple energy sectors in a distributed, hierarchical manner to improve affordability, efficiency, reliability, resilience, and security for the complex systems.

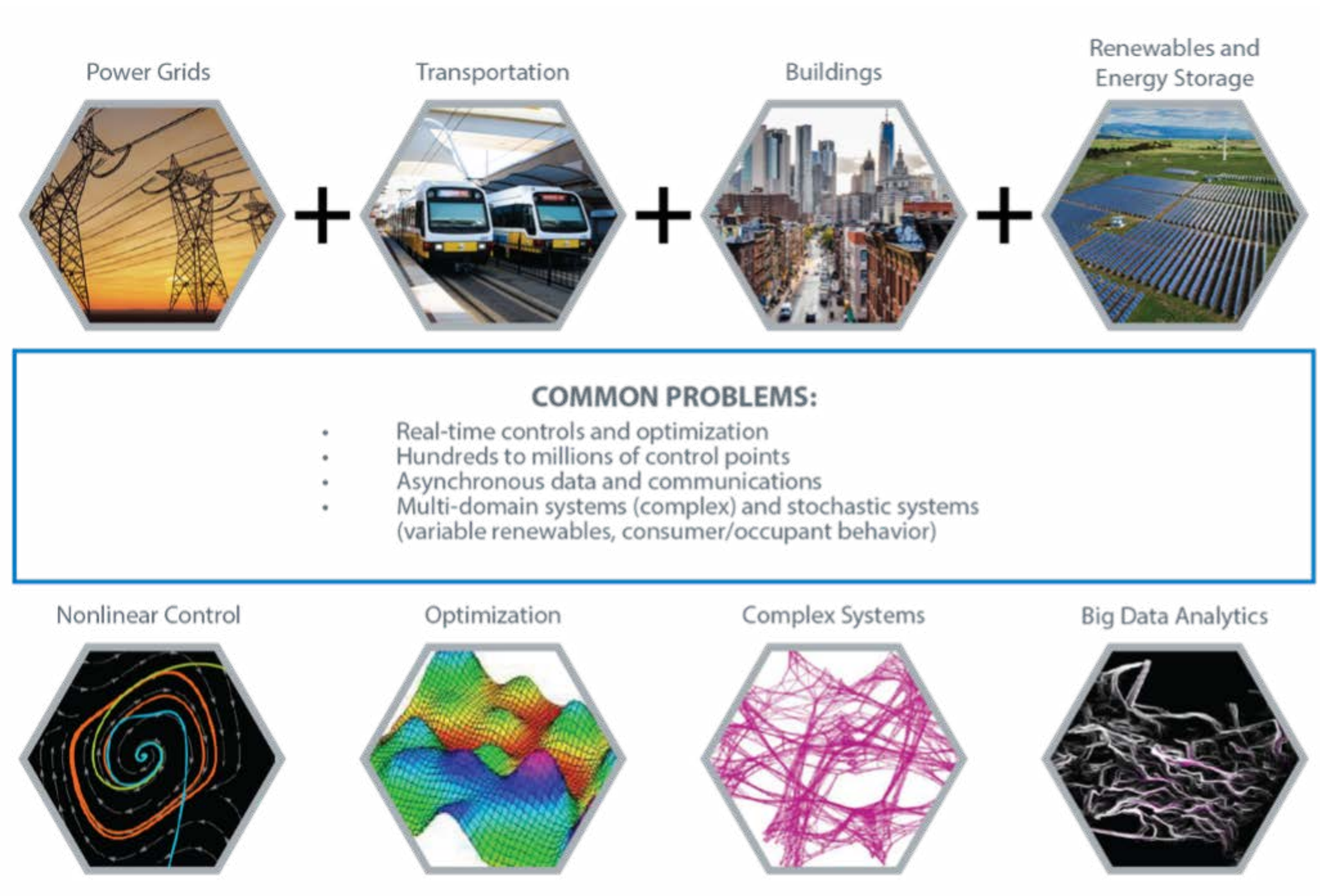

Figure 2. The core technologies of AES enable the integrated and coordinated operation of electric grids, buildings, transportation, renewables, and storage.

AES solutions deconstruct large-scale, centralized control and operations into smaller, clustered decisions so that central operators are not overwhelmed by data and communications from many distributed devices. **Small, clustered decisions are the building blocks of AES**. They allow energy systems to self-optimize and self-operate and, when interconnected to a larger network, to coordinate system-wide operations. This is a valuable asset for communities. With multilayer, multicluster methods, **AES can realize valuable applications for energy system operators and solution providers, including:**

1. Cost-effective and streamlined approaches to using variable renewable generation and emerging technologies

2. Real-time operations to balance load/demand and generation/supply at the second or subsecond timescales

3. Robust tolerance to disturbances, faults, outages, and failures in both cyber and physical networks

4. Interoperability with the integration of decisions, devices, platforms, and data with the aid of standard-based protocols

5. Scalability to control hundreds of millions of energy resources, including grid devices, renewables, storage, mobility, buildings, inverters, and microcontrollers. AES scale up controls from communities to neighborhoods to regions.

How AES Supports the Grid

Residential solar installations are expected to increase approximately 8% annually through 2050. Customer battery systems are anticipated to reach almost 1.9 GW by 2024, and current forecasts project that approximately 18.7 million EVs will be on U.S. roads in 2030.[1] Building electrification is surging due to energy-efficiency targets and decarbonization requirements. Meanwhile, each new year brings record outage times from strengthening storms. With trends like these, an AES approach becomes critical because conventional control methods and operation schemes cannot handle so many devices.

Take the San Francisco Bay Area as an example, which has approximately 4.5 million electricity customers. If each customer has a photovoltaic (PV) system, a battery system, an EV, a smart thermostat, and controllable lighting, this yields approximately 10–20 million controllable devices connected to the grid. To operate a system with this many devices would require heterogenous models, asynchronized data and communications, and versatile applications.

Currently no single system can ingest 20 million data streams and make real-time analysis and operational decisions, especially considering the high uncertainty existing in multi-energy systems and the increasing number of cyber and physical intrusion points. AES methods introduce original algorithms, operational architectures, and platform interoperability—in a single, contained solution—to meet these new requirements.

Successful AES Applications

In western Colorado, the local utility cooperative Holy Cross Energy has demonstrated the success of using AES to integrate renewable energy and customer energy devices. The co-op has automated a neighborhood's energy system and demonstrated the use of autonomous homes to achieve virtual power plants and enhance community resilience. In a 3-day test, an AES control algorithm was applied to distributed energy resources (DERs) in four homes. The AES algorithm aims to maximize the use of local generation resources to provide electricity to the home loads, so that net-power consumption of the two service transformers connecting to these four homes is as close to zero as often as possible. The algorithm also maintains the distribution voltage to be within an allowed range while dispatching power from DERs. In another test, a home energy management system developed by NREL researchers was adopted in these four homes to unlock load flexibility and manage the loads to reduce energy costs while maintaining homeowners' comforts.

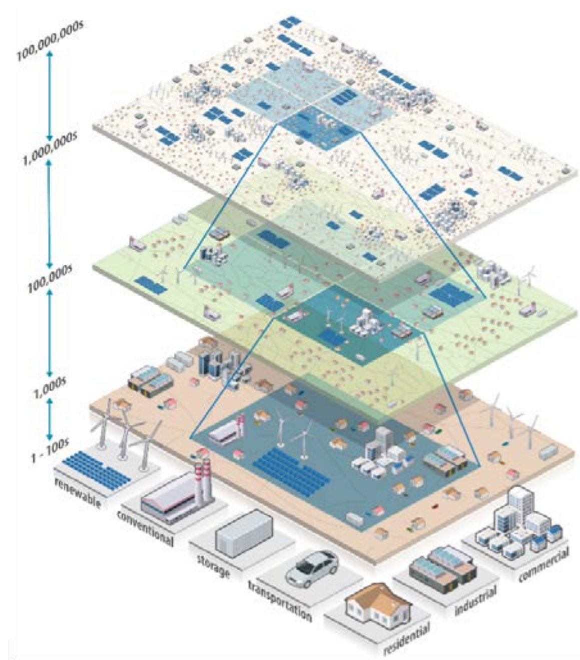

Figure 3. AES solutions use clustered decisions to scale up energy systems control and manage millions of interconnected devices.

[1] B. Kroposki, et. al., "Good Grids Make Good Neighbors," IEEE Spectrum, December 2020.

Habitat for Humanity, Pitkin County, Basalt School District

- Built 27 homes for teachers and local workforce
- 4 selected for demonstrating NREL's AES control algorithms
- Designed to Zero Net Energy standards with all electric construction

Home Equipped with Controllable Loads

- Rooftop solar
- Energy storage
- Mobility charging (EVSE)
- Comfort (hot water + HVAC)

In another AES application, Detroit utility DTE Energy, NREL, and several other partners are creating a method to dynamically form networked microgrids in a project named DynaGrid. Using AES algorithms, the microgrid boundaries are designed to adjust during operation, adapting to scenarios like large numbers of EV connections or emergency situations (e.g., heat waves or cold snaps). The networked microgrids can also be optimally formed to reduce wildfire risks by adaptively choosing which elements/parts of the network to isolate. The DynaGrid project is innovating new possibilities for microgrid operations while also setting new precedents for equity. The algorithms are designed with cognizance of energy burden and neighborhood needs, constructed with direct input from residents. The goal of the project is to empower communities to use and share local energy resources that best serve their needs.

Southern Company and NREL are also evaluating an AES strategy for a feeder with high PV deployment to address reverse power flow challenges and the optimal use of utility-scale and behind-the-meter batteries. Southern Company has experienced significant growth in utility-scale PV, and in some areas this results in reverse power flow at substations. The utility is partnering with NREL to evaluate an AES approach that relies on a substation-level controller to manage utility-scale and behind-the-meter batteries, either directly or through an aggregator, within a substation service area to minimize cost while limiting reverse power flow.

AES Benefits

With autonomous and distributed control over all DER types, AES solutions have particular value to electric utilities. They can:

- Defer transmission and distribution system upgrades by providing new control and operation solutions
- Provide non-wire solutions to increase penetrations of solar, wind, EVs, and storage and realize decarbonization and net-zero emission goals
- Provide advanced control solutions for DERs to become valuable assets to both distribution and transmission grids by delivering diverse grid services for reliability and resilience
- Apply industry standards related to DERs and communication protocols to address interoperability requirements
- Provide and demonstrate cutting-edge control algorithms and adaptable operation schemes that are compatible with existing utility setups.

Following is an example of the economic value that AES can bring to utilities. Table 1 compares the costs for utilities to upgrade their system using voltage regulators and capacitors versus using an AES control approach to manage voltages. The unit cost data of regulators and capacitors were obtained from NREL's distribution grid integration unit cost database, and the cost of devices to implement the AES algorithm were obtained from a market survey conducted in 2018. In this study, the implementation of AES control over existing DERs yields comparable voltage regulation performance to adding three voltage regulators and three capacitor banks in the distribution system. The former is estimated to cost $588,500 with each unit costing $500 and total 1,177 controllers needed. Whereas the latter option is estimated to cost $710,700 in total. In addition to reducing the costs of operation compared to using traditional voltage regulation devices, the same AES implementation can bring economic benefits, such as reducing peak demand and bringing additional revenue for utilities as well as deferring system upgrades or installing utility-scale batteries for peak shaving.

	Approach 1: Voltage Regulators and Capacitors		Approach 2
Cost Value	Regulators	Capacitors	AES Algorithm
Capital/unit	$150,000	$33,000	$200
Moving/unit	$50,000	$3,900	$0
Customer Acquisition	$00	$00	$100
Maintenance	Included	Included	$200
Net cost/unit	$200,000	$36,900	$500
Number of units	3	3	1177
Total cost	$710,700		$588,500

Table 1. Cost Comparison Between Using the AES Approach and a Traditional Voltage Regulation Device

AES Capabilities at NREL

NREL research capabilities support the full-scale deployment of AES. It starts at the local level, with targeted programs for communities, Tribes, cities, and states, helping residents define and plan their own energy goals, and formatting AES algorithms to prioritize those goals. At the level of utilities and cooperatives, NREL hosts a complete power distribution laboratory for operators to test AES applications in a realistic and risk-free environment and adjust according to their system needs.

Scaling up to large cities and generating units, NREL has the nation's most sophisticated energy system emulation platform. This allows researchers to generate highly accurate models of complex systems with millions of devices, and run power flow simulations on those modeled systems. The results provide operators and system planners with rigorously validated deployment scenarios. Finally, NREL analysis supports regulators and public utility commissions in designing a fair and functional power industry, including decision-making that facilitates automation and decentralized operation through AES.

Through this pipeline of capabilities, NREL advances AES as a key solution for operating tomorrow's energy system.

Facilities and Platforms for Demonstrating and Testing AES

AES emerged at NREL because of the unique and richly connected hardware and computational infrastructure that exist at the lab. In particular, the Advanced Research on Integrated Energy systems (ARIES) platform enables rigorous, large-scale system validation within a unique cyber-physical environment that contains a customizable 20-megawatt grid and vast virtualization abilities. Many of the capabilities below are part of ARIES and allow users to develop, test, and implement AES solutions in highly realistic systems of any scale.

- **The Advanced Distribution Management System (ADMS) Test Bed** enables partners to evaluate advanced, commercial and precommercial distribution system controls, such as AES, at the substation scale in a realistic laboratory environment. The ADMS Test Bed is being used to demonstrate AES solutions for utilities.
- **The Real-Time Analytics for Bulk Grid (RTAG)** simulates extreme bulk system events, high renewable penetration scenarios, and bulk energy system-natural gas interdependencies across steady-state, dynamic, and transient time domains. RTAG provides accurate bulk system environments for AES simulations.
- **The Power Electronic Grid Interface (PEGI)** is a megawatt-power testing platform. It is useful for studying how inverter-based generation sources and loads connect to the electric grid, and it can validate AES algorithms at realistic power over short time periods.
- **The Hybrid Energy Real-Time Emulation Hub (HERTH)** enables hardware-in-the-loop experiments to study multi-technology energy systems. HERTH can implement AES solutions in near-real-world environments.
- **The Cyber Range** provides holistic cyber-physical emulation for cybersecurity research into AES strategies.
- **Buildings research infrastructure** can be used to study commercial and residential grid-interactive building load flexibility, and it can deploy AES strategies in building infrastructure.
- **The Simulation and Emulation of Autonomous Systems (SEAS)** at Scale can simulate systems using AES to understand the impact of increased renewable penetration and the widespread adoption of controllable devices with and without the adoption of advanced controls across time and spatial scales.

Fundamental Algorithms for Realizing AES

In the past, NREL researchers have developed and demonstrated multiple novel algorithms to realize AES as described by:

- **The real-time optimal power flow (RT-OPF) control algorithm** solves real-time optimal power flow problems at the grid edge. RT-OPF coordinates DERs to collectively balance supply and demand, support grid reliability, and reduce the impact of outage events. It has been deployed in communities and extensively validated.
- **Hierarchical-distributed RT-OPF** is the extension of RT-OPF to large-scale systems with millions of devices.
- **EdgeFlex hierarchical optimization models** estimate and quantify the flexibility of grid-edge DERs and then optimize the aggregated DER flexibility to improve voltage quality, manage peak demands, and enhance system resilience. They also support DER integration with other grid-edge technologies, such as a residential building management technology (foresee™) developed by NREL researchers. They have been applied and validated on multiple real distribution utility grid models and a military microgrid model.
- **Flexible resource scheduler (FRS) algorithms** enable the aggregation and control of all types of DERs within a substation service area, and an FRS coordinator algorithm manages the operation of multiple substations on the distribution grid to provide firm bidding for wholesale market participation. The architecture considers three types of aggregation options: direct DER control, aggregator control, and a transactive approach. These algorithms incorporate the uncertainty of renewables and loads into their optimizations.
- **Low-observability state estimation algorithms** allow operators to estimate the AES state (e.g., voltages) in real time for accurate decision making. The algorithms leverage modern machine learning and signal processing tools to estimate the state even with few measurement devices and/or situations where the measurements are lost or incomplete (e.g., during disruptive events and cyberattacks).
- **Behind-the-meter DER analytics** estimates the grid-edge DER output and quantifies its uncertainty from available net load measurements at the house, community, and feeder level by combining advanced machine learning methods and physical models. The analytics have been integrated into multiple grid monitoring and control applications by providing real-time situational awareness of unmonitored behind-the-meter DERs, enhancing short-term net load forecasting, and incentivizing desirable behaviors of DERs.

Conclusion

Utilities and operators are under pressure to modernize their systems because of emerging technologies that affect customer participation, energy resource scheduling, power stability, and more. These organizations are comparing their options, but no current commercial solutions are capable of managing millions of devices in real time, which is ultimately needed to maintain stable and efficient energy systems.

AES algorithms and controls are NREL's solutions to the challenges that operators face when managing modern power systems. These solutions been validated in laboratory experiments and in field deployments, and they can be integrated into any utility control environment. Across diverse applications, they can save on costs and energy, defer system upgrades, integrate customer devices, and enable system resilience. The AES effort is still evolving through collaborations with partners, and the underlying control and optimization methods are continually being innovated by an NREL-led research team.

To learn more, visit
www.nrel.gov/grid/autonomous-energy.html.

NREL Transforming ENERGY

National Renewable Energy Laboratory
15013 Denver West Parkway, Golden, CO 80401
303-275-3000 • www.nrel.gov

NREL prints on paper that contains recycled content.

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

NREL/FS-1000-87629 • June 2024