SOUTHERN CALIFORNIA
EDISON®
Energy for What's Ahead®

# REIMAGINING THE GRID

December 2020

## EXECUTIVE SUMMARY

Expectations about the safety, reliability, affordability and environmental impact of the electricity that powers our lives continue to evolve. As we see more evidence of the impact of climate change daily, communities and consumers are adopting technologies to support a clean energy future and placing increasing value on decarbonization and resilience.

Pathway 2045 is Southern California Edison's (SCE) roadmap for enabling a clean energy future for California, laying out a path for the growth of carbon-free energy resources needed both on the generation (supply) and customer (demand) sides. Just as important as this blueprint to mitigate climate change is the need for an electric grid that enables the efficient integration of these clean resources while ensuring climate adaptation and broader resilience. Reimagining the Grid is SCE's vision of this future grid.

Technology advancements in grid software/hardware and new resources like energy storage have fostered continued progress in strengthening and modernizing the electric grid. However, the underlying design and architecture of the grid have not evolved at the same pace as its component technologies. Fundamental changes in how the grid is planned, designed, built and operated are necessary to meet future challenges.

The value of the grid goes beyond the commodity cost of the energy it delivers. The grid powers all aspects of society, especially as our dependence on electricity grows. As electricity becomes the fueling system for a larger part of the economy, we must reimagine what the future grid should look like at all levels and how it will need to function differently to meet expanded needs.

**We expect major changes in how customers will use electricity**, which will place unprecedented demands on the grid. Beyond an expected increase of 60% in electricity demand and 40% in peak load by 2045, electrification of mobility and mass adoption of distributed energy resources (DERs) like solar and batteries will make electricity demand more variable — yet increase customers' expectations for reliability and resilience.

- More than 20 million light-duty electric vehicles (EVs) are expected by 2045 in California, with each new vehicle's peak charging being roughly the equivalent of adding a new home to the grid
- For the first time since the electric grid was built, a significant amount of demand will come from devices that are not stationary, making load forecasting by location more difficult
- Connecting millions of inverter-based customer devices (e.g., solar, batteries) and electronics to the grid could cause widespread power quality impacts such as voltage distortions, which if left unmitigated, could shorten the life of customer and grid equipment alike

**Power supply challenges will become more prevalent and complex to manage.** Due to their variable nature, greater reliance on wind and solar resources will require the grid to manage a growing set of issues.

- Transmission and distribution systems will need to handle an increasingly variable power supply profile, posing challenges to safety, grid stability, asset condition, reliability and resilience
- The growth of inverter-based resources (i.e., solar, wind, storage) to replace conventional generation will lead to loss of system inertia and other grid services that ensure system reliability today
- Since the bulk of future renewable resources will be located far from customers, the uncertainty and cost of building transmission lines may stretch the grid's ability to deliver power to urban load centers

**The grid will be exposed to growing climate change effects.** The direct impact of climate change on assets and customers will be a key driver for the evolution of the grid. Both the frequency and magnitude of climate-driven disruptions will continue to increase. Recent wildfires and heat waves in California are early proof of the acceleration of these climate challenges.

- Acute events (e.g., wildfires, flooding, mudslides, storms, wind gusts) and chronic stressors (e.g., extreme temperatures, heavier rainfall, drought, sea level rise) will impact operating performance and put grid equipment under increased stress and risk of deterioration or failure

- Climate change will continue driving changes in customers' behaviors, needs and ability to access electric service without interruption

Impacts on the grid will vary by location and depend on regional topography, urbanization and demographic trends, localized exposure to climate vulnerabilities and existing infrastructure. This highlights the need to take a more targeted approach to planning and designing a reimagined grid tailored to different needs.

**Grid planning, design and operations will need to evolve.** Our approach needs to shift from a focus on systemwide reliability standards to one that meets multiple objectives based on specific and localized needs. Also, breaking silos with greater integration of generation, transmission, distribution and customer resources, and increased coordination with other stakeholders, will be required to optimize grid planning decisions. These changes will be necessary to avoid underutilized or stranded capabilities that end up being costly or perform poorly. Key changes for SCE include:

- Recognizing the increasing heterogeneity of different regions' needs, moving from uniform grid architectures to more region-specific, "modular" grid designs
- Strengthening our "forward radar" — our ability to increase visibility and track early indicators of customer trends (e.g., EV adoption), bulk power system issues (e.g., loss of system inertia), climate model changes, resource availability and new grid technologies — to reduce future uncertainty
- Moving from a deterministic grid planning approach focused on single worst-case conditions to a risk-based, multiple scenario-driven, adaptive and more proactive approach using probabilistic analyses to plan for a set of plausible and more localized events
- Incorporating system flexibility into future grid architectures (e.g., controls to rapidly reconfigure or isolate parts of the grid), including the use of storage, DERs and controllable loads as grid resources

**The grid's technological capabilities will need to be reimagined.** Grid innovation will be driven by a need-based approach focused on identifying technology gaps to be filled to address future challenges, rather than by the traditional model of equipment suppliers developing standard solutions to address uniform needs. SCE will focus on advancing critical capabilities and will center its innovation activities around them:

- The ability of the grid to sense, communicate, analyze and act, providing a targeted real-time response to changes in load and equipment condition. This will call for advances in sensors, high-speed/volume communications, edge computing, predictive analytics and artificial intelligence (AI).
- Achieving ultra-low latency (sub-millisecond) across thousands or millions of control points to maintain reliability and stability for a grid that connects to customer resources on a massive scale
- Integration of the above information/operational (IT/OT) technologies into a common, shared operating platform deployed across the system, with advanced cybersecurity as a critical enabler
- The ability to seamlessly package and deploy future technologies and hardware for location-specific needs, enabled by this systemwide IT/OT platform

And while we continue working toward further defining the capabilities and design architectures of the reimagined grid, we also need to take "no regrets" actions now to begin implementing this vision:

1. Improving our "forward radar" to anticipate changes, particularly regarding the timing, nature and magnitude of customer technology adoption and grid impacts
2. Accelerating the industry's development, testing, piloting and deployment of critical grid technologies
3. Engaging with key stakeholders (state regulators, federal agencies, industry, customers) to build a shared point of view on upcoming grid challenges and collaborate to start shaping future standards
4. Integrating new tools and grid planning processes to lower deployment time, harmonize current grid efforts with future needs and make more adaptive decisions

SCE has been entrusted to provide safe, reliable, affordable, clean and resilient power to customers. With Pathway 2045 and now Reimagining the Grid, we are thinking ahead about how to continue serving our customers in a future of continuing transformation. However, we must start developing critical grid capabilities today to ensure they are in place when needed, and we cannot do this alone. Achieving a reimagined grid for a clean energy future calls for a collaborative, industry-wide approach to be most effective and less costly to implement. It will require all parties — policymakers, innovators, customers, utilities — working together to shape the policy and technology landscape and transform how we plan, design, build and operate the grid.

# INTRODUCTION

*Pathway 2045*, SCE's 2019 in-depth analysis on how the state of California can achieve its commitment to reach 100% carbon neutrality by 2045, provides a detailed guide of thoughtfully planned actions across different sectors of the economy.

The first pillar of Pathway 2045 is to decarbonize the electric power supply. Compared to today, 2045 will see a 60% increase in electricity demand and 40% increase in peak load that will have to be met by carbon-free generation sources. To satisfy this growth and get this power to customers across California, the grid will need to integrate 80 GW of wind and solar and 30 GW of storage at the bulk power level via existing and new transmission infrastructure. At the distribution level, the grid will need to interconnect 30 GW of customer-sited solar and 10 GW of storage. For context, the historical peak in the California Independent System Operator (CAISO) system is approximately 50 GW. All of that equates to approximately $170 billion in clean energy resource investments and up to $75 billion in grid investments by 2045.

The second pillar of Pathway 2045 calls for decarbonizing other sectors of the economy by replacing the current mix of fossil fuels that powers them with carbon-free energy sources. Reduction of carbon will be achieved via transportation electrification, building electrification and switching hydrocarbons with low-carbon fuels. Pathway 2045 estimates that more than 20 million light-duty, 800,000 medium-duty and 100,000 heavy-duty electric vehicles will need to be added to California's vehicle fleet. Electrification of space and water heating in homes and businesses will have to grow to more than 70%. Low-carbon fuels like hydrogen and renewable natural gas (RNG) will be used for heavy-duty transportation, the replacement of some industrial applications of natural gas and for other hard-to-electrify energy uses.

The last pillar of Pathway 2045 is capturing the remaining carbon. Beyond the measures described above, natural processes and engineered solutions (e.g., carbon capture and storage) will be needed to sequester 108 MMT of carbon — roughly the equivalent of the entire industrial sector. Carbon capture technologies are still in development and will require continued research and development (R&D) and investment to reach economic and technical viability.

*Reimagining the Grid* is a comprehensive assessment to address how the grid must change to support California's greenhouse gas reduction goals and the imperative for power to be carbon-free by 2045 — while also adapting to other needs driven by customers and climate change. Our systematic approach starts with understanding what our customers will need from the grid, how the supply mix will change and the regional climate change effects that the grid will need to endure. As our starting point, we combine these drivers of change with the current grid, existing technologies and physical topology (the built and natural environment) of SCE's service area. We look at the unique needs of different regions, recognizing their varied energy uses, climate and existing infrastructure. We prioritize the specific grid objectives most relevant for each region and determine which technologies and solutions best address those objectives. Last, we lay out a high-level future roadmap showing how we will get there. While Reimagining the Grid is rooted in analysis tailored to SCE's footprint, we believe this blueprint can be generally applied to the rest of the state (and beyond). An overview of our approach is shown in Figure 2.

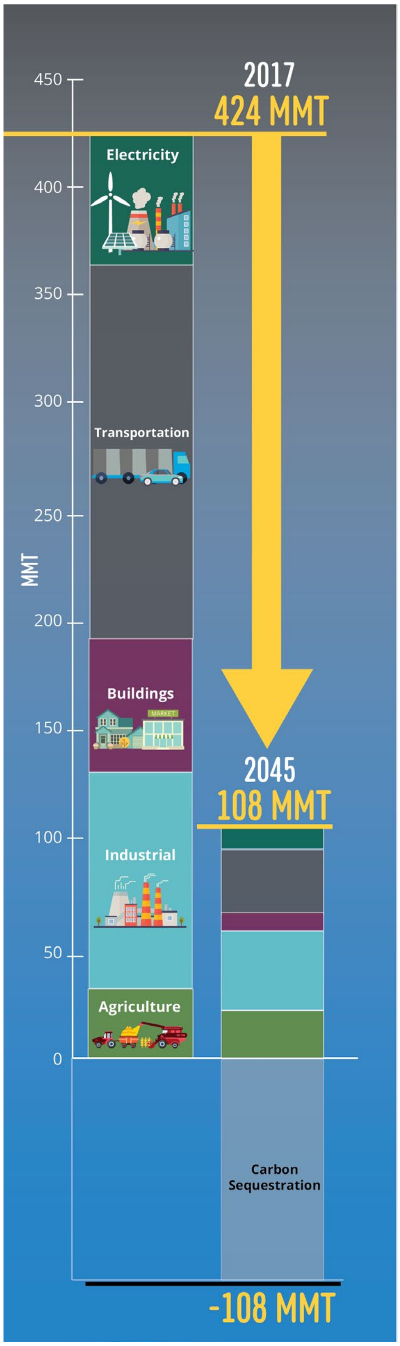


**Figure 1:** Greenhouse gas emissions reductions to meet California targets (in million metric tons)

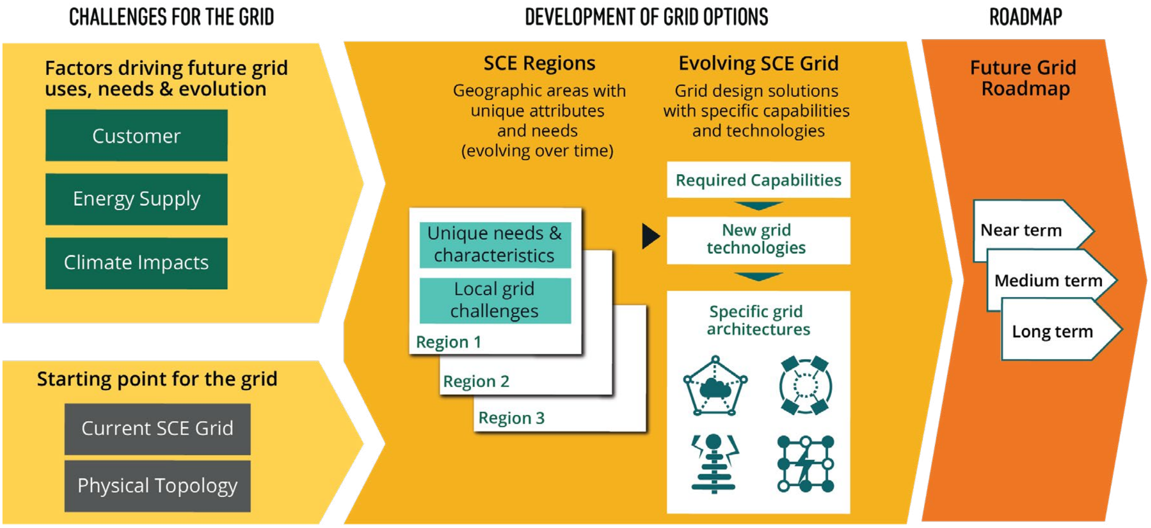


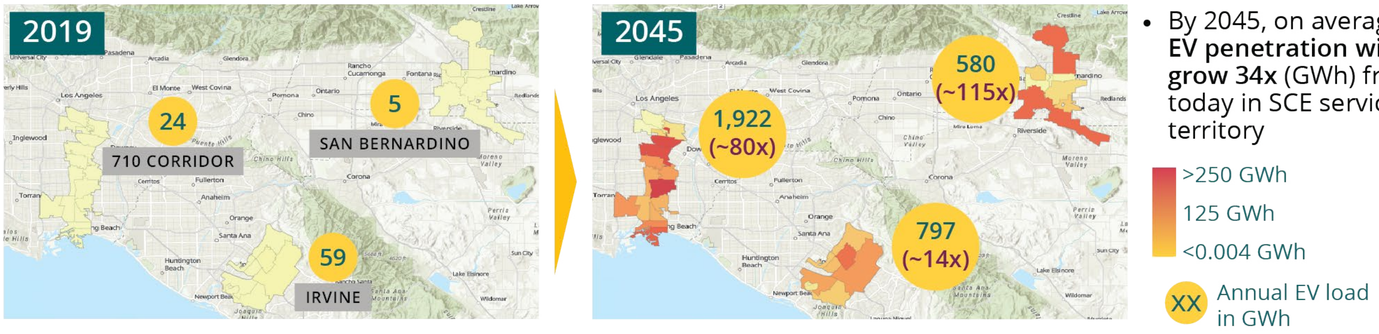
**Figure 2:** Overview of SCE's Reimagining the Grid methodology

## CHALLENGES FOR THE GRID

Achieving our Pathway 2045 goals and withstanding the long-term effects of climate change will require meeting a broad set of challenges across the entirety of SCE's grid. We organize these as driven by customers, supply and climate.

**Customer-driven:** Our customers will continue to change over the next 25 years: their number, location and, most fundamentally, how they use energy. Our service area is undergoing changes in urbanization, demographics and other local factors affecting the economy. Customers are adopting new technologies that enable them to take control of how and when they use, manage, produce and store energy. With the growing digitization of work and electrification of transportation, heating and industrial processes, we anticipate significantly higher use of electricity in the future. Customer expectations for reliability/resilience will steadily increase due to greater reliance on electricity for a wider range of critical and everyday activities.

We expect customer trends to drive greater load density by 2045, largely due to transportation electrification. EV penetration will increase by several orders of magnitude in urban/suburban areas and transportation corridors alike, and electricity usage patterns will change profoundly as a result. While we are expecting greatly expanded light-duty EV use, we know that medium- and heavy-duty EV fleets will also grow rapidly, and their charging load will likely vary widely in terms of location, magnitude and timing.



- By 2045, on average, **EV penetration will grow 34x** (GWh) from today in SCE service territory

**Figure 3:** Electric vehicle penetration in select SCE communities in LA Basin (in GWh, 2019 and 2045)[1]

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[1] Pathway 2045 light-duty vehicle target penetration allocated to regions per "Reimagining the Grid" (RTG) analysis; also includes medium- and heavy-duty vehicles. Source: Pathway 2045, Clean Power & Electrification 2030, RTG analysis

Aligned with Pathway 2045, DERs will increase significantly through growth of behind-the-meter solar, storage and controllable loads, adding variability in distribution system conditions (e.g., voltage) that the grid must manage. Power quality will also be a challenge, as more electronics-based applications will be deployed in buildings (e.g., automation, robotics, data centers), compared to end uses based on mechanical equipment. Electronic equipment will create — and be impacted by — disturbances such as voltage/current distortions. The growth of inverter-based generation and storage from both large-scale renewables and local DERs will further exacerbate these power quality disturbances.

**Supply-driven:** As the resource mix shifts from traditional fossil-fueled generation to renewable and variable sources like solar and wind, the power system will require significant buildout of additional clean energy and storage assets. These present permitting, environmental and construction challenges. Also, the nearby states that would likely supply a portion of California's future power (such as Nevada, Utah and Arizona) could all compete for the same resources. Assuming such out-of-state resources are available, new transmission infrastructure will need to be built, with similar construction challenges and additional risks associated with planning, capital investment and timing.

Given the potential difficulty and cost of importing energy into California, it may be necessary to increase the amount of renewable energy generated, captured and stored within the state. However, high-load density relative to local supply capacity, as well as limited land availability, will make it challenging to build sufficient clean resources close to load to meet peak customer demand. With a large portion of future in-state renewable resources to be located outside urban areas, additional transmission lines into load centers will need to be built. Additionally, the evolving mix of resources will require changes in how to model and plan the system, including how to design market mechanisms such as Resource Adequacy, demand response, reserve margins and other market rules or frameworks that support system planning. Failure to adequately balance local supply and demand could lead to undesired outcomes like rolling outages.

The replacement of conventional generation with a higher mix of renewables in the future will present another set of challenges related to grid reliability services they normally provide. Notable among them is the loss of system inertia, a property of the power system wherein the rotating mass from synchronous generation resources ensures a steady system frequency. Inverter-based resources such as solar lack the mechanical inertia that traditional generation resources provide, posing growing challenges to grid stability and resilience until inverter technology (e.g., grid-forming) and other solutions (e.g., synthetic inertia) are further developed.

**Climate-driven:** Increases in chronic climate risks such as extreme temperatures, and acute ones such as expected wildfires and floods, are becoming increasingly prevalent in California. The severity and pervasiveness of these changes are forecast to increase significantly. The changing climate will lead to direct impacts to the grid, including diminished performance, reliability and lifespan of assets due to harsher conditions and catastrophic events that will tax or damage equipment. Together, these impacts will result in more challenging grid operations, lowered equipment standards (e.g., derating) and increased maintenance.

Conversely, our customers' responses to adapt to more extreme climate will include population shifts and changes in customer demand (e.g., increased usage of A/C, water, etc.). There will also be effects felt on the supply side, including increased siting risks for renewable projects, long-term drought of solar and wind resources (due to smoke from fires, long-term cloud cover or shortage of high wind speeds), reduced and less predictable hydropower and potential deterioration in battery storage performance due to extreme heat.

The reimagined grid will require new capabilities to meet these diverse needs and challenges.

## DEVELOPMENT OF GRID OPTIONS

We understand that these challenges will present themselves differently throughout the grid, based on population density, topography, local climate and other factors. To address them, we first analyze how and when these challenges will show up across our service area and the communities we serve. The mix and timing of these challenges, combined with the state of today's grid as a starting point, leads us to prioritize grid objectives and target technological solutions for different regions.

- For residential suburbs or populated areas, high expected DER and EV adoption rates will require more advanced grid control and management solutions to maintain power quality and reliability
- For industrial areas, given more intensely concentrated and rapidly electrifying industrial loads (e.g., electric trucks, logistics equipment), delivering power within limited rights of way and space may benefit from more novel and compact approaches to serve highly dense loads
- For rural/remote areas and desert communities more exposed to climate-driven threats such as fires and floods, grid resilience is paramount; future designs will potentially leverage local community-scale renewable resources, DERs and customer loads to create reconfigurable nano/micro/mini-grids
- For rapidly growing mixed-use areas, there will be a combination of the above attributes with varying demands and constraints

Our current grid and modernization programs in recent years were not designed to fully address all these emerging challenges. Back when we launched SCE's Grid Modernization program in the middle of the past decade, we saw early challenges posed by the proliferation of DERs. Since then, we have seen a significant increase in the magnitude and pace of change of transportation electrification, retirement of conventional generation and rapidly intensifying effects of climate change. These new challenges — manifested in loss of inertia, limits to resource availability and acute climate risk areas, among others — will require evolved solutions that build upon the foundation being laid out by our Grid Modernization Program.

With Pathway 2045, the stakes for the grid have changed. The complexity and variability of customer demand will accelerate. The breadth, quantity and roles of resources that will become part of grid solutions will expand, including inverter-based resources (e.g., storage, DERs), flexible customer load (e.g., managed EV charging, demand response) and bundled "non-wire alternatives." Accommodating all this will require higher levels of system awareness and ever-faster levels of system control. Maintaining system stability will require ultra-rapid communication with/among millions of DERs and other grid or customer devices, exceeding the bandwidth of currently deployed communications systems (e.g., 4G), as well as automatic response capabilities and control speed required to take actions such as isolating faults and regulating frequency/voltage.

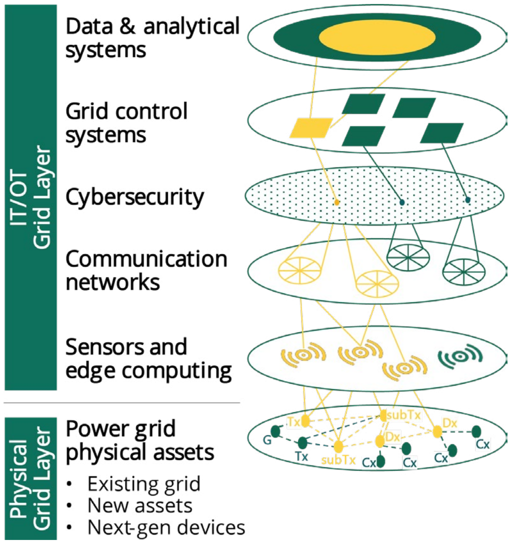


**Figure 4:** Grid technology layers

Next, we examine the different technology layers (see Figure 4) that the reimagined grid will need to address these challenges, grouping them into two categories:

1. A common digital platform of information and operational technologies (IT/OT) that includes communications, sensing, analytics, control and advanced cybersecurity
2. Physical assets and devices that enable use-specific solutions, built on top of the IT/OT platform and the existing grid infrastructure

We then define a broad set of grid capabilities that leverage these technology layers, consisting of a cluster of *foundational* capabilities working together to enable systemwide integration and operation of grid technologies and a set of *situational* capabilities that will address location-specific challenges and planning.

**Foundational capabilities** will be implemented across the entire grid as part of deploying the IT/OT platform depicted above, with grid modernization currently underway as a starting point. This will require expanding functionalities and upgrading to state-of-the-art versions of some technologies beyond what is already in place or planned. For example, SCE's Grid Modernization program identified the need for a 4G/LTE private wireless network to enable low-latency, high-bandwidth communications between the grid management system (GMS) and existing grid devices. However, an upgrade to 5G and potentially next generations of wireless technology (e.g., 6G) that can handle higher peak throughput will be required in the future — generally more than 1 gigabits per second, exceeding the theoretical upper limits of 4G/LTE — to allow ultra-low latency/high density communications with new distribution, customer and IoT devices as they grow into the millions.

We summarize the core foundational capabilities below in Figure 5:

| | Capabilities | Description |
|---|---|---|
| Ⓣ<br>Ⓓ | **Ultra low-latency communications** | Communications between grid and customer devices that are real time (milliseconds), high peak throughput (1+ GBps), high density (2M+ devices), high coverage and cybersecure |
| Ⓣ<br>Ⓓ | **Ubiquitous situational awareness** | Integrated, high-fidelity measurement and monitoring of grid state and assets (from generation to customer levels) with high spatial and temporal resolution |
| Ⓣ<br>Ⓓ | **End-to-end advanced simulations and analytics** | Prediction and optimization of grid systems and assets, leveraging virtual representation of the grid and its components with standardized data protocols |
| Ⓓ | **Localized & edge control** | Hierarchical and distributed grid control, complementing centralized optimization of resources with delegation of local control decisions to edge devices through policy-based settings |
| Ⓓ | **Adaptive protection** | Protection settings updated remotely to adapt to bidirectional power flow requirements and potential changes in grid topology to preserve safety of operations |

Ⓣ Transmission and Subtransmission Ⓓ Distribution

**Figure 5:** Overview of foundational capabilities

These foundational capabilities will enable much faster, advanced, integrated and responsive management of the grid, helping maintain system stability, reliability and power quality. Achieving this will require moving more autonomous intelligence into the edge of the grid, having ubiquitous and real-time situational awareness and enabling ultra-rapid and cybersecure response actions. Figure 6 on the next page illustrates the envisioned evolution of grid control functions enabled by these foundational capabilities.

**Situational capabilities** consist of future use cases that will leverage next-generation technologies and devices in targeted deployments to solve location-specific needs. These situational capabilities will rely on the IT/OT platform, and associated technologies will need to be integrated as either direct replacements or new additions to existing grid devices. Replacement technologies are advanced alternatives for existing components that can perform equivalent functions in a more efficient or versatile manner (e.g., solid-state transformers in lieu of traditional ones). New additional technologies are complementary and incremental to existing equipment — they do not have equivalents on the current grid (e.g., synthetic inertia response).

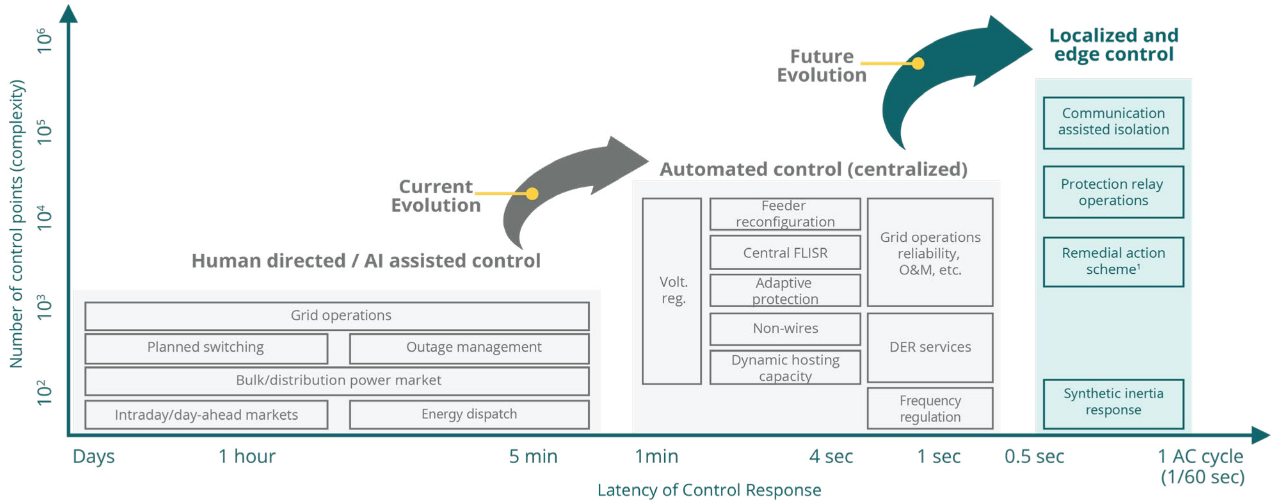


**Figure 6:** Evolution of grid control requirements

Figure 7 summarizes several of the most critical situational capabilities identified.

| | Capabilities | Description |
|---|---|---|
| Ⓣ<br>Ⓓ | **High capacity throughput (& protection)** | Augmented power supply and delivery capacity to serve new demand from transportation electrification or other load while ensuring power system stability and safety |
| Ⓣ<br>Ⓓ | **Islanding & reconfigurability** | Control and operation of interconnected loads and DERs independently from bulk power system, dynamically adapting electrical boundaries (e.g., microgrids) to optimize economic performance and reliability |
| Ⓣ<br>Ⓓ | **Energy buffering** | Alternate energy sources, located as close to the load as possible to compensate variable/ intermittent power output of renewables |
| Ⓣ<br>Ⓓ | **Inertia substitution** | Novel sources of inertia and other grid reliability services to ensure power system frequency response and stability, given rising level of renewable resources connected to the grid |
| Ⓓ | **Seamless grid flexibility** | Seamless adjustment of the grid to rapid changes in load and supply to ensure grid balancing (supply/demand), and economic and reliable performance |
| Ⓓ | **Customer load flexibility** | Controls/signals to interact with customer devices and harness the full potential of customer load flexibility |
| Ⓓ | **Bidirectional power flow control** | Management of power flow direction between DERs and the grid |

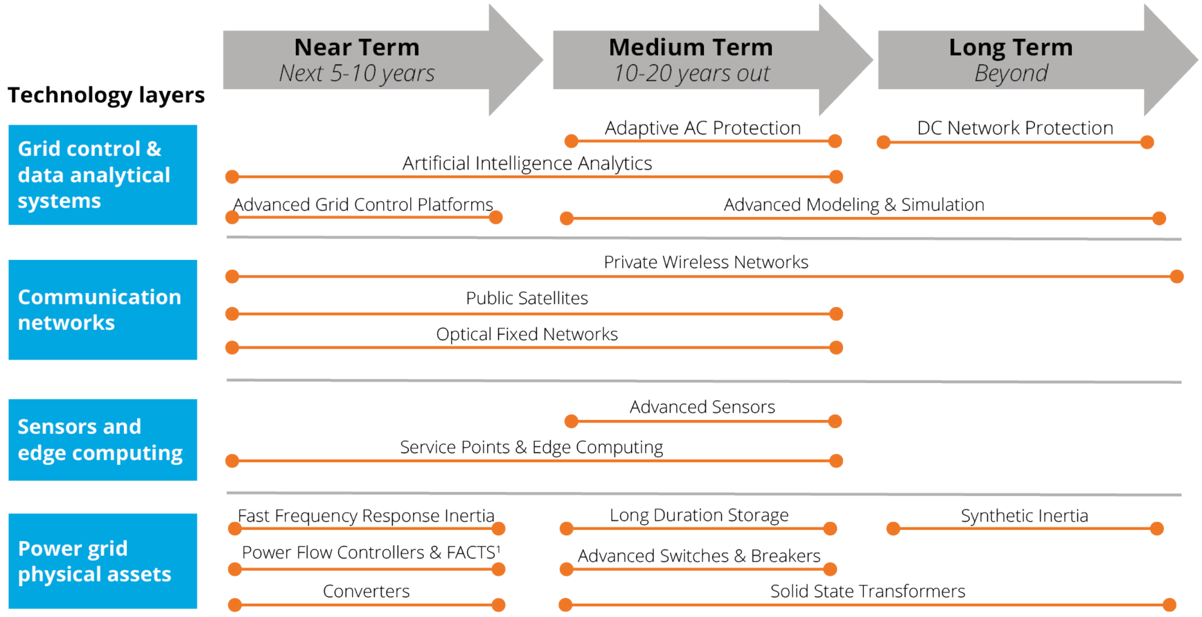
Ⓣ Transmission and Subtransmission Ⓓ Distribution

**Figure 7:** Overview of situational capabilities

To develop future grid solutions, we will combine the foundational capabilities with these situational capabilities, packaging them together into grid architectures that address specific needs. Importantly, advanced cybersecurity technologies will need to be developed and incorporated into the design of different architectures that bundle these capabilities, given the increased exposure to cyberattacks inherent in digital, software-centric grid systems. For practical implementation of these solutions, we will define several modular grid architecture design packages tailored to different geographic areas of SCE's service area.

# FUTURE GRID ROADMAP

Many of the technologies and grid architectures capable of addressing the future challenges to the grid — safely, reliably and affordably — are either emerging, under development or not yet available. A key risk for utilities is the uncertainty of whether these technologies will be available when needed. Several technologies that can enable new architectures, such as ultra-low-latency communication technologies or solid-state transformers, may still be several years away from commercialization (see Figure 8). The implementation lag for large-scale infrastructure deployment — such as adding new transmission lines or revising the underlying distribution topology (e.g., from radial to mesh design) — will likely be much longer than changes in software and communications technologies.



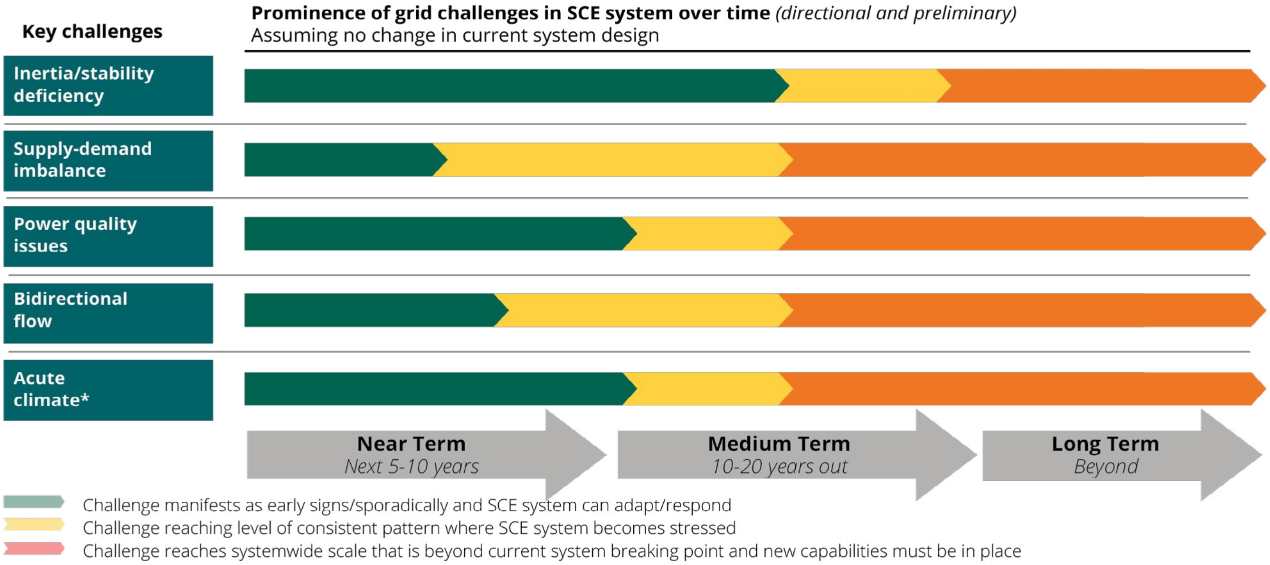
1. Flexible Alternating Current Transmission Systems

**Figure 8:** Estimated commercialization timeframes for critical grid technologies

Historically, taking a deterministic approach to planning the grid for known worst cases has sufficed. The reimagined grid must address emerging uncertainties around when and where different challenges will present themselves and include the necessary solutions when they become available. This calls for a risk-based and probabilistic approach that adapts to variations in design inputs resulting from external changes and gets ahead of them. Not adopting such an approach could result in suboptimal grid solutions, exposing customers to stranded costs. Moreover, failing to deploy the right solutions on time would create vulnerabilities to the safety, reliability and resilience of the grid, and potentially lead to additional costs.

Changing our grid planning paradigm starts with understanding the future challenges affecting grid design choices and identifying the preferred combination of grid capabilities and corresponding technology and design architectures. Given the expected lags to implement required capabilities, developing tomorrow's grid also requires anticipating future vulnerabilities where key technologies may not be available in time (e.g., synthetic inertia, solid-state devices). Figure 9 illustrates the concept of future vulnerabilities, estimating the timing of the initial appearance and growing prominence of several of the key challenges we anticipate.

Working backward from possible vulnerabilities helps determine which technologies risk being unavailable when required. This information will be critical to prioritize R&D and innovation efforts by SCE and the industry and to accelerate the development of key technologies or identify possible alternatives. Importantly, identifying the sources of potential vulnerabilities helps define a set of metrics and parameters of a forward radar: observable, early indicators of emerging trends, with the aim of monitoring and reducing the risk of being unprepared to respond to grid needs.



** Excludes wildfires, which appear as discrete events in time*

**Figure 9:** Estimated timing of key grid challenges

The basic steps to migrate to the new set of capabilities are shown in Figure 10. SCE will need to use the first part of this decade to prepare for building the foundational capabilities described above. Once established, these will provide the basis for deploying situational capabilities throughout our service area, according to specific needs and availability of technology. By preparing the groundwork now, SCE will get ahead of growing risks to the safety, reliability and resilience of the grid while reducing expenditures required to meet its commitments to decarbonization as laid out in Pathway 2045.

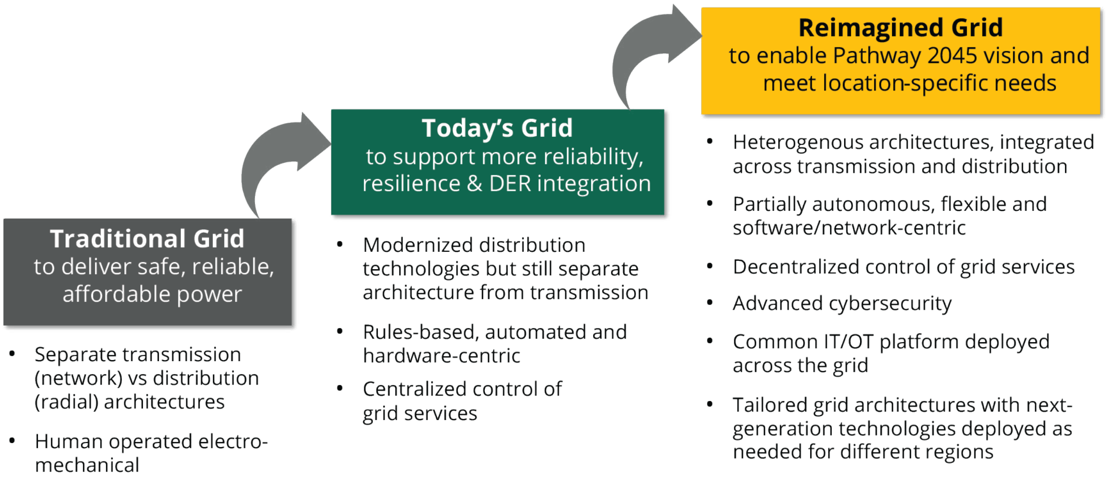
| **Near Term**<br>**(next 5-10 years)**<br>*Window to plan and prepare* | **Medium Term**<br>**(10-20 years out)**<br>*Technologies become available* | **Long Term**<br>**(beyond)**<br>*Challenges reach critical mass* |
|---|---|---|
| *Key Uncertainty:*<br>**Preparedness and alignment** | *Key Uncertainty:*<br>**Technology readiness** | *Key Uncertainty:*<br>**Timing of grid needs (at scale)** |
| Start taking "no regrets" actions and making near-term decisions | Migrate to IT/OT grid platform and foundational capabilities | Deploy full set of new grid architectures and technologies |
| • Refine our forward radar to better forecast customer and grid impacts<br>• Accelerate development of critical technologies to be deployed early<br>• Engage stakeholders and shape standards to build alignment and support for future solutions | • Identify grid needs reaching critical mass and timing of key technologies<br>• Begin upgrade of foundational capabilities and IT/OT grid layers<br>• Make early technology decisions for new grid architectures | • Forecast widespread grid needs with greater fidelity<br>• Update IT/OT grid platform with new technologies<br>• Complete deployment of new grid architectures and next-generation technologies |

**Figure 10:** Future roadmap to build capabilities and prepare for uncertainty

SCE is getting started or already underway with the following "no regrets" actions:

- **Refine our forward radar:** Improve our understanding of where, when and why customers will be adopting DERs, electric vehicles and load control technologies, what are customers' evolving needs and value from the grid and what new grid technologies are on the horizon
- **Accelerate critical technologies:** Fast-track the development of technologies required for the deployment of foundational capabilities (e.g., ultra-low latency)
- **Future-proof current grid initiatives:** Ensure ongoing grid modernization and resilience efforts are designed to handle additional complexity expected and/or are upgradable in the future

- **Engage stakeholders:** Collaborate and engage with customers and other stakeholders to align on what needs/challenges will arise and what are the right solutions and standards for the industry
- **Implement required changes to planning processes:** Explore and adopt new methodologies and tools to make more adaptive grid planning decisions in the future



**Traditional Grid**
to deliver safe, reliable, affordable power

- Separate transmission (network) vs distribution (radial) architectures
- Human operated electro-mechanical

**Today's Grid**
to support more reliability, resilience & DER integration

- Modernized distribution technologies but still separate architecture from transmission
- Rules-based, automated and hardware-centric
- Centralized control of grid services

**Reimagined Grid**
to enable Pathway 2045 vision and meet location-specific needs

- Heterogenous architectures, integrated across transmission and distribution
- Partially autonomous, flexible and software/network-centric
- Decentralized control of grid services
- Advanced cybersecurity
- Common IT/OT platform deployed across the grid
- Tailored grid architectures with next-generation technologies deployed as needed for different regions

**Figure 11:** Evolutionary steps toward the reimagined grid

Figure 11 illustrates how reimagining the grid will involve a significant evolution. It will require grid architectures that are integrated across the transmission and distribution systems instead of being operated at these levels separately. Grid operation decisions must become more instant, automated, autonomous, localized, pushed to the edge and responsive to dynamic condition changes. The use of a systemwide IT/OT platform as an enabler for this diverse portfolio of technologies will make advanced cybersecurity critical. Solutions will be tailored to specific needs and locations, using fit-for-purpose, next-generation technologies.

## BROADER IMPLICATIONS

Achieving our vision for the reimagined grid will require rethinking various aspects of the grid with a long-term lens, as well as increasing cooperation with multiple stakeholders to evolve the grid and advance our Pathway 2045 goals toward enabling a clean energy future.

**Increased technology focus and collaboration** – Our early findings can help inform what are emerging technologies that the electric industry (research organizations, national labs, academic institutions, traditional grid technology suppliers, startups and utilities) should focus on prioritizing for R&D and innovation. Similarly, the scope of collaboration will need to expand given the growing set of technologies that are connecting to the grid, like transportation, buildings and commercial/industrial applications. It will be especially important to engage with a broader set of participants such as chipset, software and AI developers because the reimagined grid will require the development of common standards for the IT/OT grid operating platform.

**Coordinated and adaptive grid planning** – Given the increased complexity and localized nature of future grid challenges, closer coordination among utilities, regional transmission organizations, policy agencies (federal, state and local), communities and customers will be essential for grid planning. Synching up grid planning efforts with urban planning by counties, cities and communities will improve coordination of grid deployments. Future market and regulatory constructs will impact and add complexity to grid planning. The changing grid will also require pushing the envelope of traditional geographic and jurisdictional boundaries as the standard dividing lines between distribution and transmission resources are rapidly evolving. Resources located behind the customer meter (like DERs, EVs and controllable loads) will need to be accounted for in the planning process to optimize them with utility-owned grid assets — and reap their potential opportunities to provide more grid flexibility and higher reliability — in contrast with viewing customers solely as electric load input. Integrated planning across all levels of the grid's value chain — from bulk power system all the way to customer resources — will be required to ensure reliability and make efficient grid deployment decisions. Lastly, the analysis used in regulatory proceedings to justify grid deployments must shift from a focus on historical data and static forecasts to a scenario-based, dynamic model.

**Reimagined approach to grid design** – For more than a century, uniformity in the design of the grid was essential to capture the benefits of scale and drive down costs. But in the reimagined grid, the benefits of uniformity/scale will lie in the different layers of the IT/OT platform. This common platform will enable multiple hardware configurations and the tailoring of solutions into grid architectures that will make more efficient use of capital than a uniformly deployed physical grid. Developing a robust menu of grid architectures will involve working closely with customers and communities to understand local challenges and needs and to co-optimize utility-side and customer-based resources. Utilities including SCE will need flexibility and discretion to deploy different architectures and address fluid changes to grid design requirements. To make this approach to grid design scalable, utilities and technology providers must agree on a common set of modular grid architectures, industry-wide design standards (including cybersecurity) and interoperability of grid components across different designs.

**More efficient and integrated licensing/permitting processes** – Millions of sensing and control devices will be needed as part of the IT/OT platform to enable the grid's foundational capabilities. In addition, substantial deployment of large-scale grid components such as transmission lines and utility-scale energy storage systems will be required over the next few decades, though long lead times will require early actions. To make this all possible, utilities, communities, regulators and customers will need to work together to simplify, streamline and de-risk the licensing and permitting processes associated with building or modifying electricity infrastructure. Better recognition of the potential benefits and impacts of specific grid deployments will help prioritize and expedite projects. Ultimately, reducing the incidence and duration of project delays has the potential to significantly reduce the cost of required changes to the grid.

**Intelligent, more autonomous grid management and operations** – How the grid is operated will undergo a significant evolution as well. The reimagined grid will require substantial advances in grid management system technologies, which will have to communicate and interact with millions of nodes across the entire grid, including at customer locations. Additionally, the traditional approach to grid management will evolve into more decentralized operation of grid assets, with edge computing helping solve localized issues. Policymakers will need to shape a common set of rules and requirements to reliably control customer devices at critical times for grid use. Customers and other stakeholders such as device manufacturers will need to be incentivized to adopt these policies. And technology providers will need to build in the application of such rules into device settings, either as customized or "set and forget" preferences.

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In summary, evolving challenges driven by disruptive changes in our customers, power supply resources and climate will require a new approach to designing and building the grid, using various combinations of grid designs and architectures to meet specific locational needs. Our grid planning approach will need to be more adaptive, agile and scenario/risk based. The future grid will rely on software-centric technologies (IT/OT) and common hardware platforms with advanced cybersecurity. New grid capabilities, technologies and architectures will build upon current grid modernization efforts. Importantly, for SCE's Reimagining the Grid vision to become a reality, we will need unprecedented industrywide collaboration and alignment across an expanded range of stakeholders.

# CASE STUDY: TRANSPORTATION CORRIDORS

## INTRODUCTION

There is no one-size-fits-all future grid solution for SCE given the variety of needs and challenges we expect communities across Southern California will face. Below, we illustrate how we would apply our reimagined grid planning and design approach for a specific type of region in SCE's service area. In this example, we describe the challenges and potential innovative solutions to serve transportation corridors, areas with concentrated movement of goods and people where we expect high adoption of electric transportation. These areas are poised for major benefits from vehicle electrification, including cleaner air for customers living in regions around freeways. Beyond light-duty EVs for passenger use, we expect significant growth of medium- and heavy-duty EVs, such as trucks or other transportation and logistics equipment for commercial and industrial uses. These regions are also typically designated by the state as "disadvantaged communities" due partly to a high degree of environmental degradation and chronically unhealthy air quality. Deploying grid solutions that enable electrification of these transportation corridors will result in substantial improvement of air quality for customers in these communities and the potential for attracting additional economic development.

## GRID CHALLENGES FACED IN TRANSPORTATION CORRIDORS

Recognizing region-specific needs is the first step in reimagining the grid. In SCE transportation corridors, several characteristics are central to understanding the expected challenges they will face in the long term.

**Load growth/changes from transportation electrification:** In addition to a large share of light-duty passenger vehicles, the electrification of medium- and heavy-duty commercial vehicles and industrial equipment has the potential to transform these corridors. More than 30% of the overseas freight in the U.S. runs through the ports that transportation corridors connect to in SCE's service area . Electrification of commercial vehicles will significantly increase local peak and total electricity demand. Electrification of industrial processes may add even more to the peak load requirements in these regions. Furthermore, evolving patterns of transportation demand may result in the magnitude and location of load to vary significantly over time across these corridors.

**Higher-voltage requirements:** While light-duty passenger vehicles sit idle for large portions of the day and therefore such EVs can be charged for hours at lower voltages (most typically 240V for Level 2 with peak power requirements usually in the 3.3kW to 7.2kW range per vehicle), many commercial vehicles are in use throughout the day. Considering their operational schedules, commercial vehicles require very rapid charging to maximize their productive use. The grid infrastructure required to serve them may need to support high-voltage DC (direct current) fast-charging equipment, with peak power ranging from 250kW to more than 1MW per vehicle. Sites with commercial EV fleets relying on fast charging will stress the existing distribution system's capacity within these corridors, and aggregate load from all EV charging in the region will push the capacity of the subtransmission system that links these corridors to the high-voltage transmission network.

**Broader customer, supply and climate-driven challenges:** In addition to the specific challenges above, we expect to see in these transportation corridors some of the same broader challenges previously described for the grid (e.g., loss of system inertia, climate disruptions, power quality, etc.).

Today's grid is prepared to meet the potential increase in demand from transportation electrification over the next decade. SCE's preliminary analysis on grid impacts of medium- and heavy-duty EV load shows that incremental work to upgrade the distribution system is within the scope of the utility's ability to manage, and enhancements in customer data and distribution planning tools/processes will address the complexity of future fleet electrification scenarios. However, as California proceeds further down the pathway to decarbonize, these factors will accelerate and amplify after the coming decade, creating potential risks or vulnerabilities to continue ensuring a reliable source of electricity and a grid infrastructure that can handle increased demand from transportation electrification. In the long term, the reimagined grid will be able to offer new and innovative solutions to build upon grid upgrades that are currently underway or being planned to enable EV growth.

# FUTURE GRID OPTIONS FOR TRANSPORTATION CORRIDORS

We will need to understand what grid attributes will be most critical in transportation corridors as customers undergo profound changes in their electricity needs and usage patterns. *Safety, reliability, affordability* and *resilience* are universal design objectives in a clean energy system. More distinctive considerations for transportation corridor communities include *flexibility* to deal with potential quick ramp-up of load associated with high-power, heavy-duty transportation charging. This requires increased control, faster response and an ability to dynamically shape the load or increase the grid's capacity. Similarly, the grid in these areas may require enhanced *agility* and *adaptability* to be rapidly reconfigured and redistribute load across the system to ensure reliability and power quality in response to large swings in demand or unexpected equipment failures.

As mentioned before, SCE will develop a set of *foundational* capabilities as part of laying out the common IT/OT functionalities required across all of our service area and will deploy more region- and use-specific situational capabilities to meet unique needs. In transportation corridors, key *situational* capabilities include:

- *High-capacity throughput:* The ability to increase the maximum level of electric power supplied to meet new, large demand from transportation electrification while preserving safety and reliability. High-power charging load will increase across these corridors, so the grid must be able to deliver additional power while facing potential transmission constraints due to geographic or space limitations.
- *Inertia substitution:* The ability to substitute the needed system inertia that will be lost when conventional generation is retired and renewable generation grows near transportation corridors, all while ensuring frequency and power system stability.
- *Seamless grid flexibility:* The ability to seamlessly adjust the grid for very rapid changes in load to ensure local supply needs are met and distribution capacity is not exceeded. This will be critical as load requirements from transportation and industrial electrification will vary in timing and intensity.

To provide these future capabilities, SCE will explore various technologies and different grid design options to address these corridors' needs. Among the bolder concepts considered is a **DC-based architecture** in the long term, once EV penetration starts reaching a point beyond what incremental distribution upgrades and existing transmission capacity can address locally in specific areas. The core concept is that given the higher voltages and increased power required to provide fast charging for a growing number of heavy-duty EV fleets, switching to a medium/high-voltage, DC-based system *could* be less costly than adding a traditional solution, including the transmission, sub-transmission and distribution level cable and transformer equipment required.

This concept offers the potential to satisfy all the critical grid objectives noted above while minimizing land use in what typically are already dense transportation corridors. However, this architecture has not been commercially deployed elsewhere yet, and to be implemented in the long term, it will require several critical technological components to be ready and available within the next couple of decades, including:

- *Solid-state substations, transformers and breakers* to enable seamless grid flexibility
- Direct high-voltage EV charging at distribution DC substations (230kV+) through dedicated power electronics to enable high-capacity throughput for transportation electrification
- *Power inverters and DC converters* to enable ancillary services and inertia substitution by helping to connect the transportation corridors with new renewable sources
- *Strategically dispersed energy storage* to meet new and localized distribution needs, leveraging *long-duration storage technology (1+ day)* developed, commercialized and deployed over the next decade

Transportation corridors will present a novel and demanding set of challenges for SCE in the long run, beyond this coming decade's planning horizon. The variability around when and where these new challenges will appear, as well as which grid technologies and architectures will be available to address them, will bring unprecedented complexity to how we plan, design, build and operate our grid in these regions. We are confident, however, that by getting in front of these developments through our vision for reimagining the grid, we will be well equipped to continue providing the diverse communities of Southern California — such as those in our transportation corridors — with safe, reliable, affordable, resilient and clean electricity.