

## ORIGINAL RESEARCH REPORT

## Chapter 5. Assessing the Need for High Impact Technology Research, Development & Deployment for Mitigating Climate Change

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Technology is a centrally important component of all strategies to mitigate climate change. As such, it encompasses a multi-dimensional space that is far too large to be fully addressed in this brief chapter. Consequently, we have elected to focus on a subset of topics that we believe have the potential for substantial impact. As researchers, we have also narrowed our focus to address applied research, development and deployment issues and omit basic research topics that have a longer-term impact. This handful of topics also omits technologies that we deem to be relatively mature, such as solar photovoltaics and wind turbines, even though we acknowledge that additional research could further reduce costs and enhance performance. These and other mature technologies such as transportation are discussed in Chapter 6.

This report and the related Summit Conference are an outgrowth of the University of California President's Carbon Neutrality Initiative, and consequently we are strongly motivated by the special demands of this ambitious goal, as we are also motivated by the corresponding goals for the State of California, the nation and the world. The unique feature of the UC Carbon Neutrality Initiative is the quest to achieve zero greenhouse gas emissions by 2025 at all ten 10 campuses. It should be emphasized that a zero emission target is enormously demanding and requires careful strategic planning to arrive at a mix of technologies, policies, and behavioral measures, as well as highly effective communication – all of which are far more challenging than reducing emissions by some 40% or even 80%. Each campus has a unique set of requirements based on its current energy and emissions. Factors such as a local climate, dependence on cogeneration, access to wholesale electricity markets, and whether a medical school is included shape the specific challenges of the campuses, each of which is a “living laboratory” setting a model for others to learn and adopt.

An additional aspect of a zero GHG emission target is the need to pay close attention to system integration – i.e., how the various elements of a plan to achieve carbon neutrality fit together in the most cost effective and efficient way. This optimization imposes an additional constraint, but also provides an important opportunity to capture the synergies that can arise from those choices. For example, one of the themes that has been proposed is the complete electrification of energy supplies, residential & commercial building operation, and transportation. The deployment of storage technologies such as batteries and/or hydrogen for both transportation and for load balancing of grid and distributed generation may provide some synergistic opportunities for integrating these systems that will accelerate the deployment of each. A specific example is the use of on-board batteries in electric vehicles for load balancing the electric grid. On-site residential storage as is now being developed by Tesla Motors, has the potential to accelerate the deployment of residential solar installations. In the case of hydrogen fuel cell vehicles, the necessary infrastructure to provide a network of hydrogen filling stations might also accelerate the use of hydrogen for storage on the electric grid by using excess solar capacity to produce hydrogen by electrolysis.

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## Fossil & Renewable Power Generation

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It is generally agreed that the deployment of renewable wind and solar power is needed to meet energy demands commensurate with achieving environmental quality goals. Eventually, the power generation sector must strive to source all of its primary energy from the sun (which is the primary source for solar PV, solar thermal, wind, and even hydro and biopower) and convert such energy into power with zero greenhouse gas emissions (GHG), and without criteria pollutant emissions, environmental disruption, water demand, or waste.

Clean fueled power generation is the technology that is used to complement the intermittent and uncontrollable wind and solar renewable power in a controllable fashion and thereby enable stable and reasonably priced electric grid performance. Today, fueled power generation meets the majority of our electricity demand and is primarily produced through natural gas combined cycle (NGCC) power plants. Alternative and emerging clean fueled power generators that can achieve low emissions (of GHG and criteria pollutants) with comparable or even higher overall efficiencies include distributed power generators such as fuel cells and micro-turbine generators. Clean fueled power generators need to be installed and operated on natural gas as a bridging fuel in the short term to reduce GHG and criteria pollutant emissions in the place of older, less efficient and higher emitting power plants. These fueled power generators should then be transitioned to renewable and zero emission fuels (e.g., biogas, renewable hydrogen) along with highly dynamic dispatch capabilities to both (1) manage the diurnal and random fluctuations associated with intermittent renewable power generators (e.g., solar and wind power), and (2) increase the maximum penetration of renewable resources that can be accommodated in the utility grid network.

Each of the technologies considered with their typical performance characteristics, a representative technology evolution path, and initial recommendations for clean fueled power generation are provided below.

### Clean Fueled Power Generation Technologies

Clean fueled power generation technologies<sup>1</sup> include natural gas combined cycle at the central power plant scale (>50 MW), and fuel cells, gas turbine generators, and hybrid fuel cell heat engines at the distributed power plant scale (<50 MW).

1. Natural Gas Combined Cycle – comprised of three main components of a gas turbine (Brayton cycle that includes compressor, combustor and turbine), a steam turbine (operating on the Rankine cycle), and a heat recovery steam generator (HRSG) that integrates the two cycles together by generating steam from the upstream gas turbine exhaust. At the central plant scale NGCC plants are capable of high fuel-to-electricity efficiency of between 50–60% and ultra-low criteria pollutant emissions when integrated with a selective catalytic reduction (SCR) emissions clean up system [1, 2].

2. Fuel Cells – fuel cells are fundamentally different than combustion in that they convert fuel directly to electricity and heat by electrochemical reactions that are similar in concept to battery electrochemical reactions. Fuel cell systems have been produced using various materials sets (e.g., solid metal oxides, molten carbonates, phosphoric acid) [3] with high electrical efficiencies (up to 60%) [4, 5] and inherently low (near zero) pollutant emissions operating on natural gas (and other fuels) even at the distributed power scale [5, 3, 6].
3. Small Gas Turbine Power Plants – These power plants can be combined with a bottoming steam turbine cycle or operated as a stand-alone Brayton cycle and can typically operate on renewable gaseous fuels, but, must be integrated with combined heat and power (CHP) to achieve reductions in GHG, and must be integrated with SCR to achieve low criteria pollutant emissions [7, 8].
4. Hybrid Fuel Cell Heat Engine Plants – These power plants integrate a high temperature fuel cell (solid oxide or molten carbonate) with a heat engine (e.g., gas turbine, reciprocating engine) to achieve even higher efficiency than a fuel cell (converting fuel cell heat to useful work) and some load following characteristics. These emerging power plants are being developed by several manufacturers (e.g., GE Fuel Cells) and have been shown to achieve electrical efficiencies up to 75% [9, 10] with ultra-low emissions even at distributed power sizes [9], and dynamic dispatch characteristics [10, 11].

Representative performance and emissions characteristics for each of these classes of technologies as operated on natural gas are presented in **Table 1**. All of these technologies are considered clean because they have substantially lower GHG and pollutant emissions compared to all other controllable power generators and can evolve from natural gas (the clean bridging fuel) to use of renewable fuels. It is expected that GHG emissions will be reduced to near zero at the point of use in this case and will only be associated with upstream fuel processing and delivery and that pollutant emissions will be unchanged or lower than that presented in **Table 1**.

### Representative Technology Evolution Path

Those clean fueled power generators that are installed today must exhibit the highest efficiency, which means that NGCC plants that are required must be built at the central plant scale where they can achieve fuel-to-electricity efficiencies approaching the 60% range. Fuel cells and hybrid fuel cell heat engine technology can achieve efficiencies greater than 60% at both the central and distributed power scales. Small gas turbines, on the other hand, must be installed only in applications where significant heat is recovered (CHP) to make a contribution to GHG emissions reduction. All of these technologies, especially the fuel cell-based technologies, can also achieve ultra-low to zero criteria pollutant emissions.

Technology Class	Fuel-to-Electricity Efficiency*	Fuel-to-Heat & Electricity Efficiency**	CHP GHG Emissions Rate (CO <sub>2</sub> equiv.)	Nitrogen Oxide Emissions Rate	Other Pollutant (e.g., CO, PM)*** Emissions Rate
NGCC (central)	50–60%	Electric only	307–368 kg/MWh	~14 g/MWh	~50 g/MWh
Fuel Cells	50–60%	70–90%	205–263 kg/MWh	~3 g/MWh	~10 g/MWh
Small Gas Turbine CHP	35–45%	60–80%	230–307 kg/MWh	~23 g/MWh	~70 g/MWh
Hybrid FC-GT	60–70%	85–95%	194–217 kg/MWh	~5 g/MWh	~15 g/MWh

**Table 1:** Representative performance and emissions of clean, fueled power generator classes operating on natural gas (bridging fuel) (after Rodriguez et al [12]) [kg = kilogram; MWh = megawatt-hour; g = gram].

\* electricity output divided by fuel higher heating value.

\*\*electricity plus heat output divided by fuel lower heating value.

\*\*\*sum of carbon monoxide (CO), particulate matter (PM), hydrocarbons, sulfur oxides.

These clean fueled power plants should replace older less efficient and higher polluting Rankine cycle power plants. Equally important is to reduce the need for low efficiency, single-cycle gas-turbine peaking power plants. From this point of installing only clean and efficient fueled power generators that can contribute both to GHG and criteria pollutant emissions reductions, all of these technologies must evolve to support the ultimate reality of a completely renewable power grid. This section provides a representative technology evolution path to illustrate the important time-dependent features of power generation that can cost effectively support the utility grid network evolution toward 100% renewable primary energy.

The technology evolution path for clean fueled power generation is one that must involve the increasing application and use of the following power generation features: (1) significant dynamic ramping capabilities to complement intermittent renewable power generation, (2) fuel flexibility to accommodate the increasing use of renewable fuels, and (3) continual high efficiency and low emissions throughout the evolutionary process.

At this juncture, it is not known if a 100% renewable grid can be sustained with energy storage only. Also, lower costs and lower emissions are likely to result from a 100% renewable grid that uses some amount of clean fueled power generation. It is prudent, as a result, to anticipate that 24/7 load following clean power generation fueled by some combination of biogas, renewable hydrogen, and renewable methane will be required to complement energy storage. For example, UC research suggests that the dynamic dispatch (fast and controllable ramping up and down as needed to complement intermittent and uncontrollable renewable power) of clean fueled power generators will be required [13]. UC research has also shown that the dynamic dispatch of fuel cell systems can complement and increase the penetration of wind and solar power with low emissions [14]. It is clear that the dynamic dispatch of controllable clean power plants is essential to the effective integration of high renewable power use in the electric utility grid network.

### Summary

Fuel cell and hybrid fuel cell heat engine power plants should increasingly be installed since they can achieve high electrical efficiency with inherently low criteria pollutant emissions at both the central and distributed power scales. At the distributed power scale, fuel cell systems are preferred since they can directly use the typically distributed availability of renewable fuels (e.g., biogas, landfill gas), and can increasingly use these resources to produce electricity, heat and fuel without transmission and distribution system losses. Such fuel cell systems can then also become highly dynamic in their dispatch capabilities (over time) to support increasingly higher levels of renewable power use [15]. Finally, these dynamically dispatched fuel cell systems can readily evolve into the ideal clean fueled power plant technology for the ultimate goal of 100% renewable primary energy use as solar and wind power that would otherwise be curtailed can be converted to hydrogen for zero emissions power and heat production from fuel cells [16].

Natural gas infrastructure (e.g., pipelines, storage facilities) may become the most critical means for electric utility grid network balancing, management, and energy transfer. Current natural gas infrastructure can be coupled with electrolyzers to cost effectively store a massive amount of otherwise curtailed renewable power in the form of hydrogen or synthetic methane to support the electric utility grid network and zero emissions transportation (e.g., via fuel cell electric vehicles) [17]. Such use of the natural gas system also enables transmission of energy from places of high renewable power generation (e.g., desert) to end uses without the additional transmission lines.

### Transportation

Scott Samuelson, UC Irvine

The transportation sector is the single largest sector contributing to greenhouse gas (GHG) emissions in California. Passenger vehicles represent the majority of GHG emissions in the transportation sector and thereby represent an opportunity to significantly reduce GHG emissions. Although heavy duty trucks, ships, aviation,

and rail contribute a smaller portion of the GHG emissions in the state, these sources emit the vast majority of criteria pollutants (86% of the NO<sub>x</sub> from the transportation segment) and are a major target, as a result, for the emissions reductions needed to meet urban air quality mandates. Transitioning to zero emission technologies for these vehicle types will not only reduce GHG emissions but also provide significant improvements in air quality across the state.

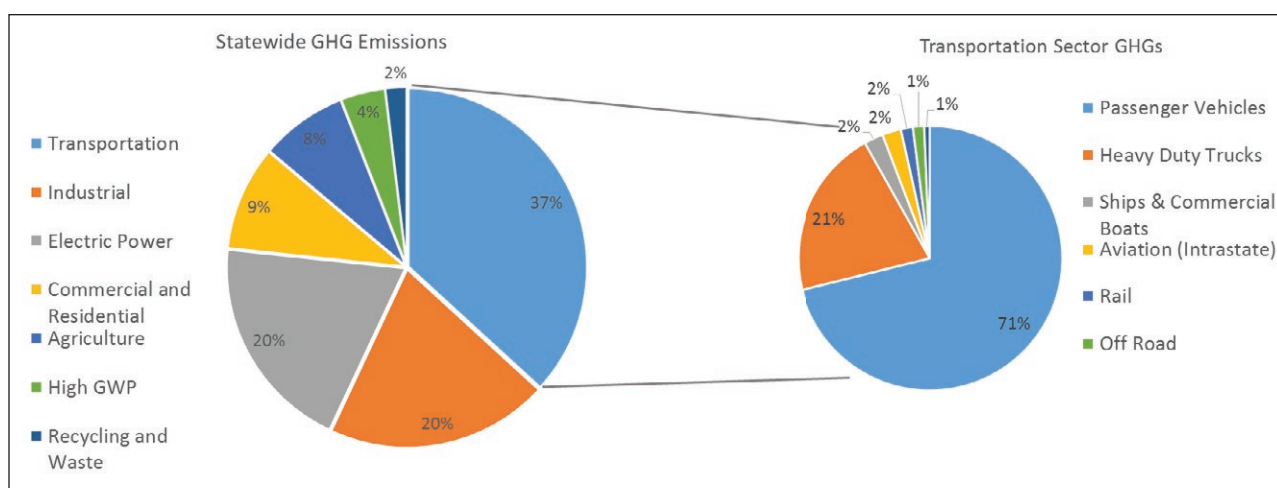
### Light Duty Vehicles

It is widely accepted that a large population of electric drive-train vehicles will be needed in order to meet the GHG reduction goals. Electrification includes plug-in hybrid vehicles (PHEVs), battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). Each of these electric vehicle types have near-zero or zero tailpipe GHG emissions. GHG emissions do occur, however, upstream in the fuel production (e.g., electricity, hydrogen, or gasoline). Studies that assess the GHG and criteria pollutant emissions associated with the extraction, production, treatment, distribution, and consumption of the fuel (referred to as well-to-wheel, WTW, emissions analyses) are required by regulatory programs such as the Low Carbon Fuel Standard. Many WTW studies have been conducted and continue to be published including those from the UC Irvine (UCI) [19], UC Davis (UCD) [20], the National Renewable Energy Laboratory (NREL) [21], and the National Academy of Sciences (NAS) [22].

As shown in **Figure 1** where GHG emissions for BEVs and FCEVs are compared to those from gasoline and compressed natural gas (CNG) vehicles, there is general agreement that the lowest GHG emitting technologies are BEVs and FCEVs. Some of the studies presented in **Figure 2** were conducted specifically for California which has an unusually low carbon electric grid. Most regions in the world today have a higher carbon grid which will translate into higher WTW carbon emissions for BEVs (which are charged from the grid), and FCEVs for cases where the hydrogen is produced via electrolysis powered by the grid (rather than powered via a renewable solar or wind resource).

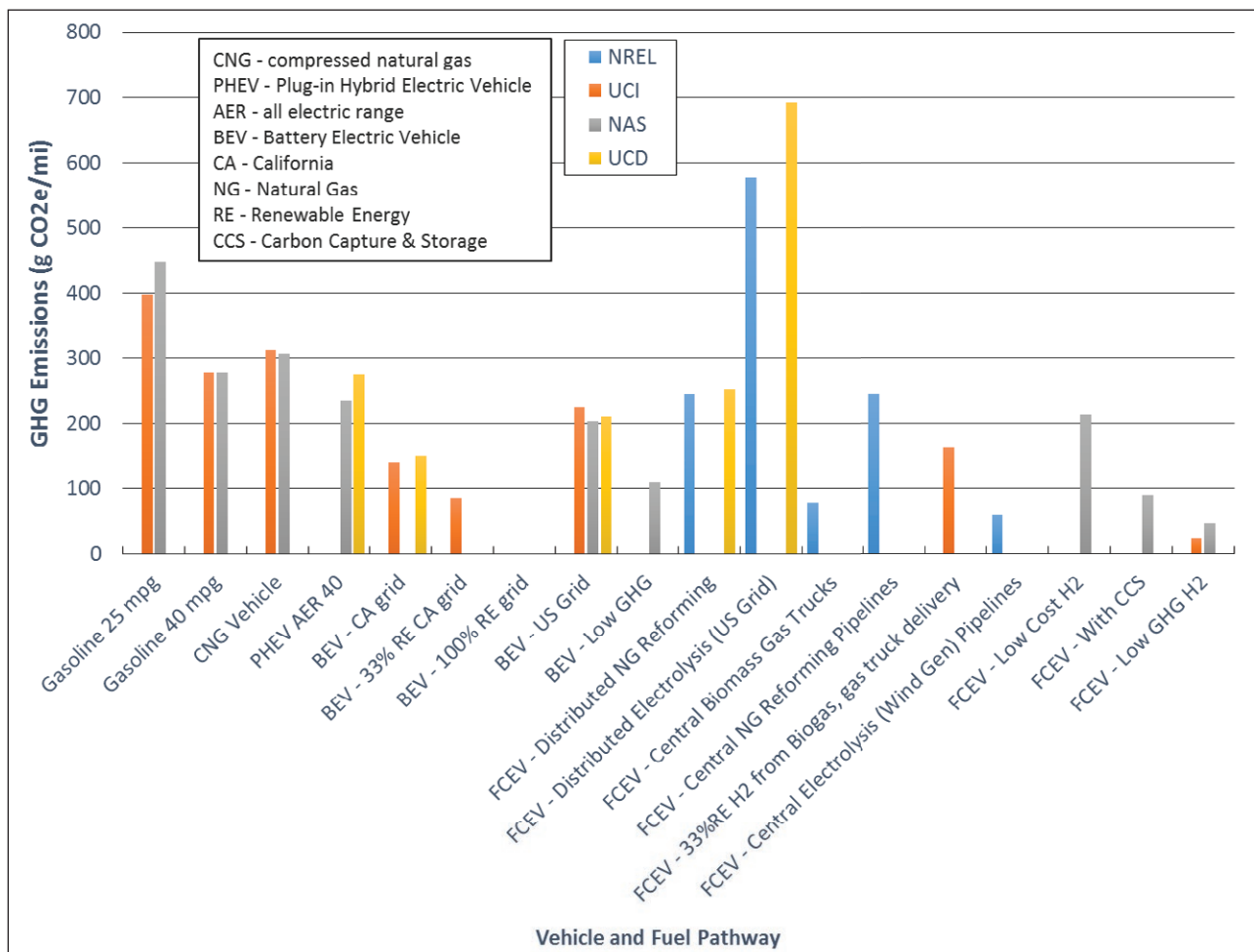
Note that using an **average** carbon emission factor for the electric grid may not correctly represent carbon emissions from BEVs or electrolysis. The electric grid requires that the load be equal to the electricity generated at all times, taking into account delivery losses. For example, BEVs may be charging from the grid at times when solar and/or wind generation are absent. At those times, in California natural gas generation must be increased (and, in the future, energy storage may be utilized), and in other areas coal increased, to keep the load balanced. This will occur frequently in the absence of communication and coordination with the electric grid and when the timing of BEV charging is based strictly on consumer travel patterns, and on the structure of the daily, weekly and seasonal variability of wind and solar generation. This is called “uncoordinated” charging. Taking this into account, the actual carbon emission factor (the so-called “weighted” carbon emission factor) is significantly higher than the “average” carbon emission factor. Studies, such as those from Tarroja et al. [23] and Ma et al. [24], account for these differences by using grid models or making assumptions regarding how the average emission factor may change depending on the amount of natural gas generation required.

Natural gas reforming for hydrogen production for FCEVs, and BEVs charging from the US grid, have similar carbon emissions per mile. However, in the case of California (CA), natural gas reforming produces more carbon emission than BEVs charging from the CA electric grid due to the low carbon nature of the CA grid. Therefore, it is important that a renewable requirement exist for the production of hydrogen such that a carbon reduction potential is maintained similar to that of BEVs. This renewable requirement should be set such that, on a WTW basis, the carbon emissions are virtually the same as BEV charging on the CA grid, and the requirement should increase in manner similar to the Renewable Portfolio Standard. In California, at least 33% of the hydrogen dispensed must be sourced from a renewable source. The potential for increasing this percentage is high, particularly due to the use of biomass and biogas resources which provides an efficient pathway for producing renewable hydrogen



**Figure 1:** Statewide GHG emissions and transportation sector GHG emissions subdivided into specific vehicle types [18].





**Figure 2:** Collection of often referenced well-to-wheel studies from the literature [19, 20, 21, 22].

compared to wind or solar electrolysis, although the latter may be used to an extent for supporting grid operations. For example, if all the existing biogas and biomass resources were used today to produce renewable hydrogen along with the projected curtailment of wind energy, the current light duty fleet in California (approximately 20 million vehicles) could be fueled by renewable energy. One of the proven technologies for producing hydrogen from biogas is “tri-generation” where a commercial high-temperature fuel cell is modified to generate, in addition to electricity and heat, hydrogen at prices competitive to gasoline. When deployed at a water resource recovery facility (i.e., wastewater treatment plant), the renewable electricity displaces grid electricity, the renewable heat displaces the emission of GHG and criteria pollutant emissions from a boiler, and the renewable hydrogen is dispensed to FCEVs. Similarly, installing higher capacities of renewable electricity resources (e.g., wind, solar) on the grid, coupled with the use of BEVs, can also allow the light duty vehicle fleet to be largely powered with renewable energy.

While the cost of BEVs and FCEVs entering the commercial market are understandably initially high, these vehicles must reach cost competitiveness with traditional gasoline automobiles in order to achieve the high market penetration required for significant carbon reduction.

Both batteries and fuel cells have experienced significant decreases in costs over the past ten years. Expectations are that these cost reductions will continue allowing these vehicles to compete economically with conventional gasoline vehicles of similar size and weight.

In summary, light duty vehicles are on a path to virtually zero-emission of GHG and criteria pollutants. Policy and regulation initiatives need to be directed to (1) accelerating the transition of light duty vehicles from gasoline to electricity-powered and hydrogen-powered electric drive-train vehicles, (2) accelerating the availability and viability of biomass and biogas resources, (3) accelerating the evolution of a low-carbon electric grid, and (4) accelerating the development and deployment of energy storage (e.g., battery and hydrogen) technology to complement and capture the special opportunities associated with an electric grid dominated by a high-penetration of renewable solar and wind resources.

While the zero-emission pathway for the light duty vehicle segment is well underway, the heavy-duty segment has only recently seen regulation on fuel economy.

### Heavy Duty Vehicles

While heavy duty sectors (trucks, rail, ships, and off-road) do not emit the majority of GHGs in the transportation sector, these sectors account for a majority of NOx

emissions (**Figure 3**). This emphasizes the importance of reducing criteria pollutant emissions from these vehicle types, particularly heavy duty trucks which account for 45% of the NO<sub>x</sub> emissions occurring in the transportation sector. Zero emission technologies, now being deployed commercially in light-duty vehicles, hold the potential to reduce criteria pollutant emissions from heavy duty trucks while also reducing GHG emissions. The upstream generation and fueling infrastructure (electricity, hydrogen) are being developed for these zero emission technologies, which can be leveraged by the heavy duty sectors. While these zero emission technologies have been demonstrated in heavy duty trucks, significant development and incentives are required to instill commercial products. Given the duty cycles and payloads of heavy duty trucks, major improvements are needed in the power and energy densities of powertrains in order to compete with current diesel and natural gas engine technologies.

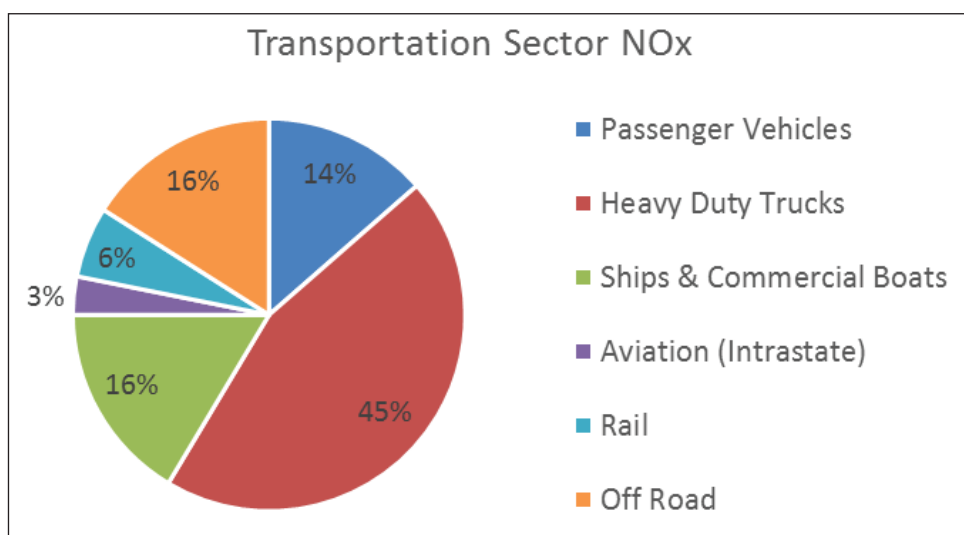
Battery electric medium duty trucks are emerging in the commercial market, but their utility is currently limited by range and time required to charge. Fuel cell electric drive trains are applicable to both medium and heavy duty vehicles with hydrogen fueled buses operating in revenue service from Germany, to California, to Japan. Demonstrations of wayside power are also underway for short haul heavy duty. However, major gaps in demonstration projects exist for the Class 8 (heavy duty) trucks. Of the heavy duty truck emissions in the state, Class 8 trucks account for 55% of the NO<sub>x</sub> emissions. This is tightly coupled to the technical and economic challenges associated with deploying zero emission technologies in these vehicles. Current advancements in natural gas reciprocating engines are underway where emissions requirements have been demonstrated, but zero emission technologies for this class of trucks requires significant development.

Policy and regulation are required to accelerate the deployment of both the vehicle technology and the fueling infrastructure requirements. The opportunity exists to leverage both the medium duty and heavy duty technology requirements and fueling infrastructure off the emerging

BEV and FCEV vehicle and fueling markets, but cost reductions need to occur to allow the freight system in the state to remain competitive.

### Summary

- Light Duty Vehicles
  - A portfolio of BEVs, and FCEVs will be needed to meet consumer demands for refueling time, range, and general convenience.
  - Further deployment of renewables on the electric system is needed to ensure low carbon electricity for the production of hydrogen and charging BEVs.
  - By requiring a renewable input contribution to hydrogen production, FCEVs remain on par with BEVs charging from the CA grid.
  - Use of biogas/biomass for hydrogen production is more effective than using renewable electricity to produce hydrogen although this may be required at high renewable penetrations for grid management.
  - Tri-Generation to produce hydrogen and electricity holds the potential for significant carbon reductions even if fueled with only natural gas.
  - Cost will remain on parity or become lower than current costs.
- Heavy Duty Vehicles
  - The heavy duty sector emits the majority of NO<sub>x</sub>, a precursor to ozone, a secondary pollutant for which several air districts are significantly out of compliance.
  - Zero emission technologies commercially deployed in the light duty passenger vehicle sector hold the potential to significantly reduce GHGs and criteria pollutant emissions from the heavy duty sector.
  - The heavy duty sectors can leverage fuel infrastructure developments made for the light duty sector.
  - Heavy duty vehicle zero emission technologies require significant advancement technically and



**Figure 3:** NO<sub>x</sub> emissions occurring in the transportation sector [18].

economically such that their deployment maintains the competitiveness of the state's goods movement system.

- Ships and rail are amenable to transition to zero-emission fuel cell based hybrid technology.

## Biomass, Biogas, and Biofuels

Bryan Jenkins, UC Davis

Biomass sources include purpose-grown organisms and crops as industrial feedstocks such as trees, grasses, algae and others; crop and processing residues from agricultural, industrial, and commercial operations; animal manures; and biogenic fractions of municipal solid wastes and wastewater among other sources. Biogas sources include gases emanating from landfills, wastewater treatment plants, food processing plants, among other sources. Biogas, as with other biofuels such as ethanol and biodiesel, originates principally from biomass materials and is generally considered within the overall framework of biomass utilization.

The properties and complex chemical compositions of biomass enable the direct replacement of many fuels and products now made from more conventional non-renewable feedstocks such as natural gas and petroleum, and provide for new products with the potential for improved economic and environmental performance (Figure 4) [25]. However, alternative markets also generate increased competition for land, water, and other resources already used by agriculture, and depending on the scale of production can both directly and indirectly affect global supplies and prices of food, feed, and fiber.

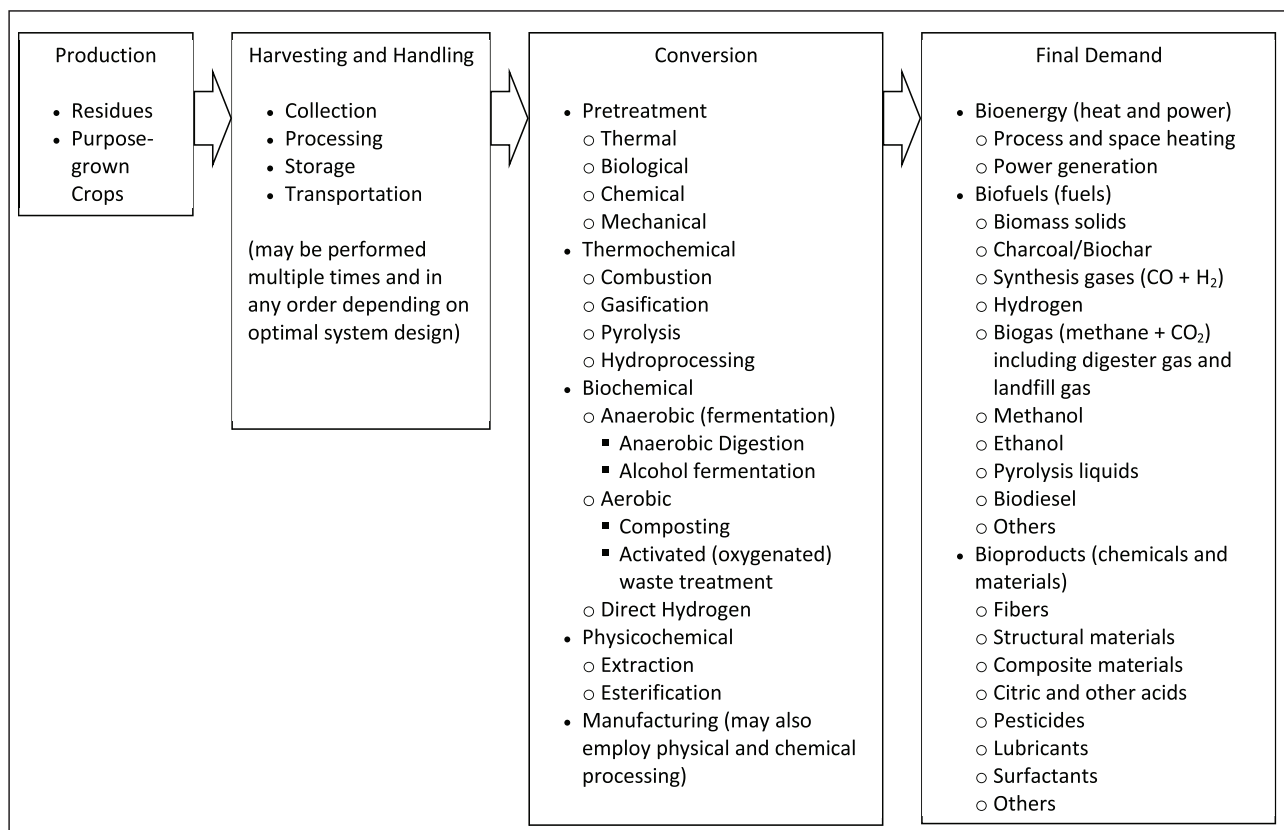
Sustainable feedstock supply requires broad system-level perspectives and detailed attention to lifecycle impacts on which to build effective policies, standards, and practices. Nonetheless, the potential remains for biomass, biogas, and biofuels to provide larger scale reductions in greenhouse gas emissions and other net environmental benefits while contributing significant economic development opportunities.

Biomass is living material, and in the context of energy and materials from agriculture and other sources, biomass is interpreted to mean non-fossil material of biogenic origin.

### Bioenergy conversion

Three principal routes exist for converting biomass to energy: 1) thermochemical, 2) biochemical, and 3) physicochemical [25]. In practice, combinations of two or more of these routes may be used in the generation of the final product or products. Chemical or biological catalysts are employed in many cases. Thermochemical conversion includes combustion, thermal gasification, and pyrolysis along with a number of variants involving microwave, plasma arc, supercritical fluid, hydrothermal, and other processing techniques [26]. Products include heat, fuel gases, liquids, and solids.

Thermochemical techniques tend to be high rate and relatively non-selective in that the chemically complex biomass is substantially degraded into simpler compounds which in some cases can be reassembled into more complex compounds or refined to make desired end products such as hydrocarbon liquids to replace gasoline and diesel



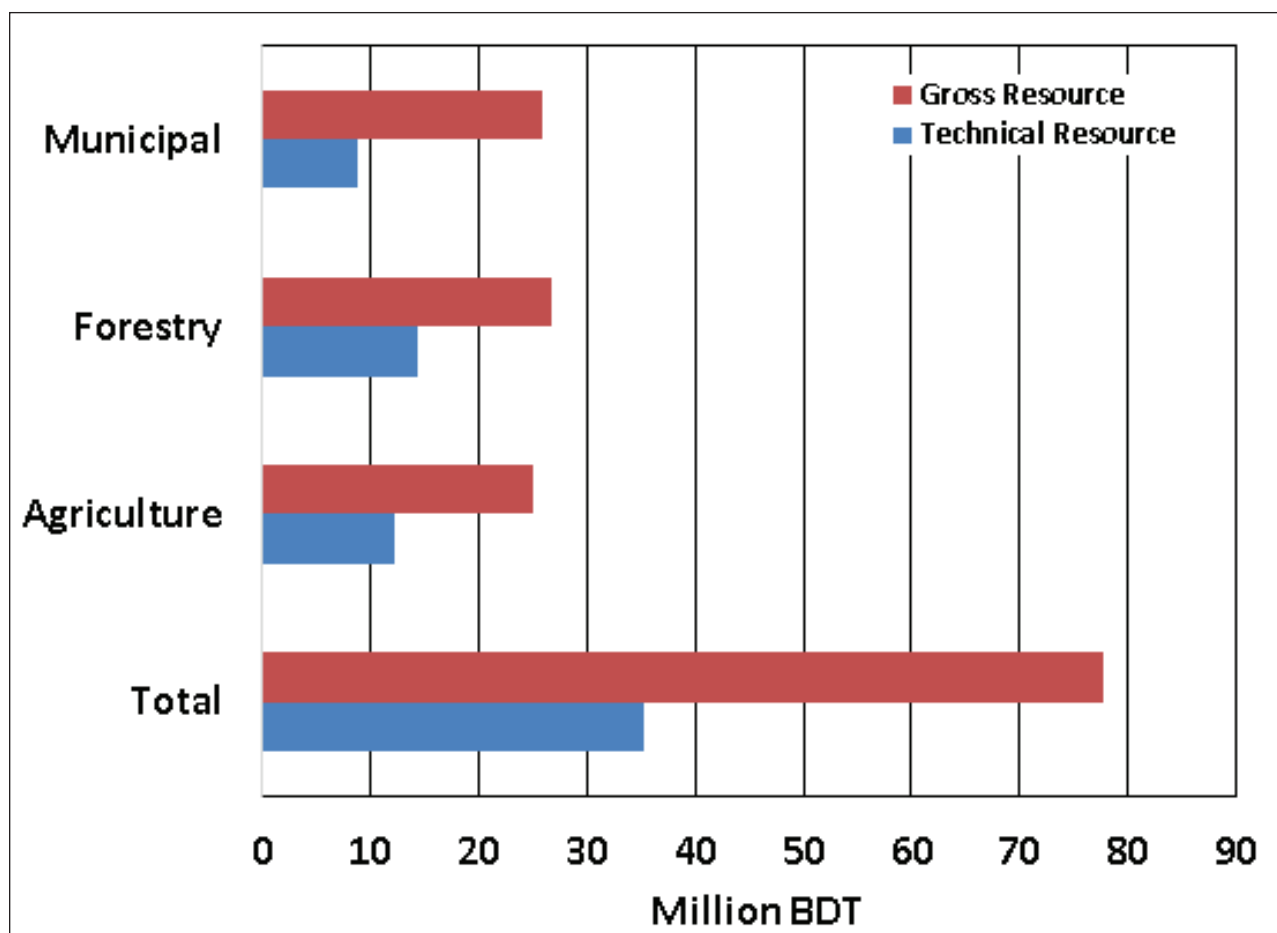
**Figure 4:** Pathways for energy and products from biomass [25].

fuels. Biochemical conversion includes fermentation to produce alcohols (e.g., ethanol, butanol), fuel gases (e.g., methane by anaerobic digestion, commonly referred to as biogas), acids, and other chemicals. Among the physicochemical methods are alkaline and acid processes, mechanical treatment, and many others, often in combination with some other thermal, biological, or chemical process. The well-known biodiesel is typically produced via a base-catalyzed esterification process although other techniques are also used or are being developed.

Biogas as produced by anaerobic digestion such as in landfills, waste-water treatment facility digesters, and other biodigesters consists principally of methane and carbon dioxide with smaller and mostly undesirable concentrations of hydrogen sulfide and other constituents. With gas clean-up, the product can be used to power spark-ignited and compression-ignited (diesel) engines (usually in dual-fuel mode), gas turbine engines, and fuel cells. The methane can also be compressed or liquefied and used as transportation fuels for light duty vehicles, buses, and both medium and heavy duty vehicles. It can also be used in the same way as natural gas is used to produce liquid hydrocarbons and other fuels and chemicals through catalytic synthesis as well as fertilizer and other biobased products.

Global biomass production uses approximately 0.02% of Earth's incoming solar radiation with an estimated annual production of 70 to 220 billion metric tons

(Gigatonnes, Gt) on a dry basis (exclusive of moisture that is nearly always present in biomass). A small fraction of the total plant biomass provides about 15% of world energy demand but in a diverse array of applications of varying quality, efficiency, and environmental impact. Plant or plant-derived biomass and animal manures in California are estimated at 71 million metric tons (Megatonnes, Mt), with 23 Mt from agriculture, 24 Mt from forestry, and another 24 Mt as urban wastes going to landfill, on a dry basis (**Figure 5**) [27]. Of this, about 32 Mt is considered sustainable for use, with 11, 13, and 8 Mt from each of the respective sources. The technical generating potential, were the sustainable resources dedicated to power generation, is in the range of 3,700 to 4,600 MWe (Megawatt electrical), with an approximately equal capacity as heat if using combined heat and power (CHP) systems [27, 28]. Renewable methane in the form of biogas from anaerobic digestion of animal manures, food wastes, green wastes, and other suitable resources is estimated at 3 billion cubic meters per year (93 billion cubic feet/year) of methane equivalent, about 4% of total statewide natural gas demand [27]. Electricity and renewable natural gas are not the only products that can be made from biomass and many other fuels (e.g., hydrogen) and chemicals might be produced to assist in reducing GHG emissions. Economic potentials for increased use of biomass depend on product type, market conditions, and incentives but are typically less than the technical



**Figure 5:** Biomass resource potentials in California, 2013 [27].



resources potentials identified here, extending over the range of 16 to 23 Mt/year [29].

Currently, biomass contributes 5.8 TWh per year to California's electricity supply amounting to 2% of total statewide electricity demand and 17% of the state's renewable power [28]. Total capacity from the 175 operating power facilities in the state using biomass or biogas is 938 MWe. Biomass facilities typically operate at high capacity factors with many in excess of 85% and a statewide average of 71%, hence are often considered as part of renewable grid stabilization schemes where variable solar and wind resources make up a larger share of total generation but at lower capacity factor. More advanced biomass systems can also accommodate dispatch, ramping power generation to help meet variable power demand throughout the day and adding economic value to the power generated to match time of use. CHP operation is conventional in the forest products industry, less so for independent power generators and greater attention to siting potentials for better heat integration offers improvement in overall efficiency and GHG reduction.

A key factor in biomass, biogas, and biofuel adoption is air pollutant emission control. Combustion systems, whether fueled with solid biomass, biogas, liquid fuels, or others derived from biomass, have the potential to degrade air quality to varying degrees [28]. Meeting permitting standards, especially for oxides of nitrogen (NO<sub>x</sub>), is an important economic factor for bioenergy and an issue recognized in the recent EPA final ruling on the nation's Clean Power Plan [30]. Transportation of feedstock biomass, biogas, biofuels and bioproducts can also contribute to pollutant as well as GHG emissions through the supply chain. Both facility and logistical support emission sources will need control for acceptable application. Integrated gasification (IGCC) and other combined cycle power generation systems have the potential to meet emission standards, and methane extracted from biogas for pipeline injection can complement natural gas in existing power systems. Significant reductions in criteria air pollutant emissions might occur with fuel cells as the technology is developed and adopted. The use of biofuels displaces emissions principally from the transportation sector, although lifecycle impacts and overall carbon intensity must also account for primary emissions from biorefining.

Sustainability of biofuels and bioenergy more generally has been a topic of considerable debate, principally for purpose-grown crops which have the potential to compete with food crops and affect prices and to indirectly induce land use changes that need proper inclusion in lifecycle GHG emission, economic, and policy characterizations [25, 31]. Water use for purpose-grown crops is also of concern, although opportunities exist for greater integrated biomass production with wastewater treatment. Sustainable large-scale production of industrial feedstocks will require a broad systems view and well-designed standards and best practices. International standards for certifying sustainable production of biofuels are currently in use and continue in development [32]. Local standards may in some cases exceed international

standards but will need close coordination to avoid conflicts with international agreements and rules such as those of the World Trade Organization (WTO). The complex issues now being researched and addressed in sustainable biomass feedstock production should provide new perspectives on the improved sustainability of the industry overall.

UC has a long history of research into biomass utilization and significant research capacity in energy and products from biomass. Pilot and development projects are also occurring on UC campuses. The renewable energy anaerobic digester (READ) facility on the UC Davis campus is designed to annually treat 18,000 wet metric tons of mixed organic waste and combines biogas from waste digestion with landfill gas from a now-closed campus landfill to generate close to 1 MWe of electricity for the campus grid including the West Village zero-net energy development. UC is a partner in the Joint BioEnergy Institute (JBEI) operating under grants from the U.S. Department of Energy, and in the Energy Biosciences Institute at UC Berkeley, although BP, the industry funding partner, has recently reduced support due to low oil prices. A similar partnership agreement between Chevron and UC Davis investigated biofuel alternatives from a wide range of feedstocks and technologies. The California Biomass Collaborative has operated under UC management since 2003 with funding from the California Energy Commission as a joint industry, government, and academic partnership and conducts a range of resource, technology, environmental, and policy assessments. The California Center for Algae Biotechnology at UC San Diego was established in 2008 as a research consortium investigating renewable energy and green chemistry options using algal production systems. The Advanced Power and Energy Program at UC Irvine conducts detailed cycle analyses with industry and the U.S. Department of Energy for advanced power generation systems operating on biomass and biogas, and is developing stationary fuel cell technology to tri-generate renewable electricity, renewable heat, and hydrogen from biogas. A number of other centers, institutes, and departments across the UC system conduct biomass, biogas, and biofuel related research in developing new technologies and understanding system level effects and lifecycle economic, environmental, and social attributes in evaluating overall sustainability at local, regional, national, and global scales. This institutional capacity forms a basis for more targeted research and development, including pilot- and full-scale projects to help evaluate potential for meeting carbon management objectives.

### Summary

Integration of biomass and biogas resources for renewable fuels and electricity generation is already providing opportunities to increase sustainable use with potential added benefits in waste and landscape management in addition to reductions in greenhouse gas emissions.

The properties and complex chemical compositions of biomass allow for the direct replacement of many fossil-based products in addition to fuels to further reduce

lifecycle GHG emissions. Biomass can also enhance stability in electricity supplies in complementing variable solar and wind generation in high penetration renewable grids by providing base-load or dispatchable power, and can be operated in combined heat and power modes for high overall thermal efficiency and to help meet heating and cooling demands. Biofuels as well as electricity from biomass and biogas provide renewable alternatives to natural gas, gasoline, diesel, and aviation fuels, as well as fossil-fuel-based electricity for transportation. Sustainability of biomass production and conversion needs careful attention through comprehensive lifecycle assessment, and air pollutant emission control can be of particular concern throughout the supply chain regardless of product whether electricity, renewable natural gas, or liquid and other biofuels.

A wide suite of technologies and resources is available to integrate and deploy renewable material and bioenergy options. UC has a long history of research into biomass, biogas, and biofuels and sustainable system design, and extensive research capabilities that can be directed at system-wide resource characterization, technology optimization, fuel substitution and other more specific objectives as well as larger scale demonstration projects to evaluate or verify technical and economic performance, emissions reductions, facility scaling, and overall sustainability.

## Nuclear Power Generation

Per Peterson, UC Berkeley

### Introduction

In California, initial enthusiasm for nuclear energy in the 1960's led to the deployment of early test reactors in Santa Susana and Vallecitos, with the first commercial boiling water reactor at Humboldt Bay starting operation in 1963. The decisions to adopt and scale up the light-water reactor (LWR) technology that had powered the first nuclear submarine, launched in 1954, became increasingly controversial in the early 1970's as studies indicated that loss-of-coolant accidents in water cooled reactors could mobilize a large fraction of the radioactive material created by fission, particularly iodine and cesium, in the form of small aerosol particles, and that the intrinsic high pressures created by steam would require containment vessels capable of sustaining high internal pressures while maintaining low leakage. Given the inertia of decisions to adapt water-cooled naval reactor technology to commercial application, major efforts were devoted to develop highly reliable emergency core cooling systems, using multiple trains of pumps and power supplies to provide capability to inject water into reactors during accidents.

The California public became increasingly skeptical, and in 1976 the California legislature passed a state law establishing a moratorium on permitting of new nuclear plants (California Public Resources Code section 25524.2). Three years later a major accident occurred at the Three Mile Island plant in Pennsylvania, caused by human errors where operators incorrectly turned off their emergency core cooling system.

### Future role of nuclear energy

Today it is not possible to predict the future role that nuclear energy will play worldwide as a low-carbon energy source; however, it is highly likely that use of nuclear energy will continue in some areas of the world. While it remains unclear whether California, with its existing policies, will ever build new nuclear power plants, the University of California has a long history and world-class capabilities in areas related to non-proliferation, physical security, safety, and waste management for nuclear energy systems. Therefore U.C. has a special obligation to support U.S. efforts to assure that where nuclear energy is used, this use is safe, secure, environmentally responsible, and consistent with international standards for nonproliferation.

Regardless of whether the U.S. expands or contracts nuclear energy use going forward, the U.S. must develop the capability to place high level wastes and spent fuel into deep geologic disposal. The University of California, particularly the Lawrence Berkeley National Laboratory and Lawrence Livermore National Laboratory, has world-class capabilities in subsurface science. Over the last 5 decades, these capabilities have contributed to establish the broad scientific consensus that in appropriate media, deep geologic disposal can provide predictable and safe long-term isolation of nuclear wastes. Just as with question of placing a price on the emission of CO<sub>2</sub>, the U.S. political process has failed to establish consensus to develop and deploy deep geologic disposal while other nations (Finland and Sweden) have been successful. While it is feasible to store spent nuclear fuel safely, no similar ability to store CO<sub>2</sub> from fossil fuel combustion exists.

Likewise, regardless of whether the U.S. expands or contracts nuclear energy use going forward, the U.S. will need to maintain its efforts to strengthen the national and international systems that provide physical security for nuclear materials and that encourage goals of non-proliferation, and develop and use our national technical means aimed at these same objectives. Fundamentally, safety, physical security, and international safeguards monitoring share a common objective of maintaining knowledge and control over where nuclear materials are. With appropriate design choices, advanced nuclear technologies can make it simpler to achieve these common objectives.

Methods to operate nuclear plants with high reliability have improved greatly, with the most important advances occurring in the 1990's, but large light water reactors, even when designed to use passive safety systems, have still proven to be challenging to build at a reasonable cost with a reasonable schedule.

### Summary

The major questions for nuclear energy, going forward, involve whether substantial and rapid improvement could be possible. Other highly regulated technologies have achieved much more rapid evolution and improvement: biotech, commercial aviation, and commercial space launch being key examples. The SpaceX Company provides a large number of lessons on best practice that could be relevant to advanced nuclear. Today, 6 of the 50 companies in the U.S. and Canada that are

developing advanced nuclear technologies are located in California. All of these commercial efforts are questioning key assumptions that were accepted during the first commercialization wave, that scaling reactor sizes to be large would reduce cost, that active (vs. passive) safety systems were necessary to obtain license approval, and that water is the most appropriate coolant.

California remains a center for innovation in advanced energy technologies. The University of California plays critical roles, and should continue to play these roles, in addressing safety, security, and non-proliferation for existing nuclear, and in inventing new technologies for advanced nuclear. Energy prices in California remain much higher than most other regions in the U.S. While California provides an important test-bed for demonstrating advanced energy technologies, California's high energy prices create challenges for broader adoption, particularly for the energy-intensive industrial and manufacturing products that California now imports rather than produces. Given the potential for advanced nuclear power to produce affordable, flexible, and dispatchable low-carbon energy, the University should continue to play a key role in research and development for advanced nuclear energy technology.

### Battery Technology

Venkat Srinivasan, Lawrence Berkeley National Laboratory

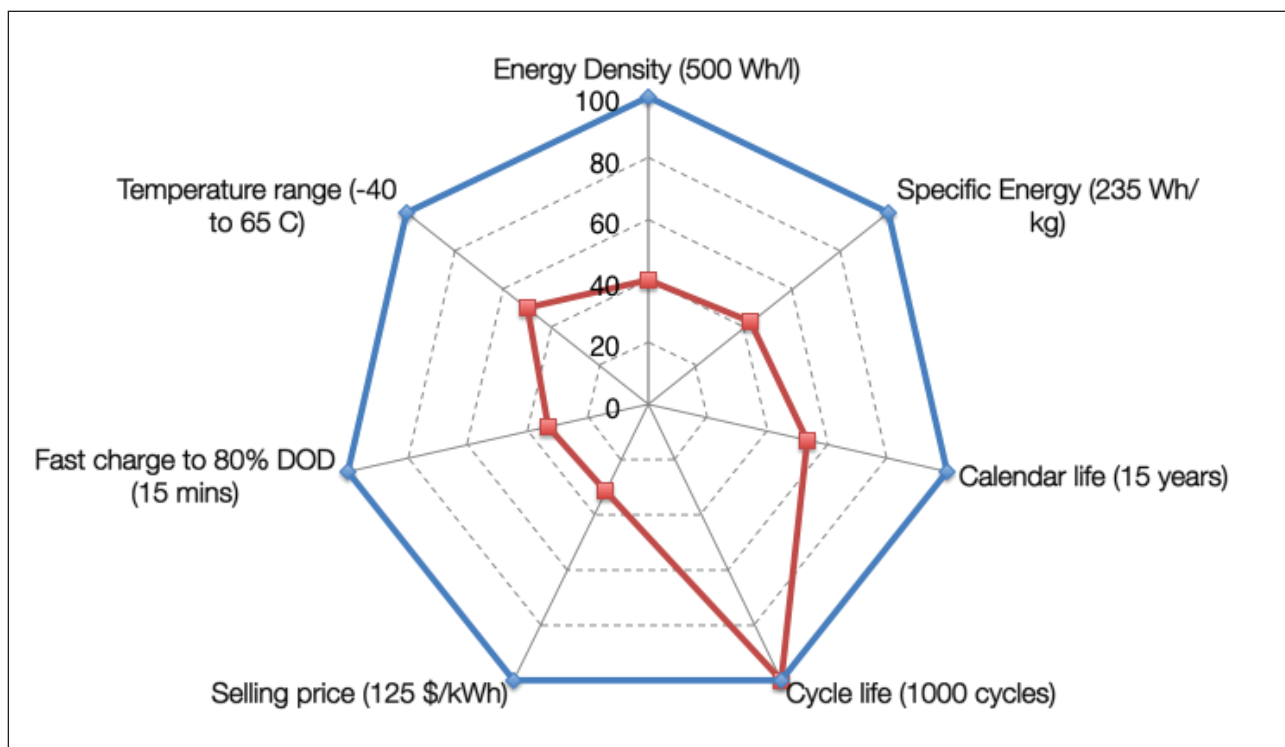
Electrochemical energy storage (i.e., batteries) is an enabling technology that holds the key to transitioning from fossil fuels for our vehicular needs and managing the intermittency of renewables on the grid. Over the

last 5 years, electric vehicles are entering the market and storage technologies are being tested on various grid applications, mainly driven by innovations in lithium-ion batteries (Li-ion). While promising, more is needed to ensure widespread deployment of batteries that will be needed to achieve the aggressive targets set by California.

For example, while Li-ion battery cost are estimated to be \$400–600/kWh today, the target for stationary storage is \$100/kWh [33] and those for vehicles is \$125/kWh [34]. This aggressive cost reduction has to be achieved while ensuring high energy (to ensure long driving range), long life, excellent safety, and fast recharge rates, making it a multidimensional problem (Figure 6).

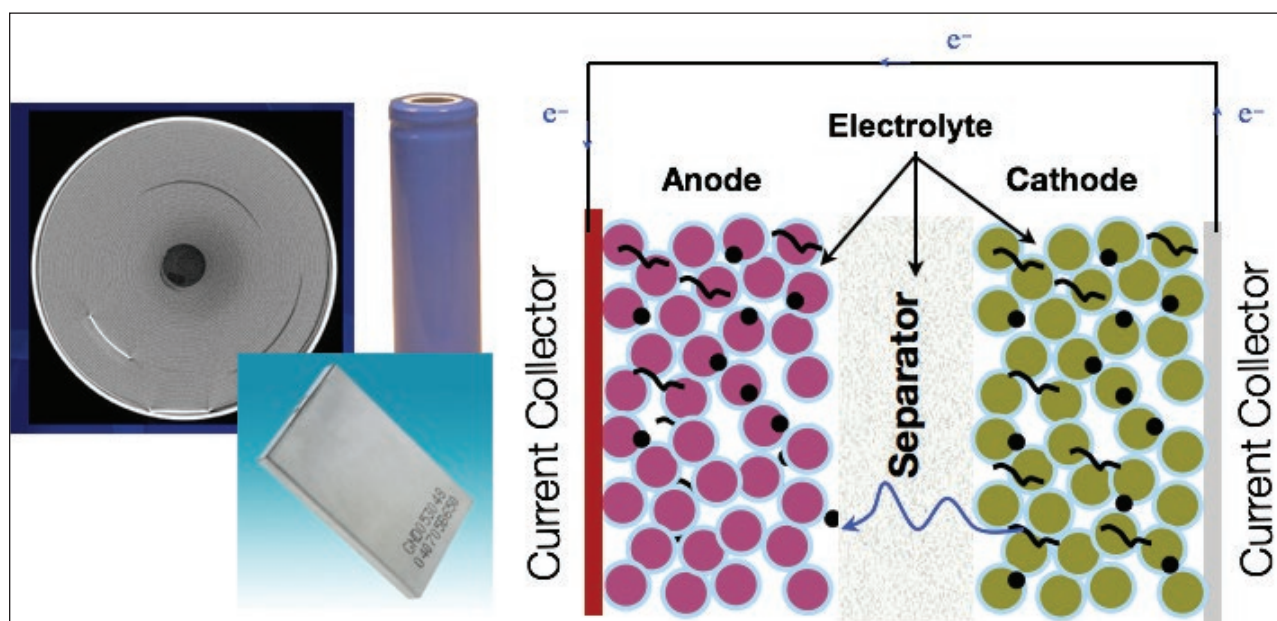
Moreover, batteries are a compromise between many metrics; increasing one metric leads to a decrease in another. Therefore, batteries with higher energy typically sacrifice safety and life, while batteries optimized for long-life tend to be higher in cost and lower in energy. Similarly, for grid applications, batteries with calendar life of 25 years are needed, 3 times higher than those available today, suggesting that known technologies, such as Li-ion, may not be the best battery for grid applications. Of all the different metrics, cost remains the single biggest challenge to displacing fossil fuels with battery storage.

Companies, like Tesla, are pursuing vertical integration and large-scale manufacturing (e.g., Gigafactory) to decrease the cost. Cost modeling suggests that such an approach can help achieve costs just around \$200/kWh by 2025, allowing further penetration of EV's and grid-scale storage [35]. However, reduction in cost by a further factor of two (in addition to the other challenges) is



**Figure 6:** Spider Plot illustrating the present status of Li-ion battery technology (red line) when compared to the targets set by the United States Advanced Battery Consortium (USABC) for all electric vehicles with a 200-mile range (blue line). The figure, generated using data available in the public literature, shows that batteries for EV's face many challenges.





**Figure 7:** Schematic illustration of a battery.

needed to ensure widespread penetration. Therefore, new systems that go beyond the Li-ion framework are needed to ensure these breakthroughs are achieved.

#### **Enabling these innovations: B**

As illustrated in **Figure 7**, batteries store energy in materials that serve as anodes and cathodes, with electrolytes to conduct the ions between the two electrodes. Electrical energy is stored by moving the electrode materials to an unstable state by supplying energy (i.e., charging). Subsequently, the energy is released to perform useful work (i.e., discharge) and the materials come back to their stable state [36, 37]. The materials are assembled into structures that are then either wound or stacked into cells, as illustrated in the figure, in order to make a working device. Cells are stacked into larger modules and packs with additional cooling and battery management systems to ensure safe operation. At each stage of assembly, inactive materials (i.e., materials such as current collectors, that are needed to complete the battery but don't hold any energy) are added, with as much as 50% of the weight of the battery consisting of inactive materials.

The cost of the final battery is a sum of the material cost and assembly costs with the fraction between the two dependent on the scale of the factory and the choice of active materials. For a typical Li-ion battery, approximately 40–50% of the cost is in manufacturing, with the rest in materials. Cost reduction can occur by (i) moving to cheaper materials or using less amount of the material; (ii) increasing the energy for the same material and manufacturing cost by decreasing the \$/kWh of stored energy; and/or (iii) decreasing the manufacturing cost [38]. No magic bullet exists and research is needed in all three areas for the reductions to be achieved.

In the area of decreasing the material cost, research is needed on new low-cost materials that do not use expensive transition metals such as cobalt and nickel. An

additional strategy may be moving to aqueous systems for stationary storage applications, taking advantage of the less stringent size and weight requirements when compared with vehicle applications. A variant of this approach is used in redox flow batteries, wherein the active chemicals are stored in a tank and the charge and discharge reactions are conducted in an electrochemical cell into which the chemicals are flowed. In such a device, the overall cost is dominated by the cost of the cell, because of the use of expensive catalysts and membranes [39]. On the other hand, judicious choice of the chemicals allows for the tank, which contains all the energy, to be cost effective. As the size of the tank is increased relative to the size of the cell, the overall cost of the device can be reduced. Therefore, flow batteries can be made cost effective for large storage times (greater than 5–6 h) while container batteries (such as Li-ion batteries) are lower cost at shorter times. New chemicals that have low \$/kWh, and new flow cell designs and materials, are needed to decrease the cost of flow batteries.

More headroom can be found in the second approach, wherein the focus is on increasing the energy density of the cell. Here research is focused on moving from the presently-used graphite and silicon anodes to lithium metal anodes (lithium has a capacity of 3860 mAh/g versus 372 mAh/g for graphite anodes), moving to high capacity cathodes such as sulfur (with a capacity of 1650 mAh/g versus 180 mAh/g for today's Li-ion cathodes), and in moving away from lithium as the working ion to magnesium (which has two electrons instead of one for lithium) and aluminum (which has three electrons). Finally, attempts can also be made to remove the inactive components in the battery to take advantage of the wasted weight and volume. Significant challenges exist in each of these avenues and research is needed to ensure success.

In the area of manufacturing, approaches that can cut down on the number of process steps, use water-based

processes instead of toxic chemicals, and allow modular manufacturing methods that show less cost sensitivity to manufacturing scale are all needed to address this component.

Finally, we remind the reader that such innovations in decreasing the cost of batteries has to be undertaken by accounting for the other metrics, including cycle and calendar life, safety, driving range, and recharge time.

While there is enormous room for innovation in developing new materials and manufacturing methods, the history of battery advances suggests that it takes more than a decade for a lab breakthrough to reach the marketplace. The slow translation is rooted in the difficulty in maintaining the performance when going from idealized small lab-devices to large format, high speed, low-cost manufacturing methods wherein the components are integrated in form factors needed for real-world use. This results in lost time in each stage of the scaling process. Moreover, examples exist of materials that were not ready for scaling moved too early to that stage, resulting in many years lost with little progress. A paradigm shift in battery development is needed to break this slow pace of innovation.

The best examples of such seamless innovation are areas like Silicon Valley, where a close collaboration exists between the public universities and the private companies. In these successful examples, lab research is informed by industrial relevance and problems encountered by industry are moved back to the lab for further research. Such a public-private partnership could be the key to accelerating the pace of innovation in batteries.

### Summary

While battery performance improvements have resulted in small penetration of electric cars, and a few demonstration projects on the grid, more is needed to ensure widespread penetration. For example, while Li-ion batteries are ubiquitous today, its cost needs to decrease from \$400–\$600/kWh to less than \$100–\$125/kWh to ensure widespread use, while ensuring long cycle and calendar life, high safety, long range, and fast recharge. Mass manufacturing is not enough and new innovations are needed. These innovations can come from new materials that are lower cost, from new higher-energy materials, and/or from new low cost battery manufacturing methods. More research is needed in each of these areas for the final targets to be achieved. While the federal government has invested heavily in the areas of vehicle batteries, much less emphasis has been paid to stationary storage systems, especially ones that have cycle life that exceed 20+ years. We suggest that this area needs more emphasis.

Further, historically, translation of lab innovations into market impact has taken more than a decade, mainly due to the difficulty of scaling from idealized lab devices to real world devices. We suggest that public-private partnerships are critically needed to focus the research in the right direction and to ensure that research innovations can be performed with industrial processes in mind, and seamless movement of ideas between industry and the universities/labs is enabled. We recommend that formation and operation of such public-private partnerships

should be supported. Consortia, such as Sematech, could serve as examples of how such partnerships can lead to successful development and acceleration of technology.

### Energy Efficiency: Lighting Technology

Steven DenBaars, UC Santa Barbara

Solid-state lighting technology has the potential to radically change the future of general lighting. The efficiency of recent LED products is already 8 times better than traditional incandescent bulbs, and 50% better than compact fluorescent. Furthermore, the efficiency of LEDs have the potential to additionally improve by a factor of 2–3, and offer new features. For example, “intelligent” lighting environments could respond to changing activities and needs through variable spectrum and intensity. Expected benefits include more responsive, comfortable, and productive building environments, coupled with substantial energy savings. Additionally, high speed communication is being incorporated into future LED lighting systems, which will create new applications in retail and industry. Smart LED systems will be able to adaptively adjust their color gamut and brightness to increase productivity at school and work. Coupled with solar powered battery systems, LED lighting can be taken off-grid, giving rise to a zero carbon footprint in pathway and roadway lighting. Intelligent LED systems have the potential to be optimized for color, and brightness to improve work and school productivity and building efficiency. Optimal LED lighting for plant growth and food stores is a fertile area of research.

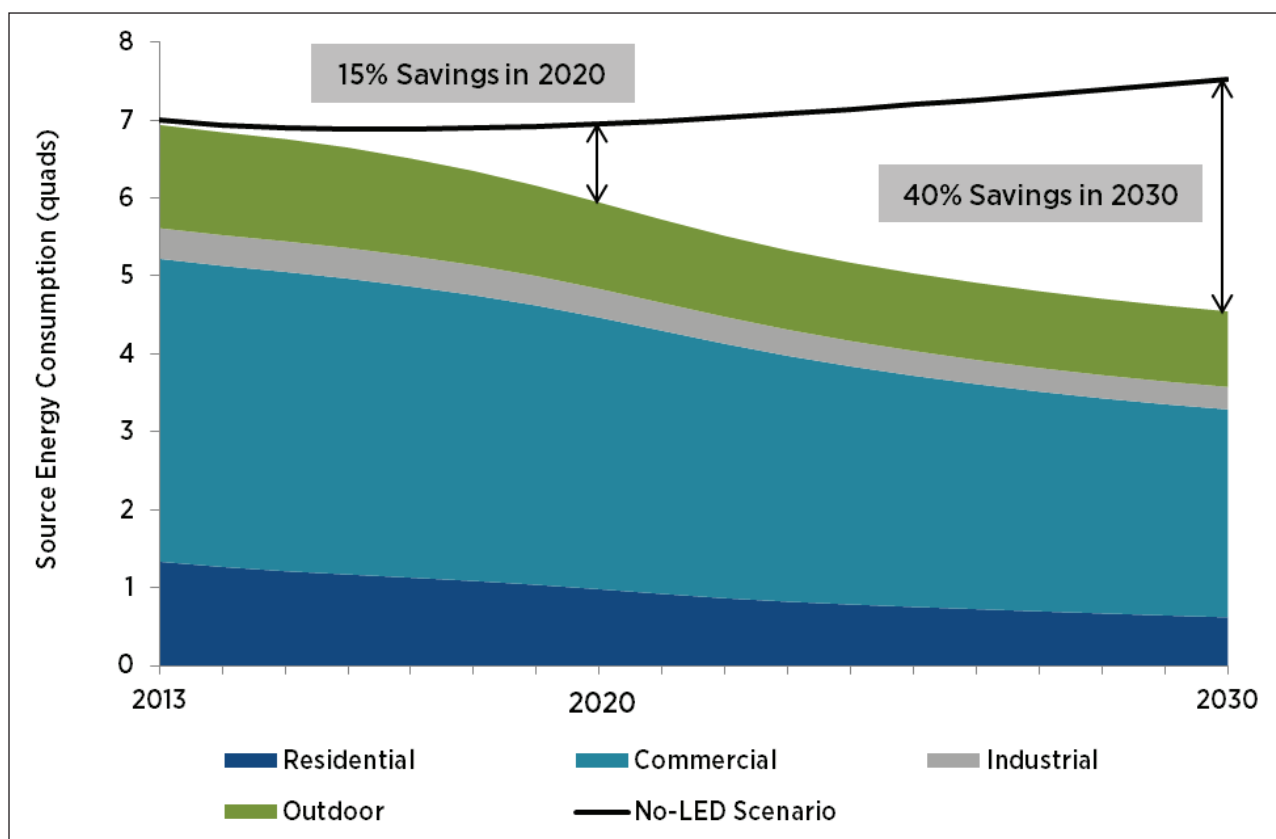
Switching to LED Lighting will greatly help California become a Carbon neutral economy. The DOE estimates that energy savings in 2030 from solid-state lighting could reach 190 terawatt (a unit of power equal to one trillion watts) hours, the annual electrical output of 24 large power plants. Scaling, this would result in a 31.4 million metric ton reduction of carbon and \$15 billion in energy savings in 2030 alone [2]. LED lighting is forecast to produce 40% energy savings in the energy consumption needed for lighting by the year 2030, as shown in **Figure 8**.

According to the DOE, Solid-State Lighting Research and Development Multi-Year Program Plan report, lighting accounted for approximately 18% of electricity usage in the United States. If implemented State wide in California, we could expect a reduction in site electricity consumption on the order of 7–8%.

### Summary

A multi-campus UC research effort in LED can further improve efficiency gains and reduce costs. One opportunity is to develop a LED-based white light emitter with no efficiency droop at high current densities and with optical and light conversion efficiencies nearing the maximum intrinsic limits. This approach targets both key metrics for energy-efficiency in lighting systems for commercial and industrial buildings – High lm/W and less than 1\$/klm – by addressing the fundamental performance limitations of LED-based systems operating at high current densities (droop) and the cost limitations of LED systems operating





**Figure 8:** Multi-Year projection of source energy consumption of lighting showing a 40% savings in 2030 with LED implementation.

at low drive currents (large chip area) through the use of a much smaller, single-chip, nearly-idealized point source of emission. The ultimate goal is the development of a 1000 lm LED-based white emitter with an efficiency of at least 200 lm/W and a cost of \$0.25/klm, far exceeding the 2020 targets in the Department of Energy's Multi Year Program Plan for Solid State Lighting.

### Energy Efficiency: Geothermal Heat Pumps

William Glassley, UC Davis

Heat pumps are high efficiency, off-the-shelf devices for moving heat from one location to another. As a consequence, they are ideally suited for heating (i.e., transferring heat from some external reservoir into a building or water heater) or cooling (i.e., transferring heat from a building to some external reservoir). Their efficiencies greatly exceed that of natural gas-consuming technologies or electrical heating and cooling systems because they take advantage of the thermodynamic fact that moving heat is generally much more efficient than making heat. Since more than 80% of California's natural gas (NG) use is for building and water heating [40], use of heat pumps can dramatically decrease both the consumption of NG and the emissions associated with its use. Technology innovations that are currently being explored will enhance these benefits dramatically.

#### Background

At depths of fifty to several hundred feet below the ground surface the temperature is constant. At that depth, the temperature range is ideal to allow the subsurface to be

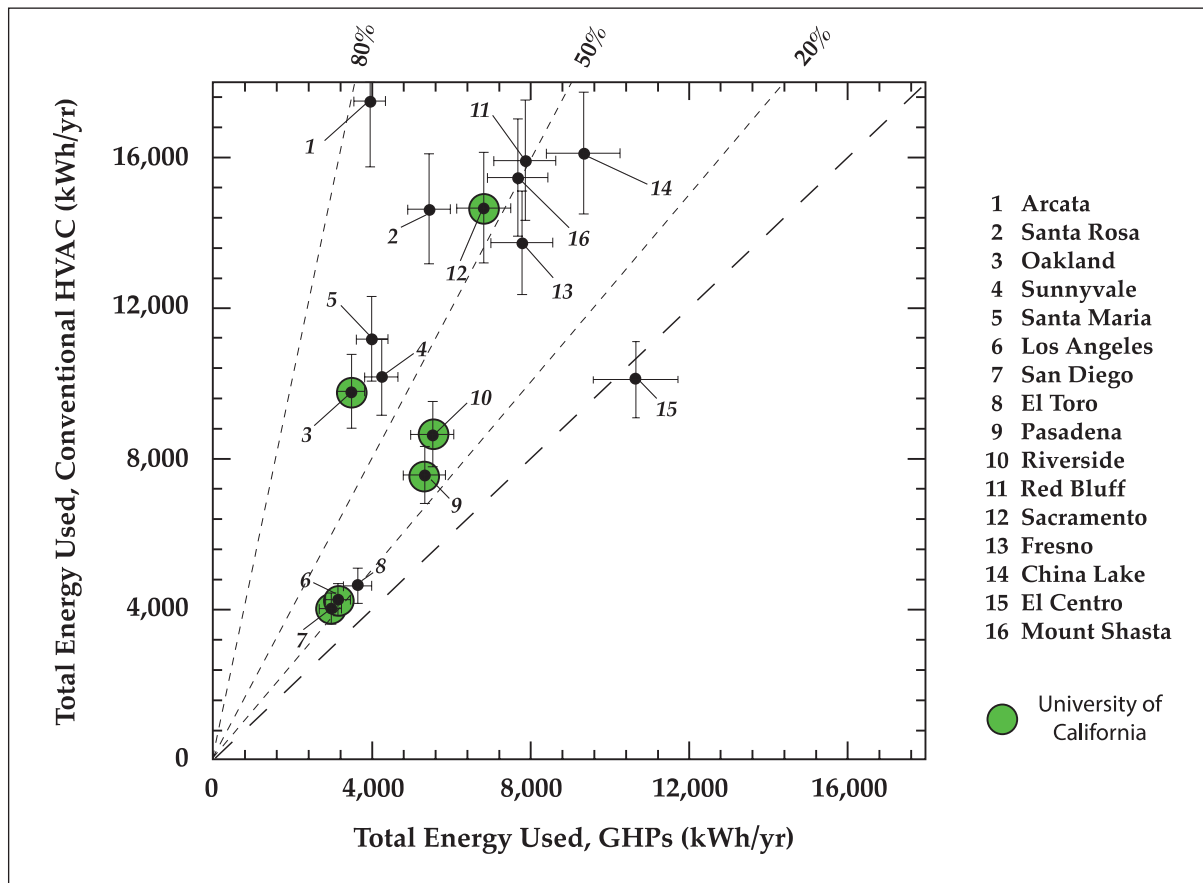
utilized as a heat sink in the summer and a heat source in the winter. Heat transfer is accomplished using a liquid-filled pipe loop in which the fluid is the heat transfer agent. By circulating the fluid through bore holes in the ground and then through a heat exchanger in the building, heat can be readily and efficiently moved back and forth between the building space and the subsurface. Geothermal heat pump (GHP) systems have efficiencies for space heating that are 3 to ~6 times that of conventional heating, ventilation and air conditioning (HVAC) equipment [41].

#### Use of Geothermal Heat Pumps in California

Previous studies have shown that the diverse climatic and geological conditions within California result in a wide range of energy and emissions savings for hypothetical deployment of GHP systems [42]. Even so, the benefits derived from such systems result in reductions in energy use and emissions that average ~50%, relative to the commonly used NG systems.

**Figure 9** summarizes energy reductions expected for all 16 climate zones present in California if GHP systems replaced conventional HVAC systems. Those climate zones within which UC campuses are located are highlighted in green. **Figure 10** shows the corresponding reductions in greenhouse gas (GHG) emissions for each climate zone.

It is important to note that the study upon which these results are based focused on residential and small commercial buildings. Buildings within the UC system are of a broad range of sizes, vintages, uses and energy intensities.



**Figure 9:** Comparison of the kWh/year that would be consumed by GHP systems (horizontal axis) and conventional HVAC systems (vertical axis) if installed in residential buildings, for all of California's 16 climate zones (representative cities for each climate zone are indicated to the right of the figure). Green highlights show those climate zones within which UC campuses are located. The dashed lines indicate the percent energy savings. Modified from Glassley et al., [42].

Hence, the actual performance that could be expected for individual campuses may differ from the results presented in the figures, but it is likely they will be similar.

#### The Future of Heat Pumps in California

The savings outlined above derive from deploying GHP systems for individual buildings. However, much greater efficiencies, energy savings and emissions reductions are likely by scaling-up GHP technology so that multiple buildings on a campus or community are linked into local "district heating" systems. Such systems, deployed in Denmark and Iceland, have demonstrated cost and energy savings that would be significantly beyond those described above. By adapting the lessons learned from those international examples to the specific situations for each campus or community, it is likely the complex of UC campuses would quickly become a global model for maximizing energy savings and emissions reductions when applied to building heating and cooling.

#### Challenges

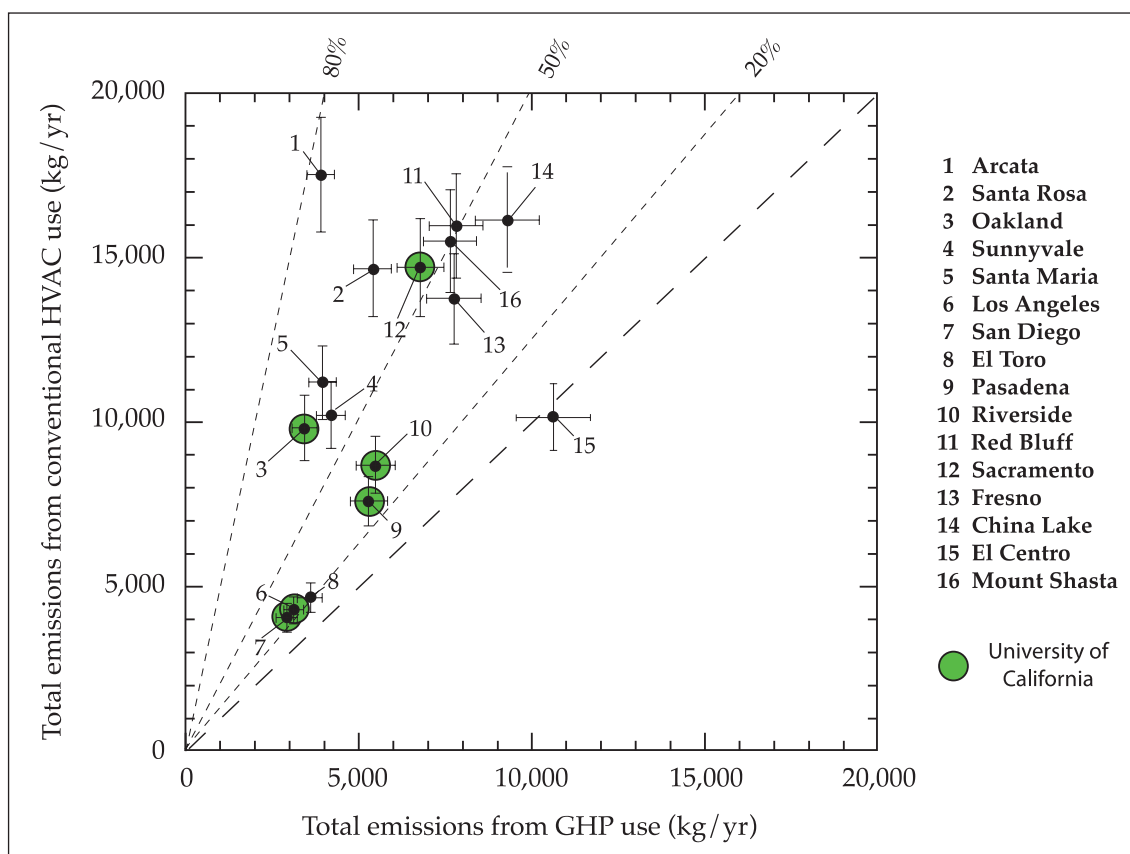
GHP systems require expert design and intimate knowledge of local geological and climatic conditions. Hence, significant dedication would be required to obtain the knowledge base to support deployment of these systems. In addition, in order to realize the necessary benefits

quickly, a quantitative inventory of campus buildings would be important to prioritize those for which retrofitting and installing GHP systems would provide the greatest benefit in the shortest timeframe.

Separate from the technological issues is the fact that GHP systems require drilling. Although the drilling technology that is utilized for water wells and for which best practices and protocols are well established, many parts of the state are not familiar with GHP systems and technology, and confuse the drilling practices with those used for oil and gas or geothermal power generation. As a result, inappropriate regulatory hurdles are mistakenly imposed by local regulatory bodies. Hence, it would be important to openly and transparently engage local jurisdictions early on, as an educational and outreach effort, to avoid unnecessary permitting delays.

#### Recommendations: Technology Outlook and Opportunities

- Broad deployment of geothermal heat pumps could reduce natural gas use and related emissions by up to 50%, using available technologies. The theoretical maximum COP for GSHP systems is 12, implying emissions reductions approaching 80%–90% are possible in the future as engineering improvements are realized in the future. Hence, a flexible



**Figure 10:** Comparison of the GHG emissions (kg/yr) that would be expected for GHP systems (horizontal axis) and conventional HVAC systems (vertical axis) if installed in residential buildings, for all of California's 16 climate zones. Labeling and source is as indicated in Figure 9.

framework for updating GSHP installations should be developed, in order to take advantage of likely technology improvements.

- New technologies that combine heat pumps with other renewable technologies, such as biomass, solar and wind, could dramatically improve efficiencies of all technologies, while reducing even further GHG emissions and reliance on fossil fuels.
- Low cost energy storage strategies are possible in which excess heat from industrial activities, biomass technologies and solar thermal systems could augment GSHP systems, thus enhancing the benefits of these applications by dramatically improving overall energy use and efficiencies.
- Coupling heat pumps with certain types of biomass systems can be highly efficient in the appropriate settings. Such systems should be explored where biomass is available (e.g., agricultural settings; near waste disposal sites or water treatment plants).

### Summary

Deploying GHP systems throughout the UC campus complex for HVAC purposes has the potential to provide energy savings and emissions reductions of at least 50%. Technological developments that are possible with these systems are likely to realize much greater benefits in the near future. Provided deployment of these systems is undertaken with due attention given to a few

key challenges, conventional heat pump systems could be a critical component in providing the UC system and the State of California with the ability to quickly meet its emissions reduction and energy sustainability goals. Likely future technology developments, along with innovative coupling of renewable technologies could enhance these benefits dramatically.

### Smart Grid Technology

Scott Samuelsen, UC Irvine

#### Introduction

Stringent energy and environmental rules and regulations, such as California's AB 32, Renewable Portfolio Standard, AB 2514, AB 785, and AB118, focus on the electricity and transportation sectors as targets for the reduction of greenhouse gas and criteria pollutant emissions. For the electricity sector, the penetration of renewable resources in the state has increased dramatically in parallel with the introduction of distributed energy resources (DERs) and energy storage. In the transportation sector, plug-in electric vehicles (PEVs)<sup>2</sup> are beginning to emerge. While the existing grid is absorbing these new resources, loads, and devices, evidence of adverse impacts on resiliency are starting to surface.<sup>3</sup> Arguably, to accommodate and manage higher levels of renewable and PEV penetration, major changes in the grid and operation of the grid must be developed and implemented. Smart grid technology is

emerging as a major strategy, and smart microgrid technology is emerging as a major complementary resource.

It took more than a hundred years for the electric industry and the grid to evolve from the first investor owned utility on Pearl Street New York serving around 60 customers. By the end of 1930s, the electric utilities were almost entirely regulated and provided generation, transmission, and distribution services as vertically integrated monopolies. In late 1970s, the Federal Energy Regulatory Commission (FERC) prepared for a gradual deregulation of the industry and, after the open access and OASIS<sup>4</sup> orders, FERC approved PJM<sup>5</sup> as the nation's first fully functioning Independent System Operator (ISO) in 1997. California ISO (CAISO) was established in 1998. Originally it used an unbundled approach in which a system operator was responsible for the reliability of the grid, and a separate entity- market operator- settled supply and demand in the market. In the original design, the day-ahead energy market was also completely separate and was run by the California Power Exchange (CalPX). CalPX went out of business during the energy crisis in early 2001 and the state of California was left without a day-ahead energy market. From 2001 to April 2009 when the Market Redesign and Technology Upgrade (MRTU) was implemented, California did not have an organized day-ahead energy market, merely day-ahead markets for ancillary services (AS) and congestion, hour-ahead markets for the same products and a real-time energy market. Today the CAISO is responsible to maintain a reliable grid and provide non-discriminatory access to transmission through competitive markets.

Most of the environmental and energy goals target 2020, 2030, or 2050. As a result, the changes in the grid need to occur quickly compared to the relatively slow evolution in the past.

A smart grid is a grid with the intelligence to (1) maintain (and increase) the efficiency and reliability of the grid [43, 44], (2) provide the grid operator with visibility and remote control of the system components through sensing throughout the transmission and distribution network, and (3) provide two-way communication and controls to enable a path for grid automation and electricity markets participation.

### **Why a Smart Grid?**

Increasing the penetration of intermittent renewable resources requires an accurate forecasting of intermittent solar and wind resources [45, 46], and a methodology to handle the uncertainty introduced by these resources into the modeling, planning, and operation of the system [47]. Managing a high penetration of PEVs requires more visibility into the distribution system in order to reduce their impact on the load profile, and to use PEVs as a grid resource for providing energy and ancillary services. Increasing the penetration of DERs (e.g., energy storage) further extends the need for more visibility and control over the distribution system.

The smart grid will provide a needed resource at a number of levels that are built on a structure that encompasses, at a minimum, the following four levels:

- **Customer Level:** Facility energy management and control by residential owner, office building manager, industrial plant manager, or campus microgrid operator.
- **PEV Level:** Automobile manufacturer and/or utility management schemes, control of PEV charging (smart charging), and potential vehicle-to-grid energy storage recovery.
- **Utility Level:** Utility management and control of distribution system services and resources.
- **Independent System Operator Level:** ISO management and control of the full portfolio of grid services and resources including electricity markets.

### **Challenges**

Smart grid technologies have been developed and improved significantly during the past decade through investment in research and demonstration projects (such as Smart Grid Investment Plan, Smart Grid Demonstration Program, SPIDERS, CERTS, microgrid projects, and several others) These efforts resulted in advances and deployment of smart metering, smart appliances, automated substations and other distribution system upgrades, advanced sensing and controls, high speed communications, smart inverters, smart switches, and microgrid components and controller. Although several smart grid technologies are available to be used today, several challenges face the evolution of a "smart grid" paradigm:

- **Interoperability:** A smart grid requires the various components of the system to communicate with one another or at least a central controller/operator [48]. To achieve this, communication protocols, standards, and a robust communication infrastructure must be developed upon which vendors, utilities, and regulatory agencies can agree and comply [49].
- **Reliability and Cost:** The reliability of the system must be ensured without having excessive redundancy in order to minimize the overall cost of the system.
- **Data management:** Collecting high resolution data is required to obtain an accurate picture of the system status and also verify the system load flow and transient models.
- **Cybersecurity:** As the system moves towards automation and remote control, the system must be secured through cybersecurity measures and encrypted communications [50].
- **Too Much Change, Too Quickly:** The smart grid paradigm will dramatically change the roles of utilities, independent system operators, aggregators, and service providers in a relatively short amount of time. Therefore, it is prudent to develop roadmaps and guidelines for the industry to follow and prepare for their revised roles. For example, with more distributed energy resources, the role of the utility changes from delivering energy to providing ancillary services<sup>6</sup> and back-up, and/or serving as an aggregator of distributed energy resources.
- **Development of a Wholesale Electricity Market:** First, the resource needs to establish an agreement

with the utility to access the transmission system (today this is done through WDATs).<sup>7</sup> Second, the grid operators need to allow the DER to participate into the market. This will present challenges since these resources can be very flexible (compared to conventional generation and even renewable resources) and are located deep in the distribution system where the ISOs do not have visibility.

### Future Grid

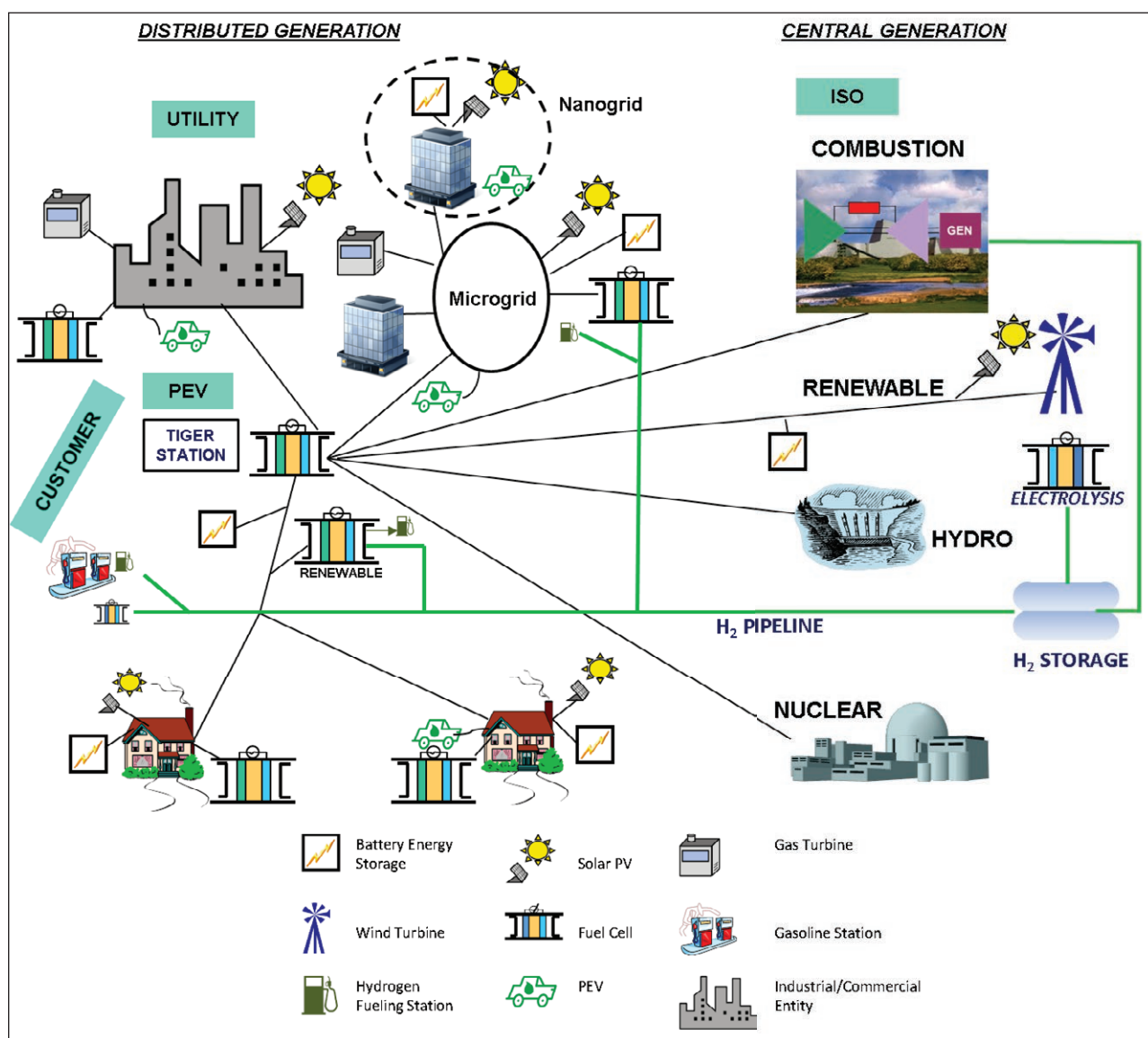
The future grid will be comprised of distributed energy resources in addition to central generation resources, renewable resources at both the distribution and transmission levels, battery and hydrogen storage, battery and hydrogen fuel cell vehicles, and both microgrids and nanogrids (**Figure 11**).

### Microgrids and Nanogrids

A microgrid is a collection of generation resources, loads, and other DER that operates as a single unit and presents itself as a single controllable entity that can separate from

the grid and operate in an islanded mode. Microgrids have the potential to facilitate grid support by managing the resources and loads locally, reducing the impacts of intermittent and flexible resources on the grid, and providing demand response capabilities [51]. Microgrids also have the potential to contribute to grid reliability and resiliency of the community through ancillary services and islanding. Microgrid controllers are evolving to communicate with loads, generation resources, and other DER (e.g., energy storage systems), and thereby (1) optimize the grid-connected microgrid performance, (2) provide ancillary services, (3) support engagement in the electricity markets, (4) manage seamless islanding and reconnection, and (5) provide emergency services<sup>8</sup> to the grid. The microgrid controller is envisioned to communicate in the future with the utility, ISO, and other microgrids to provide (or buy) the services outlined.

A nanogrid is a smart building (equipped with a Building Management System, for example) which is capable of providing ancillary services to the microgrid and separating from the microgrid (retaining building critical loads in



**Figure 11:** The Future Grid.



service) in case of a microgrid outage, and managing DER, lighting, and plug-loads within the nanogrid.

Direct current and hydrogen microgrids are also part of the future grid. The DC microgrid can improve the efficiency of delivering power to the load by eliminating the AC to DC conversion delivered to loads [52]. The hydrogen microgrid receives hydrogen generated externally from otherwise curtailed wind resources ("Power-to-Gas" or "P2G"), and/or generates hydrogen locally from excess renewable (e.g., solar) generation, stores the hydrogen, and utilizes the hydrogen on the microgrid through fuel cells, gas turbines, or reciprocating engines to meet load demands when required.

In principle, microgrids can be designed to operate at a frequency different than the grid and connect to the grid and other microgrids operating at a different frequency using a DC connection, thereby eliminating the need to synchronize to the grid.

### **Market Structure**

The electricity market structure will evolve to accommodate the upcoming changes. Accepting renewable resources as must-take resources might not work well when the penetration of these resources increases, and the distributed energy resources, energy storage, and microgrids need to be integrated fully into the market. This can be facilitated by installing synchrophasors<sup>9</sup> or Phasor Measurement Units (PMUs) throughout the transmission and distribution systems to provide high resolution data and an accurate picture of the system status in real time, and these devices will also help improve the load flow models used in market predictions.

### **Summary**

Smart grid and microgrid technology is evolving to facilitate the increasing penetration of intermittent solar and wind generation resources, the emergence of plug-in electric vehicles, the increasing demand for enhanced grid resiliency, and the challenging environmental goals associated with climate change, air quality, and water utilization. The changes portend a paradigm shift in which the grid will be designed, configured, and operated in the future from smart home appliances to central plant power generation. To achieve the compelling potential attributes of smart grids and microgrids (e.g., high efficiency, lower GHG and criteria pollutant emissions, lower operating costs, the accommodation of grid ancillary and emergency services, and the ability to enable and expand the evolving electricity), research is required to advance smart communications, controls, energy storage, high-resolution and robust sensors, power electronics, load following and high-ramping 24/7 clean power generation, smart PEV charging/discharging, and energy management systems. In parallel, research is required to establish and implement policies that support the development and deployment of the empowered concomitant electricity markets.

### **Recommendations**

1. **Interdisciplinarity:** We recommend that funding agencies, journal editors, academy committees, & other relevant entities make it a high priority to

encourage climatologists, technologists, policy makers, economists, & behavioral researchers to collaborate more frequently and more closely in the development, analysis and recommendations of work related to climate change mitigation. A greater effort needs to be made to overcome the traditional tendency of academic disciplines to work in isolation. Technology development and deployment needs to be guided and influenced by the realities of policy, economics & behavior; as do the latter need to be cognizant of the readiness of specific technologies to be deployed and the prospects for future advances so that all ensuing recommendations for action can be more credible and have greater impact.

### **2. Power Generation:**

- Balanced attention should be paid to lowering greenhouse gas emissions, criteria pollutants, and water use.
- High efficiency natural gas (bridging fuel) power plants, such as fuel cells, should increasingly be used to lower greenhouse gas emissions in the short term.
- These power plants should replace older less efficient and higher polluting power plants that include coal plants, gas turbine simple cycle or Rankine cycle power plants as well as low efficiency peaking power plants.
- The new natural gas fueled power plants must include or evolve to include significant dynamic ramping capability so that they may be dispatched to complement and expand the penetration of intermittent solar and wind power.
- Such power plants must be designed as fuel flexible to enable a longer-term transition to the use of all renewable fuels, such as digester gas, landfill gas, biomass, or hydrogen produced from otherwise curtailed renewable power.
- These plants must also have ultra-low criteria pollutant emissions, water use and waste throughout their period of use and evolution so that they have an overall positive impact on air quality.
- Research and development should be supported to achieve the evolution of dynamic dispatch and renewable fuel operation for these clean fueled power generation technologies to ultimately enable 100% renewable primary energy use.
- Special investments should be focused upon fuel cells (the cleanest of these technologies) to:
  - Accelerate development of hybrid fuel cell/gas turbine technology to achieve fuel flexible, ultra-high efficiency, zero criteria pollutant emission operation for both distributed and central generation applications,
  - Accelerate the development of load-following, high-ramp rate fuel cell systems and fuel cell hybrids (e.g., battery, SOFC/PEM, tri-generation).
- Actions should be taken to accelerate the development of renewable fuels (e.g., bio-methane, bio-hydrogen, renewable methane, renewable

hydrogen), and the development of an increasingly renewable natural gas resource.

### 3. **Transportation:**

- Promote Wide-Spread Usage of Commercially Viable Technologies Such as Battery and Hydrogen Fuel Cell Electric Light-Duty Vehicles
  - Accelerate the transition from fossil to zero-carbon, locally sourced transportation fuels such as hydrogen to power fuel cell powered electric vehicles, and a low-carbon grid electricity to power battery electric vehicles is needed to meet the carbon reduction required from the light-duty transportation sector.
- Aggressively promote innovation that can lead to quantum improvement in Battery and Hydrogen Energy Storage; Biomass and Biogas Resources; and Battery and Hydrogen Fuel Cell Electric Medium-Duty, and Heavy-Duty Vehicles.
  - Scaled up environmentally friendly renewable fuel and biofuel solutions are necessary, as are concerted research efforts that would make algal-based biofuels economically viable, and make electrolysis technology both economically viable and scalable to facilitate the production and storage of renewable fuels such as hydrogen from renewable energy that would otherwise be curtailed.
  - The development of zero-carbon fuels such as hydrogen and highly-efficient engines with zero criteria pollutant emission is required to substantially reduce the carbon signature from goods movement (medium-duty and heavy-duty vehicles, locomotives, ships) and, in parallel, achieve urban air quality goals.
  - The historically disparate electric power generation and transportation sectors are rapidly moving toward a new paradigm of an integrated system, the evolution of which portends unusual opportunities for innovation to ensure a robust design that efficiently and effectively meets reliability, economic, climate change, and urban air quality goals.

### 4. **Biomass Fuels:**

- Investigate research opportunities in support of larger scale development:
  - Complex chemical compositions of biomass enable the replacement of many fuels and products now made from more conventional non-renewable feedstocks such as petroleum, coal, and natural gas.
  - Biomass, biogas, and other biofuels can provide dispatchable or baseload power in complement to variable solar and wind generation for a high fraction of renewable electricity.
  - Alternative markets for biomass also generate competition for land, water, and other resources, including indirect effects, that require system-level consideration of lifecycle sustainability impacts for effective policy design.

- Identify and develop pilot and full-scale deployment opportunities
  - Quantify impacts through long-term monitoring and assessment.

5. **Nuclear Energy:** It is not possible to predict the future role that nuclear energy will play as a low-carbon energy source, however, it is highly likely that use of nuclear energy will continue in some areas of the world. The UC-managed nuclear security laboratories have unique competence in non-proliferation and physical security technologies, that merit further strengthening. Likewise, UC's strength in subsurface science should continue to be applied in work to develop geologic disposal capabilities for spent fuel and high level nuclear wastes. In advanced reactor technologies, further research should be performed for improved designs for small, modular reactors, and for passive safety for advanced reactors.
6. **Energy Storage:** To ensure the extensive expansion of renewable electricity generation from intermittent sources such as solar and wind and to enable the widespread deployment of electric vehicles, substantial additional research is needed to develop lower cost reliable storage technologies. Although the main thrust of these investments should be directed at electrochemical storage, it is also important to explore options for hydrogen storage systems deploying solar generated electricity with fuel cells, compressed air storage, and other non-conventional storage technologies. Each of these should be carefully assessed and developed with respect to their optimal application. We suggest that public-private partnerships are critically needed to focus the research in the right direction and to ensure that research innovations can be performed with industrial processes in mind, and seamless movement of ideas between industry and the universities/labs is enabled. We recommend that formation and operation of such public-private partnerships should be supported. Consortia, such as Sematech, could serve as examples of how such partnerships can lead to successful development and acceleration of technology.
7. **Energy Efficiency: Heat Pumps.** To reduce electricity consumption for air conditioning and cut natural gas consumption by as much as 50%, we recommend additional research in heat pumps and systems coupled to solar thermal and power generation, thermal storage, and (where appropriate) using ocean water as a thermal bath. Economies of scale for applications of heat pumps to larger commercial buildings, as well as the deployment of incentives such as rebate programs and the elimination of disincentives such as the outdated and inappropriate regulations for ground source installations should also be fully explored.
8. **Energy Efficiency: Lighting Technology.** Replace all incandescent, metal halide, and fluorescent lighting fixtures with LED lighting in all California

Government Buildings, Schools and Universities over the next 5 years. Using DOE Estimates this will reduce energy consumption from lighting by 40%. (approximately 8% of site electrical consumption). Develop a second generation of intelligent and even more efficient 200 lm/Watt LED lighting products. Intelligent LED systems will be able to optimized for color, and brightness to improve work and school productivity and building efficiency. Additionally, studies on optimal LED lighting for plant growth and food store is needed.

9. **Smart Grids and Microgrids:** Smart grid and microgrid technology is the innovation needed to facilitate an increasing penetration of intermittent solar and wind generation resources, the emergence and integration of plug-in electric vehicles into the grid infrastructure, and to proactively respond to the increasing demand for enhanced grid resiliency, and thereby meet the challenging environmental goals associated with climate change, air quality, and water utilization. The evolution of the technology is a paradigm shift by which the grid will be designed, configured, and operated in the future from smart home devices to central plant power generation. To achieve the compelling potential attributes of smart grids and microgrids (e.g., high efficiency, lower GHG and criteria pollutant emissions, lower operating costs, the accommodation of grid ancillary and emergency services, and the ability to enable and expand the evolving electricity), innovative smart communications, controls, energy storage, high-resolution and robust sensors, power electronics, load following and high-ramping 24/7 clean power generation, smart PEV charging/discharging, and energy management systems are needed. The solution to managing the high penetration of renewable resources required to mitigate climate change and meet urban air quality goals resides with the development and deployment of a resilient smart grid integrated with an intelligent battery and hydrogen storage construct for the generation of electricity and the powering of transportation systems.

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## Competing Interests

The authors have no competing interests to declare.

## Notes

<sup>1</sup> The term “clean fueled” is used in this section to designate the following power generator attributes: (1) fuel plus energy conversion technology that has substantially lower greenhouse gas emissions than current technologies such as coal, (2) fuel plus energy conversion technology that has low to zero pollutant emissions that will improve air quality and public health, and (3) fuel plus energy conversion technology that is amenable to control and dynamic dispatch to support high renewable use.

<sup>2</sup> PEVs: Battery Electric Vehicles (BEVs), Plug-In Hybrid Vehicles (PHEVs), and Fuel Cell Electric Vehicles (FCEVs).

<sup>3</sup> Examples include (1) dynamic fluctuations in grid voltage due to the diurnal and instantaneous intermittencies associated with renewable solar and wind, (2) curtailment of renewable wind energy, (3) unscheduled and uncontrolled vehicle charging loads, and (4) demand for rapid ramping spinning reserves (e.g., “Duck Curve” <http://publications.caiso.com/State-OfTheGrid2014/RenewablesIntegration.htm>).

<sup>4</sup> Order 888, a final rule regarding electric industry restructuring referred to as the “open access” rule, required all transmission line owners to provide non-discriminatory service to others seeking such services over its own facilities. Order 889 established Open Access Same-Time Information System (OASIS) for showing available transmission capacity and reserving capacity to all entities.

<sup>5</sup> PJM Interconnection is a regional transmission organization (RTO) that coordinates the movement of wholesale electricity in all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia ([www.pjm.com](http://www.pjm.com)).

<sup>6</sup> An ancillary service is anything that supports the transmission of electricity from its generation site to the customer. Services may include load regulation, spinning reserve, non-spinning reserve, replacement reserve and voltage support. In California ISO, Regulation, Spinning Reserve, Non-Spinning Reserve, Voltage Support and Black Start support the transmission of energy from generation resources to loads while maintaining reliable operation of the grid in accordance with WECC standards and Good Utility Practice.

<sup>7</sup> Wholesale Distribution Access Tariff.

<sup>8</sup> Services provided during a natural disaster or other unforeseen occurrences. These services include energizing critical loads such hospitals, shelters, and other critical facilities, as well as providing mobility to the community through providing electricity to PEVs and hydrogen to fuel cell vehicles.

<sup>9</sup> Synchrophasors are phasor measurement units that are synchronized using a GPS clock.

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