# Advanced Generation Program Roadmap - Background Paper (Current Status and RD&D Opportunities)



## PIER Advanced Generation Program

## 2009 IEPR Staff Workshop on RD&D of Advanced Generation Technologies

## August 10, 2009

Prepared by Navigant Consulting, Inc.

**Purpose is to examine status of advanced generation technologies and identify key areas for RD&D investments.**

***Objectives of Background Paper***

- Identify and review
  - Guiding policy framework
  - Current status of technologies
  - Key issues, barriers, challenges
  - Opportunities for advanced generation options in California
- Review work of other organizations/institutions
- Support 2009 IEPR Workshop proceedings
- Define the strategic framework for the PIER AG roadmap.

# California energy policy goals that impact advanced electricity generation.

- **AB 32** – Limit GHG emissions to 1990-equivalent levels by 2020
- **Governor's Executive Orders**–
  - Reduce GHG emissions to 2000 levels by 2010;
  - 1990 levels by 2020;
  - 80% below 1990 levels by 2050
- **ARB AB 32 Scoping Plan** – 4,000 MW of CHP by 2020
- **IEPR 2007** – Net zero energy for new construction through CHP
  - 2020 for residences
  - 2030 for commercial
- **IEPR 2008 Update** – Elimination of once-through cooling between 2015 and 2021
- Re-power or retire and replace aging power plants by 2012

# Policy goals largely focus on reducing emissions and environmental impacts.

| | |
|---|---|
| **General** | • Review focus on policy related to non-renewable generation, large or distributed.<br>• Natural gas is State's primary generation source |
| **California** | • No specific goals for NG power plant efficiency; implied via emissions standards.<br>• Interest in CCS research, but no targets or goals.<br>• Policy addresses the importance of CHP, little policy related to other types of DG.<br>• Goal to retire or re-power aging plants by 2012; timeframe and scope is being reviewed.<br>• Policy to eliminate once-through cooling between 2015 and 2021, SWRCB working on details to achieve goal.<br>• Advanced generation can contribute to achieving higher levels of renewables through fuel flexibility with operational flexibility to address the intermittency. |
| **Federal** | • Generation from coal is a primary concern for the Federal government.<br>• As part of the Recovery Act, DOE was appropriated $3.4 billion related to advanced generation.<br>– $1 B for R&D<br>– $2.4 B for accelerating deployment of CCS. |

# The background paper addressed 26 technologies that we will review in today's presentation.

## Primary Focus Technologies

- Distributed Generation / Combined Heat and Power
  - Fuel Cells
  - Hybrid Fuel Cell Gas Turbine Cycles
  - Reciprocating Engines
  - Stirling Engines
  - Microturbines
  - Gas Turbines
- Cooling / Combined Cooling Heating and Power
  - Absorption Chillers
- Advanced Gas Turbine Cycles
  - Industrial Cogeneration
  - Inlet Cooling
  - Recuperation
  - Intercooled/recuperated
  - Heat recovery
  - Advanced Simple Cycle for Peaking
  - Hybrid Renewable Cycles
  - Integrated Gasification Simple Cycle
- Replacement for Once Through Cooling
  - Dry Cooling
  - Wet Cooling Towers
  - Alternative Cooling Water
  - Hybrid Cooling Towers
- Carbon Reduction
  - Pre-Combustion Capture

## Secondary Focus Technologies

- Advanced Coal/Biomass Combustion
  - Integrated Gasification Combined Cycle
  - Ultra-Supercritical Pulverized-Coal
  - Supercritical Circulating Fluidized-Bed Combustion
- Carbon Capture and Sequestration
  - Post-Combustion Capture
  - Geological Sequestration
- Advanced Nuclear Power Generation
  - AP1000, ABWR, ESBWR, APWR, EPR

# Distributed Generation / Combined Heat and Power Takeaways

- Cost is still a limiting factor for most DG technologies
- CHP is typically the most cost-effective application.
- Recent research trend is focused on fuel flexibility of DG/CHP systems.
- Limited investment in communication and control technologies for DG and CHP systems.
- Rule 21 successful in removing interconnection barriers.
- Hybrid Fuel Cell/Gas Turbine Cycle systems have the highest efficiencies.
- Considerable funding for transportation fuel cells; more limited funding for stationary power fuel cells.
- PIER and the Electricity Analysis Office CHP related funding includes:
  - An industrial CHP market potential study
  - An update to the 2005 CHP market potential study.

# All of the distributed generation technologies covered in this report are used in CHP applications.

| | | Typical Applications | | | |
|---|---|---|---|---|---|
| | | CHP / CCHP | Baseload | Backup / DR / Peak Shaving | Cycling |
| DG Technologies | Fuel Cells | ✓ | ✓ | ✓ | ✗ |
| | Hybrid Fuel Cell Gas Turbine Cycles | ✓ | ✓ | ✓ | ✗ |
| | Reciprocating Engines | ✓ | ✓ | ✓ | ✓ |
| | Stirling Engines | ✓ | ✓ | ✗ | ✗ |
| | Microturbines | ✓ | ✗ | ✗ | ✓ |
| | Gas Turbines | ✓ | ✓ | ✓ | ✓ |

Source: NCI Analysis

**One of the least problematic DG technologies to site due to quiet operation, low emissions, high efficiencies, and modular design.**

| Fuel Cells | |
|---|---|
| **Current Status** | • Considerable funding for transportation fuel cells; only limited funding for stationary power fuel cells.<br>• Focus on plug-in hybrid technologies may move transportation focus away from fuel cells resulting in reduced funding for stationary fuel cell research.<br>• Non-technical barriers facing fuel cells include low production volume and capacity, and high capital costs (>$3000/kW).<br>• High temperature fuel cells offer significant advantages (efficiency >40%) over low temperature fuel cells but receive less funding and are less mature. |
| **Research Opportunities** | • Increasing fuel flexibility and stack life.<br>• Improving reliability and fuel reformer design.<br>• Reducing size and system complexity, to lower cost.<br>• Development of low cost material alternatives. |

## Highest efficiency among DG technologies and superior emissions performance.

| Hybrid Fuel Cell Gas Turbine Cycles | |
|---|---|
| **Current Status** | • In the commercial development stage<br>– Two successful demonstrations of this technology<br>– Smaller (1-5 MW) systems for DG expected in the near term<br>– Target efficiencies > 60%.<br>• Costs of systems may be high initially due to complexity of integration of two advanced generation technologies (>$5000/kW).<br>• Front-end risk with developing systems is high; broad investment from industry, national laboratories, and university R&D required. |
| **Research Opportunities** | • General advancement of SOFC and MCFC required to meet the demands that hybrid cycles might place on them.<br>• Development of specialized turbines that perform well with flow and thermal input parameters provided by fuel cells. |

# Low first costs, proven reliability, and significant heat recovery potential; Emissions relatively high.

| Reciprocating Engines | |
|---|---|
| **Current Status** | • Major barriers include high maintenance costs and frequent maintenance intervals.<br>• Current research exploring operating and maintenance cost reductions, and emission reductions.<br>• Limited to lower temperature cogeneration; full waste heat recovery still being explored. |
| **Research Opportunities** | • Full waste heat recovery.<br>• Reducing operating and maintenance cost.<br>• Increase fuel flexibility through use of landfill gas, digester biogas and other fuels.<br>• Achievement of US DOE's fuel-to-electricity efficiency target of 50% (LHV) by 2010 → 30% increase over today's average. |

# Relatively high capital costs, but can achieve low emissions compared to IC engines.

| Stirling Engines | |
|---|---|
| **Current Status** | • Has not undergone a robust R&D phase, contributes to lack of proven operation and durability.<br>• Efficiencies < 20%.<br>• Manufactured in very low quantities, resulting in high capital cost.<br>• The limited research focuses on:<br>– Landfill gas as fuel<br>– Stirling engines for concentrated solar. |
| **Research Opportunities** | • Creation of packaged systems for residential and small commercial CHP that address cost and reliability. |

# Extensive microturbine research and demonstration is currently underway.

| Microturbines | |
|---|---|
| **Current Status** | • Recent research focused on microturbines for CHP.<br>• Research needs:<br>– Improved efficiencies (currently 20-30%) and fuel flexibility.<br>• Manufacturers attempted cost reduction but significant reductions have not materialized yet . |
| **Research Opportunities** | • Cycle enhancement to address loss of power output and efficiency at higher temperatures and elevation.<br>• Improving efficiency by pairing microturbines with fuel cells. |

## Proven to be reliable power generators given proper maintenance.

| Small Gas Turbines | |
|---|---|
| **Current Status** | • Under 3MW not cost competitive with reciprocating engines<br>– Low production volumes<br>– Low commonality of parts among multiple models.<br>• PIER funded several demonstration projects to address catalytic combustion.<br>• Significant simple-cycle gas turbine CHP systems in operation<br>– Oil recovery, chemicals, paper production, food processing, and universities |
| **Research Opportunities** | • Improving energy and environmental performance to lower capital costs.<br>• Technology demonstrations, technical assistance in implementation, and reporting of lessons learned and best practices. |

# Cooling / Combined Cooling Heating and Power Takeaways

- Absorption chillers currently are the primary technology in CCHP systems.
- Electric driven chillers are another important technology in CCHP systems.
- High cost, relative to efficiency benefits, is the main barrier for CCHP.
- Overall efficiency is generally lower for systems paired with absorption chillers relative to other CHP systems.
- Primary benefits come from use in warmer climates which allow more effective utilization of waste heat.

# Most cost-effective in large facilities with significant heat loads.

| Absorption Chillers | |
|---|---|
| **Current Status** | • Most significant barrier is high cost of equipment (currently >$600/ton for double effect).<br>• Current research focuses on pairing absorption chillers with reciprocating engines and microturbines.<br>• Research on prepackaged CHP systems with absorption chillers will reduce costs. |
| **Research Opportunities** | • Reducing costs<br>• Improving efficiencies of CHP with absorption chillers. |

# Advanced Gas Turbine Cycle Key Takeaways

- Most technologies are mature and incorporated into new plants.
- Significant opportunity to improve efficiency by retrofitting existing plants
- Limited research in recent years on new developments;
  - most research performed over ten years ago.
- Limited effort to demonstrate the benefits in retrofit applications.
- Recent research by OEMs focuses on materials.
- Significant research outside US on hybrid renewable systems to address intermittency.
- Significant incentives for renewable systems, but few for hybrid systems.
- Large unrealized technical potential for industrial cogen and heat recovery.

# Provides a cost effective means to boost generation efficiency and mitigate emissions.

| Industrial Cogeneration | |
|---|---|
| **Current Status** | • Mature technology, used for many years in industrial, large commercial and institutional applications.<br>• Large unrealized technical potential in California.<br>• California's Rule 21 applies to DG up to 10 MW:<br>– Industrial cogen applications still face interconnection issues.<br>• Complex tax depreciation policies discourages industrial cogen |
| **Research Opportunities** | • Improvement in fuel flexibility and efficiency necessary to improve life-cycle cost/benefit ratio.<br>• Due to restrictive state emissions regs, near term R&D focus:<br>– Low emission gas turbines<br>– Low emission reciprocating engines<br>– NOx emission controls. |

## Cost-effective, energy-efficient, and environmentally sound way to enhance peak GT capacity/efficiency in hot ambient temps.

| Inlet Cooling | |
|---|---|
| **Current Status** | • Fundamentally limited by ambient conditions; cost-effectiveness also highly dependent on ambient conditions.<br>• Poses risks to the compressor section and other turbine parts.<br>• Lack of awareness and dated negative perceptions are barriers.<br>• Of all sub-technologies, fog intercooling shows greatest promise. |
| **Research Opportunities** | • Unknown reliability, corrosion, and pitting risks associated with fog intercooling.<br>• Performance enhancement limits of fog intercooling. |

## Exhibit higher efficiency and lower emissions than other simple cycle turbines of a similar size (~5MW).

| Recuperated Gas Turbine Cycle | |
|---|---|
| **Current Status** | • Large, high pressure GTs not suited due to pressure ratio.<br>• Retrofit to existing turbines not feasible.<br>• Cycle produces less power, and results in less waste heat for CHP |
| **Research Opportunities** | • Lacks intense research effort, most research is on more complex cycles.<br>• Success of cycle will rely on improving the cost, durability and reliability of the recuperator section. |

## ICR improves the efficiency of SC GT's more than recuperated cycle and improves power output of the turbine rather than reducing it.

| Intercooled Recuperated Gas Turbine Cycle (ICR) | |
|---|---|
| **Current Status** | • Latest design is for marine propulsion, not stationary power.<br>• Cannot be retrofit to existing turbines, requires new turbines.<br>• Limited for use in small to medium sized turbines (5-25MW) due to optimum pressure ratio. |
| **Research Opportunities** | • IRC for microturbines being developed for vehicle applications and may have stationary applications.<br>• The recuperator and intercooler add significant cost/complexity;<br>– Success relies on reducing the cost of the heat exchangers and proving reliability. |

## Heat recovery can be a clean, cost-effective and attractive method to utilize waste heat to produce 2-6.5 MW of power.

<table>
<tr><th colspan="2">Heat Recovery</th></tr>
<tr><td>Current Status</td><td>• Technology is mature; barriers to adoption mostly market based.<br>• Economics and operation resemble renewable projects (large up-front cost, minimal fuel costs), lack similar investment incentives.<br>• Large unrealized technical potential in California.</td></tr>
<tr><td>Research Opportunities</td><td>• Successful implementation highly-site specific:<br>– Limited target market characterization,<br>– Uncertain waste heat temperature and throughput have slowed adoption.</td></tr>
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## Advanced SC GT's offer high efficiency, high reliability, fast start-up and low emissions making them ideal for peaking and mid-range.

| Advanced Simple Cycle for Peaking | |
|---|---|
| **Current Status** | • Can incorporate advanced cycle technology to enhance performance such as intercooling, recuperation, inlet cooling, reheat, and steam injection.<br>• Commercially available turbines have high, proven availabilities and reliabilities.<br>• High cost compared to base-load technologies limits broader adoption for power generation. |
| **Research Opportunities** | • Lack of fuel flexibility is a significant barrier; most utilize natural gas and perceived scarcity and volatility can limit adoption. |

# Offer more efficient, cleaner operation compared to conventional GT's and overcome the intermittency issues of renewable systems.

| Hybrid Renewable Cycle | |
|---|---|
| **Current Status** | • Emerging technology in commercial development stage<br>–Focus has been small scale demonstrations<br>–Larger scale demonstrations still in planning stage.<br>• Expensive with few funding opportunities or incentives in US. |
| **Research Opportunities** | • Lack of research in US, although research on concentrated solar power will facilitate.<br>• Research on small scale demonstrations needed to further understand and optimize integration.<br>• Research needed to increase percent solar energy.<br>• Exploiting potential requires integration with combined cycle plants, this requires scale-up to above 50MW. |

**Possible way to reduce emissions and improve the efficiency of IC engines so they can meet ARB 2007 emission limits for DG applications.**

| Integrated Gasification Simple Cycle | |
|---|---|
| **Current Status** | • Extra components and complexity adds cost<br>• Older studies have shown efficiency gains in gas turbines may not be sufficient to compete with combined cycle.<br>• Lack of industry champions to develop IGSC for GT's is a major market hurdle. |
| **Research Opportunities** | • Comprehensive paper study on efficiency gains of this cycle with the latest GT and IC technology.<br>• Engineering analysis of current cost and benefits of a IGSC GT<br>• Significant demonstrations and verification of system components are required for both IC and GT's<br>• Research on combustion of hydrogen rich fuel in advanced gas turbine and IC engines is necessary. |

# Replacement for Once Through Cooling Technology Takeaways

- Equipping plants with any of the alternative technologies will be expensive and impact efficiency.
- Older, Rankine Cycle plants likely to shut down due to policy to eliminate OTC.
- Costs are highly dependent on the site.
- Typically, dry cooling is most expensive, followed by hybrid cooling, then closed cycle wet cooling towers.
- Wet cooling towers utilizing sea water still represent a significant improvement over OTC.
- Space (e.g., for cooling tower) will be a limiting factor in retrofitting..

# Pre-combustion carbon capture takeaways.

- Costs vary widely between new plants and retrofits.
- Cost of retrofitting plants is typically prohibitive.
- Costs are dependent on the amount of carbon in the fuel source
  - Cost/ton of carbon is lower with a dirtier fuel (e.g., coal)
  - Cost/MWh is lower with a cleaner fuel (e.g., natural gas).
- Lack of utility-scale demos has limited adoption; the ARRA has funding for demos.
- DOE expects new research will lead to significant cost reductions, their focus is IGCC.
- IGCC plants with pre-combustion capture have the lowest energy requirements.
- IGCC with pre-combustion capture shows the most long-term promise for CCS.
- Little research on pre-combustion capture for NG plants but opportunities exist (ie. IGSC)
- Success will depend on the success of carbon sequestration technologies.

# Advanced Coal/Biomass Combustion Takeaways

- Limited electricity generated from Coal in the state; however, 17% of power consumed is imported from coal power plants.
- DOE has extensive effort underway for the development and demonstration of advanced coal/biomass combustion technologies.
- Repowering old coal plants that export power to California could provide a significant carbon reduction opportunity.

# Post-combustion Carbon Capture and Sequestration Takeaways

- Opportunity in CA is mostly tied to NG plants linked to enhanced oil recovery.
- Better suited for retrofitting, and in the near-term better suited for NGCC plants.
- More energy intensive than pre-combustion capture, but the overall efficiency penalty (NGCC vs. IGCC) is similar.
- Requires additional development and cost improvement.
- Compared to other carbon reduction approaches, post-combustion carbon capture is more expensive.
- Success of EOR sequestration depends on alignment of interest between the oil producer and society's need to reduce carbon emissions.

# Advanced Nuclear Power Generation Takeaways

- Various advanced nuclear power technologies are competing for combined construction and operating licenses, and to be the first new nuclear reactor.
- Earliest a new nuclear reactor could be operational in the US: 2016.
- Cost in the US is highly uncertain given no new plants have been built recently.
- Still no facility for nuclear waste disposal in the US.
- Existing research abroad (e.g., China) focused on early stage modular tech.
- California's moratorium on new nuclear is still in place.

## There are a series of trends and issues which could have great impact on advanced generation technologies in California.

- Recent study found generation from NG could be reduced 15% by 2020
- Under current policy, the state will need to replace/repower 66 aging gas plants by 2012:
  - Combined capacity = 17,000 MW - 40% of gas-fired plants and 25% of all capacity.
  - The scope/timeframe of goal is under review.
- Despite improvements - energy intensity for desalination remains high; energy and GHG impacts need to be considered when assessing desalination projects.
- CA has significant electricity resources that are cleaner but less affordable than US ave.
- The Smart Grid expected to increase the value of PV and other DG systems; however, this will require coordinated involvement of various stakeholders.
- Need to overcome technical/non-technical challenges posed by renewable intermittency.
- Net zero energy/new construction may have significant impact on efficiency /DG.
- NG deliverability and supply scarcity projections vary.

## The new program vision enables PIER AG to play a key role in helping the state meet key policy goals.

Preliminary

### 2020 PIER Advanced Generation Vision

*The PIER AG program provides key RD&D that enables California to generate energy efficient, abundant, affordable, reliable, and environmentally-friendly electricity (and other forms of power) from small to large power plants, including distributed generation and combined heat and power, using clean non-renewable fuels and fuel flexibility capability in order to help reach the greenhouse gas emission reduction targets.*

**PIER AG would focus on improving efficiency and reducing GHG emissions of large-scale and distributed generation/CHP fueled with clean fuels and fuel flexible.**

Preliminary

| PIER AG Program Areas | |
|---|---|
| **Commercial CHP/CCHP Systems** | Support development of cost-effective CHP and CCHP systems for commercial buildings and their wide-scale deployment. |
| **Industrial Cogeneration Systems** | Support development of cost-effective industrial cogeneration systems and their wide-scale deployment. |
| **Advanced Gas Turbine Cycles** | Support development and wide-scale adoption of cost-effective advanced gas turbine cycles, including integrated hybrid renewable systems, which significantly improve the efficiency and fuel flexibility of natural gas power plants. |

**PIER AG will have to focus its limited resources, avoiding duplication of efforts and funding on areas addressed by other PIER Program Areas.**



- Residential single family CHP/CCHP Systems:
  - Technologies currently not cost-effective as thermal load is too small relative to electricity load.
  - Continue to monitor technology progress due to high technical potential for residential CHP/CCHP systems.
- Distributed generation systems primarily used for baseload, peaking, backup, and cycling applications
  - Primary focus on more efficient, cost-effective, and environmentally friendly CHP systems.
- DG/CHP Interconnection rules and standards
  - Addressed by Smart Grid research of PIER Energy Systems Integration Program

**PIER AG will have to focus its limited resources, avoiding duplication of efforts and funding on areas addressed by other PIER Program Areas.**



- Renewables, including management of intermittency issues through the co-location of renewable systems and traditional gas fueled generation systems –
  - Addressed by PIER Renewable Energy Technologies program.
- Water use in power plants, including replacement technologies for once through cooling
  - Addressed by PIER Energy Related Environmental Research and Industrial/Agricultural/Water End-Use Energy Efficiency programs.
- Carbon capture and sequestration
  - Primarily focused on coal fueled generation and addressed by DOE.
  - Continue to monitor cost-effectiveness of application to natural gas fueled power generation.
- Nuclear – Moratorium still in place.

## In each target research area, PIER AG will need to focus on a few key research issues.

Preliminary

| PIER AG Key Research Issues | |
|---|---|
| **Commercial CHP/CCHP Systems** | • System packaging and integration (primary)<br>• Market and regulatory mechanisms (secondary, complement CEC CHP program) |
| **Industrial Cogeneration Systems** | • System packaging and integration (primary)<br>• Identification of cost-effective sites (secondary, complement CEC CHP program)<br>• Market and regulatory mechanisms (secondary, complement CEC CHP program) |
| **Advanced Gas Turbine Cycles** | • New technology development of integrated hybrid renewable cycle systems (primary)<br>• New technology demonstration of advanced generation technologies (primary, channel DOE resources to California)<br>• Market and regulatory mechanisms (secondary, support policy development) |

**Today we would like to obtain your input / feedback on the PIER AG Vision, the preliminary research opportunities and target issues.**

- What are the additional research opportunities which should be considered as part of the PIER AG program?
- Does the PIER AG Preliminary Vision capture the right objectives for the program's future?
- Do the preliminary research areas capture the appropriate target areas for PIER AG's future program?
- Are the secondary focus areas appropriate?
- Do the preliminary research issues capture the appropriate research needs?
- What areas can the Energy Commission most effectively devote resources which will show progress in meeting California's Energy Goals as 2009 IEPR Proceedings?

## Stakeholder input is a critical element of the roadmap development process.

- Expertise in advanced generation technologies is widely spread across various stakeholder groups, including utilities, equipment manufacturers, research organizations, and policymakers.
- The roadmap development process is designed to aggressively seek input from various stakeholder groups.
- Stakeholder input opportunities are:
  - 7/23, 9:00 am PDT, 2009 IEPR workshop at CEC on Combined Heat and Power
  - 8/10, 9:00 am PDT, 2009 IEPR workshop at CEC on large-Scale Advanced Electric Generation
  - 9/3, 9:00 am - 12:00 pm PDT, stakeholder WebEx meeting to discuss draft roadmap, including recommended research issues for PIER AG funding