The Micro-CHP Technologies Roadmap

Meeting 21st Century Residential Energy Needs

December 2003

Based on the Results of the Micro-CHP
Technologies Roadmap Workshop

June 11-12, 2003
Greenbelt, Maryland

United States Department of Energy
Office of Energy Efficiency and Renewable Energy
Distributed Energy Program

Executive Summary

On June 11-12, 2003, at Greenbelt, Maryland, key stakeholders from industry, government agencies, universities, and others involved in combined heat and power and the residential buildings industry explores solutions to technical, institutional, and market barriers facing micro-combined heat and power systems (mCHP). Participants outlined a desired future for mCHP systems, identified specific interim technology cost and performance targets, and developed actions to achieve the interim targets and vision. The vision is shown below:

> By 2010, environmentally friendly, cost-effective, versatile, reliable, fuel flexible, mCHP appliances will be commercially viable for the American residential marketplace.
>
> - CHP includes heating, cooling, power, and indoor air quality
> - Includes infrastructure development (utility interconnection, supply chain, standards, etc.)
> - Addresses national energy priorities (energy efficiency, environmental emissions, fuel diversity, energy assurance)

This document, *The Micro-CHP Technologies Roadmap*, is a result of their deliberations. It outlines a set of actions that can be pursued by both the government and industry to develop mCHP appliances for creating a new approach for households to meet their energy needs. It consists of three main action areas:

- Defining Markets
- Developing Technology
- Accelerating Acceptance

Major Findings

- Meeting consumer needs is essential for mCHP technology development. mCHP systems should not be developed to meet only one specific goal, i.e., electrical efficiency, but be based on the consumer's energy needs—cooling, water and space

What is Micro-CHP?

Micro-combined heat and power (mCHP) systems simultaneously produce heat and power for a residence. The system is located on the property—in the basement, underneath the sink, hanging from a wall, or outside. It is basically another household appliance that can provide various residential building energy needs—space and water heating, electricity, and, potentially, cooling.

heating, premium power, indoor air quality, etc. The success of mCHP system development will be based on how well the system economically meets the thermal and electric loads and priorities of the residential building.

- mCHP offers potential benefits to homeowners, utilities, equipment manufacturers, and society at large. mCHP produces societal benefits such as environmental protection, energy efficiency, energy assurance, and economic growth. It is important that the U.S. Department of Energy clearly articulate and prioritize the benefits of mCHP.

- Various mCHP systems are further along in development. There are systems that are available to meet specific market segments energy needs. Societal benefits will only be met through widespread deployment of mCHP systems across the United States.

- Partnership is paramount. Implementation involves clear communication and coordination among a wide variety of organizations (equipment manufacturers, homeowners, builders, utilities, regulators, technology researchers and developers, including national laboratories, etc.) to most efficiently leverage the limited resources available.

Action Agenda

This roadmap consists of actions in three primary areas: (1) markets, (2) technologies, (3) acceptance, all of which are designed to achieve the vision.

Define Markets. There is a need to define and quantify the various residential building markets. The United States has a very diverse set of regions and types of residential buildings. Climate, new vs. retrofit, location, premium power, and building type characteristics determine the energy needs. The residential energy needs will define the market potential and drive the technical requirements in researching, developing, and demonstrating (RD&D) mCHP.

Develop Technologies. mCHP systems consist of a variety of thermodynamic cycles. All of these technologies, when integrated into a mCHP appliance, face similar system needs—reliability, flexibility, affordability, etc. Developments in energy storage, cooling, controls, and integration technology will enhance the performance and operation of mCHP appliances.

Accelerate Acceptance. There is inertia between the time a technology leaves the laboratory and when it is accepted into the marketplace. The current institutional and business setting does not encourage energy-efficient devices and particularly on-site power generation technologies. Executing pilot programs, establishing measurable benchmarks, and developing standards will give consumers, utilities, and regulators the critical information needed to ensure a friendly infrastructure for mCHP appliances.

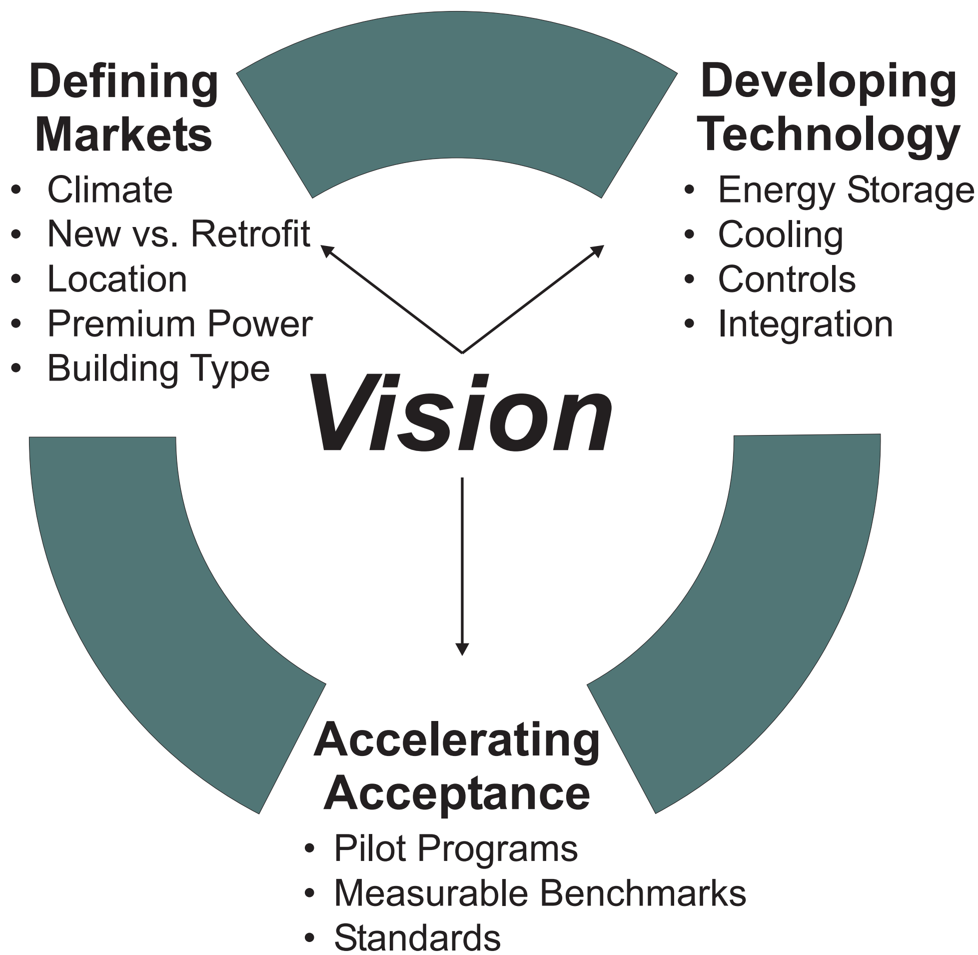


Table of Contents

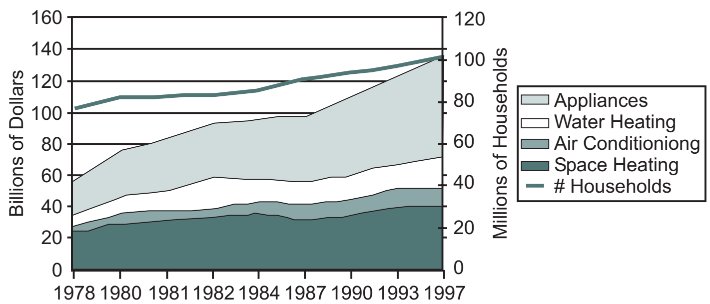
INTRODUCTION

Residential Energy Situation

There are over 105 million households in America, each consuming energy for all of life's necessities—heating, cooling, cooking, washing, lighting, etc. Heating and cooling loads are the major end uses of residential energy consumption. The most prominent fuels used for space and water heating today are natural gas, oil, propane and electricity, while electricity is the main fuel for air-conditioning. In the U.S., electricity is primarily generated from coal (50%), nuclear (20%), natural gas (15%), hydro (12%), and petroleum (3%). Even with today's increasingly efficient appliances and tighter building envelopes, residential energy consumption is projected to increase 25% from 2001-2025[1].

Part of this increase is due to the size of new homes being built which are, on average, 14% larger than existing homes. From 1978 to 1997, the number of U.S. households increased by over 30%; but, even more eye-raising is the amount that household energy expenditures have increased over the same time period. Space heating expenditures have increased 75%, air conditioning 140%, water heating 184%, and the amount households have spent to run their appliances has increased over 210%. Figure 1 shows the increase in household energy expenditures compared to the increase in physical households.

Figure 1. Household Expenditures by End Use



Source: Residential Energy Consumption Survey 1997, EIA.

Electric utilities are responsible for delivering electricity. Utilities' power plants produce electricity and transmit the electricity to a substation through high-voltage electric cables. The fleet of substations takes power from transmission-level voltages and distributes it to hundreds of thousands of miles of lower voltage distribution lines. The distribution system is generally considered to begin at the substation and end at the customer's meter. Beyond the meter lies the customer's electric system, which consists of wires, equipment, and appliances — an increased number of which involve computerized controls and electronics which ultimately operate on direct current.

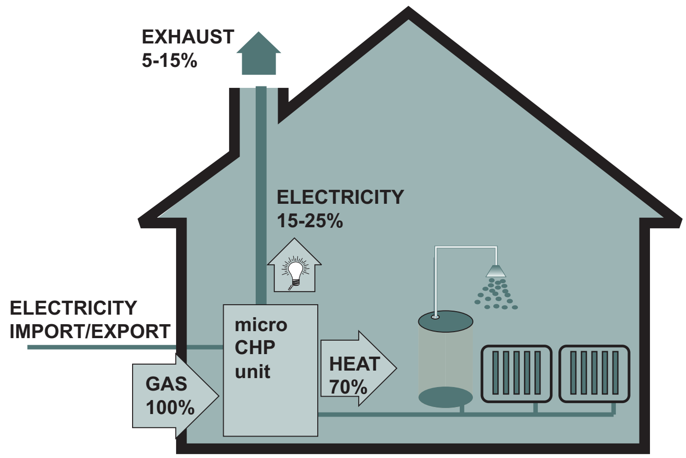
Some homes have natural gas pipelines leading to them to power their furnaces and boilers for space and water heating and cooking. Alternatively, households may have storage tanks outside for heating oil and propane to fuel their heating appliances.

[1] Annual Energy Outlook 2003, Energy Information Administration, December 2002.

Overall, today's electric infrastructure, with its wires and pipelines, is very inefficient. Only about 30% of the original fuel provided is actually available for consumption by the end user—the rest is exhausted in the form of heat into the environment.

Micro-CHP

Micro-combined heat and power units (mCHP) simultaneously produce heat and power for residences. The heat could be used to meet a household's space and water heating needs and, in the future, provide cooling needs as well. The power can be used for lighting, consumer electronics, or any other electrical needs the house may have. The system is located on the property- in the basement, underneath the sink, hanging from a wall, or outside. mCHP appliances can utilize over 80% of the fuel to provide electric and thermal energy to the household.



Source: EA Technology.

Bigger homes, higher energy costs, volatile fuel costs, recent electricity blackouts, and increasing concern over the environment have opened the door for mCHP. RKS, a leading market research firm, found that more than 38% of high-income households, (i.e., incomes > $50,000) are interested in generating their own electricity. [2]

mCHP can be developed using a variety of prime mover technologies, such as Stirling engines, Rankine cycle generators, reciprocating engines, and fuel cells. The prime movers generate electrical power. The heat exhausted from the prime mover technology may be used to provide useful space and water heating to the house. Or the prime mover may utilize the heat produced by a boiler or furnace for conventional heating needs, to produce electricity.

Stirling Engines

This technology is based on the Stirling cycle founded by Robert Stirling in the 19th century. There are two types of Stirling engines — free-piston or kinematic. Stirling engines use an external heat source to produce power. They can be operated from a variety of sources: natural gas, heating oil, biomass, solar, geothermal, and waste heat. Stirling engine systems are best suited for power applications less than 25 kW. They have a relatively low electrical efficiency (10%) but when coupled with a heating system they can achieve system

[2]Connecting Residential Power Systems to the Nation's Electric Grid.

efficiencies greater than 70%. Stirling engines have been widely demonstrated throughout Europe. In some cases, when combined with a condensing boiler, mCHP appliances have demonstrated to convert 95% of the fuel input for thermal and electric needs[3].

Rankine Cycle Generators

Rankine cycle equipment is emerging from research and development laboratories. This cycle only operates when there is a demand for space or water heating, but when in operation it produces both heat and electricity. Although its electrical efficiencies are low, 15%, developers feel that the thermal/electric ratio of these systems are well suited to match the thermal loads of houses. When coupled with a heat exchanger these systems can achieve overall thermal energy utilization efficiencies equal to current heating appliances — typically 75% and potentially higher. Rankine cycle equipment is attractive because it uses already-proven technologies, which may translate into low manufacturer costs and known operation and maintenance characteristics.

Liquid Injection Cogeneration System

Source: Climate Energy.

Reciprocating Engines

Reciprocating engines, also known as internal combustion (IC) engines, have been successfully commercialized for emergency generators of all sizes and for combined heat and power systems ranging in size from a few hundred kilowatts to several megawatts in capacity. In CHP systems, the engine drives an electric generator; the heat released through its exhaust and jacket water is captured as steam or hot water for space heating and cooling and/or water heating. There are reciprocating engine systems throughout Europe sized around 5 kWe that are used for small apartment buildings and other multi-family dwellings. Honda is currently developing a 1 kW mCHP system for the Japanese residential market. This system will have a 20% electrical efficiency and over 80% system efficiency.

Fuel Cells

A fuel cell is an electrochemical device that converts hydrogen and oxygen into electricity and water. Similar to a battery, fuel cells have an anode and a cathode separated by an electrolyte. Hydrogen enters the anode and air (oxygen) enters the cathode. The hydrogen

[3]ENATEC, www.enatec.com.

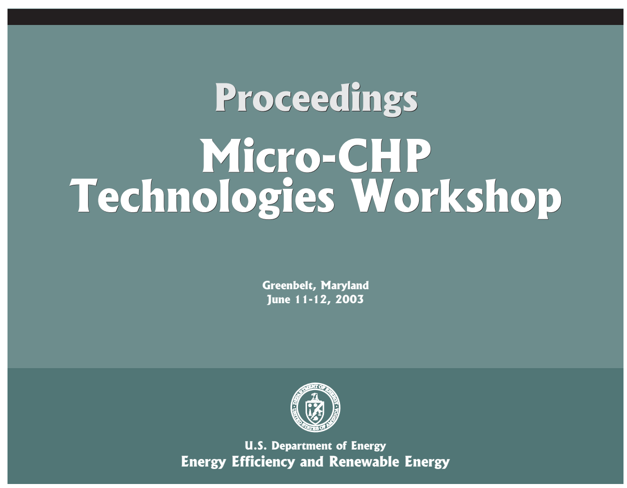
and oxygen are separated into ions and electrons, in the presence of a catalyst. Ions are conducted through the electrolyte while the electrons flow through the anode and the cathode via an external circuit. The current produced can be utilized for electricity. The ions and electrons then recombine, with water and heat as the only by-products when operating on pure hydrogen.

Background and Structure of the Roadmap

The Office of Distributed Energy Resources within the U.S. Department of Energy (DOE) facilitated a national strategy for the research, development, and demonstration (RD&D) of mCHP. This strategy is known as a technology pathway or "roadmap." DOE is uniquely positioned to undertake this process, as the leading provider of energy research and development and as it has a strong and growing portfolio in distributed energy RD&D and CHP applications.

In June of 2003, key stakeholders from industry, government agencies, universities, and others involved in combined heat and power and the residential buildings industry creatively looked at solutions to technical, institutional, and market barriers facing micro-combined heat and power systems. Participants outlined a desired future for mCHP systems, identified specific interim technology cost and performance targets, and developed actions to achieve the interim targets and vision.

Roadmap Proceedings



The Proceedings can be downloaded at www.energetics.com/microchp.html

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- Defining Markets
- Developing Technology
- Accelerating Acceptance

This Roadmap is one of the many possible strategies for developing mCHP systems. It is not concrete, it is one pathway into the future, and should be only used as a guide.

Vision and Targets

By 2010, environmentally friendly, cost-effective, versatile, reliable, fuel flexible, mCHP appliances will be commercially viable for the American residential marketplace.

- CHP includes heating, cooling, and power, and indoor air quality
- Includes infrastructure development (utility interconnection, supply chain, standards, etc.)
- Addresses national energy priorities (energy efficiency, environmental emissions, fuel diversity, energy assurance)

Various mCHP systems are in different stages in prototype development. Some systems, which are customized for specific markets, are further along than other technologies in achieving the vision. The most important driver in the development of these systems is the customer's requirements (e.g., heating, cooling, and electric loads, as well as reliability, environmental friendliness, etc.).

Cost Effective

mCHP appliances will need to be financially competitive with current heating and cooling appliances. By 2007, mCHP appliances will need to achieve 5-to-7-year simple payback and target cost less than $500/kW (adjusted to reflect both electric and thermal values) incremental cost for the mass market. In 2005, the target cost will need to be less than $1,500/kWe for customers who are willing to pay for a premium system. mCHP appliances will cost effectively meet the homeowner's energy needs and have the ability to take advantage of real-time utility pricing to improve system economics.

Flexible

mCHP appliances will need to respond to the residence's energy requirements. These requirements may vary season to season or day to day and mCHP appliances could potentially meet the changing electric and thermal demands. Control schemes incorporated into the system will enable mCHP to adjust its thermal and electric output to best suit the homeowner's needs. They will also need to be able to respond to the residence's energy requirements. Control schemes incorporated into the system will enable mCHP to adjust its thermal and electric output to best suit the homeowner's needs.

Reliable

Reliability and power quality are becoming more of a necessity than a desired attribute. New consumer electronics are requiring highly reliable and stable (voltage and frequency) electric power. mCHP appliances have the potential to provide reliable energy even during electric power outages. In addition, mCHP must be able to meet and exceed the current service intervals for conventional heating and cooling appliances.

Efficient

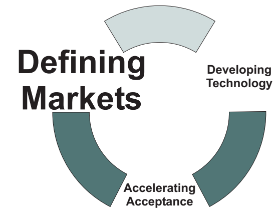
mCHP appliances have the ability to heat and provide power to a household. These appliances can convert over 80% of the fuel energy into useful electricity and thermal energy to meet the thermal needs and power to support electric loads. Efficiency metrics for residential heating and cooling appliances must weigh the relative values of heating, cooling, and electric units, and not just the percent of fuel utilized.

Transparent

New appliances support thermal and electric needs to a household. The appliances can have the same noise emissions as current heating appliances. They emit equal to or less than the same emissions as current heating appliances, meeting all regulatory emission requirements (e.g., CARB by 2007 and other RAP model rules[4]). The grid operates synergistically with the appliance. The appliance must be virtually undetectable—with long service intervals, negligible air and noise emissions, a small footprint, and is seamlessly interconnected to the electric grid.

[4] For more information: http://www.arb.ca.gov/energy/dg/dg.htm
http://www.raponline.org/ProjDocs/DREmsRul/Collfile/ReviewDraftModelEmissionsRule.pdf

DEFINING MARKETS



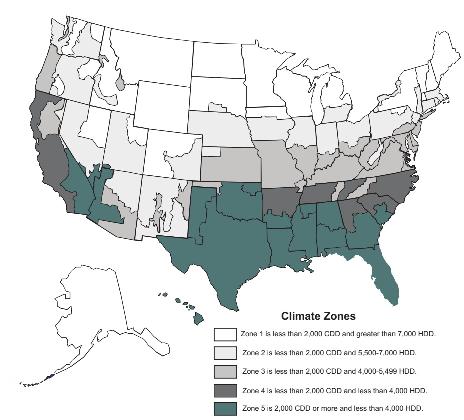
Markets are the driver for mCHP appliance technical requirements. Because the United States has a very diverse set of climates and building energy needs, it is a formidable challenge for mCHP appliance developers. mCHP appliances must attain flexibility to address the needs of various market segments considering the following market characteristics: climate zone, age of home, location, premium power, and building type.

Different market segments require very different energy needs. It is important to clearly define these needs because they will drive the development of the mCHP technology.

Climate Zone

The United States represents a very diverse set of climate zones: wet in the northwest, dry in the southwest, hot and humid in the southeast and every possible combination of temperature and weather across the nation. Each of the various climates demand different energy needs—heating, cooling, dehumidification, and electricity. These regions also have various fuels (natural gas, oil, solar, electricity) that dominate the home energy market. The South is an especially important region to look at as "sustained growth in housing in the South, where almost all new homes use central air conditioning, is an important component of the national trend….." (AEO)

U.S. Climate Zones



Source: Energy Information Administration, A Look at Residential Energy Consumption in 1997.

New vs. Retrofit

mCHP appliances are a new technology, but it does not limit the installation of the appliances to just newly constructed homes. mCHP appliances must be readily available and have retrofit capabilities to replace the traditional appliances in existing households. There has been a growing demand for emergency or back-up power in the residential sector—mCHP appliances are uniquely qualified to provide this power. It is important to recognize that most residential new construction will occur in the South, where cooling is the dominant energy end-use. mCHP developers need to interact with architects and builders in the design phase to successfully integrate mCHP appliances into the new home.

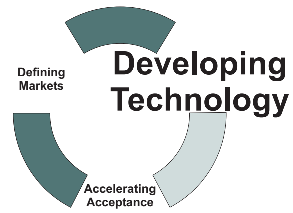
Location

Residences are located in different settings across America: rural, suburban, and urban. In a rural setting, a household might not have easy access to natural gas resources and depends more on portable fuels, such as propane, oil, or biofuels. In a remote setting, a power appliance is more likely to be isolated from the grid. Suburban and urban households have different priorities for their appliances. These households are usually on smaller lots located close to each other. It is imperative that the mCHP has a small footprint and low noise levels. In addition, most of the urban locations have air-quality problems and emissions from mCHP appliances must be negligible.

Premium Power

Residences in demand for reliable power will be an early adopter of mCHP appliances. Vacation homes, rural residences, and homes with medical equipment all require "premium power," which the grid has been unsuccessful in providing. Reliability is necessary to keep the homes heated and powered. Power appliances give the premium-power user the flexibility and assurance to generate their own on-site energy needs with less dependence on the current fuel and electric infrastructure.

Building Type



Finally, the type of building, whether it be single family home, townhome, or low-rise multi-family home, offers another market segment for expansion. These types face different size requirements for electrical and thermal output. The multi-family home market segment may drive the development of other prime mover technologies to meet the larger loads.

Developing Technology

mCHP can consist of very different prime mover technology: Rankine cycle, Stirling engine, fuel cell, IC engine, etc., but there are technologies that will improve mCHP appliance performance, regardless of the prime mover technology. Energy storage, cooling, controls, and integration technologies will advance mCHP appliances and help achieve the vision of the future.

Energy Storage

Energy storage will increase the attractiveness and value of mCHP appliances. Electrical and thermal storage capabilities can provide flexibility and reliability to the end user. During power outages, electrical storage provides the start-up power needed for the system. Electrical storage combined with power electronics can mitigate voltage sags to deliver high-quality power from mCHP appliances. Both thermal and electric storage will increase the overall performance of the appliance. The size, load, and other consumer requirements will determine the storage technology specifications. There is a need to evaluate current energy storage technologies for their suitability for mCHP applications. Manufacturers, homebuilders, and end users can work together to develop energy storage devices compatible with mCHP systems.

Cooling

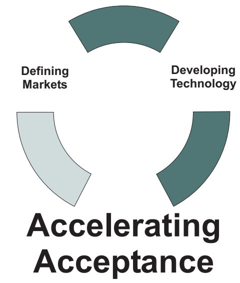
Electric air-conditioners are one of the biggest users of residential electricity. mCHP appliances can potentially supplement the cooling loads of residences. Cooling capabilities will broaden the current market of mCHP applications and can revolutionize the residential cooling industry. Heat, generated or recycled, drives the thermally activated cooling process. Identifying the specifications (cooling load, configuration, and the prime mover performance, including electric, parasitic, and thermal availability) determines which cooling technology fits the applications. Absorption, adsorption, desiccant, and energy recovery ventilators (ERV) technologies can provide direct cooling to a household. Developing lab prototypes would model the cost and performance of the cooling components. Residential-scale cooling modules could be integrated into the mCHP application. The effort will require teams of cooling component developers, system integrators, design for manufacturability (DFM) and cost experts, and a utility or commercialization partner.

Controls

Integrating controls and sensors with mCHP appliances will optimize the system's performance. The house would be able to communicate with the appliance and in return the mCHP appliance would produce the optimal combination of heat and power. The mCHP appliance would essentially be the heart of a "smart" household and the controls would be the brain. Control schemes could prioritize the loads, defer discretionary loads, and communicate with the grid to decide whether to buy or sell electricity at certain times. The virtual "Whole House Controller" needs the participation of a wide range of organizations to succeed. NAHB, national labs, utilities, A/E firms, code officials, and the European community can all provide valuable input on defining the system architecture and interoperability. Interfacing with the utilities is a must and developing a win-win proposition is critical in installing mCHP appliances. Developing relay protection into the control scheme of adopting IEEE 1547 will certainly make it easier for mCHP to interconnect with the grid.

Integration

Integrating the different components and subsystems into one packaged system deserves as much attention as the development of a single component. Successful integration allows mCHP to achieve benefits greater than the sum of its individual parts. Each residential packaged unit will be targeted for the various market segments. Field tests and demonstrations of the full system prototypes are needed to analyze the real-world performance of the mCHP appliance. The resulting performance analysis would be extrapolated to a broad range of applications. The field tests would identify further technology development needs and re-evaluation of the current market potential and performance targets. The integration would also determine the most cost-effective design. Industry-led teams need to focus on specific product development and inter-team committees would need to develop testing protocols.



Accelerating Acceptance

The successful development of mCHP appliance technologies does not ensure that they will be immediately accepted by the market. The institutional and business setting discourages energy-efficient devices and particularly on-site power generation technologies. It is important that mCHP appliances be ready for market acceptance and they are rated equally with one another as well as rated against traditional power, heating and cooling devices. To overcome the inertia by the utilities, builders, and homeowners in installing new highly-efficient energy devices, mCHP appliances need to perform financially and functionally above and beyond the best available space conditioning appliances. This must be shown through executing pilot programs of mCHP appliances, developing measurable benchmarks, and, finally, establishing standards for mCHP.

Pilot Programs

Executing pilot programs of 100's of mCHP units across the nation would showcase the performance of a mCHP. The pilots could use mCHP technologies best suited for the market and location. These prototypes need to be ready for "action." The user will have a chance to evaluate the mCHP appliance. This feedback is crucial in determining further needs. Vendors, homeowners, builders, code officials, and utilities need a chance to evaluate the readiness and applicability of the various mCHP units.

Measurable Benchmarks

Defining measurable benchmarks for efficiency, emissions, payback, reliability, and installed cost would help consumers understand the performance and costs of mCHP units. It will characterize efficiency so it is easy for everyone to understand. These benchmarks need to provide the baseline of technical performance specifications, so the units can be compared to one another, regardless of the prime mover technology.

Standards

The development of **standards** would help manufacturers develop and install the mCHP. The creation of a standardized set of metrics for the micro cooling, heating, and power systems need to be defined in collaboration with ASHRAE, ASME, NAHB, etc. to ensure fair assessments and credibility in the field of heating and cooling. Not only do performance standards need to be established, but standard interconnection rules, which are simple, safe, and "appliance oriented" are applied across the board by utilities.

PATHS FORWARD

Regardless of which prime mover technology is used for the mCHP system, the research, development, and deployment issues, as articulated by stakeholders at the mCHP workshop and described in this document, are the same. Technology development will be driven by specific customer requirements.

Implementation of this Roadmap, and development and deployment of mCHP appliances, depends on a coordinated effort among private industry, research institutions, and governmental agencies. The mCHP RD&D program will build upon other efforts that address similar issues, such as the *National CHP Initiative* and the *Building America Program*. Creation of a central focus for mCHP, such as a program or organization within or outside of government, similar to these other efforts, organization will help advocate for, and coordinate activities of, combined heat and power in residential buildings.

What is the Building America Program?

It is a private/public partnership that provides energy solutions for production housing. The Building America Program combines the knowledge and resources of industry leaders with the U.S. DOE's technical capabilities to act as a catalyst for change in the home building industry.

A key element of the future success for mCHP is utility participation. The benefits of aggregated mCHP appliances to utilities, both electric and gas, must be clearly articulated and embraced by them. At the same time, realistic concerns of utility stakeholders must be addressed.

This is the first version of the *Micro-CHP Technologies Roadmap*. It is an evolving document and therefore is expected to be amended over time. Eventual success will require new and revised strategies to achieve vision and specific actions described in this document.

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