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Nirvana Energy Systems – Thermoacoustics Micro Combined Heat and Power Generation Assessment

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ABSTRACT

As utility distribution systems evolve, many emergent technologies are targeting distributed generation roles. A subset of these technologies includes fossil-fueled generation aimed at residential-sized or "micro" combined heat and power (MicroCHP) applications. Within this subset, several technologies are apparent and are generally sized at less than 10 kilowatts electric (kWe) output. These technologies include fuel cells, internal combustion engines, nano turbines, solid-state devices, and thermoacoustic engines. This report describes a thermoacoustic technology and a specific product being developed by Nirvana Energy Systems. The report analyzes the technology, its history, relevant operating principles, and applications as well as technology development challenges and projected economics. This report further analyzes Nirvana's offering in this context and assesses its technology readiness level as well as specific challenges facing the offering.

Keywords
Cogeneration
Distributed energy resource
Distributed generation
MicroCHP
Thermoacoustic engine

EXECUTIVE SUMMARY

Nirvana Energy Systems is developing Power Stick, a thermoacoustic combined heat and power (CHP) device, which is targeted for residential applications. Thermoacoustic devices move heat based on the production or absorption of sound power. This technology operates by passing sound waves generated in a tube via a speaker or acoustic transducer, over a heat exchanger in the tube. This heat exchanger, or stack, is then coupled with external heat sources and sinks, and it can be used to supply heat and electric power. With minimal moving parts to its advantage, however, challenges are apparent when applying this technology to a residential market, namely the cost, efficiency, and attendant codes needed to allow broad placement in the market. The projected levelized cost of electricity (LCOE) of these units currently far exceeds the LCOE of alternatives and normal grid electricity because of high capital costs, in the case of residential applications (LCOE analysis for larger commercial and industrial markets shows applications closer to parity with grid cost, based on future projections– these markets will be analyzed in future efforts). This report analyzes the operating principles of thermoacoustic engines, the technology and market challenges, and further analyzes Nirvana's technology in this context and in terms of technology readiness.

The Nirvana technology faces numerous market and technical challenges, which stem from the high cost of equipment and labor. Advanced Research Projects Agency - Energy (ARPA-E) and previous Electric Power Research Institute (EPRI) studies show that a target cost of US $3000 per kilowatts electric (kWe) is necessary for parity to competing sources of energy. With a present cost target of $6000–$7000/kWe, it would appear that Nirvana faces a significant cost-reduction effort before a strong value proposition becomes possible. Future cost targets for Nirvana, however, are reported to be much lower and the approach to market may tune to a larger system – making the value proposition potentially more approachable.

Although the potential market is seemingly large, with about 70 million households being served with natural gas in the United States, only a small subset of these households have the combination of heat and electricity profiles that overlap and, therefore, could take advantage of the CHP heat production. In addition, residential mechanical and plumbing codes may need to be revised to accommodate such systems. MicroCHP and other distributed energy resources (DERs) may become more attractive with lowered costs as a result of high-volume manufacturing, advances in technology, and adoption of sophisticated controls that can operate these distributed resources based on inputs that reflect broader constraints in the overall grid. In addition, changes in pricing for electricity at the residential meter may affect the value proposition of MicroCHP units.

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1
INTRODUCTION

Nirvana Energy Systems, located in Portola Valley, California, reports producing a "breakthrough home energy system" based on thermoacoustic technology that "generates electricity and heat from clean natural gas for less than what most pay for utility power."[1] The company has presented findings to certain parties under nondisclosure agreements (NDAs), but it is presently considered in "stealth mode" and, therefore, is not generally releasing information beyond what is necessary to describe the technology to potential partners or investors.

[1] Nirvana website: http://www.nirvana-es.com/.

2 THERMOACOUSTICS PRINCIPLES OF OPERATION

Thermoacoustic devices move heat based on the production or absorption of sound power. They operate by passing sound waves generated in a tube, via a speaker or acoustic transducer, over a heat exchanger within the tube. This heat exchanger, or stack, is then coupled with external heat sources and sinks (see Figure 2-1). The devices can operate in two modes: 1) as an acoustic refrigerator by using an energy source to generate sound waves and hence move energy via the heat exchanger from a heat source to a heat sink and 2) as an acoustic engine (reversing the refrigeration process) by using heat to amplify sound waves that in turn cause the gas in the tube to do work on its environment; the heat exchanger's temperature difference creates a heat source for an external process.

Figure 2-1 shows a tube that is filled with gas that passes back and forth through a stack, or heat exchanger, which is typically made of a semiporous material with many channels that gas flows through in both directions. For a refrigeration effect, a loudspeaker or similar energy-to-sound transducer is used to generate sound waves. An induced temperature gradient or difference between the two sides of the stack allows gas passing in one direction to be compressed and therefore heated, and as the direction is reversed, the gas expands and cools. The gas releases heat to one side of the stack and absorbs heat from the other as it travels back and forth through the tube. This mode then moves heat from the cold side to the warm side of the stack, creating a refrigeration effect. For a thermoacoustic engine, such as Nirvana represents, a larger temperature differential is induced, and the sound waves are amplified by expansion and contraction of the gas as it flows through the stack, creating sound energy from heat. The sound energy is converted to electrical energy through either piezo-electric transducers or, more commonly, a linear alternator.

By moving heat through this process, work is performed, and a variety of refrigeration, cryogenic, or energy generation processes can be manifested. A key feature of these devices is fewer moving parts and the associated potential for lowered manufacturing and operations and maintenance (O&M) costs and high reliability.

A critical element related to adoption of thermoacoustic engines lies in the efficiency of not only the heat transfer process induced by sound waves within the tube but, perhaps more important, the efficiency of the overall processes of generating electricity as well as performing useful work with the heat transferred to and from the tube. The cost, duration and viability of the heat sink will also factor in heavily to any economic analysis.

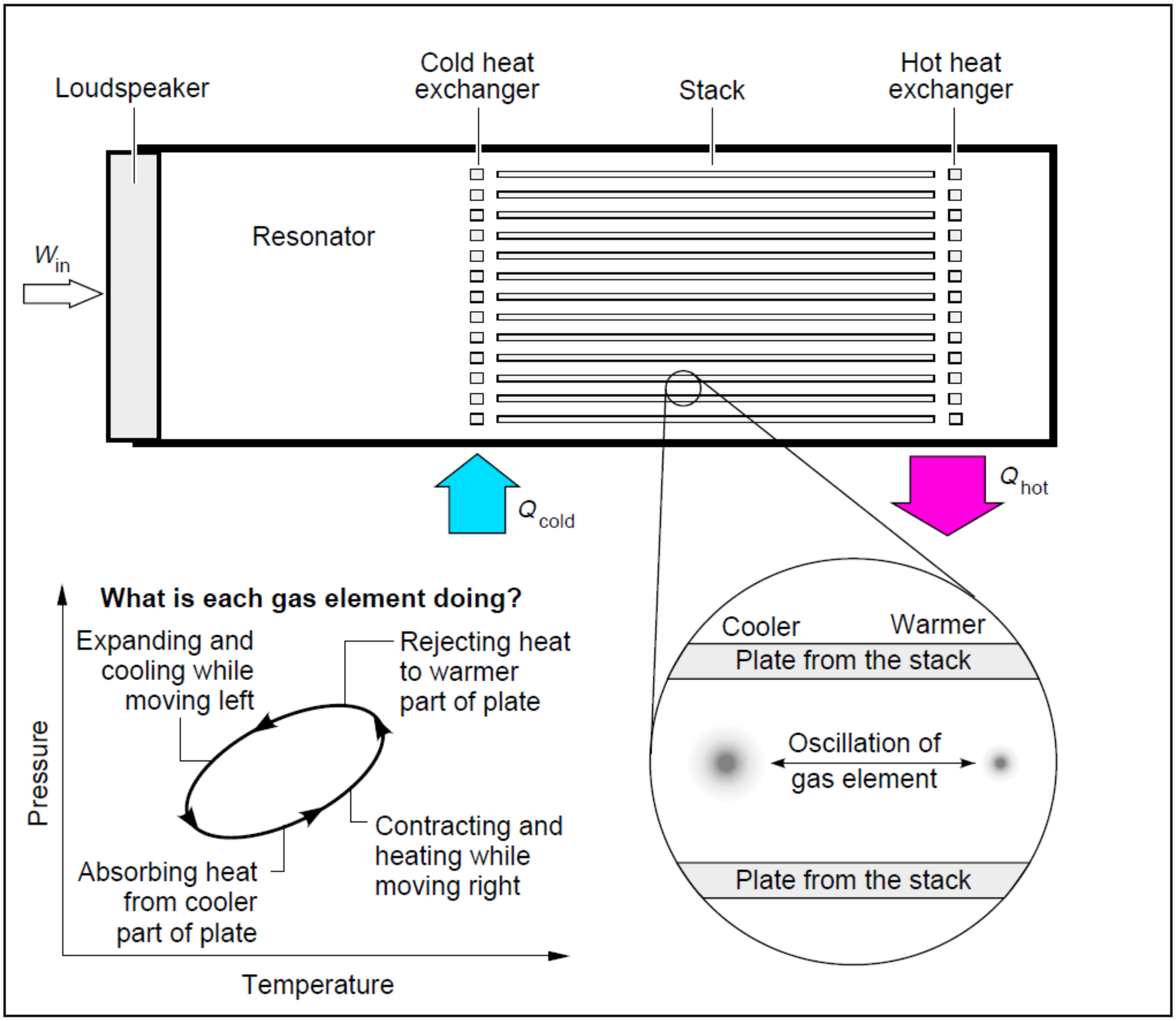

Figure 2-1
Basic schematic for a standing wave thermoacoustic refrigerator
Source: Los Alamos National Laboratory

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HISTORY AND BACKGROUND

Thermoacoustic engines have been studied for the past century and a half, with early studies in the 1850s looking at sound produced by application of heat to one end of a tube. Further developments extracted energy in the form of work through these apparatus, basically producing work in the form of sound by applying heat. More recent refinements in the technology allowed heat to be pumped from source to sink by applying heat exchangers, and embodiments of this appeared as pulsed tube refrigerators.[2]

No real commercial offerings have been developed, and most systems operate in a laboratory environment. Prototype thermoacoustic refrigerators have been developed by Los Alamos National Labs (LANL) and others, and an adaptation of thermoacoustics has been demonstrated in a natural gas liquefaction (cryogenic) commercial-scale application (by a company that has since gone out of business).[3] [4] Key patents for an intrinsically irreversible heat engine and for a heat driven acoustic cooling engine having no moving parts from LANL stem from the mid-1980s, and further patents were issued to NASA Glenn Research Center.[5] Commercialization, however, has been hindered by inherently low efficiencies, especially when contrasted to competing technologies.

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[2] [1]U.S. Patent 4489553 Whetly, Swift, Migliori 1984.

[3] S. Garrett and S. Backhaus. "The Power of Sound." *The American Scientist,* November 2000: 88:561.doi:10.1511/2000.6.516.

[4] Telephone discussion with Dr. Albert Migliori, Los Alamos National Labs (LANL) 12/15/15.

[5] U.S. Patent 4489553 Whetly, Swift, Migliori 1984 and U.S. Patent 4858441 Whetly, Swift, Migliori, Holler 1989.

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TECHNOLOGY AND KEY INNOVATIONS

Little is apparent in the available product literature about the Nirvana Power Stick technology other than some statements that it is “built using a combination of Thermal Acoustics and Stirling Technology”[6] and has achieved a “key breakthrough in cost … by teaming with Xerox PARC in Palo Alto, and NASA Glenn Research Center in Cleveland Ohio.”[7]

Thermodynamics

Many thermoacoustic approaches must operate at high temperatures in order to achieve efficiencies approaching 30% or greater. Nirvana claims, in response to an EPRI questionnaire (see Appendix A), an electrical efficiency of 25% (high heating value [HHV]), and overall efficiency of ~93% HHV and a hot water output temperature of 50°C. Nirvana also states that a 40% electrical efficiency is likely achievable.

As with all devices of this type, efficiencies face a Carnot limit, that is, producing work from heat is limited by the temperatures and pressures involved in the process: to achieve higher efficiencies, the device must operate at higher temperatures. Previous attempts achieved a purported 10% efficiency at “relatively low heat” with targets of 20–30% at 50°C, but the parameters used in the efficiency calculation are not clear.[8]

This points to an operating temperature in the thermoacoustic tube of around 700°C in order to achieve close to 30% efficiency. The tubes typically operate with helium as a working gas in a 30 bar (425 psi) environment.[9]

Operating in these temperature and pressure regimes as well as targeting 30% efficiency requires sophisticated placement of multiple heat recovery devices that can preheat incoming air and minimize exhaust gas temperatures, all while balancing emissions (especially NOx and CO). The exhaust gas temperatures must align with residential building and fuel codes, requiring a potential substantial reduction in exhaust gases from 700°C to approximately 150°C or less.

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[6] https://www.linkedin.com/in/nirvana-energy-systems-inc-04b51287.

[7] http://nirvana-es.com/news_pr120913.html.

[8] T. Hamilton, “An Engine that Harnesses Sound Waves.” *MIT Technology Review*, February 4, 2011: https://www.technologyreview.com/s/422611/an-engine-that-harnesses-sound-waves/.

[9] Telephone discussion with Dr. Greg Swift of Los Alamos National Labs 12/16/15.

One diagram on Nirvana's website appears to show a multi-stacked thermoacoustic tube with encircling process lines wrapping around the tube in a helical fashion. The equipment or parts associated with a thermoacoustic engine are evident in an apparently applicable patent from NASA Glenn Research Center (which has apparently licensed the technology to Nirvana, although the recently published patent does not list this assignment) promote a thermoacoustic device with multiple regenerators and heat exchangers.[10] The following summarizes the claims in this patent:

> In an aspect of the innovation the disclosed thermoacoustic engine overcomes … disadvantages by reshaping the conventional thermoacoustic engines from a toroidal shape into a straight co-linear arrangement and recognizing that an acoustical resonance can be achieved using electronic components instead of mechanical inertance and compliance tubes. The acoustical wave that would normally travel around a toroid instead travels in a straight planar wave. Ordinarily the wave would reflect back upon reaching the end and would form a standing wave. Instead, a transducer receives the acoustical wave and electrical components modulate the signal and a second transducer on the diametrically opposed side reintroduces the acoustic wave with the correct phasing to achieve amplification and resonance. The acoustic wave is allowed to travel in a toroidal shape as before, but part of its path if handled electrically. This eliminates many of the parts and losses occurring in the current state of the art heat engines.
>
> In another aspect of the innovation the innovation [sic], a thermoacoustic engine and/or cooler is provided and includes an elongated tubular body, multiple regenerators disposed within the body, multiple heat exchangers disposed within the body, where at least one heat exchanger is disposed adjacent to each of the multiple regenerators, multiple transducers axially disposed at each end of the body, and an acoustic wave source generating acoustic waves. At least one of the acoustic waves is amplified by one of the regenerators and at least another acoustic wave is amplified by a second one of regenerators.
>
> In yet another aspect of the innovation the innovation, a thermoacoustic engine is provided that includes an elongated tubular body, a first regenerator disposed within the body generating a first acoustic wave, a second regenerator disposed within the body generating a second acoustic wave, a first transducer axially disposed at one end of the body, and a second transducer axially disposed at an opposite end of the body. The first acoustic wave and the second acoustic wave are superimposed to form a higher amplitude acoustic wave.[11]

Electricity Generation

Although further input from Nirvana, through the questionnaire, reveals that there are moving parts associated with the system, they do not appear to be associated with the thermally active parts. Nirvana states, "no hot moving parts as opposed to traditional piston or Sterling [sic] engines that have moving parts in the hot zone of the engine." It would appear that Nirvana is pursuing an adoption of a modified Stirling cycle by using a free piston approach in which the thermoacoustic cycle induces motion in a piston at one end of the tube—the cooler end.

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[10] US Patent 9,163,581, Dyson, Bruder, 2015.

[11] Ibid.

Hot Water Generation

The controls to tap heat from the exhaust to provide hot water would necessarily tie the CHP system to the hot water delivery system, potentially involving a three-way mixing valve in order to allow for redundancy if the CHP system is inoperable. If the system is intended to heat water for domestic use and for a hydronic heating system, the controls may be required to generate hot water at separate temperatures as heating systems tend to operate above and hot water below 60°C (140°F).

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DESIGN AND CONSTRUCTION

Appendix A includes the following question:

5. What are the overall performance characteristics? Please address:

The responses from Nirvana are the following:

a. Electrical Output (kilowatts electric) [kWe])
   ANSWER: Initially 1 kWe up to 40 kWe at this time

b. Thermal Output (kWth)
   ANSWER: 2.5 kW thermal

c. Electrical Efficiency (%LHV)
   ANSWER: ~25% HHV

d. Heat Quality – output temperature of working fluid in CHP process
   ANSWER: 50°C

e. CHP Fuel Use Efficiency (%, HHV if condensing)
   ANSWER: ~93%

f. Annual Savings over "Grid/Furnace or Boiler" Case
   ANSWER: TBD

g. CHP Thermal conversion efficiency
   ANSWER: not identified

h. Projected operating hours/year
   ANSWER: CF of >95%

The Nirvana website also states "producing 2-4 KWe and 15-35 KWh." It is not clear what the kWh figures represent, given the information available.

Footprint

Nirvana's website claims system can "be placed in the kitchen, cellar or attic. It is small in size, less than 32" in length, and 8-10" in diameter … The TAPS unit weighs less than 60 pounds" and that the unit is "Dishwasher size."[12]

[12] Nirvana website.

Components

Nirvana states in the questionnaire, regarding use of off-the-shelf equipment, that “all key components are proprietary NES design.” Given the nature of the system described in the aforementioned patent and discussions with technology experts from Los Alamos National Labs, the system could potentially require the following:

- A pressure vessel, potentially rated at >28 bar (>400 psi) containing the thermoacoustic engine
- Linear alternator
- Switchgear and inverter rated at UL 1741 (Note: Website claims the unit works during power outages, thereby superseding UL 1741.)
- Mixing valve and controls for introducing heat to the separate hot water system(s)
- Gas train, controls, and safety devices
- Condensate capture and draining system if flue gases are cooled to the extent condensation occurs (which, by residential code, requires drainage into a sanitary sewer system)

It is not clear which of these components would be included in Nirvana’s design nor is it clear whether all of the components would be contained in the footprint described here.

Calendar Durability and Maintenance

Nirvana claims a 15+ year life in response to Question 25 of the questionnaire and on the website. It also claims in response to Question 2 that there are “no hot moving parts,” as mentioned before, which leads to the indication of a Stirling-type process in which the moving part or sliding piston is in the cold end of the Stirling process.

Safety Claims

Nirvana claims in response to Question 3, “Testing is underway system has been designed to meet all boiler, UL, agency requirements for safety and reliability.”

Environmental Claims

No claims specific of emissions levels were solicited in the questionnaire nor do any appear on the website. In response to Question 1, Nirvana states: “The unit is designed for…low emission [sic] by completely burning the exhaust gas meeting strict CARB requirements.” Many complexities arise in a combustion process when targeting low NOx emissions. As temperatures are raised in an attempt to improve efficiencies, NOx emissions typically increase; conversely, lowering temperatures lowers NOx emissions but raises CO emissions. Many of the apparent components in the Dyson patent may be placed into the system to help achieve low emissions.

Cost and Commercialization

Nirvana’s cost projections are US $6000–$7000 installed for 1 kWe unit.

6 EPRI ASSESSMENT OF REPORTED PERFORMANCE

Technical Maturity and Technology Readiness Level

Although thermoacoustic generators have been demonstrated in laboratory environments for decades, no commercial products are evident, and the company associated with the only commercial-scale demonstration has not survived. Low efficiency has been touted as the chief hurdle to commercialization.[13] Nirvana claims that it will have testing units available in 2016 and that it has achieved 25% electrical and over 90% overall efficiency. It is not clear how or where these tests were conducted and under what test protocol.

The apparent adaptations that Nirvana and similar technology companies are taking within the thermoacoustic space lead to more components than earlier lab test devices, including numerous heat exchangers, and require some moving parts (though not typically in the higher temperature part of the system) for electricity generation. These components add cost and complexity, and no long-term reliability figures for systems containing these parts are available. All material on its website is copyrighted in 2013, when various press stories first emerged and Nirvana stated, "We are currently in an extended testing period."[14]

With the information available, it appears that Nirvana's technology is at a technology readiness level (TRL) of 3 to 4 (see Table 6-1). Nirvana states, "Proof of concept has been demonstrated, cost reduction ongoing and optimization for DOM underway." Movement up the TRL scale could be manifested with more detail on any formalized test results and information on individual components, system/subsystem prototype demonstration in a relevant environment, and complete system prototype demonstration in an operational environment.

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[13] Discussion with Dr. A Migliori, Dr. G. Swift, LANL.

[14] W. Pentland. "Silicon Valley Start-Up Company Powers Homes With Sound Waves." *Forbes.com*, December 10, 2013. http://www.forbes.com/sites/williampentland/2013/12/10/silicon-valley-start-up-company-powers-homes-with-sound-waves/.

Table 6-1
Technology readiness level assessment

Technology Readiness Level	Description	Supporting Information	EPRI Discussion per Nirvana
1. Basic principles observed and reported	TRL 1 is the lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.	Published research that identifies the principles that underlie this technology. References to who, where, when.	Apparent key patent (assigned to NASA Glenn) received October 2015. Numerous papers from LANL et al., but not on free-piston Stirling.
2. Technology concept and/or application formulated	At TRL 2, invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.	Publications or other references that outline the application being considered and that provide analysis to support the concept.	Basic technology demonstrated in numerous labs (including LANL and NASA).
3. Analytical and experimental critical function and/or characteristic proof of concept	At TRL 3, active R&D, is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed.	No publicly available test results, only minimal three-years-old marketing material. Test results displayed? No. Independent lab testing under a uniform protocol? Not apparent. Has system changed since inception? Major components? None apparent.
4. Component and/or breadboard validation in laboratory environment	At TRL 4, basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.	System concepts that have been considered and results from testing laboratory-scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals.	Independent lab testing under a uniform protocol? Not apparent.

Table 6-1 (continued)
Technology readiness level assessment

Technology Readiness Level	Description	Supporting Information	EPRI Discussion per Nirvana
5. Component and/or breadboard validation in relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include “high-fidelity” laboratory integration of components.	Results from testing laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the “relevant environment” differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals?	Path to safety certification clear and recognized
6. System/ subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology’s demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?	
7. System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space).	Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?	

Table 6-1 (continued)
Technology readiness level assessment

Technology Readiness Level	Description	Supporting Information	EPRI Discussion per Nirvana
8. Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design?	
9. Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.	OT&E (operational test and evaluation) reports.	

Scale-Up Challenges

Nirvana states that their cost projections of \$6000–\$7000 installed for 1 kWe are “based on detailed BOM buildups in 10,000 unit quantities.” One of the key components facing a scale-up challenge could be the linear alternator, which would need to see a manufacturing base of 100,000 in order to become equivalent in cost to rotary alternators.[15]

Technical Risks

Despite the significant challenges faced by the technology, there is nothing to suggest that the approach is not scientifically possible. The stated 25% electrical efficiency claim is in line with similar past efforts but requires a high-temperature operating environment. This in turn implies a technical risk associated with placement of such a device in a residential setting and accommodating a product of this nature by applicable codes. It remains to be seen whether Nirvana can achieve projected technical and cost improvements.

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[15] Conversation with Dr. Greg Swift, LANL.

Market Risks

Although the target cost of the Nirvana system may be similar to that of other MicroCHP entrants, it is still quite difficult to find a market for products in this price range, given the challenges that the market will place on MicroCHP products. These include the following:

- Lack of a long-duration heat sink typical to a residence: Aside from heating in a cold climate, with a boiler, there is relatively little need for a heat source for hot water in a typical house during nonwinter hours. In addition, the need for hot water does not necessarily coincide with the need for electricity because most of the annual consumption of electricity is during hotter/air-conditioning periods of the year. As such, the system will operate at its target system efficiency for only a few hours per year on average. The rest of the time, the system will operate at much lower efficiencies, and the savings will diminish rapidly.
- ARPA-E—through the GENerators for Small Electrical and Thermal Systems (GENSETS) program, which is funding MicroCHP development—has recognized the difficulties of these market challenges and has set the following goals for recent GENSETS awardees (of which Nirvana is not one):[16]
  - $3000/kW
  - Efficiency >40%
  - 0.07 lb/MW-hr nitrogen oxide (NOx)
  - 0.10 lb/MW-hr carbon monoxide (CO)
  - 0.02 lb/MW-hr volatile organic compounds (VOCs)
- Residential code compliance: Placement of a new device with potentially high-pressure and high-temperature operating components may present challenges to code compliance, especially because codes enforced locally may be adaptations of uniform codes.
- Market maturity: MicroCHP systems are not common in the United States, but these small systems have gained market penetration in some European and Asian countries.[17]

Levelized Cost of Electricity Calculation

EPRI conducted research in 2009 that analyzed MicroCHP technologies.[18] The study analyzed levelized costs of electricity (LCOEs) for five MicroCHP technologies including solid oxide fuel cell (SOFC), proton exchange membrane (PEMFC), internal combustion engine (ICE), organic Rankine cycle (ORC) heat engines, and Stirling engines. In calculating the LCOE, a conservative scenario was developed with cost assumptions listed in Table 6-2. It was also assumed that aggressive cost reductions would take place, lowering the projected cost substantially, shown in Table 6-3.

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[16] GENSETS Program Overview. http://arpa-e.energy.gov/sites/default/files/documents/files/GENSETS_ProgramOverview.pdf.

[17] *Combined Heat and Power Technologies and Market Size.* EPRI, Palo Alto, CA: 2015. TR 3002006086.

[18] *Micro-CHP Technology Assessment and Benchmarking.* EPRI, Palo Alto, CA: TR 1018977.

Table 6-2
Estimates for levelized costs of electricity for several MicroCHP technologies, conservative scenario

Conservative Model	Internal Combustion Engine	Stirling	Organic Rankine Cycle	Proton Exchange Membrane	Solid Oxide Fuel Cell
Electrical output (kWe)	1.2	1.2	1	1	0.7
Thermal output (kWth)	2.8	6	8	4.7	1.3
Electrical efficiency, LHV (%)	23	19	10	32	45
2009					
Capital cost ($)	20,000			34,000	
Installation cost ($)	5,000			5,000	
Maintenance costs ($)	250			300	
Installed cost/kW ($)	21,667			39,000	
2012					
Capital cost ($)	18,000	18,000	15,000	30,000	34,000
Installation cost ($)	5,000	5,000	5,000	5,000	5,000
Maintenance costs ($)	250	150	150	300	300
Installed cost/kW ($)	20,000	20,000	20,000	35,000	53,571
2015					
Capital cost ($)	15,000	8,000	7,000	10,000	12,000
Installation cost ($)	3,000	2,500	2,500	3,000	3,000
Maintenance costs ($)	200	100	100	250	250
Installed cost/kW ($)	15,500	9,167	9,500	13,000	20,143

Table 6-3
Estimates for levelized costs of electricity for several MicroCHP technologies, aggressive cost reductions scenario

Aggressive Model	Stirling Engine	Stirling Engine Providing Water Heating	Solid Oxide Fuel Cell 2 kWe with Water Heater 7000 hr/yr	Solid Oxide Fuel Cell 3 kWe Power Only	Internal Combustion Engine 5 kWe with Water Heating	Stirling Engine 3 kWe Water Heating
Capital cost ($)	6,500	6,500	6,500	7,000	22,000	10,000
Installation cost ($)	1,500	1,500	1,500	1,000	3,000	2,500
Installed cost/kW ($)			4,000	2,667	5,000	4,167

Other assumptions used in the analysis were the following:

- Product characteristics: The capital costs assumed that MicroCHP units (capacities between 0.7 and 1.2 kWe) are adapted to the North American market.
- For the “displaced” furnace, total installation costs are $6000/kWe, and maintenance costs are $50 per year.
- Operation: In the conservative case, MicroCHP system operates for only 4000 hours per year, a typical heating season in Northeastern United States, and all heat is used when producing electricity.
- Comparison was made with a furnace with 95% overall efficiency.
- Energy prices and electricity export: Net metering was assumed with the same import/export costs of $0.15/kWh for 2009, 2012, and 2015.
- A gas price of $12/MMBtu was assumed for 2009, 2012, and 2015.
- Discount rates: Assumed discount rate of 15%.
- The target aggressive costs for capital, installation, and operation were derived by comparing typical high-efficiency gas furnace replacement and operating costs.

Results of the model showed that only through aggressive cost reductions were any of the technologies shown in Figure 6-1 able to approach the LCOE associated with grid-sourced electricity. Although the natural gas price used is greater than current prices, other inputs should be in range with current values. Nevertheless, the results validate the ARPA-E targets of $3000/kWe installed cost for MicroCHP technologies.

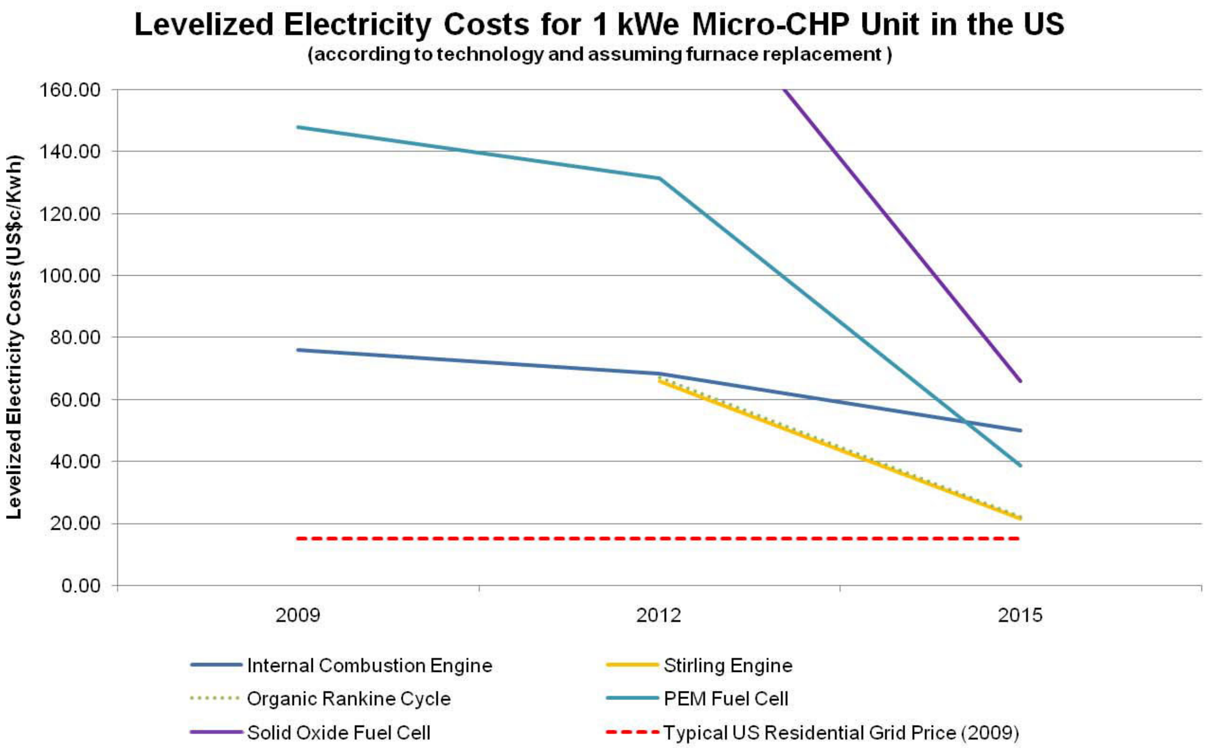

Figure 6-1
Levelized electricity costs

7 CONCLUSIONS

The Nirvana technology faces numerous market and technical challenges. The market challenges stem from the high cost of equipment and labor. ARPA-E and previous EPRI studies show that a target cost of $3000/kWe is necessary for parity to competing sources of energy. With a present cost target of $6000–$7000/kWe, it would appear that Nirvana faces a significant cost-reduction effort before a strong value proposition becomes possible.

Although the potential market seems large, with about 70 million households being served with natural gas in the United States, only a small subset will 1) have the combination of heat and electricity profiles that overlap and 2) take advantage of the CHP heat production. If the Nirvana system were operated in a mode that prioritizes electricity production, the system efficiency would probably stay at less than 30% during most operating hours because of the variance between the typical residential electricity load profile and the thermal load profile. If the system were operated in a mode that prioritizes thermal production, the system efficiency may reach the 90% level only when there is a corresponding need for all of the electricity output or if electricity can be exported to the grid. The difficulty of making the system operate at optimal efficiencies is a market challenge faced by most CHP systems.

Even though laboratory tests have long validated the thermodynamics principles involved with thermoacoustics, in order to attain high efficiencies, the system must operate at higher temperatures and pressures than most household appliances. Local codes, based on international codes or adaptations thereof, may need to be revised to accommodate such systems. In addition, because of the relatively early commercial status, the marketplace and specifically code officials are likely to seek substantial reliability and safety data for the system.

EPRI assesses the technology readiness level for the Nirvana system at 3 to 4 with some uncertainty based on lack of information available. This indicates that the technology is somewhere between the "Analytical and experimental critical function and/or characteristic proof of concept" and "Component and/or breadboard validation in laboratory environment" stages. This TRL can be increased through testing or release of test data that demonstrate how the system operates at the subsystem level and at the complete product level, particularly with respect to power generation, thermal generation, efficiency, and electrical system compatibility.

MicroCHP and other DERs may become more attractive with lowered costs resulting from high-volume manufacturing, advances in technology, and adoption of sophisticated controls that can operate these distributed resources based on inputs that accomodate broader constraints in the overall grid. In addition, advances in pricing for electricity at the residential meter may affect the value proposition of MicroCHP units. A broader market potential, accommodating commercial and industrial applications, is apparent for larger CHP systems. These systems could potentially allow for the added electrical operation flexibility needed from distributed resources.

A
SMALL NATURAL GAS DISTRIBUTED GENERATION QUESTIONNAIRE

Company Name: Nirvana

Product Name: Power Stick

Overview

1. How does the system work? Please provide a summary description with diagrams showing an energy balance within the boundaries of a typical, installed system. Also show individual component energy inputs/outputs.
   ANSWER: The TAPS system is a thermoacoustical engine that generates a sound wave at one end of the tube, amplifies the wave by added and extracting heat at specific points in the wave and captures the added energy at the opposite end of the tube. Any combustible fuel can be used, natural gas has been the fuel we have been working with, but burner can be customized for any type of fuel. Process fluid, water usually, is used to extract heat so high quality heated water is a byproduct, a typical CHP cycle. The unit is designed for ultra high efficiency, extracting heat from exhaust gas to preheat combustion air, and low emission by completely burning the exhaust gas meeting strict CARB requirements.

2. What are the advantages of the design relative to other vendors? Identify all novel aspects of the technology, particularly: performance, durability, costs (capital and operating), and safety/reliability issues.
   ANSWER: The primary advantages of the TAPS system are: high electrical efficiency of 25% to date with opportunity to reach 40%, overall efficiency of ~93% HHV, low cost estimated at $6000-$7000 installed for 1 kWe TAPS unit with plans for 20 kWe installed for $40K, and high reliability due to no hot moving parts as opposed to traditional piston or Sterling engines that have moving parts in the hot zone of the engine. The system is being designed for a minimum 15 year life, with no maintenance needed under normal conditions, UL and appropriate agency certifications.

3. How have reliability and safety concerns been addressed –especially for residential and commercial applications?
   ANSWER: Testing is underway system has been designed to meet all boiler, UL, agency requirements for safety and reliability.

4. What’s the development status of the technology?
   ANSWER:
5. What are the overall performance characteristics? Please address:
   a. Electrical Output (kWe)
      ANSWER: 1 kWe
   b. Thermal Output (kWth)
      ANSWER: 2.5 kW thermal
   c. Electrical Efficiency (%LHV)
      ANSWER: ~25% HHV
   d. Heat Quality – output temperature of working fluid in CHP process
      ANSWER: 50°C
   e. CHP Fuel Use Efficiency (%, HHV if condensing)
      ANSWER: ~93%
   f. Annual Savings over “Grid/Furnace or Boiler” Case
      ANSWER: TBD
   g. CHP Thermal conversion efficiency
      ANSWER: ????
   h. Projected operating hours/year
      ANSWER: CF of >95%
6. Does the design use commercial off-the-shelf equipment, or what equipment is under development?
   ANSWER: All key components are proprietary NES design, covered by multiple NES patent submittals

Status and Realized Performance

1. What is the realized performance? Are there any lab-scale or pilot plant test results available? In case there are test results, what is the difference between realized versus expected performance?
   ANSWER: test results are available under NDA and have been shared with key partners
2. Please describe any prototype and pilot scale efforts.
   ANSWER: Development is continuing with the 9 prototype under testing currently. It is anticipated that units for customer testing will be available in 2016. Proof of concept has been demonstrated, cost reduction ongoing and optimization for DOM underway.

Costs

1. What are the expected total installed costs? How have these been estimated? Note: Please provide justification of expected costs, and level of certainty with the various cost predictions.
   ANSWER: Cost estimates are based on detailed BOM buildups in 10,000 unit quantities, typical installation comparisons for comparable products like water heaters, boilers and solar systems
2. What economies of scale (cost reductions) are expected for a full scale systems? What is the projected capital cost for producing the initial commercial size unit? How do you expect costs to come down over time as production is ramped up to higher production levels? What are the costs for nth-of-a-kind mature systems? How many units/year need to be produced to get down to that nth-of-a-kind capital cost?
   ANSWER: Available under NDA
3. What is the distribution of various capex items for the complete mature system – major cost items? Including such things as BOP procurement, construction and installation costs, start up, engineering, installation cost, etc.
4. Who do you expect to install – licensed mechanical firms?
   ANSWER: Licensed General contractors, Solar installers, plumbers
5. Expected equipment installation time?
   ANSWER: Approx 4 hours

Economics

1. What is the business model for the unit?
   ANSWER: Selling through partners such as utilities, solar installers, ESCOs
2. What natural gas price assumptions are used for future economic projections?
   ANSWER: DOE numbers where applicable

Design

1. Sizing considerations – module sizes?
   ANSWER: Initially 1 kWe up to 40 kWe at this time
2. Footprint and site layout?
   ANSWER: 1 kWe approximately size of residential dishwasher
3. Describe challenges (technical, financial and performance) that you expect?
   - Describe/discuss any challenges in scaling up the product to the size required for commercial operation.
   - Describe/discuss any challenges in manufacturing the product at scale.
   - Describe/discuss challenges in deploying and operating the product in a real-world environment.

4. What gas infrastructure is needed?
   a. Gas pressure needed - Compression required?
      ANSWER: Standard residential pressure and volume
   b. Sensitivity to quality of gas (assumptions on LHV/HHV and heating value)
      ANSWER:
5. Describe the electrical system interface/inverter.
   ANSWER: On-board inverter to UL specifications

Operational Strategies

1. What are the expected operating hours per year?
   ANSWER: >95% CF
2. What heat sinks are assumed available? Water storage tank
   ANSWER: ~100 Gallons
3. What are the performance characteristics at part load?
   ANSWER: Ability to ramp up/down in a few cycles
4. What are the typical operating modes?
   ANSWER: 50%-100% power
5. Reliability expectations?
   ANSWER: 15+ years operating, 20 likely
6. Durability – extent of maintenance required – what is the expected life of critical components?
   ANSWER: 15+ years
7. Would your firm be owning and/or operating the systems?
   ANSWER: TBD
8. How will this system integrate to utility grid operations? What control strategies are envisioned to talk with a future grid with price signals?
   ANSWER:
9. Is stand-alone operation possible?
   ANSWER:
10. O&M expectations; fixed and variable?
    ANSWER:

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