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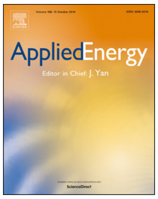

Techno-economic analysis of high-efficiency natural-gas generators for residential combined heat and power

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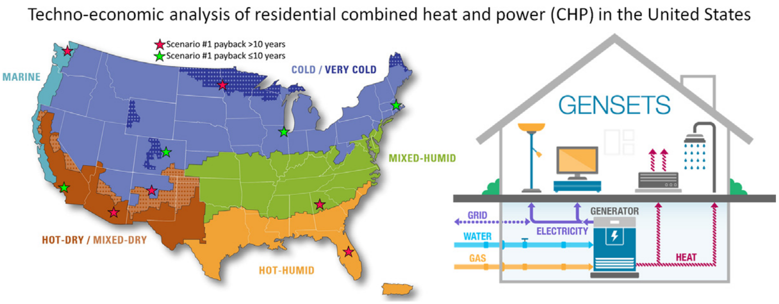
HIGHLIGHTS

- Energy consumption analysis of 10 US cities shows 1 kWe as good residential CHP size.
- Widespread CHP deployment in residences requires high efficiency low cost generators.
- Spark spread analysis shows Northeast U.S. and California as favorable deployment sites.
- Widespread CHP adoption will lead to large annual energy savings and CO_2 reduction.

GRAPHICAL ABSTRACT



Techno-economic analysis of residential combined heat and power (CHP) in the United States

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ABSTRACT

Residential combined heat and power (CHP) systems produce electricity onsite while utilizing waste heat to supplement home heating requirements, which can lead to significant reductions in CO_2 emissions and primary energy consumption. However, the current deployment of such CHP systems in the U.S. residential sector is extremely low primarily due to their high cost, short system life, and low system efficiency. Based on an analysis of average energy consumption of representative single-family homes in 10 U.S. cities across 7 different climate zones, it is concluded that there is no one-size-fits-all residential CHP system, but that a range of products are more likely to reflect consumer preferences. It is further identified via a systematic techno-economic analysis (TEA) that high-efficiency (e.g., 30–40% fuel to electricity), long-life (e.g., 15 years), low-cost (preferably less than U.S. $2,500 installed price), and low emissions are key requirements to enable widespread deployment of CHP systems in the U.S. residential sector. This article analyzes how the payback period would change for each city by varying nearly a dozen parameters and concludes with an evaluation on maximum market penetration based on a given set of parameters, and the resulting energy and emissions savings that can be practically achieved in some scenarios.

1. Introduction

In 2016, U.S. centralized power plants consumed around 37.5 quadrillion BTU (quads) of primary energy to generate 12.6 quads of electricity with an average electricity generation efficiency of 33.6% aggregated over all primary energy sources including fossil-fuels, solar-, nuclear-, hydro-, wind-, geothermal-, and biomass-power [1]. The other 66.4% of the primary energy (24.9 quads) was lost to the environment as heat. Due to the heavy fossil fuel mix of our current electricity generation, about 2 billion metric tons of CO_2 were emitted into the

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environment in 2014, which is about 38% of the total annual U.S. CO_2 emissions [2]. Combined heat and power (CHP) offers an alternative solution where a generator system located in a residence, commercial or industrial site, or a district consumes pipeline natural gas (or other fuel) to generate electricity onsite and further utilizes the waste heat for space or water heating and/or air-conditioning needs. This works well on a distributed level since more of the low-temperature heat can be used. Heat above about 80 °C is useful at large power plants because it can be used to make steam and thereby drives power turbines, while low-grade heat (less than about 80 °C) is much less useful and is dissipated into the atmosphere. However, at home, 60 °C heat is enough to provide heat to a water boiler or replace part of the heat a furnace needs to supply to the home. Thus, the combined efficiency of primary energy usage in a CHP scenario can be higher than 80%. Since about 38% of the electricity generated from all the centralized power plants is consumed by the residential sector, CHP implementation in this sector can have a huge impact on both primary energy savings and overall CO_2 emissions reduction [1].

However, adoption of small CHP systems in the U.S. has been hindered by the high price, low efficiency, and short lifetime of systems currently available on the market [3,4]. According to the Department of Energy (DOE) CHP database [5], less than 100 facilities (single family homes, multi-family homes, laundries, hotels, restaurants, hospitals, office buildings, etc.) have CHP units that are rated ≤ 10 kWe (electric) and most of these units are natural-gas-fueled reciprocating engines. Per 2009 statistics of the U.S. Energy Information Administration (EIA), roughly 70 million U.S. homes (61%) have piped-in natural gas and thus availability of long-lasting, low-cost CHP systems could lead to their widespread deployment as the natural gas infrastructure is already in place. To this end, the DOE Advanced Research Projects Agency-Energy (ARPA-E)[1] launched the GENSETS program in 2015 [6,7], which seeks to develop 1 kWe CHP generators that have high electrical efficiency ($\ge 40\%$ based on the lower heating value (LHV) of natural gas), long life (≥ 10 years), low cost ($\le \$3000$ system price without installation), and low emissions. GENSETS project teams are developing and testing advanced generators in three technology areas viz. Stirling engines, internal combustion engines (ICEs) and Brayton cycle engines that all offer the potential to meet these goals.

This article describes the techno-economic analysis (TEA) model and results of a systematic parametric study to determine which regions of the United States would benefit from the installation of small residential CHP systems. While the project teams in the GENSETS program and other researchers in the field are building specific systems with different approaches to meet the various technical targets, this model describes a generic system that consumes natural gas and air and produces electricity and heat at a specific efficiency, the full details of which are described in the Methods section below. This paper is an attempt to estimate the potential energy and cost savings of installing a 1 kWe CHP unit in a typical 2500 square-foot (sq. ft.) single-family residence in ten cities across various climate zones in the U.S. Fig. 1 shows the seven *Building America Climate Zones* [8] and the cities in each region that were selected for the analysis.

This TEA is agnostic of the specific generator technology or technologies that would eventually be installed, but there are a few classes that have a reasonable chance of meeting the target metrics. ICEs, Stirling engines, micro-turbines, micro-Rankine cycles, solid-state devices, and fuel cells all have the potential to reach 30–40% electrical efficiency and 80% total CHP efficiency in a 1 kWe device. However achieving those metrics at a price tag below U.S. $2500 total installed cost is a daunting challenge both from a technical and economic point of view. Reaching these metrics is important to keeping the customer payback period as low as possible, thus enabling greater market adoption. We explore how the payback period would change for each city by varying these parameters and concluding with an evaluation on maximum market penetration, based on a given set of parameters, and the resulting energy and emissions savings that can be practically achieved.

2. Review of state of the art technologies

The technologies that have been investigated for small CHP include ICEs or commonly called reciprocating engines, Stirling engines, micro-turbines, micro-Rankine cycles, solid-state devices, and fuel cells. The ARPA-E GENSETS program funded research for all heat and mechanical engine concepts except fuel cells as natural gas fuel cell research was funded by a prior ARPA-E program named Reliable Electricity Based on ELectrochemical Systems (REBELS) [9].

A detailed review of the performance metrics of state of the art small-scale CHP devices scale can be found in the literature [10–29] and a brief summary is given here. State-of-the-art ICEs have electrical generation efficiencies (based on LHV) between 20% and 26% for 1 kWe generation and up to 31% for 10 kWe. The heat recovery efficiency is greater than 50% for all cases and together the CHP efficiency is typically higher than 80% for all the ICE CHP systems. To raise the electrical generation efficiency in order to meet the ARPA-E GENSETS program targets, novel strategies for reducing in-cylinder heat transfer and friction, innovative combustion strategies, and economical methodologies for harvesting coolant and exhaust heat by using heat exchangers need to be developed and integrated. Stirling engines can achieve total CHP efficiency of more than 90%, while the electrical efficiencies are typically lower, around 15% for 1 kWe systems. High-efficiency Stirling engines can be enabled by increasing the maximum working fluid temperature (up to 900 °C) using state-of-the-art high-temperature alloys, reducing interfacial heat transfer losses, and reducing the engine friction and parasitic losses in converters and electronics. The biggest challenge for enhancing Stirling engine efficiency is the conversion of fuel energy to useful heat energy for the working fluid (helium in most Stirling engines). Micro-Rankine-cycles have performance metrics similar to Stirling engines, around 10–19% electrical efficiency, and can exceed 90% heat recovery efficiency for systems in the 1–3 kWe range. Microturbines are typically larger with one of the smallest microturbine systems, a prototype 3 kWe system (15 kW thermal load) system for CHP applications, having been built by Micro Turbine Technology BV (MTT) and reaching 16% and 80% electric and thermal efficiencies, respectively. Combined topping and bottoming cycle systems can also be found in the literature and may be required for meeting the metrics of the GENSETS program. There are significant challenges for any of these systems in reaching both the 40% fuel to electrical generation efficiency (henceforth termed electrical efficiency for the sake of brevity) and the system cost target of < \$3000 (without installation cost). It is expected that with greater penetration of small CHP systems and hence with larger volume production and/or the use of lower cost materials, the cost target will be feasible.

3. Methods

This section details the methods used for calculating energy savings, emissions metrics and payback period for each city considered for the

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[1] The Advanced Research Projects Agency-Energy (ARPA-E) invests in transformational ideas to create America's future energy technologies. ARPA-E focuses exclusively on early stage technologies that could fundamentally change the way we generate, use, and store energy. ARPA-E invests in innovative ideas from academia, private industry, national labs, start-up companies, and small businesses—providing project teams with an average award of \$2–3 million over several years. Every project team receives hands-on guidance to meet ambitious technical milestones that push the boundaries of energy innovation. ARPA-E's unique Technology-to-Market program also empowers project teams with business insight and strategies to accelerate the adoption of their potentially game-changing technologies. To date, ARPA-E has invested in more than 500 energy technology projects across 30 + focused program areas. The agency also issues periodic open funding solicitations to address the full range of energy-related technologies, as well as funding solicitations aimed at supporting America's small business innovators. To learn more visit our website at arpa-e.energy.gov.