Interplay of Gas and Electricity Systems at Distribution Level

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1. Introduction

Distributed energy resources for space conditioning comprise a set of varied technologies, ranging from mature well established systems such as furnaces, boilers, and air-conditioning (AC) units to emerging ones such as micro combined heat and power (micro-CHPs), reversible heat pumps, and hybrid gas-electricity conditioning systems. Micro-CHP systems, for instance, will have different prime movers depending on the underlying conversion process. Therefore, reciprocating engines, microturbines, and fuel cells-based CHPs have different technological characteristics and dissimilar market maturity levels, which make them attractive for a variety of applications at various scales. Depending on the quality of the thermal energy contained in the exhaust gas and cooling systems, this can be used to produce hot water, low- to medium-pressure steam, and heating and cooling for space conditioning.

This paper looks into the relative value of using gas- and electricity-based systems for space conditioning for residential consumers. The profitability of these technologies is the key metric for comparison, as it is what consumers mostly consider when deciding to adopt one technology over another. Performance characteristics such as efficiency and heat-to-power ratio, as well as economic characteristics such as capital and operational costs, energy prices and their associated tariff structure are expected to have a major impact not only in their profitability, but also on how they compete each other to meet the consumers' energy needs. Motivated by this, the specific question we explore in this case study is: "*What would the costs and benefits be of gas and electricity DERs used for space conditioning under different market and climatic conditions?*"

The structure of the paper is a follows. In the first half of this document, we concisely describe the salient features of these gas- and electricity-based systems for space conditioning. In the second half of this paper, we assess the relative value of using gas- and electricity-based systems for space conditioning for residential consumers, looking at the primary energy, their profitability and annual energy costs savings under several scenarios,

2. Technology description

In this section, we present an overview of the most salient characteristics of a set of gas-based technologies consisting of reciprocating engines, microturbines, fuel cells, and Stirling engines normally used in CHP applications, as well as electricity-based heat pumps used for space conditioning.

For the purpose of the Utility of the Future project, we focus on a set of technologies that are either well established in the market or look promising in the near future. These technologies differ mostly on the underlying energy conversion process, ranging from an engine- and a turbine-based combustion process, in the case of reciprocating engines and microturbines, to an electrochemical conversion process in the case of fuel cells. Given their dissimilar market maturity levels, in addition to their different technological characteristics, we believe that these three technologies encompass a representative set worth of analyzing within the context of this project.

2.1. Reciprocating internal combustion engines

Reciprocating internal combustion engines are a well-established and widely used technology, with a worldwide mass production. Reciprocating engines include both diesel and spark-ignition configurations. They are important for both transportation and for stationary uses. In general, this technology is a reliable and economic choice for stand-alone applications and as a prime mover for CHP applications (EPA, 2015).

Reciprocating engines are available in multiple sizes, ranging from few kWs up to several MWs for DG applications. They can produce hot water, low pressure steam, and chilled water by means of an absorption chiller. They are characterized for having a fast start-up, making them suitable for peaking or emergency situations. In the event of an electric outage, they can provide black-start capability[1] with minimal auxiliary power requirement, normally only batteries. The availability[2] of this technology is usually over 95% in stationary applications. In addition, these engines have a good part-load efficiency performance making them appropriate for electric load following applications.

Reciprocating engines are widely used in combined heat and power (CHP) applications in universities, hospitals, water treatment facilities, industrial facilities, and commercial and residential buildings. Thermal loads most amenable to engine-driven CHP systems in commercial/institutional and residential sectors are space heating and hot water requirements, being hot water the simplest one to supply. According to the 2015 EPA Report (EPA, 2015), there are 2,194 sites or about 2.3GW of installed capacity in the U.S. using this technology as prime mover in CHP applications.

Another common application is for emergency. Standby generators are used in a wide variety of settings from residential homes to hospitals, scientific laboratories, data centers, telecommunication equipment, and modern naval ships. Residential systems include portable gasoline fueled spark-ignition engines or permanent installations fueled by natural gas or propane. Commercial and industrial systems more typically use diesel engines. Usually, diesel engines have low upfront cost, ability to store on-site fuel if required for emergency applications, and rapid start-up and ramping to full load. However, they tend to have relatively high emissions of air pollutants (NOx and particulates)[3].

Within CHP applications, two main components can be identified:

- **Engine**. *Spark ignition engines* use spark plugs, with a high-intensity spark of timed duration, to ignite a compressed fuel-air mixture within the cylinder. Natural gas is the predominant spark ignition engine fuel used in electric generation and CHP applications. Natural gas engines for

[1] Black-start capability is provided by gas-DERs when they are equipped with auxiliary power requirements that can provide electricity in the event of a utility outage.
[2] Availability indicates the amount of time that a unit is either up and running or available for use. Systems are unavailable during periods of scheduled maintenance or forced outages.
[3] Another application can be for peak shaving. Facilities enrolled in these type of programs are asked by the local utility to run its on-site generator during the utility's peak load period. In exchange, the utility will provide the facility with payments.

power generation applications are primarily 4-stroke engines, available in sizes up to about 18 MW. *Diesel engines* are increasingly restricted to emergency standby or limited duty-cycle service because of air emission concerns[4] and also because of the high cost of fuel. Consequently, natural gas-fueled spark ignition engine is now the *engine of choice for the higher duty cycle stationary power market.*

- **Heat recovery**. Thermal energy contained in the exhaust gas and cooling systems, which generally represents 60 to 70% of the inlet fuel energy. Most of the waste heat is available in the engine exhaust and jacket coolant, while smaller amounts can be recovered from the lube oil cooler and the turbocharger's intercooler and after-cooler (if so equipped). Usually, the waste heat from engine systems recovered from jacket cooling water and lube oil cooling systems is at a temperature too low to produce steam but can produce hot water (190 to 230°F). However, steam can be produced from the exhaust heat if required (maximum pressure of 400 psig). Exhaust temperatures can range from 720 to 1000°F.

Based on the information provided by EPA (2015), **Table 1** presents some of performance characteristics for typical commercially available natural gas spark ignition engine CHP systems over a 100 kW to 9 MW size range[5]. The power ratings of the technologies will depend on the operational mode the engine is intended for:

- **Standby**. Maximum power output rating, if continuous full or cycling load for a short duration --usually less than 100 hours.
- **Prime**. 80 to 85% of the standby rating, if continuous operation for an unlimited time[6] but with regular variations in load.
- **Baseload**. 70 to 75% of the standby rating, if continuous full-load operation for an unlimited time.[7]

[4] Depending on the engine and fuel quality, diesel engines produce 5 to 20 times the NOx (on a ppmv basis) of a lean burn natural gas engine
[5] In the EPA report (EPA, 2015), CHP thermal recovery estimates are based on producing hot water for process or space heating needs.
[6] Except for normal maintenance shutdowns.
[7] *Ibid.*

CHP Technology: Reciprocating Internal Combustion Engines			
Metric	**Units**	**Range**	**Notes**
Nominal electricity	[kWe]	100 - 10,000	
Overall efficiency	[%]	80% - 76.5%	
Electric efficiency HHV	[%]	27% - 42%	
Thermal efficiency HHV	[%]	53% - 35%	
Power-to-heat ratio	[p.u]	0.51 - 1.19	
Start-up time	[sec]	10 seconds	
Black-start capability		With power storage unit	
Availability	[%]	96% - 98%	
Part-load efficiency		OK, minor loss of efficiency	
Hours to overhaul	[hour]	8,000 - 30,000	
Thermal output		Space heating, hot water, cooling, low pressure steam	
Emissions	[kg/MWh]	NOx: 0.032 - 1.197	[3]
		CO2: 226 - 245	[4]
O&M costs	[$/kWh]	0.025 - 0.0085	[1],[2]
Installed cost	[$/kW]	2,900 - 1,500	[1]
Economic life	[hour]	30,000 - 72,000	

Notes:
[1] Costs figures in US dollars for year 2013
[2] Costs based on 8,000 annual operating hours
[3] NOx, CO and VOCs can be important in natural gas-fired engines
[4] CO2 emssions after taking credit for heat. In stand-alone application CO2: 671 - 448 [kg/MWh]
Source: 2015 Catalog of CHP Technologies, U.S. Environmental Protection Agency.

Table 1: Cost & performance characteristics for commercially available gas-fired internal combustion engine CHP systems. [8]

Regarding part-load efficiency, reciprocating engines generally drive synchronous generators at constant speed to produce steady alternating current (AC) power. As load is reduced, the heat rate of spark ignition engines increases and efficiency decreases as shown in **Figure 1** for a 9.3MW natural gas engine genset. The effects of ambient conditions on performance are less significant on engines than on gas turbines. Reciprocating engine efficiency and power are reduced by approximately 4% per 1000 feet of altitude above 1000 feet, and about 1% for every 10°F above 77°F[9].

[8] Characteristics are for representative natural gas engine gensets commercially available in 2013. Data based on (1) Tecogen Inverde Ultra 100, (2) GE Jenbacher (GEJ) JMS-312C65; (3) GEJ JMS-416B85, (4) GEJ JMS-620F01, and (5) Wartsila 20V34SG.

[a] All engine manufacturers quote heat rates in terms of the lower heating value (LHV) of the fuel. However, the purchase price of fuels on an energy basis is measured on a higher heating value basis (HHV). For natural gas, the average heat content is 1030 Btu/scf on an HHV basis and 930 Btu/scf on an LHV basis – a ratio of approximately 0.9 (LHV / HHV).

[b] At rated load. The unit operates at variable speeds from 1,000 to 3,000 rpm, with a peak output of 125 kW while producing 60 Hz power through the inverter.

[c] The unit operates through a gearbox to produce 60 Hz power.

[9] Reciprocating engines are generally rated at ISO conditions of 77 °F and 0.987 atmospheres (1 bar) pressure.

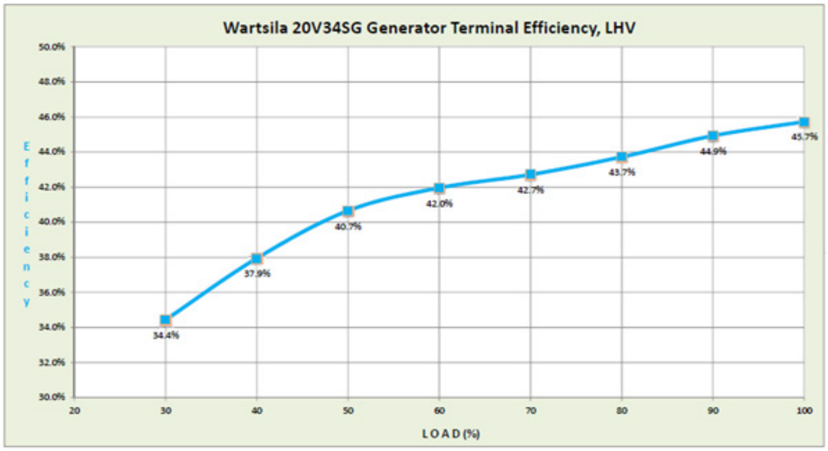


Figure 1: Part-load generator terminal efficiency for a 9.3MW Wartsila 20V34SG model. Source: EPA (2015).

Performance curve for a 100kW CHP module is given in the **Figure 2**, where it is observed a good part-load performance --around 25-27% of electrical efficiency-- for a wide speed range.

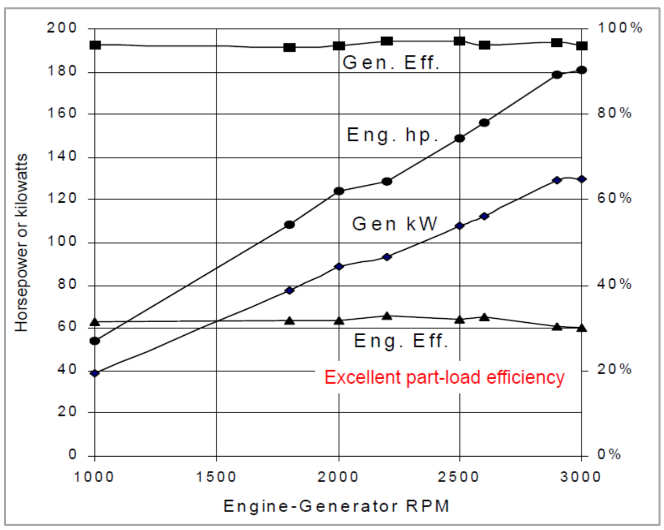


Figure 2: Performance curve for a 100kW Tecogen InVerde Ultra INV-100 model. Source: Tecogen.

2.2. Microturbines

Microturbine technologies are a mature one traditionally used in the automotive industry, but since the early 1990s developed for CHP installations. Microturbines can provide stable and reliable power, and voltage regulation thanks to the use of inverters. Moreover, their ability to provide black-start capability and to run under outage conditions makes microturbines particularly of interest as back up for consumers with critical load requirements (e.g., hospitals). Exhaust heat applications to obtaining hot water and heating, or cooling is another significant advantage of microturbines.

As of 2014, in the U.S., microturbines are not widely extended, since they only represent 8.4% of CHP installations, and 0.1% of total CHP installed capacity (barely 80 MW). Their high capital and maintenance costs and reduced size for industrial purposes may explain their current situation. However, research is being conducted to reduce capital and maintenance costs, increase efficiencies and achieve better economics of operation. In addition, several microturbines can be paralleled to reach larger power outputs.

Microturbines operation is based on the thermodynamic cycle, known as Brayton cycle. During this cycle, air at atmospheric pressure is first compressed, then heated –by adding and combusting gas–, and finally expanded in a turbine that drives a driveshaft capable of providing mechanical power and to which the compressor is also connected. The exhaust heat is partially used for preheating the air before entering the combustor in order to increase the efficiency. Microturbines operate at high rotational speeds, up to 60,000 rpm. Two solutions are implemented when producing electricity: 1) to connect directly the driveshaft to a high-speed generator and use power electronics to obtain 50/60 Hz electricity, or 2) to connect the driveshaft to a gearbox and reduce the speed to 3,000/3,600 rpm (50/60 Hz). The advantage of using power electronics is reducing harmonics and controlling voltage output, but at the expense of penalizing the efficiency (about 5%).

A summary of the main technical characteristics and economic aspects is shown in **Table 2.** The production costs depend on the price of the input fuel, which includes natural gas, sour gas, or landfill gas, and also liquid fuels (e.g., gasoline, diesel fuel or kerosene). A useful characteristic of microturbines is the possibility of operating in island mode and their black-start capability (a power storage unit like a battery is necessary to start up). The generator can also operate at part load and, hence, follow power demand variations, although dropping its electric efficiency. As the thermal output does not decrease at the same rate, the overall efficiency loss is reduced. Microturbines present a low power to heat ratio which implies more heat than electric production in relative terms. For this reason, microturbines should be designed for applications that make the most of heat utilization. The exhaust gas temperature, around 500-600ºF (260-315ºC), and its cleanliness, makes it suitable for both heating and cooling applications.

CHP Technolgy: Microturbines			
Metric	**Units**	**Range**	**Notes**
Nominal electricity	[kWe]	30 - 1,000	
Overall efficiency	[%]	63% - 70%	
Electric efficiency	[%]	49% - 57%	[1]
Thermal efficiency	[%]	36% - 48%	
Power-to-heat ratio	[p.u]	0.5 - 0.7	
Start-up time	[sec]	60 seconds	
Black-start capability		With power storage unit	
Availability	[%]	98% - 99%	
Part-load efficiency		Minor loss of efficiency	
Hours to major overhauls	[hour]	20,000 - 40,000	
Thermal output		Hot water, heating, cooling	
Emissions	[kg/MWh]	NOx: 0.03 - 0.07	[2]
		CO2: 325 - 330	[3]
O&M costs	[$/kWh]	0.009 - 0.016	[4],[5]
Installed cost	[$/kW]	2,500 - 4,300	[5]
Economic life	[hour]	40,000 - 80,000	

Notes:
[1] Electric efficiency in the range of 22% - 28% for stand-alone applications
[2] In stand-alone application NOx 0.06 - 0.22 [kg/MWh]
[3] In stand-alone application CO2 645 - 820 [kg/MWh]
[4] Costs based on 6,000 annual operating hours
[5] Costs figures in US dollars for year 2013
Source: 2015 Catalog of CHP Technologies, U.S. Environmental Protection Agency.

Table 2: Cost & performance characteristics for commercially available gas-fired microturbine CHP systems.

The input fuel supply pressure reaches as much as 50 to 140 psig (3.5 to 10 bar) while the final distribution pipelines distribute gas at 1 to 50 psig (0.04 to 3.5 bar). For this reason, a compressor is habitually needed unless the microturbine is directly connected to the local medium-pressure distribution network, whose pressures range from 30 to 130 psig (2 to 9 bar). The compressor consumes about 4-6% of power capacity. The ambient conditions also affect the performance of the microturbine. First, an elevated inlet air temperature reduces both power capacity and efficiency. The inlet air is sometimes refrigerated. Second, the inlet air pressure impacts the power output, but not the efficiency. The density of the air decreases with the altitude; hence, the power output reduces with the altitude. Finally, there are relevant economies of scale. A common multiple is 80%, i.e., a 100% increase in size results in an 80% increase in capital cost.

2.3. Fuel cells

Fuel cells technology was developed during 1830s, but first practical applications took place more than 100 years later when the U.S. space program rekindled its research. Nowadays, fuel cells are again being developed and installed in distributed generation applications. Fuel cells are particularly suitable for installations which require clean, reliable, quiet and efficient power generation. Although they are more expensive than other gas-based CHP technologies, consumers who require high quality power are willing to pay its decreasing extra costs. Their main advantages are a consequence of the approach to producing electricity through an electrochemical process instead of an electromechanical one. Fuel cells work in a similar manner to batteries, but using a continuous stream of fuel supply. By-product heat is mainly used in the form of hot water, but low- to medium-pressure steam is also possible depending on the fuel cell type.

As of 2014, in the U.S., fuel cells were rarely utilized among the gas-based CHP technologies. The number of installation represented 3.7% and the total capacity amounted to 0.1% (equivalent to 84 MW) of total CHP installations. Capital costs remain high despite the recent effort to reduce them; hence, discouraging their installation. However, market subsidies together with their negligible emissions rate of main pollutants and quietness put fuel cells in a promising position.

Fuel cells operation is based on an electrochemical process, similar to common batteries, in which a continuous supply of fuel is required. In short, the process is based on the electrolysis of water: the reactants, hydrogen and oxygen in the form of gas, when combined produce water and electric power[10]. This chemical reaction produces zero pollutant emissions. The hydrogen is however generated out of a hydrocarbon fuel (typically, natural gas) in a process that produces some CO2 emissions, but negligible amounts of other pollutants. The oxygen is obtained from ambient air.

A fuel cell system is normally composed of three elements:

- **Fuel processor** converts natural gas (or other hydrocarbons) into hydrogen. When a continuous stream of hydrogen fuel is available, the fuel processor is not required. There are three main types of fuel processors which differ in the thermal balance and the source of oxygen to combine with the carbon and release the hydrogen. Steam reformers use steam and require an addition of heat input; partial oxidation reformers use oxygen gas and produce heat; and auto-thermal reformers use both steam and oxygen, and are close to neutrality. During this process CO2 is emitted.
- **Fuel cell stacks** in which hydrogen and oxygen combine generate direct current electricity.
- **Power conditioners** either regulate the direct current electricity or generate alternate current electricity. The presence of an inverter allows for obtaining high-quality power and enhancing the power factor.

There are four main types of fuel cells for stationary purposes, such as CHP units. Each type is defined by the electrolyte that makes the reaction between the hydrogen and oxygen possible. Accordingly, it can be distinguished polymer electrolyte membrane (PEMFC), phosphoric acid (PAFC), molten carbonate (MCFC) and solid oxide (SOFC) fuel cells. Besides the electrolyte material, two relevant differences can be found: 1) the operational temperature which change from 65-85ºC for PEMFC and 150-200ºC for PAFC to 600-700ºC for MCFC and 700-1000ºC for SOFC; and 2) the electrical

[10] For a detailed description of the basic operation of fuel cells, please refer to Larminie (2003).

efficiency which increases with the temperature from 25-35% for PEMFC and 35-45% for PAFC to 40-50% for MCFC and 45-55% for SOFC.

Fuel cells hold some outstanding advantages. Systems are very flexible in capacity since they are constructed out of individual cells that generate from 100 W to 2 kW. Besides their high-quality output power, fuel cells have shown in practical instances over 90% availability. They perform greatly well under partial load conditions (even better than typical natural gas engines), although the required start-up time, which is proportionally related to the working temperature (hence the electric efficiency), may suggest avoiding operating cycles. Some of the main technical characteristics and economic aspects are shown in **Table 3**. As above mentioned, the values mostly depend on the type of fuel cell. Ambient temperature and elevation may decrease their performance when auxiliary equipment, such as air compressors, are utilized. Finally, fuel cells maintenance is cheap, but after 5 to 10 years fuel cells require an expensive stack replacement.

CHP Technology: Fuel Cells

Metric	Units	Range	Notes
Nominal electricity	[kWe]	200 W – 2,800 kW	
Overall efficiency	[%]	55% - 80%	
Electric efficiency	[%]	30% - 63%	
Thermal efficiency	[%]	20% - 50%	
Power-to-heat ratio	[p.u]	0.7 - 2.8	
Start-up time	[sec]	From seconds to few hours	
Black-start capability		Yes	
Availability	[%]	> 95%	
Part-load efficiency		Good	
Hours to major overhauls	[hour]	32,000 - 64,000	
Thermal output		Hot water, low- to high-pressure steam	
Emissions	[kg/MWh]	NOx: 0.001	
		CO2: 185 - 310	[1]
O&M costs	[$/kWh]	0.020 - 0.007	[2],[3]
Installed cost	[$/kW]	23,000 - 4,600	[3]
Economic life	[hour]	30,000 - 120,000	

Notes:
[1] In stand-alone application CO2 330 - 515 kg/MWh
[2] Costs based on 6,000 annual operating hours
[3] Costs figures in US dollars for year 2014
Source: 2015 Catalog of CHP Technologies, U.S. Environmental Protection Agency.

Table 3: Cost & performance characteristics for commercially available gas-fired fuel cells CHP systems.

2.4. Stirling engines

These engines were invented and patented in 1816. This technology is a heat engine that is based on an external combustion system, which allows to use different primary energy sources including fossil fuels (oil, natural gas) and even renewable energy sources (solar, biomass). This flexibility is one of the attractive features of these engines, which has helped this technology to become a component of CHP systems for various applications. Stirling engine packages can be quite compact and they can be used for micro-CHP units targeted to the residential sector. However, as of today, this technology has not been able to fully consolidate in the CHP market and current developments are focusing on bio/landfill gas and solar applications.

Stirling engines work by alternatively heating and cooling a working gas, with the combustion process taking place externally in a separate burner. The working fluid -- usually nitrogen, hydrogen or helium -- is enclosed within a hermetically sealed pressure vessel. Heat is provided at a constant temperature at one end of a cylinder (the hot end), while heat is rejected at a constant temperature at the opposite end (the cold end). Work is created as the expanding gas pushes against a piston. The working gas is transferred back and forth between the two chambers, often with the aid of a displacer. While the gas moves from the hot to the cold chamber, a regenerator captures the heat from the gas and then returns the heat to the gas as it moves back to the hot chamber, which enhances the energy-conversion efficiency of the process. All SEs have two pistons. In the kinematic engines, these two pistons are physically connected by a crank mechanism (connecting rods and a crankshaft, or a swash or wobble plate); whereas in the free-piston engine, there is no physical linkage and the displacer oscillates freely Refer to Goldstein et al. (2003) and Pehnt et al. (2006) for further information on this technology.

The size of natural gas Stirling engines ranges from typically 1kWe up to 10kWe. They have good performance at partial load, offer fuel flexibility, have low emissions level and have low vibration and acceptable noise levels (Angrisani et al, 2012). However, they have very low electric efficiency compared to other gas-based distributed generation technologies --ranging from 12 up to 25%-- with an overall energy efficiency in CHP applications usually above 90%, and therefore high the heat-to-power ratios.

The heat recovered from the SE engine cooling and lubrication system and the exhaust gas results in significant amounts of heat suitable for space heating, cooking, potable hot water, and low temperature processes (below 60°C). Given the high thermal output of SEs, they clearly represent an alternative to gas boilers or furnaces for single-family homes, large residences with heated pools or even small commercial applications if multiple systems are installed.

2.5. Heat pumps

From all described technologies in this document, heat pumps are the only ones that do not produce electricity, hence only provides space conditioning services (i.e., heating and cooling). Heat pumps have been in the market since the 1950s. The physical principle behind heat pumps operation is transferring heat in the opposite direction which heat would spontaneously flow. When in heating operation, heat pumps move heat from the cool outdoors into the warm indoor space. In contrast, when in cooling operation, heat pumps move heat from the cool indoor space out to the warm outdoors. The required energy to move heat in the unnatural direction is habitually provided in the form of electricity.

In detail, a heat pump consists of a circuit that is composed by compressor, a valve, and two coils: the condenser and the evaporator. A refrigerant fluid flows within the circuit. The fluid, in gaseous state, is first compressed while increases its temperature, to then let it flow though the condenser in which the fluid releases heat and warms the area. The condensed refrigerant fluid is subsequently passed through a valve, or any other lowering-pressure device, in which the fluid cools. Finally, the refrigerant fluid flows through the evaporator and absorbs heat from the space that is being cooled. After this last stage, the cycle starts again.

From the three type of heat pumps that exist (air-to-air, water source and geothermal), the most common ones are air-source heat pump. Air-to-air heat pumps utilize ambient air as the heat source and sink. In large facilities, water-source heat pumps are used since water holds more capacity to move heat than air. Hot water (heat source) is obtained by means of a boiler or solar panel, while cool water (heat sink) is produced in a cooling tower or supplied by a river, a lake, or the sea. Geothermal-sources heat pumps take advantage of constant underground temperature which is used as heat source and sink.

Heat pumps are efficient systems to covering moderate heating and cooling needs. However, their utilization has not exploded yet. According to Matley (2013), three main reasons can explain the delay in adopting heat pumps:

- Initial cost. Home and business owners must face high upfront costs. Although the payback period is relatively low (5 to 10 years), risk aversion may prevent from investing a relevant amount of capital.
- Lack of knowledge. There is limited awareness about the technology and its cost savings. Consumer acceptance may also unite to previous drawbacks as some heat pumps configurations are related to other poorly performing devices. Finally, in case of take-off, there is a lack of qualified installers and system designers.
- Difficult of retrofit. Very related to the upfront cost problem, retrofitting usually involves a significant project that most of the times require that the previous installation is close to the end of its lifetime and a new configuration that cannot take advantage of the previous installation.

3. Methodology

In order to assess the economic viability of DERs, we used a combination of three modeling tools: DOE-Quick Energy Simulation Tool (eQuest), LBNL-DERCAM and MIT-DRDRE as briefly described below:

- The eQUEST model is a building design and energy simulation tool supported as part of the Energy Design Resource program[11], which allows users to perform detailed energy related

[11] Funded by California utility customers and administered by Pacific Gas and Electric Company, San Diego Gas & Electric, and Southern California Edison, under the auspices of the California Public Utilities Commission. More information can be found in the eQUEST official website at http://www.doe2.com/equest/. The EDR Building Simulation Design Brief also offers additional information available at http://www.energydesignresources.com/Resources/Publications/DesignBriefs.aspx

analysis of different building designs in a relatively simple and intuitive way. By means of eQuest, we generate a set of different energy profiles for each of the type of building that it is later used to assess the economics of different technologies used to meet the energy requirements.

- The Distributed Energy Resources Customer Adoption Model (DER-CAM) is an economic and environmental optimization tool developed by the Laurence Berkeley National Lab (LBNL) and funded by the U.S. Department of Energy. DER-CAM has been evolving and improving for more than a decade and has multiple versions tailored for different objectives[12]. For this paper, we used and adapted a version that minimizes the total energy related cost of utility customers by implementing optimal distributed energy technologies and deciding their respective operating schedules. The model is based on a mixed integer linear programing and utilizes CPLEX as the solver[13].
- The Demand Response and Distributed Resources Economics (DRDRE) model is used to analyze the DER technical capabilities and end-user responses to price signals. The model is designed to optimize the operation of a customer's on-site energy resources and energy purchases in response to economic signals (as a price-taker). For this paper, we implemented a gas and electricity module intended to analysis of the suitability of different technologies for space conditioning. Details of its formulation are provided in the Appendix.

The DRDRE's gas-electricity module (still under development) adopts a formulation that minimizes the annual energy costs of a consumer who adopts a distributed technology to meet the building energy needs. It assumes a price-based strategy as opposed to a more stringent operational one that follows the consumer's heat or electricity load. In the case of micro-CHP systems, the unit produces electricity and heat at an assumed fixed heat-to-power ratio which will be different depending on the prime mover technology. In the case that the generated electricity is beyond the on-site demand, the excess power is fed back into the grid. Alternatively, if the produced electricity is below on-site demand level then supplementary power is acquired from the grid to cover any deficit. The model also includes supplemental firing that supports the micro-CHP operation in those situations where additional heat is needed by the consumer. In the case of heat-pump systems, the electricity for space conditioning, either heating or cooling, is obtained from the grid. Heat pumps and CHP systems are direct competitors, i.e., mutually exclusive installed, for which a supplemental firing could be available.

3.1. Formulation

In order to assess the profitability of DERs, the DRDRE's gas-electricity module formulation maximizes the profit or alternatively minimizes the annual energy costs of an end-user that adopts a distributed technology to meet the building energy needs. As noted above, this is a price-based strategy

[12] More information about DER-CAM can be found at https://der.lbl.gov/der-cam and https://building-microgrid.lbl.gov/projects/der-cam

[13] For the use of DER-CAM, MITEI and Lawrence Berkeley National Laboratory (Berkeley Lab) signed a collaboration agreement.

as opposed to a more stringent operational strategy based on either the consumer's heat or electricity requirements.

The annual costs C are given by DER capital and operational expenditures, emission costs if a tax is charged on customers, and expenditures (or revenues) associated to utility purchases (or sales).

$$Min\,TAC = \left[C^{opex} + C^{capex} + C^{emissions} + C^{utility} - S\right]$$

The objective function has five general terms:

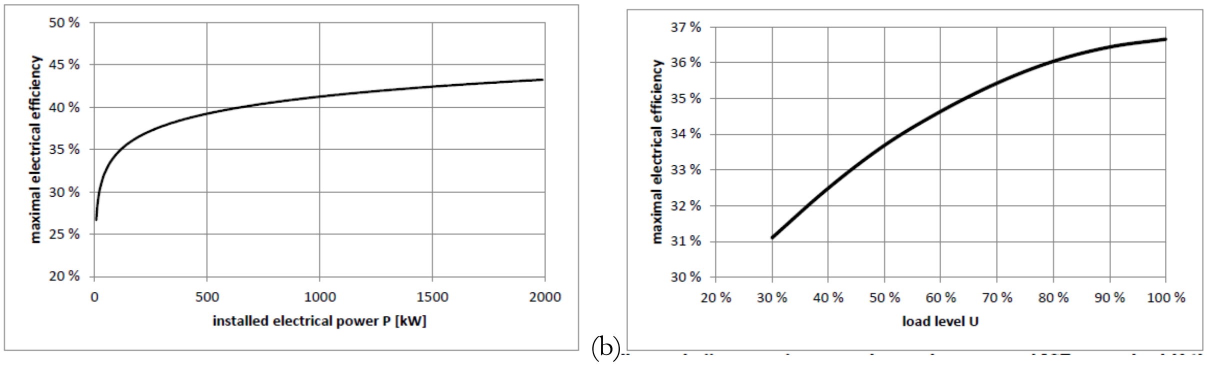
- *Operational costs* C^{opex}. Production costs depend on the quantity of fuel and cost of fuel. Also, this term includes O&M costs which account for the costs related to the service contracts offered by manufacturers that normally cover both scheduled and unscheduled events. For simplicity, O&M costs be recalculated in terms of power production.
- *Capital costs* C^{capex}. The relevant economies of scale suggest the utilization of a cost function that depends on the level of investment[14]. However in this work, we define the investment decision variable for the most common size(s) of the equipment when applicable. For example, for microturbines we define variables for 30kW, 250kW, etc.
- *Emissions costs* $C^{emissions}$. In the case of emissions, CO_2 and NO_X emissions are proportional to the energy production. These costs represent an additional costs to consumers, if an emission price is set in the market.
- *Utility costs* $C^{utility}$. This term includes both consumer's expenditures associated to utility purchases or revenues when selling back to the system.
- *Subsidies* S. This is a term to be defined in the case of production, investment or other type of subsidy.

Total production is limited by the installed capacity of the equipment, which we assume to be a continuous decision[15]. In addition, on-site energy balances need to be taken into account for heat and electricity, as well as equipment minimum operating requirements. In our formulation, exhaust heat production is simply considered proportional to the power production through a given heat-to-power ratio characteristics for each technology[16].

The electrical efficiency is a critical factor that impact the performance of the energy system. By and large, the efficiency is load and size dependent. As seen in **Figure 3** for a natural gas-fired ICE, efficiency is lower for small capacities, with a clear non-linear relationship between the installed electrical power and the maximum efficiency. The figure also shows the dependence on the load operating level with a poor part-load efficiency performance below 50%. According to Milos et al.

[14] This approach would however introduce a non-linear term $A/x^{0.2}$, where x is the investment level.
[15] Discrete investments would require the classical constraints of any investment problem such as the continuity constraint.
[16] The exhaust heat could be used for either heating or cooling applications.

(2015) internal combustion engines and microturbines exhibit considerable efficiency variations during part-load operation, while gas turbines and also fuel cells exhibit better part-load efficiency.



(a) (b)

Figure 3: Electrical efficiency as a function of unit size (a) and operating load level (b) for a natural gas-fired ICE. Source: Milan et al. (2015)

Going back to our formulation, the load-dependence could be represented by piecewise linearizing the efficiency function through binary variables as follows[17]:

$$v = v(Q_0) + \sum_{i \in P} [v(Q_{i+1}) - v(Q_i)] \cdot \delta_i$$

$$q = Q_0 + \sum_{i \in \wp} (Q_{i+1} - Q_i) \cdot \delta_i$$

$$\delta_{i+1} \leq \gamma_i, \forall i \in P-1 \quad \gamma_i \leq, \delta_i, \forall i \in P-1 \quad 0 \leq, \delta_i \leq 1, \forall i \in P$$

Where δ_i are continuous variables representing the load of each segment, and γ_i are binary variables to force the so-called filling conditions. If an interval *i* is chosen, then all intervals to its left must be completely used.

For this paper we have adopted a simple approach, where fuel consumption for gas-DER units and furnace systems is a linear expression that depends on the energy production. *Finally, the detailed mathematical formulation can be found in the **Appendix** of this document.*

3.2. Key assumptions

Several assumptions and simplifications have been adopted for this paper:

a. *Price-responsive consumers*. We assume that consumer's demand for heat and electricity is price elastic and able to adapt based on energy prices. We also assume that self-generation coming from a micro-CHP unit is able to respond to these price signals, i.e. consumers can decide the operation of their machines at times when it is most favorable.
b. *DERs technical performance*. We examine a set of various residential space conditioning systems that differ mostly on the underlying energy conversion process, from micro-CHPs, to boilers and to heat pumps. These technologies have dissimilar power and heat capacities, fuel conversion efficiencies, heat quality, heat-to-power ratios, coefficient of performance, etc.

[17] If the formulation avoids binary variables, then the electric efficiency should be considered constant with a value close to its value at full capacity.

which for this case study are based on Hawkes et al. (2014) and Navigant Consulting and Leidos (2015).

c. *DERs ramp times and start-up costs*. Equipment start-up costs and ramping limits depend on the technology being used. For ICEs and MTs these values tend to be negligible[18], but for FCs startup time could be quite important depending on the materials being used. For this paper, however, we ignore ramp times and start-up costs.

d. *Metering scheme*. We assume an hourly net metering scheme, where energy usage and price signals are registered hour by hour. There is no daily or monthly aggregation. The meter records the purchases or sales of electricity and, under this formulation, it is not possible to have imported and exported power simultaneously during the same hour. Only in the case that micro-CHP production is larger than on-site demand, excess of electricity is possible (and the other way around, when micro-CHP is lower than on-site demand the deficit of electricity will be bought from the grid). Information on the retail prices for electricity and gas is available to consumers in order to decide the economic valuation of the energy usage on an hourly basis.

e. *Consumer energy tariff*. We adopt a simple flat volumetric pricing scheme for retail consumers that aggregates the various pricing components such as energy price, network costs and policy costs. This simple $ per kWh allocation purportedly deviates from a more cost efficient allocation, but it is an approach extensively used in many countries nowadays.

4. Case study

This section presents the cases we analyzed for assessing the relative value of using gas- and electricity-based systems for space conditioning for residential consumers, looking at their primary energy, profitability and annual energy costs savings under different market and climatic conditions.

4.1. Description

Consumers consider the adoption of DER technologies with the goal of meeting their energy demand at a reduced energy cost. However, this decision is not trivial as heating and cooling manufacturers offer a plethora of technologies to choose from. In addition, this decision is often influenced by other factors such as climate which determines energy requirements, and the market and regulatory conditions existing at the time of choosing the equipment. Inspired by this, we explore the question of "*what would the costs and benefits be of gas and electricity DERs used for space conditioning?*" under different market and climatic conditions.

[18] These limitation are ignored, since normally they are less than one minute and our formulation is based on hourly time periods.

For this purpose, we analyzed a case study that simulates a single family house of about $150m^2$ and consider two distinctive climatic conditions, namely cold and warm[19]. In addition, we use two combinations of energy prices based on their electricity-to-gas ratio, with values of 3.6 and 1.9 for high and low ratio scenario respectively. In terms of technologies, we include a set of six different DERs technologies used for space conditioning: four micro-CHPs units with different prime movers, a high efficient gas-fired condensing boiler, and an air-to-air heat pump. The **Table 4** below illustrates the scenarios used in the quantitative assessment.

Scenarios	Description	
Building	1 Single family house	~150 m^2
Locations	2 Cities	City Cold | City Warm
Energy prices	2 Combinations based on EG ratio[1]	Ratio High | Ratio Low[2]
Technologies	4 Residential CHPs[3]	ICE (1.2kWe) | SE (1.0kWe) PEMFC (0.75kWe) | SOFC (0.70kWe)[5]
	2 Residential HVACs	Boiler | A-to-A HP[4]

Notes: [1] Electricity-gas ratio; [2] High is an electricity and gas price of 3.6, and low is an electricity and gas price of 1.9; [3] Gas-fired combined heat and power (CHP) systems; [4] Gas-fired condensing boiler, and air-to-air electric heat pump; Internal combustion engine (ICE, Stirling engine (SE), Polymer electrolyte membrane fuel cell (PEMFC) and Solid oxide fuel cell (SOFC).

Table 4: Description of case study.

Based on the set of optimization and simulation tools above described, we evaluate the costs and benefits of the set of technologies and compared outcomes to a base case that includes a conventional distributed heating and cooling system --i.e. a high efficient gas-fired condensing boiler for water and space heating and electricity from the grid for an AC unit-- used for central space conditioning. Then, for each technology, we examine its primary energy, profitability and annual energy costs savings under the different market and climatic conditions.

4.2. Results

The figures below portray the results in terms of primary energy, annual energy costs savings and simple payback period for the six different DER technologies presented in the above table.

In **Figure 4**, we observe that most of them perform well and they reduce primary energy with respect to the case of having separate production of heat and electricity, although climatic conditions impact their performance. It is important to note that since primary energy depends not only on technology efficiency but also on the so-called "source to site"[20] efficiency, electricity-based technologies tend to

[19] Cold weather is characterized by having 2405 heating degree days (HDD) and 669 cooling degree days (CDD), while the warm one has 735 (HDD) and 1159 (CDD). Under these conditions, the peak thermal demand of the building is 11.4kWth and 5.2kWth for the cold and warm climatic conditions respectively.

[20] The global efficiency of building space conditioning systems is dependent on two metrics: the efficiency of the actual equipment also called the "site" efficiency, and the losses associated of bringing the energy to the consumer that is then

be quite sensitive to the grid characteristics and energy portfolio. In our case, we observe that fuel cell-based micro-CHPs and heat pumps outperform other technologies, but heat pumps seem to be more sensitive to climate and they are a better choice in warmer climates.

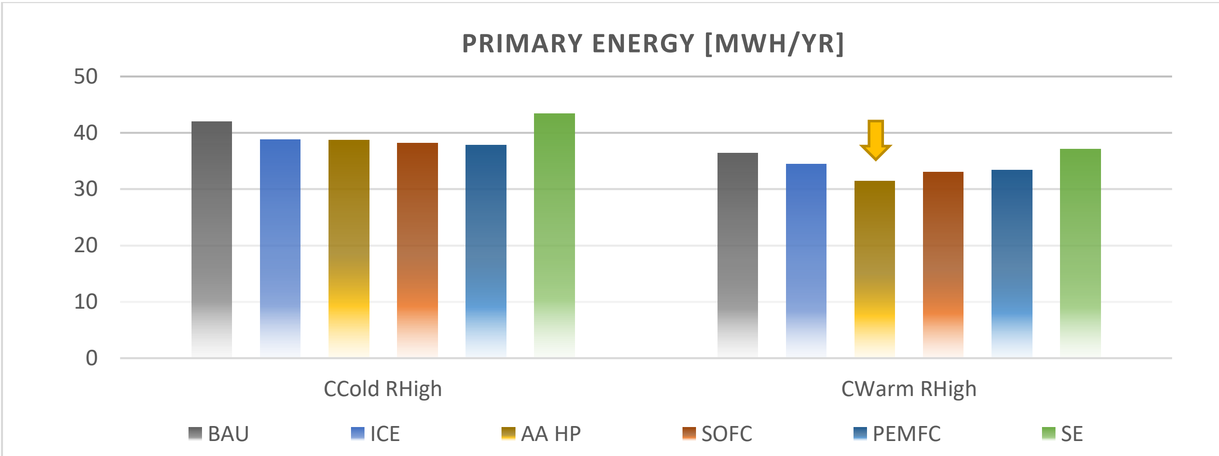


Figure 4: Impact of climate on primary energy of gas- and electricity-based technologies under high electricity-to-gas price ratio.

In **Figure 5** we observe that energy prices have a great impact on potential energy savings. The trade-off between electricity costs and fuel costs is key, as high electricity prices with high electricity-to-gas ratio clearly favor the economics of micro-CHPs, whereas electric heat pumps find themselves as better alternatives in markets with lower electricity prices. However, as noted in **Figure 6** the profitability of DER technologies also depends on climatic conditions, with cold climates favoring cogeneration systems.

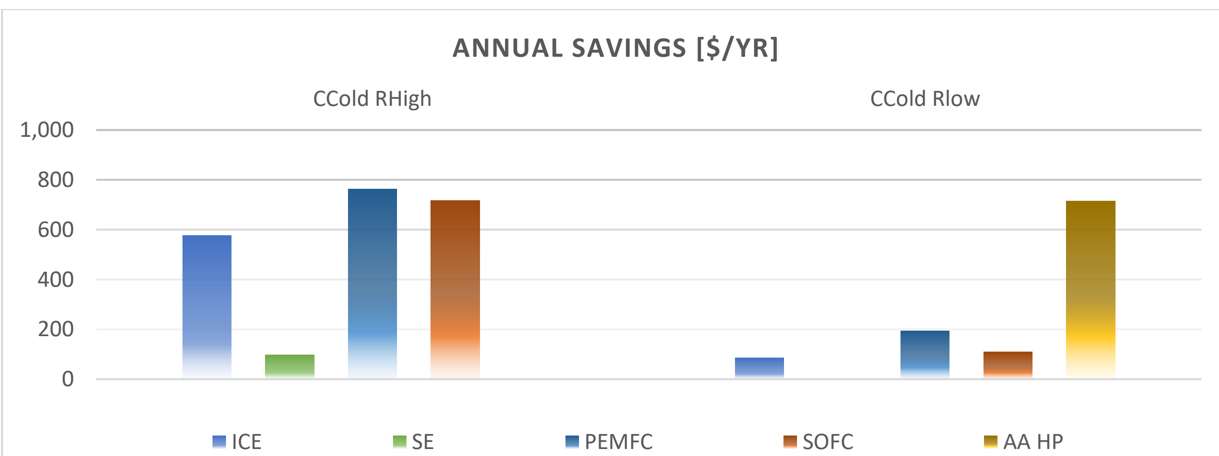


Figure 5: Impact of energy prices on annual savings of gas- and electricity-based technologies under cold climatic conditions.

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used to operate the equipment given by the "source to site" energy efficiency. "Source to site" losses result from the extraction, refinement, conversion, and transportation of the fuels to the end user and are more pronounced in the case of electricity because they are associated to the generation process. These electrical "source to site" losses are highly dependent on the characteristics and energy portfolio of the electricity grid. For gas, the "source to site" losses are dependent on the natural gas distribution network and the method of extraction.

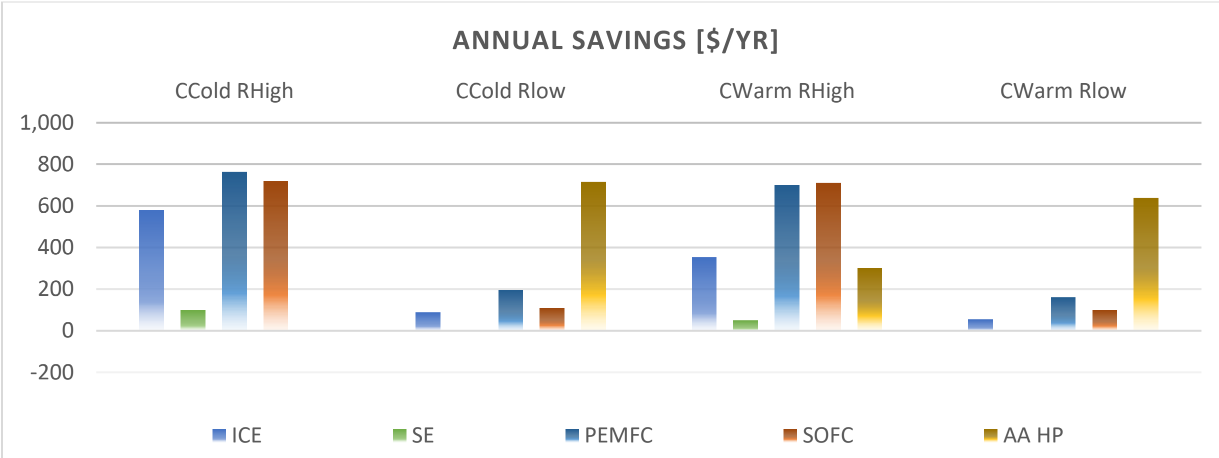

Figure 6: Impact of energy prices and climatic conditions on annual savings of gas- and electricity-based technologies.

Finally, upfront costs of the various technologies significantly determine their economic viability. **Table 5** displays a sample of current retail prices for micro-CHP systems for residential applications based on Hawkes et al. (2014).

Residential System	Current Retail Price [$]
ICE - 1.2kWe	8,823
SE - 1.0kWe	6,620
PEMFC - 0.75kWe	11,556
SOFC - 0.70kWe	15,259

Table 5: Technology retail prices as of year 2014.

Based on these numbers, the systems' simple payback periods are above the expected equipment lifetime even when evaluated under favorable conditions i.e. cold climate and high electricity prices (see **Figure 7**).

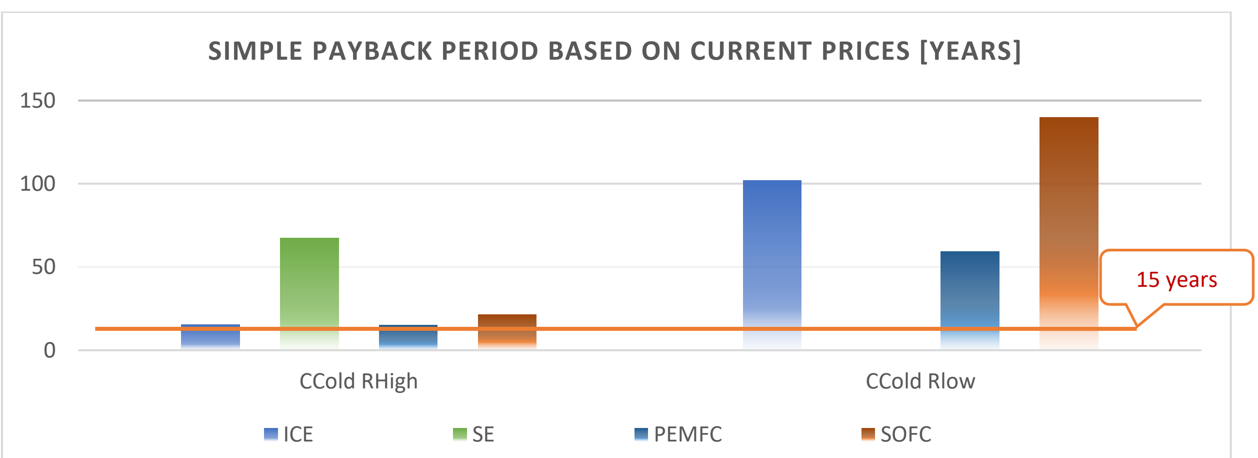

Figure 7: Impact of energy prices and upfront costs on simple payback periods based on current retail prices.

If instead we assess the economics of these technologies taking projected prices available from various public sources[21], we observe that their expected internal rates of return are still very high (see **Figure 8**).

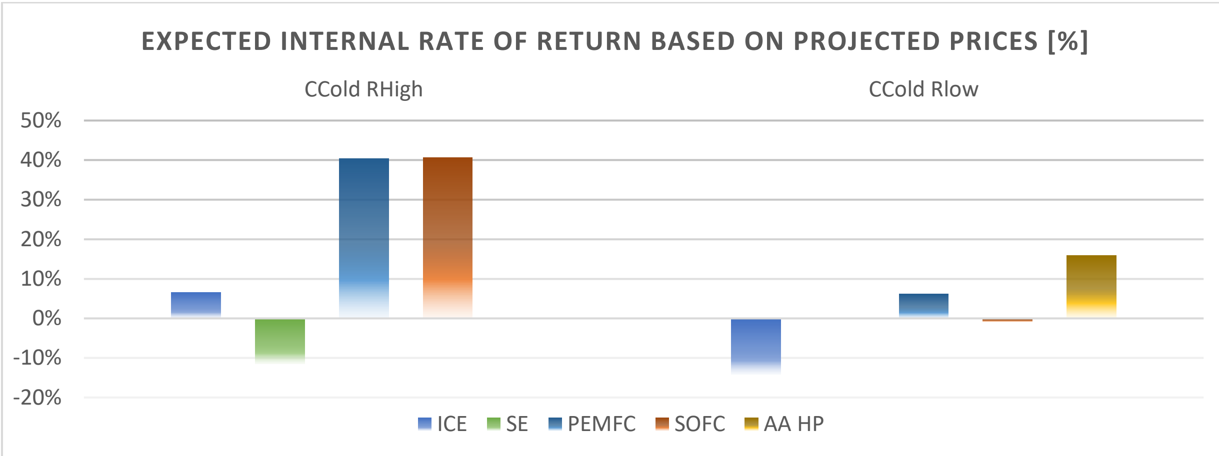

Figure 8: Expected internal rates of return of different DERs based on technology price projections (and not current prices).

Therefore, cost reductions are crucial to make these technologies competitive. Under favorable market conditions and current selling prices, significant costs reductions are needed to make these technologies a viable alternative for space conditioning.

5. Conclusion

This paper has addressed the question of assessing the relative value gas- and electricity-based systems used for space conditioning by residential consumers under different market and climatic conditions.

We noted that micro-CHP systems continue to face extraordinary upfront costs today (see **Table 5** above). Although reciprocating engines are the most mature and established technology for large and medium applications, their costs are still high for smaller applications and cause environmental concerns. Fuel cell-based systems are promising given their high electrical efficiencies and low primary energy consumption. However, their high equipment costs continue to be a barrier for their further deployment. In the case of heat pumps, these are already an available technology that is very efficient when providing cooling and heating need in areas where temperatures are moderate. However, the

[21] For the purpose of this analysis, we use projected costs as provided by various U.S agencies. Specifically, projected total costs for heat pumps are based on the U.S. Energy Information Administration (EIA) Report - Updated Buildings Sector Appliance and Equipment Costs and Efficiencies, April 2015 (available at: https://www.eia.gov/analysis/studies/buildings/equipcosts/pdf/full.pdf). Projected costs for residential combined heat and power engines are based on ARPA-E Generators for Small Electrical and Thermal Systems - GENSETS Program Overview (available at: https://arpa-e.energy.gov/sites/default/files/documents/files/GENSETS_ProgramOverview.pdf). Finally, projected costs for residential CHP fuel cell systems are based on the U.S. Department of Energy's (DOE's) Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan - 3.4 Fuel Cells, Updated November 2014 (available at http://energy.gov/sites/prod/files/2014/12/f19/fcto_myrdd_fuel_cells.pdf).

high upfront costs together with lack of customer awareness have not allowed this technology to take off. Therefore, cost reductions are crucial to make these technologies competitive in the near future.

We observed that the profitability of DER technologies for space conditions depends on the energy prices and their relative difference, as well as climatic conditions. Markets with low prices and low electricity-to-gas difference do not favor cogeneration systems, while markets with low electricity prices favor electric heat pumps. Cold climates favor cogeneration systems, while mild ones favor heat pumps. Finally, the format of the electricity tariff impacts not only the DER sizing decision but also their operation, which ultimately determines primary energy consumption and related emissions.

Our results are aligned with other reports and studies. However, as long as the technologies evolve, new quantitative analyses with the presented modeling tools, or more advanced ones, will be required to support the transition towards more economically efficient and environmentally friendly technologies.

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7. Appendix: Mathematical formulation

The formulation will depend on the configuration of the building heating system and the technology adopted. For example, in warm-air heating applications, hot air from a CHP unit and auxiliary gas-fired furnace can be used for central space heating. In hydronic heating applications, hot water from a CHP unit and auxiliary gas-fired boilers combined with a water tank can be used for space heating and hot water. In addition, different technologies can be used as prime movers in CHP systems ranging from internal combustion engines (ICE), microturbines (MT) and fuel cells (FC). Different technologies will have dissimilar power and heat capacities, fuel conversion efficiencies, heat quality and heat-to-power ratios, among other characteristics.

The model presented in this work (*under development*) is based on two possible heating configurations comprised of a "behind the meter" CHP unit along with an auxiliary heating system (**Figure 9**). For both configurations, the CHP unit produces electricity and heat at an assumed fixed heat-to-power ratio which will be different depending on the prime mover technology. In the case that the generated electricity is beyond the on-site demand, the excess power is fed back to the grid. Alternatively, if the produced electricity is below on-site demand level then supplementary power is acquired from the grid to cover any deficit. On the heating side, both configurations include supplemental firing that supports the CHP operation in those situations where additional heat is needed by the consumer.

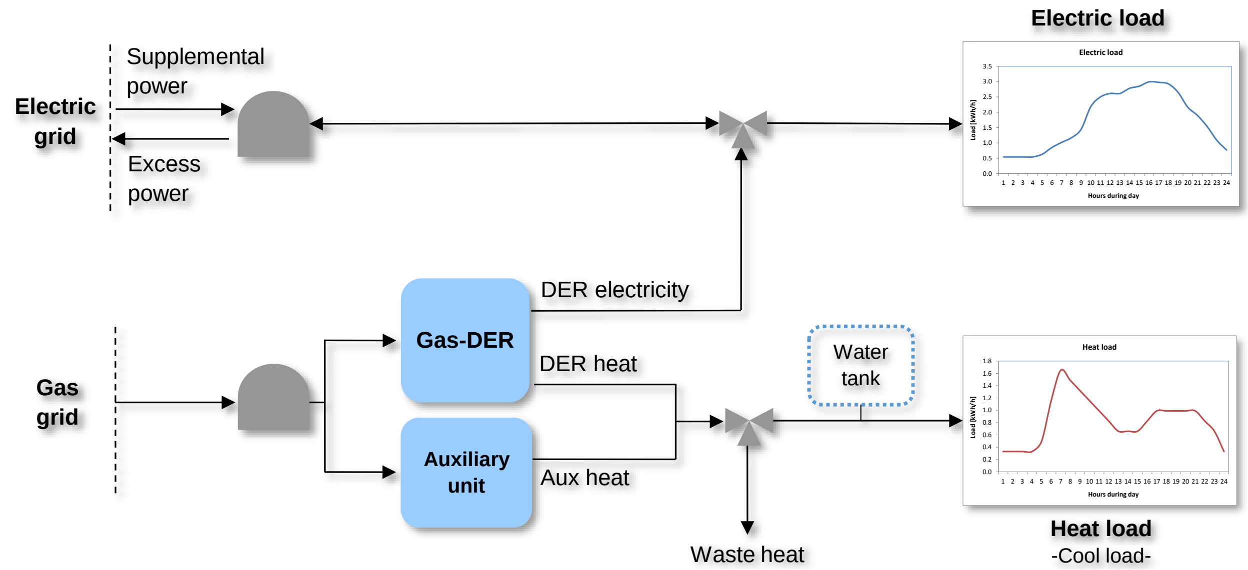

Figure 9: Heating and electric systems using a CHP unit.

The first configuration is the so-called forced hot air configuration and includes a tank-less (on-demand) hot water heater. The second configuration is the so-called hydronic configuration and comprises an auxiliary boiler that delivers heat to a hot water tank. The heat from the tank can be later used for space heating and domestic hot water. The tank provides flexibility to the heating system to store heat and using it later when needed. In this case, the dynamics of the storage unit should be included in the formulation, i.e. the amount of heat that needs to charge or discharge from one hour to the next one. The hydronic configuration also allows including an absorption chiller after the water tank to provide cooling.

Based on this, the mathematical formulation represents a least-cost operation of a CHP unit at residential level subject to on-site energy load conditions. This means that a consumer operates the CHP only if it is more cost-effective than buying electricity and gas from the utility company. As shown in the figure above, some of the decision variables include electric power imported from the grid, excess power fed back into the grid, generated power and heat from the CHP unit, heat from the furnace, and any excess heat beyond on-site heat demand.

7.1. Nomenclature

Indexes

i	Hour
I	Total number of hours
m	Month
M	Total number of months

Data

ic_e^{chp}	Total installed cost for CHP unit

ic_{th}^{aux}	Total installed cost for auxiliary heating system
crf^{chp}	Capital recovery factor for CHP unit
crf^{aux}	Capital recovery factor for auxiliary heating system
pf_i	Retail fuel price
pe_i^{imp}	Retail electricity price
pe_i^{exp}	Selling electricity price
$pe_m^{contracted}$	Electricity contracted price
p^{CO2}	Price for CO2 emissions
ef_{NG}^{CO2}	CO2 emission factor for natural gas
ef_{system}^{CO2}	CO2 emission factor for system marginal plant
e_i^{light}	Light and other non-heating uses hourly load profile
h_i^{water}	Hot water hourly load profile
$\underline{T}^{space}, \overline{T}^{space}$	Comfort space interval temperature
$T_i^{outdoor}$	Outdoor temperature
R^{space}, C^{space}	House indoor thermal characteristics
$\underline{T}^{water}, \overline{T}^{water}$	Water interval temperature
C^{water}	Heat requirement to increase one degree water tank volume
α	Heat-to-power ratio of CHP
mt^{chp}	CHP unit minimum technical
mt^{aux}	Auxiliary heating system minimum technical
η_e^{chp}	Electrical efficiency for CHP unit
η_{th}^{chp}	Thermal efficiency for CHP unit
η_{th}^{aux}	Thermal efficiency for auxiliary heating system
om^{chp}	O&M cost for CHP unit
om^{aux}	O&M cost for auxiliary heating system

Decision variables

vE_i^{chp}	Hourly generated power by CHP unit
vH_i^{aux}	Hourly generated heat by auxiliary heating system
vT_i^{space}	Hourly house indoor temperature
vT_i^{water}	Hourly water temperature
vE_i^{imp}	Hourly electricity imports from grid
vE_i^{exp}	Hourly electricity export to grid
$vH_i^{chpwaste}$	Hourly heat waste from CHP unit

vIC_e^{chp}	Installed electric capacity of CHP unit
vIC_{th}^{aux}	Installed thermal capacity of auxiliary heating system

Dependent variables

vH_i^{space}	Hourly space heating requirement
$vH_i^{cooling}$	Hourly space cooling requirement

7.2. Objective function

The formulation maximizes the profits or alternatively minimizes the annual energy costs associated to the energy needs of a consumer in a particular building. These annual costs are given by gas-DER capital and operational expenditures, emission costs if a tax is charged on customers, and expenditures (or revenues) associated to utility purchases (or sales).

$$Min\,TAC = \left[C^{opex} + C^{capex} + C^{emissions} + C^{utility} - S\right]$$

Operational costs include production costs that will depend on the quantity of fuel and cost of fuel. Also, this term includes O&M costs which account for the costs related to the service contracts offered by manufacturers that normally cover both scheduled and unscheduled events. For simplicity, O&M costs be recalculated in terms of power production:

$$C^{opex} = \sum_{i=1,I}\left[g\left(vE_i^{chp}\right)\times pf_i + g\left(vH_i^{aux}\right)\times pf_i\right] + \sum_{i=1,I}\left(vE_i^{chp}\times om^{chp} + vH_i^{aux}\times om^{aux}\right)$$

Capital costs include investment and annual fixed costs. The relevant economies of scale suggest the utilization of a cost function that depends on the level of investment[22]. However, as a first approach, in this work we will define the investment decision variable for the most common size(s) of the equipment when applicable (for example, for microturbines we will define variables for 30kW, 250kW, etc.):

$$C^{capex} = \left(vIC_e^{chp}\times crf^{\,chp}\times ic_e^{chp}\right) + \left(vIC_{th}^{aux}\times crf^{\,aux}\times ic_{th}^{aux}\right)$$

Emissions costs include costs associated with CO2 and NOX emissions, which are considered proportional to the energy production. These will represent an additional costs to consumers, if an emission price is set in the market:

$$C^{emissions} = \left[\sum_{i=1,I}\left(g(vE_i^{chp})\times ef_{NG}^{CO2}\right) + \sum_{i=1,I}\left(g(vH_i^{aux})\times ef_{NG}^{CO2}\right)\right]\times p^{CO2}$$

[22] This approach would however introduce a non-linear term $A/x^{0.2}$, where x is the investment level.

Utility costs term includes both consumer's expenditures associated to utility purchases or revenues when selling back to the system:

$$C^{utility} = \sum_{i=1,I} \left(vE_i^{imp} \times pe_i^{imp} \right) - \sum_{i=1,I} \left(vE_i^{exp} \times pe_i^{exp} \right)$$

We note that any additional benefits will be included in the formulation in the case of any relevant production, investment or other type of subsidy.

As we observe, fuel expenses is the main component within operational costs. In general, fuel consumption will depend on how efficient the DER technology is under different operating levels. As a first approach, we can express fuel consumption for a gas DER unit and a gas furnace system as a linear expression that depends on the energy production:

$$g\left(vE_i^{chp}\right) = \frac{vE_i^{chp}}{\eta_e^{chp}\left(vE_i^{chp}\right)} \approx A + B \times vE_i^{chp}$$

$$g\left(vH_i^{aux}\right) = \frac{vH_i^{aux}}{\eta_{th}^{aux}\left(vH_i^{aux}\right)} \approx \frac{vH_i^{aux}}{\overline{\eta}_{th}^{aux}}$$

Finally, this formulation ignores ramp times and start-up costs.

7.3. Constraints

Several constraints need to be included in the model formulation in order to get a more realistic representation. First, the heat-to-electricity relationship in CHP applications is key if a DG is connected to a heat exchanger, which it is assumed constant following the linearization of the efficiency curves of the technology being represented.

$$\alpha = \frac{\eta_{th}^{chp}}{\eta_e^{chp}}$$

The heat output will be proportional to the electricity produced by the CHP. Thus for example, a machine with $\alpha = 2.7$ will generate 2.7 units of heat for every unit of produced electricity (on an energy equivalent basis). This formulation assumes that efficiency is constant. However, and depending on the technology being used, the electrical efficiency could vary with the unit size and operating load levels. For instance, for ICEs efficiency is lower for small size units and for operating levels below 50%.

$$vH_i^{chp} = \alpha \times vE_i^{chp}$$

The electricity balance considers not only on-site electric load e_i^{load} and the electricity generated by the system vE_i^{chp}, but also any potential import or export of electricity from and to the grid given by vE_i^{imp} and $vE_i^{\exp}$ respectively. Under this formulation, it is not possible to have imported and exported power during the same hour i.

$$vE_i^{chp} + vE_i^{imp} - vE_i^{exp} = e_i^{load}$$

$$0 \le vE_i^{imp} \le \min(0, e_i^{load} - vE_i^{chp})$$

$$0 \le vE_i^{\exp} \le \min(0, vE_i^{chp} - e_i^{load})$$

Regarding heat balance, we have two configurations. The expressions below which represent the forced hot air configuration, take into account on-site hot water load h_i^{load} covered by an auxiliary heating unit[23] vH_i^{aux}. The heat generated by the CHP system vH_i^{chp} and excess heat $vH_i^{chpwaste}$ in the event that the CHP unit produces more heat than the required one to maintain the indoor temperature between the set comfort limits $\left(\underline{T}^{space}, \overline{T}^{space}\right)$. This excess will be released into the atmosphere when needed.

$$vH_i^{aux} = h_i^{load}$$

$$vH_i^{chp} - vH_i^{chpwaste} = vH_i^{space}$$

On the other hand, the following expression corresponds to the hydronic configuration. The heat generated by the CHP system vH_i^{chp} and by an auxiliary heating unit vH_i^{aux} is used for maintaining the water temperature within the range. The excess heat $vH_i^{chpwaste}$ in the event that the CHP unit produces more heat than the required one will again be released into the atmosphere. The generated heat is used for space heating or cooling, and hot water needs.

$$vH_i^{chp} + vH_i^{aux} - vH_i^{chpwaste} = C^{water} \cdot \left(vT_i^{water} - vT_{i-1}^{water}\right) + vH_i^{space} + vH_i^{cooling} + h_i^{load}$$

The relationship between the space heating/cooling is given by the below expression. Heat is converted to cold through an absorption chiller, which is simplified into its COP parameter (≈ 0.7).

$$vH_i^{space} - COP^{cooling} \cdot vH_i^{cooling} = C^{space} \cdot \left(vT_i^{space} - vT_{i-1}^{space}\right) - R^{space} C^{space} \cdot \left(T_{i-1}^{outdoor} - vT_{i-1}^{space}\right)$$

[23] Electric heating pumps are omitted in the formulation as this paper only considers gas-based technologies, but they may be present to provide additional space heating and also air conditioning.

The operating limits of the various equipment used in the building are given by the manufacturers' size and any technical minimum. A semi-continuous variable is used to define the output of the CHP and auxiliary heating devices. Thus, the output could adopt a continuous value between its minimum level and maximum levels, or zero in the case of the output being lower than the acceptable minimum operational level[24].

$$mt^{chp} \times vIC_e^{chp} \leq vE_i^{chp} \leq vIC_e^{chp} \quad \text{or} \quad vE_i^{chp} = 0$$

$$mt^{aux} \times vIC_{th}^{aux} \leq vH_i^{aux} \leq vIC_{th}^{aux} \quad \text{or} \quad vH_i^{aux} = 0$$

Finally, all the decision variables are non-negative.

$$vE_i^{imp}, vE_i^{\exp}, vE_i^{chp} \geq 0$$

$$vH_i^{aux}, vH_i^{chpwaste}, vH_i^{space}, vH_i^{cooling} \geq 0$$

$$vIC_e^{chp}, vIC_{th}^{aux} \geq 0$$

[24] Minimum load requirement will be different depending on the technology being used, and it is required to maintain a reasonable electrical efficiency level of the system.