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# Domestic Micro-cogeneration: A High Efficiency, Cost Effective, Simple Solution

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## ABSTRACT

A new, patented concept for a small cogeneration system is introduced in this paper. A small turbogas driven generator is inserted into the cold air duct of a condensing heating boiler for domestic use. The electric production takes place only when heating is active in winter. The turbogas exhaust and the cooling air are ingested by the burner of the boiler giving to the electric unit a nearly unitary efficiency. The generator is very small when compared to the total power of the system. The heat to electric power ratio is more than twenty. In this way it is possible to run the turbogas-generator unit always at full power. Even if the turbogas needs a biennial replacement, the economical balance of the system is very convenient. In addition, the heating boiler does not necessitate of an external electric power supply. Therefore, it will run even in case of black-out. The reliability of the original heating boiler is preserved. In fact, in case of turbogas failure, the heating boiler is identical to the traditional unit. The simultaneous production of electrical and thermal energy from a single fuel source increases efficiency and reduces greenhouse gas emissions.

## 1. INTRODUCTION

Residential cogeneration or microcogeneration or small-scale-combined-heat-and-power is a research field with a high potential to deliver huge combined economical and environmental benefits. The simultaneous production of electrical and thermal energy from a single fuel source can increase efficiency and largely reduces greenhouse gas emissions. The distributed generation of the electric power also has the potential to reduce grid losses, installation and maintenance costs, alleviating peak power demand problems. In Italy the majority of domestic users has natural-gas-fired/LPG boiling-heaters under 24 kW and installed electric power under 2.5 kW. Several technologies have been used in the past for this purpose: proton exchange membrane fuel cells, solid oxide fuel cells, Stirling engines and internal combustion engines. The residential cogeneration industry is in an early stage of development. The products on the market are immature, but interest in this field by end users, manufacturers, government agencies and energy utilities are strong. Typically, the electric generators for domestic applications have modest efficiency. Therefore, it is imperative to use the wasted heat energy in the thermal portion of the cogeneration output for heating space and hot water. Unfortunately, the domestic thermal energy utilization is complicated by strong coupling between the cogeneration unit, environmental heating, ventilation and air conditioning electrical demands. In Italy there are more than 27 million residential buildings that are used for residential purpose with 22 million of them that are regularly lived and heated. The main part of them are single family houses, while the remaining 900.000 are multifamily residence. The square footage can be used to calculate annual electric demand while the geographical location adds indication of heat loads. In the solution described in this paper, the micro cogeneration unit is installed in the house as a substitution of traditional heating boiler and supplies energy to the heating system and to the house. A secondary boiler supplies the hot water when the heating is very low or not required. The power grid is still connected to receive the excess of electric energy generated by the micro-cogeneration-unit, to compensate energy surges and for electricity during summer. An insulated-tank may be used as thermal energy storage permitting to have a delay between produced heat and used hot water and to compensate occasional thermal request surges. A separated tank in the unit may provide also hot water. The dispatch strategies of heat and electric power should be separated. However, the system operates only when a heat load is required. The system may also operate so to minimize $CO_2$ emissions. The micro-generation system needs an electricity grid connection because prolonged peak requests at 2.5 kW requires a huge battery storage that can be justified only when other energy supply system are available, for example solar panels. This solution is the more convenient for the Italian regulations. In Italy, the grid connection system can have priority distribution with net metering [1]. Therefore, the user has no need to produce all the electricity required because the final balance is realized yearly. It is not convenient to produce more electric energy than the consumed one: the target is to produce the user year electricity demand. From statistical data it is not necessary to have a generator that exceeds 1 kW. This brings to very small generators even if the system operates only in winter, at least in the northern part of Italy. This solution also means that no modulation of the electric generation system is required. This is particularly advantageous since in many cases electrical and thermal loads are alternated. For example, domestic lighting and appliance demands peak in the evening while heating is slightly reduced for the incoming night.

## 2. THE PROPOSED, PATENTED SOLUTION

The patented solution [2] introduced in this paper starts from condensing heating boilers used in most of Italian houses (Figure 1). They are designed to supply hot water for heating and domestic use. Two heat exchangers in serial arrangement cool down the exhaust gases produced by a burner. The burner is optimized for emissions and efficiency, therefore metering systems in the LPG/CNC and air supply are always present. The forced air mass flow entering in the boiling unit is accurately measured and a defined quantity of fuel is mixed to this air. A few of these boilers have a lambda sensor to check the combustion efficiency. The solution proposed in this paper is to insert an Internal Combustion Engine (ICE) driven generator inside the “fresh” air duct. The ICE uses the cold air for combustion and cooling, while the exhaust becomes part of the oxydizing gas supplied to the boiling unit. In this way, the efficiency of the ICE-generator is nearly unitary. In fact, the cold air cools down also the generator and the power converter to the national power grid. The oxidizing gas enters the heating unit with a temperature well below the maximum allowed for the heating system, in fact the difference of power output between the heating boiler and the ICE-generator is approximately 24: 1. Even at lower heating loads, the difference is large and only at very reduced heating demand, it is necessary to reduce the electric power output. The inlet duct of the air supply to the heating boiler should be replaced to assure room to the ICE-generator and to allow the higher temperatures in the air inlet duct.

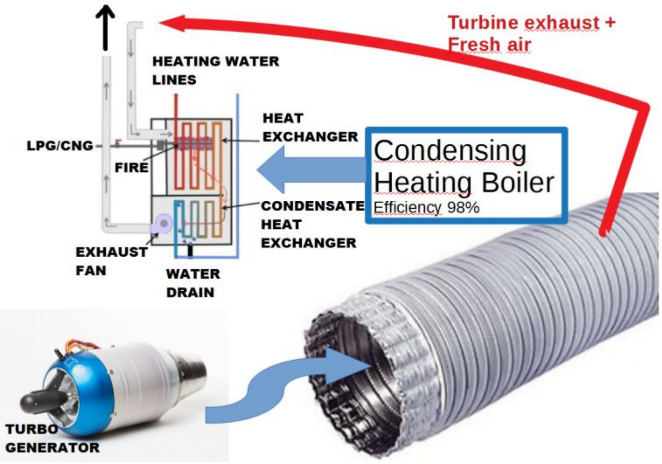

**Figure 1.** The proposed solution

## 3. THE CHOICE OF THE ICE TYPE

Two different solutions are available for the electric power generator: piston engines and turbogas. Figure 2 shows a 1 kW piston-engine-generator. With the very high octane natural gas, its Brake-Specific Fuel Consumption is ***BSFC***=220 gr/kWh. Therefore, its efficiency is more than $\eta$=37% (1).

$$\eta = 1/(\mathrm{BSFC} \times 0.0122225) \approx 0.37 \tag{1}$$

However, it lasts only 300 h (or 12 days) of continuous run with meanwhile spark plug replacement. It also needs separated lubrication. A microturbine-generator with externally pressurized gas bearings lasts up to 5,000h or 6 months continuous run. In Bologna (Italy) the heating boilers are fired by Law from October, 15th to April, 15th or 182 days. The heating can be used for 14 h a day for a total of 2,548 h. The microturbine-generator would last 2 years, that is the minimum maintenance interval required by the heating boiler. Unfortunately, its efficiency is very low, with BSFC=900 gr/kWh and $\eta_T$=0.9 or 9 %. In our cogeneration system this is not really a problem since the wasted heat energy is completely recycled inside the heating-boiler. Even the high temperature of the exhaust is acceptable, since the input air ventilation is forced and fresh air can be mixed to reduce the maximum temperature to the best one for the heating boiler. The problem is the minimum boiler heat-energy output with the generator running at maximum rated power (1 kWe).

**Figure 2.** The 1 kWe piston engine generator

In this case, having an average efficiency of the heating boiler at lower energy output of $\eta_B$=0.9, the minimum heat-energy output will be $E_{heat,min}$=10 kW (2).

$$E_{heat,\min} = \frac{P_e}{\eta_T}\eta_B = 10[kW] \tag{2}$$

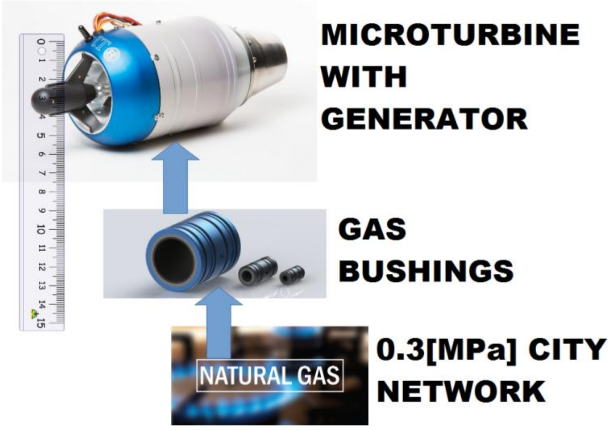

**Figure 3.** The 1 kWe micro turbine generator (example)

Therefore, if the heating energy required is less than 10 kW the electric energy output should be reduced. In any case, the electric power output is sufficient for the boiler-heating requirement. Therefore, the boiler heating can be installed in areas without electric energy supply and it will be protected from black-outs. Figure 3 shows an example of microturbine. A tiny generator should be added to the turbogas between the starter motor (black in front of the air intake) and the compressor. The gas bushings can be pressurized directly by the city network pressure or a small compressor can be installed. Magnetic and gas-dynamic bushings are commercial available, but their reliability is unknown to the Author. An electronic unit that converts the power output to the national-power-grid standard is also necessary. Even if the dissipation of this unit is very small, also its cooling can be made with the fresh air to the heating boiler.

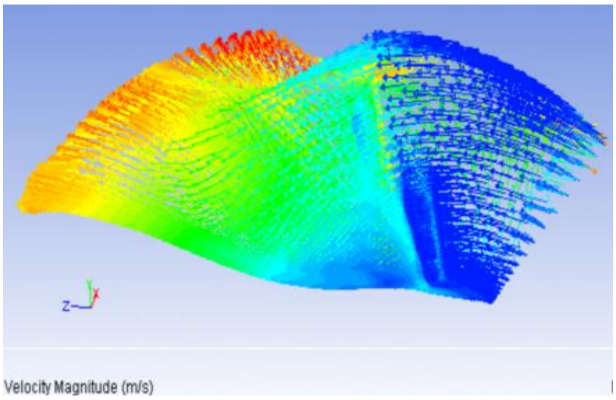

**Figure 4.** Velocity pattern simulated in a centrifugal compressor vane

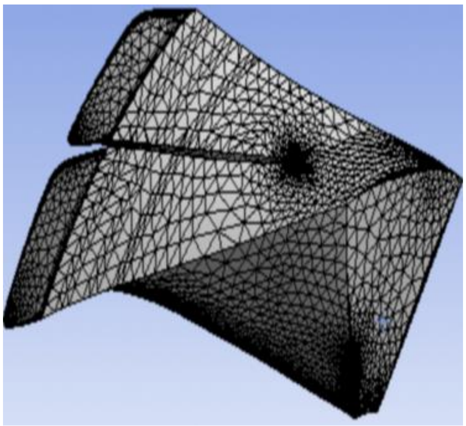

**Figure 5.** Computational domain of the CFD simulation of Figure 4

## 4. SMALL TURBOGAS DESIGN

The design of a small turbogas unit is quite straightforward with modern CFD (Computational Fluid Dynamic) and FEA (Finite Element Analysis) software available in modern CAD/CAE (Computer Aided Design/Computer Aided Engineering) software. The progressive downsizing and diffusion of turbochargers in automotive ICEs has introduced new and proven technologies to mass produce very small turbogas units. At the same time, the mass production of modern jewellery makes it possible to manufacture very small parts of outstanding quality in large numbers. Turbojets for RC (Radio Controlled) models are commercially available. These units usually combine a radial compressor to an axial turbine. The radial compressor is less critical than the axial one and it can reach the required compressor ratio, usually slightly inferior to 2, in a single stage. The axial turbine avoids the curved paths for hot gases of the radial ones. This mixed arrangement (radial compressor and axial turbine) makes it possible to design a compact and extremely stable unit. The reliability is affected by the problems of the roller bearings, usually with ceramic balls and steel races. These units need separate lubrication and suffer of thermal cycling. Fully ceramic bearings still suffer of reliability issues. The installation of a pressure gas bearing units solves the problem. If the design is correct and the unit is well balanced, the axial and radial loads are very small. Maximum rotational speed ranges from 100,000 to 170,000 rpm and usable range is from 70 % to 100 % rpm. The efficiency of these small turbogas cannot be high, since the gap between blade tip and casing is quite large in comparison to the compressor and turbine blade size. Another limitation is given by the blade thickness that is also proportionally large. However, it is possible to design the system quite easily. Modern CFD [3-4] is able to predict compressor performance in term of pressure and speed quite reliably (Figures 4-5). Compressor and turbine maps can be easily simulated. Efficiency is more difficult to evaluate because the diffuser is of paramount importance and a complete system evaluation is computationally prohibitive [5-10].

## 5. SYSTEM DESCRIPTION

An example of a possible bill of materials for the cogenerative system is summarized in Table 1.

**Table 1.** Itemized list (bill of materials) of the main components

| Item | Power [kW] | Efficiency [%] |
|---|---|---|
| Condensing Heating Boiler | 23.7 ($\boldsymbol{P_H}$) | 98 ($\boldsymbol{\eta_H}$) |
| Generator | 1.1 ($\boldsymbol{P_e}$) | 9 ($\boldsymbol{\eta_T}$) |
| Inlet air fan | 0.1 ($\boldsymbol{P_F}$) | - |

The global efficiency of the system of Table 1 at maximum power output of the APU (Auxiliary Power Unit i.e. turbine generator) can be calculated as follows: the net power output from the APU will be $\boldsymbol{P_{APU}}$=1 kW (3).

$$P_{APU} = \mathrm{P}_e - P_{\mathrm{FAN}} = 1[kW] \tag{3}$$

In fact, the net electric power form the APU ($\boldsymbol{P_e}$) should be used to energize the cold air fan ($\boldsymbol{P_{FAN}}$). Therefore, net power output of the APU and the boiler will be $\boldsymbol{P_{max}}$=24.7 kW. The amount of heat energy coming from the APU to the boiler will be $\boldsymbol{P_{heat,APU}}$=11.1 kW (4).

$$P_{heat,APU} = \frac{P_e+P_{FAN}}{\eta_T} = 12.2[kW] \tag{4}$$

At this power the burner of the boiler will be inactive and the efficiency will be $\boldsymbol{\eta_{Total}}$=0.99 (5).

$$\eta_{\mathrm{Total}} = \frac{P_{\mathrm{heat,APU}}\eta_H+P_e}{P_{\mathrm{heat,APU}}} = 0.99 \tag{5}$$

At full power of boiler and APU the efficiency will be slightly less. The amount of burner heat energy required by the boiler at maximum rated power is $\boldsymbol{P_{heat,BOILER}}$=24.16 kW (6).

$$P_{heat,BOILER} = \frac{P_H}{\eta_H} = 24.16[kW] \tag{6}$$

At maximum power the efficiency will be $\eta_{Total}$=0.98 (7).

$$\eta_{\text{Total}} = \frac{P_H + P_e}{P_{\text{heat,BOILER}} + P_e + P_{FAN}} = 0.98 \qquad (7)$$

Therefore, the system produces electrical energy with at least 98 % of efficiency. Table 2 and Figure 6 summarize the efficiency and calculation results.

## 6. THE INTEGRATION STUDY

The proposed cogeneration system should substitute the traditional boiler in the heating system. A few cogeneration system operating strategies are present in literature. They depend on type of contract, loads and energy storage. These systems are electricity-led, where the unit operates when electrical load is present, or heat-lead where the system operates when heat load is required. Additional strategies are aimed to minimize the cost of operation or $CO_2$ emissions.

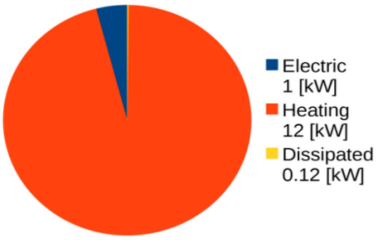

**Figure 6.** Pie chart of the cogenerative system at maximum efficiency

**Table 2.** A few data calculated on the example of par. 3

| Description | (Symbol) | Value [Unit] |
|---|---|---|
| Electrical efficiency at full thermal power (23.7 kW) | $\eta_{eF}$ | 98 [%] |
| Electrical efficiency at optimum thermal power (12 kW) | $\eta_{e,O}$ | 99 [%] |
| Thermal efficiency | $\eta_{tCHEP}$ | 98.1 [%] |
| Thermal to electric ratio | $TER$ | 23.7 |
| Thermal to electric efficiency ratio | $TER\eta$ | 1 |
| Yearly ratio between operating hours and the total one (24hx365gg) | $OT$ | 0.3 |

In our case the system is heat-lead because it was originally conceived to keep the heating system working in case of black-out. The system introduced in this paper purchases thermal energy when required and it is always connected to the national electric power network. In fact, produced electricity is send directly to the grid. This choice is related to the Italian grid rules and requirements. Italy has a priority distribution with a tariff scheme based on net metering. This energy balance is realized at the end of the year with additional costs if the energy used exceeds the one produced. The yearly electrical demand is the boundary condition because there is not an economical advantage in producing more electricity than user's necessity. Our system does not need to use a thermal heat storage for problems with thermal cycle or long start-up time. However, the system necessitates of a minimum operating heating power and it has also and optimum power output, that is when the APU is at full power and the boiler burner is not working. The system will work only when the heating system is active. The OT (Operating Time) is calculated for Bologna (Italy). To compare our Cogeneration Heat-Electric Power system (CHEP) to standard production of electricity and heat, a few parameters can be calculated [1]. The Primary Energy Save (PES), is the ratio between the CNG saved over the standard production. In the case of full power output, our CHEP has a PES of 0.686 (8).

$$PES = 1 - \frac{1}{\frac{\eta_{eF}}{\eta_e} + \frac{\eta_{tCHEP}}{\eta_t}} = 0.686 \qquad (8)$$

The PES at optimum power output is 0.689 (9),

$$PES = 1 - \frac{1}{\frac{\eta_{eO}}{\eta_e} + \frac{\eta_{tCHEP}}{\eta_t}} = 0.689 \qquad (9)$$

where $\eta_e$=0.5 is a national standard for electric energy production and $\eta_t$=0.9 is the average efficiency of a condensing heating boiler. The Cogeneration Economical Save (CES) is the ratio between the cost saved over the cost of traditional solution. In this equation $\boldsymbol{R}$=0.4 is the ratio between energy cost per kWh for heat and electricity produced with natural gas. At full power the CHEP has a $\boldsymbol{CES}$=0.727 (10).

$$CES = 1 - \frac{1}{\frac{\eta_{eF}}{R} + \frac{\eta_{tCHEP}}{\eta_t}} = 0.727 \qquad (10)$$

At optimum power the CHEP has $\boldsymbol{CES}$= 0.729 (11).

$$CES = 1 - \frac{1}{\frac{\eta_{eO}}{R} + \frac{\eta_{tCHEP}}{\eta_t}} = 0.729 \qquad (11)$$

Table 3 reports a few data for comparison taken from Ref. [1]. PEM are Polymeric Electrolyte Membrane fuel cells and SOFC are Solid Oxide Fuel Cells.

**Table 3.** PES and CES of a few cases form Ref. [1]

| Technology | $\eta_e$-$\eta_t$ | PES-CES |
|---|---|---|
| ICE | 0.3-0.6 | 0.21-0.3 |
| Stirling | 0.1-0.8 | 0.08-0.13 |
| PEM | 0.4-0.5 | 0.26-0.37 |
| SOFC | 0.5-0.4 | 0.31-0.42 |

## 7. AN EXAMPLE

Our test case is a 200 m$^2$ single family house with eight people, located in Bologna (Italy): climate area E. A total yearly electric demand is 5,000 kWh from Ref [11]. Space heating is a very spread parameter because it depends on the building insulation properties and family habits. An average value of 175 kWh/m$^2$ is common in Literature. Table 4 summarizes the data for this example. The heating time can be easily calculated by the number of days in which heating is allowed by Law. Heating is allowed for 14 hours per day. The average heating power demand is therefore $P_{h\_ave}$= (12).

$$P_{h\_ave} = \frac{H_{\text{total}}}{T_{\text{heating}}} = 13[kW] \quad (12)$$

**Table 4.** Itemized list (bill of materials) of the main components

| Item | Quantity (Symbol) | Unit |
|---|---|---|
| House floor area | 200 | $m^2$ |
| Heating demand | 35,000 ($H_T$) | kWh per year |
| Electricity demand | 5,000 | kWh per year |
| Heating time | 2,548 ($T_{heating}$) | Hours x year |
| Average heating power | 13 | kW |

During the 2,548h of heating time the system will produce 2,548 kWh. A family will therefore save about 500 Euro per year with a cost of 0.2 Euro per kWh. The industrial cost of the cogeneration system is below 100 Euro per unit for a mass produced system of more than 1,000,000 units per year. Every two years the turbo-generator should be replaced. Even if the spare part is sold at five times the cost, the family of our example will save approximately 200 Euro per year. Therefore, this cogenerative system seems to be convenient.

Table 5 summarizes costs and savings for a 6 years use of the cogeneration system. The industrial cost of the cogeneration system is around 100 Euro. Therefore, it is possible to assume that the additional purchase and the successive replacement cost will be of 500 Euro. The first column is referred to a cash payment, the second one (Loan 1) is for 3 loans of 500 Euro for the buy and the two-biennial replacement of the turbogas. The third (Loan 2) is for a single loan for the whole amount at the purchase of the unit (1500 Euro).

**Table 5.** Savings with the cogenerative system

| Year | Saving (Euro) Cash | Saving (Euro) Loan 1 | Saving (Euro) Loan 2 |
|---|---|---|---|
| 1 | 0 | 389 | 166 |
| 2 | 500 | 389 | 166 |
| 3 | 0 | 236 | 166 |
| 4 | 500 | 236 | 166 |
| 5 | 0 | -40 | 166 |
| 6 | 500 | -40 | 166 |
| **Total** | **1500** | **1170** | **996** |

## 8. CONCLUSIONS

The cogeneration system proposed for domestic heating boilers is relatively simple. A small turbogas generator is installed in the cold air duct of the heating boiler. The cold air supplies the air to the turbogas and to the boiler. In this way all the heat dissipated by the turbo-generator is recycled in the heating unit. Therefore, the efficiency of the generator is nearly unitary. In this way several advantages are achieved. The heating boiler is protected from black-outs, since the generator can keep the electric supply to the boiler. The heating unit conserves the original reliability in case of failure of the turbogas. In Italy, the generated electric energy can be directly put into the national grid. At the end of the year, a balance between the produced and consumed energy is made to calculate the difference to be paid. However, the electric energy is produced only when the heating system is active. This means that it works only during winter. In addition, the turbogas should be replaced every two years with additional costs. In any case, in the example introduced in this paper, the economic advantage is huge. The global advantage to the national energy production is large, since the distribution losses are reduced to a minimum and the electric energy is produced with nearly unitary efficiency.

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## NOMENCLATURE

| | |
|---|---|
| $P_e$ | Gross electric power kW |
| $\eta_T$ | Turbogas efficiency |
| $\eta_B$ | Heating boiler efficiency |
| $E_{heat,min}$ | Min heat @ max. turbogas kW |
| $P_{APU}$ | Net electrical power output kW |
| $P_{FAN}$ | Power absorbed by cold air fan kW |
| $P_H$ | Max heating power of boiler kW |
| $\eta_{Total}$ | Efficiency of the whole apparatus |
| $P_{heat,BOILER}$ | Max boiler burner power kW |
| $\eta_H$ | Condensing heating boiler efficiency |
| $\eta_{eF}$ | Efficiency of the whole apparatus (CHEP) at maximum output power |
| $\eta_{eO}$ | Max. efficiency of the whole apparatus (CHEP) |
| $\eta_e$ | National standard efficiency for electrical production |
| $\eta_t$ | Standard efficiency for cogenerative heating boilers |
| R | Cost of electric kW over cost of heating kW |
| $\eta_{tCHEP}$ | Thermal efficiency of the apparatus (CHEP) |
| $P_{h\_ave}$ | Average heating power demand kW |
| $H_{total}$ | Total heating energy per year kWh |
| $T_{heating}$ | Heating time per year h |