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Parametric study of the operational and economic feasibility of Stirling microcogeneration devices in Spain

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ABSTRACT

This paper analyses the operational and economic viability of Stirling engine-run micro-cogeneration units in single-family houses in Spain. Thermal demands for the reference dwelling, sited in three different and representative climatic zones, are obtained based on heating and domestic hot water requirements. By carrying out dynamic simulations of both the conventional and cogeneration installations, their performances are obtained and compared. Additionally, based on the results obtained in the simulations, economic viability of the Stirling engine-based micro-CHP is evaluated, taking into account Spanish regulation and economic framework, particularly fuel and electricity prices.

Finally, a sensibility study is carried out in order to evaluate how economic results of these plants are affected by both variations in fuel and electricity prices as well as in initial investment costs.

It is concluded that there is no opportunity for these devices to be feasible in new and retrofitted single-family dwellings sited in any climatic zone of Spain but in the coldest ones, where the micro-CHP plants could become viable if the Stirling engine investment cost decreases.

Keywords: Stirling micro-CHP; dynamic simulation; viability; single-family dwelling; Spain.

Nomenclature

C_F	cost of the natural gas consumption (€)
C_M	cost of operation and maintenance (€)
E	electricity produced by the cogeneration unit (kWh)
F	natural gas used by the cogeneration unit (kWh)
H	heat produced by the cogeneration unit (kWh)
i	annual hour
I_{AC}	cost of the natural gas avoided consumption (€)
I_E	avoided costs owed to sales and self-consumption of the electricity generated in the µCHP (€)
Inv	total investment (€)
LT	lifetime (years)
NPV	net present value (€)
NS	annual net savings (€)
PES	primary energy saving
r	ratio of discount
$RefE_\eta$	harmonised efficiency reference value for separate production of electricity
$RefH_\eta$	harmonised efficiency reference value for separate production of heat
t	year of operation of the plant

Abbreviations

CS	climatic severity
CTE	Technical Building Code
DHW	domestic hot water
ECBCS	Energy Conservation in Buildings and Community Systems Program
GHG	greenhouse gas
GWP	global warming potential
IDAE	Institute for Energy Diversification and Saving
IEA	International Energy Agency
LCA	life cycle assessment
LCI	life cycle inventory
RD	Royal Decree
µCHP	micro combined heat and power

1. INTRODUCTION

Nowadays all countries are developing sustainable energy policies to reduce energy consumption in buildings, and to produce that required amount of energy in a more efficient way. Thus, technologies such as micro-cogeneration, which has been developed and promoted during the last years, become an attractive alternative to conventional energy plants for fulfilling energy demands in residential buildings, as they feature many environmental, functional and economic advantages [1-3].

Stirling engine-based micro-CHP devices are becoming a widespread solution for supplying heating, domestic hot water (DHW) and electric power in dwellings, as they feature not only the advantages of CHP but also the benefits of Stirling technology, such as carbon dioxide low emissions, low noise and vibration-free operation, and multi-fuel capability [4,5]. Such devices are mainly designed to be used in single-family houses, so that most part of thermal and electric demands can be covered. As mentioned by Van Bael et al. [6], many field tests and research projects executed in several countries reveal that this technology provides potential benefits in domestic using. Ren et al. [7] affirm that currently five countries – Japan, Germany, United Kingdom, Netherlands and United States – are the most actively involved in researching and introducing these gas-fired systems in the market. In this sense, Kuhn et al. collect in [2] results of field tests carried out with different Stirling micro-cogeneration devices in various regions of Germany, as well as in other countries such as United Kingdom, France and the Netherlands, reaching satisfactory results for small-scale applications.

Alanne et al. [8] carried out a simulation-based techno-economic assessment of a Stirling micro-CHP device installed in a single-family house located in Finland, achieving 3-5% decrease in primary energy consumption and CO_2 emissions compared to a traditional heating system, and obtaining substantial economic savings. More recently, Magri et al. [9] developed an economic and energetic performance analysis of a Stirling engine with an electric output of 1 kW, installed in a detached house in Italy. Results show that installing the studied system leads to reducing primary energy consumption and greenhouse gas emissions, as well as obtaining economic benefits. In the case of Spain, no significant research has been developed in this area, so the building-integrated performance of this technology is rather unknown.

Despite the satisfactory results obtained through the researches carried out, there are still many market entrance barriers, and this kind of equipment is only commercially available in a few countries all over the world.

There are several Stirling engines developed in a wide range of power capacities. Free piston Stirling engines cover an electric power range from approximately 1 to 25 kW, representing a suitable technology for small micro-cogeneration applications [1]. Nowadays, there are some commercially available Stirling engine-based µCHP systems, such as Ecogen™ and eVita™ of BDR Thermea® or Whispergen EU1™ by Whispertech® [10], being the most spread and characterized one the latter. This unit is based on a four cylinder alpha kinematic engine. Detailed information about the Stirling cycle and its configurations can be found in [11].

In this paper, a study that constitutes a first step in estimating the techno-economic potential of the Stirling engine-run micro-CHP devices is developed for residential buildings in Spain, approaching the case of new constructed and retrofitted detached houses. The work aims to provide a global view of the performance and economic results this technology can achieve in a Spanish generic single-family dwelling, distinguishing among different representative climatic zones, and considering both present and possible future economic and regulatory conditions.

This article is organized in five main different sections, as follows: Section 2 provides an overview of the current normative and economic framework for cogeneration in Spain. Section 3 provides a description of the characteristics of the building and its use and the climatic conditions the building has to withstand and the consequent obtained demand profiles it has to cover. It also includes the definition of the designed micro-CHP and conventional plants for supplying the estimated energy demand in terms of heating and DHW, and a brief mention of the simulation procedure. Likewise, performance and economic basis used to analyse the viability of Stirling micro-cogeneration devices are described. Section 4 presents the results of both performance and economic feasibility studies under current economic conditions, while a sensibility study is carried out under different future scenarios for the economic variables taking part in the analysis in Section 5. Finally, Section 6 sums up the main conclusions obtained throughout the whole study.

2. SPANISH NORMATIVE AND ECONOMIC FRAMEWORK

In Spain, during the last years, it has been the RD 661/2007 which has regulated the economic activity of electricity production under Special Regime [12]. This Royal Decree regulated both renewable and cogeneration based electric energy productions, ensuring a reasonable payment to the owners for their investments to get feasible [13].

However, all the remunerative complements were revoked with entry into force of the Royal Decree-Law 1/2012 on the suspension of the procedures of retribution and omission of the economic incentives for new cogeneration and renewable installations for electric energy production [14], involving a moratorium in the legislation. Recently, a new Law on fiscal measures for the energetic sustainability (LAW 15/2012) has been approved [15], establishing a new tax for electric energy producers taking part in the different engagement modalities of the electric energy production market. Nevertheless, the in-pass situation has not been settled yet.

In this sense, a forthcoming new Royal Decree, together with the RD 1699/2011 which regulates the connection to grid of low power electricity production installations [16], is expected to solve the baffling situation in which the cogeneration is submerged, establishing the regulation of the administrative, technical and economic conditions of the so called Electric Energy Supply with Net Balance [17].

On the other hand, electricity and natural gas acquisition prices are determined by the Ministry of Industry, Energy and Tourism, through tariffs called TUR. In case of natural gas, tariffs are updated quarterly, provided that there is a variation in the cost of the raw material greater than ±2% [18]. Electricity tariffs are modified quarterly as well [19].

3. METHODOLOGY

3.1. Building definition, climatic conditions and energy demands

The target building is a two-floor single-family house, with a habitable attic and a garage, occupied by four people, with a net thermally conditioned area of 273.61 m². The envelope, whose transmittances are summarized in Table 1, is designed according to the requirements of the Spanish Technical Building Code – which from now on will be referred to as CTE – for new and retrofitted dwellings [20].

Table 1: Transmittances of the constructive elements.

	U-value [W/(m²·K)]
Exterior walls	0.479
Roof	0.566
Ground floor	0.709
Windows	2.89

The occupancy profiles and internal gains, set point temperatures, and air infiltration values of the dwellings are based on the criteria given by IDAE [21], while ventilation requirements are those established in the Indoor Air Quality document of the CTE [22]. This way, set point temperature is set to 17°C from 11 p.m. to 7 a.m., and to 20 °C the rest of the day. On the other hand, according to the CTE, 2.31 renovations per hour are needed for this construction.

The analysis is carried out for three different climatic zones of Spain, chosen in function of their climatic severity (CS) defined in the HE1 Section of the Energy Savings Document of the CTE [20]. These weather data are obtained from the Meteonorm database [23].

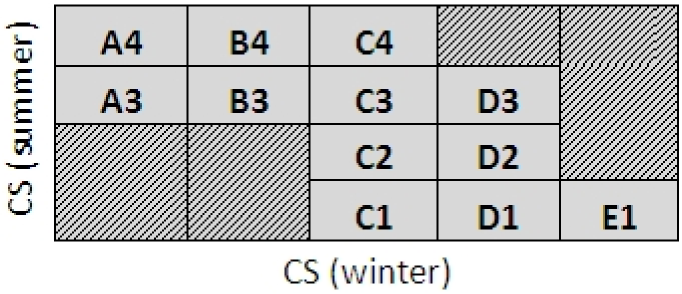

Figure 1: Climatic zones in Spain.

As indicated in the CTE, the climatic severity of a place is defined as the quotient between the energy demand of any building in that zone and that corresponding to the same building in the reference zone, i.e. Madrid. Two climatic severities are distinguished: one for summer and another one for winter. This way, climatic zones are defined according to their climatic severities in winter (A, B, C, D, E) and summer (1, 2, 3, 4). The climatic severity combines degree-days and solar radiation of a locality, so that when two places have the same winter climatic severity the heating demand of a building sited in both locations is quite the same.

Thus, the three cities chosen in this study are Almeria, Burgos, and Madrid. As shown in Figure 1, Almeria (A4 zone) has extremely hot summers and warm winters; Burgos (E1 zone) has very cold winters and warm summers, while Madrid (D3 zone) has cold winters and hot summers.

DHW consumptions, depicted in Figure 2, are also calculated according to the profiles given by IDAE [24].

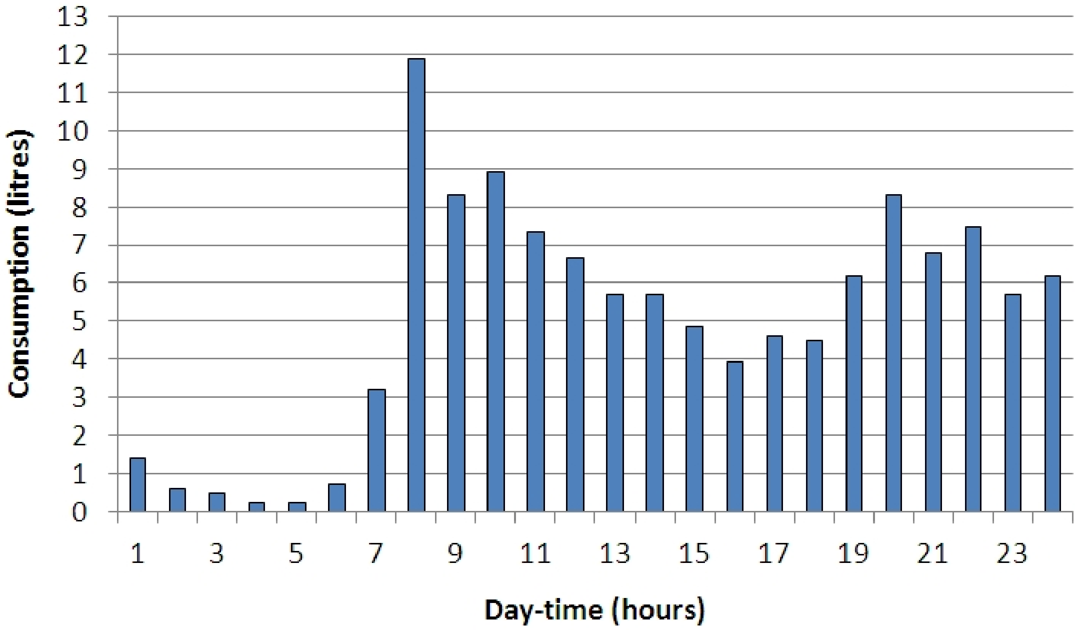

Figure 2: DHW consumption profile.

Taking into account the aforementioned conditions, the annual thermal energy demands of the dwellings obtained in TRNSYS 17 for Almeria, Burgos and Madrid, considering both heating and DHW, are 8.79 MWh, 38.60 MWh and 23.90 MWh respectively. Cooling demands are not considered.

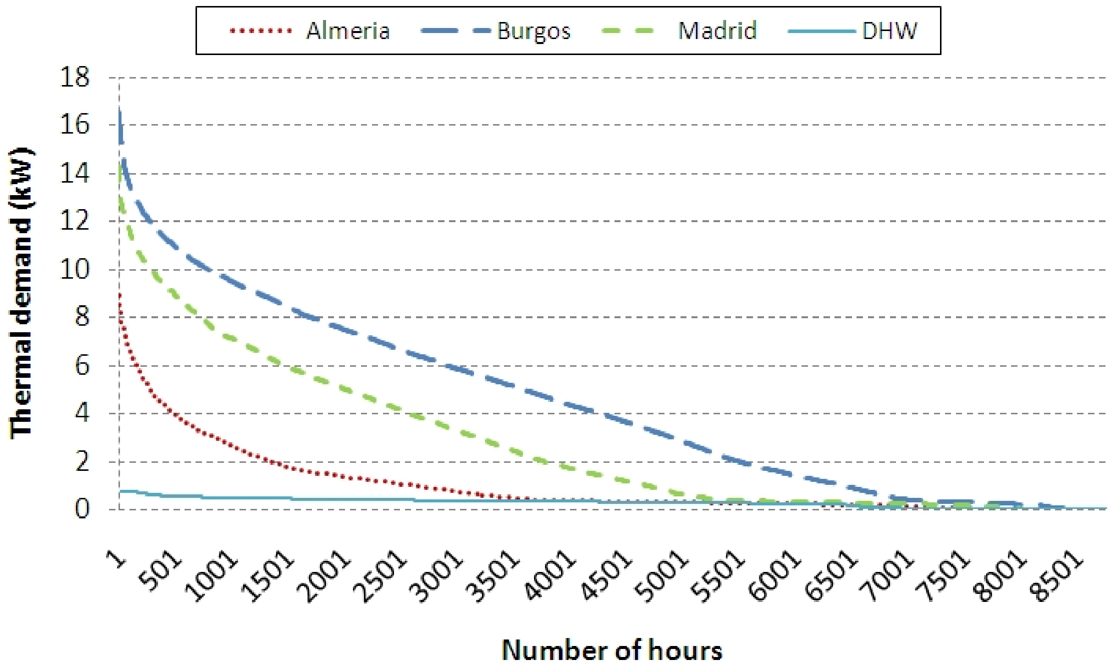

Figure 3: Monotonic heat demands.

In the monotonic heat demand curve presented in Figure 3, the annual total thermal energy demand of each case study is depicted, as well as the DHW curve, which is common for the three cities. It can be appreciated that there is only DHW demand throughout most part of the year in Almeria, while there is a strong need for heating almost all year long in Burgos. This representation helps to get a first impression of how the micro-CHP can adapt to those conditions.

Regarding the electricity demand, it is assumed that the mean demand of a single family dwelling in Spain is about 4560 kWh [25]. Hourly electricity consumption is obtained from the product of hourly multiplication factors given in the daily profiles (Figure 4) and monthly consumption values depicted in Figure 5 [26]. As shown in Figure 4, two daily consumption profiles are distinguished, depending on the period of the year.

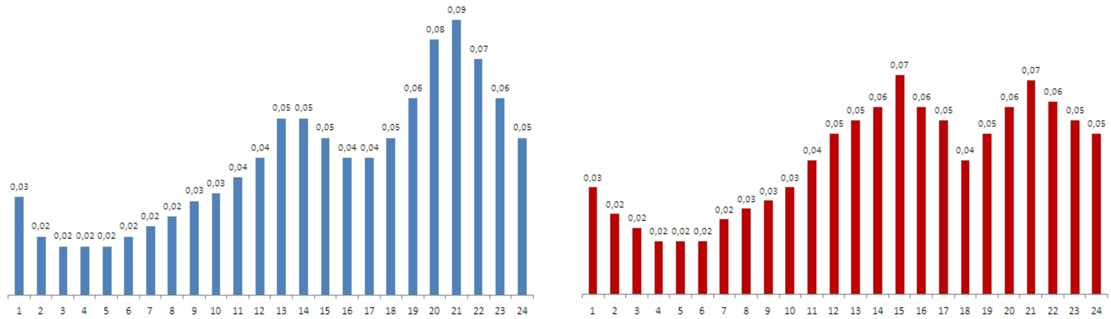

Figure 4: Daily electricity multiplication factors. (Left) Winter Period, (Right) Summer Period.

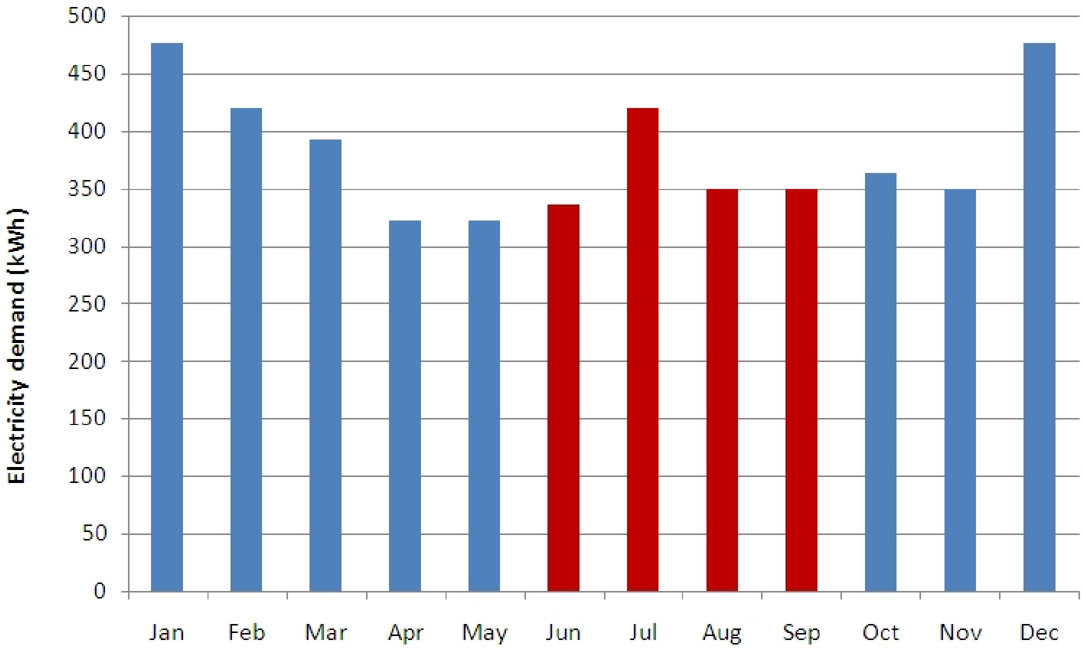

Figure 5: Annual profile of electricity demand.

3.2. Installation description

The micro-cogeneration plant designed for covering both heating and domestic hot water demands consists of a hydraulic system that allows connecting a Whispergen EU1™ Stirling micro-CHP unit (specification in Table 2) with its 750 litres associated storage tank – as there is need for buffering due to the variability of the demand, so that the performance of the cogeneration can be improved [27,28] – in parallel with an auxiliary boiler. This way, given priority to the µCHP by the disposed control system, the boiler acts as backup for peak demands. The operation of the plant is defined so that when there is need for thermal energy, the CHP device is the first to come into service, regardless what period of the day it is, that is, there is no designed scheduling.

Table 2: Whispergen EU1™ Specification [29].

Thermal Power [kW]	7.5-8.3 (*)
Electric Power [kW]	1
Fuel Consumption [kW]	9.5
Electric Efficiency [%]	10-11 (**)
Thermal Efficiency [%]	>85

(*) Nominal thermal output at 60-80 °C

(**) Electric efficiency at 60-80 °C

Hot water flow is initially impulsed through the 250 litres DHW tank, where a flat-plate heat exchanger is used to avoid mixture of both consumption water and working fluid, and later on provides heating for thermal conditioning, as shown in Figure 6.

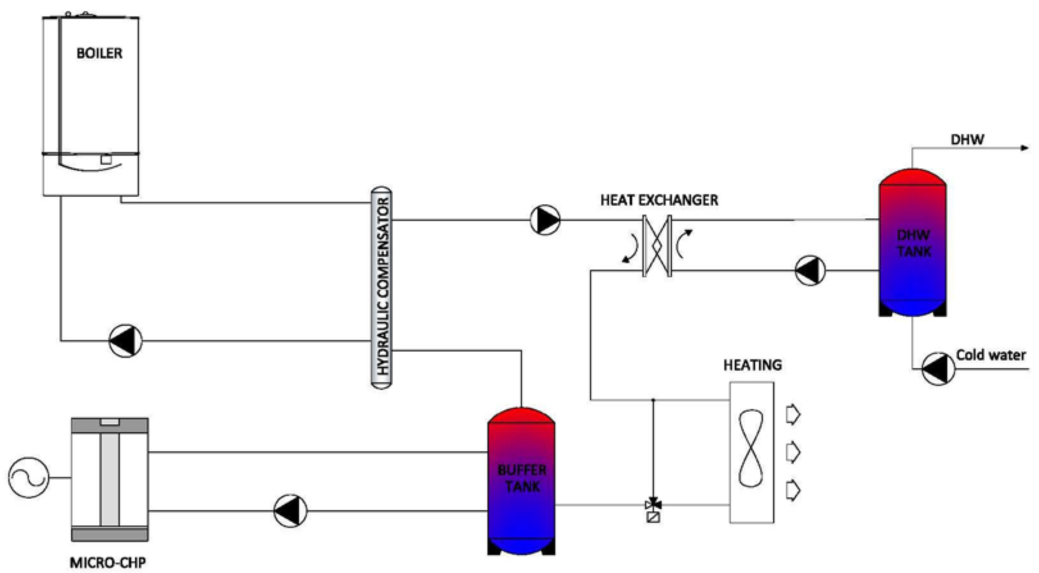

Figure 6: Schematic view of the micro-cogeneration plant.

The backup boiler considered is a conventional one by Baxi®, with a nominal thermal power output of 23.3 kW and an overall efficiency of 93.1%, controlled so that generation temperature never exceeds 80 °C.

In regard to the electric point of the micro-cogeneration device, taking into account legislative, economic and energy efficiency aspects, all the possible electricity generated in the plant is self-consumed in the building, reducing the amount of electric energy purchased from the grid when the demand is higher than the production, and feeding the production surplus to the low voltage network at market price when the production is higher.

On the other hand, the conventional plant, where the cogeneration device is replaced by solar thermal panels, consists of the same hydraulic system operating in a similar way except for the connection of the storage tanks. In this case, domestic cold water flows from a 500 litres solar tank into the DHW tank, where additional heat required is supplied by the boiler, as shown in Figure 7. A 2.82 m² net area of Escosol Sol™ solar collectors is disposed for the three cases under study, so that the minimum requirements of the Spanish CTE for solar contribution to DHW are fulfilled [30].

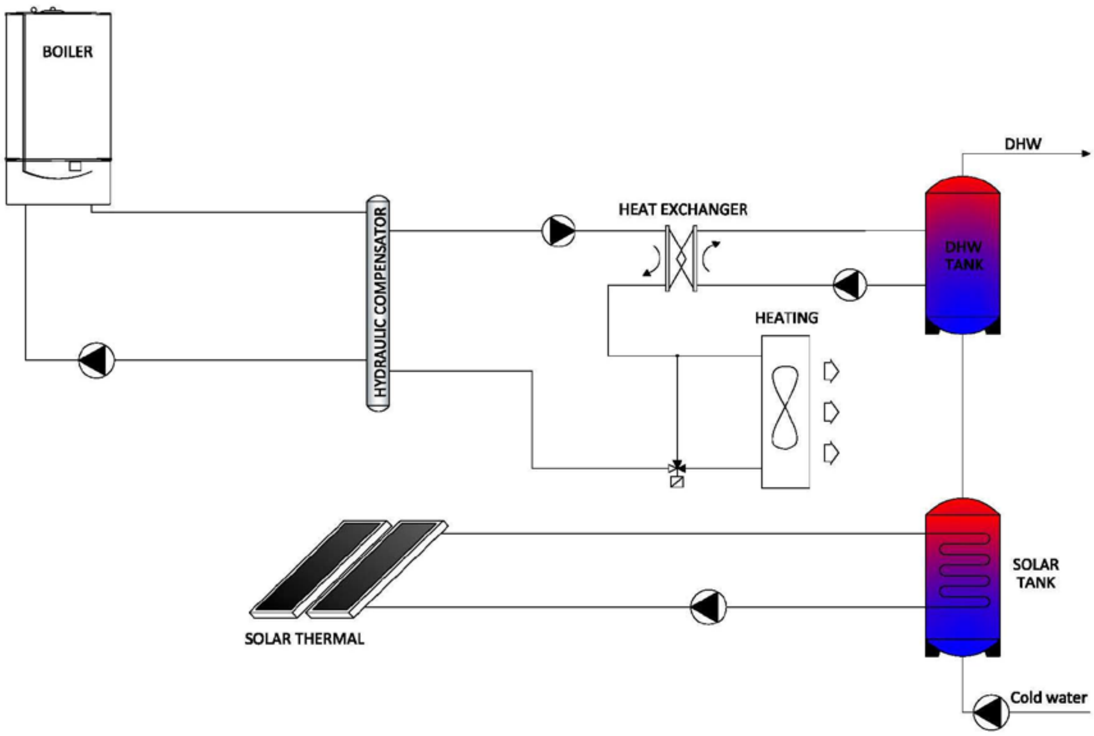

Figure 7: Schematic view of the conventional plant.

3.3. Simulation and performance analysis

According to the aforementioned information, both micro-CHP and conventional plants are implemented in Trnsys 17 dynamic simulation software. For simulating the performance of the Stirling engine, the model developed in the IEA/ECBCS's Annex 42 [31] is used, where experimental data obtained from experimental tests are used for calibrating and modelling the different phenomena of the Whispergen EU1™ engine.

To characterize the operation of the micro-CHP plant, annual operating hours are obtained, in order to be able to guarantee that the cogeneration device is properly used, as this kind of equipment is not designed to work sporadically or intermittently. Furthermore, five vectors are calculated every 6 minutes to perform the operational study: the natural gas consumed by the low temperature boiler, the natural gas consumed by the micro-CHP unit, the heat produced by the boiler, the heat production of the µCHP unit, and the electricity produced by the alternator of the micro-cogeneration. This low enough timestep ensures that transient effects are taken into account in the calculations [32].

On the other hand, besides the overall efficiency of both the micro-CHP device and the whole installation, the efficiency of the Whispergen™ throughout the whole-year operation with respect to the separate production of those thermal and electric energies is obtained, in terms of Primary Energy Saving (PES).

Primary Energy Saving is the efficiency index established by the 2004/8/CE Directive [33], defined as follows:

$$PES = 1 - \left[F/\left(E/RefE_{\eta} + H/RefH_{\eta}\right)\right] \quad \text{(Eq. 1)}$$

where F, E and H are the fuel consumed, the electricity produced and the useful heat produced by the micro-CHP plant, respectively; and $RefE_{\eta}$ and $RefH_{\eta}$ are the harmonised efficiency for separate electricity and heat productions respectively [34]. Efficiency reference values $RefE_{\eta}$ and $RefH_{\eta}$ are 0.45 and 0.9 respectively, according to the aforementioned Directive.

Additionally, an electricity balance is carried out, in order to evaluate the contribution of the µCHP plant to the electricity demand of the building.

Finally, thermal productions and fuel consumptions of the conventional installation are also obtained.

3.4. Environmental analysis

The environmental analysis takes into account the greenhouse gas (GHG) emissions during the operation of the plants, considering those associated to both the natural gas consumption and the electricity production. GHG emissions associated to the extraction and fabrication of the components are negligible [35].

GHG emissions are calculated according to the Global Warming Potential (GWP) defined in the IPCC 2007 method developed by the International Panel on Climate Change. The GWP is defined as the potential of global warming in a period of 100 years, in kg of carbon dioxide per kg of emission, comparing the effect of the liberation of any GHG with that caused by the CO_2. All emission factors are given in kg of CO_2 equivalent.

The GHG emissions associated to the natural gas and the electricity have been extracted from the Ecoinvent 3.0 database, which is the most widely spread database for Life Cycle Inventory (LCI) data on energy supply, materials, chemicals, metals and transport services used in the Life Cycle Assessment (LCA) tool.

In the case of the emissions related to a kWh of electricity, the Spanish energy mix is taken into account (Figure 8), from which a value of 0.601 kg CO_2–eq/kWh is obtained. On the other hand, an emission factor of 0.212 kg CO_2–eq/kWh is considered for the natural gas combustion.

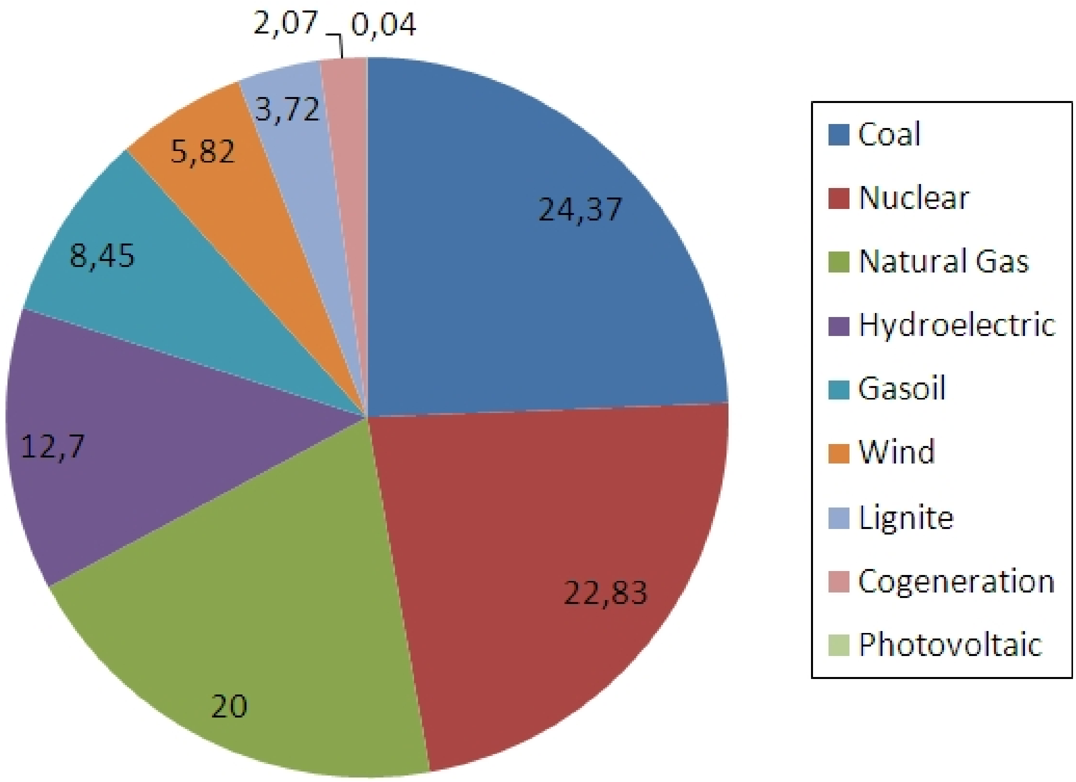

Figure 8: Spanish energy mix.

3.5. Economic analysis

In order to perform the economic study, the Net Present Value (NPV) and the Pay-back period are selected to evaluate the investments. NPV considers all incomes and outcomes in the economic lifetime of the plant in relation with the initial investment of the project, while the Pay-back period represents that moment when the investment gets recovered. Assuming that the whole investment is made in the beginning of the project, the NPV value is obtained through the following equation:

$$NPV = -Inv + \sum_{t=1}^{t=LT} [NS/(1+r)^t] \quad \text{(Eq. 2)}$$

where *Inv* is the total investment of the project, taking into account the costs avoided of the conventional plant, LT is the number of years to consider the investment, r is the rate of discount, and NS represents the annual cash flows generated, which are calculated using the variables obtained in the energetic performance study by means of the forthcoming equation:

$$NS = \sum_{i=1}^{i=8760} (I_E + I_{AC} - C_F - C_M)_i \quad \text{(Eq. 3)}$$

where I_E are the avoided costs owed to sales and self-consumption of the electricity generated in the µCHP, I_{AC} are the avoided costs related to the fuel consumed in the conventional plant, C_F are the costs related to the natural gas consumed in the current cogeneration plant, and C_M represents the difference between maintenance costs of the micro-CHP and the conventional plant.

According to the current situation exposed in Section 2, I_E is obtained by multiplying each value of the self-consumed and sold electricity vectors by the stipulated price. Avoided natural gas costs (I_{AC}) are obtained by multiplying the total consumption of the previous installation by the current natural gas tariff, while costs related to the fuel consumed in the current installation (C_F) are calculated by multiplying natural gas consumption of both the micro-CHP device and the auxiliary boiler to the current natural gas supply price. Maintenance costs (C_M) are obtained by substracting the maintenance costs associated to the solar thermal panels to those corresponding to the micro-cogeneration device, as the remaining maintenance costs exist for both the conventional and the µCHP plants.

The considered price for electricity is 14.55 c€/kWh [36], while natural gas cost is established in 0.053 €/kWh [37]. No fixed term is considered for these tariffs, as they are common for both installations. Stirling micro-cogeneration devices require a maintenance priced at 0.6 c€/kWh [11], while a usual value of maintenance costs of solar thermal panels in single-family houses is 15 €/m^2 per year [38].

Investment costs of the micro-cogeneration device add up to 8540 €, including 8000 € of its initial price [6], and the correspondent electric connection to the low voltage network, estimated at a 5% of the total cost of the whole plant [39]. Solar thermal panel and its structure's price is set at 659 € [40], while auxiliary equipment and installation costs are not considered as they are estimated to be similar for both the conventional and the micro-CHP plants.

4. RESULTS

Applying the methodology explained in the previous sections, the performance and viability study is carried out for the three considered climatic regions.

Operational results of the conventional plant show that in the three considered cases, the established solar surface is enough for fulfilling the Spanish CTE, as the required 70%, 30% and 60% for Almeria, Burgos and Madrid respectively are exceeded by the 90%, 66% and 83% obtained.

Taking a look at Table 3, where annual operation parameters of both plants are summarized, it can be seen that the number of hours of operation of the micro-CHP device is extremely short for the case of Almeria, increasing but being still low for the case of Madrid, and getting up to more than a half of a year for the case of Burgos, which is a reasonable number of working-hours. Furthermore, a very high overall efficiency is achieved for the whole plant, which indicates that primary energy is used efficiently.

Table 3: Annual operation results of the micro-CHP and the conventional plants.

	Almeria	Burgos	Madrid
Heating demand [kWh]	6535.33	36060.71	21508.56
DHW demand [kWh]	2253.43	2537.25	2388.72
Number of hours of operation of the µCHP	1113.70	4533.20	2095.90
Thermal production of the µCHP [kWh]	8800.20	36604.54	23344.47
Electricity production of the µCHP [kWh]	1079.91	4394.75	2816.57
Fuel consumption of the µCHP [kWh]	10333.67	41980.54	26918.82
Net Efficiency of the µCHP [%]	95.61	97.66	97.18
PES [%]	15.09	16.71	16.34
Thermal production of the boiler [kWh]	124.96	2003.58	419.51
Fuel consumption of the boiler [kWh]	134.26	2154.45	451.08
Net Efficiency of the plant [%]	95.58	97.43	97.12
GHG emissions [kg CO2-eq]	1570.17	6855.74	4507.60
Thermal production of the solar collector [kWh]	2025.06	1683.36	1970.65
Contribution to DHW [%]	89.87	66.35	82.50
Thermal production of the boiler [kWh]	5903.18	35410.00	20896.08
Fuel consumption of the boiler [kWh]	6347.46	38075.25	22468.88
GHG emissions [kg CO2-eq]	1345.66	8071.95	4763.40

In this sense, PES results remark that primary energy savings with respect to the separate production of both thermal and electrical energy increase with the augmentation of the micro-CHP device running-time, as operation periods are longer, with less warm-up and cool-down periods where the efficiency decreases. Results of the three cities far exceed the minimum value of primary energy savings requested in the 2004/8/CE Directive.

Regarding the GHG emissions, results remark that, except for the warmest climate, better environmental results are achieved with the micro-CHP installation. It can be seen that GHG emissions are closely related to non-renewable primary energy savings, getting lower as the PES gets increased.

On the other hand, Table 4 collects the data obtained from the annual electricity study of the micro-CHP plant. Analyzing the hourly balance of the plant, results show that almost 60% of the electricity produced with the Stirling engine is self-consumed in the three cases under study. Furthermore, as the winter climatic severity raises, the net electricity coverage of the Stirling device, i.e. the electricity production-to-consumption rate, grows significantly, from about 24% in the case of Almeria up to over 96% in the Burgos case. This means that in the latter case, although only 57% of the electricity produced in-situ is directly consumed, the micro-CHP production almost reaches the total demand value.

Table 4: Annual electricity balance of the micro-CHP plant.

	Almeria	Burgos	Madrid
Electricity demand [kWh]	4560.00	4560.00	4560.00
Electricity production [kWh]	1079.91	4394.75	2816.57
Electricity purchase [kWh]	3942.84	2045.98	2874.63
Electricity sales [kWh]	458.74	1876.73	1127.20
Self-consumed electricity [%]	57.52	57.30	59.98
Net electricity coverage [%]	23.66	96.29	61.71

Finally, having a look at the economic results summarized in Table 5, and taking into account that the initial investment difference between micro-cogeneration and conventional plants raises to 7,900 € approximately, it can be seen that after the 15 years lifetime, the extra investment is not recovered in any of the cases, being the percentages of recovery in that instant 22% and 41% for Madrid and Burgos, respectively, while there is no recovery for the case of Almeria, as the overall annual cash flows are negative with respect to the conventional plant.

Table 5: Economic results of the micro-CHP plant.

	Almeria	Burgos	Madrid
Investment [€]	7883.00	7883.00	7883.00
Overall annual savings [€]	-25.44	334.20	175.46
NPV [€] (year 15)	-8130.16	-4637.25	-6179.02

For the best case, that is, the Burgos one, the pay-back period would not be reached even if the plant lifetime were 30 years. Therefore, it can be categorically stated that under current conditions, Stirling engine-run micro-cogeneration devices are completely unprofitable for detached houses in Spain.

5. SENSITIVITY ANALYSIS

The previous viability calculations have been done under a concrete and steady economic situation. Because the feasibility of this kind of investments depends heavily on some economic factors such as the prices of natural gas and electricity and the inflation rate, a sensitivity analysis is carried out to study how they influence the economic results. Additionally, and taking into account the results obtained in the previous case, variations of the cost of the micro-CHP device are also considered.

First of all, variations in electricity and natural gas prices are considered. In this sense, a very optimistic case is only highlighted, that is, a 25% increase of the electricity price and a 25% reduction in that of the natural gas. In this context, economic results improve considerably, but Stirling-based μCHP still remains highly unfeasible for the three studied cases. Therefore, any possible and realistic change in prices of both products will not consequently vary the viability of the installation by themselves, although they could satisfactorily contribute in combination with changes in other parameters, as depicted in Figure 9 for the most favourable case under study. In case of the increase considered for the price of the electricity, it must be noted that this augmentation is completely feasible, as it was until a year ago, when the regulation of the complements for electricity produced through cogeneration were still in force.

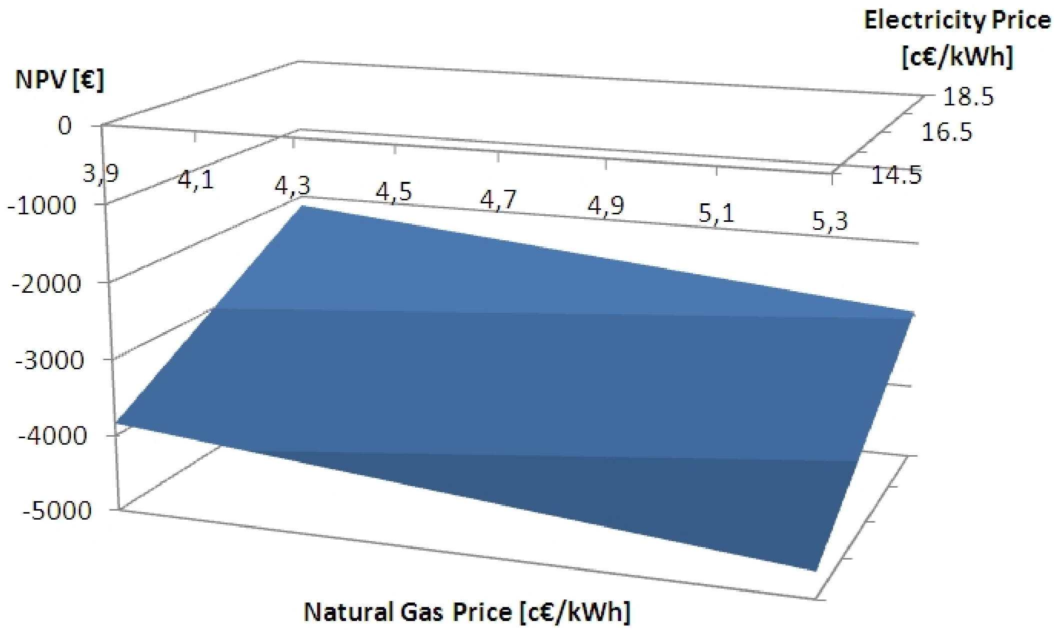

Figure 9: NPV as a function of different combinations of gas and electricity prices for the Burgos case.

On the other hand, the effect of the rate of discount is studied. For this purpose, three additional values (5%, 4% and 3%) to the initial one are considered, with no fully satisfactory results in the viability.

Finally, considering that the initial price of the micro-cogeneration device can get lower if a consolidated implantation of the device happens in the global market, the price below which the investment would be viable is determined for each of the three cases. Thereby, it is regarded that there is no possible viability in Almeria even though the unit was at zero cost, as annual cash flows would make the investment unfeasible after its 15 years lifetime. For the other two cases, Madrid and Burgos, limit prices of the device are set to 1161 € and 3362 € respectively for the plants to be feasible.

The variations of the different aforementioned factors affecting the feasibility study of the plant are summarized in Table 6.

Table 6: Main economic results of the sensibility analysis.

NPV (15 years)		Almeria	Burgos	Madrid
Electricity Price variation	+25%	-6579.82	-1837.59	-3996.09
Electricity Price /Natural Gas Price variations	+25%/-25%	-7218.39	-2304.85	-4553.27
Rate of discount value	5%	-8147.14	-4414.20	-6061.92
	4%	-8165.93	-4167.32	-5932.30
	3%	-8186.78	-3893.42	-5788.50
Device price cost [€]	6000	-6130.16	-2637.25	-4179.02
	4500	-4630.16	-1137.25	-2679.02
	3500	-3630.16	-137.25	-1679.02
	2500	-2630.16	862.75	-679.02
	1000	-1130.16	2362.75	820.98

Thereby, it can be concluded that this kind of equipment could only get feasible for supplying heating and DHW in cases of single-family dwellings for extremely cold climates in Spain, provided that commercial prices decrease considerably. For intermediate climates such as the one at Madrid, with cold winters and hot summers, there is a need to increase the number of running-hours of the micro-CHP device. This could be achieved by covering cooling demand through thermally activated chillers. In this case of trigeneration, the global viability including the chiller should be studied.

On the other hand, as mentioned in previous sections, complements for cogeneration electricity sold to the net have been paralyzed, so there is a legislative in-pass nowadays. Moreover, electricity tariff in Spain has a structural deficit, i.e., the costs of producing electricity in conventional plants is about 20% more expensive that the price established by the TUR tariff. This fact, together with the above-mentioned, penalizes micro-CHP feasibility. This situation is supposed to get solved soon, so viability of these devices will experience an economic improvement in the near future.

Figure 10 shows the variation of NPV with the Stirling engine price for five different electricity prices. According to the exposed, there are real possibilities of having both electricity remuneration considerably increased and initial cost of the cogeneration device decreased, which could make economic viability more feasible. Results show that having a 58% decrease in the investment cost of the unit, current conditions make the µCHP feasible. If the electricity remuneration increased a 15%, a 47% drop in the unit cost would make installing this device economically viable. Finally, it is also reflected in the data that less that a 37% of decline in the micro-cogeneration price makes any realistic increase of the price of the electricity generated insufficient for viability.

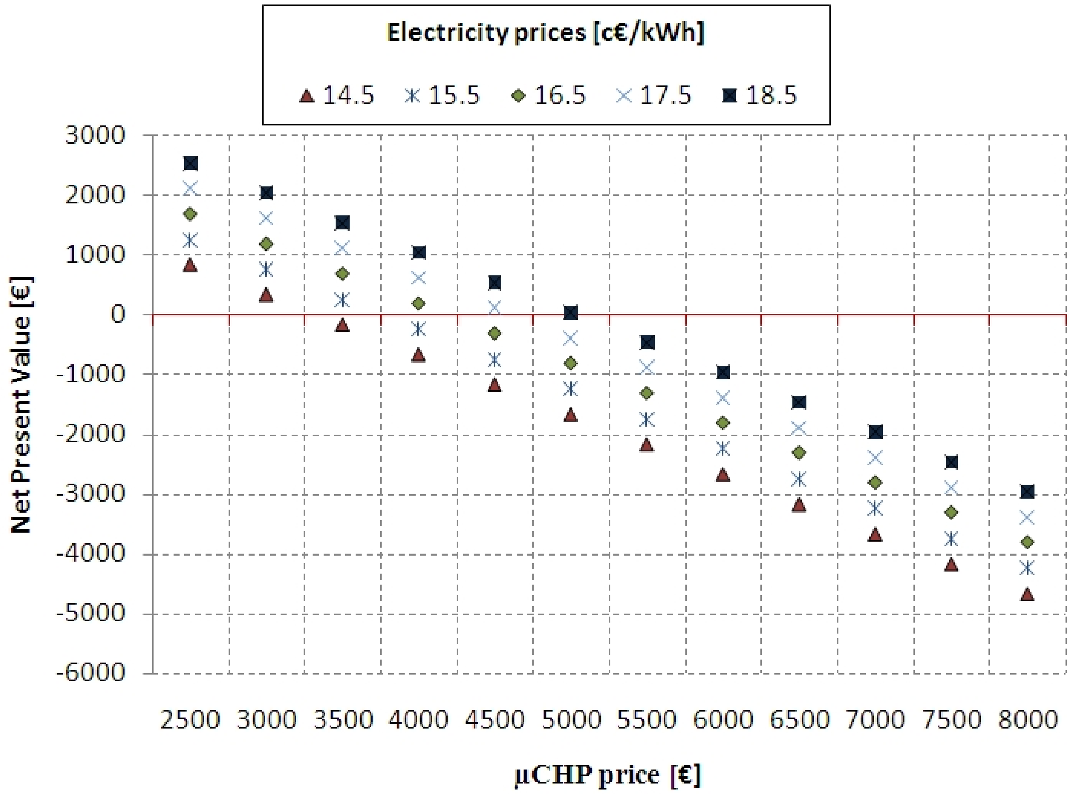

Figure 10: NPV (year 15) as a function of different combinations of investment costs of the Whispergen EU1™ and electricity prices for the most favourable case (Burgos).

6. CONCLUSIONS

Small-scale residential Stirling cogeneration systems are widely recognised to be efficient systems with a great potential to reach economic, energy and environmental savings. However, the behavior of this technology is rather unknown, and they are not commercially widely spread in market, especially in the Spanish one, where there is not even the possibility to acquire them. The main issue treated in this paper is the techno-economic viability associated to the performance of a Stirling engine-run micro-CHP unit operating for satisfying the heating and DHW demands in a detached housing for different climatic conditions in Spain.

Once thermal and electric profiles are calculated for each housing, performance data of two energy plants, a conventional one and a micro-CHP one, are obtained from dynamic simulations. From these simulations, an economic analysis is carried out, taking into account present economic conditions and regulatory framework.

It is concluded that there is no possible economic viability for any of the three climatic zones. Additionally, it is also observed that implanting this technology for covering DHW and heating demands in warm climates is not worth either from the economic or operational and environmental points of view while for the case of Madrid, although both PES values and environmental results are good enough, running-hours are quite low, so an increase in the number of hours with demand would be necessary to increase the number of hours of operation.

On the other hand, a sensibility analysis is carried out, varying electricity and natural gas prices, the investment cost of the Stirling engine, and the rate of discount. Results reflect that improvements in the conditions of both electricity and natural gas prices and the rate of discount themselves do not represent a sufficient amelioration in the economic results, even for the most optimistic cases considered. However, decreasing the price of the μCHP device to a reasonable amount, which could be achieved by a major introduction of this equipment in the global market, allows the plant to be feasible for the coldest climatic zone.

Finally, it is important to highlight that, although nowadays there is no possible economic viability in Stirling micro-cogeneration installations for new and retrofitted single-family dwellings in Spain, feasibility in medium-term could be reached in cold climatic zones by regulating the electricity market and the cogeneration policies and by spreading out the use of this equipment for manufacturing costs to get cheaper. In case of older homes, with worse envelopes that turn into higher thermal demands, reaching viability could be considerably more achievable.

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