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Influence of the regulation framework on the feasibility of a Stirling engine-based residential micro-CHP installation

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ABSTRACT

In this paper an economic analysis of a 1 kW_e Stirling engine-based micro-CHP residential plant is developed, approaching the case of a Spanish detached house sited in a cold climatic zone. The work focuses on analysing how the latest modifications in the Spanish micro-CHP and renewable energies regulation affect viability of this technology, as well as predicting what results could be achieved if policy support mechanisms in Spain were like those in two other European countries, Germany and United Kingdom, where this kind of equipment has good acceptance.

For that purpose, once defined the reference dwelling, with the consequent consumption patterns, an installation for covering heating and DHW demands of the building, as well as part of the electric load, is designed and simulated in TRNSYS 17, getting results of those performance parameters necessary for applying the economic analysis. A condensing boiler supported by solar thermal collectors is taken as the reference installation. Results show that pay-back conditions of this kind of installations have turned hardly achievable with new remunerative conditions, getting widely better results with economic frameworks of other European countries.

Keywords: Stirling micro-CHP; transient simulation; regulation changes; economic analysis; Spanish detached dwelling.

Nomenclature

C_{dh}	complement for delivery in on-peak hours (€)
C_{eff}	complement for efficiency (€)
C_{f}	cost of the natural gas consumption (€)
C_{m}	cost of operation and maintenance (€)
C_{reac}	complement for reactive power (€)
E_{CHP}	electricity produced by the cogeneration unit (kWh)
E_{DEMAND}	electricity demand of the building (kWh)
E_{GRID}	electricity exported to grid (kWh)
$E_{PLANT_{CHP}}$	electricity consumed by the cogeneration plant (kWh)
$E_{PLANT_{CONV}}$	electricity consumed by the conventional plant (kWh)
F_{CHP}	natural gas used by the cogeneration unit (kWh)
H_{CHP}	heat produced by the cogeneration unit (kWh)
i	annual hour
i_{e}	electricity sale-price (€)
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 (€)
Inc	incentives for µCHP (€)
Inv	total investment (€)
LT	lifetime (years)
n	year of operation of the plant
NC_{E}	net electricity coverage (%)
NPV	net present value (€)
NS	annual net savings (€)
PES	primary energy saving (%)
r	ratio of discount
RC_{E}	relative electricity coverage (%)
REE	equivalent electric efficiency
$RefE_{\eta}$	harmonised efficiency reference value for separate production of electricity
$RefH_{\eta}$	harmonised efficiency reference value for separate production of heat
Rinv	retribution to investment (€/MW)
R_{O}	retribution to operation (€/MWh)
Rt_{e}	regulated tariff for electricity sale (€)
SC_{E}	self-consumed electricity (%)
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
INE	Spanish Statistical Office
RD	Royal Decree
RDL	Royal Law Decree
SE	Stirling engine
TUR	last resource tariff
µCHP	micro combined heat and power

1. INTRODUCTION

Buildings represent about 40% of total primary energy consumption and 36% of carbon dioxide emissions in the European Union [1]. Consequently, all countries are developing sustainable energy policies addressed to restricting this energy usage and to strengthening and promoting efficient active systems. This way, technologies such as micro-cogeneration, which has proved capable of providing many environmental, functional, as well as economic advantages, are becoming a recurrent solution for fulfilling energy demands in residential buildings [2 – 6].

Stirling engine-based micro-CHP devices, apart from the intrinsic benefits cogeneration possesses, also offer multi-fuel capability and low carbon dioxide emissions due to the external heat supply, as well as reduction of noise levels due to their vibration-free operation [7, 8]. Consequently, they have appeared as an attractive alternative to conventional energy plants for covering heating, domestic hot water (DHW) and electric power demands in residential appliances. Although there have been various Stirling engine (SE) models for small-scale cogeneration applications in the last years, the main effort has been focused on developing low-powered residential devices suitable for covering most thermal and electric demands in single-family houses. However, there are still technical, economic and regulatory barriers for a massive market entrance, and this kind of equipment is only commercially available in a few countries. The impact this technology can have on electricity and gas networks when applied on a large scale, the need for further development for reducing manufacturing costs and strengthening on-site performance, together with the evolution of energy prices and the lack of incentives and support policies for micro-CHP, as well as the country-dependant regulation complexity and instability in some cases, are some of the main obstacles that should be overcome [9].

There are studies aimed at deepening in the thermodynamics of the Stirling cycle itself, such as [10], other investigations focused on certain components of the units, such as [11], or laboratory testing for characterizing thermal, electric and environmental features of the devices [12, 13], as well as those researches which approach performance-predicting modelling [14].

Apart from these sorts of studies, many experimental and simulation-based building-integrated researches on this technology have been conducted in various countries, demonstrating that satisfactory results can be achieved within small-scale domestic applications, enabling potential reductions in primary energy consumption [4, 15 - 22]. Ren and Gao [23] state that Japan, Germany, United Kingdom, Netherlands and United States have been the most actively involved countries in researching and introducing these gas-fired reciprocating engine-based systems in the market.

In the case of Spain, some studies on a 1 kW_e micro-CHP Stirling engine were carried out for applications such as recreational sailing boats [24] and caravans [25]. However, in the small residential area where, according to data extracted from the Spanish Statistical Office (INE) database [26], in 2011 there were more than 90,000 houses in the coldest regions with surfaces above 180 m^2 and therefore susceptible of having this kind of technology introduced, few significant researches have been carried out so far. One meaningful study approaching this issue, which consisted of a preliminary techno-economic assessment of the potential of the building-integrated performance of this technology, showed that despite the good operational results achievable in the coldest regions of the country, integration of Stirling engine-based residential micro-CHP needs further investigation for improving aspects concerning economic feasibility [27].

Thereby, this work aims to deepen in the economic aspect of the implementation of SE in housing applications, approaching the case of single-family dwellings. In this paper, a study that constitutes an estimation of how the support mechanisms of each country influence the economic feasibility of these small-scale Stirling micro-cogeneration devices is assessed, focusing on the regulation governing the electric side of the micro-CHP and the incentives existing for this sort of equipment in Spain, Germany and the United Kingdom.

This paper is organized in three main different sections, as follows: Section 2 firstly introduces the evolution of the normative and economic framework for cogeneration in Spain, as well as a brief description of German and British support mechanisms and regulations. Then, it provides a description of the case study, defining the reference building and its use and the conditions it 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 the simulation procedure and the intermediate results required for the analysis. Likewise, performance and economic basis used to analyse the viability of Stirling micro-cogeneration devices are described. Section 3 presents the economic results obtained with the current legislation in Spain, including a sensibility analysis, as well as the comparative study of such results with those achievable in the previous Spanish framework and with the German and the British regulations. All results are discussed in this section. Finally, Section 4 sums up the main conclusions obtained throughout the whole study.

2. METHODS

2.1. Economic and regulation frameworks

Spain

In Spain, during the last years, the RD 661/2007 has regulated the economic activity of electricity production under the so called Special Regime [28]. This Royal Decree regulated both renewable and cogeneration based electric energy productions, giving feed-in priority and ensuring a reasonable payment to the owners for their investments to get feasible.

The efficiency of a cogeneration plant was established through the equivalent electric efficiency (REE), as defined in Eq. 1:

$$REE = \frac{E_{CHP}}{F_{CHP} - \left(\frac{H_{CHP}}{RefH_{\eta}}\right)} \quad \text{(Eq. 1)}$$

where E_{CHP}, F_{CHP} and H_{CHP} are the annual electricity production, fuel consumption and heat production of the cogeneration plant, respectively, while $RefH_{\eta}$ is the harmonised efficiency for heat production. For a small size reciprocating engine-based micro-CHP plant being considered a high efficiency producer, the annual REE of the cogeneration plant had to be over 0.495.

Electricity fed into the grid could receive not only a regulated feed-in tariff, but also complements for reactive power and efficiency, as well as an optional complement for delivery in on-peak hours, as summarized in Eq. 2:

$$i_e = Rt_e + C_{eff} + C_{reac} + C_{dh} \quad \text{(Eq. 2)}$$

where i_e is the incomes due to electricity sales, Rt_e the regulated tariff, and C_{eff}, C_{reac} and C_{dh} the complements for efficiency, reactive power and hourly discrimination, respectively.

An accurate summary of this normative, where each term contained in Eq. 2 is defined, was presented by Campos-Celador et al. in 2011 [29].

However, the publication of Royal Decree-Law 1/2012 on the suspension of retributive procedures and omission of economic incentives for electricity-production new cogeneration and renewable installations revoked all the aforementioned remunerative complements [30].

Later on in 2012, a new Law on fiscal measures for energetic sustainability (Law 15/2012) was approved [31], establishing a new 7% tax for electric energy producers taking part in the different engagement modalities of the electric energy production market. Together with this Law the so-called green-cent was created, a new tax for each GJ of natural gas consumed.

During 2013, cogeneration in Spain suffered substantial cutbacks concerning retribution, which joined the aforementioned moratorium and the repeal of the regulatory framework of the activity. In this sense, apart from the RDL 2/2013 [32], which eliminated the bonus when selling the electricity produced in the free market, complements for efficiency and reactive power were abolished through the RDL 9/2013 [33].

Later in 2013, Law 24/2013 was published, regulating the electric sector for the electric supply to be guaranteed with the required quality levels and the lowest cost, and ensuring economic and financial sustainability of the system [34]. This Law solved the existing uncertainty for those CHP plants affected by the onset of the electrical reform.

Despite all the aforementioned regulations, it was not until June 2014 when the baffling situation in which cogeneration was submerged was partially solved, when the new legislation substituting the previous complement-based regulation and developing the new Law on the Electric Sector was published. This normative establishes a new retribution framework for renewable energy, cogeneration and waste-based electricity production installations, both new and existing [35]. According to this RD 413/2014, retribution is only applied to those installations which cannot reach a reasonable feasibility with existing market prices, provided that they fulfill the high efficiency conditions defined in RD 661/2007. This new retributive framework distinguishes between some fix costs (investment, operation and fix maintenance) and other variable costs (fuel, operation and variable maintenance).

In consequence, the payment is divided into two main groups: electricity sales at market price and specific retribution. This second term, in turn, is split into two categories: retribution to investment (R_{inv}), which stands for the investment costs of the reference installation that cannot be recovered just with electricity sales during each year, and retribution to operation (R_o), which is set as the difference between the ideal operative costs and the estimated incomes of the installation, which is obtained by multiplying the stipulated value and the sold electricity.

Both retributive parameters, which are determined in Order IET/1045/2014 [36] and may be modified in periods of three or six years, are tabulated and sorted out by categories depending on the fuel, power range and technology of the plant and its year of installation, which subsequently stand for different reference cases. For the current case-study, a natural gas-fired engine with a power output below 0.5 MW, and installed in 2014, R_{inv} and R_o acquire values of 163,121 €/MW and 78.05 €/MWh per year, respectively.

Finally, natural gas purchase tariffs, abbreviated TUR, are quarterly determined and published by the competent Ministry of the Spanish Government, and may be updated provided that a variation greater than ±2% in the cost of the raw material occurs [37]. In the case of electricity, tariffs worked in a similar way to those of the natural gas until July 1st 2014 [38], when all the procedures for establishing electricity prices were updated [39]. However, the main commercial companies, apart from the new tariffs where prices are estimated daily or even hourly, still offer the previous pricing modalities, now available for periods of no less than a year.

Prices of both products are divided into 2 terms: fixed and variable. In the case of natural gas, the fixed term is not dependent on any factor. In the electricity case, the fix-term depends on the consumption peak power, which may be contracted according to some preset power ranges. For the variable electricity term, 3 tariff typologies are available: without time discrimination (constant pricings during the whole day), with 2-period discrimination, and supervalley (3-period discrimination).

Germany

As described more in detail in the Annex 54 of the International Energy Agency (IEA) on the Integration of micro-generation and related energy technologies in buildings, in Germany, a law to support cogeneration was approved in 2002, which was last revised in July 2012 [40]. This law grants access to the electrical network and gives priority for the feed-in of the electricity generation. For each kWh of electricity generated with a CHP system with an output capacity below 50 kW_e, a generation premium of 5.41 c€/kWh_e is paid to the generator, regardless of if the electricity is delivered to the net or self-consumed. These generation premiums are paid until 30,000 hours of full load operation are reached, or, alternatively for operators of systems with a capacity below 50 kW_e, over a period of 10 years instead. Furthermore, as the premium is paid on approved amounts of generated electricity, operators of systems up to 2 kW_e can decide whether to get the payment of the whole bonus in advance or not. Additionally, electricity fed-in to the grid is paid at 3.35 c€/kWh for the first quarter of 2014.

Furthermore, there is a tax refund related to consumed natural gas, receiving back 0.55 c€ per each kWh of natural gas feeding the micro-CHP unit. Similarly, there is a tax refund, normally between 0.5-1.5 c€/kWh, related to electricity fed-in to the grid, due to avoided grid charges for distribution companies.

Finally, for micro-generation systems with capacities below 20 kW_e, an investment subsidy can be obtained through a support program [41], provided that some requirements are met. This grant, which was initially in the range of 1500 to 3450 € depending on the size of the system, was reduced in a 5% from January 2014.

United Kingdom

As summarized by Hawkes [42], in the UK there is a feed-in tariff mechanism available for electricity generated with micro-CHP devices with power outputs below 2 kW_e. Each generator receives two different payments: a generation reward and an export reward. The generation reward is applied to every kWh_e the system produces (15.93 c€/kWh_e during 10 years), while the export reward is applied to every kWh_e exported to the grid (5.73 c€/kWh_e). Both values were last checked in March 31st, 2014. The values of the tariffs were results of converting £ to € at the moment of writing this paper.

2.2. Case study

2.2.1. Thermal and electric demands

The case study focuses on the application of Stirling engine-based micro-CHP plants in single-family dwellings. Thus, the target housing is a typical detached dwelling, built early in the current decade, with 273.61 m^2 of thermally conditioned surface distributed among two floors and a habitable attic. The building was geometrically modeled using Google Sketch Up 7 along with the Trnsys 3d plug-in.

The dwelling is located in Burgos, a city sited in the coldest climatic zone of Spain (E1 zone), with very cold winters and warm summers according to the climatic severity (CS) defined in the HE1 Section of the Energy Savings Document of the Spanish Technical Building Code (CTE) [43]. The weather data of the geographic position were obtained from the Meteonorm database [44].

Each of the main elements of the envelope was defined for fulfilling its respective reference transmittance value established by the CTE in force at the moment of the execution of the project for both new and refurbished buildings sited in the aforementioned climatic zone [43]. The main features of the envelope are summarized in Table 1.

Table 1: Transmittances of the constructive elements.

	U-value [W/(m²·K)]	
	Real	Reference
Exterior walls	0.48	0.74
Roof	0.41	0.46
Floors	0.61	0.62
Windows	2.89	3.10

Except for ventilation rates, which were based on those values required by the Indoor Air Quality document of the CTE [45] (2.3 renovations per hour), the main use patterns of the building, i.e. occupancy profiles, internal gains, infiltration rates and heating set-point temperatures (17°C from 11 p.m. to 7 a.m., and 20°C the rest of the day), were based on the schedules given by IDAE [46, 47].

For estimating the thermal demand on account of the DHW, the reference values indicated in the Spanish Technical Building Code were utilized. Thus, taking into account that the occupation for this sort of dwelling with 3 bedrooms is 4 people, that the reference daily demand at 60°C rises up to 30 litres per person, and using the distribution profiles for Spain given by IDAE [47], the daily DHW consumption depicted in Figure 1 was obtained. These values, being representative of hourly total consumption of DHW in the dwelling, do not match accurately the real instantaneous nature of DHW consumption characterized by sharp instantaneous peaks. Thus, when sizing the generation devices of the thermal plant, a security margin must be considered in order to deal with these greater peaks.

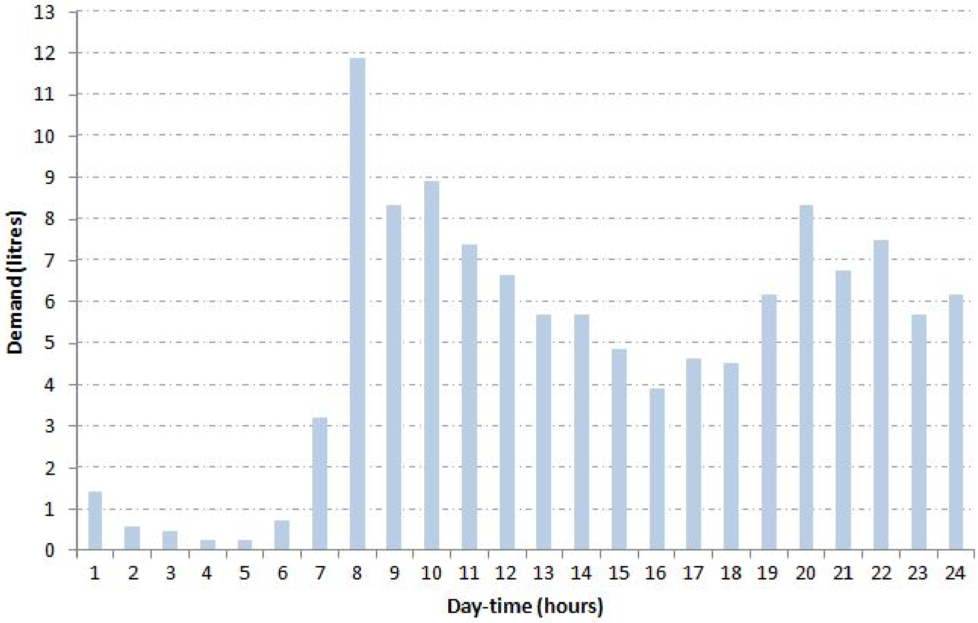

Figure 1: DHW consumption profile.

Bearing all the described parameters of the household in mind, i.e. the thermal features of its envelope, together with its shape and geometry, as well as its total net surface and usage patterns, the selected building is susceptible of being considered as a typical detached dwelling for Spanish cold climatic zones. Furthermore, it also represents refurbished detached dwellings, as once a deep renovation on a housing is assessed, those requirements for new constructed buildings must also be fulfilled.

Once defined and introduced all the aforementioned inputs in TRNSYS 17, the simulation procedure was completed. TRNSYS is a widely used transient system simulation software tool, modularly structured, that has been specifically designed for developing complex energy-related systems and their coupling to building modeling and simulation. According to Sousa [48], which carried out an analysis of some of the most important energy simulation programs, except for certain cases where others can get more appropriated in terms of needs-complexity, TRNSYS is generally the most complete tool for building-scale simulation.

Hence, the obtained thermal energy demand on account of the heating and DHW required in the housing (cooling was not considered) was 38.60 MWh/a, presenting a 16.5 kW peak demand in December 25th.

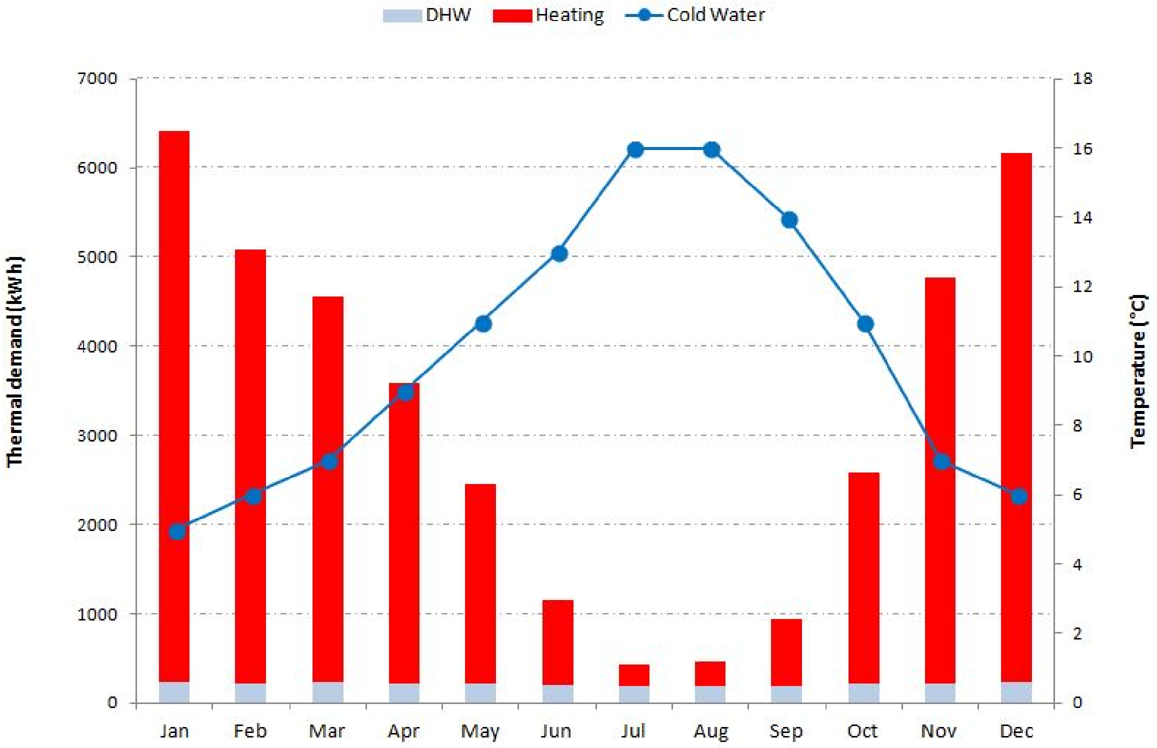

Figure 2: Annual total thermal demand.

Referring to the electric side of the demand, being the mean year value of a single family dwelling in Spain about 4560 kWh/a [49], the hourly consumption values were obtained taking into consideration the hourly multiplication factors depicted in Figure 3 (where summer and winter day-profiles are distinguished) and those monthly values shown in Figure 4 [50]. It is observed that the highest electricity consumption in the dwelling takes place in December, while July is the summer-month with greatest demand and the third in overall. Finally, the peak electricity consumption is considered to be 1.3 kW on an hourly basis.

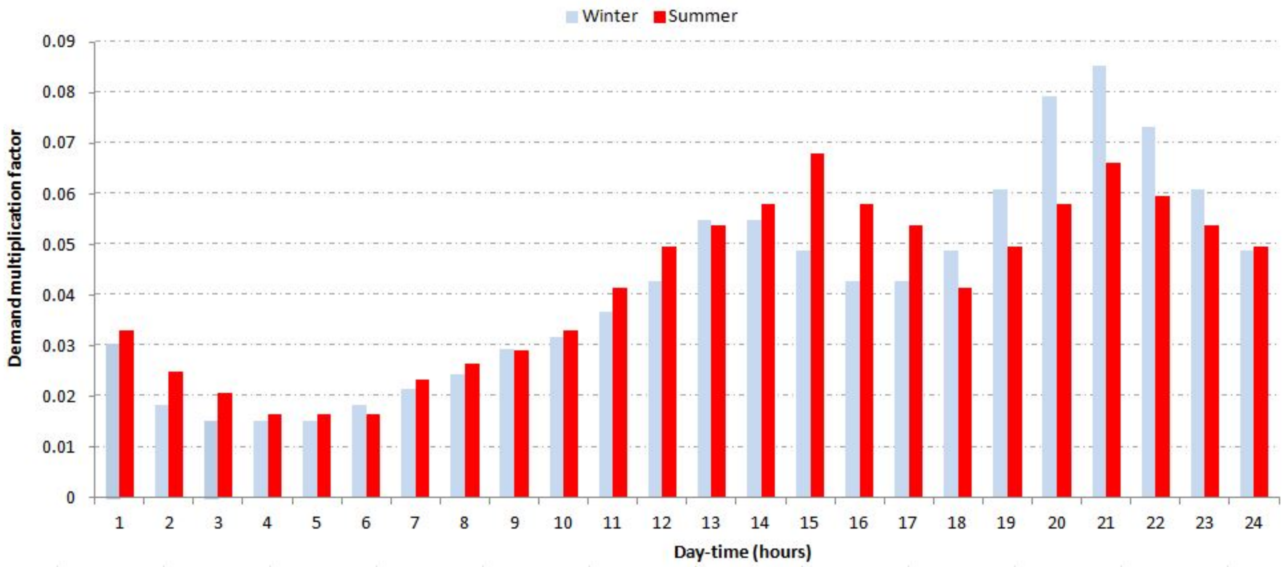

Figure 3: Daily electricity multiplication factors.

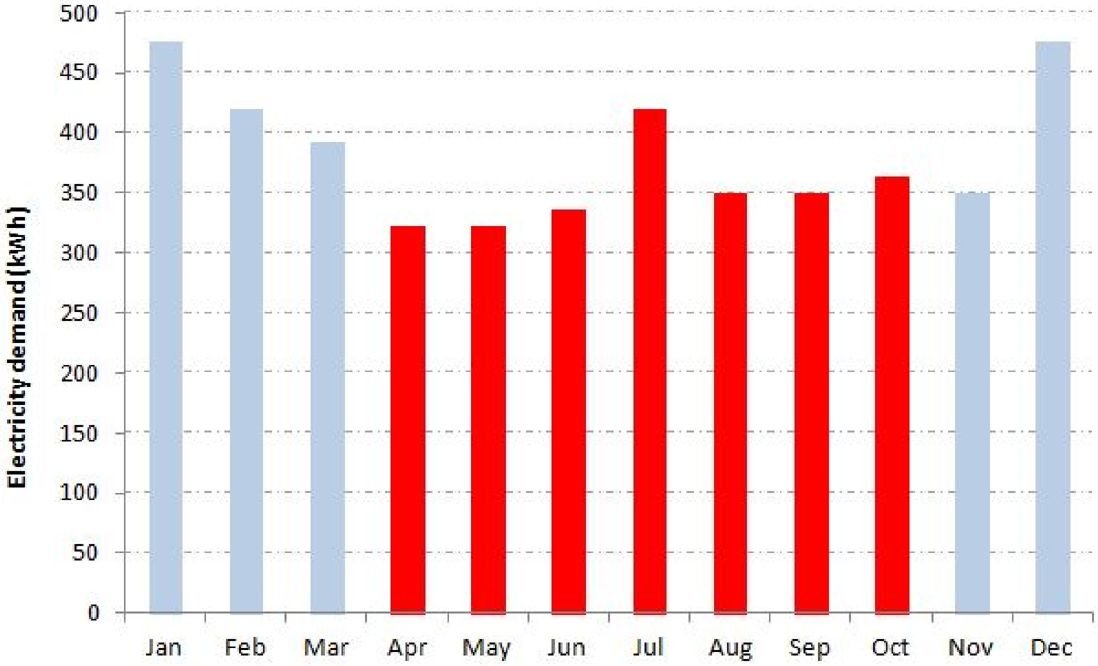

Figure 4: Annual profile of electricity demand.

2.2.2. Installation design and simulation

Since the entrance into force of the CTE in 2007, there is a minimum percentage of the DHW demand that must be covered by solar thermal or other renewable sources or cogeneration [51]. Accordingly, the whole analysis carried out in this paper was based on comparing the micro-cogeneration plant with the considered reference case of installation, i.e. the most common in Spain. Both installations are described below.

Reference installation

In Spain, the most common generation device for space heating and DHW in dwellings is the natural gas-run condensing boiler, normally supported by solar thermal panels for base domestic hot water production.

As required by the CTE, both solar and conventional productions must be independent, so two tanks were disposed, one for the solar circuit and another one for DHW production, as depicted in Figure 5. According to the regulation, the ratio between the solar tank volume and solar collector surface must be between 50 and 180 litres per square meter. Thus, disposing a 2.82 m^2 net area of Escosol Sol™ solar flat collectors in order to fulfill the requirements of the Spanish CTE for solar contribution to DHW, the size of the solar tank was established in 500 litres.

The principle of operation is so that domestic cold water is preheated in the solar tank, flowing then into the 250 litres DHW tank, where extra heat required for maintaining the temperature over 60°C is supplied by the boiler (with respective nominal thermal power and efficiency of 23.3 kW and 93%), as established by the regulation to avoid the appearance of legionellosis.

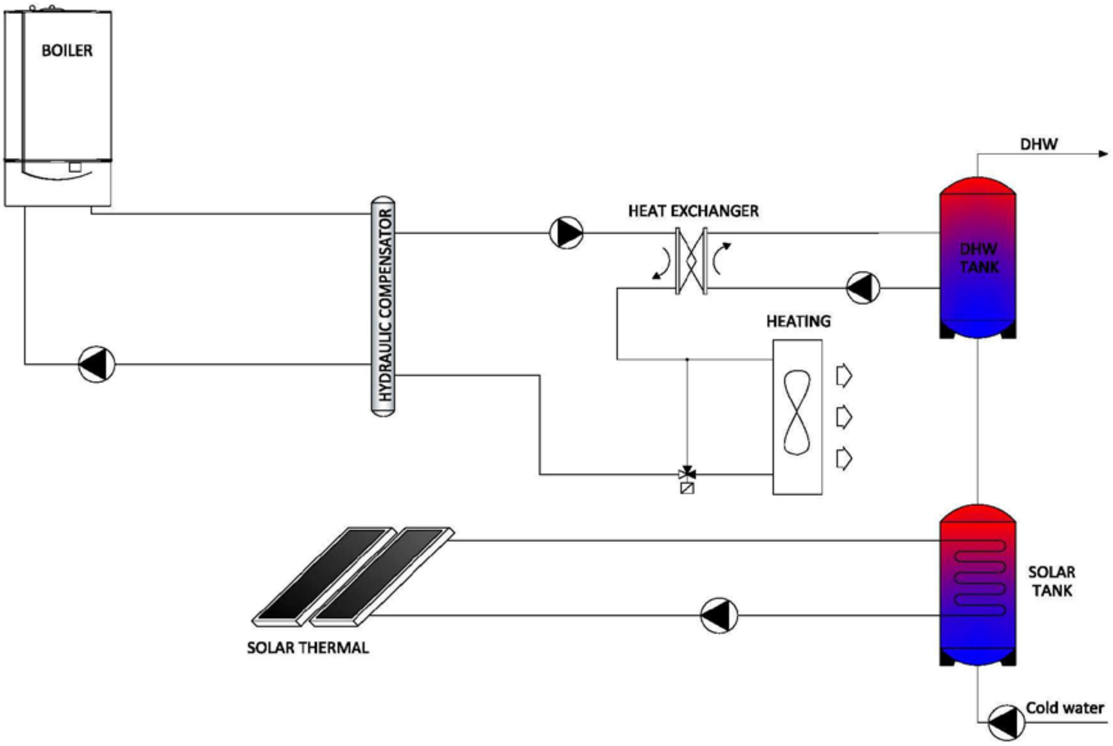

Figure 5: Schematic diagram of the reference conventional plant.

Hot water exiting the boiler passes through the hydraulic compensator disposed in order to balance generation and distribution flows, and then flows through the heat exchanger used for heating up the DHW tank. Afterwards, hot water exiting the hot side of the exchanger is conducted to the space heating loop.

Micro-CHP installation

The main energy producing device of the micro-CHP installation designed for the case study is based on a Stirling engine. Amongst the lately commercially available Stirling micro-cogeneration devices, such as those developed by BDR Thermea® around the Microgen® engine or the Whispergen EU1™ property of Whispertech® [52], the latter was selected. The Whispergen EU1™, which is the most widespread and characterized Stirling engine-based µCHP unit, is based on a four cylinder double-acting alpha type Stirling boiler which runs on natural gas, with a nominal power output of 1 kW_e. For extensive information on the Stirling cycle, a report published by the EPRI [53] can be looked up. The engine has a thermal output from 7.5 to 8.3 kW and runs at full load, with a nominal thermal efficiency above 85%, reaching an electric efficiency up to 11% [54]. The unit can increase its thermal output up to 14.5 kW when running the auxiliary burner included. However, the usage of the auxiliary burner was declined because it cannot cover peak demands of the dwelling - which may be appreciably greater in reality than the hourly integrated peak values indicated by the IDAE, due to the instantaneous and brief nature of DHW consumption -, and it was replaced by a condensing boiler.

Thus, the micro-cogeneration plant basis of the current analysis consists of a Whispergen EU1™ unit and the same 23.3 kW condensing boiler used in the conventional plant, integrated in the same plant for meeting both heating and DHW demands, as well as part of the electricity required in the housing.

The control strategy chosen for the micro-CHP unit was thermal tracking. This operation mode is based on the useful heat demand as defined by the Directive 2004/8/CE [55]. Thus, whenever there is need for thermal energy, the micro-cogeneration unit is the first to come into service, and it will keep on working until there is no necessity for thermal production. Even though this sort of units can be controlled either following electricity or heating tracking strategies, in residential uses this latter operation mode increases the runtime of the micro-CHP and consequently secures the useful heat demand-based high efficiency production principle [56]. Moreover, the intermittent nature of the electric loads in households, together with the fact that these loads in the case-study are often below the electricity output of the micro-CHP, which, furthermore, is not able to modulate its output, makes thermal tracking a better option.

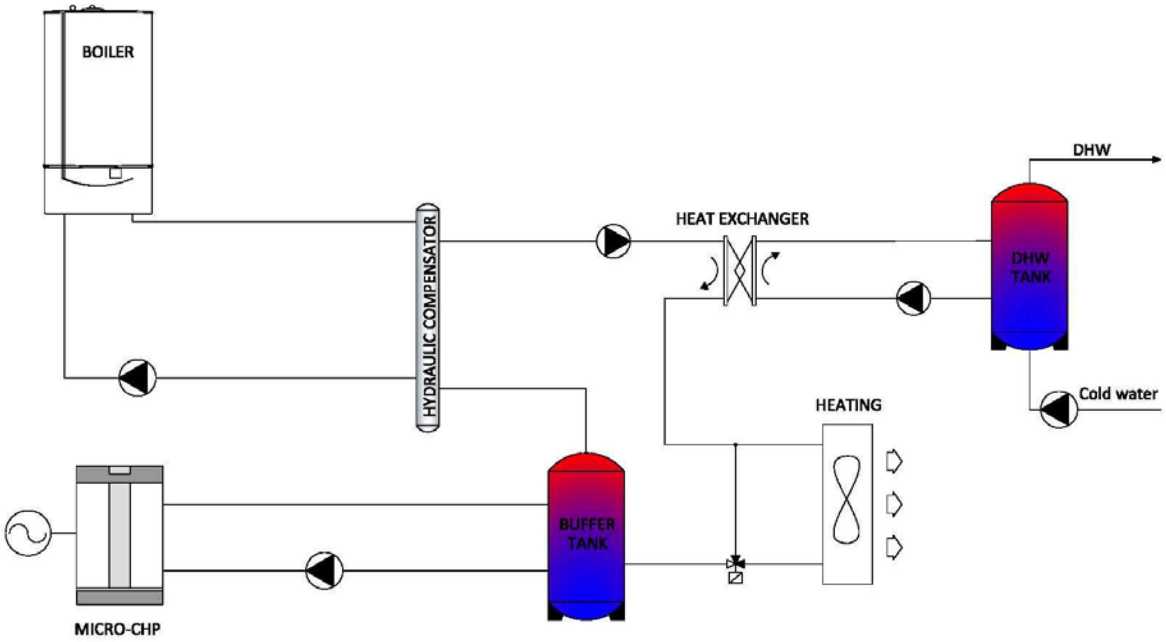

Figure 6: Schematic diagram of the micro-cogeneration plant.

Due to the variability of the thermal demand, the micro-CHP device is connected to a 750 litres buffer tank, which makes the unit operate for the maximum number of hours uninterruptedly an so improving its performance [57 - 59]. Once switched off, the unit will need its temperature to drop to a lower value; this drawback is also corrected with the inertia provided by the buffer. A detailed diagram of the plant is shown in Figure 6.

The water stored in the tank is discharged in order to meet the space heating and DHW loads. In case the heat provided from the storage deposit is not enough to meet the required thermal energy, additional heat is supplied by the condensing boiler. A hydraulic compensator is disposed in order to balance generation and distribution flows.

Hot water from the hydraulic compensator flows initially through the DHW loop, which is hydraulically isolated from the distribution loop through a flat-plate heat exchanger. The water heated up with the heat exchanger is afterwards stored in the DHW tank, so that the temperature of the consumption water is kept over 60°C.

The outlet of the hot side of the heat exchanger flows then to the space heating loop. The heating system is controlled with a 3-way valve governed by the main room temperature, which regulates the amount of hot water flowing through the radiators.

Table 2: Main components employed in the TRNSYS simulation.

Component	Model	Source
Conventional boiler	Type 700	TESS
Whispergen micro-CHP unit	Type 156	Annex 42*
Hydraulic compensator	Type 38	Standard
Constant flow pumps	Type 114	TESS
Hot water storage tank	Type 4a	Standard
Inner tank	Type 4c	Standard
Flow diverter	Type 11f	Standard
Flow mixer	Type 11h	Standard
Proportional controller	Type 669	TESS
Differential controller	Type 2b	Standard
Heat exchanger	Type 91	Standard
Radiator	Type 682	TESS
Solar thermal collectors	Type 73	Standard

Both micro-cogeneration and reference installations were modeled in Trnsys 17 dynamic simulation software according to the aforementioned definitions, taking into account thermal and electric loads. Table 2 contains the list of components employed in the simulation of the plants and their source. All the components used in the simulation were taken both from the standard and TESS libraries, except for the Whispergen micro-CHP unit. The performance of the Whispergen EU1™ was simulated using the so-called Type 156 developed in the IEA/ECBCS's Annex 42 [60] as a starting point, afterwards applying calibration and modelling of improvements in different phenomena of the engine through data obtained from experimental tests [61].

Even though a time-step of one hour is typically applied to this sort of simulation, in this case a 6 minute-based time-step was used, so that warm-up and cool-down periods of the engine and transient processes occurring in the storage tanks could be appreciated [62].

2.3. Energy and environmental analyses

From the simulations, flow-rates and temperatures of all flows were obtained for each time-step, as well as electricity and fuel powers. Main results are summarized in Table 3.

Table 3: Energy results from the annual simulation of the plants.

	Heating demand [kWh/a]	36,060.71
	DHW demand* [kWh/a]	2537.25
Micro-CHP installation	Hours of operation of the µCHP	4798.20
	Fuel consumption of the µCHP [kWh/a]	44,447.89
	Thermal production of the µCHP [kWh/a]	38,867.07
	Useful heat production of the µCHP [kWh/a]	37,491.05
	Electric production of the µCHP [kWh/a]	4652.46
	Fuel consumption of the boiler [kWh/a]	2807.94
	Thermal production of the boiler [kWh/a]	2611.38
	Electric consumption of the plant [kWh/a]	1015.77
	DHW production [kWh/a]	2961.23
	Overall efficiency of the plant [%]	90.27
Reference installation	Fuel consumption of the boiler [kWh/a]	42,879.87
	Thermal production of the boiler [kWh/a]	39,878.28
	Thermal production of the solar panels [kWh/a]	1591.89
	Useful heat production of the solar panels [kWh/a]	1159.60
	Contribution of the solar panels to DHW [%]	43.19
	Electric consumption of the plant [kWh/a]	907.59
	DHW production [kWh/a]	2684.95
	Overall efficiency of the plant [%]	88.24

** Reference DHW demand at 60°C*

As shown in Table 3, there is some electric consumption within the plants due to the use of the pumping systems, as well as to the auxiliaries of the production devices, which was consequently subtracted to the gross electric output when calculating the overall efficiency of the plants. This overall efficiency was obtained relating the overall energy outputs of the plants (electric and heat outputs) with the overall fuel consumptions. Additionally, it can also be appreciated that the real DHW production in both installations, which together with the heating supply constitutes the useful heat output, differs from the reference demand, as water in the DHW tank is not stored at 60 °C exactly but between 60 and 80 °C.

In order to better define the specific performance of the micro-CHP unit within the plant the Primary Energy Saving (PES) concept was introduced (Eq. 3). The PES, which is the efficiency index established by the 2004/8/CE Directive, determines the efficiency of a cogeneration plant with respect to getting the same thermal and electric productions separately [55]. The Directive states that a high-efficiency micro-cogeneration should achieve some primary energy saving, i.e. PES > 0%.

$$PES = \left(1 - \frac{F_{CHP}}{\frac{H_{CHP}}{RefH_{\eta}} + \frac{E_{CHP}}{RefE_{\eta}}}\right) \cdot 100 \qquad \text{(Eq. 3)}$$

where F_{CHP}, H_{CHP} and E_{CHP} are, respectively, the fuel consumption, the useful heat production and the electricity output of the cogeneration plant, whereas $RefH_{\eta}$ and $RefE_{\eta}$ are the harmonised efficiencies for separate heat and electricity productions respectively [63]. These reference efficiencies, with values of 0.9 and 0.45 respectively for heat and electricity, are determined by the aforementioned cogeneration Directive. For the calculation of H_{CHP}, losses in the buffer tank (rated at 0.36 W/m^2K) must be removed from the thermal production of the micro-CHP unit, as they cannot be considered as useful heat. Thereby, the PES of the plant is 14.5%.

Analogously, the electric efficiency of the cogeneration compared to a traditional plant, defined through the REE introduced in Section 2 was calculated. This parameter shows a value of 166.7%, hugely exceeding the minimum 49.5% value established for reciprocating engine-based micro-cogeneration plants.

These two values demonstrate that the micro-CHP reaches high efficiency and consequently substantial energy savings, and can therefore be regarded as high efficiency cogeneration.

On the other hand, for establishing the percentage of solar thermal contribution to DHW supply in the case of the reference installation, the net solar production was considered, that is, not the thermal production of the solar panels but the useful heat supplied to the DHW tank, which takes into account thermal losses in the solar tank and the efficiency of the heat exchanger. It is observed that the value obtained for this contribution is significantly above the 30% required as a minimum.

Finally, an hourly-based electricity balance was carried out, so that the contribution of the µCHP plant to the demand of the building could be evaluated, and so enabling the performance of the economic assessment afterwards.

Data collected in Table 4 show that almost 71% of the annual net electricity produced in the plant is self-consumed within the building at the moment of the generation (Eq. 4), i.e. 29% of the net electricity output is exported to the grid. When attending to the electric energy supply with net balance, it is observed that the net electricity coverage of the micro-CHP unit, i.e the net production of the plant with respect to the total consumption in the dwelling as defined in Eq. 5, is approximately 80%. For this calculation the consumption of the plant itself was deduced from the power output. On the other hand, if this net balance was applied to the conventional plant, a negative contribution would be obtained. To take into consideration this effect, the relative coverage was introduced, as defined in Eq. 6. This coverage considers the net balance of the micro-CHP plant with respect to that of the conventional installation by means of its electricity consumption, which is discounted. This way, the coverage of the µCHP to the demand of the dwelling would be virtually 100%, which indicates that the Stirling-based plant designed for covering thermal demands produces a yearly-amount of electricity equal to that consumed in the dwelling and the plant-consumption differential when installing the micro-CHP plant instead of the conventional one.

$$SC_e = \left(\frac{E_{CHP} - E_{GRID}}{E_{CHP}}\right) \cdot 100 \qquad \text{(Eq. 4)}$$

$$NC_e = \left(\frac{E_{CHP} - E_{PLANT_{CHP}}}{E_{DEMAND}}\right) \cdot 100 \qquad \text{(Eq. 5)}$$

$$RC_e = \left(\frac{E_{CHP} - \left(E_{PLANT_{CHP}} - E_{PLANT_{CONV}}\right)}{E_{DEMAND}}\right) \cdot 100 \qquad \text{(Eq. 6)}$$

where SC_e, NC_e and RC_e stand for self-consumed electricity, net electricity coverage and relative electricity coverage, respectively, E_{CHP} is the electricity produced by the micro-CHP, E_{GRID} is the electricity exported to the grid, and $E_{PLANT_{CHP}}$ and $E_{PLANT_{CONV}}$ are the respective electricity consumptions of the micro-CHP and the conventional plants.

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

Electricity demand [kWh/a]	4560.00

Electricity production of the µCHP [kWh/a]	4652.46
Electric consumption of the µCHP plant [kWh/a]	1015.77
Electricity purchased from the grid [kWh/a]	2293.42
Electricity sales [kWh/a]	1366.10
Self-consumed electricity [%]	70.64
Net electricity coverage [%]	79.68
Relative electricity coverage [%]	99.57

As far as the environmental impact is concerned, a greenhouse gas (GHG) emissions-based analysis was tackled, taking into consideration those emissions on account of the natural gas consumption and the electricity generation taking place during the operation of the plants, whereas the impact due to the extraction and fabrication of the components of the installations was neglected due to its low weight [64].

Calculations of GHG emissions were carried out following the IPCC 2007 method of the International Panel on Climate Change, where the Global Warming Potential (GWP) is introduced. This indicator, defined as the potential of global warming in a 100-years period, enables comparing the effect of liberating any GHG with that of the CO_2.

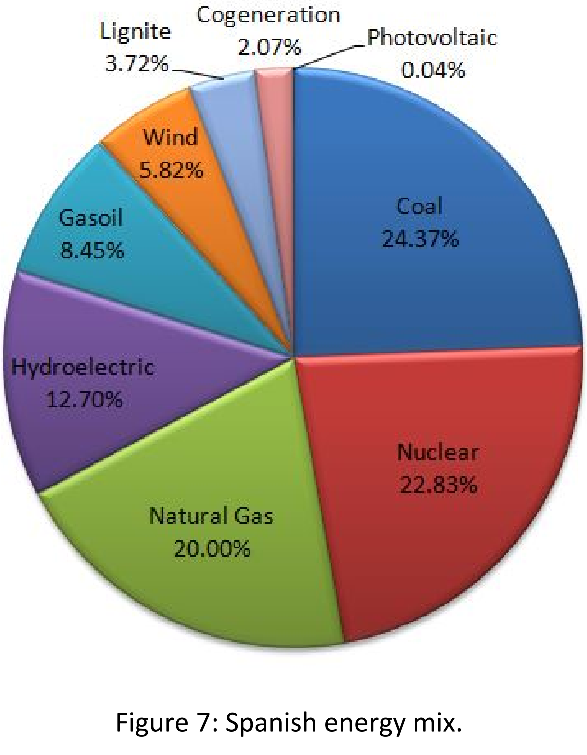

Figure 7: Spanish energy mix.

Emission factors of natural gas and electricity, in kg CO_2-eq / kWh, are 0.212 and 0.601, respectively. The first was obtained from the Ecoinvent 3.0 database, while the second was based on the Spanish energy mix depicted in Figure 7.

Taking into account all the aforementioned premises, and deducting emissions associated to the electric output of the micro-CHP unit, 7832 kg CO_2-eq are emitted with the micro-CHP, which constitutes a reduction of 18.7% with respect to the reference emissions of the conventional plant (9636 kg CO_2-eq).

2.4. Economic analysis

The financial evaluation of the yield associated to the implementation of the SE-based installation instead of a conventional one was based on the Net Present Value (NPV) and the depreciated Pay-Back period.

The NPV relates all incomes and outcomes existing through the lifespan of the plant to the initial investment. Therefore, assuming that the investment is entirely paid out in the beginning, the NPV is calculated as presented in Eq. 7.

On the other hand, the depreciated Pay-Back period, which contrary to the simple payback takes into account the time value of money, represents the moment when the return of the initial investment of a project takes place, i.e. when the NPV in Eq. 7 is equal to zero.

$$NPV = -Inv + \sum_{n=1}^{n=LT} \left[\frac{NS}{(1+r)^n} \right] \qquad \text{(Eq. 7)}$$

where Inv is the initial investment, which stands for the price difference between the micro-CHP device and the solar thermal panels in this comparative analysis, LT is the lifetime of the plant, r is the rate of discount, and NS represents the annual cash flows generated, calculated as indicated in Eq. 8. For this kind of projects, a lifetime of 15 years is assumed, and a rate of discount of 5% is lately considered to represent faithfully the available bank products under the current economic situation [65, 66].

$$NS = \sum_{i=1}^{i=8760} \left(Inc + I_e + I_{ac} - C_f - C_m \right)_i \qquad \text{(Eq. 8)}$$

where Inc is the applicable incentives and complements in each case (according to Section 2.1) to the different hourly electricity vectors, I_e is the incomes associated to the electricity generation of the micro-CHP (sales and avoided costs due to self-consumption), I_{ac} stands for the costs related to the fuel of the conventional plant (boiler), C_f is the fuel costs of the micro-CHP plant (boiler and SE), and C_m represents the difference between maintenance costs of the micro-CHP device and the solar thermal panels (as the remaining maintenance costs are common for both installations).

The prices assumed for the different electricity-tariff modalities considered for Spain are summarized in Table 5 [67], while the peak power-based fixed term of 42 €/kW·year was neglected. This is due to the fact that, although the peak consumption of the dwelling in the case of the micro-CHP installation is slightly lower (7%), the contracted power is the same for both cases. Meanwhile, natural gas cost was established in 5.04 c€/kWh [68]. As the economic analysis was made from a comparative point of view, no fixed term was either considered for natural gas supply, as it is common for both installations.

Table 5: Pricing periods and costs of the different electricity-purchase tariff modes.

		Electricity cost [€/kWh]						
Tariff		0-1 h	1-7 h	7-12 h	12-13 h	13-22 h	22-23 h	23-24 h
No discrimination		0.124107	0.124107	0.124107	0.124107	0.124107	0.124107	0.124107
2-periods discrimination	Summer	0.057995	0.057995	0.057995	0.057995	0.148832	0.148832	0.057995
	Winter	0.057995	0.057995	0.057995	0.148832	0.148832	0.057995	0.057995
Supervalley		0.071879	0.044146	0.071879	0.071879	0.150812	0.150812	0.071879
Pool	Summer	0.045222	0.037542	0.048460	0.050322	0.048039	0.052655	0.047759
	Winter	0.035107	0.022540	0.038418	0.040728	0.043309	0.046083	0.042105

Taking into consideration the electric profiles and pricings defined in Table 5, the tariff with two discrimination periods turned out to be the cheapest one (Table 6), and all the calculations were accordingly carried out.

For the case of electricity sales, the pool price was considered, that is, the hourly value at which commercial companies acquire electricity in the market. These hourly values were averaged in periods corresponding to those applied to the electricity-purchase tariffs, as shown in Table 5.

Table 6: Annual electricity-purchase cost for different tariff modes.

	Electricity cost [€/a]	
Tariff	Conventional plant	Micro-CHP plant
No discrimination	679.06	284.63
2-periods discrimination	595.58	253.15
Supervalley	616.44	262.45

Additionally, a sensitivity analysis of the energy prices for the case with the current legislative situation in Spain was carried out, encompassing the combination range of constant prices with annual variations on both natural gas and electricity prices of ±5%.

On the other hand, respective prices for electricity purchased in the German and the British markets were 27 and 18.45 c€/kWh, while natural gas prices stood for 5.3 and 6.59 c€/kWh, respectively.

The whole amount of the investment due to the installation of the micro-CHP device came to 8542 €, both including the cost of 8000 € of the device itself [15], and its electric connection to the low voltage network, rated at a 5% of the total cost of the whole plant [69]. The cost of the selected solar thermal panel and its structure was 659 € [70], while all the auxiliary equipment and installation costs were neglected due to the similarity of both plants.

Finally, according to the manufacturer, 75 € per year are necessary to be invested in the cleaning, inspection and gaskets exchange of the Stirling micro-CHP unit (hypothetical exchanges of other components were neglected), while a typical value of the costs associated to the maintenance of solar thermal panels installed in single-family houses is 15 €/m² per year [71].

3. RESULTS AND DISCUSSION

Applying the methodology explained in the previous section, the economic study was carried out. Main intermediate results for the current Spanish regulation with constant energy prices, summarized in Table 7, show that being the initial investment much higher for the micro-CHP case, within the framework described, savings with respect to the reference scenario are very low compared to that extra cost, being the only positive relative income the term related to electricity, which accounts for the sales and the self-consumption, as well as the incentives to operation. As so, according to data shown in Table 8, around a 54% recovery of the initial investment is only reached after the 15-years lifetime considered. Even though when comparing these results with those obtained when no incentive is considered (Table 8), i.e. the in-pass situation which took place between January 2012 and June 2014, an obvious amelioration of the feasibility is observed (2800 €), feasibility is far from being achieved.

Table 7: Main economic flows of the two plants under the current Spanish situation.

	Cost [€/a]	
Concept	Conventional plant	Micro-CHP plant
Specific Investment	659.00	8542.11
Natural Gas	2161.11	2381.65
Electricity	595.58	96.34
Specific Maintenance	42.30	75.00

Table 8: Main economic results of the micro-CHP for Spain.

	Electricity savings [€/a]	NPV (year 15) [€]	Payback [years]
No-incentives	392.62	-6436.46	No payback
Previous regulation	994.14	-192.88	15.71
Current regulation	499.24	-3636.65	No payback

Concerning the influence of energy prices on the final economic results, as depicted in Figure 8, it is observed that, as expected, augmentations in electricity prices and decreases in fuel prices favour annual savings. However, the weight of the electricity percentage variation in the annual cash flows is virtually twice the influence of the natural gas tariffs. Thus, if a 5% annual decrease in the natural gas price happened, together with a 5% decrease in the electricity price, NPV after year 15 would be considerably lower than that in the no-variation scenario (ΔNPV= -450 €). On the contrary, if a 5% annual augmentation in the prices of both products took place, the NPV final result would get improved in 670 €. Finally, it must be highlighted that, even for the most optimistic variation tendency considered, no positive NPV was achieved.

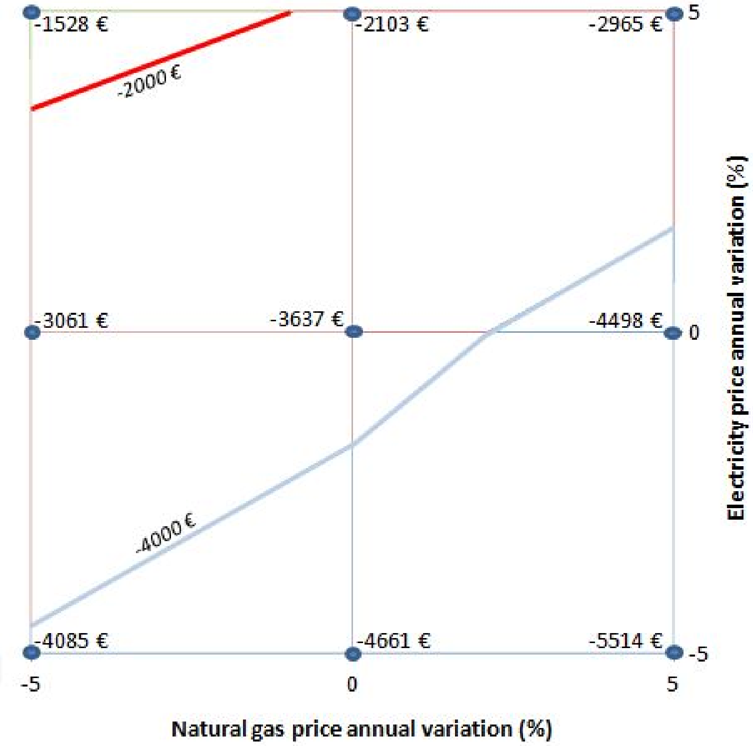

Figure 8: NPV results depending on the evolution of the energy prices.

On the other hand, calculating the results which would be achieved applying the previous regulation, approved in 2007 and in force until late 2011, with current fuel and electricity pricings, and without considering any complement due to reactive power, payback would be reached during the second half of the year after the considered lifetime of the plant is passed by. Comparison between these two economic results shows a final difference in the net present value of almost 3500 € after 15 years of operation, out of a relative investment of less than 8000 €. This fact constitutes a great step back for the implantation of this efficient technology.

Besides the exposed difference between the two case-studies, which lies in the elimination of the incentives for high efficiency generators and the implementation of the new regulation, the trend of fuel and electricity prices in the last few years in Spain is also negatively affecting the feasibility of this technology. As shown in Figure 9, while the natural gas price has increased by 34%, composed by 13% and 35% raises in the fixed and the consumption terms respectively, the electricity tariff increment has almost reached 17%, which comes from a respective augmentation of 104% and 5% of the power and the variable terms.

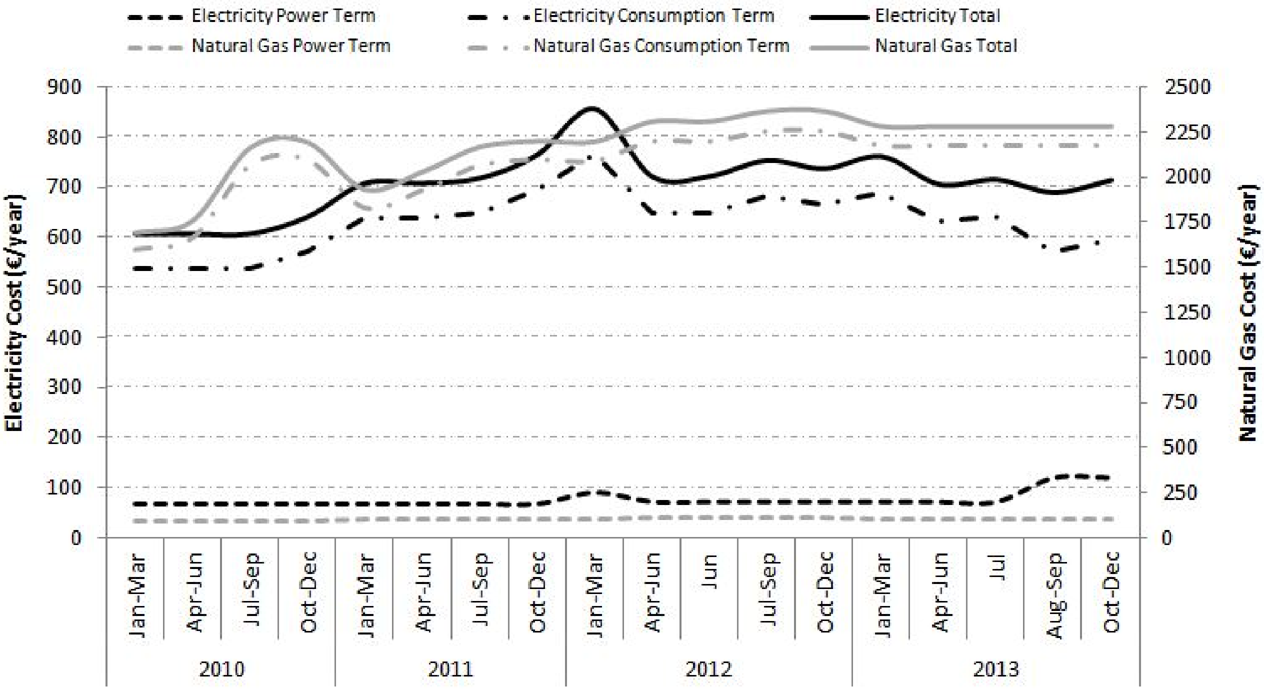

Figure 9: Evolution of natural gas and electricity prices in Spain applied to the reference scenario.

In the case of electricity, the increase of the price, which is expected to keep on rising progressively in the coming years in order to deal with the so-called tariff-deficit, has mainly led to a huge augmentation of the term corresponding to the contracted power instead of the consumption term. Given that the power term contract works with prearranged and stepped values, and the achievable peak power demand reduction is not enough to shift from one step to a lower one, no savings are possible in this sense. This fact constitutes a very noteworthy drawback for the economic feasibility of micro-CHP, since savings due to self-consumed electricity do not rise even though electricity gets more expensive.

When comparing results obtained in Spain with those achievable in Germany and United Kingdom, with and without considering incentives existing in those countries, a vast difference is detected. Seven cases were considered in order to perform the comparative analysis, as presented in Figure 10. The letters are the code of each country (ES: Spain, DE: Germany, UK: United Kingdom), while numbers 1 and 2 indicate if there is not any incentive or if complements are considered, respectively. In the case of Spain, 2.1 makes reference to the previous incentives, while 2.2 regards the current situation.

In the German scenario, results achieved when the considered lifetime of the plant is passed by show that, even neglecting economic incentives (DE1), net present value is only smoothly below that obtained in Spain when applying previous economic bonuses (ES2.1). This fact is partially explained with the electricity-to-natural gas price ratio. In Spain, this value has decreased from 3.16 to 2.46 in the last 4 years, while it is 5.09 for Germany. Thus, when generating a kWh of electricity for self-consumption, economic savings got in Germany are twice those achieved in Spain. Meanwhile, after the 15th year of operation, while payback is not even reached with any Spanish regulation, NPV under the current German framework (DE2) shows profits of almost 5000 € out of an initial extra investment of less than 8000 €, resulting in an absolute NPV difference with respect to the RD 413/2014 case (ES2.2) of almost 8500 €. Consequently, aside from the mentioned ratio, it is obvious that support mechanisms in Germany are broadly more effective than those which have ever existed in Spain. For this case (DE2), a payback period of 6.8 years is achieved, which is considered to be a reasonable value for such investment to get attractive.

On the other hand, taking a look at the results obtained with the conditions in force in the United Kingdom, the effectiveness of the support mechanisms applicable can be highlighted. While no payback is possible without considering any incentive (UK1), nearly achieving a 50% recovery of the initial investment after 15 years, a payback period of 9.2 years is obtained under the current legislation (UK2), with a final NPV of 1604 €. Comparing the ratio relating electricity and natural gas prices for the UK with that obtained for Germany, a large difference is also observed, being the British value 1.8 times lower. Considering this difference and that the relation of the final NPV of cases 5 and 7 is rated at 3, it can be concluded that economic support in force in the UK also rewards suitably benefits provided by micro-CHP.

When comparing support mechanisms adopted in the UK with those governed in Spain by both the RD 661/2007 previously and the RD 413/2014 currently, and taking into account the similarity of the electricity-to-natural gas price ratios for both countries, it can be concluded that incentives applied in the UK allow obtaining a final money recovery with respect to the initial investment around 23% higher than the value for the conditions established in the aforementioned revoked Spanish Royal Decree, while the final NPV reached is 5240 € higher than the one currently in Spain.

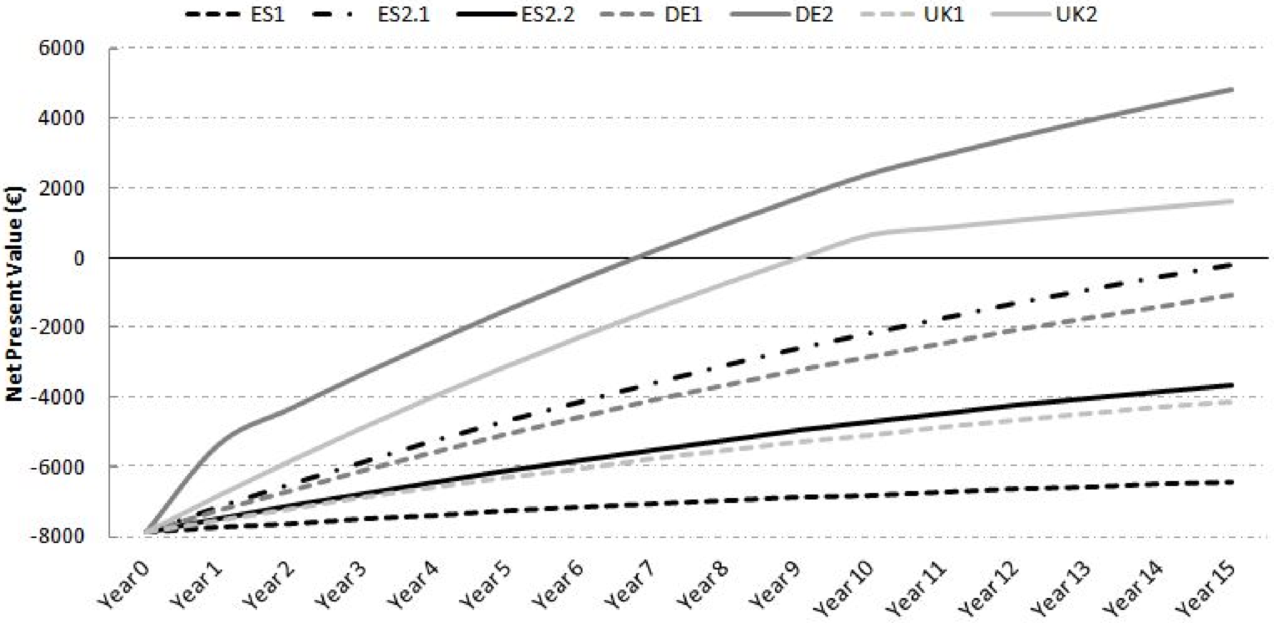

Figure 10: Net Present Value in the end of the lifetime of the micro-CHP plant for different cases.

All these results show that there is still a long way to go in the regulation matter in Spain. Analysing how current incentives work, two main aspects, related to each other, can be highlighted. On the one hand, the incentive to operation is not applied to the whole electricity generated by the micro-CHP but to that amount which is sold. Considering this bonus for all the electricity produced, the pay-back period would be reached after 18 years, that is, after a period of 1.2 times the lifetime of the plant. On the other hand, retribution related to the investment of the device is calculated with relation to a much lower amount to that necessary to acquire the Stirling unit, which is partially due to the high cost of this small-scale technology - which may decrease with improvements in the regulation framework which could make feasibility possible and so turn into a major introduction of this technology -. However, it is also noteworthy that using a linear relationship between the nominal power and the initial cost of the CHP for a very large power range is not appropriate, as it is obvious that features of a 1 kW_e and a 500 kW_e CHP differ hugely. Furthermore, it must be remarked that these incentives are calculated and applicable taking a lifetime of 25 years as a reference, even though the typical useful life of this kind of installations is 15 years.

This way, an appropriate basis for the determination of the investment incentive, combined with the previously mentioned assumption of the operation retribution, could make feasibility possible, and so progressively boost other economic facts affecting profitability.

4. CONCLUSIONS

Residential micro-cogeneration systems in general, and those based on Stirling engines in particular, have lately emerged as efficient systems with great potential to provide economic, energy and environmental savings. However, there is need for further research to better characterize the behaviour of this technology, so that it can be progressively introduced in the market. In the case of Spain, where they are not commercially available, little research has been done in this issue. Thus, this paper deals with an economic assessment of the implementation of this technology into a micro-CHP plant for covering heating, DHW and electric demands in a detached reference Spanish housing, analysing how different regulations and economic frameworks influence viability of such devices.

Once thermal and electric profiles are calculated, performance data of two energy plants, constituting the reference and the Stirling micro-cogeneration scenarios, are obtained from dynamic simulations. Following the methodology described, an economic analysis is carried out, taking both the previous and the current regulations for cogeneration in Spain. Likewise, results achievable with the regulatory frameworks existing in Germany and the UK are also calculated, and the influence of their support mechanisms is also analysed.

It is concluded that, even though technical results achieved confirm the benefits micro-CHP and in particular the Stirling technology can offer, the current situation for cogeneration in Spain is still untenable. Being the initial investment quite elevated, the money recovery is extremely low when the lifetime of the plant is passed by - not much better than when omitting incentives -, nearly achieving pay-back with the previous regulatory framework. This confirms that there is much to improve in regulation matters in Spain for this efficient technology to get competitive.

On the other hand, comparison between results obtained for Spain and those achievable in Germany and United Kingdom show that feed-in tariffs and support policies in force in these latter countries allow obtaining very attractive payback periods, getting improvements in relation to the no-incentive cases more than twice than in the case of Spain.

Finally, it must be remarked that besides the unfavourable framework recently approved in Spain, one of the main drawbacks for installing micro-CHP devices lies on the uncertainty existing on the regulation and prices related to the field of cogeneration and renewable energies, which result detrimental when attempting to invest on this technology. Thus, taking into account the obvious potential this technology can offer for reaching the energy challenges existing, and the weight regulation has on its feasibility itself and in other parameters directly related to feasibility, some steps forward should be taken for promoting such efficient units which evidently bring numerous benefits sooner or later.

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