Abstract

This PhD Thesis deals with the technical, energetic, environmental and economic evaluation of the potential utilization of Stirling engine-based micro-cogeneration installations for meeting the thermal and electric requirements of the building sector, focusing on single family dwellings.

The interest of the thesis was awoken by the current energy situation, where the construction sector is responsible for the 40% of the total energy consumption of the European Union. In the case of Spain, this sector accounts for the 17% of the total final energy consumption, corresponding about 60% to heating and domestic hot water demands.

It is the heating demand which, due to health and comfort requirements established by the standards amongst other factors, represents one of the main causes for the building sector consumption to maintain an increasing tendency during the last years. Furthermore, the growing concern about reducing this consumption, together with the environmental impact it implies, have given raise to numerous modifications in the regulatory framework, directed towards getting higher energy efficiency in buildings and employing renewable or high efficiency technologies.

Amongst these latter technologies, the European Union and all its Member States recognize the important role cogeneration can play in the energy transition, as well as in the consecution of the objectives defined from the Kyoto Protocol on. This way, according to Directive 2004/8/EC and its corresponding revision settled through Directive 2012/27/EU, cogeneration possesses a great application potential in all those activities where high thermal energy consumption exists, as it is the case of the residential sector.

Micro-cogeneration or small-scale cogeneration encompasses cogeneration units with electric power outputs below 50 kW. Its features – small power, compactness and disposed connections – make micro-cogeneration be oriented to in-situ generation in small residential and tertiary applications.

Among the different micro-cogeneration technologies, the Stirling engine offers some features that make its utilization very suitable for domestic applications. Besides the intrinsic advantages micro-cogeneration offers, the Stirling technology can be fed with different energy sources, from combustion to residual heat recovery or solar energy. Likewise, since it has low number of moving parts and its heat source is external, the Stirling engine offers low noise and dioxide carbon emissions levels.

Nevertheless, it is a fact that it is a little spread technology within these applications, and its performance and suitability is not sufficiently known yet. Thus, it is essential to study

this technology in order to improve its design and operation, as well as to know the way it behaves when integrated in a domestic thermal installation. For that purpose, it becomes necessary to develop simulation models that, besides improving the design, allow analysing and evaluating the technical, environmental and economic performance of this technology.

This way, this thesis faces the necessary steps to perform a complete analysis of the implications installing these Stirling engine-based micro-cogeneration units in Spanish single family dwellings have. The analysis is carried out both from energy and environmental and economic points of view.

The thesis starts with an analysis of the different technologies that enable obtaining energy efficiency and environmental improvements. Then, the Stirling technology and its applicability in the residential cogeneration field is assessed. Afterwards, the current state of the Stirling micro-cogeneration is presented: evolution and commercial status of Stirling engines, techno-economic research carried out so far, both methodologically and in terms of results achieved, as well as mathematical models developed and the different approaches existing.

Once defined the context of the thesis, based on the objectives previously defined, the development of a mathematical model that is able to reproduce the performance of small Stirling engines applicable to single family buildings is assessed. Amongst the existing alternatives, taken into consideration the field where it is to be applied, a grey-box modelling approach is used. The main objective of the model is to overcome some of the weaknesses of previous models, as well as to boost their strong points.

This way, the second chapter of the thesis focuses on defining the mathematical equations that govern the general performance of Stirling micro-cogeneration units, taking into consideration their architecture and the different modes they can operate on. Then, once defined the mathematical model proposed, it is specifically applied to the Remeha eVita micro-cogeneration unit. Thus, the different operation modes and logic of this unit is conscientiously described next, in order to design an appropriate testing routing that allows fully characterizing its performance. For that purpose, and experimental installation is developed in the Laboratory for the Quality Control in Buildings of the Basque Government, where the Stirling engine is integrated and can be tested both individually or integrated with other components of thermal plants. This way, the performance of the unit, submitted to different operation conditions, both steady and transient, is characterized. Using data obtained together with a parameter identification procedure allows calibrating the model and so adapt the model to the engine selected. Three different approaches were contemplated when identifying parameters, from lower to higher level of sophistication. It is concluded that advanced techniques based on optimization algorithms, even though they can make the variables to be quantified lose their physical sense, allow reducing to a greater extent the error committed and so obtain the combination that provides the best results.

Once calibrated the model, its validity is checked. For that, both steady and transient performances were validated, by comparing values predicted by the model with those

measuring in laboratory tests. Additionally, results provided by the model were also compared to those predicted by a model already validated. Both approaches confirm that the proposed model possesses the capacity to successfully predict both the fuel consumption and the by-products of the micro-cogeneration unit. This mathematical model is programmed in Fortran language and is implemented in TRNSYS building energy simulation tool.

One of the main problems to come up when implementing a micro-cogeneration unit in buildings lies in the high variability of thermal demands in the residential sector and the difficulty to predict them. Amongst the different alternatives existing to face these features, thermal energy storage offers the possibility to improve effectiveness of these plants, awarding the micro-CHP unit with a more important role and allowing separation of energy production and demands. In this sense, in order to maximise the exploitation of the micro-CHP device, the integration of sensible heat thermal energy storage systems within this kind of installations is approached.

For that purpose, based on annual simulations using the previously developed model, the effect of both the size and the way thermal energy is arranged within the thermal plant is analysed. By means of a heuristic analysis, different plant configurations and thermal energy storage sizes are analysed, both in terms of inertial and domestic hot water storage. Taking into account results obtained from the energy, environmental and economic indicators defined to face the analysis, it is concluded that, on the one hand, it is desirable to dispense with domestic hot water storage. On the other hand, it is also concluded that sensible thermal energy storage systems are traditionally oversized. Likewise, even though series arrangement of the thermal storage systems provides slightly better energy results, it is also verified that parallel arrangement enables a faster recovery of the purchase of the tank.

On the other hand, as summarized in the state-of-the-art initially presented, Spain is one of the countries in the European Union where micro-cogeneration in general and that based on Stirling engines in particular is less extended, and no significant research analysing its behaviour has been carried out so far. In this sense, this PhD Thesis considers an analysis methodology, applied to a representative case-study, that allows going in depth in the techno-economic impact of such a residential installation in Spain. For that purpose, a comparative analysis with a reference installation made up of a conventional boiler and a solar thermal installation that satisfies the renewable contribution requirements in relation with domestic hot water is carried out.

The first part of the study focuses on analysing the main factors related to the design of the solar thermal installation that constitutes the reference scenario micro-cogeneration has to compete with. This way, it is verified that, whatever the climatic zone is, if the economic aspect is exclusively considered, the minimum solar surface that enables reaching the requirements established should be disposed. Besides this, within the broad range defined by the Technical Building Code, the desirable capacity of the solar tank per square meter of collector disposed is also determined. Once the reference scenario is defined, together with the optimum configuration obtained for the micro-cogeneration installation, the technical, energetic, environmental and economic

performance of the latter is assessed. To do so, a parametric analysis where the influence of climatic conditions is taken into consideration is presented. This influence is analysed by means of representative climatic zones. It is evinced that, even though under current conditions substituting the reference installation with Stirling micro-cogeneration is not economically justified, technical and energy results show that important primary energy savings can be achieved.

For analysing the influence of the main factors that affect the economic viability of this technology, a parametric analysis is then considered. This analysis takes into consideration different scenarios in terms of energy (fuel and electricity) and investment costs and, on the other hand, the influence of the regulatory framework. Results show that, even though realistic variations in energy prices do not allow reaching profitability by themselves, if combined with a moderate decrease of the initial cost of the unit –which could be achieved with a major introduction of the technology in the market –, the extra investment could be recovered during the lifetime of the plant in dwellings sited in cold climatic zones. Likewise, as far as the regulatory framework is concerned, it is confirmed that, in comparison with British and German normatives, whose incentives seem highly effective, Spain has gone backwards in this sense.

Key words: