Cost Competitiveness of a Novel PVT-based Solar Combined Heating and Power System: Influence of Economic Parameters and Financial Incentives

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Abstract

The cost competitiveness of an optimised solar combined heating and power (S-CHP) system based on a novel PVT collector is assessed in three different locations (Zaragoza, London and Athens). A series of sensitivity analyses are undertaken to evaluate the extent of the influence of the several economic parameters on the cost competitiveness of the proposed solar solution, and evaluate the need for financial incentives to boost the installation of this technology, in particular in the residential sector. From the different systems components' costs, the results show that the PVT collector price is the one that influences more the system economics, as it responsible of the highest share of the total investment (~38%). High market discount rates and/or low inflation rates significantly and negatively affect the system cost competitiveness, leading to higher payback times (PBTs). Government incentives, if correctly applied, have the potential to improve the system economics in the short-term. However, in low latitude locations these incentives might not be necessary as high irradiance levels and energy prices lead to reasonable PBTs. Finally, the analysis of potential future scenarios, considering a combination of several economic parameters, demonstrates that the S-CHP system cost competitiveness is feasible in the short term.

Keywords:

Hybrid PVT solar collector; Solar Combined Heat and Power system; Feed-In-Tariffs; Renewable Heat Incentive; Payback time

1 Introduction

A strong increase in the uptake of solar technologies in the urban environment has been observed in the last years. This can be attributed to the decrease in the prices of these technologies in conjunction with the introduction of relevant financial incentives [1,2]. These solar technologies include not only solar photovoltaic (PV) systems and solar hot-water heating systems, but also hybrid photovoltaic-thermal (PVT) systems. Among the different solar technologies, hybrid PVT technologies appear as a particularly promising solution when roof space is limited or when heat and electricity are required at the same time; since these systems can deliver both heat and electricity simultaneously from the same installed area, and at a higher overall efficiency compared to individual solar-thermal and PV collectors installed separately [3–5]. Moreover, optimised PVT systems coupled with low-carbon heat pumps or absorption refrigeration units can provide power together with combined heating and cooling in the urban environment. In this line, previous research [6] concluded that PVT technology has the potential to cover more than 60% of the heating and between 50-100% (depending on the location) of the cooling demands of a single-family household.

For the mass deployment of hybrid PVT technologies, the high initial investment cost and administrative barriers appear as the main barriers to overcome [7]. It is expected that administrative barriers will disappear with market development and with the adoption of policies that facilitate the development of these solar hybrid systems [8]. Regarding the technology costs, the cost competitiveness of solar PVT technologies in the urban environment depends on several factors amongst which the most important ones are: the availability of solar irradiance, the characteristics of the building's energy demand, the system investment cost, and the costs of the available alternatives for heat and electricity provision (utility prices). In this work, the cost competitiveness of a proposed solar combined heating and power (S-CHP) system based on a novel hybrid PVT technology is thoroughly studied.

Earlier economic studies on hybrid PVT systems [9–13] considered constant economic parameters such as the inflation and discount rates, or constant 'daily average' profiles for the energy demands. In a more recent study [14], the International Energy Agency (IEA) considered three different discount rates (3%, 5% and 7%) to estimate the levelised cost of generating electricity (LCOE) for different baseload power stations (fossil fuel based and nuclear) and several renewable technologies (solar PV and onshore/offshore wind). In the aforementioned report, the influence of several parameters in the LCOE of the analysed technologies was also assessed; specifically, the variation of the discount rate, overnight costs, lifetime, capacity factor, fuel cost and lead time. In this line, in the present research, a sensitivity analysis is undertaken to study explicitly the influence of the utility prices and the inflation and market discount rates on the economics of the proposed S-CHP system. Furthermore, this work explores variations of financial incentives, both for electricity micro-generation and renewable hot-water production (including domestic hot water, DHW, and space heating, SH). Typically, previous studies [11,15,16] did not consider Government support in their economic analysis. A more recent study [17] analysed the influence of Feed-In-Tariffs (FITs) both proportional to the electricity produced and based on the primary energy savings, and they concluded that electricity-related FITs do not incentive the production of the thermal energy by the PVT panel. They also concluded that a FIT based on primary energy is not practical as primary energy savings are difficult to measure.

A previous study of the IEA [14] concluded that system costs, market structure and policy measures play an important role in the LCOE of electricity generating technologies, particularly in renewable systems. Therefore, the aim of this work is to analyse the influence of different economic parameters on the cost competitiveness of the proposed S-CHP system for a single-family house in three different climates: Zaragoza (Spain), Athens (Greece) and London (UK). The reference house was previously modelled in EnergyPlus software to estimate its annual energy consumption in the aforementioned locations [18]. The novel S-CHP system was also previously modelled, sized and optimised for the same three locations. It is worth mentioning that there are methods available for optimization problems where a number of parameters can be varied, weighed and prioritised, such as meta-heuristic methods and fuzzy optimization approach [19–21]. However, despite these techniques are no problem specific, they are not considered in this work since it is not the objective here to obtain the optimal solution from an economical point of view, or to weigh, rank and prioritize criteria, but to analyse how the different external economic parameters under study influence the cost competitiveness of proposed S-CHP system when these parameters vary within a realistic range.

In this work, firstly a review of the investment cost and utility prices within Europe is undertaken, followed by an outline of current policies and subsidies for solar technologies. In Section 2, the optimised S-CHP systems for each of the selected locations are presented, together with the methodology followed in the present study. Then, in Section 3, the influence of the price of the main S-CHP system components (PVT collectors, water storage tank and battery storage) and system installation costs are analysed, as well as the influence of the market and fuel inflation rates, and the utility (electricity and natural gas) prices. Afterwards, the effect of the implementation of financial incentives on the system economics is studied, considering both electricity and heating incentives. Finally, a set of different potential future scenarios are analysed, simultaneously varying several of the aforementioned economic parameters in the different locations under analysis. The main conclusions are drawn in Section 4.

1.1 Investment cost and cash flow uncertainty

A primary barrier for the accelerated uptake of renewable energy technologies arises from their high upfront capital costs compared to conventional fossil-fuel systems, in which a significant fraction of the levelised costs is incurred during operation (fuel costs) [22]. The total investment cost of solar technologies consists mainly of: system components cost, labour and administration costs.

Figure 1 shows a breakdown of the investment costs (including installation) of a representative solar S-CHP system for a single-family house based on PVT collectors (8 PVT collectors, 12.4 m^2, and 0.72 m^3 water storage tank). The prices considered are from different European retailers, as it is believed they could supply the components to any country in Europe. For different system sizes (e.g. different number of PVT collectors or storage tank volume), the cost of those components should be varied proportionally. As shown in Figure 1, the PVT collectors' price is the main cost (around 38%) in an S-CHP system, so there is a large potential for designing and manufacturing cost-competitive PVT collectors. A decreasing trend in the capital costs of solar technologies is foreseen, along with a growing market size. Indeed, the cost of solar-thermal collectors has decreased by 23% in Europe along with a doubling in the installed capacity [23,24], which is comparable to the drop in PV module prices that showed a learning rate of 16-30% in global scale studies [25].

Currently, the lack of local retailers and trained on-site personnel affects the installation costs [9,26], which currently account for around 23% of the total fixed costs in a S-CHP system based on PVT collector [27] (Figure 1). However, these costs significantly vary from country to country and increase further if solar installations require permits, which also create delays and additional costs [28]. The International Energy Agency (IEA), in its Task 35, indicates a potential cost reduction of roughly 10% for PVT installations compared to the combination of separate systems with market development [29].

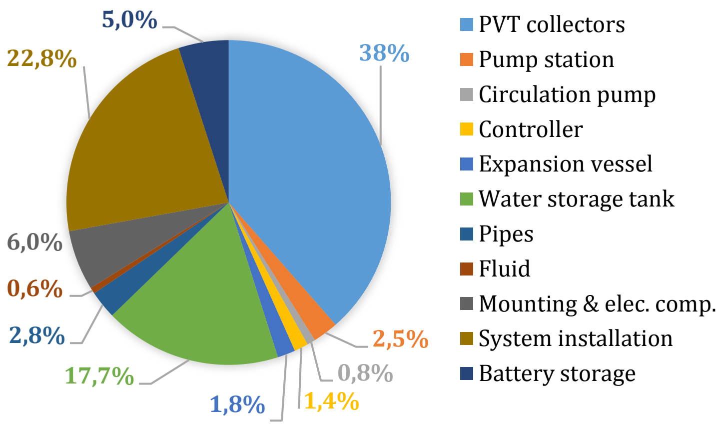

Figure 1. Breakdown of the investment costs (including installation) of a representative solar S-CHP system for a single-family house based on PVT collectors (8 PVT collectors and 0.72 m³ water storage tank) [27,30–35].

On the other hand, the cash generated over a system's lifetime depends on variable external factors such as utility prices. As a consequence, incoming cash flows are uncertain, while the expenditure is certain and immediate. Investors need to hedge this risk through adequate financial structures. In Spain, for example, if SH and DHW are provided by a natural gas boiler, the cost is ~0.11 €/kWh, while if it is provided by electric heaters, a much higher cost is incurred, ~0.23 €/kWh. Meanwhile, in the UK those numbers are ~0.05 €/kWh and ~0.18 €/kWh; and in Greece ~0.10/kWh and ~0.17 €/kWh, respectively. The aforementioned values are the prices when all taxes and levies are included, and are values as of the second half of 2016 [36]. For electricity prices, the band DC[1] (2,500 kWh < consumption < 5,000 kWh) is selected [36], as the total household electricity consumption is ~2,800-3,500 kWh [18]. For the natural gas prices, the band D1 (consumption < 20 GJ, 5,555 kWh) is considered for Zaragoza and Athens, as the total natural gas consumption to satisfy the SH and DHW demand is ~3,800 kWh and ~2,400 kWh respectively, assuming a boiler efficiency of ~90% [37]; while for London a band D2 (20 GJ, 5,555 kWh < consumption < 200 GJ, 55,555 kWh) is selected [36], as the total natural gas consumption is ~7,000 kWh [18]. It should be noted that the natural gas price for London is significantly lower than in the other cases due to the band that should be selected according to the household thermal energy demand. If the demand was lower than 5,555 kWh, the natural gas price would increase to 0.0768 €/kWh.

[1]The electricity and natural gas prices vary depending on the annual energy consumption within different bands: D1, D2 and D3 for natural gas consumption and DA, DB, DC, DD and DE for electricity consumption.

The following figures show the trends of the utility prices from 2007 to 2017 in different EU countries and the EU (28 countries) average. It is observed that the natural gas prices have fluctuated at higher or lower extent in the different EU countries in the last ten years, and that there is a significant difference in the natural gas prices between the different countries. Specifically, the natural gas prices in Sweden are almost 6 times higher than the corresponding prices in Romania (Figure 2). Countries such as France, Italy, Spain or Greece show very fluctuating prices, while others such as Croatia, Bulgaria or Romania are more regular throughout the different years. In general, an increasing trend in the natural gas prices is glimpsed.

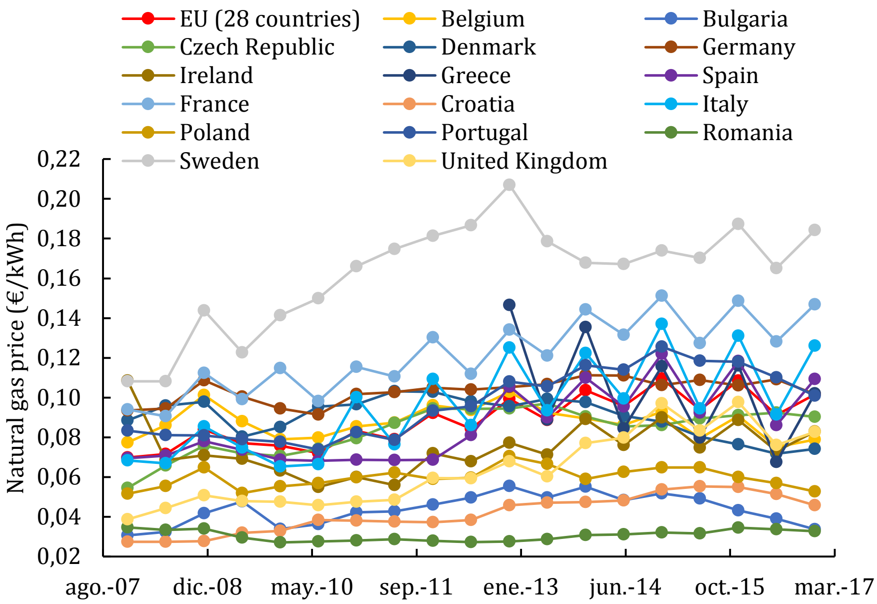

Figure 2. Trends of natural gas prices from 2007 to 2017 in different EU countries and the EU (28 countries) average for band D1 (consumption < 20 GJ, 5,555 kWh) [36].

Looking specifically at the trends in the countries under study, Figure 3 shows that since approximately 2012, the natural gas prices in Spain and Greece have fluctuated significantly and at higher extent that the EU average (continuous lines). It should be noted that natural gas prices in Greece are only available from December 2012 in the selected database [36]. The natural gas prices in the UK are considerably lower because the band D2 should be selected for the household located in London according to its thermal energy demand. As shown in the EU average, the prices of band D2 (dashed lines) are considerable lower than those of band D1, which are the ones applicable to the households located in Zaragoza and Athens.

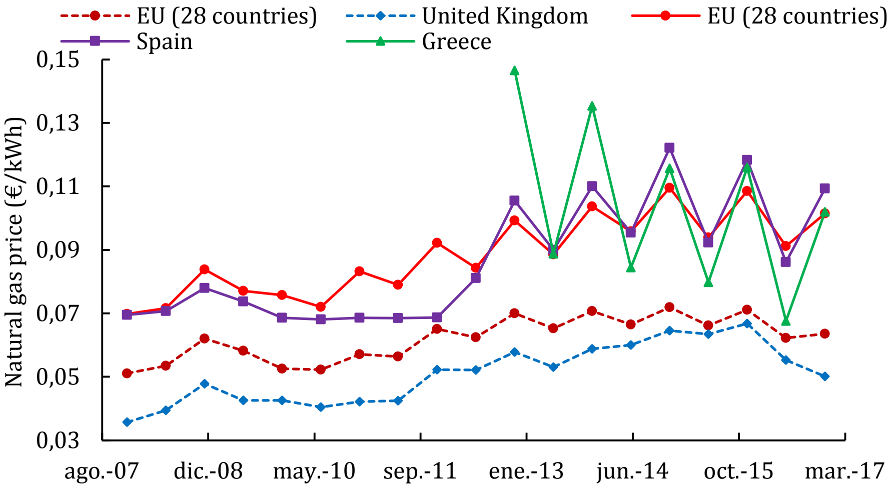

Figure 3. Trends of the natural gas prices from 2007 to 2017 in the countries considered in this research and the EU (28 countries) average. The dash lines refer to the prices of band D2 (20 GJ, 5,555 kWh < consumption < 200 GJ, 55,555 kWh), which are applicable to the household in London, while the continuous lines correspond to band D1 (consumption < 20 GJ, 5,555 kWh), considered for Zaragoza and Athens [36].

Figure 4 shows the trends of the electricity prices from 2007 to 2017 in different EU countries and the EU (28 countries) average. Similarly, as before, in general, an increasing trend is observed, at higher or lower extent depending on the specific country. There are also considerable differences between the country with the highest electricity prices (Denmark) and the one with the lowest prices (Bulgaria), having the former 3 times higher electricity price than the latter. It is observed that electricity prices fluctuate less than natural gas prices, and in general a higher increasing trend is observed.

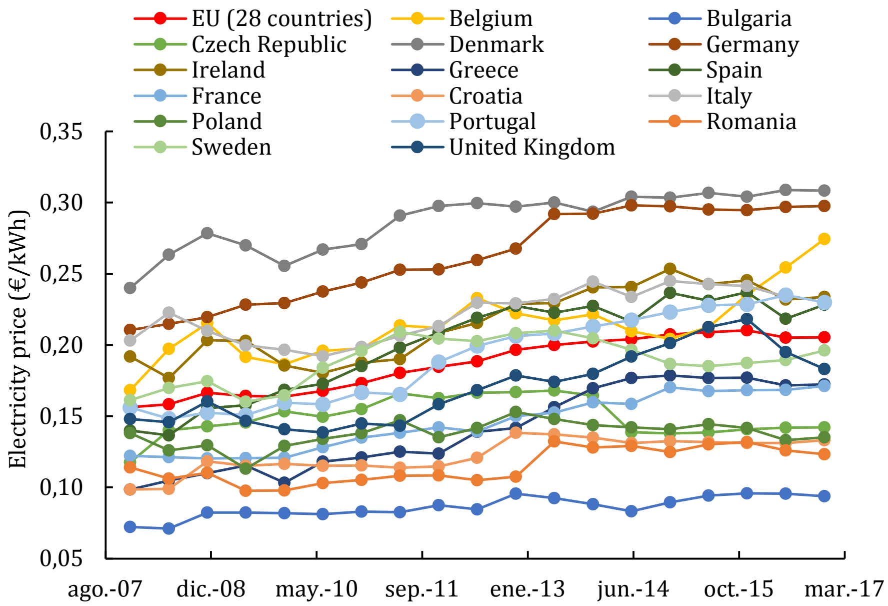

Figure 4. Trends of the electricity prices for band BC (2,500 kWh < consumption < 5,000 kWh), considering all taxes and levies, from 2007 to 2017 for different EU countries [36].

Figure 5 shows that the electricity prices in Spain have increased at significantly higher rate than the EU average, with considerably higher values than the average since 2011. The electricity prices in the UK have also notably increased in the last 10 years but, except in a few occasions, the prices are below the EU average. Similar trends are observed in Greece, but in this case the prices are considerably lower than the EU average (16%), as well as than the prices in Spain (25% lower).

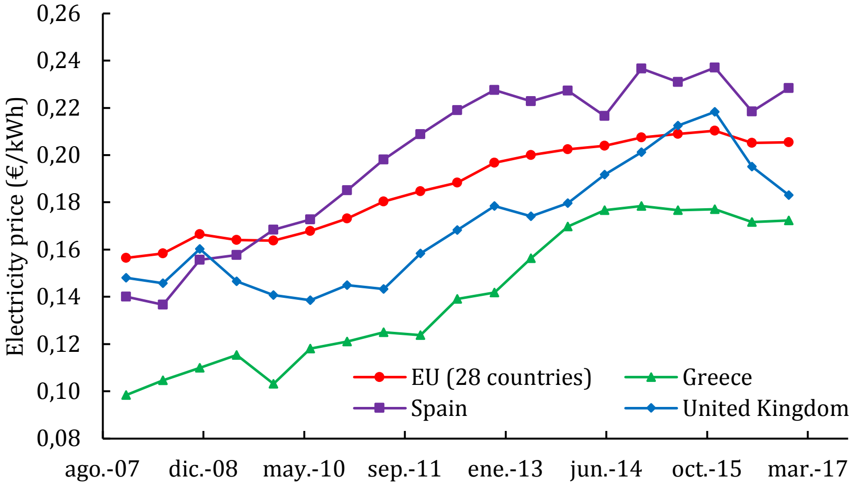

Figure 5. Trends of the electricity prices for band BC (2,500 kWh < consumption < 5,000 kWh), considering all taxes and levies, from 2007 to 2017 for the countries analysed in this research [36].

The inflation rate has also significantly varied in the last 10 years in the three countries analysed in this research (Greece, Spain and UK). Table 1 shows the mean value, standard deviation (σ), and mix/max values of the inflation rate, as well as of the electricity and natural gas prices, estimated considering the historical values of the last 10 years [36,38,39]. Therefore, it can be concluded that there is a high volatility in the utility prices and inflation rates which leads to a high uncertainty when projected cash flows from renewable energies should be estimated.

Table 1. Statistical analysis of the inflation rate, electricity price and natural gas price over the last 10 years in the three countries analysed in this research.

	Inflation rate (%)			Electricity price (€/kWh)			Natural gas price (€/kWh)		
	Greece	**Spain**	**UK**	**Greece**	**Spain**	**UK**	**Greece**	**Spain**	**UK**
mean	0.92	1.24	2.38	0.141	0.199	0.170	0.104	0.087	0.051
σ	2.26	1.29	1.31	0.030	0.034	0.025	0.026	0.019	0.009
min	-2.61	-1.04	0.20	0.098	0.137	0.139	0.068	0.068	0.036
max	5.17	2.99	4.20	0.179	0.237	0.218	0.147	0.122	0.067

1.2 Policies and subsidies

A previous report of the IEA [14] concluded that Governments should play a major role to boost the deployment of renewable technologies, through their support in innovative research and development, but more importantly through the development of policies that support market creation and the cooperation with industry, in order to develop appropriate market conditions that allow renewable technologies to overcome current barriers.

In Europe, there are two main financial incentive mechanisms to promote renewable energies: grants or subsidies, and tax credits or reductions. The incentives are usually removed once a technology becomes mature, as demonstrated by the experience of the solar-thermal market in countries such as Greece and Austria. However, in some cases, financial incentives led to increased costs as consequence of increased demand, such as in France and in Sweden, where the cost of solar water heaters started to rise with increasing market penetration after financial support schemes were adopted [40,41].

The most widespread subsidy for renewable electricity generation is the Feed-In Tariff (FIT), which, if appropriately designed, is capable of driving technological development and market expansion [27]. In order to be successful, FITs should include a yearly reduction in accordance with the technical, industrial and market progress [4]. It should be noted that this subsidy is a temporary measure and will no longer be necessary once grid parity is reached or surpassed by a particular technology, since at that point the market becomes self-sustained. Loans to help customers pay the high initial investment cost may be kept for about 30 years [42]. Currently, there are still some European countries with FIT for distributed renewable energy generation, specifically for small scale PV installations, such as in the UK (0.048 €/kWh) [43] and Greece (0.105 €/kWh) [44].

On the other side, Government incentives to support renewable heat generation are not as common within Europe. An example of these incentives can be found in the UK, where there is also a financial support, the domestic Renewable Heat Incentive (RHI), which can be claimed for biomass boilers, solar water heating and certain heat pumps. This incentive consists of payments for 7 years based on the amount of renewable heat generated by the heating system [45].

In line with previous studies [8,27], it is believed that policies such as obligations, incentives and financing schemes to support private customers in accessing capital, as well as fast and transparent procedures in response to regulatory frameworks, are key components for the further development of solar-thermal technologies and, in particular, hybrid PVT systems.

Currently, in Spain there is a renewable heat obligation scheme which sets a minimum contribution of solar-thermal energy for DHW provision in new or highly refurbished buildings (section HE4 of the "*Documento Básico de Ahorro de Energía*", Basic Document of Energy Savings in English) [46]. Furthermore, the Spanish Building Technical Code also establishes a minimum contribution of PV energy in new or highly refurbished buildings of more than 5,000 m^2 constructed area (section HE5 of the "*Documento Básico de Ahorro de Energía*", Basic Document of Energy Savings in English) [46]. To boost the installation of solar-thermal systems in buildings, IDAE (which stands for "*Instituto para la Diversificación y Ahorro de la Energía*" in Spanish) established a funding scheme, SOLCASA program, in the framework of the Renewable Energy Plan 2005-2010, with the European Funding for Regional Development. The aim of this financing scheme is to improve the quality and adaptability of the commercial offer to satisfy the DHW and SH needs in buildings using solar-thermal energy [47].

The combined electrical and thermal energy yield of S-CHP systems based on PVT collectors make them eligible for a range of subsidies, including FITs for the electricity generated by the PV module and RHI for the hot water produced by the thermal collector component. Therefore, to encourage the uptake of these systems and thus to fully harness their potential contribution to the reduction in primary energy and emissions, it may beneficial to consider possible modifications to these incentives or to implement additional ones. For example, a full solar-thermal subsidy [4] would act to incentivise PVT installers, facilitate the deployment of this technology, and accelerate the commercialisation of PVT systems [4,42]. Furthermore, the dual (thermal and electrical) generation of S-CHP systems based on PVT collectors makes them an interesting alternative to meet renewable obligations such as the ones mentioned above while at the same time makes them eligible to different funding schemes such as SOLCASA program.

2 Methodology

The core components of the complete S-CHP system are (see Figure 6): i) the PVT collectors, ii) a stratified water storage tank, iii) a closed loop with a water circulator pump that connects the PVT collector with the storage tank through an internal heat exchanger, iv) electrical storage (by means of a number of batteries connected to the PVT collector and to the grid), and v) an auxiliary heater. It should be noted that detailed energy balance equations of all of these system components were integrated in the overall system model developed in the EES software [18]. The energy demand of a reference house was also previously modelled in EnergyPlus, considering a single-family house (2 floors of ~58 m^2 floor area each) of new construction that meets the actual standards on energy efficiency according to the Energy Performance of Buildings Directive [48]. It is assumed that the household consumes natural gas for SH and DHW, with the former provided via underfloor radiant heating; and electricity is consumed for lighting, cooling and home appliances. The energy demand breakdown is then integrated as an input of the one dimensional (1-D) S-CHP model together with the weather conditions [18].

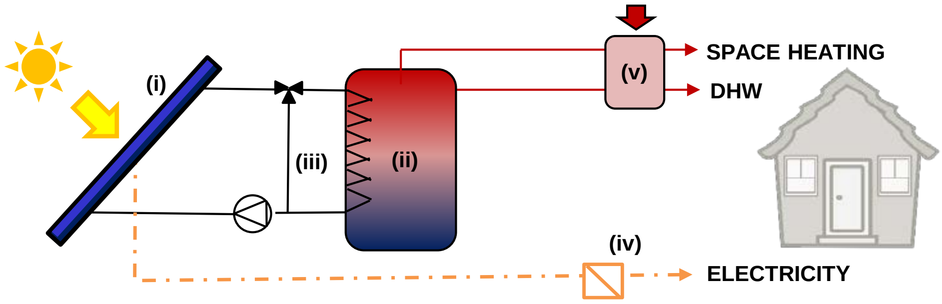

Figure 6. Schematic diagram of the main components of the S-CHP system: i) PVT collectors, ii) stratified water storage tank, iii) PVT-tank closed loop, iv) electrical storage and v) an auxiliary heater.

The S-CHP system is based on the most promising PVT collector previously identified, 3×2 polycarbonate (PC) flat-box PVT collector [30]. The optimised S-CHP configurations for each of the locations under study (Zaragoza, London and Athens) are used as a starting point for the sensitivity analysis. The optimum system size (number of PVT collectors and storage tank volume) and operating conditions selected for each location were those that minimised the system payback time as well as its associated Levelised Production Cost (in terms of costs per kWh of household energy covered). It is worth mentioning that the selected S-CHP system size in each case also minimised the interaction with the grid (energy imported *vs*. energy exported) and aimed at limiting the amount of excess heat dumped to the atmosphere to avoid tank overheating.

Table 2 summarises the S-CHP system size (number of PVT collectors, N, and storage tank volume, V_t), the annual energy results (electricity generated, E_{PVT}, covered, E_{cov}, exported, E_{exp}, imported, E_{grid}, the thermal energy covered, Q_{cov}, and auxiliary heat, Q_{aux}) and the Payback Time (PBT) (obtained from previous research); when the S-CHP systems are installed in a single-family house located in each of the cities under study. To obtain the aforementioned values, the economic parameters were set constant. The utility prices were the actual prices in each country (Subsection 1.1) [36]. The market discount rate was estimated to 3.5%, for projects of 0-30 years lifetime [49], while the fuel inflation rate was set to 2.7% based on the inflation rates in the different countries under study [38,39], which is in line with the 3% average inflation rate over the last 50 years in the OECD countries [14]. No FITs were considered for any location, despite nowadays both UK and Greece have FITs applicable to small scale PV installations [43,44]. The reason for this is to start in all locations from the same starting point and be able to estimate the FIT that would be required in each particular case to make the proposed S-CHP system cost-competitive.

Table 2. S-CHP system size (number of PVT collectors, N, and storage tank volume, V_t), annual energy (electrical and thermal) generation and payback time (PBT) (when all taxes and levies are included in the utility prices) for each of the locations under study (Zaragoza, London and Athens).

	N (-)	V_t (m^3)	E_{PVT} (kWh/year)	E_{cov} (kWh/year)	E_{grid} (kWh/year)	E_{exp} (kWh/year)	Q_{cov} (kWh/year)	Q_{aux} (kWh/year)	*PBT* (years)
Zaragoza	8	0.72	3,487	2,096	1,058	1,044	1,600	1,931	11.62
London	11	0.825	3,025	1,823	957	909	1,634	3,939	22.70
Athens	9	0.675	3,674	2,263	1,249	1057	1,283	811	15.59

Regarding the system economics, Table 3 details the price breakdown of the S-CHP system components estimated from price lists available from solar retailers in the EU (VAT included). The cost of the storage tank is estimated using a correlation based on market prices of existing tanks across a range of storage volumes. The total installation costs are also considered [27]. The auxiliary heater price is not considered as it is assumed that the households already have one installed.

Table 3. Price breakdown of S-CHP components.

Component	Value	Unit	Reference
Benchmark (S&T) PVT collector	380	€/Collector	[50]
3×2 PC flat-box PVT collector	301	€/Collector	[30]
Pump station	265	€	[31]
Controller	110	€	[32]
Expansion vessel	140	€	[31]
Water storage tank	$0.874 \cdot V_t$ (L)+ 763.5	€	[33]
Pipes (including insulation)	11	€/m	[31]
Heat transfer fluid	3.3	€/L	[34]
Mounting	59	€/Collector	[31]
Lead-acid batteries	$69/840 \cdot C_T$[a]	€	[35]
System installation	1,800	€	[27]

[a]C_T = Battery energy capacity (Wh)

To analyse the cost competitiveness of the S-CHP system, two main economic parameters are estimated: the Payback Time (*PBT*), and the Levelised Production Cost (LPC), in terms of both the total (electrical and thermal) energy generated (LPC_{gen}), and the total (electrical and thermal) energy covered in the household (LPC_{cov}) [51].

To estimate the fuel savings (electricity and natural gas in this particular case), the annual savings, $FS_{\mathrm{S\text{-}CHP}}$, are estimated, which refer to the total utility (electricity and natural gas) costs saved in the household due to the electricity and thermal (SH and DHW) energy demand covered by the S-CHP system (Eq. (1)). Then, these values, are converted into present worth values and added to obtain the Life Cycle Savings (LCS), considering the market discount rate (d) and the fuel inflation rate (i_{F}), as follows,

$$FS_{\mathrm{S-CHP}} = E_{\mathrm{cov}} \cdot c_{\mathrm{e}} + \frac{Q_{\mathrm{cov}}}{\eta_{\mathrm{boiler}}} \cdot c_{\mathrm{ng}} \,, \tag{1}$$

$$FS_{\mathrm{LCS}} = \sum_{n=1}^{N} \frac{FS_{\mathrm{S-CHP}} \cdot (1 + i_{\mathrm{F}})^{n-1}}{(1 + d)^{n}}, \tag{2}$$

where c_{e} is the electricity price (€/kWh) and c_{ng} is the natural gas price (€/kWh).

Similarly, the net present value (*NPV*) of the S-CHP system can be estimated as follows,

$$NPV = C_0 + FS_{\mathrm{S-CHP}} \cdot \frac{1}{d - i_{\mathrm{F}}} \cdot \left[1 + \left(\frac{1 + i_F}{1 + d}\right)^{n}\right], \tag{3}$$

where C_0 is the total investment cost of system, n is the system's lifetime (assumed to be 25 years) [14,52,53].

The *PBT* can be then calculated as the time (n) when the $NPV = 0$.

On the other hand, Levelised Production Cost (LPC) is calculated as the total cost per kWh incurred by the S-CHP system installed in the household throughout its lifetime. Therefore, it considers the investment cost (C_0) and the operation and maintenance (O&M) costs ($C_{\mathrm{O\&M}}$) of the system, as well as the utility (electricity and natural gas) costs that are incurred to satisfy the rest of the electrical (E_{grid}) and thermal (Q_{aux}) demand of the household that cannot be covered by the system ($A_{\mathrm{S\text{-}CHP}}$, in €/year),

$$A_{\mathrm{S-CHP}} = E_{\mathrm{grid}} \cdot c_{\mathrm{e}} + \frac{Q_{\mathrm{aux}}}{\eta_{\mathrm{boiler}}} \cdot c_{\mathrm{ng}} + C_{\mathrm{O\&M}} \,, \tag{4}$$

In this case, the NPV is calculated substituting $FS_{\text{S-CHP}}$ by $A_{\text{S-CHP}}$ in Eq. (3), an annualising it to estimate the levelised cost (L_{e}),

$$L_{\text{e}} = \frac{NPV}{\frac{1}{d - i_F}\left[1 + \left(\frac{1 + i_F}{1 + d}\right)^n\right]}, \tag{5}$$

which is used to calculate the LPC,

$$LPC = \frac{L_{\text{e}}}{E_{\text{Teeq}}}, \tag{6}$$

where E_{Teeq} refers to the total "equivalent" electrical energy (in kWh_{eeq}) so as these results can be compared with other renewable energy technologies. This term is calculated converting the total primary energy (E_{Tpe}) with the electricity conversion factors specific for each country where the analysis is undertaken [54–56]. To estimate the LPC per energy generated (LPC_{gen}), the total electricity (E_{PVT}) and thermal (Q_{cov}) energy generated are converted to primary energy through the corresponding conversion factors, so as they can be added up. Meanwhile, to estimate the LPC per energy covered in the household (LPC_{cov}), only the electricity (E_{cov}) and thermal (DHW and SH) energy (Q_{cov}) covered are considered.

Based on the S-CHP system presented in Table 1 in each location, the influence of the following parameters in the PBT, LPC_{cov} and LPC_{gen} is assessed through sensitivity analyses (these analyses are conducted varying one parameter at a time, maintaining the rest of them constant with the aforementioned values):

- System components' costs: PVT collector, water storage tank and battery storage.
- System installation costs.
- Market discount rate and fuel inflation rate.
- Utility (electricity and natural gas) prices.
- Financial incentives: FIT for electricity generation and RHI for thermal energy covered.

A summary of the methodology followed in this work is presented in Figure 7 in the form of a blocks diagram. The authors would like to clarify that the work presented here does not comprise any optimisation analysis. The aim of the present effort is to analyse the influence of the aforementioned parameters on the cost competitiveness of the proposed S-CHP system (PBT, LPC_{cov}, LPC_{gen}) in three different locations.

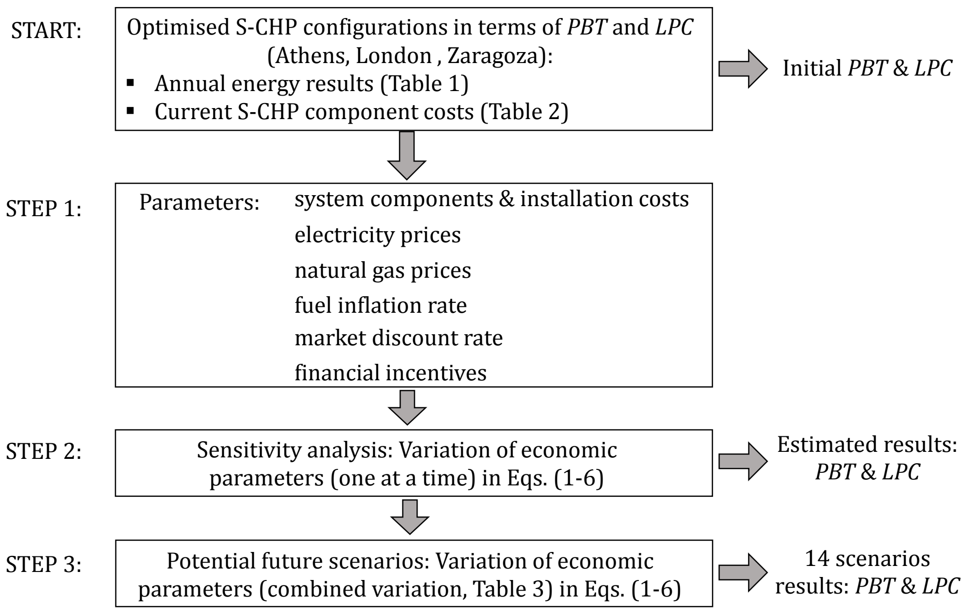

Figure 7. Blocks diagram of the methodology approach followed in the present research.

3 Results and Discussion

In this section, a detailed analysis of the influence on the cost competitiveness of the proposed S-CHP system of the parameters mentioned above is presented. Moreover, different potential future scenarios in the near future (considering reasonable assumptions) are also proposed and the system cost competitiveness is analysed, in an attempt to outline the potential of hybrid PVT systems in the urban environment.

3.1 Influence of the system components' costs and installation costs

As shown in Figure 1, aside from the system installation costs, the main S-CHP system costs are due to the PVT collectors, the water storage tank and the battery storage. The cost of the PVT collectors is the highest cost (around 38%); thus, the effect of a reduction of the PVT collector price, from 0% (no reduction) to 50% (half of the actual price), on the cost competitiveness of this technology is analysed for the three locations under study (Zaragoza, London and Athens).

The results of the influence of the PVT collector price on the payback time (*PBT*) and on the Levelised Production Cost per energy covered (LPC_{cov}) and per energy generated (LPC_{gen}) of the S-CHP system are presented in Figure 8. As expected, for any of the locations, the reduction of the PVT collector price leads to a decrease in the *PBT* (Figure 8 left) as well as in the LPC_{cov} and LPC_{gen} (Figure 8 right). In particular, a reduction of 10% in the PVT collector price leads to a decrease of 3.3-3.9% in the total S-CHP system cost (depending on the S-CHP configuration). As a result, the *PBT* is reduced by 3.4-4.2%, while the LPC_{cov} and LPC_{gen} only decrease by 1.5-2.4%. To achieve a reduction of 10% in the *PBT*, the PVT collector price should decrease by 30% in the case of Zaragoza, by 24% in London and by 27% in Athens. It is observed that to obtain a similar *PBT* in London than in Athens (~15 years), the PVT collector price should be reduced by ~80%; and even if the PVT collector cost was zero, for example if there was a full-subsidy for the PVT collectors, the *PBT* of the S-CHP system installed in London would still be higher than for the S-CHP system installed in Zaragoza (~13 years *vs*. ~12 years for the S-CHP system with no-reductions in Zaragoza).

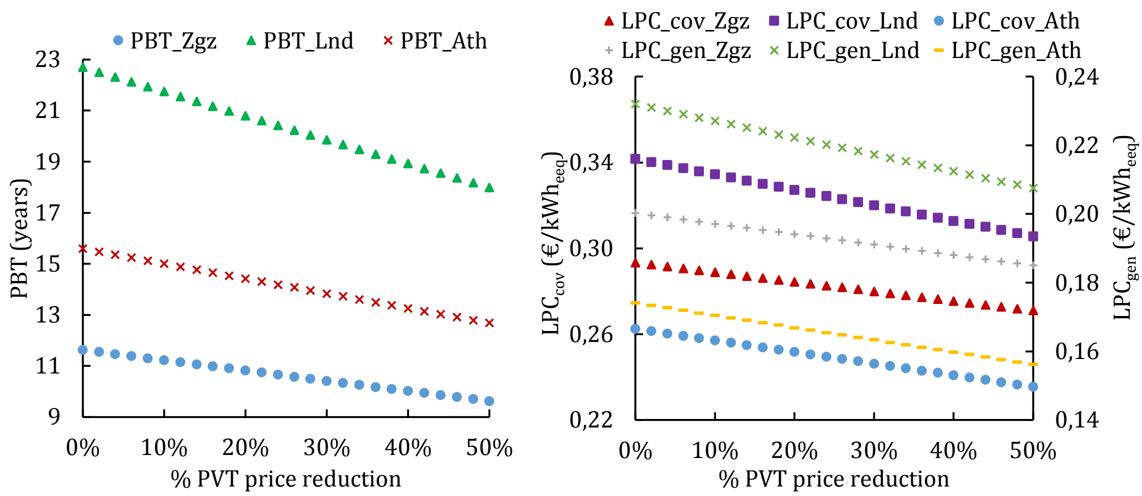

Figure 8. PBT (left) and LPC_{cov} *and* LPC_{gen} *(right) when the PVT collector price is reduced from 0% to 50% for the three optimised S-CHP systems in each respective location: Zaragoza (Zgz), London (Lnd) and Athens (Ath).*

As mentioned above, the water storage tank price also accounts for a significant share (around 18%) of the total S-CHP system cost. Thus, similarly as before, the effect of a reduction of this price, from 0% to 50%, on the cost competitiveness of this technology is analysed for the three locations under study. Similar trends as in Figure 8 are observed, as expected. However, in this case, the storage tank price should decrease by 50% in the three locations to achieve a reduction of ~10% in the *PBT*. The LPC_{cov} and LPC_{gen} only decrease by up to 4-5%, so it can be concluded that a reduction in the water storage tank price, although beneficial, it is not as critical as the PVT collector costs reduction.

The battery storage price is around 5% of the total S-CHP system cost (Figure 1). As previously, the effect of a reduction of this cost, from 0% to 50% is analysed for the studied locations. The results show that battery storage price do not have an important influence of the overall S-CHP system economics. The *PBT* is only reduced by up to 2.8-3.5% and the LPC_{cov} and LPC_{gen} by up to 1.2-1.8% when the batteries' price is halved in all the locations. Therefore, in the cases considered in the present research, it can be concluded that this component is not critical to enhance the cost competitiveness to S-CHP systems; since the effect of the reduction of the different components' costs on the *PBT* and *LPC* of the S-CHP system is proportional to the share of the corresponding component on the total system cost, as expected.

As discussed in Section 1.1, the system installation costs accounts for the second highest cost of the S-CHP system (around 23%), being these costs significantly variable from country to country. Furthermore, it is expected that the widespread installation of these systems will lead to a reduction in the associated costs, as local retailers and trained on-site personnel will most probably increase accordingly. Therefore, similarly as before, the effect of a reduction of system installation costs from 0% to 50% is analysed for the three locations. The results show that, to achieve a 10% reduction of the *PBT*, the system installation costs should decrease by 38% in Zaragoza, by 40% in Athens and by 44% in London. The LPC_{cov} and LPC_{gen} only decrease by up to 5.7-8.1% when the system installation costs are halved in all the locations. Therefore, it can be concluded that, even though a reduction in the system installation costs is indeed necessary, it is not sufficient to achieve cost-competitive S-CHP systems, particularly in countries such as the UK with low irradiance levels and low natural gas prices.

3.2 Influence of the market discount rate and fuel inflation rate

In literature, different authors consider different market discount rates, ranging from 5% [11,15], 8% [57] and even 10% [58], which depend on several factors such as the time and location when/where the study was undertaken, and the type of technology under study. More recently, the IEA in the Solar Heating and Cooling technology roadmap [59] assumed a discount rate between 3-6% for solar heat cost calculations. Other reports of the IEA [14,60] of "Projected Cost of Generating Electricity" considered in the 2010 edition two different discount rates (5% and 10%), while in the 2015 edition estimated the LCOE of different electricity generation technologies with three different discount rates: 3% which according to the study would approximately correspond to the "social cost of capital", 7% which would correspond to the "market rate in deregulated or restructured markets" and 10% which would correspond to an investment in a "high-risk investment". Bearing in mind these studies, the influence of the market discount rate (*d*), on the system economics (*PBT* and *LPC*) is analysed here, to assess the extent to which the system cost effectiveness is affected. To this end, *d* is varied from 0.25% to 10%, being 0.25% a very low value which would imply that future cash flows almost do not depreciate with time and 10% the highest value used for the analysis of this type of systems found in literature.

As shown in Figure 9 left, the *PBT* increases exponentially with the increase in the market discount rate. The reason is that, as the market discount rate increases, the present worth of future household fuel savings decreases. As a consequence, more time is required to pay back the initial investment cost. It is observed that, to reach a *PBT* of ~20 years in the S-CHP system located in London, to be able to at least recover the investment in the system's lifetime, the market discount rate would need to be ~2.5%. In this location, only when the market discount rate is set to 0.25%, the *PBT* reached (16.6 years) is similar to the one of the optimised S-CHP system located in Athens.

Similarly, although at much lower extent, the LPC_{cov} and LPC_{gen} increase with the market discount rate, as the Levelised Cost (L_e, in €/year) of the S-CHP system increases at higher *d*. The grey vertical line and dark red arrow indicate the initial starting point. Similar trends are found in a previous study [14], where the LCOE of different electricity generation technologies is estimated as a function of the discount rate.

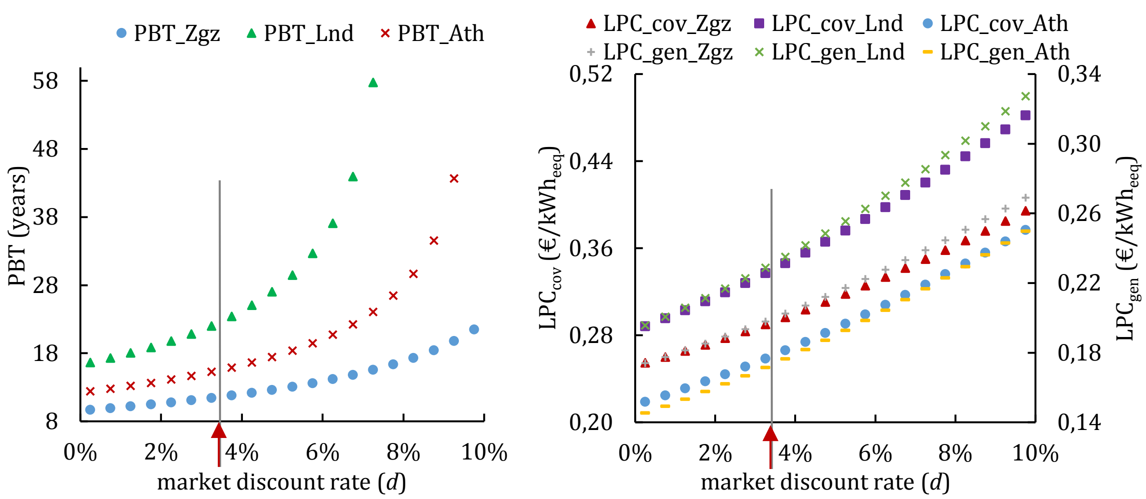

Figure 9. PBT (left) and LPC_{cov} and (LPC_{gen} (right) when the market discount rate is varied between 0.25-10% for the three optimised S-CHP systems in each respective location: Zaragoza (Zgz), London (Lnd) and Athens (Ath). The vertical line and arrow indicate the value considered to obtain the results presented in Table 1.

The fuel inflation rate refers to the inflation rate that the annual household fuel savings achieved thanks to the installation of the S-CHP system suffer. Historical values of this rate in the different countries significantly vary, e.g., between 0.25-4.2% in Spain, 0.8-5.2% in Greece and 0.2-4.2% in the UK, from 2007 to 2016 [38,39], so a specific value that might look reasonable today might considerably differ in a few years' time. Therefore, similarly as before, the fuel inflation rate, i_F, is varied from 0.25% to 5.25% and the *PBT*, LPC_{cov} and LPC_{gen} are estimated for the optimised S-CHP systems installed in the three locations under study. As before, the grey vertical line and dark red arrow indicate the initial starting point.

Figure 10 left shows that the *PBT* decreases with the increase in the fuel inflation rate. The reason is that, as the fuel inflation rate increases the present worth of future household fuel savings increases, so less time is required to pay back the initial investment cost. In other words, the proposed S-CHP system replaces energy otherwise generated from more expensive fuel. It is observed that, increasing the i_F from 0.25% to 1.25% leads to a decrease of the *PBT* of 7% in the system located in Zaragoza, while this number is increased to 18% and 9% for London and Athens respectively. If the inflation rate is increased by 2% absolute points from 0.25% to 2.25%, the *PBT* decreases by 12%, 29% and 17% for Zaragoza, London and Athens; while if i_F is further increased to 5.25%, those numbers become 24%, 46% and 32%, respectively (all compared to the i_F = 0.25% values). The *PBT* achieved when i_F = 5.25% are 10.3 years, 18.0 years and 13.3 years in the aforementioned locations respectively. The different results obtained for the different case studies are attributed to the different starting points regarding annual fuel savings ($FS_{S\text{-}CHP}$, €/year) and total initial investment cost (C_0). The S-CHP system located in London has the highest C_0, and a much lower $FS_{S\text{-}CHP}$ than in the case of Zaragoza. As consequence, the system economics are more affected by the variation of the fuel inflation and market discount rates (Figures 9 and 10). The LPC_{cov} and LPC_{gen} also decrease with the fuel inflation rate, although at much lower extent. This trend is due to the lower Levelised Cost (L_e, in €/year) of the S-CHP system at higher i_F.

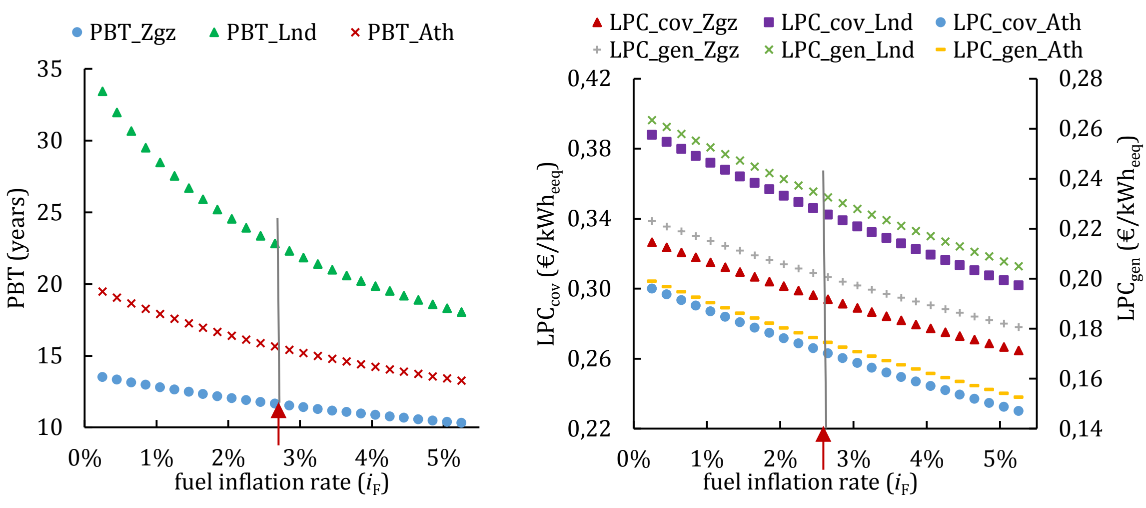

Figure 10. PBT (left) and LPC_{cov} and LPC_{gen} (right) when the fuel inflation rate is varied between 0.25-3.5% for the three optimised S-CHP systems in each respective location: Zaragoza (Zgz), London (Lnd) and Athens (Ath). The vertical line and arrow indicate the value considered to obtain the results presented in Table 1.

3.3 Influence of utility prices

As shown in Section 1.1, utility (electricity and natural gas) prices have suffered a considerable variation in the last 10 years, with no clear trends for future prices, although an increasing trend in the prices, in particular in electricity prices, is outlined in Figures 2-5. Specifically, electricity prices have varied from 0.098 €/kWh (lower limit in Greece) to 0.237 €/kWh (upper limit in Spain), while natural gas prices have varied from 0.036 €/kWh (lower limit in UK) to 0.146 €/kWh (upper limit in Greece), from 2007 to 2016. This high volatility in the utility prices leads to a large uncertainty about the future household savings over the S-CHP system's lifetime, referred to as annual fuel savings in this research; as they come from the fuel (electricity and natural gas) that the household does not buy thanks to the generation of electricity and thermal energy by the installed S-CHP system. Therefore, this section analyses the influence of the utility prices on the system economics (*PBT* and *LPC*). To this end, both the electricity and natural gas prices are varied (one after the other one) from 0.05 €/kWh to 0.5 €/kWh, maintaining the fuel inflation rate, i_F, constant at 2.7% (initial value), so the current utility prices are varied, but not their future variation which has been already considered in the previous section.

Figure 11 left shows that the *PBT* decreases logarithmically with the increase of the electricity price, as the annual fuel savings ($FS_{S\text{-}CHP}$) are larger for the same initial investment cost (C_0). The results show that to obtain a *PBT* for the system located in London comparable to the one of Athens (~16 years), the electricity price should be ~0.28 €/kWh, while to lower it down to ~12 years (as in Zaragoza), the electricity price should be ~0.37 €/kWh. Higher electricity price is required in London than in the other countries, as the initial investment cost is higher, and the amount of electricity covered, E_{cov}, is lower than for the other cases. In the case of the system located in Athens, the electricity price should be ~0.24 €/kWh to achieve the same *PBT* than the system located in Zaragoza. The grey vertical lines and dark red arrows indicate the initial starting points for each location.

On the other hand, Figure 11 right shows that, as expected, the LPC_{cov} and LPC_{gen} increase with the electricity price, as to cover the household electricity demand that cannot be covered with the S-CHP system, E_{grid}, more money should be spent (higher $A_{S\text{-}CHP}$), so the Levelised Cost (L_e, in €/year) increase for the same total energy covered or generated. These results are in line with the findings of the IEA report [14], which concluded that solar remains the most capital-intensive technology, and thus it is more sensitive to volatile electricity prices.

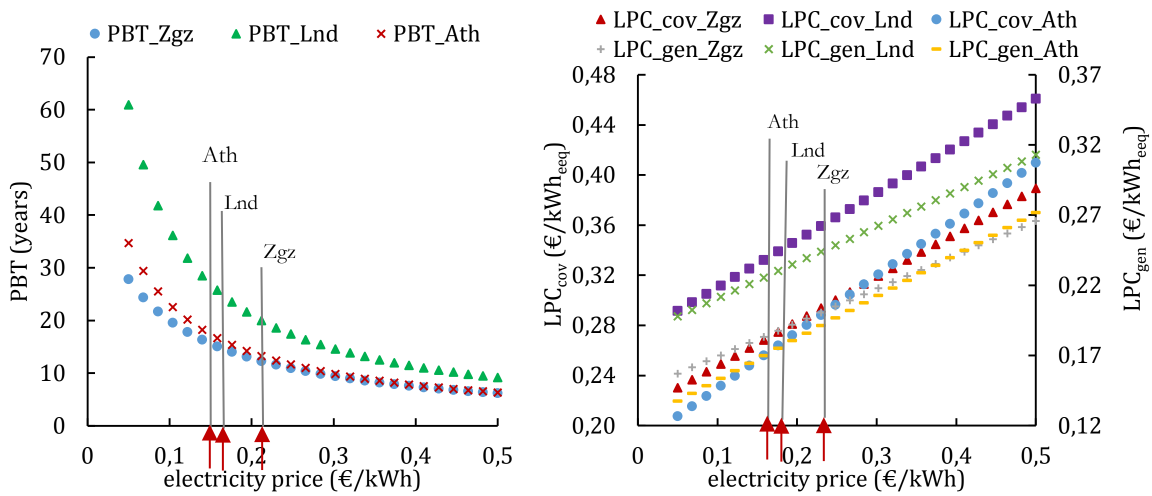

Figure 11. PBT (left) and LPC_{cov} and LPC_{gen} (right) when the electricity price is varied between 0.05-0.5 €/kWh for the three optimised S-CHP systems in each respective location: Zaragoza (Zgz), London (Lnd) and Athens (Ath). The vertical line and arrow indicate the values considered to obtain the results presented in Table 1.

Regarding the influence of the natural gas price, which is used to cover the household thermal (DHW and SH) demand, similar trends as before are found (see Figure 12). However, in this case, the variation range of the *PBT* is significantly lower (from 60 to 9 years for electricity prices and from 23 to 7 years for natural gas prices in the case of London). The reason is the higher influence of electricity prices on the annual fuel savings, as in this case the electricity price is fixed at the current value which is significantly higher than the current natural price fixed for the previous analysis (~0.17-0.23 €/kWh in the former *vs*. ~0.05-0.11 €/kWh in the latter). It is also observed that the *PBT* for the system located in London decreases at higher extent than for the system located in Athens, reaching a similar *PBT* at high natural gas prices (Figure 12 left), which is attributed to the higher thermal energy covered, Q_{cov}, in the former.

In this line, the LPC_{cov} and LPC_{gen} results show that the S-CHP system located in London is the one more affected by the natural gas prices, which is due to the significantly higher auxiliary heating energy, Q_{aux}, required to cover the total household thermal energy demand (see Table 1). As consequence, the household annual running costs ($A_{S\text{-}CHP}$) increase at much higher extent than in the other cases, leading to a higher the Levelised Cost (L_e, €/year) and hence LPC_{cov} and LPC_{gen} (Figure 10 right).

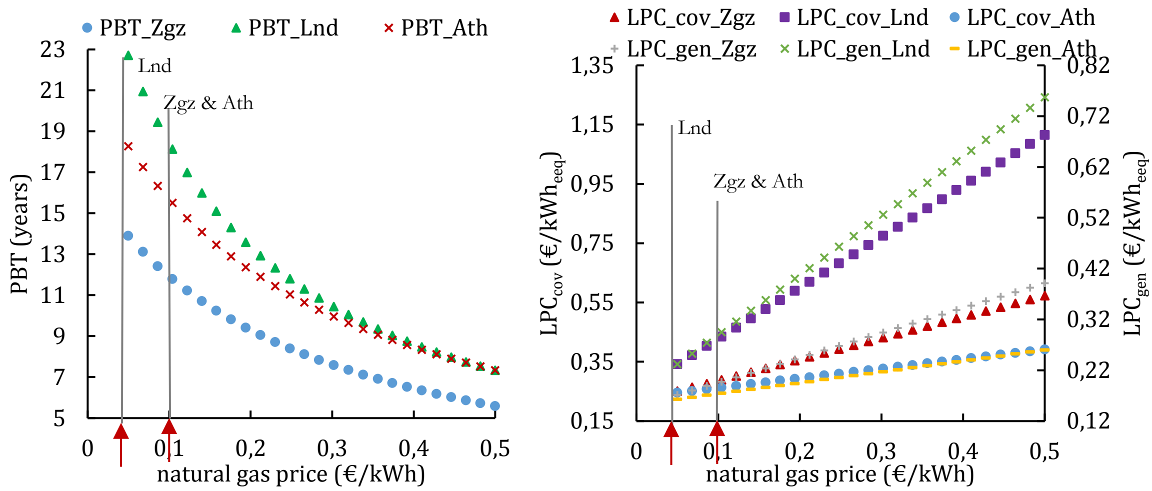

Figure 12. PBT (left) and LPC_{cov} and LPC_{gen} (right) when the natural gas price is varied between 0.05-0.5 €/kWh for the three optimised S-CHP systems in each respective location: Zaragoza (Zgz), London (Lnd) and Athens (Ath). The vertical line and arrow indicate the values considered to obtain the results presented in Table 1.

3.4 Influence of financial incentives

Finally, the last sensitivity analysis undertaken in the present research aims to analyse the influence that Government incentives, specifically subsidies, have on the cost competitiveness of the proposed S-CHP system in the three locations under study.

As mentioned above, the most widespread subsidy within Europe is the FIT for renewable electricity generation, while subsidies for thermal energy generation are scarcer. As detailed in Section 1.2, the combined electrical and thermal energy generated by the proposed S-CHP systems based on PVT collectors make them eligible for both FITs for the electricity generated and a thermal subsidy for the thermal energy generated, such as the domestic RHIs available in the UK. Therefore, in this section, the FITs and RHIs are varied (one after the other one) between 0-0.25 €/kWh, being the upper limit slightly higher than the actual electricity price in Spain; and the *PBT*, LPC_{cov} and LPC_{gen} are estimated.

As shown in Figure 13 left, the *PBT* considerably decreases with FITs, as expected. It is believed that in the case of Zaragoza, the S-CHP system has an acceptable *PBT* (11.6 years) without incentives, so FITs are not essential. The system located in Athens has also a reasonable *PBT* without incentives (15.6 years), so it can be concluded that FITs are not crucial for the cost competitiveness of this technology. If the actual FIT available nowadays for small roof-PV installations (vertical line in Figure 13 left) are considered, the *PBT* decreases down to 12.7 years, so these incentives could be used to incentivise its wider installation. Finally, it is observed that the *PBT* of the S-CHP located in London is still considerable when the actual FIT available for rooftop PV installations in the UK are considered (20.4 years, see vertical line in Figure 13 left). The main reason is the higher cost of PVT collectors *vs.* PV modules, as well as the costs of other S-CHP system components such as the water storage tank; so a higher incentive would be required to make S-CHP PVT-based systems competitive with conventional PV installations. Specifically, it is estimated that, to obtain a similar *PBT* than in Athens (~15.6 years), a FIT of 0.19 €/kWh would be required, while to lower the *PBT* down ~12 years such as in Zaragoza, a FIT of ~0.38 €/kWh is estimated.

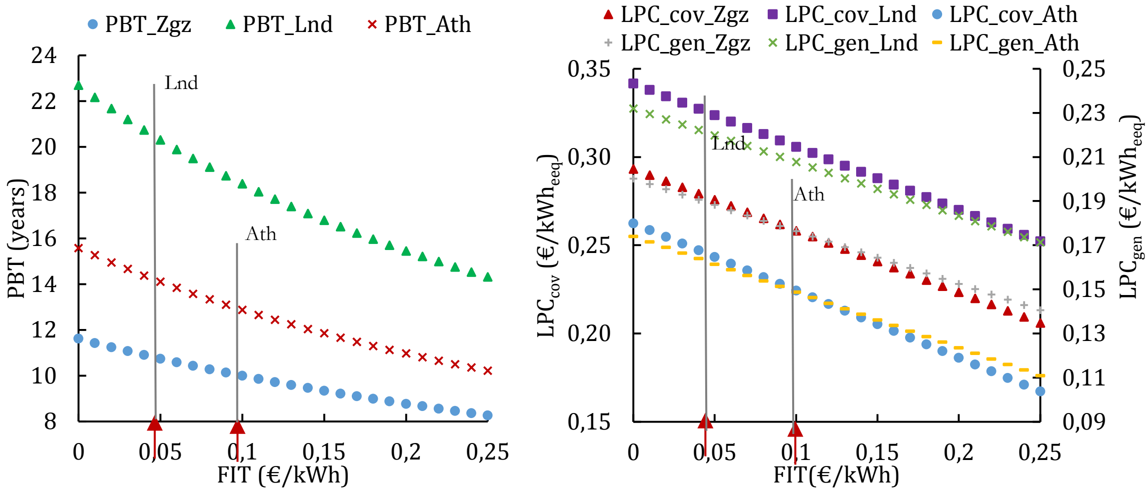

Figure 13. PBT (left) and LPC_{cov} and LPC_{gen} (right) when the FITs are varied between 0-0.25 €/kWh for the three optimised S-CHP systems in each respective location: Zaragoza (Zgz), London (Lnd) and Athens (Ath). The vertical line and arrow indicate the values considered to obtain the results presented in Table 1 (in London FIT = 0.048 €/kWh and in Athens FIT = 0.105 €/kWh).

Figure 13 right shows that, as expected, the LPC_{cov} and LPC_{gen} decrease as the FIT increase, as the incomes received for the electricity sold to the grid reduce the annual running costs ($A_{S\text{-}CHP}$) incurred to satisfy the overall household energy demand. Similar trends are found in the three different case studies analysed.

Similar results are found when a RHI is applied to the household thermal energy covered, Q_{cov} (Figure 14). The S-CHP system located in London is the one more affected by this incentive, as it is also the one with higher thermal energy demand covered (see Table 1). In this case, a RHI of ~0.11 €/kWh would decrease the *PBT* to 15 years. If a RHI of ~0.19 €/kWh is applied, a similar *PBT* than in Zaragoza is achieved (12 years). Meanwhile, in Athens, with a RHI of ~0.10 €/kWh, the *PBT* drops down to 12 years.

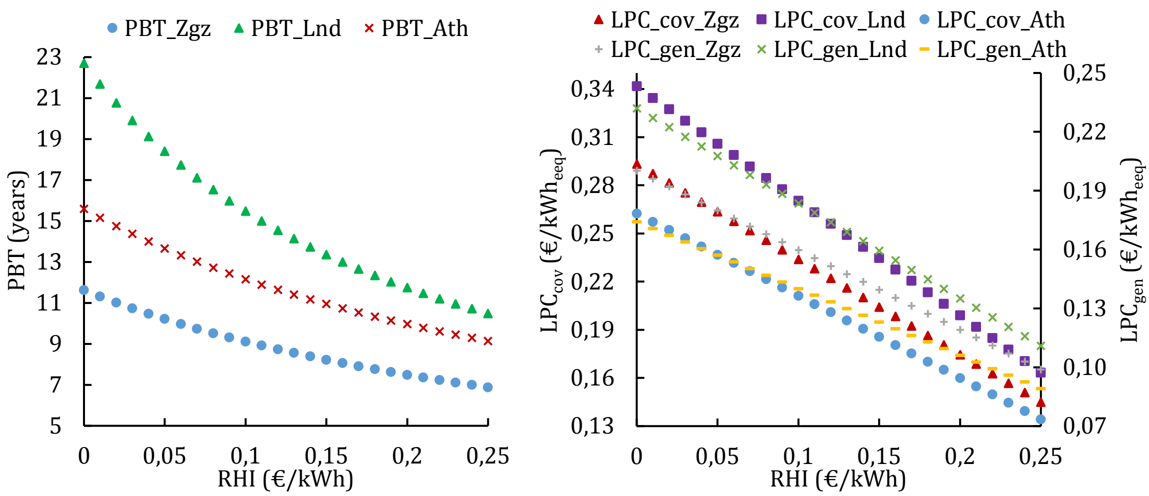

Figure 14. PBT (left) and LPC_{cov} and LPC_{gen} (right) when the RHIs are varied between 0-0.25 €/kWh for the three optimised S-CHP systems in each respective location: Zaragoza (Zgz), London (Lnd) and Athens (Ath). The vertical line and arrow indicate the values considered to obtain the results presented in Table 1.

In general, it is observed that lower *PBT* are achieved for lower incentives when those are applied to the thermal part (RHI) than to the electrical one (FIT). The reason is that in the case of the RHI, all the household thermal energy covered, Q_{cov}, is considered, while the FIT only applies to the electricity exported, E_{exp}, which is considerably lower (Table 1). Regarding the LPC_{cov} and LPC_{gen}, Figure 14 right shows that, in this case, the results for the system located in London are more affected than in the other two locations, due to the higher thermal energy covered, Q_{cov}, in this case.

Bearing in mind these results, it can be concluded that for the type of technology considered in this research, with which a combined electrical and thermal energy output is obtained, the current incentives would need to be revised to adapt them to this type of technology.

3.5 Potential future scenarios

In the near future, it is more likely that more than one of the economic parameters studied above vary simultaneously; for example, the reduction of more than one of the S-CHP components or the variation of both the market discount rate and the fuel inflation rate. Therefore, in this section, the effect of the simultaneous variation of several of the above studied parameters on the S-CHP system economics is analysed. In particular, 14 different scenarios are assessed, starting with the initial conditions that provide the economic results of Table 1.

Table 4 summarises the values for the different parameters considered in each proposed scenario. The utility prices have not been considered in this analysis as both the market discount rate and fuel inflation rate already have an effect on the annual fuel savings and annual running costs. Besides, both aforementioned rates are parameters that should be selected for the economic analysis, while the utility prices are imposed by external factors (i.e. the country where the system is installed). The scenarios are ordered from less optimistic (scenario 0, initial case) to more optimistic (scenario 14). In the first scenario, it is assumed that the three main costs of the total S-CHP system (PVT collectors, storage tank and installation costs) are reduced by 10% each. Then, scenario 2 considers a further reduction in the installation costs (20%), although also a higher market discount and fuel inflation rates. In this line, scenarios 3 to 6 consider different percentages of cost reduction (10-25%) in the aforementioned system components, as well as different market discount rates (2.5-4.5%) and fuel inflation rates (2.7-4%). The former rates have been previously considered in other studies, and the latter selected are based on historical inflation rates in the countries under analysis. From scenario 7 to 14, different combinations of RHI and FIT values are also implemented.

Table 4. Values for the different parameters considered in each of the 14 scenarios analysed ("No." in the table).

No.	**% PVT price reduction**	**% tank price reduction**	**% installation costs reduction**	**Market discount rate (*d*)**	**Fuel inflation rate (i_F)**	**RHI** (€/kWh)	**FIT** (€/kWh)
0	0%	0%	0%	3.5%	2.7%	0	0
1	10%	10%	10%	3.5%	2.7%	0	0
2	10%	10%	20%	4.0%	3.5%	0	0
3	15%	10%	25%	4.5%	4.0%	0	0
4	10%	10%	20%	3.5%	4.0%	0	0
5	15%	10%	25%	3.5%	4.0%	0	0
6	10%	10%	20%	2.5%	3.5%	0	0
7	10%	10%	20%	3.5%	3.5%	0.00	0.10
8	10%	10%	20%	3.5%	3.5%	0.05	0.05
9	10%	10%	20%	3.5%	4.0%	0.05	0.05
10	10%	10%	20%	3.5%	3.5%	0.10	0
11	10%	10%	20%	3.5%	4.0%	0.10	0.05
12	15%	10%	25%	3.5%	4.0%	0.10	0.10
13	15%	10%	25%	3.5%	4.5%	0.10	0.10
14	15%	10%	25%	3.5%	4.5%	0.15	0.05

The results show that for the S-CHP system located in Zaragoza, it would only be required a modest reduction of the costs of the main system components (PVT collectors and storage tank) as well as of the installation costs (between 10% and 25%) to have a *PBT* lower than 11 years. If in addition the fuel inflation rate increases, which is likely to happen given the utility prices trends (see Figures 2-5), it is possible to obtain a *PBT* of ~10 years or lower, even if the market discount rate increases. This is demonstrated from scenario 2, where a *PBT* of 10.3 is achieved, onwards (see Figure 15).

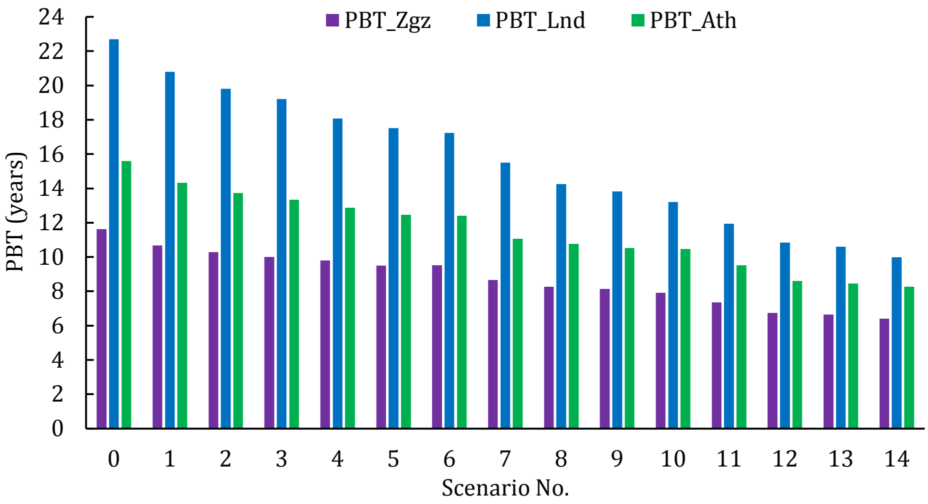

Figure 15. PBT in the different potential future scenarios (see Table 4) for the three optimised S-CHP systems in each respective location: Zaragoza (Zgz), London (Lnd) and Athens (Ath).

In the case of Athens, as shown in Figure 15, it is possible to decrease the *PBT* down to 11 years with a 10% reduction in the PVT collectors' price and storage tank price, as well as 20% reduction in the installation costs, together with an increase in the fuel inflation rate up to 3.5% (which is within the historical inflation rates), considering also the actual FIT available in Greece for small PV rooftop installations (scenario 7 in Table 4). It is believed that this is a realistic scenario in a few years' time. Furthermore, if instead of incentivising the electricity generated through FITs, the same incentive is given to the thermal energy generated (by means of the RHI), then the *PBT* drops to 10.5 years (scenario 10).

For the S-CHP system installed in London, a reasonable *PBT* of ~14-15 years can be achieved with the conditions set in scenarios 7 and 8. Those are: a 10% reduction in the PVT collectors' price and storage tank price, a 20% reduction in the installation costs, an increase in the fuel inflation rate up to 3.5% (which is within the historical inflation rates) and either a FIT of 0.10 €/kWh (scenario 7), which is double of the current FIT available in the UK for small PV rooftop installations, or a FIT of 0.05 €/kWh as the actual one, together with a RHI of 0.05 €/kWh (scenario 8). As shown in Figure 15, scenario 14, to achieve a *PBT* of ~10 years, further components' cost reductions are required, as well as a higher fuel inflation rate (of 4.5%) and larger financial incentives (FIT = 0.05 €/kWh, RHI = 0.15 €/kWh).

In conclusion, the analysis undertaken demonstrate that the S-CHP systems proposed in this research appear as a promising and cost-competitive alternative under different realistic and feasible scenarios such as the ones proposed in this section, even in countries with low irradiance levels and ambient temperatures such as UK.

4 Further Discussion and Conclusions

Previous research concluded that the economic parameters significantly influence the cost competitiveness of solar PVT technologies. Particularly, a previous report of the IEA concluded highlighted that capital intensive technologies such as solar energy, are more sensitive to volatile utility prices. To verify the extent of these effects, a sensitivity analysis is undertaken on the following parameters: main system components' costs, system installation costs, market discount and fuel inflation rates, utility prices, and financial incentives (FIT for electricity generation and RHI for thermal energy covered). The optimised S-CHP system configurations based on the most promising novel PC 3×2 PVT collector for each of the locations under study (Zaragoza, London and Athens) are used as a starting point.

From the different systems components' costs, the results show that the PVT collector price is the one that influences more the system economics, as it is also the highest share of the total S-CHP system investment (around 38%). However, for the S-CHP systems located in London, the PVT collector price should be reduced by ~80% to obtain a similar than in Athens (~15 years), and even if the PVT collector cost was zero, e.g. if there was a full-subsidy for the PVT collectors, the *PBT* would still be higher than for the S-CHP system installed in Zaragoza (~13 years *vs*. ~12 years for the system in Zaragoza). Certainly, lowering also the costs of the water storage tank and the battery storage leads to a *PBT* reduction, but a much lower extent. Therefore, it can be concluded that lowering the total investment cost of an S-CHP system, for example through partial-subsidy, is a potential and interesting measure to improve the cost competitiveness of the proposed technology, particularly in locations with low irradiance levels such as the UK. However, it is believed that in conjunction with this potential subsidy, other additional measures should be put in place. For example, the results show that a reduction in the system installation costs, which accounts for the second highest cost of the S-CHP system (around 23%), has the potential to shorten the system's *PBT.* It is believed that if the installation of this technology is widespread, for instance through the implementation of policies and subsidies such as those analysed in this research, the number of local retailers and trained on-site personnel would increase, which would lead to a decrease of the system installation costs.

It is observed that both the market discount rate and the fuel inflation rate, which depend on several factors such as the time when the study is undertaken, the location and the type of technology under study, significantly influence the S-CHP system economics. Therefore, it is very important to select reasonable values when this technology is analysed, as different conclusions can be extracted. Specifically, if high market discount rates and/or low fuel inflation rates are considered, the cost competitiveness of the system is negatively affected, leading to *PBT* times higher than the system's lifetime, which would make this technology non-attractive. Conversely, if low market discount rates and/or high fuel inflation rates are considered, the proposed S-CHP systems become an interesting alternative even in the locations where the external determinants (such as solar irradiance levels and/or utility prices) are not beneficial for solar technologies.

The utility prices are also decisive for the cost competitiveness of this technology, while they are an external factor that cannot be acted on. A clear example is the S-CHP system installed in Athens, with which it is possible to cover a significant part of the household energy demand, and has the highest amount of electricity exported, but which has a higher *PBT* (~4 years more) than the S-CHP system installed in Zaragoza, despite the energy generation/covered is similar. This is attributed to the significantly lower (~25% lower) electricity price in Athens than in Zaragoza. In the case of London, due to the higher investment cost and less electricity covered, the electricity price should be ~0.28 €/kWh to achieve a similar *PBT* than in Athens (~16 years), and ~0.37 €/kWh to achieve a similar *PBT* than in Zaragoza (~12 years). Regarding the natural gas price, it is observed that if a similar value than the electricity price is considered, the *PBT* of the S-CHP systems considerably decreases. Specifically, in Zaragoza the *PBT* drops to ~9 years (for a ~0.23 €/kWh natural gas and electricity prices), in London it drops to ~14 years (for a ~0.18 €/kWh natural gas and electricity prices) and in Athens to ~12 years (for a ~0.17 €/kWh natural gas and electricity prices). Therefore, it can be concluded that the significantly lower price of natural gas than electricity hinders the widespread adoption of S-CHP technologies over other technologies such as PV whose only output is electrical and are more economic (as less components are required).

The results regarding the influence of Government incentives on the cost competitiveness of the proposed S-CHP systems show that subsidies, if correctly applied, have the potential to improve the system economics in the short-term, as they can help to reduce the uncertainty of future cash flows, while decreasing the *PBT*. It should be noted that in some locations (such as Zaragoza and Athens in this study), these incentives might not be necessary as thanks to the external factors (like high utility prices and/or high irradiance levels), among others, the *PBT* of the proposed technology is already reasonable (11.6 years and 15.6 years respectively). In addition, if in Athens the actual FIT available nowadays for small roof-PV installations are considered, the *PBT* decreases down to 12.7 years, so these incentives could be used to incentivise its wider installation. Conversely, the results show that the currently available FITs in London for rooftop PV installations are not enough for the S-CHP systems proposed in this research. The main reason is the higher cost of PVT collectors *vs*. PV modules, as well as the costs of other S-CHP components such as the water storage tank. It is estimated that, to obtain a similar *PBT* than in Athens (~15.6 years), a FIT of ~0.19 €/kWh should be implemented, while to achieve the *PBT* obtained in Zaragoza (~12 years), a FIT of ~0.38 €/kWh is estimated.

Another (complimentary) option analysed is the implementation of a RHI for the household thermal energy covered. The results show that is this is a very interesting alternative, in particular in locations such as London where the thermal energy demand is a significant share of the total household demand. It is observed that with a RHI of ~0.11 €/kWh, the *PBT* of the system located in London drops down to 15 years, while if RHI is ~0.19 €/kWh, a similar *PBT* than in Zaragoza is achieved (12 years). Therefore, it can be concluded that this subsidy is also a very promising alternative not only to improve the cost competitiveness of S-CHP systems but also to incentivise the technologies that generate heat to help decarbonising the urban sector. In the studied S-CHP system locations, the results show that it is more beneficial for the system cost competitiveness to implement incentives on the thermal energy generation rather than on the electricity exported. That is, a lower *PBT* is obtained when a fixed amount (€/kWh) of incentive is implemented as RHI rather than equally split that amount for RHI and FIT.

Finally, the effect of the simultaneous variation of several of the above studied parameters on the S-CHP system economics is analysed. In particular, 14 different scenarios are assessed for each particular location. For the S-CHP system located in Zaragoza, the *PBT* has the potential to decrease down to ~10 years with a 10% reduction in the PVT collectors' price and storage tank price, as well as 20% reduction in the installation costs, together with an increase in the fuel inflation rate up to 3.5% (which is within the historical inflation rates), considering also that the market discount rate increases from 3.5% to 4%. In the case of Athens, considering the actual FIT available in Greece for small PV rooftop installations, when the aforementioned cost reductions and fuel inflation rates are considered, and the market discount rate is maintained at 3.5%, a *PBT* of 11 years is achieved. Furthermore, if instead of incentivising the electricity generated through FITs, the same incentive is given as the RHI, then the *PBT* drops to 10.5 years. It is believed that both cases are realistic scenarios in these countries in a few years' time. For the system located in London, further components' cost reductions are required (10-25%), as well as a higher fuel inflation rate (of 4.5%) and larger financial incentives (FIT = 0.05 €/kWh, RHI = 0.15 €/kWh), to achieve a *PBT* of ~10 years. Still, considering the historical inflation rates in the UK, the current financial incentives for small-scale PV installations (0.048 €/kWh), and the existence of a domestic RHI scheme, the proposed scenario is considered a realistic and feasible scenario in the near future.

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