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Power from the people

Stirling engines for Domestic CHP

Domestic CHP offers the potential for households in the UK to generate their own electricity. We could see energy bills fall radically and carbon dioxide emissions reduced. But the technology just has not taken off. Fred Starr explains some of the challenges and the benefits of Domestic CHP with particular reference to one possible power generator, the Stirling engine.

Introduction

The 21st century will see the concept of 'Domestic' CHP (Combined Heat and Power) turning from a pipe dream to commercial reality. In a nutshell, the principle of Domestic CHP is to produce most of the electricity needs of a single household using a miniature generator driven by a small engine.

In the UK and Northern Europe, such an engine would be fuelled by natural gas. The waste heat from the engine would go into the household central heating system, offsetting in part the fuel that would normally be burnt in the gas boiler. The central heating boiler would contain the engine–generator combination to produce electricity, plus an ancillary boiler to produce supplemental heat. This would be needed when the waste heat from the engine was insufficient for household needs (see Figure 1).

Like other forms of combined heat and power, Domestic CHP will result in substantial energy savings. Pushed to its limit, Domestic CHP could supply all of the electric power that the UK demands. In so doing, it would use about two thirds of the natural gas used in the best combined cycle plants. It therefore gives the promise of extending North Sea gas reserves and of reducing CO_2 emissions. For the consumer there would also be substantial gains. Although domestic gas consumption would rise, the consumer could expect to reduce energy bills by between £100 and £200 per year.

Power units for Domestic CHP

For Domestic CHP to become reality the choice of prime mover, that is the 'engine' which converts the fuel energy in natural gas to electrical or mechanical power, should be logical and realistic. However, every system for producing 'domestic power' presently has some sort of Achilles heel.

I believe that, in the near term at least, the Stirling engine is the best of the available options. But there are many myths that surround this type of prime mover. One intention of this review is to inject a measure of objectivity into the claims that are often made for Stirling engines. Another is to consider why the time is ripe for Domestic CHP and how, in the longer term, it could provide a secure basis for power generation in this country and elsewhere.

What then are the main contenders, apart from the Stirling engine? Perhaps the most obvious is the internal combustion engine, the power unit in every car and truck. Its major shortcoming is the high level of carbon monoxide in the exhaust. Despite the use of catalytic converters to reduce CO levels, safety issues preclude the use of such an engine in the house. Gas turbines would seem to be another near-term option. Here again there are safety and cost considerations. The gas supply would need to be pressurised so that the risks of an explosion, if there were leakage, would be very high.

That is all that what might be termed 'normal technology' has to offer. Most of the drawbacks of internal

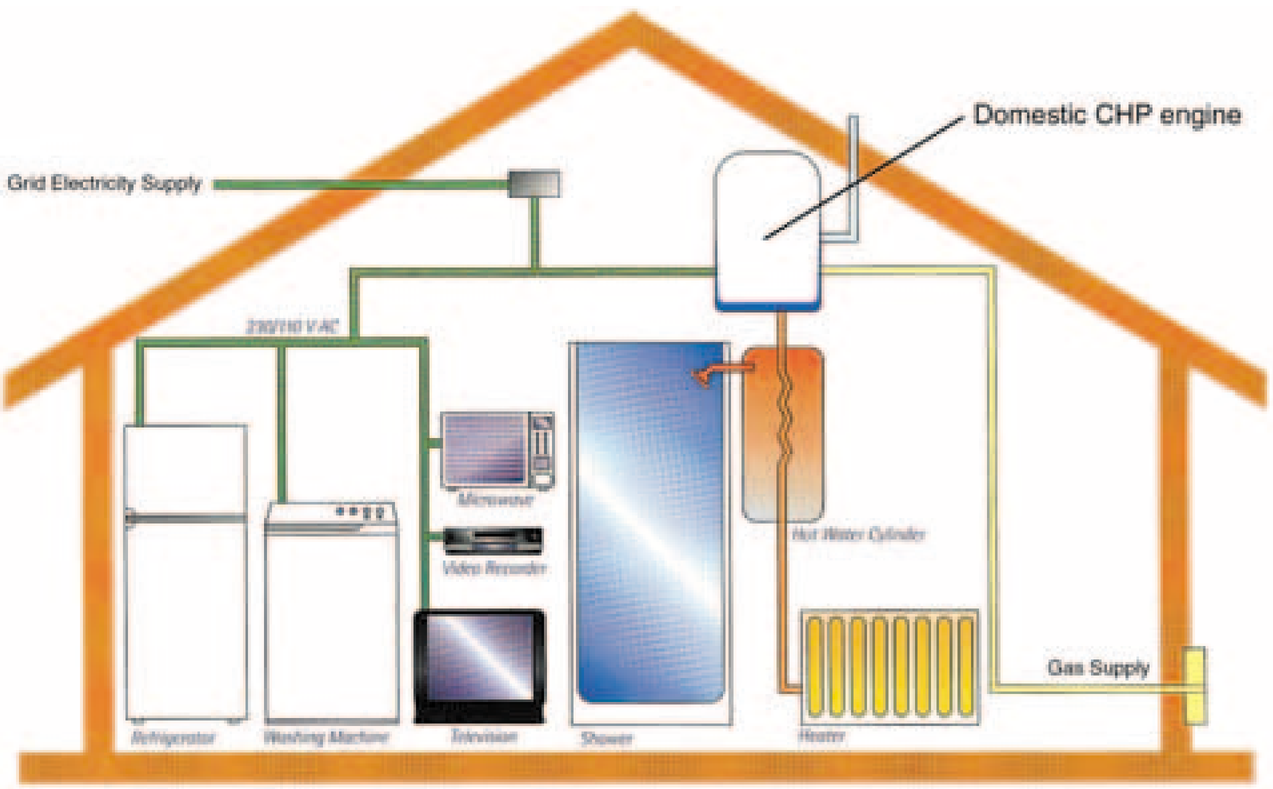


Figure 1: Schematic diagram of a Domestic CHP system. (Courtesy of Whispertech Ltd.)

combustion engines and small gas turbines can be overcome, but only at a prohibitive expense, and we are in a mass production market where the consumer is very sensitive to first cost.

Some proponents of Domestic CHP have turned to other, less conventional approaches that are better in terms of safety and environmental impact. Thermoelectric devices are already in commercial use in certain niche applications, such as cathodic protection for pipelines. Thermoelectrics directly convert the heat from a burning flame into electricity. Sadly, the efficiency of conversion is too low for Domestic CHP: at best they offer under 5%. The fuel cell can also be classed as another direct energy converter. It is the most efficient of all the contenders. The problem here is that the small fuel cell requires hydrogen as a fuel, rather than natural gas, which is methane-based. Nevertheless a Domestic CHP system based on a fuel cell would fit very well into a future hydrogen economy, but it is not a near-term option.

Operation of the Stirling engine

Let us now take a look at the Stirling engine itself, which in some ways can be regarded as a combination of advanced and conventional technology. Indeed the Stirling might be likened to an old-fashioned steam engine, but without water or a boiler. In the Stirling engine, a pressurised gas such as air, nitrogen or helium is used as the ‘working fluid’, which is sealed within the engine casing.

Let us suppose that the working fluid is helium. When the engine is running, the helium is shuttled back and forth between a hot space and a cold space in the engine by means of a ‘displacer’ piston. When the helium is in the hot space, the pressure and volume rise. Conversely when the helium is in the cold space, the pressure and volume fall. These pressure and volume changes are made to drive a ‘power piston’ up and down a separate cylinder within the engine, just as in a steam engine (see Figure 2). In this way the Stirling engine can be made to produce power. To maximise efficiency one needs to have a big temperature difference between the hot and cold parts of the engine, and to maximise power the helium must be at high pressure.

For the engine to operate, the high-temperature end must be kept continuously hot. In a Domestic CHP Stirling the heat is supplied by burning natural gas. Again, in order for the engine to operate, waste heat must continuously be removed from the cool end of the engine. With Domestic CHP the heat is taken away by the water in the central heating system. We can see how the Stirling engine fits in well with conventional central heating: in one sense, we have simply replaced the boiler with a power unit.

The prospects for the Stirling engine

The Stirling engine has been with us since the Industrial Revolution. Thousands of small ‘hot air’ engines, working on the principle of the Stirling engine, were built to replace horse or manpower in small industrial and commercial sites. With the coming of the internal combustion engine and later still of electric power, this market died. Since then the Stirling engine has continued to be an also-ran, despite efforts to resurrect it for low-emissions motor vehicles. Why then might it have a future for Domestic CHP?

The key feature of the Stirling is that it is an externally fired engine in which the heat passes from the outside of the engine into the working fluid within the engine. Because of this, burning natural gas at atmospheric pressure will produce the necessary heat energy. Hence emission levels, in terms of NOx and carbon monoxide, are low. As noted earlier this is vital where combustion products could seep out into kitchens or other rooms. The Stirling engine is reasonably silent, another desirable feature. Unlike the internal combustion engine there is no explosion noise, and unlike the gas turbine there is no aerodynamic whine from the compressor or turbine. Quietness is next to godliness in this context.

However we are beginning to need to tread very carefully when weighing up the claims about Stirling engines. When we think about car engines, we know that – whoever the manufacturer – they are all basically of the same design. In comparing one make of internal combustion engine with another, we can use the same basic ideas of compression ratio, piston speed, bore-to-stoke ratio, etc, in making our judgements about likely power output, efficiency and reliability.

This is far from true with the Stirling engine. Each designer has his own idea of how the engine should look. The picture is further complicated by the needs of Domestic CHP. Here, in many cases the generator is contained within a pressurised crankcase to prevent the escape of helium from the engine, and is a major factor in the overall engine design. Accordingly, one needs to be very cautious in one's assessments.

For example, earlier Stirling engine designs ran with oil lubrication and, due to the dampening effect of the oil film, were extremely quiet. The difficulty with oil is that it can work its way into the hot zones of the engine and coke up heat exchangers. To overcome this problem, modern crankshaft–piston Stirlings use grease-packed roller bearings and polymeric piston rings. These are not as good at cutting out noise. However there is a type of Stirling engine in which the piston is supported with a combination of springs and gas bearings. When people see these in operation, the first question is often: 'Is the engine on?' The big issue with this type of machine is the need to fabricate pistons and cylinders with a high degree of accuracy. As far as I know this has yet to be demonstrated in quantity production.

To summarise, there are few established guidelines for judging the worth of an engine. About the only things that all modern designs have in common is that heater temperatures are in the 550–750°C range and, as noted previously, air, nitrogen or helium are used as working fluids. All use water cooling. These parameters should result in a Domestic CHP engine with an efficiency in the 15–25% range and, for a machine about the size of a small TV set, a power output somewhere in the region of 1–3 kW.

The statement about efficiency levels may surprise some readers. It is generally accepted that the Stirling

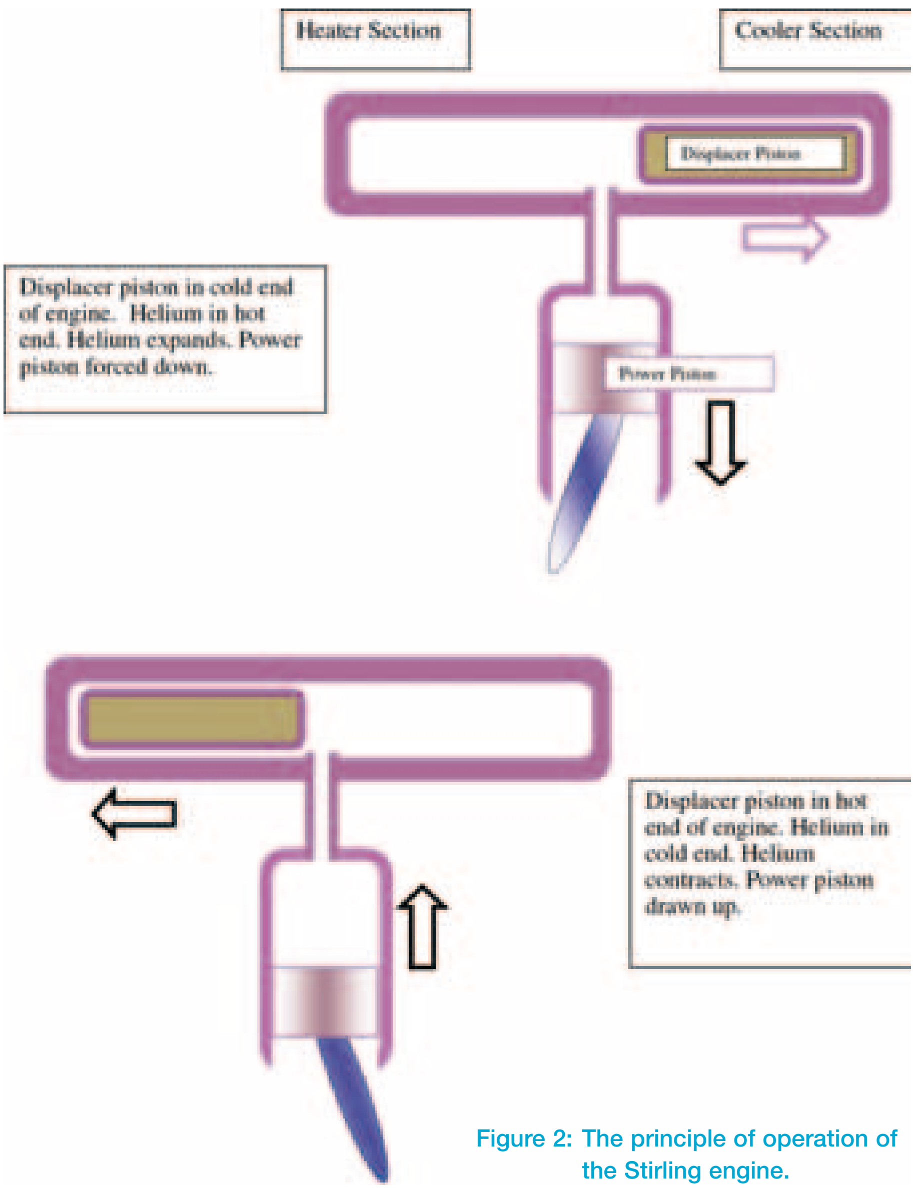


Figure 2: The principle of operation of the Stirling engine.

engine is far superior to more conventional power units. In practice it is difficult to get the aerodynamics and heat transfer in the engine right, since the air flows are never steady. Frictional and associated losses in most machines are also high due to the impossibility of using oil lubrication.

Engineering challenges

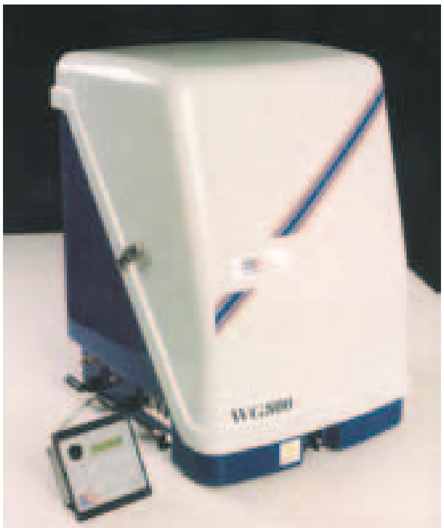
The biggest engineering problem is that of getting the heat into the engine in the first place. This is done using a 'heater', which is a compact heat exchanger that transfers the heat from the combustion products into the working fluid. The heater is a severely compromised piece of hardware. To maximise power output and efficiency it needs to have the smallest possible internal volume. However, to maximise the flow of heat into the engine, the surface area of the heater has to be as large as possible. Similar comments can be made about the design of the other heat exchangers within the engine. The struggle to maximise heat transfer surface areas whilst minimising heat transfer volumes has led to the multiplicity of Stirling engine designs.

In most Stirling engines the combustion air supplied to the natural gas burner is preheated, using the heat in the spent combustion products after they have left the heater. Here we have another set of problems. An air preheater must be incorporated into the combustion system and the natural gas burner must be able to utilise high-temperature combustion air without coking up, lighting back or corroding. Such problems have been overcome on the industrial scale. It is another matter to build a burner/preheater combination that will fit into a cornflake packet.

This discussion about the air preheater brings into focus yet another illusion many people have about the Stirling engine, and that relates to long-term reliability. Apart from the capital cost of a Domestic CHP system this is perhaps the most pressing issue. An engine in a Domestic CHP set would need to have a life of at least ten years and require virtually no maintenance. The heater would be subject to pressure and temperature cycling 3–4 times a day, so thermal fatigue is a serious matter. As we have seen, oil lubrication is prohibited in the Stirling. Accordingly all of the crankshaft-type engines use polymeric piston rings and, in most cases, grease-packed roller bearings. There is concern about the maintenance demands which these design features create. In motorcar terms we want a vehicle that will run for around 1.5 million kilometres with minimal attention. Nevertheless, good progress is being made. For example, some of the Whispergen machines which rely on greased bearings and polymeric rings are reaching acceptable servicing intervals. A cutaway section of this engine heads this article; the Domestic CHP packaged version is shown below.

Finally the Stirling engine is not ideal in responding to load changes, for example, the effect of electric lights or microwaves being switched on and off. Due to the thermal mass of the heat exchangers, the Stirling engine will take some time to warm up. Conversely, once everything is at working temperature the engine will continue to run for a period, even when the gas burner is turned off. Some designs incorporate control systems to stop or slow the engine when the power demand drops, but there is no way around the start-up problem.

Fortunately in the Domestic CHP concept most of these load-response problems disappear, since the Stirling is only intended to supply a proportion of the peak electrical demand in the house. For example, when an electric



The SIGMA PCP, the Whispergen 800 Domestic CHP package and the Sunpower Biowatt.

cooker is running most of the electricity will come from the grid, even though the engine is operating. Conversely, when there is little demand for power but the central heating system is on, power will be exported.

We begin to see why it is that the hunt for the perfected Stirling has been so long and difficult. We can also see that a deep knowledge about one particular design of machine is not always useful in making a judgement about another.

However, despite the issues outlined above we are getting near to a commercial machine. A number of organisations are close to putting the first pre-production models on the market. The principal players at this point in time are:

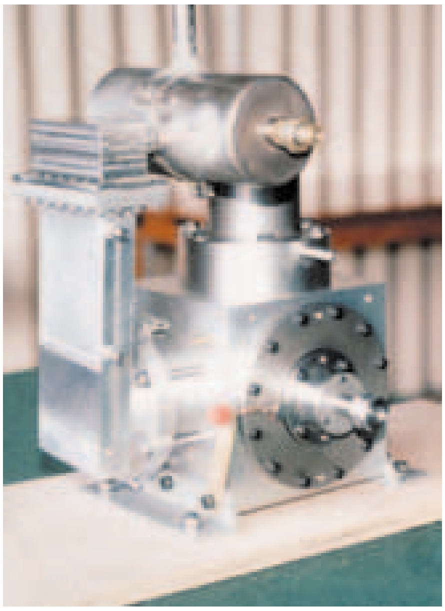
- SIGMA PCP: Sigma Elektroteknisk AS (Norway);
- Whispergen 800: Whisper Tech Ltd (New Zealand);
- Sunpower Biowatt Type: Sunpower Inc. (United States of America);
- STC RemoteGen Type: Stirling Technology Company Inc (United States of America).

It will be noted that the UK does not have an engine of its own, even though Reading and Cambridge Universities were at one time leaders in the Stirling engine field. The sole near-commercial machine in the UK is an efficient 20 kW design, under development by SES Ltd, although it is understood that this machine could be scaled down to make it suitable for single-household CHP.

The technology for Domestic CHP

Why should small-scale CHP have such a good future in Great Britain in particular? And why has the awareness of its potential only begun to grow quite recently? The reasons can be itemised as follows:

- The reserves of natural gas, either indigenous or from Norwegian and Russian sources, are considerable.



The Cambridge University Stirling.

Schematic view of the SES 20 kW Stirling.

- Of the 22 million gas consumers, over 14 million have central heating; that number is still rising. The consumer must have a central heating system to absorb the waste heat in the engine cooling water.
- All consumers are connected to a reliable electrical supply. This is essential for a Domestic CHP system, since any high electrical demand has to be met by importing power from the grid.
- The ratio of heat to electrical energy used in the typical house is about 5:1. This implies that the efficiency targets for a Stirling engine are attainable.

Of course Domestic CHP will only be of interest to the average consumer if he or she can anticipate savings in fuel bills. The figures in the table show the maximum likely savings which could accrue to a householder, in the London area, assuming an electricity cost of 5.5 pence/kWh and a gas cost of 1.4 pence/kWh. The figures assume that no power is exported but also assume that all the electricity is produced using a Domestic CHP system. In the near term this is an unrealistic assumption. There would need to be imported power, particularly in the summer, so that savings would be about 60–70% of these levels.

In the more distant future savings would increase. One reason for this will be increasing fuel costs, but in addition as the technology surrounding the Domestic CHP package grows more sophisticated, it will be possible to store and export larger amounts of power. By around 2030, the savings will be approximately 25% higher than today.

Even so, the target price for the Domestic CHP add-on to a central heating boiler could not be much more than £400–£500, giving a payback to the customer in 3–4 years. Companies working in the Domestic CHP field are reluctant to release figures, but all are working to this type of target, which is realisable in a mass-production scenario. The real issue, as all the companies admit, is kick-starting the market: initial sales will be low and hence unit costs will be significantly higher than the price quoted.

In this regard there appear to be two distinct philosophies with respect to Domestic CHP. Some favour the nil-export scenario, where there is never a need to export power to the grid: this gives the cheapest possible power unit and implies a relatively small engine of around 1 kW output. The principal merit of this approach is that it avoids arguments with the Regional Electricity Companies about safety aspects and export payments. The other approach assumes that the engine will be exporting power for a good deal of the

Dwelling	Current gas and electricity bills (£)	Domestic CHP bills (£)	Saving on combined bill (£)
Detached	845	630	215
Semi detached	620	425	195
Terraced	515	370	145
Flat	330	210	120
1990-built lower energy house	470	310	160

Savings in domestic energy bills.

time. This leads to a 3–5 kW sized engine, but at a higher first cost.

With either approach, the efficiency targets for the engine need to be set so that the household is able to accept all the waste heat that the engine produces. It follows that the more powerful the engine, the more efficient it has to be. One would need something like 15% from a small nil-export engine but about 25% for the bigger engine which would be exporting a good deal of its power. These efficiency targets are attainable, even with current engine designs.

There are no real problems in exporting electricity to the grid. The near-term option is to use an induction generator which is 'excited' at grid frequency when connected to the household supply. This avoids the need for sophisticated controls and has been done, as I understand, through a normal 13 amp plug! The downside here is that the engine has to work within a set range of speeds. The longer-term option, which I favour, is the use of a power conditioner or harmoniser. This will convert any voltage and frequency to that of the grid supply (which is not always at 50 cycles and 230 volts).

A good deal of nonsense is talked about the problems of exporting power. When I buy and use a vacuum cleaner, I do not have to obtain approval from the local electricity board or National Grid to decide when to switch it on or off. A domestic CHP system can be regarded as a sort of negative electrical appliance. The main issue is that if there is a short-circuit on the grid, the engine should stop supplying power to the system. One advantage of the induction generator approach is that it automatically stops working when the grid supply fails.

The longer-term future

The feasibility of Domestic CHP is based at present on the long-distance supply and transmission of natural gas and the advances in electronics which permit the export of small amounts of power from millions of micro-generators. But would the development of Domestic CHP lead to a technological cul-de-sac?

I believe not. In the more distant future every Domestic CHP set would be linked to a power conditioner or harmoniser. This would enable any number of household-based 'micro-generator' devices to input power into the grid. Photovoltaic (that is, solar) systems already use power conditioners of this type. One could also envisage miniature flywheel systems to store surplus power from a Domestic CHP set. However, a harmoniser is a vital feature in a flywheel system. The frequency is extremely high and both it and the voltage will drop as the flywheel slows down.

But let us turn our attention to the natural gas grid. At some stage we will exhaust the reserves of natural gas. However, the reservoirs and long-distance pipelines will still be serviceable and could be used for the storage and transmission of alternatives to natural gas. Hydrogen generated by electrolysis in central stations is one option, but hydrogen-rich gases can be produced quite easily from renewable crops or, if there is the will, from a resurrected coal industry. The electricity for the electrolysis units would be produced primarily from offshore wind but a significant fraction would come from domestic photovoltaic. Hence, by using the components that make up the UK electricity and gas supply system, there seems no reason why Domestic CHP should not form the basis of our energy system for the indefinite future.

It is a fact, however, that although the UK is of all the industrialised nations best placed to take advantage of Domestic CHP, we cannot be considered to be leading the race. There is no UK CHP Stirling in the domestic power range. But rather than concerning ourselves too much with designing an engine which is superior to some of those already mentioned, our focus should instead be on developing the Domestic CHP market and in particular on manufacturing Stirling CHP sets in this country. Here both the Government and the Energy Utilities need to play their part in getting the market started. Given the right drive and support, the construction of Domestic CHP and its ancillary technologies could help regenerate the UK's ailing manufacturing industry. ■

For some thirty years Fred Starr has specialised in the application of high-temperature materials to advanced energy conversion processes. In so doing, he initiated the British Gas programme to develop a Domestic Combined Heat and Power system. He is currently working with ETD Ltd on, amongst other issues, micro-gas turbines, for which the company has received a SMART award from the DTI.
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