Is there a future for Micro - CHP ?

THE RESONANCE STIRLING MAY PROVIDE THE ANSWER

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An important share of our fossil fuel consumption serves to heat our homes and to prepare hot sanitary water. When burning these resources, energy is released at temperatures of some 1200 to 1400°C, serving to heat radiators up to merely 40 or 50°C. This downgrading of the heat is an irreversible, highly inefficient process.

In Combined Heat and Power units (CHP), the combustion heat released at high temperatures powers an engine producing electricity; in addition, the engine cooling heat remains available for heating purposes. This dual use of the fuel reduces substantially the primary energy demand as compared to their separate production. Small units offer the advantage of supplying dwellings directly with electricity and heat, without the need of any demanding heat distribution system.

In the following, **a new type of free-piston Stirling engine** is described, which has been developed to an advanced prototype stage. Intensive testing campaigns confirmed the expected, favourable operating characteristics of this new concept, which suitably meets a long list of exacting demands imposed to modern heating equipments, as e.g.:

- the heat is supplied to the engine from the outside; the continuous, external combustion is complete, with clean flue gases which are fully compatible with the most stringent standards imposed to residential areas;
- the units may be operated flexibly within a large power range at high efficiency. The number of on-off cycles, hence the exposure to repetitive thermal stress cycles, can be reduced to a minimum. Start-up of the engine may be performed within a few minutes, with a moderate primary heat input;
- the engine is contained within a hermetically sealed compartment; the free pistons operate on gas bearings, without needing any crankshaft. As no lubrication is required, engine maintenance is reduced to a minimum.

ENGINE DESCRIPTION

The proposed CHP-unit comprises a new free-piston Stirling engine, schematically represented in Figure 1. The heat released in the burner is transferred from the heater tubes to the working gas of the hot volume, where it is expanded. This gas is then conveyed through the regenerator and cooler tubes into the compression chamber, where it is recompressed and returned via the regenerator back into the hot expansion volume.

The displacer piston periodically shuttles the working gas between these two variable volumes. In the proposed new concept, **the displacer is fixed against the work piston, forming together the main engine or transfer piston**; its periodic movement is accurately controlled in amplitude and phase by the associated linear electric generator.

This transfer piston is provided with a piston rod of important section upon which the engine work is exerted. The movement of this main piston induces only a rather small pressure variation of the working gas.

The **cyclic pressure variation** of the working gas results essentially from the periodic movement of additional **resonance pistons**; these spring-mass-oscillators are of high quality: they oscillate in a stable mode within a narrow frequency band, without requiring any particular control. Their amplitude depends upon the excitation exerted by the main piston, hence upon the heat supplied by the engine burner.

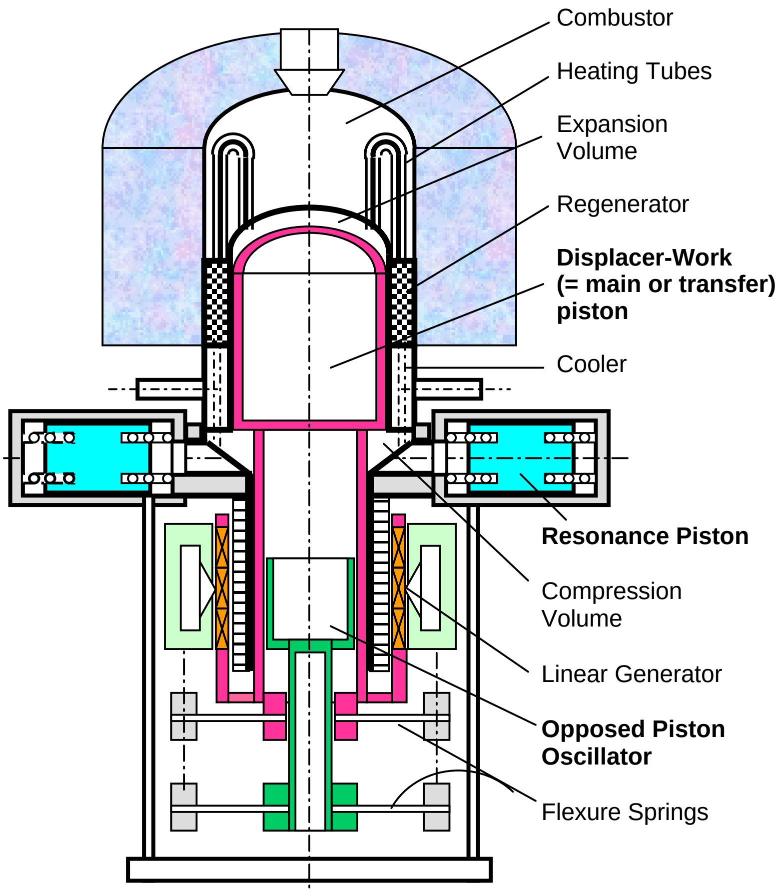


Fig.1: **Schematic Representation of the Resonance Stirling Concept**

COMPARISON WITH EXISTING STIRLING FREE-PISTON ENGINES

In usual free piston Stirling engines, the movement of the work piston may be controlled by the associated linear generator. The displacer free piston movement depends upon the time-varying working gas pressure; it may indirectly be influenced by the electric action exerted upon the working piston. However, this control is relatively slow; the piston movement becomes unstable when the working gas is subject to important cyclic pressure changes. When exceeding a critical pressure amplitude, the engines tend to vibrate and then to stall.

For avoiding such an unstable behaviour, these engines operate at moderate heating temperatures, what restricts the Carnot efficiency of the thermal cycle. In addition, the working gas is exposed to rather low periodic pressure variations only; important specific gas flow rates (per unit power output) through the engine regenerator are required, entailing considerable pressure drop and heat exchange losses in this component. As a consequence, the overall thermal efficiencies of these engines are rather limited.

In the new resonance concept, the transfer piston – comprising the displacer – is electrically controlled, what considerably improves the dynamic stability of the entire system; these engines may thus be operated at high heating temperatures. The working gas may be subject to important cyclic pressure changes, at correspondingly low flow rates and pressure drop losses .

Engine Characteristics

In Figure 2, typical operating characteristics of the presently known Stirling engine and of the new resonance concept are compared with each other. The broken lines show the expected thermodynamic performance for these two engines, under assumed mechanically stable conditions. This plot readily shows that the two engine configurations reach similar performance levels when operated at a nominal heater head temperature of some 700°C.

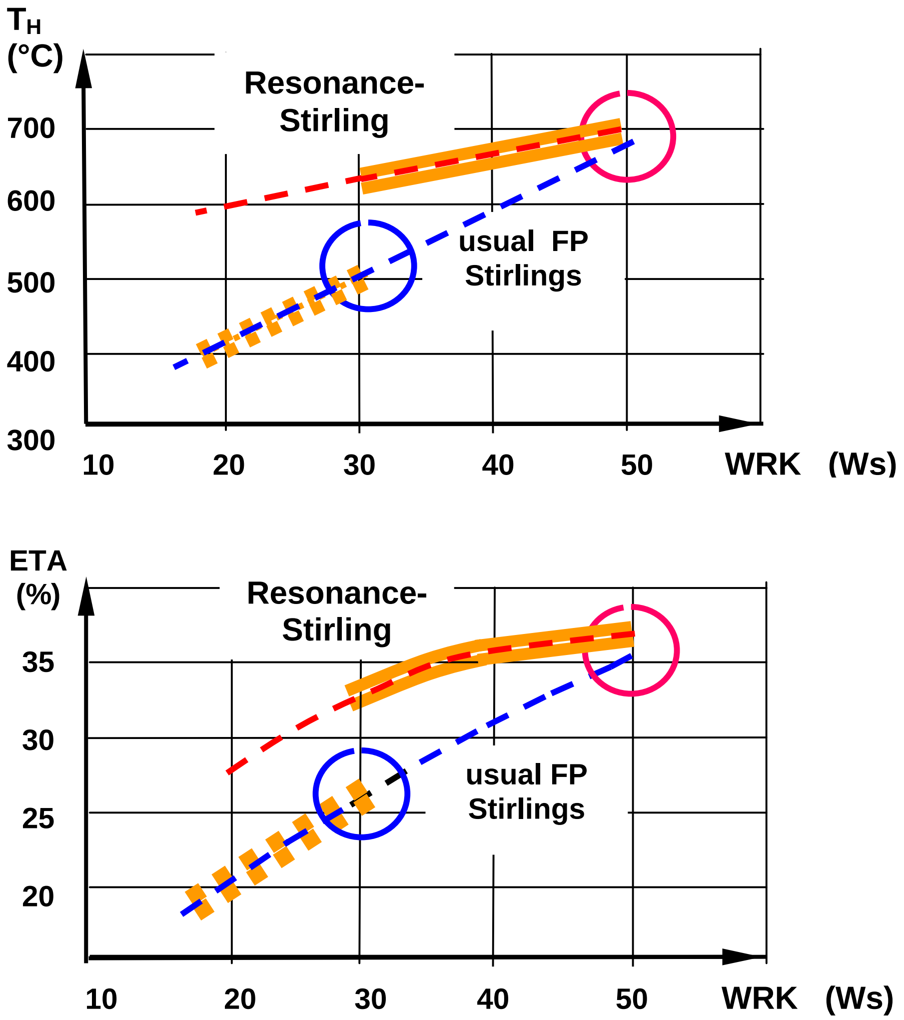


Fig. 2: Heater tube temperature T_H and thermal cycle efficiency ETA as a function of the cyclic work WRK of the engines

However, in order to avoid piston instabilities from occurring, the heater head temperature of presently existing free-piston systems need to be kept below a critical limit of some 525°C. The above shown characteristic performance curve may only be exploited within a limited range.

In contrast, the new resonance Stirling engine may be operated in a stable mode at considerably higher heating temperatures and engine efficiencies. In Figure 2, the effectively exploitable operating ranges of the respective engines are marked by broad band lines.

The new engine is characterised by favourable part-load operating characteristics. Its power may be set by adjusting flexibly the burner according to the heating demand of the dwelling. By providing these installations with an appropriate hot water boiler, on-off cycling can be reduced to a minimum. The engines may thus be operated smoothly and efficiently, without exposing them to an important thermal fatigue.

Vibration Suppression

The resonance pistons are arranged in pairs; by their opposed movement, no net force is exerted upon the engine.

The displacer-power piston is associated with an additional oscillating piston, forming together a dual pendulum. By their opposed movement, the vibration of the engine body is reduced to a minimum. As is illustrated in Fig.1, this additional mass may be arranged within the large piston rod section of the main piston, resulting in a compact engine structure.

Engine Burner

The combustion air is preheated to high temperatures in a counter-current heat exchanger by the exhausting gas stream. In the burner, this preheated air is then mixed internally with the combustible gas; this strongly diluted, homogeneous gas is then burned in a flame-free oxidation (FLOX-) process. Even with minimal excess air rates, complete combustion is achieved, without producing any noticeable amount of noxious gas (CO, NO_X). An additional condensing heat exchanger serves to extract humidity contained in the exhaust gas stream and to efficiently use its residual heat content.

MAJOR OPERATING CHARACTERISTICS OF THE UNITS

The new engine may be conceived with high flexibility. With a fixed piston geometry, different power ratings may be obtained by adjusting e.g. the flexure spring rates, the piston masses, the average working gas pressure or a combination of these parameters:

Resonance Stirling Power ranges		small	medium	large
Nominal combustion heat input	kW_{TH}	8	10	15
Available heating power	kW_{TH}	5.5	7	10.5
Electric power produced	kW_{EL}	1.5	2	3
Total efficiency (electr. + heat)	%	88	90	90
Overall electric efficiency	%	19	20	20
part-load power range	%	60 – 100	60 - 100	60 - 100

PROTOTYPE OPERATION

A series of prototypes of steadily increasing complexity have been built and operated. The measured engine performances are compared with analytical simulation runs performed by means of specific numerical programs, based on the thermodynamic and dynamic processes taking place in the engine.

The following table summarises most pertinent experimental results obtained with the last prototype unit built. Electric output efficiencies of up to 18% have been measured, with heater tube temperatures of approx. 700°C. It may be noted that the pressure ratio of the working gas ranges up to $\pi_C \sim 1.30 – 1.33$, considerably higher values than those achieved with other existing free-piston engines.

		measured results	**expected data range**
Max. combustion heat input	W_{TH}	10’000	-
Electric power output	W_{EL}	1800	1500 – 2000
Electric efficiency η_{EL}	%	18	20 – 22
Total efficiency η_{TOT}	%	?	90
Pressure ratio $\pi_C = p_{MAX}/p_{MIN}$	-	1.26 – 1.33	1.32 – 1.40
Operating frequency f	Hz	40 - 44	44 - 50

Experimental results obtained with the prototype Resonance Stirling Engine

Best results were obtained when operating the burner in the FLOX-mode. By further improving this burner and the engine heater head, it is expected that overall electric efficiencies of at least 20% may be reached. At present, the flue gas exhaust is not equipped with a condenser, a reason for which the total efficiency of the CHP-unit (available heat + electricity) cannot be determined.

All major engine components are continuously operated on separate, specifically conceived endurance test benches. At present, complete field testing units are being assembled for performing long-term tests under specific operating conditions.

ECONOMY

Small CHP-units need to be operated according to the varying heat demand of the dwelling. By using a hot water boiler, electricity may mainly be produced during peak power demand periods. Owing to their local production, neither heat nor electricity are affected by transport losses. Any surplus electric energy may be injected into the local grid and used in the neighbourhood.

To assess the energetic gain of a CHP-unit, account needs to be taken of the electric energy produced, as well as of the heating power output. This evaluation depends upon the value attributed to the produced electric energy relative to the heat. An endless debate can be opened around this question. A rather pragmatic assessment can be made in assuming that all electric energy produced by a CHP in one home serves to operate a heat pump (HP) installed in a neighbouring house. A pure thermal balance may thus be established around this combined plant, which schematically is illustrated in Fig. 3. As both dwellings need heating at the same time, production and consumption are well synchronised, without requiring any significant intermittent storage. The heat flows marked in this figure show that the combined plant results in overall energy savings of between 37 and 45% as compared with individual, standard heating systems.

This **energetic gain of some 40%** is to be attributed as well to the CHP- as to the HP-heated home. In fact, the CHP offers the additional advantage of producing electricity during peak power demand periods, in winter, during which it may partly compensate the reduced power outputs of hydraulic or solar plants.

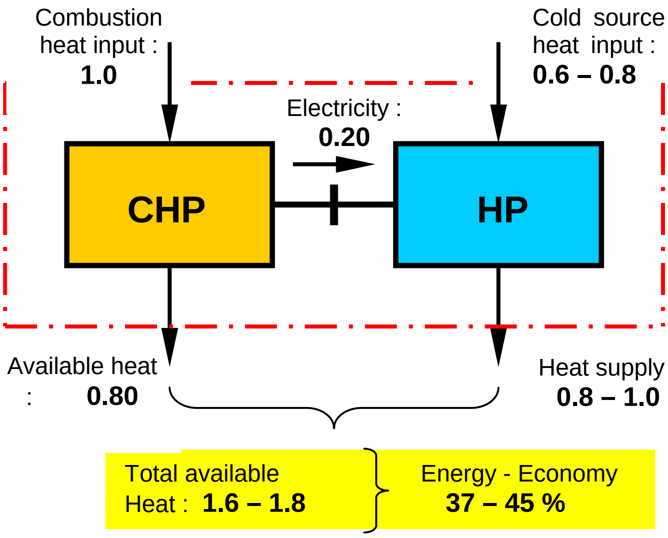


Fig. 3: Combined Heat and Power (CHP) Unit Entraining a Heat Pump (HP)

The energy savings realised by these CHP-units serve to pay back their investment cost. This economic balance can only be met when producing these equipments in large series, at low cost. The required investments for the industrial manufacturing facilities are spent most appropriately when they serve to produce equipments yielding important energy savings. The efficiency and high specific power rates are decisive economical assets of the proposed new resonance concept.

Comparison with alternative CHP-concepts

The resonance Stirling concept is compared with alternative CHP-units proposed for the heating of individual homes. The appended table summarises the most relevant characteristics of various concepts, including the newly developed resonance Stirling system. In this table, favourable characteristics are marked by white fields, more questionable characteristics by darker ones. This qualitative assessment may be summarised by the following comments:

- small internal combustion engines may offer somewhat higher thermal efficiencies than the proposed, new Stirling engine. However, the flue gases are far more polluting than those emanating from continuous combustion burners of Stirling engines. For cost reasons, scrubbing systems will hardly be applicable for small I.C.-engines. These techniques may more particularly be suited in industrial premises and for engines with higher power ratings.
- the presently existing Stirling systems as well as organic Rankine cycles (ORC) fall short in efficiency. They are at least as complex and expensive to manufacture as the proposed concept.
- an enormous research effort is devoted world-wide for developing small fuel cell systems, for similar applications as discussed here. The PEMFC-fuel cells are operable, but require pure hydrogen as a fuel. Their application depends on a future (still questionable) hydrogen economy; otherwise, each individual

fuel cell needs to be equipped with an additional reformer, what hardly may be economically acceptable for the considered low power units.

- another route consists in the development of high temperature SOFC-fuel cells; they are heavily propagated by claiming impressive efficiency figures, ranging between 30 and 60%. However, these fuel cells are extremely sensitive to thermal stress exposure; they need to be operated for long duration at as constant temperature and power levels as possible. Because of their sensitivity and inflexible operation, a backup heating system is required for covering the daily fluctuating heat demand of a dwelling. As schematically illustrated in Fig. 4, this peak-power system needs to supply a major share of the heating demand, more than the fuel cell itself. Even under favourable conditions, the complete home heating system (fuel-cell and backup system) will hardly reach the overall energy gain of the proposed, new Stirling concept.

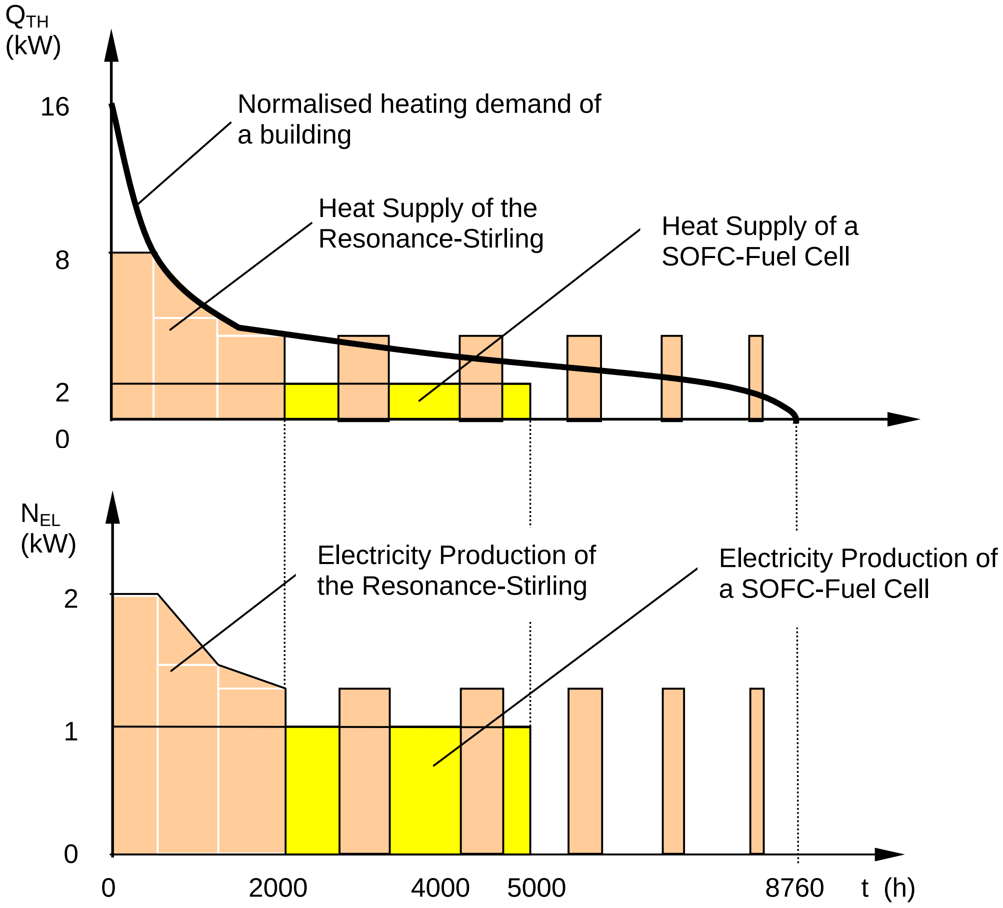


Fig. 4 : Schematic comparison of the Heat- and Power Production of a continuously operating Fuel Cell (1 kW_{EL}) with a flexibly operating Stirling-Resonance unit (2 kW_{EL}) for an assumed annual heat demand of 30' – 35'000 kWh_{TH}

EXPECTED COMMERCIAL DEVELOPMENT

The need for reducing our ecological footprint will promote the use of CHP-units for heating small buildings. Despite of the large variety of concepts proposed, not a single existing technique is yet commercially established at a significant scale. An ideal situation prevails for launching a new concept into this virgin market.

For taking best advantage of this situation, a technical and commercial cooperation is proposed to be established with major heating equipment companies. The promoters of the new CHP-concept are interested in discussing such agreements, including the tasks to be attributed to the respective parties, as well as their rights to commercialise corresponding products.

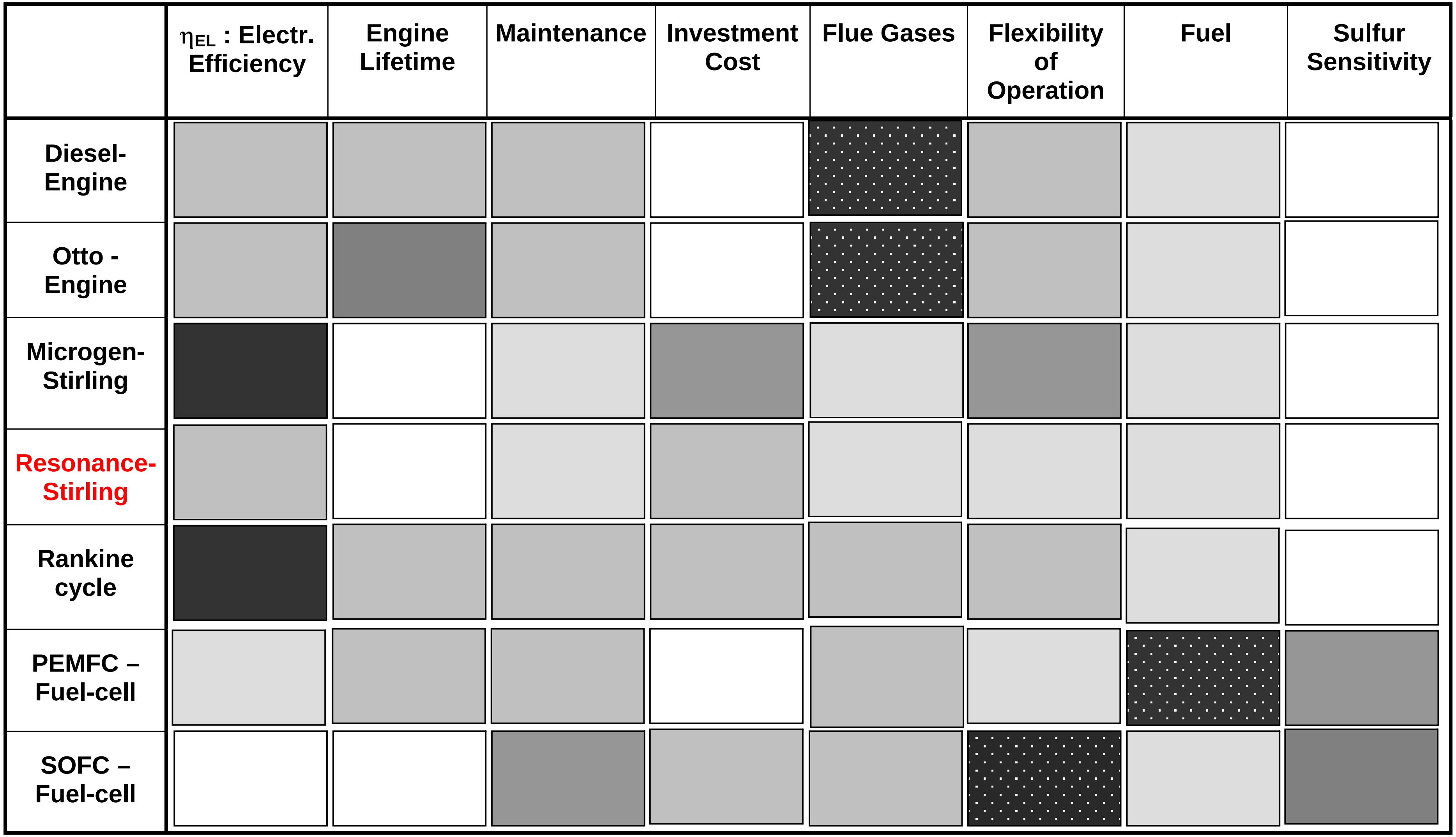
CONCLUSIONS

- A new free-piston Stirling concept is proposed, which is more efficient and of higher power density than presently existing concepts. The use of a combined displacer-power piston facilitates the stable, periodic movement of the free pistons. This control is rapid and precise, making it possible to operate these systems at high heating temperatures and important cyclic pressure variations of the working gas.
- Appreciable fuel savings may be realised as compared to a separate production of heat and power. Based on a given heating demand, more electricity may be generated with the new concept than with existing free-piston units. The surplus in investment cost of resonance systems may be paid back within a few years by the realised energy savings.
- The favourable economic perspectives offered by the new technique will facilitate its market penetration. Most important market segment concerns the retrofit of domestic oil- or gas burners for small dwellings. The continuously augmenting requests for applying energy-conservative solutions should further promote the proposed resonance concept.
- Heating equipment manufacturers should seize the opportunity to engage themselves into this domain in view of setting up their own series production. The launching of such a new industrial activity may be promoted by means of a well-tailored technical cooperation program, making available to the interested industry the basic know-how acquired over the years when developing the proposed concept.
- The described technology is protected by an internationally registered patent, against which no objection has been formulated so far.
- Further information may be obtained and contact established with the promoters and patent owners of the resonance Stirling by e-mail under www.stirling.ch

REFERENCES:

[1] **US 2013/0031899 A1 : STIRLING MACHINE** (Feb. 7, 2013)
US Patent Application Publication

Major Criteria for applying various μ - CHP - Options



	η_{EL} : Electr. Efficiency	Engine Lifetime	Maintenance	Investment Cost	Flue Gases	Flexibility of Operation	Fuel	Sulfur Sensitivity
Diesel-Engine	▒	▒	▒	□	▦	▒	░	□
Otto - Engine	▒	■	▒	□	▦	▒	░	□
Microgen-Stirling	█	□	░	▓	░	▓	░	□
Resonance-Stirling	▒	□	░	▒	░	░	░	□
Rankine cycle	█	▒	▒	▒	▒	▒	░	□
PEMFC – Fuel-cell	░	▒	▒	□	▒	░	▦	▓
SOFC – Fuel-cell	□	□	▓	▒	▒	▦	░	■