FLUIDCELL

ADVANCE M-CHP FUEL **CELL** SYSTEM BASED ON A NOVEL BIO-ETHANOL **FLUID**ISED BED MEMBRANE REFORMER

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WP02 - INDUSTRIAL SPECIFICATIONS OF FUEL CELL CHP SYSTEM

D2.3
Industrial and market introduction requirements for bio-ethanol fuelled Fuel Cell CHP system

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Content

1. EXECUTIVE SUMMARY

Systems for the simultaneous production of useful heat and electricity (Combined Heat and Power, *CHP*) are the most powerful instruments for the reduction of fossil fuel consumption (via increased carbon efficiency) in a world where primary energy demand is continuously increasing.

A review of available CHP systems is proposed. The focus of the work is on devices with an electrical power output up to 50 kWe, defined micro-CHP (μ-CHP) systems, according to the definition given in Directive 2004/8/EC. The field is further restricted to devices suitable for home installation (as for the system developed in *FluidCell*) and only a small fraction of the available products satisfies this constrain.

The aim is to provide an overview of the state-of-the-art of micro-CHP systems currently available on the market as systems near to commercialization. A focus on state-of-the-art fuel cell-based CHP system will be provided, with particular attention to those fed by bio-ethanol.

For the correct evaluation of the potential success of the m-CHP system being studied, an economic comparison with current available CHP systems present on the market will be done, in order to quantify the real economic feasibility of the *FluidCELL* system.

The description of the variables and data assumed for the analysis will be first introduced; afterwards, different cases will be evaluated to understand which size or configuration for the micro-CHP is more attractive for the market.

Afterwards the main components of a fuel cell-based CHP system will be shown, and their constraints discussed. The technical features that the system being studied must have, to be marketed according to the Standards in force and regarding micro cogeneration, will also be discussed.

Finally, the annexes paragraph provides further information on m-CHP systems and a detailed description of some companies' systems.

2. m-CHP systems overview

Nowadays the environmental policies, focused on carbon reduction and a rational use of primary energy, are leading to a development of various µ-CHP technologies to improve efficiency in energy conversion to useful heat and electric power compared with the separate generation.

Different technologies are available for µ-CHP such as Fuel Cell (*FC*), Internal Combustion Engine (*ICE*), *Stirling* engine, micro Gas Turbine (*µGT*), Organic Rankine Cycle (*ORC*), Thermo-Photovoltaic (*PV-T*). Table 1 summarizes the main characteristics of each system.

Table 1. m-CHP system comparison.

	FC	ICE	Stirling	µGT	ORC	PV-T
Electrical Efficiency	35-45%	25-30%	<20%	25-33%	14%	25%
Overall Efficiency	>90%	80-85%	65-85%	70-85%	80-85%	80-85%
Cost €/kWe	20000	800-6000	10000	1500	-	-
Availability	Pre-Commercial	Commercial	Pre-Commercial	Commercial	Under research	Under research

2.1. Existing m-CHP systems

The Internal Combustion Engine is a well-known, mature and reliable technology. CHP systems based on these engines are commercial, with good electrical and overall efficiencies, due to the wide experience from automotive sector.

These systems are available on a wide range of sizes, from <1 kW to hundreds of kW, with higher costs for smaller cogeneration systems such as the *Honda*'s cogeneration unit, with an electrical power output of 1 kWe, that costs about 6000 €/kWe.

Larger sizes (over 20 kWe) can achieve reduced costs of 800 €/kWe; the lower costs are due to high production volumes.

Problems of ICE systems are the noise, vibration and polluting emissions. Moreover, maintenance efforts and costs are usually another negative aspect of this technology.

Stirling engines operate with lower vibration and noise level and emissions than reciprocating ICE. An interesting feature of this technology is the possibility of external combustion process that allows the use of a large variety of fuels, and even solar heat. Nowadays, these CHP systems are not yet commercial, but they are on an earlier stage of commercial development. This delay is due to the high specific costs of this technology. Indeed, 1 kW electrical power engine costs over 10000 €/kWe (*Microgen*). Even Stirling engine size can reach hundred kW, with low investment costs than small size.

As for ICE, micro gas turbine derives from a mature and tested technology employed in different fields such as automotive, large size stationary power and aeronautical. The maturity of the technology justifies the high efficiency and low specific costs (less than 1500 €/kWe). Now µTG are commercial, but, unlike other CHP systems, size under 30 kWe (*Capstone* 28 kWe) are not available.

ORC and PV-T are so far behind other technologies in commercialization. Indeed, the systems are still related to few laboratory trials, so that no information about costs is available, and efficiency values are still lower than other commercial CHP systems.

As Stirling engines, ORC has an advantage in external combustion, but a disadvantage related to the required working fluid which could be toxic for some systems.

2.2. Fuel Cell based m-CHP systems

Fuel cells based micro-CHP systems are more interesting and studied despite the higher costs than other technologies. Indeed, fuel cells, which convert fuel directly into electricity without combustion, appear to offer very low emissions and high efficiency; furthermore, there are no moving parts which results in very low noise levels.

Table 2 summarizes the available information on the state-of-the-art and the available system (the information is based on internet search and direct contact with vendors at industry fairs).

Table 2. Fuel Cell based CHP system comparison

Who	Availability	FC type	Costs [€]	Performance [kW el/th]	Electrical efficiency	Total efficiency
CFC Limited	Commercial	SOFC	25000	1.5/0.6	60	85
JX ENEOS	Commercial	SOFC	25000	0.7/0.7	45	87
ELCORE	Field trial	HT-PEM	9000	0.3/0.6	33	>90
HEXIS	Field trial	SOFC	31500	1.0/1.8	35	>90
BAXI	2015	LT-PEM	14000	1.0/1.87	34	>90
VAILLANT	Field trial	SOFC	30000	1.0/2.0	25	90
TOSHIBA	2015	PEM	23000	0.7/1.0[1]	38.5	>90
PANASONIC & VIESSMAN	Japan Commercial	PEM	25000	0.75/1.0	37	90
JAPAN GROUP[2]	Japan Commercial	SOFC	20000	0.7/0.65[1]	46.5	90
CERES POWER/KD NAVIEN	2016	SOFC	-	1/-	-	-
TOPSOE	Field trial	SOFC	-	1/0.9[1]	45	85
ACUMENTRICS	2015	SOFC	-	1.5/1.7[1]	40	85
SOFC POWER	2015	SOFC	-	1/-	32	-
CLEAR EDGE POWER	Commercial	PAFC	-	5/6.2	40	90
BOSCH	Field trial	SOFC	-	0.7/-	45	-
BUDERUS	2016	SOFC	22000	0.7/0.7	45	90
TROPICAL S.A.	Pre-Commercial	PEM	-	5.6/6	-	>90
RBZ	Field trial	HT-PEM	-	5/7.5	34	>90
IRD	Field trial	LT-PEM	-	1.5/1.6	44	>90

It can be noted that the costs of these systems are higher than normally predicted and can be over 14000 €/kWe depending on the technology used. Nevertheless, many systems are available by now and several fuel cells based micro-CHP systems have been installed. In particular in Europe both German

[1] Calculated Values
[2] Osaka Gas Co., Ltd., Aisin Seiki Co., Ltd., Kyocera Corporation, Chofu Seisakusho Co., Ltd., Toyota Motor Corporation

Callux project and European *Enefield* project have been installed hundred 1 kWe systems, while in Japan thanks to *Ene-Farm* project about 50000 1kWe systems have been installed so far.

The most available systems presented in the previous table have an electrical production of around 1 kWe, lower than the one being developed within the FluidCell project that is a 5 kWe. Nevertheless, the comparison of these systems is a good guideline for defining the context in which the FluidCell is being developed and understands the possibilities of commercial success.

As far as the electrical efficiency is concerned, the strength of fuel cells over other system is evident: some FC based systems could achieve values over 40% with also a great total efficiency around 90%.
Some companies have already a commercial product, while others have systems in field trial. Some others plan to have a commercial product from next years. Thus, the FC technology can be considered to be commercially available by now.

2.3. Bio-ethanol Fuel Cell based m-CHP systems

All CHP technologies presented in paragraph 2.1 can be fed with bio-ethanol fuel, with both internal and external combustion systems. Also fuel cell-based CHP systems can be fed with ethanol (which is the aim of the project). Indeed, systems shown in last paragraph are all feed with natural gas or biogas but further internet research brought a few bio-ethanol fuel cell based micro CHP systems to light. Some of them could be fed with natural gas, LPG and biogas as well as bio-ethanol.

Companies that have fuel cell CHP systems based on bio-ethanol in their portfolio are *Helbio*, *Tropical S.A.*, *Prototech* and *Zsw-Bw*, however, no information about systems’ costs are available.

Helbio has a system based on both LT and HT-PEM, with size from 1 to 20 kWe, which can be fed with natural gas, LPG and biogas as well as bio-ethanol. No information about efficiency is available.

Also, *Tropical S.A.* seem to have a fuel flexible CHP system based on PEM fuel cells, with a size of 5.6 kWe, 6 kWth and a total efficiency around 93%.

Prototech has only a laboratory system of 1 kWe based on HT-PEM. No more information has been found.

Finally, *Zsw-Bw* has a bio-ethanol reforming 1 kWel PEM fuel cell system with a 2 kW thermal power output and an electrical efficiency greater than 29%. Another interesting feature of this system is the steam reformer operating temperature that is around 900°C.

3. Economic feasibility analysis

For the correct evaluation of the potential success of the m-CHP system being studied in this project, a detailed comparison with current available systems present on the market must be carried out. Thus, an economic evaluation will be done in order to quantify the real economic feasibility of the *FluidCELL* system.

It is well known that the energy market (both natural gas and electricity) can be different from country to country, depending on the primary energy used to produce these commodities, which is strictly related to the context and resources of the location. To better understand the impact of micro cogeneration, it is a good practice to evaluate the specific situation of the individual country in which the interventions are performed.

3.1. Variables and countries

First are presented the main variables that must be considered, and which change among countries:

- Standards and regulations;
- Government grants;
- Cost of bioethanol;
- Cost of electricity;
- Cost of natural gas;
- Dwellings average consumption of electric energy;
- Dwellings average consumption of hot water;
- Period of heating and dwellings average consumption.

Investment and O&M costs are considered independent on the country studied.

Standards and regulations are much different among countries but all of them come from European Directives. Thus, it was decided to only consider European Standards and not consider those of the individual countries, assuming that with time, all member states will implement and comply with the various European Directives regarding micro cogeneration. Reference has been made to the CHP Directive 2004/08/EC (On the promotion of cogeneration based on useful heat demand in the internal energy market)[3] and its correlated documents (2007/74/EC and 2008/952/EC).

Also, government grants differ among countries. For example, the Italian grant (*ESC Energy Saving Certificate*)[4] corresponds to an average remuneration of 120 €/toe (0.022 €/kWh)[5] for electricity produced by a high energy efficiency system. In Netherlands the grant is the price difference between fossil and renewable power production, up to a max price of 0.15 €/kWh. Switzerland gives grants to programs that are most efficient and are based on the kWh_e consumption avoided[6]. Instead, Portugal government grants are fiscal benefits on Individual Income Tax for high energy class level homes, which are an indirect subsidy for high efficiency systems installed.

Thus, for the analysis of this deliverable has been assumed the Italian grant for all countries. This is due to lack of information on the other countries government grants and the difficulty to apply their own grants to Portugal and Switzerland. The choice of the Italian grant instead of the Dutch one is due to the

[3] http://europa.eu/legislation_summaries/energy/energy_efficiency/l27021_en.htm
[4] http://www.mercatoelettrico.org/it/
[5] Delibera EEN 3/08 del 20-03-2008 (GU n. 100 del 29.4.08-SOn.107)
[6] http://www.bfe.admin.ch/prokilowatt/index.html?lang=it

lowest impact that it should have in the economic analysis. Energy costs and consumptions of sample countries across Europe, will be presented in next paragraph, while for the bioethanol cost has been assumed the same price for all countries because its market isn't enough widespread like that of gas and electricity. The price assumed is the quoted price which at the beginning of June (2014) was 2.15 $/gal[7] (0.076 €/kWh).

3.2. European countries cross section

The European countries taken into account as sample are the participants to this project, representing different Europe areas (thus France, Italy, Netherlands, Portugal, Spain, Switzerland), plus other countries like Austria, Germany, Greece, Ireland, Sweden, considered interesting for the electricity to natural gas price ratio (Table 3). This index identifies countries where systems like the one studied in this project could be much profitable due to high electricity price and low natural gas price. Some of these countries are also interesting for the dwelling average energy consumption rate (Table 4), which is very high; thus, economic saving could be desirable.

Table 3 and Table 4 summarize data on energy cost and consumption, useful for an economic evaluation, obtained from European websites.

Table 3. Natural gas and electricity prices in [€/kWh][8-9]

Country	Natural Gas	Electricity	EE/ NG Ratio
AUSTRIA	0,1224	0,2046	1,672
FRANCE	0,0729	0,1589	2,180
GERMANY	0,0689	0,2921	4,239
GREECE	0,0888	0,1697	1,911
IRELAND	0,0722	0,2405	3,331
ITALY	0,0945	0,2323	2,458
NETHERLANDS	0,0846	0,1915	2,264
PORTUGAL	0,0933	0,2131	2,284
SPAIN	0,0892	0,2075	2,326
SWEDEN	0,0754	0,2018	2,676
SWITZERLAND	0,0970[10]	0,1752[11]	1,806

[7] http://www.nasdaq.com/markets/ethanol.aspx?timeframe=7d
[8] http://epp.eurostat.ec.europa.eu/cache/ITY_PUBLIC/8-21052014-AP/EN/8-21052014-AP-EN.PDF
[9] Prices include all taxes and levies
[10] http://www.gas-naturale.ch/fileadmin/customer/erdgasch/Data/Erdgas/Preise/confronto_costi_i.pdf
[11] http://www.elcom.admin.ch/themen/00002/00097/index.html?lang=it

Table 4. Unit consumption per dwelling by end uses [kWh/year][12]

Country	Electricity	Space heating	Water heating
AUSTRIA	2674,9	15467,9	2326,0
FRANCE	2793,2	12432,1	1841,1
GERMANY	2209,7	13723,4	2209,7
GREECE	3023,8	10815,9	1046,7
IRELAND	2575,6	15834,8	3666,2
ITALY	2184,6	9379,8	1169,1
NETHERLANDS	2752,2	11687,7	2460,1
PORTUGAL[13]	1996,0	1980,0	1986,0
SPAIN	2231,9	4793,1	2911,8
SWEDEN	3721,6	12676,7	1977,1
SWITZERLAND[14,15,16]	3274,5	13193,7	2680,9

It must be underlined that the analysis will be performed on average data values concerning energy consumption; indeed, big differences within the same country on the use of energy, both heat and electricity, may be significant (for example the difference in Italy between Sicily and Alpine places is huge when considering heating). Differences also exist about number of family members, energy class, dwellings size, etc. Therefore, it is important to keep in mind that the data reported in this deliverable are only semi-quantitative and every application must be analysed individually in order to obtain the maximum benefit in consumption reduction terms (the so called *ESCO,* energy management companies, can find the ad-hoc configuration for each situation).

[12] Calculated from Table 18 in Annex II
[13] http://www.eci.ox.ac.uk/research/energy/downloads/countrypictures/cp_portugal.pdf
[14] http://www.bfs.admin.ch/bfs/portal/fr/index/themen/01/04/blank/key/haushaltstypen.html
[15] http://www.bfs.admin.ch/bfs/portal/fr/index/themen/08/02/blank/key/ein-_und_ausfuhr.html
[16] http://declics.romande-energie.ch/articles/quelles-sont-les-sources-principales-de-consommation-dun-m%C3%A9nage-suisse

4. Preliminary analysis

A preliminary analysis will be carried out in order to evaluate the economic feasibility of each system discussed in paragraph 2.1. To do this evaluation an ideal case must be considered. This consists to reduce some variables, in particular the ones linked to energy consumption of each country (which will be treated later). Thus, it will be assumed that all thermal and electrical power produced by each system is totally consumed and it is the only energy required from consumers, without a boiler or grid supply. This ideal case allows to eliminate costs about boiler back-up and electricity from the grid, reducing pay-back time and enhancing profit.

For all systems a service lifetime of 10 years and a reasonable availability of 7500 hours per year is assumed.

Concerning natural gas and electricity prices, no assumption will be done.

4.1 Systems available

Table 5 shows systems taken into account with their electrical and thermal performances, electrical and global efficiencies, from Table 1 and Table 2; while in Table 6 are summarized investment and O&M costs (from Table 1, Table 2 and Annex III Table 19), and electrical and thermal energy produced by each system in a year, according to the above hypothesis.

Table 5. Systems powers & efficiencies.

System	EE Power (Size)	EE Efficiency	Tot. Efficiency	TH Power
	[kWe]	[%]	[%]	[kWt]
ICE 1kW	1	30	85	1,8
ICE 20kW	20	30	85	36,7
Stirling	1	20	85	3,3
µTG	30	33	85	47,3
FC	1	40	90	1,3
FluidCELL	5	40	90	6,25

Table 6. System costs & yearly energy produced.

System	Investment Cost	O&M Cost	Electricity	Thermal energy
	[€/kWe]	[€/year]	[kWh_e/year]	[kWh_t/year]
ICE 1kW	6000	85,8	7500	13750
ICE 20kW	1600	1716,4	150000	275000
Stirling	10000	114,0	7500	24375
µTG	1700	3103,9	225000	354545
FC	20000	117,4	7500	9375
FluidCELL	5000	587,0	37500	46875

The investment cost used for the *FluidCELL* unit is the target of this project which would be achieved in mass production. While, for *Stirling* and *Fuel Cell* systems are used the actual investment cost, referred to a production of only few units. It is clear that for mass production these systems will be cheaper. However, it is not possible to forecast the future cost, and for this reason this analysis will be performed with the values in Table 6.

4.2. Ideal case analysis

The economic analysis consists in the evaluation of some economic parameters like *pay-back time* (PBT), *Net Present Value* (NPV) and *Internal Rate of Return* (IRR): an investment results interesting if NPV>0, IRR is highest, and PBT is lowest.

The ideal case will be discussed, has incomes associated to the costs of natural gas and electricity avoided for separate generation (average boiler efficiency considered is 90% for all country), avoided cost for boiler maintenance which, for wall-hung boilers, is about 100 €/years, and the government grants. Costs are associated to the investment, natural gas consumed by CHP (bioethanol in the case of *FluidCELL* system) and its maintenance.

For the evaluation of the economic indexes the cash flow is discounted with an inflation long term forecast rate of 2%17 and a nominal real risk-free rate of 4.5%.

Table 7, Table 8 and Table 9 summarize the three economic parameters for each CHP system and for each sample country.

Table 7. Systems NPV for sample country.

Country	ICE 1kW	ICE 20kW	ST	TG	FC	FluidCell
AUSTRIA	-2193	34781	-7359	48052	-16012	31446
FRANCE	-1089	56869	-5981	79688	-15456	-2777
GERMANY	7187	222387	2317	327844	-7224	35391
GREECE	-1676	45134	-6656	62566	-15867	7056
IRELAND	3845	155553	-1043	227694	-10530	21332
ITALY	1626	111170	-3386	161793	-12502	28142
NETHERLANDS	-1388	50880	-6345	71059	-15626	5120
PORTUGAL	571	90066	-4434	130101	-13570	21902
SPAIN	554	89725	-4428	129465	-13633	18525
SWEDEN	1283	104304	-3623	150916	-13057	11089
SWITZERLAND	-1983	38999	-7008	53611	-16083	12106

Table 8. Systems IRR for sample country.

Country	ICE 1kW	ICE 20kW	ST	TG	FC	FluidCell
AUSTRIA	-8%	17%	-18%	15%	-21%	20%
FRANCE	-4%	27%	-14%	24%	-20%	-2%
GERMANY	19%	92%	4%	86%	-8%	22%
GREECE	-6%	22%	-16%	19%	-21%	5%
IRELAND	11%	66%	-2%	62%	-12%	14%
ITALY	5%	49%	-7%	45%	-15%	18%
NETHERLANDS	-5%	25%	-15%	22%	-20%	4%
PORTUGAL	2%	41%	-10%	37%	-16%	14%
SPAIN	2%	41%	-9%	37%	-16%	12%
SWEDEN	4%	46%	-8%	43%	-15%	8%
SWITZERLAND	-7%	19%	-17%	17%	-21%	8%

[17] http://www.ecb.europa.eu/pub/pdf/mobu/mb201405en.pdf

Table 9. Systems PBT for sample country.

Country	ICE 1kW	ICE 20kW	ST	TG	FC	FluidCell
AUSTRIA	>10	4	>10	4	>10	3
FRANCE	>10	3	>10	3	>10	>10
GERMANY	3	1	7	1	>10	3
GREECE	>10	3	>10	3	>10	7
IRELAND	5	1	>10	1	>10	4
ITALY	7	1	>10	1	>10	4
NETHERLANDS	>10	3	>10	3	>10	7
PORTUGAL	8	2	>10	2	>10	4
SPAIN	8	2	>10	2	>10	5
SWEDEN	7	1	>10	2	>10	6
SWITZERLAND	>10	3	>10	4	>10	6

The data reported in the tables show that, on an economic point of view, *Stirling* engines and *1 kW Fuel CELL* systems are not suitable in almost all countries due to highest investment cost (yearly cash flow is always positive). Furthermore, in countries like France with a low energy costs (both natural gas and electricity) small size micro-CHPs seem to be not competitive, while countries like Germany and Ireland with high electricity to natural gas price ratio, have an acceptable PBT also for small sizes CHP systems, due to high electricity cost and low natural gas cost.

In the next step we consider the systems which are economic feasible from this ideal evaluation, and analyse them in the real case, introducing dwellings consumption. Thus, *Stirling Engine* and *FC* system will be neglected.

5. *FluidCELL* integration in European countries

Only the case of the *FluidCELL* system is going to be studied. The evaluation that will be performed in this paragraph is similar to the previous; moreover, in this case dwellings energy consumption per year will be taken into account.

Natural gas and maintenance costs of back-up boiler must be considered in cash flow. Also, the cost of electricity pick up from the grid or the income related to the trade of exceeding electricity produced will be taken into account (price considered for all countries is 39.2 €/MWh[18]: unfortunately this is due to lack of information on the other countries).

Also, in this case, it is assumed a service lifetime of 10 years and an availability of 7500 hours per year. Furthermore, it was supposed that the system operates for 3924 hours in winter season and 3576 hours in summer season. Remembering that the dwellings energy consumption data are an average value, a simplification on system partial load is introduced: two periods of regulation, winter load and summer load. Thus, it is supposed that all the season the system has the same (average) load in order to follow household average thermal load.

5.1. One dwelling and 5 kW *FluidCELL* system

As first case, is considered one dwelling and *FluidCELL* system with the project target size (5kW). Results from this case are common to all sample countries: PBT>10, and NPV<0; a relevant aspect is the negative yearly cash flow, also varying both winter and summer load till the minimum (25%). Indeed, thermal and electrical energy produced by the system in a year always exceed the dwelling energy demand and if on one side electricity can be sell to the grid (even if at low cost) on the other side thermal energy must be transferred to the environment as a waste product. To satisfy the dwelling average energy demand it is possible to work at full load, reducing the operation hours, but if on one side it produces a useful effect making positive the yearly cash flow, on the other side PBT becomes huge.

An interesting case could be a *FluidCELL* system with a smallest size for only one dwelling, like that of the system summarized in Table 2.

5.2. One dwelling and 0.7 kW *FluidCELL* system

The second case considered is than one dwelling with a 0.7 kW size *FluidCELL* system. Even in this case, as in the previous paragraph, results a PBT>10 and a NPV<0 for all countries, with 100% load both in winter and in summer. Also, yearly cash flow is negative.

To have an improvement in economic indexes it is possible to act on system load. The parameter chosen to be maximized is NPV, varying both summer and winter load. The result obtained is an operation at minimum load in summer for all countries, and also a partial average load in winter (Annex IV, Table 20), but it is not sufficient because NPV and PBT are still negative. Only the yearly cash flow is become positive. The operation hours reduction, makes the same consideration of previous paragraph. System size is than still large to supply a single average dwelling energy demand with a reasonable economic upturn. At this point it is necessary to find a new solution to have a reasonable PBT.

[18] http://www.gse.it/it/Ritiro%20e%20scambio/Ritiro%20dedicato/Pages/default.aspx#tabella-prezzi

5.3. Several dwelling and 5 kW *FluidCELL* system

As seen above, cogeneration systems have maximum PBT when all electrical and heat energy produced is used. Furthermore, as efficiency is normally higher when working at full capacity rather than with reduced loads, CHP full power is always considered both in winter and in summer.

If the heat and electricity produced are used completely when working at full capacity, it must be considered that installations cover the energy demand of different dwellings, in which a back-up boiler is surely required.

Thus, this last case takes into account a 5 kW size *FluidCELL* system which supplies energy for several dwellings. The analysis now consists to find the minimum dwellings number which make interesting the investment, minimizing PBT.

Table 10 summarizes the results obtained and Figure 1. pinpoints PBT across Europe.

Table 10. FluidCELL system economic indexes and saving per year

Country	Dwellings	PBT	NPV [€]	IRR	Saving[€]
AUSTRIA	14	4	20272	13%	6149
FRANCE	26	>10	-5331	-4%	2794
GERMANY	18	3	29216	19%	7321
GREECE	40	8	2281	2%	3791
IRELAND	14	5	15526	11%	5527
ITALY	17	5	13408	9%	5249
NETHERLANDS	19	8	2181	2%	3778
PORTUGAL	19	5	14838	10%	5437
SPAIN	17	5	15054	10%	5465
SWEDEN	19	7	5100	4%	4161
SWITZERLAND	17	6	8401	6%	4593

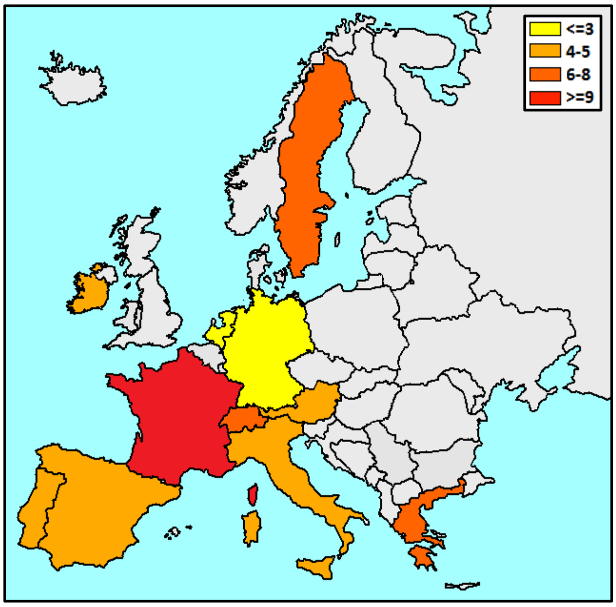

Figure 1. *FluidCELL* system PBT across Europe.

For the France case is shown the dwellings number which consume all *FluidCELL* system energy produced, but as it can possible to see PBT>10 and also the remaining economic indexes are negative; it seems that with low energy price this system is not competitive in the market.

About other countries, for most of them results a system economic feasibility due to the reasonable PBT obtained (around 5 years or less), lower compared with system lifetime.

Table 10 shows also yearly savings for each country: they are relevant for some countries like Austria and Germany. In France, where PBT>10, it is possible to save more than 2500 €/year, even if it is not sufficient to recoup the investment in a few years.

It has also been seen that buildings with more than 11-19 average dwellings (depending on country) have the best size for the introduction of *FluidCELL* system. This case proposed can cover the yearly electricity demand using also all heat recovered. Obviously, the back-up boiler is required especially for winter heating demand.

It must be remarked that *FluidCELL* system investment cost considered is 5000 €/kWh which is the project target cost for large production volumes.

If on one side this case could seem unfeasible for private citizen, due to high financial risk, management of several dwellings involved, low production volume etc., on the other side it become very interesting with the support of an ESCO which take on all risks linked to the manufacture and management of the systems and the lack achievement of performance targets, providing a favourable contract to consumers. Indeed, ESCOs can operate in energy market (as a trader) more easily than a private citizen and also can easily attained loan.

With its several system management (which have, or could have), an ESCO is able to allocate all thermal and electrical power produced by the system to several consumers (dwellings). From the economic analysis, the optimization in energy production and consumption, satisfying all dwellings summer heat demand (which is the constraining parameter) and operating the system at full load, bring to the same results of Table 10. Moreover, the ESCO must provide for the electricity and winter thermal power to the dwelling residual demand.

6. Available systems integration in European countries

Considering the integration of the others CHP systems in dwellings, the evaluation consists only to find the dwellings number (to compare with *FluidCELL* system) which make interesting the investment, because systems that we are going to consider have the smallest size available in the market. "Minimum PBT than" is the parameter taken into account for the evaluation.

Table 11, Table 12 and Table 13 summarize results obtained for each system and country, underlining also the yearly money saved.

Table 11. 1kW ICE system economic parameters and saving per year

Country	Dwellings	PBT	NPV [€]	IRR	Saving[€]
AUSTRIA	6	>10	-3900	-15%	327
FRANCE	8	>10	-2844	-10%	466
GERMANY	7	4	5076	14%	1503
GREECE	14	>10	-3405	-13%	392
IRELAND	4	7	1878	6%	1084
ITALY	12	>10	-245	-1%	806
NETHERLANDS	6	>10	3130	-12%	428
PORTUGAL	7	>10	-1255	-4%	674
SPAIN	5	>10	-1271,5	-4%	671,5
SWEDEN	7	>10	-574	-2%	763
SWITZERLAND	6	>10	-3699	-14%	353

Table 12. 20kW ICE system economic parameters and saving per year

Country	Dwellings	PBT	NPV [€]	IRR	Saving[€]
AUSTRIA	114	4	25422	13%	7801
FRANCE	124	3	37661	19%	9406
GERMANY	53	1	102387	46%	17888
GREECE	256	3	37667	19%	9407
IRELAND	53	1	101584	45%	17783
ITALY	135	2	58627	28%	12153
NETHERLANDS	102	3	37464	19%	9380
PORTUGAL	106	1	58872	28%	12186
SPAIN	71	2	58253	28%	12104
SWEDEN	76	2	58797	28%	12176
SWITZERLAND	94	4	25308	13%	7787

Table 13. µGT system economic parameters and saving per year

Country	Dwellings	PBT	NPV [€]	IRR	Saving[€]
AUSTRIA	151	4	40474	13%	12429
FRANCE	169	3	59600	19%	14935
GERMANY	79	1	162420	45%	28410
GREECE	295	4	39576	13%	12311
IRELAND	79	1	162010,1	45%	28356,4
ITALY	174	2	93227,8	28%	19342,2
NETHERLANDS	139	3	59828	19%	14965
PORTUGAL	142	2	93275	28%	19348
SPAIN	100	2	94857	28%	19556
SWEDEN	101	2	93350	28%	19358
SWITZERLAND	125	4	39816	13%	12342

From above tables it is possible to understand how *1kW ICE* is not feasible in a real case even if it supplies a few dwellings, with a yearly saving of some Euros; except for Germany and Ireland. Indeed, these countries have energy cost that make feasible also systems with high investment costs.

The other two systems are very interesting on an economic point of view, with their low PBT, lower than *FluidCELL* system, and their significant yearly savings. But the problem is in the dwellings number which they have to supply to obtain this result: buildings with several tens dwellings (over hundred in some cases) are necessary.

7. System components & constraints

To better understand the potential success of the m-CHP system being studied in this project, after the economic assessment discussed previously, in this paragraph are analysed the main system components in order to evaluate their constraint and investigate what the system should have in order to be attractive in the market.

The main system components identified can be summarized as:

- Fuel;
- Fuel processor;
- Fuel cells;
- Inverter;
- BOP;
- Controller.

In next paragraphs each element will be analyzed in more detail, and then the final feature the FluidCell system must have will be discussed.

7.1. Fuel

Bio-ethanol is already a major fuel in Brazil and in the USA and is making its way to Europe. Its current price is significantly lower than that of gasoline on an equivalent heating value. It is a very attractive fuel since it is clean, with negligible sulfur or metal contents, and it is CO_2 neutral because it is produced by biomass. Besides, it has a relatively high hydrogen content, it is non-toxic and easy to carry and store. Another useful aspect of bio-ethanol for steam reformer is the intrinsic water contents in ethanol blend. But on the other hand, there are some compounds which could poison or create problems to the reformer catalyst (including carbon formation). Indeed, bio-ethanol blend includes one-, two- and three-carbon unbranched alcohols: methanol, ethanol and propanol, four- and five-carbon branched alcohols: isobutyl alcohol and the two isomers of pentanol (also known as amyl alcohol) 2-methyl 1-butanol (active amyl alcohol) and 3-methyl, 1-butanol (isoamyl alcohol). Furthermore, ethyl acetate and, the di-ether, 1,1-diethoxyethane could be present as well.

7.2. Fuel Processor

Fuel processor is the core of fuel cell-based CHP systems since it supplies syngas to stacks.

Development is in progress for systems that reform natural gas, gasoline, diesel, and renewable fuels. Companies like *Precision Combustion Inc., Innovatek*, *WS-Reformer-GmbH* provide prototypes in the small size range that are of interest for the project, but they are not yet plug & play, and an operator presence is still necessary. No price information is available, nevertheless it is well known that they are very expensive. A reasonable price is thousands €/m^3 of hydrogen supplied, due to the small number of fuel processors produced. So, this technology is not yet commercial at all and only research laboratories systems are available.

The fuel processor must be able to supply pure hydrogen or the best suitable syngas to feed PEM stacks. Indeed, the fuel cell behavior is influenced by the CO content in the syngas which can't exceed 1% for HT-PEM and 20 ppm for LT-PEM. Thus, attention must be paid to design and realize the fuel processor keeping in mind that the aim is a commercial product in a competitive market. Each component and the final assembly shouldn't be produced in a hand-built manner to avoid quality instability, linked to the operator, and a cost increase.

Another aspect to consider are noble metals present in the fuel processor as catalyst that are much expensive (for example today palladium costs around 18 €/g). Indeed, their availability as row material is very limited. So, a great effort must be put into the determination of the necessary catalyst load to achieve the hydrogen quantity demanded and its purity and further attention could be paid to recover catalyst once the fuel processor has reached the end of its life.

Fuel processors for reforming should tolerate a small content of impurities that may be encountered such as methanol, gasoline (denaturant), butanone, propanol, methyl butanol, thiophene.

7.3. Fuel Cells

A fuel cell-based CHP system needs stacks that are stable, reliable and cost competitive in the market. Nowadays, this technology is making their way for a commercial product mature, resistant and at feasible costs. Several reports on fuel cell market edited last year and referred to 2012 reveal a growing request on this technology and a continuous price decrease. Fuel cell companies are continuously trying to develop technologies to provide a more cost-effective reduction to commercialize competitive products in market.

The most commercial technologies available within fuel cells technologies are LT-PEMs, HT-PEMs and SOFC; the last two are still a step behind the other. So, the project will use the LT-PEM which is the most mature technology available at acceptable prices, even if there are several uncertainties about stability and duration.

Using LT-PEM, poses stringent requirements to the fuel processor because this kind of cells need pure hydrogen or, according to stacks manufacturers, CO content in syngas up to 20 ppm, even if experimental data have shown that CO values less than 5 ppm give the best electrical performance.
So, a close restriction on syngas composition is highlighted.

7.4. Power conditioning

Power conditioning is one of the system component which is commercial since some time ago, with mainly application in solar solutions. So, the inverter is a known technology available on a large scale and on a wide size range, easily adapted to fuel cell technology. No relevant problem about this system was highlighted.

7.5. Balance of Plant

The so-called BoP of CHP systems are all the remaining components like pumps, blowers, heat injectors, demineralizer and analyzers. All these components must be selected from commercial product for costs and reliability reasons. Indeed, elements developed ad hoc are much costly and less reliable than commercial one. Also, quality and reproducibility are essential for a mass-produced.

It is well known that failure of one BoP component causes the whole system malfunction, especially when a water management element (like pumps or valves) failure occurs. Experience proves that statistically the main system problems come just from these components. So, attention must be paid to an ordinary maintenance of each element to avoid problems in normal operation.

7.6. Controller

The development of a plug & play CHP system is the industrial final aim. So, the controller has a key role in the management of the system and seems to be one of the most critical components. Several variables must be acquired and monitored to control the correct system behavior.

7.7 FluidCELL final feature

The success of the system being developed within the project is close dependent to its duration and maintenance as it was highlighted in above paragraphs. It was also indicated that the use of standard instruments for the production of this CHP system is necessary to overcome these issues.

In the light of the economic considerations mentioned above, the European Standards and taking into account information emerging last paragraphs, some features that the CHP under development in the *FluidCELL* project must have, in order to be industrially attractive, are summarized in Table 14.

Table 14. FluidCELL CHP target.

Production costs [€/kW$_e$]	5000
Electrical efficiency [%]	40
Total efficiency [%]	90
Lifetime (at least) [year]	10
Availability [hours/year]	7500
Maintenance per year	1
starting time hours	3
Regulation [%]	25 - 100
CO content	< 20 ppm
Catalyst lifetime	5 years
Membrane lifetime	5 years

Concerning catalyst and membrane made of noble metal, actually a lifetime of about 3 years (or slightly more) is considered a reasonable value, due to the formation of several undesirable products from ethanol steam reformer reaction (carbon soot) and due to the presence of complex or poison compound pointed out in paragraph 7.1, even if their contents are limited (Annex V, Table 21). Nevertheless, a lifetime target of 5 years could be reached, like catalysts commercially available for methane steam reforming.

Besides the lifetime, the possibility to recover the catalysts and the membrane during the system lifetime and recycling them at the end of system life, are important. Indeed, considering the current palladium quoted price of around 18 €/g it is fundamental to recycle it. Furthermore, it is advisable to use materials for all the system which must be recyclable (as much as possible) and environmental friendly.

Also Fuel Cell stacks must have a lifetime as long as possible (at least 40000 hours are recommended) and must be stable, reliable and cost competitive as highlighted in paragraph 7.3.

It must be underlined that the FluidCELL system has already issues that make it more industrially attractive, such as limited maintenance, reforming of bioethanol at temperature around 500 °C (use of less expensive materials and long-term durability are the major consequences), compactness of the system (reduction of BoP overall cost) and high electrical and overall efficiency.

Also, the supply of bioethanol with all its water content in the blend, allows to avoid costs linked to water separation; to be noted that this process is very expensive, thus the savings are significant.

Furthermore, the possibility to have off-grid and remote FluidCell system installations is given by the same bioethanol, due to its non–toxicity and because it is easy to store and transport.

8. Conclusions

- Both higher electric and overall efficiency target, makes *FluidCELL* system more attractive than other systems, for an energy, economic and environmental saving.
- The use of bioethanol makes the system suitable for all kind of application, both on-grid and off-grid.
- This system cannot supply only one average dwelling even reducing its size (it's hold good for all countries).
- It becomes competitive if it can supply several dwellings, also when compared with different systems (as well as when compared with other fuel cell systems).
- System is not competitive in the market if the natural gas and electricity costs are low, but it becomes very suitable if the electricity to natural gas price ratio is highest.
- Around 5 years PBT is however still a long time if the estimated lifetime is 10 years. In order to start large sales volumes, it is necessary to drop below 3 years. This means a reduction in specific price.
- Until production costs cannot be reduced, it is indispensable to make use of government grants.
- Good lifetime and good availability are essential.
- The recycling of precious materials and the use of standard components seems to be a way to reduce production costs.

9. ANNEXES

Annex I

I.I Internal Combustion Engines

Internal combustion engines were mainly developed for automobiles, thanks the capability to immediately vary the power output and their compactness. The same characteristics make them suitable for small portable generators. Generators are useful to provide energy to isolated utilities or in case of blackout, for instance when natural disasters like tornados or heart quakes damage the electrical grid.

Ecowill[19]
The micro-CHP appliance for single home use *Ecowill* is in the Japanese market since 2003. The generator (MCHP1.0K2) is developed by *Honda* and the heating unit by *Osaka Gas*, *Tokyo Gas*, *Toho Gas*, *Saibu Gas* and *Noritz*. The electrical output is 1kW, the thermal output 2.5kW, to add 42kW from the auxiliary boiler.

The core is the *Honda* engine *EXlink* (Extended Expansion Linkage Engine)[20], a single-cylinder, water cooled, four strokes engine, fed by natural gas or LPG. A calibrated system to keep the air/fuel ratio at the stoichiometric value is present to control the combustion process. Engine is characterized by an exhaust expansion stroke longer than air compression stroke. The exhaust displacement is 163cm^3 and air intake volume is 110cm^3, thus the ratio 1.4 of expansion over compression allows maximizing the work extracted from the heat of combustion. The adoption of *EXlink* engine improved the generation efficiency from 22.5% to 26.3%. The mechanical power is transformed into AC electric power by the alternator, then conditioned by a proprietary inverter to match the electrical grid. The integration of the 3-way catalyst, to control the emissions, in the exhaust heat exchanger and a new layout of the cooling system rose the thermal efficiency up to 65.7%, being the total efficiency 92% (LHV). *Ecowill* is usually provided with a hot water tank of about 90l.

The ***Ecowill Plus*** (2012)[21] has an autonomous operation function that enables system use in a power outage or other emergencies: it is equipped with a recoil starter that enables starting without a battery or other auxiliary power.

Ecopower[22]
Ecopower is the product commercialized in Europe by *Power Plus Technologies*, a wholly-owned subsidiary of *Vaillant*. It relies on one piston, 4 strokes engine (272 cm^3) fed by natural gas or LPG. The speed range is 1200-3600rpm and consequently output is 1.3-4.7kW of electricity, and 4-12.5kW of heat. Thanks to the variable adaptation of the engine speed, the system always operates with optimized efficiency for a very high number of hours. The micro-CHP unit is orientated to operate in "heat led" mode, nevertheless an auxiliary boiler is required to cover the peak heat demand. The exceeding electrical power is phased into the grid as 3-phase, 400V, 50Hz AC current, thus the grid connection is required.

Ecopower micro-cogenerator can run also in island operation and as emergency power supplier for 1-phase, 230V, 50Hz systems if coupled with the modular *Ecoisland* battery-powered inverter.

[19] [Online]. Available: http://www.igu.org/IGU%20Events/igrc/igrc2011/igrc-2011-proceedings-and-presentations/poster-papers-session-3/P3-56_Hiroki%20Tanaka.pdf/.
[20] [Online]. Available: http://world.honda.com/powerproducts-technology/exlink/.
[21] [Online]. Available: https://www.hondarandd.jp/point.php?pid=969&lang=en.
[22] [Online]. Available: http://www.vaillant.de/ecopower/.

The system needs maintenance stops every 4000 operation hours or once per year and it is designed for a lifetime of about 40000 hours.

The ***Ecopower 1.0***, introduced in Germany in 2011, uses the *MCHP1.0K2* as the core unit (*Honda EXlink* engine and heat recovery system previously described for the *Ecowill* cogenerator) coupled with a heating/hot water unit made by *Vaillant.*

Freewatt Plus[23]

Another system powered by the *Honda EXlink* engine is the *Freewatt Plus* cogenerator in the USA. The main difference is the electric output, set at 1.2kW. There are two versions, different for the engine cooling system, and thus the form of thermal output: air cooled model for room heating only and liquid cooled for hot water.

SenerTec

German company *SenerTec* was founded in 1996 ad hoc to produce and commercialize micro-CHP systems based on *Fichtel & Sachs* engine: one piston, four strokes, 580cm[3]. *SenerTec* offers a wide choice of products under the *Dachs* series. The main feature of the series is the flexibility on the fuel: the most common is natural gas (G model), but it can operate with propane, LPG (F model), diesel (HR model), heating oil, biodiesel, diesel (HR model) and rapeseed oil (RS model) and thus the engines have slightly different design and equipment, like filters and muffler for emissions containment.

Depending on the model, the electrical power is about 5kW, while the thermal one can be as high as 15kW when the condensing heat exchanger is installed to cool down the exhausts to 55°C. The electric efficiency is higher than 26% (up to 30%) and the total efficiency can reach 100% (LHV reference) if condensing heat exchanger is present. The system was born as support to a conventional boiler, in “heat led” operation and in parallel to the electric grid (European standards), but with minor modifications, it can supply power to isolated loads.

The G series uses lean combustion and 3-way catalyst is not required if compared with the *Honda* stoichiometric engine.

Dachs RS[24]

The *Dachs RS* is the first rapeseed oil m-CHP unit produced in serial production. The reference is the HR diesel engine, with injection system adapted for the use of pure rapeseed oil. The fuel must be of high quality, low on phosphorous, calcium and magnesium content, to reduce the amount of deposits in injection nozzle, piston and exhaust valve. *SenerTec* has established its own specification, failing a standard for this fuel more detailed than the German V DIN 51605[25].

The fuel strongly influences the life of the engine, but with a regular maintenance (after 3500 hours of service for G units and 2700 hours for HR units) it can be as long as 80000 hours.

Yanmar[26]

Yanmar produces the CP W series (5, 10, 25kW electric)[27], commercialized in UK by *Ener-G*. These m-CHP units make use of the advanced Miller Cycle. The lean-burn system optimizes ignition timing and matches the excess intake air; turning out in low-NOX emissions and low-fuel consumption. The engine offers a maintenance interval of 10000 hours, which is one of the industry's longest for a cogeneration reciprocating engine.

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[23] [Online]. Available: http://www.google.it/url?sa=t&rct=j&q=&esrc=s&source=web&cd=4&ved=0CEsQFjAD&url=http%3A%2F%2Fwww.propanecouncil.org%2FWorkArea%2FDownloadAsset.aspx%3Fid%3D3366&ei=QfhrU7qjD4GqyAT7z4DABQ&usg=AFQjCNHyjT0xw3UVMlSPPFtdbgVUv_emfQ&sig2=vC91es45X1pZgNvKtFClaQ&bv.
[24] [Online]. Available: http://www.buildup.eu/cases/19159.
[25] [Online]. Available: http://www.beuth.de/en/standard/din-51605/133509390?SearchID=671663655.
[26] [Online]. Available: http://www.yanmarenergysystems.eu/Products/Micro-Cogeneration/.
[27] [Online]. Available: http://yanmar.com/product/energy/catalog/pdf/microCogenerationPackage/cp.pdf.

***ZuhauseKraftwerk*[28]**

ZuhauseKraftwerk system is based on *Volkswagen 2.0l CNG-EcoFuel*, which is derived from *Caddy* and *Touran*. It supplies 20kW electric and 34kW thermal power to satisfy heat demand of a single large house without a backup boiler, a block of flats or small businesses, and the exceeding electricity phased into the grid, to realize a sort of "large virtual power plant". The careful design guarantees a service period of 6000 hours. It is equipped with an asynchronous generator.

The same *Volkswagen* engine is mounted on the ***Dachs Pro 20*** of *SenerTec* commercialized also by *BDR Thermea*[29].

Tandem T20

Tandem T20 by Asjagen[30] is the evolution of the progenitor *Totem* manufactured in the 70s by *FIAT*. Its nameplate data are 19.9kW electric (3-phase, 400V, 50Hz), 47.5kW thermal output, which correspond 28.1% electrical efficiency and 94.8% global efficiency.

Other companies offering m-CHP devices based on ICEs, with size still suitable for home installations are, for instance, *Proenvis* (*Prio 5.2*: 2kW electric; Prio 1.4: 4kW electic), *Kirsch* (*Nano*: 1.9kW; *Micro*: 4kW), *Viessman* (*Vitoblock EM5/13*: 5kW), *RMB Energie* (*Neotower 5.0*: 5kW), *Denso* and *Aisin Seiki* (6kW), *Ecopower* (*XRGI*:6-20kW).

The same companies, and many others, offer a portfolio of products with increasing power, also much beyond 50kW, which is the threshold for micro-CHP.

Table 15. ICEs comparison

Model	Fuel	Electrical power [kW]	Thermal power [kW]	Electrical efficiency	Total efficiency	Service interval / lifetime [h]
Ecowill	NG, LPG	1	2.5	26.3	92	6000 / na
Ecopower	NG, LPG	1.3-4.7	4-12.5	-	>90	4000 / 40000
Freewatt	LPG	1.2	-	-	93	
Yanmar CP 5	NG, LPG	5	-	-		10000 / na
Dachs G	NG	5	14.6	26	100	3500 / 80000
Dachs RS	Rapeseed oil	5	10.3	29	89	2700 / 80000
Zuhause Kraftwerk	NG	20	34			
Tandem T20	NG	19.9	47.5	28.1	94.8	

I.II Stirling Engines

Long life, long service intervals, and external combustion, that means low noise, low emissions and fuel flexibility, make Stirling engines good candidates for domestic CHP. Despite their good theoretical characteristics, only a limited number of cogenerators exists.
The engines can be classified as:

Kinematic Stirling Engines, when reciprocal piston motion is converted in rotational motion by some mechanism to the alternator, and the displacer too is actuated by mechanical linkage;

[28] [Online]. Available: http://www.lichtblick.de/microsites/zhkw/index_en.php.
[29] [Online]. Available: http://www.bdrthermea.com/dachs-addition-at-ISH-2013/.
[30] [Online]. Available: http://www.asjagen.com/.

LFPSE (Linear Free Piston Stirling Engine), without rotating parts, linear alternator (usually permanent magnet), and the displacer actuated by pressure variation of the fluid.

Another classification in alpha-, beta-, and gamma-type can be made on the base of relative motion of displacer and main piston. For alpha-type, if useful work is produced by symmetrical pistons they are double-effect, otherwise single-effect.

WhisperGen

WhisperGen was the first Stirling engine micro-CHP system to be commercially available (mass production from 2009) in many mid-Europe Countries thanks to a capillary network distribution.

It is a 4-cylinders double-acting, alpha-type engine and belongs to the kinematic Stirling engine category. The technical novelty is the mechanism, named “wobble yoke”, to transform the alternating motion of the pistons into rotation, in order to connect easily motor and conventional alternator. The working fluid is nitrogen, charged at 20barg. It undergoes pressure and temperature difference from the hot side, heated by flame, to the cold side, cooled by water.

WhisperGen EU1 has an electrical power of 1kW and a thermal power of 7.5kW as recovered heat, plus 7kW from a supplementary burner, included in the compact enclosure, that provides enough heat for space and domestic hot water. The electrical efficiency is around 11%, rather low if compared with ICE-based m-CHP system, nevertheless low investment cost, reliability and long service periods made its success.

Baxi Econgen, ***Viessmann Vitotwin*** *300-W* and *350-F*, and ***Remeha*** are other m-CHP systems based on Stirling engines available on the market. They are all based on *MEC* (*Microgen Engine Corporation*)[31] technology. It is a beta-type LFPSE with helium as working fluid, manufactured by *Sunpower*. Fueled by natural gas, the *MEC* engine produces 1kW of electricity and 6kW of heat.

In wall-mounted devices, the engine assembly is suspended and there is a counterweight to contrast vibrations typical of mono-cylindrical LFPSE.

The ***Cleanergy AB*** (ex ***SOLO***[32]) cogenerator uses a V160, 2-cylynder alpha-type motor fueled by natural gas, biogas or landfill gas. The cubic capacity is quite high in comparison to other Stirling-based m-CHP units, in fact the electrical power can vary in the range 2-9.5kW. This is done changing the working gas (helium) pre-charge pressure from 40-130bar with a small compressor, which pumps the helium from the engine to a storage bottle with a higher-pressure level. By opening a second magnetic valve, the engine pressure can be raised again. In this way the power is modulated with constant rotating speed, namely 1500rpm. The heat recovered is about 8-26kW, the electrical efficiency higher than 22% and total efficiency up to 96%. About the combustion, an air pre-heater and an Exhaust Gas Recirculation technology are schemed in order to rise the flame temperature, and then the performance, and to control the pollutants formation slowing down the reaction of combustion till a flameless oxidation (FLOX). The device requires maintenance after 4000-6000 hours of operation. Operation costs and pollutants emissions are much lower than natural gas Otto engines.

Other commercial products are offered by *Qnergy* (3.5kW and 7.5kW electric), *KD Navien* (1kW with its own *NCM-1130H* engine)[33]. *Stirling Biopower* sells *Flexgen*, a CHP station (38kW), with a 4-piston engine, hydrogen as working fluid, adapt to a variety of gaseous and liquid fuels (natural gas, biomethane from anaerobic processes, coal bed gases, LPG, volatile organic compounds).

[31] [Online]. Available: http://www.microgen-engine.com/.
[32] [Online]. Available: http://www.buildup.eu/cases/19164?CommunityId=16279.
[33] [Online]. Available: http://en.kdnavien.com/product/product_detail.aspx?skin=product&num=24.

Pellet-Stirling-Storage-CHP project (1kW) and the company *Sunmachine* (3kW) tried to exploit the flexibility of the external combustion selecting wood pellets as fuel, but not reliable results are available yet.

Table 16. Stirling engines comparison.

Model	Fuel	Electrical power [kW]	Thermal power [kW]	Electrical efficiency	Total efficiency	Service interval / lifetime [h]
Whispergen	NG	1	7.5	11	96	
Baxi Ecogen	NG, LPG	1	6.4			Maintenance free
Viessmann Vitotwin 350-F	NG	1	3.6-5.3		98	Maintenance free
Remeha	NG	1	5			Maintenance free
Solo/Cleanergy AB	NG, LPG	2-9.5	8-26	22-24.5	92-96	5800 / na

I.III Fuel Cells

FC m-CHP plant is essentially composed by fuel processor, FC stack (and water management system, depending on FC type), power conditioning, heat recovery (with eventual storage system), auxiliary burner, control system. The fuel processor and the FC stack are the most critical, where a breakthrough is the key for commercialization.

In the beginning PEMFC were preferred to SOFC, which looked not suitable for domestic CHP because high operative temperatures impose long start up time and constant operation. Thanks to recent results, many companies abandoned PEMFC and switched to more efficient SOFC.

FC technologies have been and are still supported by several public founded to overcome the major technical obstacle: service life, characterized by continuous degradation of performance.

In general, the lower electrical output of Japanese micro-CHP units than European ones is a consequence of the Japanese market requirement where generated electricity shouldn't be sold to the grid. In Europe, m-CHP is seen as a "distributed virtual power plant" (see the "Virtual Fuel Cell Power Plant" project[34]) with several points of input (besides output) into the grid.

Until 2012, the global m-CHP market was dominated by products powered by ICEs, but their appliances based on fuel cells overtook the ICEs, covering 64% of installations[35].

The main contribution to the sales came from the ***ENE-FARM*** project, in Japan, where manufacturers and utility companies have cooperated, and mass production has been effective since 2009. *ENE-FARM* systems exploit LT PEMFC, thus pure hydrogen must be fed to the stack.

The primary feeding is natural gas. After desulfurizing, it is converted into H_2-rich mixture in a single vessel, where steam reforming, water gas shift and selective CO-oxidation reactions occur at different temperatures (700°C, 250°C, 150°C respectively) with innovative catalysts. The fuel processor is light (11kg), compact (12l), and cheaper than traditional technology. The m-CHP system generates 0.2-0.75kW of electricity with 35% electrical efficiency (up to 39% at partial load operation, as typical of FCs) and with a total efficiency of about 95%. Auxiliary burner and hot water tank are present. The careful

[34] [Online]. Available: http://ec.europa.eu/energy/efficiency/industry/doc/euvpp.pdf.
[35] [Online]. Available: http://www.cospp.com/articles/2013/07/fuel-cells-overtake-engines-in-micro-chp-scene.html.

design of the product makes it suitable also for installations inside little flats. The latest high-performance model is available from April 2014[36].

NEDO and ***NEF*** Japanese organizations conducted the "Demonstrative Research on Solid Oxide Fuel Cells Project" to develop m-CHP systems based on SOFC. Some actors, besides gas utilities, are ***Mitsubishi***, ***Toyota***, ***Aisin Seiki***, ***Kyocera*** and ***TOTO***, who developed different layouts for their cells: tubular, flatten tubular, disk-type planar cells.

T*OTO*[37] advanced a micro-tubular ceramic SOFC, which operative temperature is 600°C because the LSGM (Lanthanum Strontium Gallate Magnesite**)** electrolyte has higher oxygen-ion conductivity in 500-700℃ temperature range. The lower operative temperature brings uniform temperature distribution inside the stack, thermal stability of electrodes, thermal shock resistance and faster start up. Due to low temperature, the reformer cannot be integrated in the fuel cells stack, so there is a dedicated fuel processor. The m-CHP system produces 0.7kW of electricity, runs in "power led" and includes boiler and hot water tank to satisfy the heat demand.

NextGenCell (2004)[38] is a joint EU and USA collaboration to develop a PEMFC for domestic application. The goal is 1-5kW electric power from HT PEMFC prototype (160-180°C). At this temperature the electrodes tolerate higher CO content than traditional LT PEMFC. The membrane is composed of heat-resistant polymer polybenzimidazole (PBI) and phosphoric acid. The desulfurizer instead of adsorbing directly the odorants (standard solution in small systems), transforms the sulfur compounds in H_2S, then adsorbed on zinc oxide bed at 350°C, that requires heat and H_2 recycle. After the autothermal reforming reactor there is only a water gas shift section to low CO below 650ppm. The water management has been eliminated with further simplification of the system, while the auxiliary burner is still present. The research activity resulted in the ***GenSys Blue*** m-CHP series by *Plug Power*[39].

Callux[40] is the German field test project, started in 2008, for FC heating systems for domestic use, 1kW electric power size. The constructors in the project, *Baxi Innotech*, *Hexis* and *Vaillant*, developed their own appliances and totally installed about 500 units.

Ene.field[41] is the (ongoing) European project in progress in 12 Counties, with the target of 1000 m-CHP installations. The manufacturers are *Baxi Innotech, Bosch, Ceres Power, Dantherm Power, Elcore, Hexis, RBZ, SOFC Power* and *Vaillant*.

Many types of fuel cells are investigated: LT and HT PEMFC, HT and IT SOFC. PEM-based systems (1-5kW electric, 1.4-10kW thermal) are expected to have 35% electrical efficiency, while for SOFC-based systems (0.8-2.5kW electric, 1.4-25kW thermal) it is up to 40% and the total efficiency always 85-90%.

Elcore 2400 is a HT PEMFC with an unusually low electrical power of only 0.3kW. Due to the low output, the fuel cell can run continuously (around 8000h/y). It is intended as an add-on to an existing heating system, rather than a replacement, for homes with low space heating demand or where only domestic hot water is required.

Ceramic Fuel Cells Limited (CFCL) is a global leader in SOFC technology: ***BlueGen***[42] cogenerator has the world's highest electrical efficiency (up to 60%).

[36] [Online]. Available: http://www.tokyo-gas.co.jp/techno/stp1/00h2_e.html.
[37] [Online]. Available: http://www.fuelcellseminar.com/media/9333/a399_1.pdf.
[38] [Online]. Available: http://www.nextgencell.eu/NextGenCell%20Website.htm.
[39] [Online]. Available: http://www.plugpower.com/userfiles/GenSys%20HT%20MK.pdf.
[40] [Online]. Available: http://www.callux.net/.
[41] [Online]. Available: http://enefield.eu/.
[42] [Online]. Available: https://www.bluegen.net/.

EnGen by *SOFCPower* is a m-CHP prototype in size of 0.5 and 1kW electric that uses a catalytic partial oxidation as fuel processor.

Morphic Helbio[43] offers two micro cogenerators (*APS-5000* and *GH2-BE-5000*, 5kW electric, also for island applications) based on LT PEMFC. Innovation relies in proprietary and innovative catalysts inside the fuel processor for natural gas, LPG, bioethanol and biogas.

Many companies are active in FC research and production. Here we mention:
Acumentrics, which uses ceramic SOFC with integrated reforming (750°C). The tubular FC is robust to thermal cycles and can accept a variety of fuels (natural gas, diesel and biofuels) with minimal fuel processing and the extra equipment of the system is minimal.
CeresPower, which has developed a metallic SOFC that is certainly suitable for cogeneration, therefore developments of CHP units are expected.

[43] [Online]. Available: http://www.h2fc-fair.com/hm09/images/pdf/Helbio_Productsheet_01.pdf.

Table 17. FC systems comparison

Model	Fuel	Electrical power [kW]	Thermal power [kW]	Electrical efficiency	Total efficiency	FC type
Toshiba	NG, LNG, LPG, 13A city gas	0.7		35		PEMFC
Panasonic	13A city gas	0.75		39	>90	PEMFC
TOTO	NG	0.7		46	86	SOFC
GenSys Blue	NG	3-8		32	82	HT PEMFC by Plug Power
Baxi Innotech Gamma Premio	NG, biomethane	1	1.87	34	>90	LT PEMFC by Ballard
Baxi Innotech Beta 1.5 Plus	NG	1.5	3			LT PEMFC by Ballard
Hexis Galileo 1000N	NG, biomethane	1	1.8	30-35	>90	SOFC
Vaillant	NG, biomethane	1	2	31	87	SOFC by Staxera
Vaillant EURO2	NG	1.5-4.6	3-9.1	>30	>86	LT PEMFC by Plug Power
Elcore 2400	NG	0.3	0.6	32.5	>90	HT PEMFC
Bosch	NG	0.7	0.7			Ceramic SOFC by AisinSeiki
IRD γ-m-CHP	NG	1.5	1.6	44	>90	LT PEMFC by IRD
Bluegen	NG	1.5-2	0.54	60	85	Ceramic SOFC by CFCL
Morphic Helbio APS-5000	NG, LPG, propane	5				LT PEMFC
Morphic Helbio GH2-BE-5000	bioethanol	5				LT PEMFC

Annex II

Table 18. Unit consumption per dwelling by end uses [toe/year][44]

Country	Electricity	Space heating	Water heating
AUSTRIA	0,23	1,33	0,20
FRANCE	0,24	1,07	0,16
GERMANY	0,19	1,18	0,19
GREECE	0,26	0,93	0,09
IRELAND	0,22	1,36	0,32
ITALY	0,19	0,81	0,10
NETHERLANDS	0,24	1,00	0,21
PORTUGAL	-	-	-
SPAIN	0,19	0,41	0,25
SWEDEN	0,32	1,09	0,17
SWITZERLAND	-	-	-

The conversion factor adopted to convert toe in kWh is 11630 kWh/toe.

Annex III

Table 19. CHP systems O&M costs[45]

System	Sum of Life-time Overhauls	Other O&M
	[$/kW$_e$]	c$/kWh
ICE 1kW	560	0,81
ICE 20kW	560	0,81
ST		2,07
μTG	635	1,03
FC	922	0,9
FluidCell	922	0,9

[44] http://www.eea.europa.eu/data-and-maps/figures/households-energy-consumption-by-end-uses-5
[45] http://www.hydrogen.energy.gov/pdfs/14003_lcoe_from_chp_and_pv.pdf

Annex IV

Table 20. 0.7 kW *FluidCELL* system seasonal load for a single dwelling

Country	Winter	Summer
AUSTRIA	100%	35%
FRANCE	79%	25%
GERMANY	58%	25%
GREECE	90%	25%
IRELAND	71%	25%
ITALY	57%	25%
NETHERLANDS	100%	90%
PORTUGAL	48%	27%
SPAIN	90%	25%
SWEDEN	100%	39%
SWITZERLAND	96%	25%

Keep in mind that seasonal load are average values.

Annex V

Table 21. Standard European ethanol specifications[46]

Properties	Unit Limit	Min-Max Method	Standard
Ethanol + higher saturated alcohols content	% mass	min 98.7	EN 15721
Higher saturated (C3-C5) mono alcohols content	% mass	max 2.0	EN 15721
Methanol content	% mass	max 1.0	EN 15721
Water content	% mass	max 0.3	EN 15489 EN15692
Total acidity (as acetic acid CH3CHOOH)	% mass	max 0.007	EN 15491
Electrical conductivity	µS/cm	max 2.5	EN 15938
Appearance (at ambient temperature or 15ºC whichever is higher)	-	Clear & colourless	EN15769
Inorganic chloride content	mg/kg	max 6.0	EN 15484 prEN 15492
Sulphate content	mg/kg	max 4.0	prEN 15492
Copper content	mg/kg	max 0.1	EN 15488 EN15837
Phosphorous content	mg/liter	max 0.15	EN 15487 EN 15837
Involatile material content	mg/100 mL	max 10.0	EN 15691
Sulphur content	mg/kg	max 10.0	EN 15485 EN 15486 EN 15387

[46] http://www.platts.com/IM.Platts.Content/methodologyreferences/methodologyspecs/biofuelsglobal.pdf

GLOSSARY

BoP	Balance of Plant
CHP	Combined heat and Power
ESCO	Energy Service Company
FC	Fuel Cell
HT	High Temperature
HT-PEM	High Temperature Proton Exchange Membrane
ICE	Internal Combustion Engine
LPG	Liquefied Petroleum Gas
LT	Low Temperature
LT-PEM	Low Temperature Proton Exchange Membrane
m-CHP/µ-CHP	Micro Combined heat and Power
NPV	Net Present Value
ORC	Organic Rankine Cycle
PAFC	Phosphoric Acid Fuel Cell
PBT	Pay Back Time
PV-T	Thermo-Photovoltaic
SOFC	Solid Oxide Fuel Cell
µGT	Micro Gas Turbine