Fuel Cell Heating System a Meaningful Alternative to Today's Heating Systems

Robert Staiger and Adrian Tantau

***Abstract*—Fuel cell heating FCH) systems are now available mostly from gas appliances manufacturers. After a ten-year test phase, these devices are a *considered* promising alternative on the heating market for disposal. These new heating systems devices could open a new market Segment with new opportunities and new business models. Fuel Cell ́s in compare to a Carnot process shows a far higher efficiency with less emission. FC heating systems using the thermal energy for heating and the electricity for feed-in. These systems are called combined heat and power plants (Micro CHP). The fuel of this new FCH system is fossil gas. The existing FCH systems are not powerful enough for the energy demand of standard buildings. For this reasons on top of this new FCH systems a condensing gas boiler driven with a fossil gas source is integrated.**

This article attempts to compare the FCH System with present alternative heating systems and try to answer question from an environmental and economic view and give alternative outlooks to this kind of heating technology.

Methodologically a model is used to show the dependency of environmental and economic factors. The economic and technical data ́s are based on latest manufacturing and research institutions.

***Index terms*—Fuel cells (FC), fuel cell heating (FCH), combustion heat and power (CHP), micro CHP, heating innovation.**

I. Introduction

Fuel Cells as an alternative device for producing electricity and thermal energy is invented over 170 years ago from Sir W. Grove and C.F. Schönbein [1]-[3] in the same time combustion engine were invented. Unfortunately, on that time materials for fuel cells and the technology state was not high enough to go further. As well the new steam engines and especially the fossil fuel was cheap available on that time. In the 1960th because of the space program fuel cell are developed further more. The first energy crises in the 70th and the following energy crises [4], [5] up to date more research work was done. Today we have a variation of different fuel cell types [6] and application on the market [7], [8], [9]. A fuel cell is a device (chemical energy converter), which takes H_2 and O_2 as a fuel. The output for this "cold burning process" is thermal energy and electricity [10]. The "exhaust" is poor water (H_2O). Depending of the type of fuel cell the electrical efficiency, size of the fuel cell, operation temperature output and the type and quality of fuel varies which shows Table I. The efficiency of a fuel cell is defines [11]-[15]:

$$\eta_{FC\ \max} = \frac{\text{produced amount of energy}}{\Delta H} \tag{1}$$

$$\eta_{FC\ \text{elec.max}} = \left(1 - \frac{T*\Delta S}{\Delta H}\right) \times 100\% \tag{2}$$

$$\eta_{FC} = \eta_{syst}\eta_{F\max}\eta_{Elec.\max} \tag{3}$$

where H=enthalpy, S=entropy of reaction

The overall fuel cell efficiency of today's micro Fuel cell (CHP) system is around 85-100 % depending of the type of FC and the calculation method of NCV (Hl) and GCV (Hh) of the fuel [16].

TABLE I: FC Types and Specifications [17], [18]

Type	Fuel Type	Operation Temp ℃	Elect. Efficiency %	Energy density W/cm ²	Applications
AFC Alkaline FC	H2	60-80 ℃	60%		Space program, Military (submarines)
PEFC Proton Exchange	CH3OH Methanol	80 ℃	40-50%		Power supplies, Car/Bus, Home heating, CHP, USV up to 250kW
DMFC Direct Methanol	H2	80-100 ℃	40-50%	0,6 W/m ²	Development phase
PAFC Phosphoric Acid	H2	200 ℃	40-45%	0,2 W/m ²	CHP ́s, Power generators > MW
MCFC Molten Carbonate FC	H2 (CH4) Biogas	650 ℃	55-60%	0,1 W/m ²	CHP ́s, Power generators > MW
SOFC Solid FC	H2 (CH4)	800-1000 ℃	60%	0,4 W/m ²	Home heating, power generators

A. *The Function Principal of a Proton Exchange Membrane FC*

Fig. 1 shows the chemical reaction of a Proton Exchange Membrane Fuel Cell, PEMFC. The entire chemical reaction can be described by the equation:

$$\rightarrow 2H_{2\ (gas)} + O_{2\ (gas)} \rightarrow 2H_2O_{\ (liquid)} \tag{4}$$

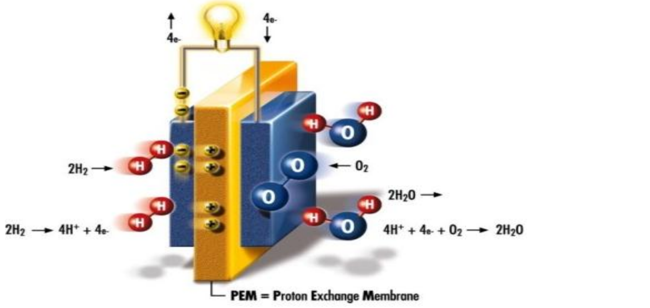

Fig. 1. PEMFC chemical reaction [19].

Manuscript received September 7, 2015; revised December 23, 2015.

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doi: 10.18178/jocet.2017.5.1.340

B. Fuel Cell Heating Systems

Alternative Heating appliances with an integrated "chemical energy converter" (Fuel Cell) which operates with H_2 is far more efficient as a Carnot cycle system. The FCH System produces thermal and electrical energy like in a conventional CHP System. Today's FCH Systems are using fossil gas for operation. To operate the FC, H_2 is necessary. For this reason, a reformer is used to generate the H_2 part out of a fossil fuel like CH_4. The efficiency of a standard reformer is around 80% depending of caloric value of the fuel [20]. The chemical equation for this reforming process is:

$$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2 \qquad (5)$$

The amount of CO_2 of the reforming process can be calculated with the chemical stoichiometry. *Molecular mass are*: Methane = 16g, Carbon Dioxide = 44g, Water 18g, Hydrogen =1g [periodic]

Molecular mass equation: 16g+ 36g = 8g + 44g → 1kg H_2 → 5.5kg CO_2

With the energy contents of 33.33 kWh/kg H_2 → CO_2 equivalent → 166g CO_2 /kWh

This calculation procedure is used for the environmental impact in Sections II-III. To compare a condensing gas boiler for burning fossil gas 0.24 $kgCO_2$/kWh will be emitted in compare to 0.17kg CO_2/kWh with a 100% efficient reformer.

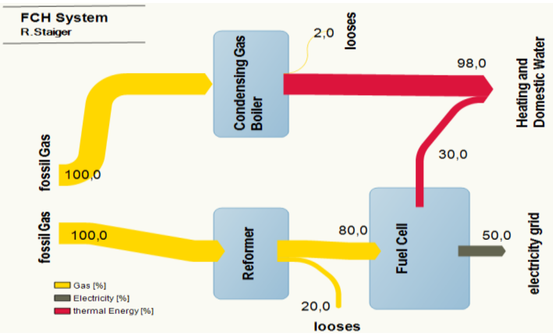


Fig. 2. FCH System and their efficiency dependencies contribution R. Staiger.

Today's FCH systems are not powerful enough to cover the thermal energy demand in standard buildings. For this reasons on top of the FCH System a condensing gas boiler is integrated. Fig. 2 shows the efficiency dependency.

C. Fuel Cell Heating Systems

Typical heating appliances show in Table II and the percentage of installations in German homes. Nearly 70% of heating appliances are older than 10 years and not in the latest technology [21], [22]. From 2017 the new EPBD [23] will banned normal fossil fuel boilers (Gas/Oil) through the calculation procedure for the primary energy factor in new and existing Buildings. All private as well public new buildings from 2018 should be nearly zero energy buildings through EU law [24].

TABLE II: ESTIMATIONS OF HEATING APPLIANCES TODAY IN GERMANY

Type	Number of heat generator in Germany	Percentage %
Oil/Gas	14 Mio	70%
Condensing oil/gas	4,8 Mio	23%
Heatpumps (HP)	0,6 Mio	3 %
Fossil CHP	< 0…	0
Electricity fossil	< 0…	0
Pellets/Wood chips, Gasification logs	0,9 Mio	4%
FC Heating fossil/H_2	Test Phase Ca 500 units	0

3.4 million Boilers from 14 Mill working Boilers for example in Germany are older than 24 years. Much of this waste is in single and two-family houses installed.

94% of the heating systems in Germany are driven with fossil energy source. The last 10 years over 600.000 HP systems were installed as an alternative System [25]. Fossil driven Micro CHP ́s from 2-3 kWh electrical and 8-12 kW thermal output are available on the market. The overall efficiency of this Micro CHP ́s is higher than a conventional gas boiler and electricity from the grid. Fig. 3 shows the efficiency flow in a Sankey diagram. The total efficiency is > 40 % means less fuel and less CO_2 emissions

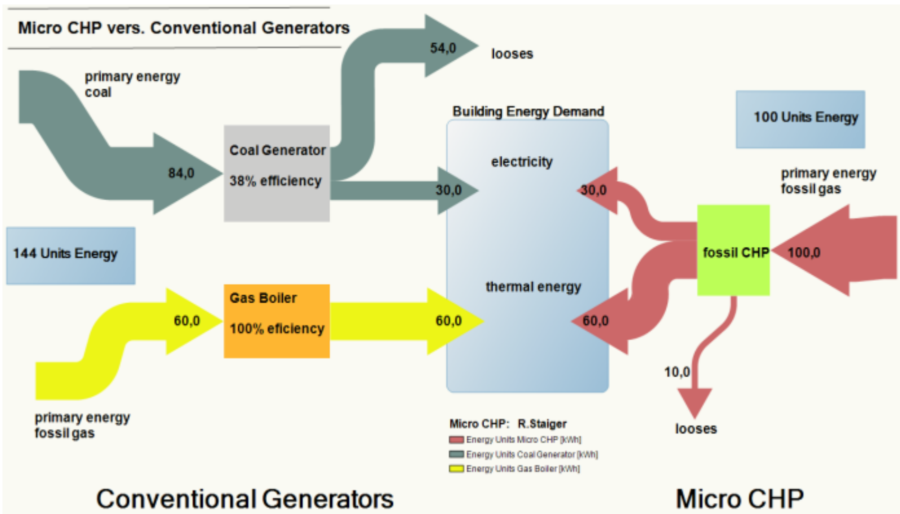


Fig. 3. Comparison micro CHP to conventional generator and gas boiler contribution R.Staiger.

II. METHODICALLY

Data ́s from field test trials in Germany [26], from the EU [27] and from Japan [28], [29] are examined and analyzed. Detailed data's of the different FCH manufacturer [30] are examined for an environmental and economic analysis. With a heat appliance model (Fig. 4) the analysis and conclusion are compared.

A. Heating Appliances Model

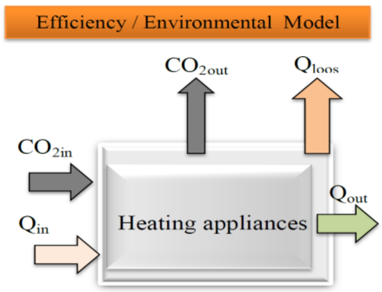


Fig. 4. Model contribution R.Staiger.

All heating appliances have in common a flow of Energy going IN and a flow of energy going OUT. The Energy flows OUT of the appliances are usable and not usable energy (looses). Energy IN is different primary and secondary energy sources like fossil fuel, electricity, renewable sources (geothermal, PV, Biomass, Wind ...) and auxiliary Energy for periphery components (pumps, controls, electrical heaters …). Energy OUT can be thermal, mechanical and electrical. Depending what kind of energy transformation device it is (Carnot process [31] or chemical transformation FC) more or less energy loses (not usable energy) will be generated.

Mathematical equations and simulations are done with software packages from ETU Köln [32] through the latest EU directives. To calculate and to compare the CO_2 emissions and the economic situation on heating appliances one building as a case study is used (see Table III).

For the heat appliances comparison a standard building with following parameters will be used. With a heat demand calculation program the base data's are calculated. For plausibility checks the program is used.

TABLE III: CASE STUDY PARAMETERS [33]-[37]

Indices	Parameters	Data´s
a	Heated living area	200 m ²
b	Energy demand of the building heating and domestic water W/m ²	70W/m ²
c	Output Power of the Heat appliances $\underline{P}$ $(a \times b)$	14 kW
d	Operation hours/a	1800 h
e	Thermal energy demand/a $\underline{Q_{out}}$ $(c \times d)$	25.200 kWh/a
f	Electricity demand (4-5 people)	4.000 kWh
g	Heating System (low temp heating system 40 °C)	Underfloor/ Wallheating
h	*Energy cost Cent/kWh Germany:* Gas = 7.48, Oil = 6,21, HP elec. = 21.47, Elect. = 20.38, tariff feed = 0.09, elect.= 0.31, Pellets = 4, Logs = 2.5	
i	*Energy cost Cent/kWh Romania:* Gas = 5.18, Oil = 5.8, HP elect. = 14, Elect. = 14, tariff feed = 0.0, Pellets = 3.5, Logs = 2	

Investment costs from field test systems, future investment outlooks, wholesaler, direct supplier of heating appliances and experience of over 20 years in installing renewable systems are used. Experts from research institutes [38], [39] and heating appliances manufacturer monitor the field test trials in Europe and Germany. Interviews with the users are evaluated and analyzed. The evaluation and analysis are done over the last 8 years field test trail! [40]-[46].

The objective is to compare the different appliances with the FCH System and show the results, advantages, and disadvantages of these systems. With this information, new ideas can be developed and new strategies can be brought forward for heating appliances players (stakeholders).

B. Efficiency and Economic Calculations Method

$$\sum Q_{in} = \sum Q_{out} + \sum Q_{loos} \quad (6)$$

$$\dot{Q_{in}} = \sum Q_{in_1} + \sum Q_{in_2} + \cdots + \sum Q_{in_n}$$

$$\dot{Q_{out}} = \sum Q_{out_1} + \sum Q_{out_2} + \cdots + \sum Q_{out_n} \quad (7)$$

$$\dot{Q_{loos}} = \sum Q_{loos_1} + \sum Q_{loos_2} + \cdots + \sum Q_{loos_n} \quad (8)$$

$$\eta = \frac{\sum Q_{out} + \sum Q_{loos}}{\sum Q_{in}} \quad \eta = \frac{\dot{Q_{out}} + \dot{Q_{loos}}}{\dot{Q_{in}}} \quad (9)$$

A so called investment factor is used in the analysis. This factor compares a standard condensing gas boiler system with the other heating appliances. In this calculation the basis installation is the same (Underfloor/low temperature system) for all. The distinction is due to the different types of boilers, storage capacities and other unique factors in the technical room. The figures are based on manufacturer and wholesaler figures [47], [48]. The energy cost is based on the German and Romania price structure for retail (Table III). Various political instruments in Germany, like the actual tariff feed system, tax relieve, and financial assistance is considered. In Romania this tariff feed system are not available. The CO_2 eq. figures are from GEMIS Database [49] and Information from EU, Germany and Romania statistic offices [50]-[54].

C. Environmental Calculation Method

Calculation of CO_2 is more complex depending of the heat appliances. For all Carnot cycle processes like gas/fossil and biomass boilers the CO_2 emissions are defined through the CO_2eq figures and the amount of Energy for operating the appliances in kg CO_2 per kWh. The GEMIS Simulation program defines the figures for the OECD countries. As well other Data´s from National and International organization will be used for plausibility checks .The factor depends, how the energy carrier is produced. For example Pellets as a Biomass source or electricity for the grid system. The factor can differ for each country especially the electricity. A fossil fuel CHP will produce heat and electricity. The total amount of Energy IN (Gas) can be calculated with the CO_2eq figures as well. In addition the electrical energy which is delivered can be subtracted from the substituted electrical energy which is normally used. To compare and to analysis the environmental impact of heating appliances a closer look should be also to the refrigerant in heating appliances like HP. These refrigerants could have a high GWP [55] and will influence the environmental impact balance. Following example shows the impact of the refrigerant of a standard HP. Example: The base is the total energy produced from the HP over the live time. Refrigerant live time 10 years, 1400h/a operation hour, average size of HP 12kW, refrigerant GWP 3800 and 2.5kg refrigerant [56].

D. Calculation Procedure for GWPF

$$GWPF = \frac{GWP \times m}{P \times t \times \text{livetime}} \left[\text{kg} \frac{CO_2}{\text{kWh}}\right] \quad (10)$$

100% refrigerant looses

$$GWPF = \frac{3800 \times 2{,}5}{12 \times 1400 \times 10}$$

➔0,056 kg CO_2 /kWh

This amount of CO_2 emission must be included in the CO_2 calculations for HP appliances. As well the chemical energy converter (FC) which operates over a reformer with fossil gas will have an environmental impact. It means that a fuel cell system which use fossil emits still CO_2 over the reforming process. In our fossil driven FCH with 80% reformer efficiency a figure > 0.2 kg CO_2 /kWh is calculated. In these calculations there is no savings over the reformer and FC devices (similar like a normal burning process). Following Equation can be used for calculating the total CO_2 for heating appliances.

$$CO_{2\,total} = CO_{2eq.\,fuelin} \times Q_{in} + Q_{in} \times GWPF_{HP} - CO_{2eq.elect} \times Q_{out\,elc.} \quad (11)$$

To compare the economic and CO_2 impact for existing heating appliances with the new FCH system, a standard building will be used for this case study. The existing heat appliances are all from Europe. For FCH systems, Japan has installed more than 50.000 Units. With the "enefarm" [57] program the Japanese government pushed this technology in the market (especially after the Fukushima disaster). Panasonic and Toshiba are the leading companies in this field. In Europe enefield [58] as a European program up to date 500 systems are in field test.

III. Research Analysis and Results

The calculation procedure depends on the following factors.

- The average energy efficiency of heat appliances shows Table IV row 1. Depending of the quality of the devices and the installation the variation can be enormous. For the calculation methods, an average efficiency is taken from technical data of heating appliances. For Micro CHP an electrical and thermal efficiency is taken.
- The total amount of energy (Table IV row 2) for the heat appliances the average efficiency factor is used. The basis for the thermal energy amount (heating/DW) is for all heating appliances calculation the same. For Micro FCH system the electrical energy is the base (4.000 kWh/a).
- The demand of electricity for the building is 4.000 kWh/a (4-5 people).
- The energy price for thermal and electrical Energy is calculated with the average energy prices see Table III.
- The amount of CO_2 emissions is depending of the fuel type and the total energy amount. For calculation the CO_2eq the figures from GEMIS is used. For the Fuel Cell heating appliances the amount of energy which is produced over the FC, the CO_2 is calculated with theoretical chemical equations and the efficiency of the reformer.

A. *Comparison Energy Cost and Energy Savings*

Fig. 5 shows the energy saving potential for installed heating appliances in Germany. For the comparison energy cost and saving potential of the heating appliances, the reference system is the FCH. The FCH system installed in Germany has the lowest energy cost. The reason for the saving potential is the actual electricity cost (0.3 €/kWh) in Germany, which will be substituted with the FCH system. All other systems are more expensive to run (negative value). Biomass systems have clear advantages through the lower energy prices in compare to fossil driven systems. HP system can vary quit significant depending of the efficiency (SPF) [59] and the electricity prices. Micro CHP´s are more complex. Depending of a heat-controlled supply or electrical controlled supply [60]-[62] the savings can vary. In our case study the fossil CHP System is heat controlled, electricity output depends of the thermal energy demand. The electricity is used for direct usages (smart grid) and overcapacity feed back to the grid (tariff feed). A FCH system is different of the size of the chemical converter (FC) and there electrical efficiency. In this case, study the calculation is based on the electricity demand in the building. The thermal demand can be controlled with the internal condensing gas boiler. The advantage of an electrical controlled supply system is significant.

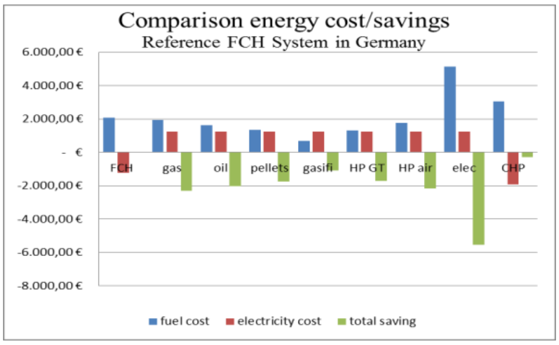


Fig. 5. Contribution R.Staiger.

TABLE IV: Germany

Type	CO_2 emission elect. kg	Total energy cost €	Cost savings €	CO_2 savings kg
gas	2.400	3.163	-2309	-4251
oil	2.400	2870	-2016	-5955
pellets	2400	2592	-1738	860
gasific	2400	1940	-1086	1360
HP gt	2400	2563	-1709	-1860
HP air	2400	3004	-2150	-3120
Elect.	2400	6372	-5518	-13200
CHP 10kw 4064h	-6828	1132	-278	1404
FCH 1kw el. 0.8 kw th.	-2400	1.047	0	0

Type	Efficiency	Total energy kW	Energy cost €	CO_2 emission kg	Energy cost elect. €
gas	0,98	25.714	1923	6.171	1240
oil	0,96	26.250	1630	7.875	1240
pellets	0,95	26.526	1352	1060	1240
gasific	0,9	28000	700	560	1240
HP gt	SPF 4	6300	1323	3780	1240
HP air	SPF 3	8400	1764	5040	1240
Elect.	1	25200	5135	15120	1240
CHP 10kw 4064h	0,90	40.600	3036	9744	-1240
	28% el.	11.380			-664
	62% th.	25.200			
FCH 1kw el. 0.8 kw th.	0,90	28.000	2.094	6.720	-930
	45% el.	4.000			-90
	35% th.	3.000 rest gas 21800			

Table V shows the calculations with the data's from Romania for energy cost and CO_2 emissions.

TABLE V: ROMANIA

Type	Efficiency	Total energy kW	Energy cost €	CO_2 emission kg	Energy cost elect. €
gas	0,98	25.714	1332	6.171	560
oil	0,96	26.250	1522	7.875	560
pellets	0,95	26.526	928	1060	560
gasific	0,9	28000	560	560	560
HP gt	SPF 4	6300	882	3780	560
HP air	SPF 3	8400	1176	5040	560
Elect.	1	25200	3528	15120	560
CHP 10kw 4064h	0,90	40.600	2103	9744	-560
	28% el.	11.380			-0
	62% th.	25.200			
FCH 1kw el. 0.8 kw th.	0,90	28.000	1459	6.720	-400 -0

Type	CO_2 emission elect. kg	Total energy cost €	Cost savings €	CO_2 savings kg
gas	2000	1892	-833	-3451
oil	2.000	2082	-1023	-5155
pellets	2.000	1488	-429	1660
gasific	2.000	1120	-61	2.160
HP gt	2.000	1442	-363	-1060
HP air	2.000	1736	-677	-2320
Elect.	2.000	4.088	-3.029	-12400
CHP 10kw 4064h	-5690	1543	-484	666
FCH 1kw el. 0.8 kw th.	-2000	1.059	0	0

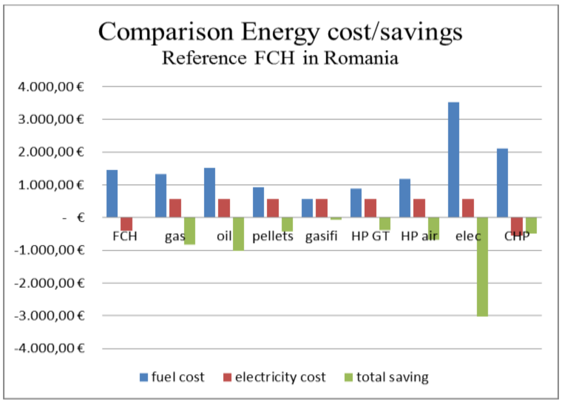
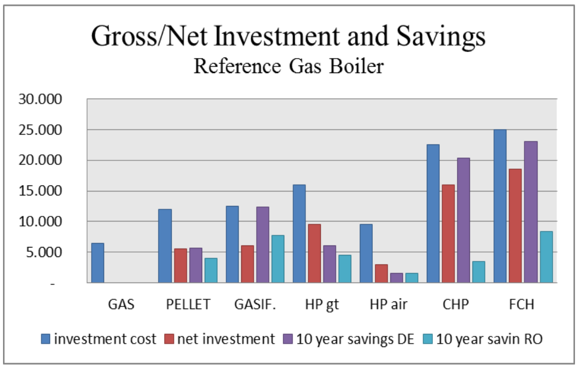


Fig. 6. Contribution R.Staiger.



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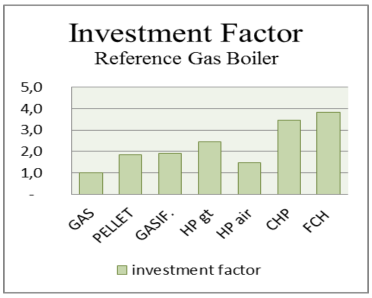

Fig. 8. Contribution R.Staiger.

For comparing energy cost and savings in Romania the reference is the FCH as well (see Fig. 6 and Fig. 7). In this analysis, the FCH System has still the lowest energy cost. But through the lower Energy prices and no tariff feed systems the Micro CHP are not economical to run (see Fig. 8 and Fig. 9).

B. Economic Calculation for Germany/Romania (Reference Condensing Gas Boiler)

The investment cost and the investment factor is based on average cost of the different appliances. The appliances are standard systems which are available in the EU market. An average figure is used. For FCH system the actual cost are used. A Saving potential of >40% can be reached with higher quantities and new innovations in R&D and production [63].

C. Investment Comparison

With an Investment analysis the result shows clearly the dependencies of the energy prices and possible tariff feed programs. Payback times from an *energy saving* point of less than 10 years in Germany are possible. In compare to Romania it is a factor 2 to 3 higher (see Fig. 9). Attention must be paid with this new Micro CHP system on warranty details, service and maintenance cost in compare to established heating appliances. A full cost accounting should be done to minimize the investment risk. FCH system has the highest investment factor in compare to a standard condensing gas boiler. The reason is using a new unique technology (FC, Reformer) in small quantities with high R&D costs involved. The Economy of Scale Effects [64] will reduce the prices in the future.

Comparing the savings on CO_2 emissions (see Fig. 10) only the Biomass and CHP appliances will have positive effects. Fossil operated heating appliances emitting much more CO_2. HP system depending of the SPF can be also quit significant. In comparison with CHP the emissions are negative because of calculating the electricity in the building. Micro CHP ́s have the potential reducing CO_2 emissions. As more electrical energy is produced on side (decentralized systems) for own use with more intelligent controls (smart grid) as higher will be the saving potentials.

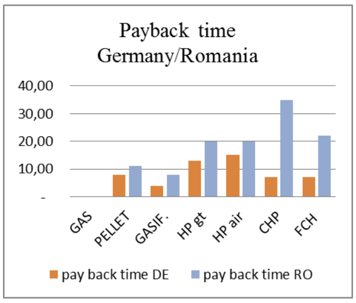

Fig. 9. Contribution R.Staiger

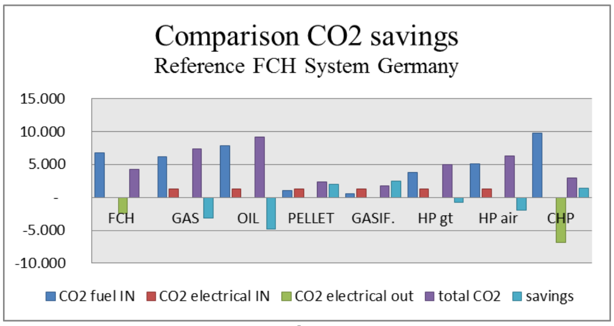

Fig. 10. Contribution R.Staiger.

With over 14 Million old heating appliances in Germany the potential saving CO_2 is enormous for the future [65].

In Romania the CO_2 savings in compare to Germany is for this analysis smaller. The CO_2eq figure in Romania is 0.5 kg CO_2 /kWh in compare to 0.6 kg CO_2 /kWh in Germany, because of the higher renewable contribution in the electrical network through hydroelectric power plants in Romania [66], [67].

IV. Conclusion

The Analysis shows the FCH system could be an alternative for today's existing heating systems in accordance with the analysis in this article. Through the political intention changing the energy structure in a renewable energy future (Energy transition) in Germany, the tariff feed system and different grand schemes makes it economical feasible installing this kind of FCH systems. Without pushing this technology forward with political instruments like tax relieves, special tariff feed systems, allowances, subsidies, grants contributions, financial assistance, the volumes are too low to achieve a comparable price in compare to today's existing heating systems. The aim for the EU governments reducing greenhouse gas emissions, increasing the efficiency and using less fossil energy sources for independencies this Micro CHP system could be one way to achieve the objectives. With over 14 Million old fossil heating systems alone in Germany this saving potentials for energy efficiency and CO_2 reduction in the EU is enormous. The market potential in domestic houses as well public and industry building is as well huge.

Using a FCH system for replacement of existing heating system and new installation following important point must be considered.

- Micro FCH heating systems are more efficient, it can reduce greenhouse gas emissions, it is noiseless, the FC has a cold burning process with significantly higher efficiency compared to separate production of electricity and heat
- FCH system will deliver thermal and electrical energy. To generate electricity and using this direct in the building (decentralized) makes this device so interesting from an energy cost and environmental point.
- FCH systems are due to their efficiency, flexibility and decentralized applications an ideal module for future energy supply
- Possibility of crosslinking to "virtual power plants"
- Decentralized Micro FCH systems can make an important contribution to grid discharge and stabilization, flexible use and ideal for balancing fluctuating renewable energy sources
- Micro FCH system relocated the production of electrical energy to the local level, avoiding transmission losses
- Micro CHP consumers can strengthen by controlling their electric bill itself (smart grid!)
- Due to the high power to heat ratio and good scalability performance fuel cell heating appliances are also suitable for the renovated existing buildings with low heat demand
- Object related CHP systems, for example with integrated heat storage systems, can supplement the fluctuating of electricity production from wind and solar power quit flexible and helps to stabilize the grid system (seasonal anti correlation to photovoltaics, wind and Power to Heat etc.)
- Installing a FCH is quit more complex as standard biomass or fossil driven systems. This knowledge of installation with good quality is an important issue (similar like HP Systems).
- The correct planning and sizing of a Micro FCH system for saving energy cost and reducing CO_2 emissions is essential.
- The different countries with the different political instruments like grands, tariff feed system, electricity cost, gas cost etc. can make this system less economically.

An ideal future outlook for this kind of FCH system would be:

Ideally using instead of a fossil source driving FCH system, a renewable produced H_2 gas (carrier) produced locally (decentralized) over biomass reforming processes and electrolysis with Wind and PV Energy.

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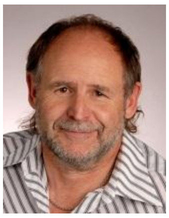

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