Performance monitoring of Stirling CHP units in an industrial district in Poland

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Abstract

The present work presents monitoring results obtained from the operation of three natural gas-fed Stirling micro-CHP engines integrated into an assembly of three interconnected industrial buildings in Warsaw, Poland. One unit with 1 kW_{el} and 7 kW_{th} nominal production, has been installed in each separate building. A back-up central boiler, a central heat storage tank and insulated district heating pipes are used to dynamically exchange heat between the buildings and cogeneration units, thus establishing thermal balance between heat production and consumption. Within the context of the present work, an advanced management and control system has been developed for the optimal operation of the Stirling units. User interfaces for the units have been developed, as well as new control strategy algorithms. An extensive monitoring campaign has been designed based on the measurement of several variables in the district heating installation. Monitoring took place during several months and the collected data allows for the real time calculation of the generated electrical power, the heat produced by any unit and the heat transferred to each zone/building. Analysis of the new control strategy shows the performance of the different components, of the management software and their impact on the overall operation.

1. Introduction

The high costs of delivered electricity can be partially attributed to a strong dependence on centralized energy production systems, which operate mostly based on fossil fuels and require huge investments for setting-up transmission and distribution grids that can penetrate remote regions. Furthermore, fossil fuel combustion may result in increased emission of greenhouse gases (GHG) and noxious pollutants, which are directly related to global warming and health hazards [e.g. 1]. The use of efficient, sustainable and eco-friendly power generating technologies, operating on clean and/or alternative fuels, can help in mitigating the above concerns. In this context, micro-co-generation systems (μ-CHP, commonly defined as systems with less than 15 kW capacity), producing both heat and electricity, provide potential reductions in carbon emissions and costs through efficient fuel use and by offsetting the use of centrally-generated electricity from the grid [e.g. 2]. Major benefits of Distributed Generation (DG) systems are savings in electric losses over the long transmission and distribution lines, reduced installation cost, local voltage regulation, and ability to switch on small units instead of a larger one during peak load conditions [e.g. 3].

While the technological and economic viability of large scale systems has been proven [e.g. 4, 5], energy efficient solutions at a smaller, local scale, have not yet been widely demonstrated. Simulation studies [6] have shown that heat trading could be a functional way to develop DG systems, targeting the size of communities with a few buildings. A

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potential advantage to be utilized, is their installation in buildings with thermal consumption profiles - different in shape and/or time –via a district heating network.

The aim of this work is to present monitoring results from the operation of such a DG system at a real scale pilot district, located in the Polish Institute of Energy (IEn) in Warsaw, Poland. The district comprises a de-centralized μ-CHP network that is based both on electrical and thermal integration. The work has been performed within the frame of the FP7 EU-NMP FC-DISTRICT project "New μ-CHP network technologies for energy efficient and sustainable districts" [7]. The overall objective of the FC-DISTRICT project is to use efficient, sustainable and eco-friendly technologies in order to optimize and implement an innovative energy production and distribution concept for sustainable and energy efficient refurbished and/or new districts exploiting decentralized co-generation coupled with optimized building and district heat storage and distribution network.

2. Industrial district for demonstration

Three micro-CHP units, based on ehe's owned Stirling engines developed by Whispergen (NZ), have been installed in the so-called "Polish district" (IEn premises). The units are thermally interconnected via novel insulated pipes which ensure efficient heat circulation within the district with very low thermal loses. A hot water tank has also been installed to serve the thermal storage needs of the district network. Electrical integration via a local micro-grid has been realized and a wireless communication solution (hybrid mesh sensor network) has been developed. Advanced control/management strategies have been employed in order to optimize the combined operation of the three Stirling engines and for matching the thermal demand of the three zones, resulting in a significant primary energy saving.

The district comprises three separate buildings, as shown in Figure 1. Each building is considered as a single zone: Building HVA – Zone 1, Building CPC2 – Zone 2, Building CPC1 – Zone 3. The new district heating system supplies heat into the three zones: zone 1, with thermal demand 7,16 kW in HVA building, zone 2, with thermal demand 3,5 kW in CPC1 building, and zone 3, with thermal demand about 5 kW for the entire CPC2 building.

One ehe Stirling CHP unit has been installed in each building. The three units are interconnected by a heating loop, which is also connected to the water tank for heat storage/release purposes. Figure 2, shows the Polish district's thermal and hydraulic scheme. The three independent zones are additionally heated by typical radiators, and feature one CHP unit each. The three ehe units are connected only to the district's return pipe, as shown in Figure 2. An already existing gas boiler acts a back-up boiler for supplying additional heat when needed, thus ensuring the fulfillment of the zones' heat demand under any circumstances. The gas boiler is connected to the district loop through a plate heat exchanger. The district heating loop serves as a means for sharing heat among the three CHP units and the zones, and for the temporal storage of excess heat produced by the CHP units and not demanded by the zones in the water tank. The district circuit also features a powerful water pump, while a non-return valve has been added upstream the main pump. Finally, a multi-function valve, a k-flow valve, has been placed in the end of the district's circuit to ensure a minimum water flow in the circuit when there is no thermal demand from any zone.

Figure 1. The demonstration industrial district setting in Warsaw, Poland. (left) location of each building in the district. (right) heat distribution network between the buildings.

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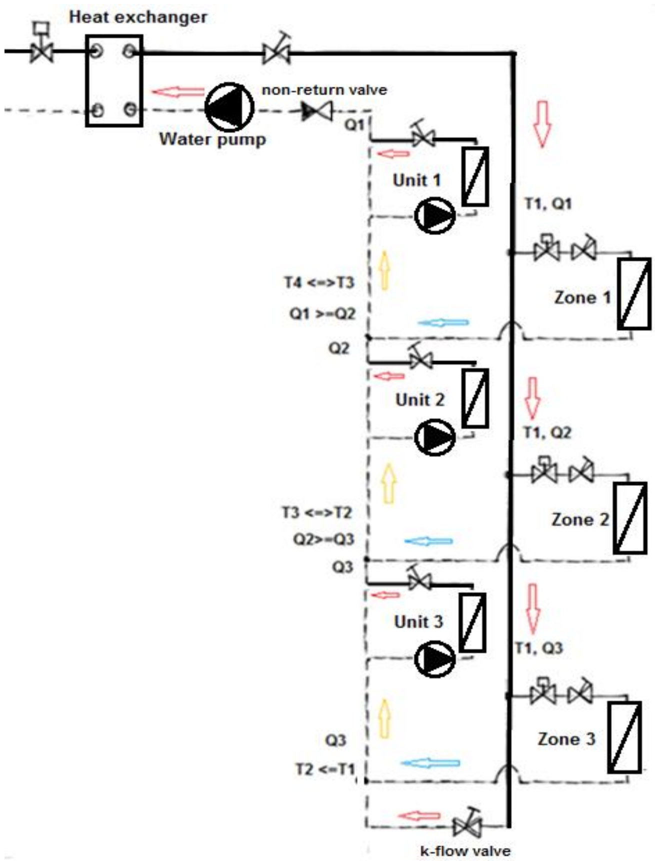

Figure 2. Polish district's thermal and hydraulic layout with the ehe Stirling cogeneration units.

The installed multi-function valve allows the water flow to be fully by-passed, only when none of the zones is demanding heat. If any of the zones is demanding heat, the valve will still let a minimum water flow to be by-passed. In this configuration, the water tank must be permanently connected to act as a "thermal inertia" system. The on-off controlled valve should be fully open, and the circuit connecting the water tank requires an additional valve, together with a water flow meter, to manually adjust the water flow by-passed through the water tank.

General performance features of the described thermal-hydraulic layout are as follows:

1. All zones receive hot water from the circuit at similar temperatures. The maximum water flow to any zone, required to deliver its peak thermal demand, can be adjusted with the manual valves installed in the zones' circuits. The autonomous, and automatic, PID zone's temperature control modulates the water flow to the zone according to its actual thermal demand.
2. The water flow through any unit depends on its position in the return pipe and on the operation of its associated zone. Thus, water flow through Unit 3 will be limited by the flow through zone 3 plus the water by-passed at the end of the circuit, while water flow through Unit 2 will be limited by the sum of the flows through zones 2 and 3 plus the aforementioned flow bypass.
3. Every unit rises the temperature of the water in the return pipe. Therefore, the inlet water temperature of any unit depends on the operation of the previous zones and the units in the circuit. This will cause different temperatures to be found in different sections of the return pipe.
4. Therefore, the availability of any unit for safe operation and the potential overheating of any unit, must be analysed for each unit before it is switched on. The working conditions of anu unit, with repsect to water temperatures can be very different.
5. As a consequence, the same number of working hours cannot be ensured for all units.

3. Micro-CHP units

The integration of a μ-CHP unit into a particular building can take many forms. Installation requirements vary widely depending on the type and size of the CHP unit and the operating strategy (thermally driven, electrically driven, or constant output). In this work, the three Stirling μ-CHP engines (EU1 model Stirling CHP from ehe supplied by

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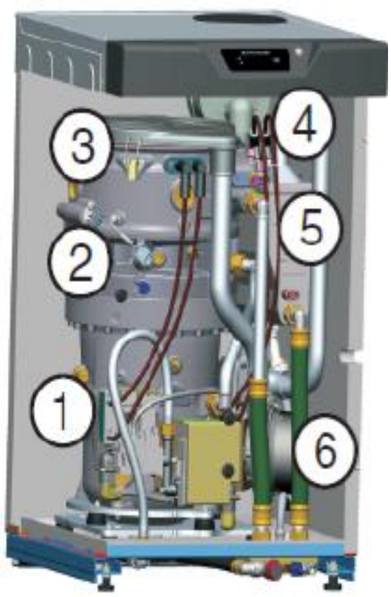
Mondragon Componentes) have been installed into the polish demonstration district. Each μ-CHP unit is fed with natural gas, and produces 1 kW_{el} nominal electrical output and 7 kW_{th} nominal thermal power, with no power modulation capabilities. Figure 3 shows the main components of the ehe unit, as well as its main technical features.

1. Electrical generator (230Volt AC power)
2. Stirling engine, that provides mechanical power for the generator
3. Gas burner assembly, that provides the heat needed for the operation of the Stirling engine
4. Auxiliary burner, for additional heat output
5. Fumes-water heat exchanger that recovers heat from hot gases produced by the burner
6. Two fans that provide combustion air for the main and auxiliary burners and exhaust, the combustion gases from the process, to the atmosphere via the flue



Electrical output (nominal)	Up to 1000 W (230V 50Hz)
Thermal Output (min/nominal/max)	5500/up to 7000/up to 14000W
Power consumption (net)	
Standby	9W
Generating	60W
Fuel	Natural gas
Dimensions	491(W)x563(D)x838(H)
Weight(dry)	148kg
Engine	4 cylinder double-acting Stirling cycle

Figure 3. Main components of the ehe Stirling CHP (left) and relevant technical features.

The ehe cogeneration units are able to produce up to 14 kW thermal output, by means of a combination of the primary and secondary burners. The secondary burner is automatically activated in case of failure of the primary burner. If the secondary burner is activated, a huge amount of heat would be transferred to the district heating circuit, (much higher than the heating demand of the zone) and the other CHP units would be automatically switched off to avoid the circuit overheating. This is not an appropriate way of operating the units (the electric efficiency would be very low) and therefore, the secondary burners have been blocked. Moreover, the best way of operating these units is by producing long operating periods, since very low electric power is produced during the initial heat-up process of any unit.

In order to assess the influence of the transitory heat-up period of any unit several tests have been carried out at the Stirling Centre with two Stirling CHP units. Three variables have been monitored: gas input, electric output, and thermal power. Figure 4 below presents an experimental characterization of the CHP unit, performed at the Stirling Center, with hot start, 70 ºC water initial temperature, and 60ºC set point.

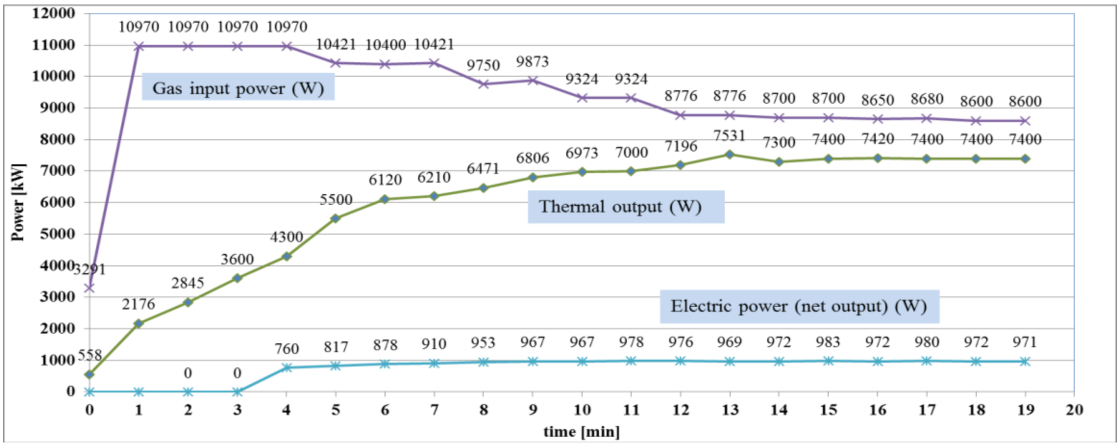


Figure 4. Experimental values for the Thermal output, Electric power and Gas input for the ehe Stirling engine used in the present work. Unit operating conditions: hot start, 70 ºC water initial temperature, and 60ºC set point. Characterization performed by the Stirling Center.

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Finally, the units require very clean water to operate, as the refrigeration circuit inside the unit is very tortuous. Therefore, a water cleaning device (Spirotrap Junior Dirt Separator, G3/4ery cleaSpirotech) has been inserted in the water line of the units. For the same reason, a deaerator (Spirovent Junior Microbubble Eliminator, G3/4nator, G3/4or, G3/4tor, G3/4/4Spirotech) has been also installed in the main circuit, in the boiler room section, in the outlet pipe to the zones. Its purpose is to remove air bubbles from the water in the circuit that could damage internal parts in the CHP units.

4. Performance monitoring

4.1. Stirling CHP unit monitoring and control

The heat produced by the units and the heat delivered to the zones have to be continuously monitored. Therefore, real time heat flow measurements have been considered. Nevertheless, it was necessary to determine the gas based input power and the electric output, since the Stirling units operate as “black boxes”, and have no modbus communication capacity. As each unit is running on an “on-off” basis, the simplest solution is to monitor the unit’s thermal output and calculate the values of the other variables based on this thermal output. To do so, repetitive tests have been carried out with the ehe units running in the Polish district, and the following correlations between Thermal output and Gas Input and Electric output have been obtained (Figure 5). Regarding the measurement of the electric output, the pump power consumption has not been included (its inclusion would produce a lower “net” electric output from the CHP unit).
Based on the monitoring results, correlations between the Thermal output, and the Gas Input and Electric output, have been produced, based on recorded values from Table 1. As shown in Figure 5 the ehe units show a very low electric efficiency during the first 10-15 minutes of operation (the units are being heated-up during this period). Therefore it is important to keep the units running for long periods to obtain significant electrical efficiencies. This allows also for more simple linear correlations, as the errors produced in the heat-up and cold-down periods will be negligible in long unit’s operating periods.

Time (min)	Therm out (W)	Electr Out (W)	Gas input (W)
11:00	2600	0	11000
11:02	3121	138	10500
11:04	4358	397	10500
11:06	6294	711	10500
11:08	7372	878	10500
11:10	8331	961	10500
11:12	8718	1020	10500
11:14	8973	1015	10500
11:16	9050	1002	10500
11:18	9170	1002	10500
11:20	9116	1002	10500
11:22	9235	978	10500
11:24	9232	994	10500
11:26	9169	989	10500
11:28	9195	990	10500
11:30	9174	994	10500
11:32	9161	1000	10500
11:34	9244	993	10500
11:36	9296	985	10500
11:38	9262	1005	10500
11:40	9263	988	10500
11:42	9173	995	8500
11:44	8340	305	0
11:46	7084	183	0
11:48	5278	56	0
11:50	3803	22	0
11:52	2732	0	0
11:54	1850	0	0
11:56	898	0	0

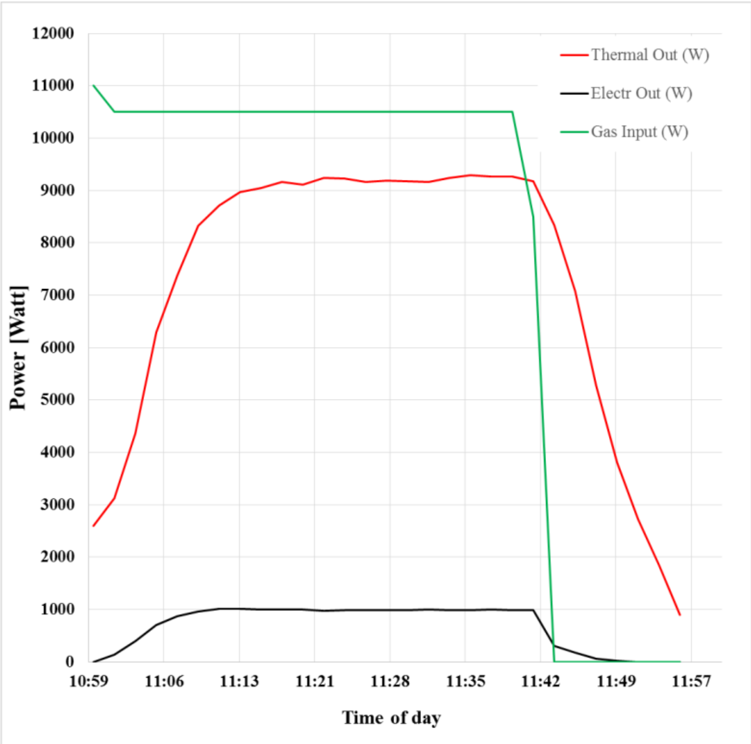

Figure 5. Thermal output, Electric power and Gas input values in CHP Unit 2, as monitored at the Polish demo district. The Unit was switched-off at 11:42 h.

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Table 1. Correlations between the Thermal output and the Gas input and Electric output, in the Unit tested.

Time (min)	Therm. out (W)	Electr. Out (W)	Gas input (W)
0	0	0	110000
15	8700	1000	11000
	10000	1000	11000

4.1.1 Performance and limitations

From the information received from the unit's manufacturer, as well as from the tests carried out in the units, the following performance characteristics arise for each unit:

- Minimum operating time is 30 minutes
- Minimum time between consecutive unit operations is 8-10min
- Minimum water flow rate and corresponding pressure drop in unit: 15,5 l/min and $\Delta P < 230$ mbar
- Outlet water temperature that causes the automatic unitau shutdown: 85ºC
- Outlet water temperature for automatic unittausesand c after a forced shutdown due to overheating, : ≤ 70 ° C
- Initial time without electricity production: 3 min
- Transitory time with increasing electricity production after electricity production starts: 7 min
- Time till full electrical output is achieved, from start: 10min
- Time till stable operation : 18-20 min
- Average electrical output ramp rate till stable operation: ~ 54 W/min.
- Time needed from full power to a zero thermal output: ~18min

4.2. Thermal unit and zone management in the district.

The district heating of the Polish demo site can operate in two different modes:

- *Thermal mode:* the units are activated/de-activated sequentially to fulfill the heat demand of the zones in the district. This is the standard mode of operation.
- *Electrical mode:* the district manager demands the maximum possible electricity production. Thus, the activation of all available units is requested. However, operation should ensure that none of the units is overheated.

The electrical mode operation is activated by the district manager, and switches automatically to the thermal mode after a certain time. In the district demo site, there is no continuous manager control of the district. Thus, the electrical mode has to be activated automatically, one hour per day, simulating the manager request.

In practical terms, the objective of the thermal mode operation is to compensate for the thermal demand of all zones in the district, while still ensuring that no unit will become overheated. Thus, before activating one unit, it must be assured that the unit can work for a reasonable time without exceeding the maximum acceptable outlet water temperature. The ultimate target for the district is to keep the water in the flow pipe of the main circuit at temperatures in the range of 65-70 ºC. Therefore, the set-point for controlling the heat transfer from the back-up boiler to the district should be set at 65 ºC and, similarly, the set-point for the tank associated thermostat should also be set at 65 °C.

Higher values would make unit 3 to operate only during extremely cold days: As shown in Figure 2, unit 3 will receive hot water directly by-passed from the district's flow pipe (at 65-70 ºC) and water cooled in Zone 3 (at 55-60 ºC). The inlet water temperature to unit 3 will depend on the ratio between those two flows. If this temperature is higher than 65ºC, the unit's outlet water temperature can surpass 85 ºC, causing the automatic shutdown of the unit due to overheating.

In addition to the above generic operation strategy, there are several design and operational constraints that must be considered to ensure the system's smooth operation. These constraints refer to both district and unit levels. When total demand exceeds heat production by a certain amount (6 kW) an additional CHP unit is activated. On the other hand, when heat production is larger than the total thermal demand by 4 kW, one CHP unit is deactivated. Any unit not operating will be considered as being in a stand-by mode and, if the unit's inlet water temperature is lower than a maximum value, the unit's is ready for being activated.

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For the district thermal management it is necessary to perform several operations to decide the activation or de-activation of the units, in order to balance the thermal demand from the Zones with the heat produced by the Units. The aim is to keep the district's water circuit between the maximum and minimum temperatures, avoiding, when possible, the operation of the back-up boiler (in cases of low water temperature in the circuit) and the automatic shutdown of Units (when there is high water temperature).

4.3. Polish district Continuous monitoring and performance analysis

The district performance analysis can be done with the monitored and stored data from the Units and Zones. The analysis will be based on the continuous monitoring of district Units and Zones, with values received every second, and the respective data manipulation in by the monitoring program.

At every second, the manager PC establishes communication with the Boiler room (BR) and each Zone, and monitors all variables in these systems. A data record is created including the following information: Month, date, hour, min, second, and the values of the variables monitored.

Furthermore, every 20 seconds, key performance variables are calculated from the monitored values (e.g. heat output) are produced.

The following variables, relevant to each Zone & Unit performance analysis, are taken into consideration from the monitoring program.

1. Monitored variables from the Boiler room’s panel:
   - Supply temperature (hot water) from the plate heat exchanger to the district loop Return temperature (cold water) from the district loop to the heat exchanger
   - Water tank temperature
   - Water flow to the district loop
2. Monitored variables from every Zone’s panel:
   - Return (cold) water temperature from the district's circuit to the Unit
   - Flow temperature (hot) water from the Unit to the district's circuit
   - Return temperature (cold) water from the Zone (radiators)
   - Flow temperature (hot) water to the Zone (radiators)
   - Water flow to the Zone
   - Water flow through the Unit
   - Electric power generated by the Unit (calculated via correlations)

In the case of no communication with the Zone’s panel, some (or all) of the above values are invalid. To indicate the state of the unit, the manager PC creates some additional variables:

- Total working hours of the unit (h)
- Continuous Run time of an operating unit during the last cycle (s)
- Continuous Stop time of a non operating unit during the last cycle (s)
- Operational state of the Unit (manual off, manual on, automatic)
- Availability of the Unit for operation (serviceable, not serviceable)
- Connected (no, yes)
- Unit’s working state (no, yes)
- Unit’s next action (nothing, waiting to run, waiting to stop)

Some additional variables, needed for the management of the Zone, are also calculated:

- Thermal power transferred to the Zone (W)
- Input power to the Unit: calculated via correlations, as a function of the thermal power (W)
- Thermal power generated by the Unit (W)
- Unit’s thermal efficiency (%)
- Unit’s Electrical efficiency (%)
- Unit’s Total efficiency (%)
- Heat balance of the Zone (W): Heat from the Unit - Heat to the Zone

A spreadsheet has been created in order to collect all required measured data and to execute the thermal balance calculations. Information contained in it is as follows:

- The period analyzed, in text (eg PERIOD: November 2013)
- Gas properties: NATURAL GAS LHV (MJ/m3)

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- Emissions: Fumes Temperature, CO 2 (%), CO (ppm) and NOx (ppm)
- Flow temperature (hot) water from the plate HE to the district circuit (ºC)
- Return temperature (cold) to the Plate HE (ºC)
- Water flow through the HE (l/min)
- Water tank temperature (ºC)
- Boiler's availability (always to set to 1; the back-up boiler is available)
- Heat received from the back-up boiler (W)
- Heat transfer to Zone 1 (W)
- Heat obtained from Unit 1 (W)
- Heat transfer to Zone 2 (W)
- Heat obtained from Unit 2 (W)
- Heat transfer to Zone 3 (W)
- Heat obtained from Unit 3 (W)
- Unit 1's total working hours (h)
- Unit 2's total working hours (h)
- Unit 3's total working hours (h)
- District's total heat generation (W) in Units. Calculated in Excel
- District's total heat consumption (W) in Zones. Calculated in Excel

The above data can be utilized to produce graphs of the monthly distribution of the following thermal and efficiency variables:

Power variables	**Efficiency variables**
Thermal power to the Zone,	Unit's electric efficiency,
Input power to the Unit (gas),	Unit's thermal efficiency,
Unit's thermal output,	Unit's overall efficiency,
Unit's electric output.	Thermal balance of the Zone

4.3.1 Monitoring panels

The user can monitor the performance of the whole system as well as the performance of a single zone and a single unit. The performance of the whole system is shown in the following window of the management program (Figure 6):

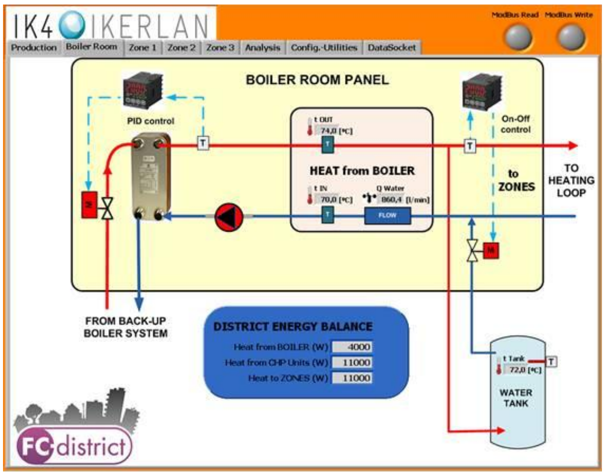

Figure 6. "Boiler room" window, in the User interface.

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The following information is then available to the user:

- *t OUT:* Water inlet temperature, from the zones to the plate HE
- *t IN:* Water outlet temperature, from the HE to the zones
- *Q Water:* Water flow in the district's main loop
- *T TANK:* Water tank temperature (used as the reference for the analysis of Units activation/de-activation)

The district global thermal balance is also shown, with:

- *Heat from the BOILER:* Heat transferred from the back-up boiler to the district
- *Heat form CHP Units:* Heat produced for all active Units in the district
- *Heat to ZONES:* Heat transferred from the main loop to all Zones

Similarly, the thermal balance of a single zone is shown in another window of the management program.This window shows, in real time, what is happening in the Zone (1, 2 or 3), including both, the Zone itself and the associated Unit, and gives the manager a clear idea of the thermal balance of the Zone. When the user activates this window the synoptic shown in the figure will be shown.

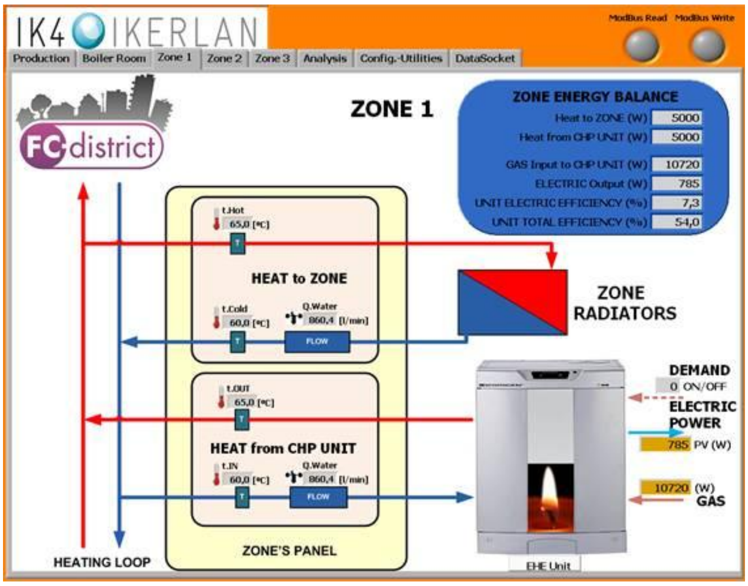

Figure 7. "Zone 1" window, in the User interface.

The following information will appear...

a- regarding the Heat transferred to the Zone:

- *t Hot:* Water flow temperature, from the main loop to the Zone
- *t Cold:* Return Water temperature, from the Zone
- *Q Water:* Water flow in the Zone's loop

b- Regarding the Heat from the CHP Unit:

- *t OUT:* Water outlet temperature, from the Unit to the main loop
- *t IN:* Water inlet temperature, from the main loop to the Unit
- *Q Water:* Water flow in the Unit's loop

c- Regarding the state of the Unit

- *DEMAND:* Thermal demand: active (1) or inactive (0)
- *ELECTRIC POWER:* Electric output from the Unit (calculated)
- *GAS:* Gas based power input to the Unit (calculated)

And the Zone's thermal balance is also shown, with:

- *Heat to ZONE:* Heat transferred from the main loop to the Zone's radiators
- *Heat form CHP UNIT:* Heat produced for the Zone's associated Unit
- *Gas Input to CHP UNIT*: Gas based power input to the Unit
- *ELECTRIC Output*: Electric output from the Unit

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- *UNIT ELECTRIC EFFICIENCY*: Electric Output / Gas Input power
- *UNIT TOTAL EFFICIENCY*: (Electric Output + Thermal Output) / Gas Input power

4.4. Analysis of data collected in the Polish district demo site

The following Figure 8 shows the trend of several variables monitored in the district heating during several days. The purpose of this analysis is to show the performance of different components out of the control of the District management program, the consequences of their behavior and, finally, to set some recommendations for the future management of the units and zones.

Figure 8. Monitoring data from various variables in the Polish district.

The variables shown in the figures are:

- *Boiler Room. Temp. OUT*: Water outlet temperature in the Boiler room. It should be also the water temperature in the whole flow pipe of the district heating circuit.
- *ZONE 3. Temp. HOT:* Water inlet temperature to Zone 3. It should be similar to the water temperature in the district the whole flow pipe of the district heating circof thermal insulation in the pipes connecting the panel with the district circuit.
- *ZONE 3. Temp. COLD:* Water outlet temperature from Zone 3.
- *UNIT 3. Temp. IN:* Water inlet temperature to Unit 3. It should show intermediate values between the *ZONE 3. Temp. COLD* and the *BR. Boiler Room. Temp. OUT*.
- *UNIT 3. Temp. OUT*: Water outlet temperature from Unit 3
- *ZONE 3. Water flow:* Water flow through the Zone 3 radiators circuit. This flow is discharged in the district return pipe, upstream the inlet of UNIT3, and mixed with the flow bypassed trough the K-flow valve located at the end of the district heating circuit.

The data collected show the behavior of some components in the district, as well as of the district itself, that makes the district heating unmanageable, or difficult to manage, in some scenarios (see numbers in the figure):

1. There are communication failures lasting for more than one hour. During these periods of no communication, the District management program does not receive any information about the zones' thermal needs and the units' thermal production. It cannot also send any On-Off command to the units. According to the adopted management strategy, this scenario would cause units' blockage.

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2. When there is small thermal demand in one zone, the control of the heat transferred to this zone, makes the water flow to the zone to become unsteady (opening and closing the two-way valve). The associated unit, that receives cold water flow from the zone, receives an also unsteady inlet water temperature. As a consequence, the calculation of heat flow in the Unit becomes unsteady due to the thermal inertia of the system (very quick changes in the Unit's Inlet water temperature with less rapid changes in the Unit's outlet water temperature).
3. The Inlet water temperature to any zone should be identical to the Boiler room's outlet water temperature (the temperature of the whole flow pipe in the thermally insulated district circuit). As can be seen, the *Zone 3 Temp HOT* is a bit lower than the *Boiler room temp OUT* when there is a thermal need in the zone, and becomes much lower when the zone's valve for controlling the heat demanded is closed. The only consequence is an additional instability in the calculation of the heat produced by the Unit and the heat consumed by the Zone. Moreover, the *Unit 3 Temp. IN* should always show values between the *Zone 3 Temp. COLD* and the boiler room's outlet water temperature. Nevertheless, the *Unit 3 Temp. IN* values shown are always higher than the *Boiler room temp OUT* values. The only plausible explanation for this fact is that there is a small water recirculation through the unit's bypass, with hot water entering, again, the unit after having been heated in it. This too hot water inlet temperature to the Unit can cause the units automatic shutdown due to overheating. Form the data collected so far it is not possible to investigate whether there is water recirculation in all units or it is restricted to unit 3. Recommendation: Eliminate the water recirculation in the Unit's loop, either by means of a non-return valve or by increasing the pressure drop in the Unit's circuit.
4. As already described in point 2, with a small thermal demand in one Zone, the control of the heat transferred to this zone, makes the water flow to the Zone to become unsteady, and the calculation of heat flow in the Unit becomes unsteady too.In this case, if the calculated unit's heat production is "increasing" and the unit is switched off, the time required for the unit's heat output to be reduced down to an alarm threshold is longer than expected. As a consequence the UNIT FAULT message will be produced, together with the Units blockage. The order for the units' de-activation should come from the management program. Nevertheless, once per day the unit is automatically stopped for about one minute (late information coming from the unit's manufacturer), without any order from the management program. Despite the fact that this de-activation is non abnormal, the Management program will produce UNIT FAULT messages, together with the Units blockage.
5. If one unit has not been switched-on for more than 24 h, the unit, automatically, switches the water pump ON, to avid the pump blockage.

5. Conclusions

The paper presented shows the configuration and the innovative operation concept of a model district in Poland, comprising three zones, each equipped with a ehe μ-CHP unit. Operation results have been analysed.

There are some components in the Polish district demo site (zone temperature control, the Stirling units, etc.) whose behavior is, in some cases, absolutely uncontrollable from the District management program. Nothing can be done to overcome this but to take it into account for the alarm management.

Similarly, unexpected communication failures make the district uncontrollable from the District management program.

The unit's loops in the district's return pipe produce undesirable water re-circulations to the units (at least to unit 3), thus increasing the unit's inlet water temperature and risking for the unit's overheating and the consequent unit's self-deactivation. This water recirculation through the working units should be either minimized or eliminated.

There are too many uncontrolled situations causing false UNIT FAULT messages to appear. Provided that the units are self-protected, a new version of the program has to developed and implemented with a single UNIT FAULT check: after an ON order.

The units shall be operated as long as possible because of their low electrical efficiency during startup.

The district control must take into consideration the heat demand of each consumer (zone), so that units are switched on and off according to their position in the network, in order to avoid overheating and forced shut-down.

A storage tank is needed to act as thermal inertia. The auxiliary burner of the units is only needed to cover peak demands, when there is no other backup heating system installed. In the current setup it has been deactivated completely.

With all those recommendation set in the district management program, as well as in the district heating layout, additional long term tests, fully monitored, will be carried out to assess the performance of the Stirling units in the district.

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