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SMART POWER GENERATION IN WASTEWATER TREATMENT PLANTS

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The reported research results are part of the activities dedicated to the development of the concept of "Positive Energy Yield WWTPs". The main contribution of the paper consists on the emphasis that the energy balance of a WWTP has to be evaluated from the perspective of the energy bill rather than quantitative supply and consumption of energy.

The paper presents the approach that has been followed in the development of process modeling in a WWTP including mass and energy balance and exergy analysis in order to identify possibilities for flexible operation of CHP units from WWTPs as smart power suppliers.

Keywords: smart power generation, smart grids, wastewater, demand side management, energy bill

1. Introduction

The demographic evolution at world scale and the concerns related to the degradation of the environment favored the unprecedented development of renewable energy sources. In the current context power engineering is evolving towards sustainable energy solutions that are aggregating the achievements on energy efficiency, reengineering of the energy production and energy consumption patterns and integration of renewable energy sources.

With a massive tendency of urbanization which determined the current situation where 60% of the World's population is living in urban agglomerations, the problems of water supply and sanitation, waste collection and treatment become more and more relevant. In the case of wastewater treatment sector the main concerns are related to higher efficiency of the treatment process, better control of the quality of separated sludge with minimal consumption of energy and other resources [1,2].

Among the solutions that are envisaged the production of electricity inside the wastewater treatment plants (WWTPs) became classical solutions and there is a continuous effort to increase the quantity and quality of produced power. In the

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last two decades the production of electricity is moving towards the concept of smart grids as shown in Fig. 1.

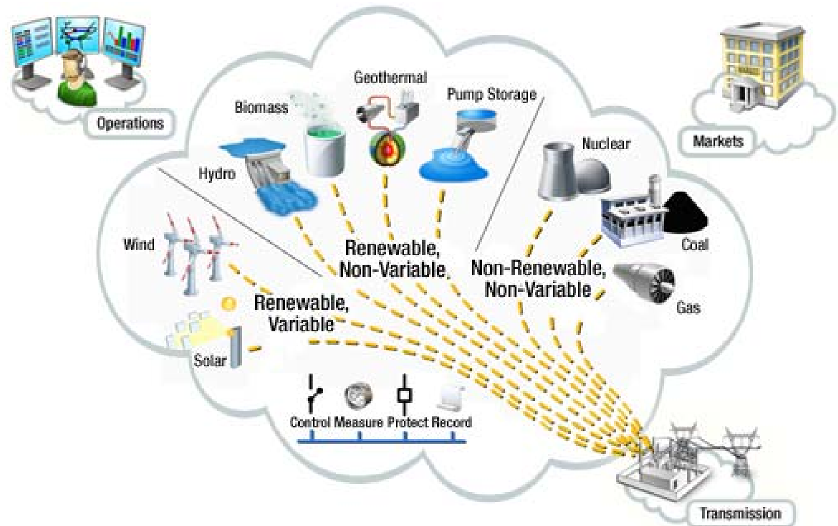


Fig 1. The concept of smart grids.

According to the US Department of Energy, “a smart grid brings the power of networked, interactive technologies into an electricity system, giving utilities and consumers unprecedented control over energy use, improving power grid operations and ultimately reducing costs to consumers”[3].

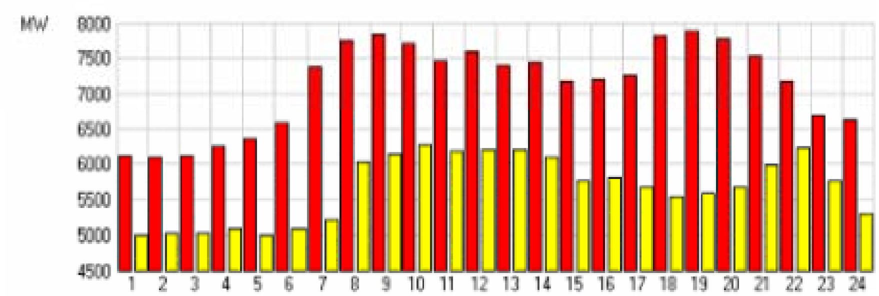
Within the EU, it has been established a dedicated technology platform – European Energy Platform for Electricity Networks of the Future [4]. In the Strategic Research Agenda 2035 [5], there are listed the top priorities in terms of scientific research and among these priorities a very important role is allocated to the distributed self-organization versus central control system and the development of power technologies to increase network flexibility.

Smart power generation (SPG) is a concept that is part of the overall approach to smart grids and consists on matching the electricity production with the demand according to the topology of the grid by using single or multiple generators which could start, stop or operate efficiently at a specific chosen load that makes them suitable to generate electricity either for base load or for peaking power [6]. Within this concept the load balancing (matching supply and demand) is moving from a specific task of operators of power transmission systems towards the suppliers of electricity. In such a way the classical supply centered grids are replaced by demand driven supply grids.

The production of electricity using cogeneration systems in wastewater treatment plants has to be reconsidered and redefined from the perspective of smart power generation [7]. In the following paragraphs the authors intend to demonstrate that the wastewater treatment process has the potential to offer a larger flexibility to the CHP (combined heat and power) units using the biogas generated from the anaerobic digestion of the activated sludge.

2. Energy trading

The energy market is regulated by the demand and supply law. As might be seen in Fig. 2, the typical demand curves are characterized by two major peak regions. For supplying the electricity at the required quantity and quality there are organized platforms for trading.



hours

Red: January 17th2001 (winter day) ; Yellow: June 20th 2001 (summer day)

Fig 2. Typical load curves for winter and summer seasons in Romania.

According to the Romanian regulations there is organized a dedicated platform for electricity trading named Romanian Gas and Electricity Market Operator – OPCOM. At present the section that is functional for energy trading is the Day Ahead Market (**DAM**) and there are preparations for starting the Intra-Day Market (**IDM**) [8].

The **DAM** is a part of the electricity wholesale market where active electricity is traded for each trading interval of the corresponding delivery day. The DAM creates a centralized market framework for selling and buying electricity by the Romanian wholesale electricity market participants, needed for:

- Facilitation of the setting up of a competitive, transparent and non-discriminative wholesale electricity market in Romania;
- Reducing the trading prices for electricity;
- The establishment of the reference prices for other wholesale electricity market transactions.

The DAM provides a functional tool in order to archive the equilibrium between the bilateral contracts, load forecast and technical availability of the production units for the delivery day on hourly basis. The active electricity surplus or the deficit can be managed through selling or buying that on the DAM.

The **IDM** is intended to be a part of the electricity wholesale market where active electricity is traded for each trading interval of the corresponding delivery day. The IDM creates a centralized market framework for selling and buying electricity by the Romanian wholesale electricity market participants, needed for:

- Facilitation of the setting up of a competitive, transparent and non-discriminative wholesale electricity market in Romania;
- Fair and transparent trading prices for electricity.

The IDM provides a supplementary functional tool for participants in order to adjust their contracting portfolio and to achieve the equilibrium between the bilateral contracts, load forecast and technical availability of the production units for the delivery day on hourly basis, closer to physical notification sending deadline. The active electricity surplus or the deficit can be managed through selling or buying that on IDM.

Depending on the specific technologies, management structures and business models, the power suppliers are categorized according to the region of the load curve on which they are operating as might be observed in Fig. 3:

- ZB – base region where the plants are operating in steady state continuous regimes;
- ZSB – intermediate-base region that is characteristic for plants suitable to operate also at partial loads;
- ZSV – intermediate-peak region suitable for plants that could operate at large variations of load and even to be shut down in different periods of the week;
- ZV – peak region suitable for plants operating for short periods of time covering the peak hours demand.

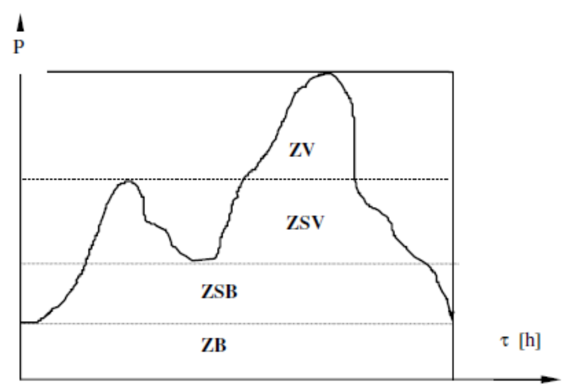


Fig 3. Operating regions on the daily load curve.

As it might be seen, a power supplier could earn very good revenues if operates at peak hour region, having the capacity to have quick response to the market needs by following the Intra-Day market.

It is also worth to mention that according to the current regulation the biogas plant operators could benefit of 3 green certificates for each MWh supplied. The green certificates are traded on a separate market organized under OPCOM.

3. WWTPs with positive energy balance

According to recent studies, the municipal wastewater may be considered as a large carrier of chemical and thermal energy. As an example [9] in a country like The Netherlands, treating the wastewater require 8,1 PJ/y while the potential for recovery energy based on Biogas production is estimated at 9,4 PJ/y, with an additional 1,2 PJ/y from sludge incineration.

Taking into account such arguments and other similar [10, 11], there is an increasing interest on the recovery of energy from secondary resources in sewerage and wastewater treatment plants.

The energy content of wastewater include the energy accumulated as physical enthalpy of the wastewater, chemical energy that might be yielded from the biochemical reactions of the organic and inorganic substances contained in the wastewater and biochemical energy of the primary sludge and secondary biosolids. The typical energy content in wastewater is presented in table 1 [12].

Table 1

Energy content of wastewater

Constituent	Value	Unit
Average heat in wastewater	41,900	$MJ/10^{o}C \cdot 10^{3}\ m^{3}$
Chemical oxygen demand (COD) in wastewater	250 – 800 (430)	mg/L
Chemical energy in wastewater, COD basis	12 – 15	MJ/kg_{COD}
Chemical energy in primary sludge, dry*	15 – 15.9	MJ/kg_{TSS}
Chemical energy in secondary biosolids, dry	12.4 – 13.5	MJ/kg_{TSS}

*total suspended solids (TSS)

The consumption of energy in the WWTPs is distributed among different processes depending on the type of the plant and the specific composition of the wastewater [13,14].

Energy consumption varies considerably between treatment processes and wastewater facilities, but typically the most energy intensive processes are aeration for biological treatment and pumping, as presented in Fig. 4 [15].

In the context of global concerns related to the impact of greenhouse gas emissions on global warming and climate change, the reduction of carbon footprint at water industry is becoming a very "hot" topic and from several perspectives it was proposed a concept that is becoming a label or a trend towards self-sufficient or even energy producing WWTPs. Proposals as: "energy self-sufficient WWTPs", "positive energy plant", "WWTPs with positive energy balance", "net zero energy WWTPs", "WWTPs with positive energy yields" and even "e+ WWTPs" may be found in the literature.

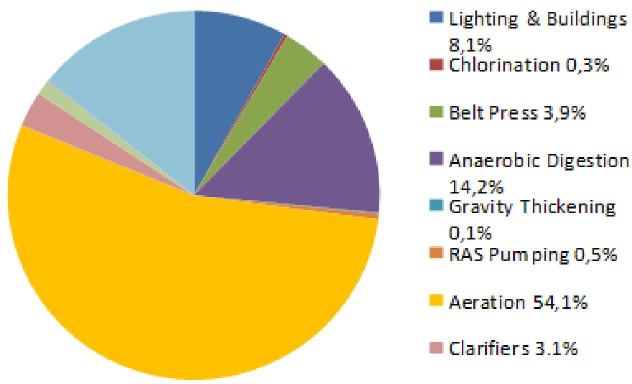


Fig 4. Typical energy breakdown of WWTP

The detailed analysis of the energy consumption, efficiency and potential of secondary energy sources at the level of each process and subprocess requires the combination of three basic engineering tools as mass balance, energy balance and exergy balance with lifecycle assessment methods.

4. Mass, energy and exergy balances of WWTPs

There is a large variety of sewage treatment plant types which makes the activity of modeling to be very complex. For the purpose of this paper we will use one of the reference layout proposed in the literature [10] as presented in Fig. 5.

Due to the complexity of the processes the different streams of flows have very complex structures and a dynamic change of properties. Usually at the inflow there is the main stream of sewage waters or wastewater that is a complex solution including different fractions, either in aqueous solutions or solid suspensions. The mixtures are reacting based on biochemical processes, both aerobic and anaerobic, the wastewater stream finally resulting in two new streams: the treated water or purified water and the sludge stream concentrated in biomass. The sludge stream is following also several processes depending on the type of the WWTP, it might be fermented releasing high value biogas and resulting neutralized sludge that, depending on the composition, can be either used or disposed to the environment. If the final two streams might be considered as stabilized media with homogenous properties, the intermediate streams are much more complex evolving between different processes and facilitating physical, chemical and biological reactions.

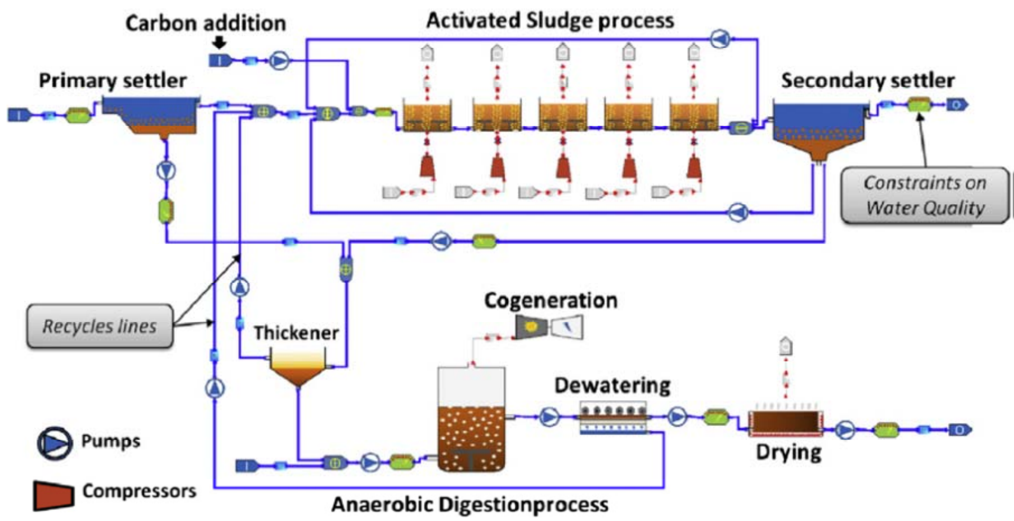


Fig 5. Reference WWTP layout [10]

The modeling process consists basically on decomposition of the processes in subprocesses and definition of a topology of systems and components.

Based on the defined topology there are identified the inflows and outflows in each system and subsystem. The key element at this point is to identify the thermophysycal properties of the inflow and outflow streams at the level of each system and subsystem of the plant. Using these properties, there are computed the conservation equations for mass energy and exergy and the kinetic equation for each process [16,17]. The mass balance equations are usually written for liquid phase and gas phase and for a specific control volume it should take the following form:

$$\frac{dm_{cv}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e \quad (1)$$

where:

$$\dot{m}_i = \int_A \rho \dot{V} dA \quad (2)$$

The equations (1) and (2) have to be written in particular for each component of the stream and should take into account the transfer factors between different species. The terms used in the equations (1) and (2) represent the following:

- m_{cv} – mass accumulated in the control volume;
- $\dot{m}_i$, $\dot{m}_e$ – mass flows at inlet and exit from the control volume for each specie;
- ρ – local density of the flow streams;
- V – volume flows for each stream.

Energy conservation equations have the general format as follows:

$$\frac{\partial \Phi}{\partial t} + \nabla \cdot J = q \tag{3}$$

where

- Φ represents a form of energy;
- J are convective or diffusive flows;
- q represents source/sink terms as chemical reactions, rate processes or external sources.

Exergy conservation equations are defining the maximum work that could be obtained from each stream and have the following general format:

$$e_j = h_j - h_0 - T_0\left(s_j - s_0\right) + \sum_k \left[\Delta g_k + R_k T_0 \ln\left(\frac{c_k}{c_{k,0}}\right)\right] + \frac{V^2}{2} + g\left(z - z_0\right) \tag{4}$$

where the notations are:

- e – specific exergy;
- h – specific enthalpy;
- s – specific entropy;
- g_k – specific Gibbs potential for component k,
- R – gas constant;
- c – concentration of a certain species;
- V – velocity;
- g – gravitational constant;
- z – dimensional height, index j refers to a specific stream and index 0 refers to reference state.

Analyzing the above-mentioned equations there might be identified the basic thermophysical properties characterizing the streams exchanged between different systems and subsystems of the WWTP. Generically there were selected as reference fluids the wastewater, activated sludge, biogas and the outflowing water stream.

5. Characterization of fluid streams

The inflow streams to the WWTPs have a generic name as wastewater. The sources of wastewater may be very different from human activities to industrial. The main constituents of wastewater are according to the categories listed in the table 2.

The contribution of constituents can vary strongly. As seen in table 2, the organic matter is the major constituent of the wastewater. The organic fraction can be measured as COD and BOD (biochemical oxygen demand).

Table 2

Constituents present in wastewater

Constituents	Result	Outcome
Microorganisms	Pathogenic bacteria, virus and worms eggs	Risk when bathing and eating shellfish
Biodegradable organic materials	Oxygen depletion in river and lakes	Fish death, odors
Other organic materials	Detergents, pesticides, fat, oil and grease	Toxic effect, aesthetic inconveniences, bio accumulation in the food chain
Nutrients	Nitrogen, phosphorus, ammonium	Eutrophication, oxygen depletion, toxic effect
Metals	Hg, Pb, Cd, Cr, Cu, Ni	Toxic effect, bioaccumulation
Other inorganic materials	Acids, bases	Corrosion, toxic effect
Thermal effects	Hot water	Changing living conditions for flora and fauna
Odor (and taste)	Hydrogen sulphide	Aesthetic inconveniences, toxic effect
Radioactivity		Toxic effect, accumulation

COD measures the organic fraction presented in the sample through chemical oxidation by dichromate. These measurements are needed for the mass balance in wastewater treatment

BOD measures the quantity of oxygen needed for oxidation of the given organic matter. The BOD analysis is used for the effluent control and it usually takes 5 days.

The wastewater is a combination of various pollutant loads mixed together in a water fraction [1,18,19, 20]. The daily or yearly polluting loads can form a good basis for a wastewater composition evaluation. Following the treatment process result two out-flow streams as the "treated" water stream and the activated sludge stream.

In the context of the current challenges related to the flexibility of the WWTP operation and particularly in the case of power supply based on the biogas generated from the sludge digestion, there is a need for increasingly details and precise information on the thermophysical properties of the main streams in the WWTPs. The major problem which is encountered is the variation of composition and of the flow of different streams. Just as an example, in Fig. 6 the variation in flow, COD and suspended solids are presented.

For an accurate analysis and optimization process the dynamic variation of compositions and flows have to be measured and estimated with a very high precision.

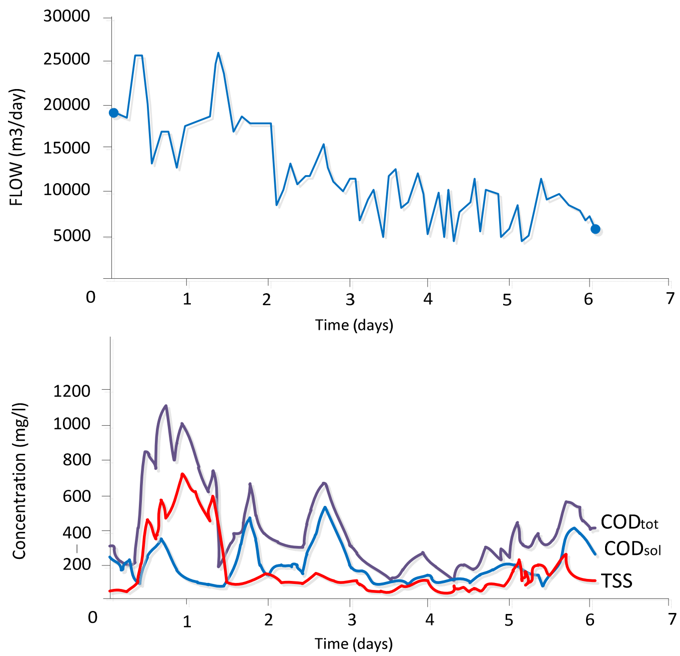


Fig 6. Variation in wastewater flow, COD and suspended particles

6. Power generation and power management schemes in WWTPs

The conversion of a WWTP from a power consumer to a smart power supplier might be done only in the conditions of using the separated sludge from the treated process or the biochemical processes as electricity generation sources. In this respect there are three generic technologies as follows:

- Anaerobic fermentation of separated sludge and conversion of biogas to electricity;
- Combustion of separated sludge and conversion of heat to power;
- Integration in the water treatment process of microbial fuel cells.

In the case of the present work there were taken into consideration the WWTPs equipped with digesters and CHP units with internal combustion engines. The flexibility of power generation depends on the buffering capacities in the sludge treatment line by appropriate dimensioning of the different tanks. Also, on the biogas generation and supply line by appropriate dimensioning of the gas tanks. At the same time the energy consumption inside the plant has to be rescheduled for maximizing the advantage of the minimal tariffs in the off-peak regions of the daily load curves.

In this respect, in reference [21] there are presented several strategies for rescheduling the pumping units and compressors in order to avoid their operation in the peak regions.

For improving the flexibility, in the case of air compressors there were also conceived special schemes with compressed air accumulators. The supply of heat to maintain the operation temperature of the digesters has been solved by integration of hot water buffer tanks and heat pumps able to recover the heat from inflow streams using electricity from the grid in low tariff off-peak regions.

The supply of electricity to the grid has been improved by shifting the connection schemes of the generators from classical supply schemes to intelligent connection schemes.

An example of a classical scheme is resented in Fig. 7 where in case of main failures the generator circuit breaker is opened and the CHP will shut off. Consumers have no power until utility returns. When utility returns, the CHP has to be reset manually and set back to automatic mode

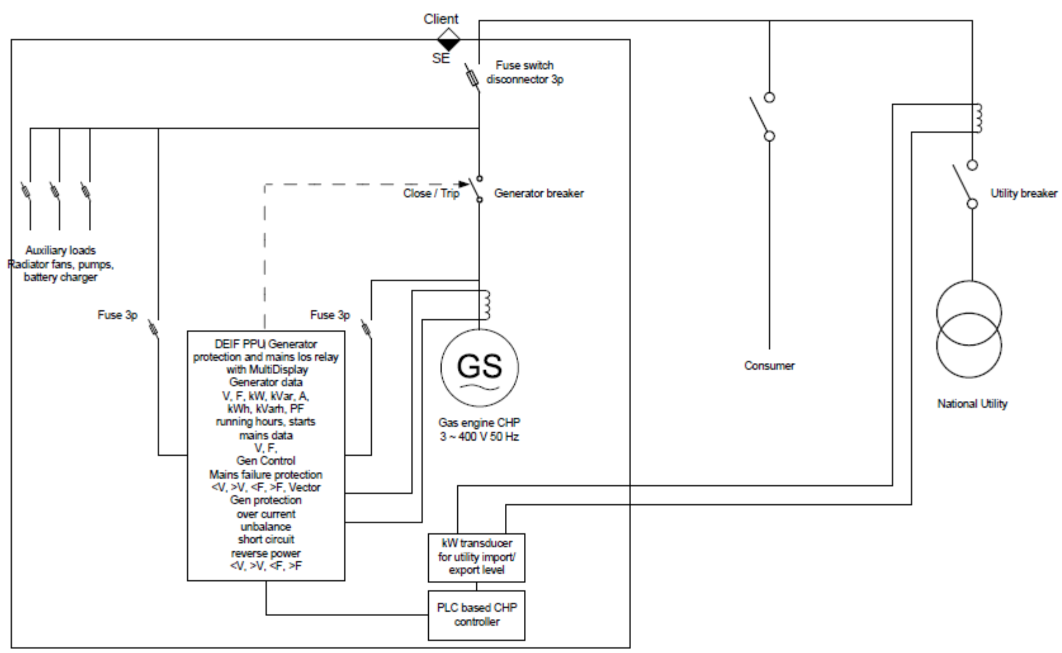


Fig 7. Single line diagram CHP, grid parallel operation only.

In Fig. 8 the improve scheme includes resynchronization loops. In case of utility breakdown, the utility breaker is opened and the CHP will keep running. Customer has to make sure that the consumer load is less than the nominal power of the CHP. When utility returns, the CHP re-synchronizes to the utility automatically, the utility breaker will be closed and the CHP is running again in parallel mode.

The concept of operating the CHP units from WWTPs has been tested in the case of a plant in Constanta. At present, there is under final phase of implementation a program of investments that include the installation of a 0.4 MW_e CHP unit and of several measures for the improvement of the power supply and electricity consumption.

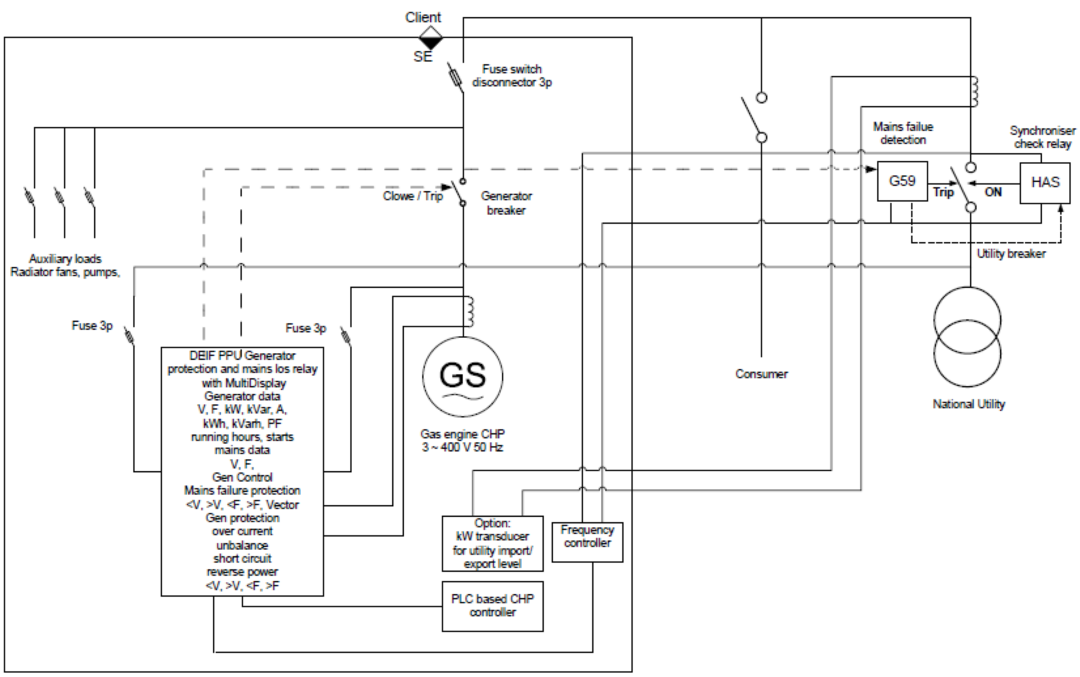


Fig. 8. Single line diagram CHP, grid parallel and island mode with re-synchronization

7. Conclusions

Smart power generation is a concept that is part of the overall approach to smart grids and consists on matching the electricity production with the demand from the energy trading markets in order to maximize the incomes from electricity sold.

WWTPs are suitable to be operated by putting as objective function the maximization of the incomes on generated electricity by the implementation of the SPG concepts. In such a way it has been developed an original approach to the WWTPs with positive energy balance by concentrating on the energy bill of the plant.

Acknowledgement

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