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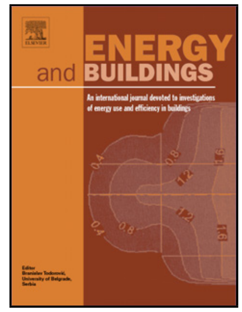

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Ecological sanitation, organic animal farm, and cogeneration: Closing the loop in achieving sustainable development-A concept study with on-site biogas fueled trigeneration retrofit in a 900-bed university hospital

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HIGHLIGHTS

- In this paper the overall environmental and economic problems that may be associated especially with large university hospitals are addressed.
- The aim was to show a rational methodology to convert their energy and environmental disadvantages by applying ecological sanitation and developing an energy, water, food, and education nexus
- For this purpose on-site biogas possibilities and potential were investigated for a 900-bed existing hospital to be retrofitted by a trigeneration system.
- Optimum fuel share and optimum trigeneration system cascading and optimum sizing methodology shown.
- The concept study comprised two scenarios and three stages. These were namely the base scenario, which utilizes three trigeneration engines 1,25 MW_e, and two 2,2 MW_e capacity each, all running on natural gas with a total capacity of 5,65 MW_e.
- The first stage of the second scenario mixes biogas produced on-site with natural gas for driving the 1,25 MW_e engine, which satisfies the constant base load of the hospital for 24 hours a day.
- The second stage of this scenario produces biogas on the large surrounding free premises in a new eco-farm and replaces the fuel input of the 2,2 MW_e engine, which operates 16 hours per day.

- In the third stage of this scenario the last trigeneration unit with 2,2 MWe capacity remains on natural gas fuel input, which only operates approximately 8 hours per day (peaking engine).
- Both scenarios also involve the same absorption cooling capacities and an 8 MW_c-h ice tank.
- This common base of identical capacities was employed for a ten-year operational period to analyze the environmental and economical benefits of biogas substitution.
- In order to provide sufficient biogas supply, two biogas systems were envisioned. The first one utilizes the waste of the hospital. The second system involves a new organic 6000 livestock-animal farm and dairy installation, which completes the food, water, energy, education and environment nexus and serves as a full-scale hands-on farm for the Department of Agriculture students and R&D platform, thanks to the available very large land area around the hospital.
- The application is expected to have a large economical impact and important contributions also on the dietary needs of the patients. The organic farm also incorporates greenhouses, wind and solar farms.
- Yet the analysis of this study covers only the impact of the biogas supply to the trigeneration system.
- CO_2 emissions from biogas production are utilized for dry ice production.
- Analyses show that the additional cost of on-site biogas anaerobic digester and its ancillaries of the first-stage (1,25 MW_e) biogas+natural gas mix trigeneration unit may pay back itself in four years.
- The corresponding prediction for the second stage biogas trigeneration system with biogas fuel (2,2 MW_e) is also four years. Attributable to the biogas supply, these two stages satisfy 51 % of the annual-average peak power load and 46 % of the peak cooling load.
- Total reduction in CO_2 emissions attributable to biogas conversion of the trigeneration system is 74720 tons over a ten-year period taking into account the additional reductions due to improvements in exergy management. The net total savings from biogas conversion in two stages will be about 4 M€ for a ten-year period.

ABSTRACT

Healthcare facilities mostly consume natural gas or fuel oil, utilize grid power, and are the second most energy intensive sector in the USA. Besides their high fossil fuel expenditures, hospital buildings generate large amounts of plumbing wastes and others, such that they are the largest producer of GHG emissions in the building sector. Energy costs are consuming up to 15 percent of their annual profits. In this paper the overall environmental and economic problems that may be associated especially with large healthcare facilities are addressed by showing ways to convert their energy and environmental disadvantages into advantages. In this respect, a concept study with ecological sanitation and formation of an energy, water, food, and education nexus by primarily employing a trigeneration system operating with biogas at an optimum fuel share with natural gas for retrofitting an existing 900-bed University hospital is presented. This case study covers two scenarios. The first scenario is the base scenario, which utilizes three trigeneration engines, with 1,25 MW_e, and two 2,2 MW_e capacity each, all running on natural gas with a total capacity of 5,65 MW_e. The second scenario includes three stages. The first stage mixes biogas, which is to be produced on-site by primarily using plumbing wastes, with natural gas for driving the 1,25 MW_e engine, which satisfies the constant base load of the hospital for 24 hours a day. The second stage produces biogas by making use of the widely available surrounding free land of the hospital in a new eco-farm development and replaces the fuel input of the first 2,2 MW_e engine, which operates 16 hours a day on average. In the third stage the second trigeneration unit with 2,2 MWe capacity remains on natural gas fuel input and operates approximately 8 hours a day (peaking engine). Both scenarios have an absorption cooling system with the same capacity and an 8 MW_c-h ice tank. This common base of identical power, heat, and cold capacities was aimed to focus on the environmental and economic benefits of biogas substitution covering a ten-year operational period. In the second scenario two biogas systems were envisioned. The first one for the first stage utilizes the plumbing waste of the hospital. The next system for stage two involves a new organic 6000 livestock-animal organic farm and a dairy factory to be owned by the University, which completes the food, water, energy, education and environment nexus and serves as a full-scale hands-on farm for the Department of Agriculture students and an R&D platform. It has been shown that such an application closes the loop towards sustainability. The organic venture is expected to have a large economic impact and important contributions also on the dietary needs of the patients. The organic farm is envisioned to incorporate greenhouses, wind, and solar farms. Yet this study only covers the impact of the biogas supply to the trigeneration system. CO_2 emissions from biogas generation is assumed to be captured and utilized for dry ice production. Analyses show that the additional cost of on-site biogas anaerobic digester and its ancillaries of the first-stage (1,25 MW_e) may pay back themselves in four years. The corresponding prediction for the second stage biogas trigeneration system with biogas fuel (2,2 MW_e) is also four years. Total reduction in CO_2 emissions attributable to the biogas conversion of the trigeneration system is 161558,2 ton CO_2 over a ten-year period, taking into account the additional reductions due to improvements in rational exergy management of the energy resources. The net total savings from biogas conversion in two stages is expected to be about 4 M€ for a ten-year period.

Keywords: *Biogas generation, Organic farm, Eco-sanitation, Hospital energy system retrofit, Trigeneration, Absorption cooling, Rational Exergy Management Model*

1. INTRODUCTION

Rising energy costs challenge the operating margins and further drain hospital funds originally targeted for better healthcare quality, medical research, and safety improvements. The latest trend in large hospitals is to use cogeneration or trigeneration systems to provide power and heat on-site, which are particularly becoming popular after the Katrina Hurricane when the only hospital remained operational in the entire region was the Mississippi Baptist Medical Center with a trigeneration plant. Although trigeneration systems may save up to 30% primary fuel; they still operate on natural gas or fuel oil in many hospitals. This relatively modest primary fuel savings may not be the only and ultimate answer to offset the rising fuel costs and to reduce the environmental impact. So far, the use of renewable energy resources is also quite limited in hospitals. According to the US DOE statistics, health care buildings are one of the most energy-intensive buildings all over the world [1]. Hospitals consume large amounts of energy because of how they are operated and the many people that use them. They are open 24 hours a day; thousands of employees, patients, and visitors occupy the buildings daily; and sophisticated heating, ventilation, and air conditioning (HVAC) systems control the comfort temperatures, hygiene, indoor air quality, and air flow. In addition, many energy intensive activities occur in these buildings: laundry, medical and lab equipment use, sterilization, computer and server use, food service, and refrigeration, to name a few. The 2007 Commercial Building Energy Consumption Survey (CBECS) [2] data showed that large hospitals (greater than 18500 m^2) accounted for less than 1 % of all commercial buildings and 2 % of commercial floor space, but consumed 4,3 % of the total delivered energy used by the commercial sector in 2007 [2, 3]. Data from the 2007 CBECS show that the amount of major energy sources (electricity, natural gas, fuel oil, district heat) consumed by large hospitals was 5,5 % of the total delivered energy used by the commercial sector in 2007. **Fig. 1** shows that natural gas is the most common main heating and cooking fuel, used by 74 % of the hospital buildings, followed by district heating with 20 %. All hospital buildings have air conditioning and nearly all, to be exact, 92 % of them, use electricity for air conditioning.

Value of Combined Heat and Power in Medical Centers

In recent years, cogeneration and trigeneration systems in many variations are penetrating hospital energy market due to their fuel savings potential [4, 5]. Many hospitals are retrofitted with trigeneration systems mainly for economic reasons and in order to provide a high level of back-up, emergency, and stand-by features to the hospitals, particularly during disasters [6, 7]. The 624-bed Mississippi Baptist Medical Center (MBMC) was the only hospital with its energy island based on a 4,6 MW_e combined heat and power system for critical infrastructure [8].

During the Katrina hurricane which took place on August 29, 2005, this hospital,

- Remained open and treated a high volume of patients,
- Provided clothing, food, and housing for displaced patients,
- All laboratories were kept open, subjects and specimens were saved,
- Opened a round-the-clock day care to allow employees to focus on patient care.

Large hospital buildings have the potential of protecting the environment by reducing their green-house emissions by employing trigeneration systems. This is also true for other large commercial buildings especially for airport terminal complexes [9].

Fuel Savings

Although according to EU/2004/8/EC Directive (repealed by Directive 2012/27/EU) [10], cogeneration (aka CHP: Combined Heat and Power) may save fuel up to 30%, fossil fuel costs are high enough that further solutions for new designs and applications using substitute fuels like biogas [11] and renewable energy systems in cogeneration format like solar photo-voltaic thermal and cooling (PVTC) systems are in order [12]. However, the solar energy approach requires high initial investments and may not be technically feasible for retrofit jobs due to limited architectural, visual, and structural constraints of existing hospital buildings. Consequently, in many retrofit cases the most feasible step is to introduce trigeneration systems partly relying on alternative fuels like biogas. In this respect, the biogas potential of the hospital itself may be tapped in an economical and environmentally safe and sound manner. The advantages in this case are mainly two-fold, namely fuel savings by trigeneration and converting hospital wastes to alternative fuel by on-site biogas production, provided that corresponding CO_2 emissions are captured and utilized in a useful and environmentally benign manner. **Eq. 1** gives the so-called Primary Energy Savings (*PES*) percentage in terms of reference values for separate power and heat generation efficiencies $RefE\eta$ and $RefH\eta$, respectively, compared to the partial power and heat efficiencies of the trigeneration system, $CHPE\eta$ and $CHPH\eta$, respectively [10]:

$$PES = \left[1 - \frac{1}{\left(\frac{CHPH\eta}{\mathrm{Re}\,fH\eta} + \frac{CHPE\eta}{\mathrm{Re}\,fE\eta}\right)}\right] \times 100 \quad \text{or,} \tag{1}$$

$$PES = \left[1 - \frac{1}{CHPH\eta\left(\frac{1}{\mathrm{Re}\,fH\eta} + \frac{C}{\mathrm{Re}\,fE\eta}\right)}\right] \times 100 \tag{2}$$

where, C is the power to heat ratio of the system.

$$C = \frac{CHPE\eta}{CHPH\eta} \tag{3}$$

According to EU/2004/8/EC the reference values are 0,52 and 0,85 in normal practice, for *RefEη* and *RefHη*, respectively [10]. The total First-Law efficiency of the same system is given by **Eq. (4-a)**.

$\eta_T = CHPE\eta + CHPH\eta$. Consequently, (4-a)

$P_e = CHPE\eta \times P_f$, (4-b)

$P_h = CHPH\eta \times P_f$. (4-c)

Here, P_f is the power of the input fuel based on the lower heating value (LHV). *CHPHη* includes heat used to drive heat operated cooling machines in a trigeneration system. P_e is the electric power capacity and P_h is the thermal power capacity. According to **Eq. 1**, *PES* is limited in normal practice by about 30% and depends on the total efficiency of the trigeneration engine and *C* (see **Fig. 2**).

2. LITERATURE SURVEY

The increased interest in cogeneration and trigeneration systems in hospital buildings using fossil fuels has led to new research topics primarily in economic feasibility, energy savings, and environmental assessment areas. Yet detailed research and application about the production and use of biogas in hospitals are limited. Although the fuel savings have been pretty much known in terms of the First Law, the application of the Second Law of Thermodynamics in those research areas is almost nil. In a broader context, Kilkis, B. has introduced the Rational Exergy Management Model (REMM) to hospitals and applied to a complex green mechanical system [3]. He considered trigeneration with a steam bottoming cycle, thermal storage, ground-source heat pumps, absorption and adsorption cooling machines, ice and cold water storage, solar energy, and photovoltaic. He showed that while the standard method of calculating exergy efficiency for a sample hospital case was about 0,5, the Rational Exergy Management Efficiency could reach a value of up to 0,94 with a careful optimization of the systems and equipment bundle. This efficiency directly relates to CO_2 emissions [4]. Renedo et al. studied different cogeneration alternatives based on the First Law for a Spanish hospital center. They compared diesel engines and turbines and concluded that diesel engines are more advantageous because of their higher electrical power output [5]. Desmarais concentrated on the demand side of a hospital retrofit with 340 beds in Canada and showed that substantial savings are possible and these measures must be taken into effect before retrofitting or designing a cogeneration or trigeneration system [6]. Manning investigated the cogeneration opportunities with fossil fuels in hospital buildings based on a 264-bed acute care center and exemplified the fuel savings and reduction of harmful emissions [7]. Kilkis, B. extended his REMM analysis to other large building complexes like airport terminals with a similar approach [9]. Murai et. al on a broad context and comprehension, covered the energy cost minimization topic with biomass-fueled cogeneration in NetZero and Positive Energy Buildings. They introduced a method of solution for cost minimization and applied it to a large building in France and showed that such buildings may be energy positive [11]. Lozano et.al stated that trigeneration systems are particularly useful in warm areas where cooling loads are also involved [13]. They developed an optimization model on an hourly load basis with the objective function for minimizing annual total cost. They applied their model to a hospital in Zaragoza in Spain. According to their results a significant reduction in the annual energy cost (90%) with a payback period of less than 3 years in relation to conventional energy supply systems was possible. Beihong, Z. and Weiding, L. have developed an optimal sizing method for cogeneration plants based on a sizing problem formulated in terms of mixed-integer nonlinear programming problem with the constraints of energy demands, equipment performance characteristics and the energy relationships of the whole system. They applied their method to a gas turbine cogeneration case in Shanghai [14]. Seo, H. et al. studied the economic gain of introducing cogeneration system to a housing complex and found more than 30% of fuel savings [15].

Hourly load prediction is very important to optimally size the cogeneration and trigeneration systems and it directly affects the economics and fuel savings of the installation. Usually load prediction is not easy and in many existing buildings proper and accurate hourly data is not available. In order to solve this issue, Pedersen, L., Stang, J., and Ulseth, R. have developed a load prediction method for different building categories based on statistical data obtained for a district heat system and power consumption [16]. They also provided a load aggregation methodology to estimate the peak loads. Shariatzadeh et. al modeled and optimized the Solid Oxide Fuel Cell (SOFC) for the tri-generation hybrid system fed by biogas produced from hospital waste. A 50 kW_e tubular SOFC combined with a chiller, heat recovery steam generator, combustion chamber, and required equipment was considered in their study. The system provides 50% of total electricity required using the produced biogas and also provides the whole cooling load of the hospital using an absorption chiller [17]. Lozano, M. A., Cravalho, M. and Serra, L. M. have developed a cost allocation method that is valid for all possible operation conditions of the trigeneration system. The heat produced by cogeneration modules is disaggregated into three fractions: heat that meets the heat demand directly, heat utilized to drive absorption chillers (producing cooling), and heat dissipated to the environment. Cost allocation to all cogeneration co-products is determined by applying the principle of avoided expenditures. The cost allocation proposal is applied to a trigeneration system providing energy services to a hospital with 500 beds located in Zaragoza (Spain) [18]. According to calculations carried out by Kantola, M. and Saari, A., when considering a facility, the size of the new Espoo Hospital (56600 m^2) in Finland, the most affordable solutions were biogas energy, wood chip heating and ground source heating. They have also stated that biogas energy is only suitable for large-scale projects and some uncertainty risk has to be added because the system is not yet commonly used [19]. Ziher, D. and Poredos, A. have considered a natural gas turbine trigeneration system for one of the largest hospitals in Slovenia. Their analysis concentrated on cooling loads and found out that the most economical solution was steam absorption along with compression chillers with cold storage. The pay-back period was 5,8 years [20].

None of the above mentioned studies have referred to the Second Law of Thermodynamics. Probably the earliest exergy dedicated analysis of cogeneration was carried out by Kilkis, B. and Kilkis, S. [21]. Later Dinçer, I. and Rosen, M. A. and Ahmadi, P. reported a thermodynamic model based on both energy and exergy analysis for trigeneration system greenhouse emissions [22]. Huang et al. argued that if grown sustainably, biomass can be considered to be CO_2 neutral. A trigeneration system consisting of an internal combustion engine integrated with biomass gasification may offer a feasible combination for delivering heat, electricity, and cooling cleanly and economically. They carried out their analyses by using the ECLIPSE process simulation package over selected buildings, which showed that the high capital cost of the trigeneration plant reduces the economic viability for small scale systems and this system performs much better economically in a building with a higher cooling load spread over a 12-month period. [23].

Meegoda et al. have developed a fully sustainable sanitation system for a rural hospital in Haiti. Their proposed design was a hybrid anaerobic/aerobic system that maximizes methane production while producing quality compost. A toilet is designed to separate liquid and solid human waste at the source to control carbon to nitrogen ratio and moisture content to facilitate enhanced biodegradation. The separated solid human waste is collected and decomposed in an anaerobic digester to capture the methane gas for heating or cooking [24].

3. BIOGAS PRODUCTION IN HEALTHCARE FACILITIES

3.1. Categories of waste water and waste

Large hospitals are a good source of a diverse amount of wastes in different streams for biogas production as shown in **Fig. 3**.

The yellow water contains the highest proportion of nutrients (nitrogen, phosphorus and potassium), which are directly available to plants and equally effective as mineral fertilizers. Urine contains approximately 90 % of the total nitrogen, 55 % of the total phosphorus and a substantial portion of the potassium contained in human excrement. The brown water mainly comprises of human faeces. The grey water from washing, rinsing, and shower drains, while representing the largest fraction of the total wastewater flow, has only a very low nutrient content. Therefore, it can be treated by simple techniques such as constructed wetlands, waste water ponds, biological treatment, membrane technology, filters and biofilms and is thereafter ready for reuse as service water and for irrigation purposes and may also be discharged into surrounding watercourses. The brown water consists mainly of faeces which are the predominant source of pathogens of all streams of domestic wastewater and therefore responsible for the major hygienic hazards. It is also rich in organics, nutrients and trace elements. It is treated, if necessary together with organic waste by composting, stabilization, or anaerobic digestion. Thus, the organics and nutrients contained in faeces can be used in concentrated and hygienically safe form as a dry fertilizer, compost or fluid fertilizer. Dependent on the type of treatment, energy can be produced if necessary in the form of biogas after anaerobic digestion. Urine diversion is principally a collection system of separating human urine at the source before it mixes with faeces. This is achieved with specially designed toilets and urinals, piping systems and storage containers. By separating urine from faeces, separate treatment options can also ensure a more manageable faecal fraction and reduce potential odors. The technological options available for urine diversion and collection include many different designs of urinals and toilets connected to a collection container via drain pipe or channel. When the urine is separately collected by a urine diversion toilet or urinal, then a piping system normally consisting of two separate pipes for urine and faeces and at least one storage tank is required. Anaerobic digestion is the controlled break down of organic matter in the absence of oxygen to produce a combustible biogas and nutrient rich organic by product. Converting faeces into biogas and using urine as a substitute for mineral fertilizer will contribute to the reduction of greenhouse emissions (CO_2, CH_4 and N_2O). EcoSan can therefore be promoted according to

Article 2 of Kyoto Protocol which denotes "Research on, and promotion, development and increased use of, new and renewable forms of energy, of carbon dioxide sequestration technologies and of advanced and innovative environmentally sound technologies; Limitation and/or reduction of methane emissions through recovery and use in waste management, as well as in the production, transport and distribution of energy" [26-a]. EcoSan can also be regarded as clean production mechanism under Article 12 of Kyoto Protocol. Biogas, which is mainly composed of methane and carbon dioxide, is produced during the decomposition of organic matter in anaerobic conditions. The organic matter is decomposed in a number of steps in collaboration between several different types of microorganisms. The efficiency of the biogas production depends on how suitable the conditions are for the microorganisms. To initiate a biogas process, sludge containing the bacteria for starting the process is inoculated.

3.2. EcoSanitation (EcoSan)

The EcoSan system is considered for large hospital complexes. The sanitation devices included are: gravity separation toilets using rainwater for flushing which allow the separate collection of 80% of undiluted urine apart from faeces, i.e. 20% of urine is misdirected with faeces flow, one waterless urinal, one sink and one small kitchen (sink and dish-washer).

Wastewater output from the building consists of 3 main flows: brown water including flushing water, faeces and 20% of misdirected urine; yellow water, corresponding to 80% of urine left; grey water from the utilization of water for sinks, washing machines, and kitchen. Yellow water is collected and discharged by gravity into pump wells, from which it is pumped to the holding tanks for at least 6 months in order to meet the sufficient hygienic requirements before the application onto farmland as fertilizer. Brown water is assumed to be drained off by gravity to the pumping station from where the mix is pumped to the solid–liquid separator. The solid fraction is further thickened and transported to the anaerobic digester, where it is treated and converted into biogas assumed to be composed of only CH_4 and CO_2. Grey water is collected by gravity drainage and treated (**Fig. 4**). Biogas contains roughly 53-73% methane, 30-40% carbon dioxide and trace of other gases such as nitrogen and hydrogen sulphide. **Table 1** presents the typical composition of biogas [26-a].

3.3. Assumptions

This study assumes that the CH_4 content in biogas is 65% and its CO_2 content is 35%. The biogas production from human faeces is based on certain assumptions [27]:

- Average daily production of human manure is: 0.12 kg/person, with average composition of 71% water and 29% dry matter
- Organic matter makes up 86% of dry matter
- Hydraulic retention time: 20 days.
- Anaerobic digestion efficiency 50%.
- Produced biogas is composed of 65% CH_4 and 35% CO_2.
- The reactor remains at atmospheric pressure throughout the whole digestion process. Results are obtained calculating the theoretical production of biogas by decomposition of organic matter.

Daily organic matter availability per person and correspondent amount of produced biogas are given in **Table 2** [26-b]. Volumes are calculated at standard conditions, (1 atm, 20ºC); under these conditions 1 mol of gas occupies a volume of 22.4 liters.

4. CONCEPT STUDY: TURGUT OZAL UNIVERSITY HOSPITAL

Turgut Özal University Hospital **(Fig. 5)** surrounded with a large unused land is an existing 900-bed capacity university hospital in Malatya belonging to the Inonu University [28]. The existing central power plant, located about 1,5 km from the hospital involves steam boilers that run on natural gas. Steam is delivered to the hospital with steam piping. Then, steam is reduced to hot water for HVAC applications in the hospital. Steam for sterilization,

cooking, and laundry services are generated again on site by in-floor electrical steam generators. This rather awkward situation poses an irrational exergy management of the primary energy (Natural gas) source [9,12]. Comfort cooling relies on electrical power driven chillers. Because the continuity and quality of the hospital services were of prime concern, the energy and comfort delivery systems within the hospital buildings need to be kept untouched. Therefore, all the retrofit shall take place only in the mechanical rooms. For this reason, the trigeneration system was designed to work parallel with the existing central energy system.

4.1. Loads

The hourly hospital load data were virtually non-existent. Therefore, the hospital building complex was energy simulated after an extensive on site survey in an earlier study by using the Energy Plus® program package [28]. The results were compared with available limited monthly power and fuel consumption data and a good correlation was observed.

4.1.1. Thermal Loads

Using the simulation package, hourly HVAC (both heating and cooling) loads, domestic hot water demand, steam demand, and power demand of the hospital were predicted. HVAC loads primarily depend on the outdoor climatic conditions, because the number of patients, employees, type of daily services and other factors remain fairly constant throughout the year. **Fig. 6** and **Fig. 7** show the heating and cooling degree-hours of Malatya generated through a new study partly supported by ASHRAE [29].

4.1.2 Electrical loads

Besides power load predictions the limited amount of hourly power load data was also employed for different months, which are shown on **Fig. 8** [28]. This figure shows that there are at least two power demand peaks in the range of 8000 kW_e throughout a typical day during morning hours, when most of the medical equipment and operating rooms are in full service including medical services for outpatients. During the night-time period the power demand stabilizes to about 2000 kW_e. The annual average peak electrical power demand is about 5000 kW_e. It must be noted that **Fig. 10** does not include chiller loads in the cooling season, which according to **Fig. 9**, the cooling load peaks to about 4200 kW_c. Therefore, taking into account the cooling demand, the instantaneous peak electrical power demand may reach up to 12200 kWe. When trigeneration is employed, part of the cooling demand is satisfied with absorption and or adsorption cooling machines.

4.2 Trigeneration Engines

Base Scenario: In the base case, natural gas driven CHP units with 1x 1,25 MW_e, and 2 x 2,2 MW_e capacities were considered. These CHP units have the following features:
$CHPE\eta$ = 0,37 (rounded), $CHPH\eta$ = 0,46 (rounded), C = 0,37/0,46 = 0,8 (rounded), n_T = 0,83.

All efficiencies are corrected hourly with respect to air pressure, outdoor temperature, outdoor humidity and one-time correction with respect to local altitude and averaged over 8200 hours. Single Effect Absorption system and ice storage system driven by deep chillers using surplus power from first-stage CHP engine during night time are also used.

<u>Biogas Transition Scenario and its Stages:</u> The same CHP units are used but biogas fuel is introduced in order to drive them.

Stage 1: Ecosan biogas system supports the first stage CHP unit with biogas-natural gas mix with the same design capacity of 1,25 MW_e. 5320 hours of winter operation, 2880 hours of summer operation (8200 hours per year at 24 hours per day average) are foreseen. Biogas is produced from hospital wastes and locally obtained additional raw material from apricot produce **(Table 3).**

Stage 2: Second stage 2,2 MWe capacity CHP unit is to be entirely driven by the biogas from the new Eco Farm and organic dairy. 5456 hours of winter operation, 1920 hours of summer operation (7376 hours per year at 16 hours per day on average) is foreseen. For stage 2, the economic life of the CHP unit may be somehow shorter, in the order of one or two years. Yet in this analysis it has been assumed that this effect may be compensated by high quality filtration of the biogas, which has been taken into account in the biogas fuel costs. Nevertheless, this effect is already small for Stage 1, because the CHP engine runs primarily on natural gas.

Stage 3: 2,2 MW_e CHP remains on natural gas and is aimed at 8 hours of operation per day. Envisioned operating hours regarding Scenario 2 and the triple power charge tariff periods are shown in **Fig.11**.

Table 3 summarizes all the pertinent features of the CHP systems, including the single-effect absorption machine and the cold storage system.

4.3 REMM Analysis

In almost all energy efficiency, fuel consumption, and CO_2 emissions calculations, world-wide, only the First-Law of thermodynamics is considered, i.e. the quantity of energy is taken into account during the flow of energy use and energy conversion. On the other hand, the Second-Law of thermodynamics deals with the rational utilization of the energy quality and pays attention to the exergy match between the supply and demand, which is also responsible from avoidable CO_2 emissions. Better the exergy match, lower the avoidable CO_2 emissions are and lower is the exergy destruction. This has been recently formulated by the *Rational Energy Management Model* (REMM) by Şiir Kilkis [12, 21, 30, 31, 32].

This paper focuses on the quality of different energy resources aka exergy-including waste energy and biogas- that may be optimally tied in with diverse and non-simultaneous energy demands of a health care facility by using REMM.

Based on ideal Carnot cycle, REMM defines a new efficiency metric named *Rational Exergy Management Efficiency*, ψ_R. It is also denoted by ψ_{RCHP} to signify it when associated with a CHP (cogeneration or trigeneration) system. In a CHP system, power is generated first and exergy is destroyed next. In this case ψ_{RCHP} is defined by the following formula [12]

$$\psi_{RCHP} = 1 - \frac{\sum \varepsilon_{des}}{\varepsilon_{\sup}} \qquad \text{Here:} \qquad (5)$$

The unit exergy (ε) is defined according to the ideal Carnot Cycle:

$$\varepsilon = \left(1 - \frac{T_{ref}}{T_i}\right) \qquad \{T_{ref} < T_i\} \qquad \text{(6-a)}$$

$$\varepsilon = \left(\frac{T_{ref}}{T_i} 1\right) \qquad \{T_{ref} < T_i\} \qquad \text{(6-b)}$$

T_f for natural gas and biogas (filtered) are almost the same [33] and taken to be 2220 K, which corresponds to the adiabatic flame temperature of the fuel. T_i represents any application temperature, including the supply temperature (T_{sup}). The temperature (T_{ref}) is the reference environment temperature. REMM plots these temperatures on an exergy flow bar that is shown in **Fig. 12** for a given CHP system. In the analyses described herein, T_{ref} is taken 283 K for winter and 288 K for summer. For 120 days for the cooling season the average T_{ref} is taken to be [283 x (365-120) + 288 x (120)]/365 = 284,6 K. After power generation, the hot gas entering the engine exhaust is about 470 K (T_E). Heat output of the engine at the heat exchanger outlet is 363 K This is the supply temperature (T_{sup}) for thermal output. Therefore, exergy is destroyed between 470 K and 363 K (ε_{des1}). Useful heat is utilized in space heating, domestic hot water preparation, and in cooling through the absorption system. The return temperature is 333 K (T_{ret}). This is a closed cycle between 363 K and 333 K. Second exergy destruction (ε_{des2}) takes place between 333 K and the annual average reference temperature of 284,6 K.

According to **Fig. 12**, power is generated between the temperatures of 2220 K and the 470 K, which is the exhaust inlet temperature' measured or calculated right after the power generation step in the CHP engine. The total exergy supplied to the CHP system, ε_{sup} by the fuel is between 2220 K and 284,6 K. In the entire process, there are two exergy destructions. One takes place in the exhaust heat exchanger during thermal power production. The second destruction takes place after thermal power generation with respect to the reference point, T_{ref}. Then, from **Eq. 5:**

$$\psi_{RCHP} = 1 - \frac{\left(1-\frac{363}{470}\right)+\left(1-\frac{333}{363}\right)}{\left(1-\frac{284,6}{2220}\right)} = 0,65,$$

Eq. 1 from the EU Directive [10] was modified by factoring in the Ψ_{RCHP} in an earlier study [12].

$$PES_{RCHP} = \left[1 - \frac{1}{CHPH\eta\left(\frac{1}{\mathrm{Re}\, fH\eta} + \frac{C}{\mathrm{Re}\, fE\eta}\right)\times\left(\frac{2-\psi_{base}}{2-\psi_{RCHP}}\right)}\right]\times 100 \qquad (7)$$

ψ_{Rbase} is 0,20 for a conventional combination of separate boiler, chiller, grid power [12]. Then from **Eq. 7** and using the specific properties of the CHP units listed in **Table 3**:

$$PES_{RCHP} = \left[1 - \frac{1}{0,46\left(\frac{1}{0,85} + \frac{0,8}{0,52}\right)\times\left(\frac{2-0,2}{2-0,65}\right)}\right]\times 100$$

$= 40\%$

4.4. Stages of Biogas Retrofit of the Hospital

In the first stage, an AD (Anaerobic Digester) system is dedicated to the hospital waste and locally supplied organic waste of fruit (Mainly locally grown and processed apricots). The second stage involves a new large organic farm, which is envisioned as a commercial entrepreneurship for the university, which is expected to pay-back by its own income. This entrepreneurship is excluded from the economic analysis of the on-site biogas production except that most of the added value of the second stage is assumed to contribute to the economic balance sheet of the organic farm.

Stage 1. EcoSan: Anaerobic Digester

Typically, one cubic meter of *Methane* has a calorific value of about 9 kW_h-h [34]. Daily production of methane from 1 person's faeces is 8,445 L (see **Table 2**) corresponding to a unit methane production value, e_B of 0,076 kW_h-h/person/day. Methane production capacities through the first stage biogas digester were calculated for the hospital complex from different sources E_B, which are given in **Table 4.** The daily total energy output, E_B may be converted to an average fuel power, denoted by the symbol P_f, based on a catalysis factor C_T (≥1), average daily operating hours of the trigeneration system, T_d, and PES_{RCHP}:

$$P_f = \frac{E_B \cdot C_T}{\left(1 - \frac{PES_{RCHP}}{100}\right)} \cdot \left(\frac{1}{t_d}\right) \tag{8}$$

Whey is used as a catalyst in the reactor with $C_T = 1{,}3$. This means that for a given biogas reactor tank volume, more biogas fuel per time is produced. PES_{RCHP} is 40% from **Eq. 7** and the first stage 1,25 MW_e engine runs approximately 24 hours per day (t_d). Therefore, from **Eq. 8**:

$$P_f = \frac{10721 \times 1{,}3}{(1 - 0{,}4)} \cdot \left(\frac{1}{24}\right) = 968 \ \ kW_h = 0{,}968 \ MW_h$$

With CHPHη = 0,46 (From **Table 3**), P_h = 0,968 x 0,46 = 0,445 MW_h

In the cooling season 80% of the heat generated is used in absorption chillers. Then the cooling power attributable to the biogas mix is:

P_c = 0,445 MW_h x 0,8 x 0,65 = 0,23 MW_c, and

From **Eq. 4-b** and **Table 3**, P_e **=** 0,968 MW_h x 0,37 = 0,36 MW_e.

This is about a fraction of 29 % of the electric power generation design capacity of stage 1 (0,36 MW_e/1,25 MW_e). Then the fuel cost of the natural gas-biogas mix is:

$$FM = NG \times (1\text{-}0.29) \quad (9)$$

In other words, biogas contribute only 29% to the design capacity. The annual operating cost, C_o is taken to be a fraction, *m* of the annual fuel cost.

$$C_o = m \times FM \quad (10\text{-a})$$

The fraction *m* for natural gas operation and biogas operation were taken to be 0,07 and 0,2 and respectively. In Stage 1 of the case study (biogas mix), an average value of (*m*) may be used:

$$C_o = [0{,}07 \times (1\text{-}0{,}29) + 0{,}2 \times 0{,}29] \times FM \quad (10\text{-b})$$

Stage 2: Eco Animal Farm and Dairy

A comprehensive design and analysis was carried out in view of circular economy and medical education for the Inonu University, which houses the hospital complex. The main asset of the complex will be the livestock mainly consisting of 6000 cows. Besides animal solid waste, farming shall also provide substantial amount of biogas digester supply material. Another important asset is the whey output from cheese production of the dairy factory, which is an important catalyzer for anaerobic digestion. Whey is an environmental problem and cannot be disposed without careful processing. Therefore, the use of whey in biogas generation is also advantageous from the point of view of environmental issues. According to **Fig. 13** there are four components in this nexus. These are given below:

1- Energy (High Efficiency CHP Plant)

2- Water (Solar and Wind energy driven irrigation and fresh water wells)

3- Food (New Organic farm and dairy)

4- Education (Inonu University Engineering Faculty and Faculty of Agriculture)

In this study, out of the four components, only the first component (Energy) is considered in the comparative analyses of the second stage. Biogas is supplied through the biogas digesters maintained at about 45°C using an array of solar PVT (Photo-Voltaic and Thermal) systems. There are three raw material input sources to the digesters. These are namely, the sludge from the water treatment facility, animal (solid) waste, and farm (solid) waste.

The average daily biogas output from the animal and farm solid waste is calculated from the following equation for average sized dairy cow by Yavuzcan [37]:

$$G_1 = C_T\,(V \cdot c + EV/6 + A_o/25) \qquad \{m^3/day\} \qquad (11\text{-a})$$

$$G = G_1 + G_2 \qquad \{m^3/day\} \qquad (11\text{-b})$$

Here, G_2 is the daily biogas production from waste water treatment. Corresponding values of this design case are given below.

V = 6000 cows, c = approximately 1m^3/day/cow, EV = 10000 kg/day, A_o = 5000 kg/day, G_2 = 200 m^3/day, and C_T = 1,3. Then from **Eq. 11-b**:
G = 1,3 x (6000x1 + 10000/6 + 5000/25) + 200 m^3/day = 10427 m^3/day

In trigeneration applications, the lower-heating value is used. The average lower heating value after desulphurization and filtering the *biogas* product with 73% methane content is about 6,6 kW$_h$-h/m^3 [38]. Therefore, the total biogas energy output per day is:
E_B= G x 6,6 kW$_h$-h/m^3 = 10427 m^3/day x 6,6 = 68818 kW$_h$-h/day.

Based on 16 hours of operation per day and using **Eq. 8** (C_T is already included in **Eq. 11**) the daily thermal energy output corresponds to an average power of about:
P_f = 68818 kW-h/day/16 h/day/(1-0,4) = 7168 kW$_h$.
Using *CHPEη* of 0,37 and ancillary loss factor of 0,85 the biogas engine power, P_e will be:
P_e = 7168 x 0,37 x 0,85/1000 = 2,25 MW$_e$.

This power is sufficient to drive the second-stage trigeneration engine. When this second-stage engine runs at part loads, surplus biogas supply may be used for a richer biogas mix of the 1,25 MW_e engine (first stage engine). This may further shorten the pay-back period. With CHPHη = 0,46 (From **Table 3**), P_h = 7,168 MW_h x 0,46 = 3,29 MW_h. In the cooling season 80% of the heat generated is used in absorption chillers. Then the cooling power attributable to the biogas mix is, P_c = 3,29 MW_h x 0,8 x 0,65 = 1,7 MW_c.

Fig. 13 shows the principles of the eco animal farm and the organic dairy farm, which establishes the energy, water, food, and education nexus in the campus along with the hospital. The first element of the nexus, namely the energy relies on a CHP plant that also drives the absorption chiller for the hospital in the cooling season. Electrical power output is enhanced by a bottoming organic Rankine Cycle (ORC) system. Wind turbines add more electrical power to the system. Yet wind energy is excluded in the economic analysis of this study, which focuses on the impact of biogas use only. Solar PVT systems through hot-water storage tanks maintain the biogas reactors at the proper digestion temperature. Part of the electrical power generated by the CHP unit may optionally drive ground-source heat pumps (GSHP) for added heating and cooling capacity. For peak thermal power demands peaking boilers are used, which may also run on biogas. Part of the biogas may also be used for farm mobility along with electrical vehicles supported by wind electricity. Water, food, and education elements, which are beyond the scope of this study were explained in detailed in an earlier paper [36].

4.5 Economic Analysis

Economic analyses were based on the ten-year fuel and power predictions made in an earlier study [28]. Electricity cost is broken down to peak demand, day, and night tariffs.
Fuel costs (Natural Gas) are derived from European Union statistics [39, 40].

Electricity costs

Electricity price (*P*) for peak demand hours is given by Equation 12 [28], which also agrees with EU-28 (28 European countries) [40] data:

$$P = a \cdot y - b \text{ , where,} \qquad (12)$$

a = 0,02551 €/kW$_e$-h/calendar year, b = 50,88 €/kW$_e$-h, and the calendar year (y) varies between 2016 and 2025 (Column 1 of Tables, 5, 6, 7, and 8). This prediction is listed in column 2 of Tables 5, 6, 7, and 8. Electricity prices listed in columns 3, 4, and 5 respectively for other periods of the day (N: Night, D: Day, A: Daily average) are a function of P:

$N = 0{,}231P$ {8 hours a day} (13)

$D_e = 0{,}55P$ {11 hours a day} (14)

$A = (11D_e+5P+8N)/24 = 0{,}537P$ (15)

Fuel cost (NG) for natural gas is inferred from EU-28 data and is given in column 6. For biogas mix price (FM) in Stage 1, **Eq. 9** is used and is given in **Table 6**. Biogas fuel cost is the operating and maintenance cost only, which is given by **Eq. 10** and listed in **Table 8**.
Annual fuel cost (C_f) listed in column 8 depends on the fuel type used (NG, FM, or BG):

$$C_f = t_o \times P_e \times C_{FA} \times (BG, \text{or } FM, \text{or } NG) / CHPE\eta \quad (16\text{-a})$$

To be more precise, Eq. 16-a may be written in the following format:

$$C_f = (t_{ow} \times C_{FW} + t_{os} \times C_{Fs}) \times P_e \times (BG, \text{or } FM, \text{or } NG) / CHPE\eta \quad (16\text{-b})$$

Comparing seasonal power and heat outputs of CHP with natural gas prices for a boiler with efficiency (η_b) and average grid electricity cost (A), seasonal added values are:

$$AV_w = t_{ow} \times P_e \times C_{Fw} \times \left(A + \frac{1}{C} \times \frac{1}{\eta_b} NG \right) \quad \text{\{For winter\}} \quad (17)$$

AV_s in **Eq. (18-a)** is composed of four sub-incomes, namely B (savings from grid power), C (savings from natural gas for heat with respect to a separate boiler with η_b), D (savings from cooling with respect to chillers with a day-time COP_c of 3), E (savings from peak demand time cooling with the use of C_{IT} : 8000 kW$_c$-h ice tank, IT), and a sub-expense F, which is the expense of charging the ice tank during night time with deep chillers with a night-time COP_c of 4,5. The income and expense of IT operation is prorated into the three trigeneration systems with respect to their electrical power output capacity ratios to the total capacity (5,65 MWe). IT is used 120 days in a year.

$$AV_s = B+C+D+E-F \qquad \text{\{For summer\}} \qquad (18\text{-a})$$

where:

$$B = t_{os} \times P_e \times C_{Fs} \times A \qquad (18\text{-b})$$

$$C = t_{os} \times P_e \times C_{Fs} \times \left(\frac{0{,}2}{\eta_b \times C} \right) \times NG \qquad (18\text{-c})$$

In summer 0,2 of the total thermal power is used for heat.

$$D = t_{os} \times P_e \times C_{Fw} \times \left(\frac{1}{C \times COP_c} \times COP_{abs} \times [1-0{,}2] \times A \right) \qquad (18\text{-d})$$

$$E = [120 \times \eta_{ITD} \times C_{IT} / 3 \times P] \times P_e / 5{,}65 \quad \text{\{IT discharged during peak demand\}} \qquad (18\text{-e})$$

$$F = [120 / \eta_{ITC} \times C_{IT} / 4{,}5 \times N] \times P_e / 5{,}65 \quad \text{\{IT charged during night\}} \qquad (18\text{-f})$$

For the second stage, the *NG* term in Equations 17 and 18-c is replaced by *BG*, because the major part of the added value is reserved to contribute to the income of the organic farm, although it is excluded from the economic analysis of the biogas systems. Other calculations are given below. In these equations, *NS* is the annual net savings, C_o is the annual operating cost, C_f is the annual fuel cost, *E* is the annual electricity generation in GW_e-h, *H* is the annual thermal energy generation, E_T is the annual total energy generation (electricity and heat), and E_X is the exergy of energy generated. All calculations are tabulated in Tables 5, 6, 7, and 8.

$$NS = AV_w + AV_s - C_o - C_f \qquad (19)$$

$$E = \frac{t_o \times P_e \times C_{FA}}{1000} \qquad \{GW_e\text{-h}\} \qquad (20)$$

$$H = \frac{P_e}{1000C} \left(t_{ow} \times CF_w + t_{os} \times CF_s \times 0{,}2 + t_{os} \times CF_s \times COP_{abs} \times [1-0{,}2] \right) \{GW_e\text{-h}\} \qquad (21)$$

$$E_T = E + T \qquad (22)$$

$$E_{XT} = E_{Xe} + E_{Xh} = 0{,}96E + \frac{t_{ow} \times C_{Fw} \times 0{,}2P_e}{1000C} \times \left(1 - \frac{T_{ref}}{T_{\mathrm{sup}h}}\right) + \frac{t_{os} \times C_{Fs} \times 0{,}8P_e \times \eta_{I\,abs}}{1000C} \times \left(\frac{T_{ref}}{T_{\mathrm{sup}c}} - 1\right) \tag{23}$$

4.6 Sensitivity Analysis

Annual capacity factor (C_{FA}) is quite important on the system economics. In this study, it has been divided into summer and winter capacity factors, namely C_{Fs} and C_{Fw}, respectively, because the operational scheme for winter and summer are different. These capacity factors represent how suitable the capacities of the CHP engines were selected for each season and how well the load predictions were made, such that the CHP units may efficiently operate and keep running for most of the time that they were designed for. For example, if the CHP capacity is selected too high, the units will operate at part loads, thus at low efficiency for most of the time. On top of that, many CHP manufacturers do not permit CHP units to operate below 40% of the installed capacity load. All these constraints effect the seasonal capacity factors, which in turn effect the seasonal earnings, namely AV_w for winter (**Eq. 17**), AV_S for summer (**Eq. 18-b**, **Eq. 18-c**, **Eq. 18-d**). In order to quantify this fact, 2,2 MW_e biogas trigeneration system (Stage 2) has been subjected to various values of C_{FA}, one of which is the original case (Case 2) used in the study (**Table 9**). Summer and winter capacity factors of the trigeneration system were varied and applied to the above-mentioned equations, in order to determine their impact on cumulative earnings, C_s.

Using the information given in **Table 9**, **Fig. 14** was prepared, which shows that the net cumulative earnings is directly and linearly proportional to the annual capacity factor, which like mentioned above, largely depends on the sizing and cascading of the CHP units in relation to the load aggregates. Lower the C_F values, lower are the capacity-demand match for operation. Therefore, it is very important to measure/predict/calculate all types of demand loads accurately in order to match the most appropriate size in terms of a high capacity factor.

On the other hand, thermal storage may be helpful, if systems are somewhat undersized. From **Fig. 14,** it may be inferred that:

$$\frac{\Delta C_s}{C_s} = \frac{a\Delta C_{FA}}{aC_{FA} - b} \qquad (24)$$

Here a is the slope and b is the intercept of the line in **Fig. 14**. It may be further inferred that the sensitivity of the net cumulative earnings, C_s may be minimized by reducing the intercept b, where it gives at the same time the C_{FA} value for zero cumulative earnings.

5. RESULTS

The only cost difference between the natural gas trigeneration plant and the same trigeneration plant running on biogas or a mix of biogas is the AD (Anaerobic Digester) tank system and its ancillaries for on-site biogas production. The rest of the system (CHP engines, absorption system etc.) are identical. Therefore, when the additional savings (Cost difference on **Fig. 15** and **Fig. 16**) are considered, the associated additional investment cost is the installation of the AD system and its ancillaries. Ancillaries primarily include the envisioned PVT (Photo-voltaic and heat) system, which generates electric power and heat simultaneously using solar energy. Heat is stored in hot water tanks in order to be used continually for thermally charging the AD tank. The unit cost of AD tank system (*i*) was derived from [41, 42]. Generally, AD tank and ancillary systems cost is one third of the total biogas power generation system in the sector [42].

5.1. Pay-Back Periods

The biogas component of the trigeneration system for Stage 1 and Stage 2 may be calculated separately from the economic analysis tables given above (Tables 5, 6, 7, and 8). In Stage 1, the economic and environmental contribution of mixing biogas with NG fuel is considered. In Stage 2 NG fuel is completely replaced by biogas and the operational cost is only the maintenance cost including biogas filtration.

Stage 1: On an annual base the difference in net cumulative savings over the ten-year period may be obtained from **Table 5** and **Table 6**. The savings difference between the NG and biogas mix case is attributable to the biogas production and use. The savings difference on an annual base is shown in **Table 10**. These data are shown in **Fig. 15**.

For biogas production, the unit installation cost (*i*) of AD tank, ancillaries, and the PVT per kW_e capacity (excluding all other investment costs regarding power generation, like CHP units etc.) is taken to be 1600 €/kW_e. A rough breakdown of the unit cost is:

- Mechanical digester tank, supports, foundation etc. 500 €/kWe
- Digester tank auxiliaries (Heat exchanger, stirrer, heater, etc.) 100 €/kWe
- BG tank, pressure regulator, controls. 250 €/kWe
- Other auxiliaries like waste silos, conveyors, motors, pumps etc. 300 €/kWe
- Material handling. 100 €/kWe
- PVT solar arrays. 200 €/kWe

- hot water tank. 150 €/kWe

From **Eq. 4-b**, electric power generation potential (P_e) from the first stage raw material from the hospital AD is 360 kW_e.

For a period of 10 years between 2016 and 2025, Column 12 (Net Earnings) in Table 5 for NG and Column 12 in Table 6 for BG were compared. The net difference between the earnings is directly attributable to biogas use (See the last column in Table 10). For example, in 2016 the net earning is 390925,5 € for NG mix scenario. For the same calendar year, the net earnings for the NG scenario is 307156,6 €. There is a positive difference of 83768,0 €. These values were plotted in **Fig.15** and compared with the biogas reactor tank and ancillary investment cost.

Concerning the overall tank cost, *I*, the catalysis factor, C_T is important in determining the tank size, because a smaller tank may be used with the action of the catalyst. Therefore:

$$I = \frac{iP_e}{C_T} \qquad (25)$$

Then, for Stage 1 the tank cost will be:

$$I = \frac{1600 \times 360\ \mathrm{kW_e}}{1{,}3} = 443100\ €$$

Savings from electric power generation from the PVT system and the sales of organic fertilizer is not included in the calculations, which are actually additional income sources for the economic analysis. Back-up NG burner system is used when solar energy is not sufficient. NG fuel cost for this purpose is embedded into the operating cost. According to **Fig. 15**, the biogas AD and ancillary costs are paid back in slightly less than four years. Subtracting these costs from the cumulative earnings at the end of the ten-year period in **Table 7**, the net cumulative earnings is 674735 € (1117735 € – 443000 €).

Stage 2: On an annual base, the difference in net cumulative savings over the ten-year period may be obtained from **Table 7** and **Table 8**. The savings difference between the NG and biogas replacement case is attributable to the biogas production and use. The savings difference on an annual base is shown in **Table 11**. These data are shown in **Fig. 16**.

For biogas production, the unit installation cost (*i*) of AD tank, ancillaries, and the PVT per kW_e capacity (excluding all other investment costs regarding power generation, like CHP units etc.) is taken to be 1400 €/kW_e (slightly lower than Stage 1 due to higher capacity).

Electric power generation potential (P_e) from the first stage raw material from the new organic animal farm, which was calculated previously is (The ancillary loss factor of 0,85 is being compensated at AD):

$P_e = 7168 \times 0{,}37 = 2652\ kW_e$.

Then from **Eq. 25**:

$$I = \frac{1400 \times 2652\ \mathrm{kW_e}}{1{,}3} = 2856000\ €$$

According to **Fig. 16**, the biogas AD and ancillary costs are paid back again in slightly less than four years. Subtracting these costs from the cumulative earnings at the end of the ten-year period in **Table 10**, the net cumulative earnings is 4131211 € (6987211 € – 2856000 €).

After summing up the earnings for Stage 1 and Stage 2, the total net earnings at the end of the ten-year period is calculated to be 674735 €+4131211 € = 40805946 €.

Fig. 17 shows the predicted annual change of *R* value (ratio of electricity cost to natural gas cost). *R* value is an important factor for the pay-back period and it is desirable to be high so that power, which is more expensive on the market is generated with less fuel cost. The predicted value is about 2,2 beyond 2019 and remains stable while natural gas and electricity costs change almost proportionally. In the case study however the impact of *R* value on pay-back periods is relatively small, because Stage 2 is fully and Stage 1 is partially free of natural gas. Thus these scenarios are practically free of the changes in the *R* value. However, the pay-back period for Stage 3 depends more on *R*, while it runs on natural gas.

CO_2 calculations

For natural gas operation of the trigeneration systems, the First-Law of thermodynamics may be simply used in order to calculate the CO_2 emissions with c_i equal to 0,2 kg CO_2/kW_h-h of the fuel input over a ten-year period. For Stage 1, the emission savings is proportional to the natural gas amount by biogas, which is a factor of 0,29. CO_2 emissions in biogas production are assumed to be used in dry ice generation for medical industry. For Stage 2, savings in emissions is the entire emissions replaced by entirely switching from natural gas to biogas. Then the CO_2 emissions savings, SCO_2 from Stages 1 and 2 in a ten-year period will be:

$$SCO_2 = E_1 \times 10^3 \times (0{,}2 \times 0{,}29) \times 10 / CHPE\eta + E_2 \times 10^3 \times 0{,}2 \times 10 / CHPE\eta \quad \text{\{ton/ten year\}} \quad (26)$$

Here, E_1 is and E_2 are the annual electricity production in GW_e-h units in Stages 1 and 2, respectively. From **Table 3**, $CHPE\eta$ is 0,37. After inserting the values for $CHPE\eta$, E_1 and E_2 found in **Table 6** and **Table 8** (See columns 14):

$$SCO_2 = 9044{,}6 \times 10^3 \times (0{,}058) \times 10 / 0{,}37 + 14114{,}5 \times 10^3 \times 0{,}2 \times 10 / 0{,}37$$
$$= (14178{,}0 + 76294{,}6) \cdot 10^3 \text{kg } CO_2 = 90472{,}6 \text{ ton } CO_2$$

After applying the REMM equation, compounded CO_2 emissions reductions calculation is possible by taking into account the increase in ψ_R:

Compounded CO_2 emissions reduction ratio = 1- (1-ψ_{RCHP})/(1- ψ_{Rbase}) (27)

After inserting the corresponding values for the case study, this ratio is 0,56. This modifies the total CO_2 emissions reduction over a ten-year period:
90472,6/0,56 = 161558,2 ton CO_2.

6. DISCUSSIONS AND CONCLUSIONS

This study showed that large hospitals with around 900 to 1000 beds may domestically produce biogas that may only satisfy 10 to 15 percent of the base power load. However, as exemplified in the case study, up to 30 percent of the base power load may be economically satisfied by importing locally available raw material, if available and feasible. In this case study, the region is a large apricot producer and processor, yielding two types of waste - a solid waste of peel/skin, seeds, etc. and a liquid waste of juice and wash waters [43]. This resource was taken into account in the analyses.

The biogas fuel mix with natural gas or replacement of natural gas with biogas may pay back their additional costs over fossil fuel based trigeneration systems in about four years and provide substantial additional earnings according to the results of the case study. However, the sensitivity analyses have shown that the biogas fueled trigeneration systems must be very carefully sized and the loads must be precisely predicted in order to maximize the capacity factors. Otherwise, the earnings decrease linearly with the actual capacity factor. The case study further showed that whenever possible an energy, food, power and even education nexus is a serious potential to improve the overall performance. The case study showed that by integrating an organic animal farm and dairy plant establishes a robust nexus but also enables much higher power satisfaction percentages with biogas produced on site. One important advantage of the organic dairy plant is the local availability of catalyst (whey). In the case study, about 45 percent of the peak power demand (excluding power for comfort cooling which is satisfied by the heat operated cooling machines driven by the trigeneration system) is possible to be satisfied by biogas fuel. The case study also exemplifies the advantages of the Circular Exergy and Economy approach in satisfying the need to reduce resource flows in the society to establish more integrated production and consumption systems. Organic animal farm and dairy complex, coupled with large hospitals have demonstrated in detail that such combinations may present almost ideal places for realizing a complete circular economy. Going beyond circular economy concept proof, results have shown that the same circular concept may apply to a new concept of circular exergy. The latter has resulted in an overall rational exergy management efficiency, ψ_R of 0,65. Similar but even better results were also shown for health care facilities in an earlier study [3, 4]. Compare this with a base case system, which uses boilers, chillers, and grid power, which has an average overall rational exergy management efficiency of 0,20. This is the base value for most applications (ψ_{Rbase}). According to REMM, this also translates into a predictive methodology of reduction in CO_2 emissions [31]:

$$\text{Reduction in } CO_2 \text{ emissions} = 1- (1-\psi_{RCHP})/(1- \psi_{Rbase}) = 0{,}56.$$

It must be noted that this reduction figure takes into account the REMM efficiency. The somehow lower figure obtained with the First-Law of Thermodynamics in previous sections (**Eq**.**26**) clearly show that exergy analyses are a must for emissions calculations. Last but not least, Sustainable Development is defined in the report by the Brundtland Commission in 1987 as “Our Common Future: To meet the needs of the present without compromising the ability of future nations to meet their own needs” [44]. Hospital buildings in many respects may be role models in achieving and sustaining this noble target. Furthermore, in order to accomplish the

Johannesburg Plan of Implementation, new universal sanitation concepts are needed, focusing on economically feasible closed-loop ecological systems rather than on expensive end-of-pipe technologies. Ecological sanitation (EcoSan) systems are based on the systematic implementation of the reuse and recycling of nutrients and water as a hygienically safe, closed loop. Again hospitals may be exemplars of this approach.

Finally, the Biogas Mix Scenario involving Stage 1, Stage 2, and Stage 3, the base CHP scenario (all NG CHP units), and the existing power plant of the hospital were compared. The existing power plant comprises a central steam boiler set with overall thermal efficiency of 0,55. Power is received from the grid with an overall thermal, transmission, and transforming efficiency of 0,27. The grid power fuel mix in Turkey is such that the average c_i value for the mix is assumed to be 0,3 kg CO_2/kWh-h. The power and thermal outputs of the CHP units were taken to be the basis and the same loads were prorated for the existing plant. In other words, because the CHP Scenarios were not intended to completely replace the existing power plant (they run parallel to the plant and replace only a number of steam boilers), the total power and heat (including cold) output of the CHP scenarios (From Columns 14 and 15 of **Table 5** and **Table 7** were applied to the existing power plant in order to determine the CO_2 emissions share and fuel consumption share of the existing power plant. Columns 14 and 15 of **Table 7** were multiplied by two and the fact that the second 2,2 MW_e CHP units remains to operate with NG. It must be noted that 2,2 MW_e CHP units are designed for operating less than 24 hours a day. CO_2 emissions reduction potential is given in **Fig. 18**.

These figures show that CO_2 emissions may be greatly reduced compared to the steam power plant. For example, for the CHP with BG mix case, CO2 emissions are reduced by about 67 %. This is a strong indication that hospital disadvantages in terms of environmental pollution may be converted to disadvantage and the sustainability loop may be effectively closed while other elements of the energy, water, food, and education nexus are supplemented.

7. SYMBOLS

A	Daily average electricity price, €/kW_e-h
B,C,D,E,F	Sub-incomes and sub-expense of AV_s during summer operation of the trigeneration system (see **Eq. 18-a**), €
A_o	Reactor input from green leaf and organic waste, kg/day
AV_w	Added value of trigeneration operation in winter, €/season

AV_s	Added value of trigeneration operation in summer, €/season
a	Coefficient, (**Eq.12** and **Eq. 24**)
b	Constant (intercept), (**Eq.12** and **Eq. 24**)
c	Daily volumetric biogas potential per cow, app. 1m^3/day/cow)
c_i	Unit CO_2 emissions of any fuel combustion (*i*), kg CO_2/kW$_h$-h
C	Power to heat ratio, dimensionless
C_f	Annual fuel cost, €/annum
C_F	Seasonal average capacity factor, dimensionless
C_{Fw}	Capacity factor for heating season, dimensionless
C_{Fs}	Capacity factor for cooling season, dimensionless
C_{FA}	Annual average capacity factor, dimensionless
C_o	Annual operating cost, €/annum
C_s	Cumulative earnings, €
$CHPE\eta$	Partial electrical power generation efficiency of CHP, dimensionless
$CHPH\eta$	Partial thermal power generation efficiency (including steam if produced) of CHP, dimensionless
COP_{abs}	Coefficient of performance of single-stage absorption cooling machine, dimensionless
COP_c	Cooling coefficient of performance of chiller, dimensionless
CO_2	Carbon dioxide emission, kg CO_2
C_T	Catalysis factor, dimensionless
D_e	Day-time electricity price, €/kW$_e$-h
E_1	Annual total electricity generated in Stage 1, GW$_e$-h/annum
E_2	Annual total electricity generated in Stage 2, GW$_e$-h/annum
E_{Xc}	Annual exergy of cold generated by the trigeneration system, kW$_c$-h/annum
E_{Xh}	Annual exergy of heat by the trigeneration system, kW$_h$-h/annum
E_{XT}	Total annual thermal exergy (heat and cold) by the trigeneration system, kW$_h$-h /annum
E	Total annual electricity production of trigeneration, GW$_e$-h/annum
E_T	Total annual energy production of trigeneration (power, heat, and cold included), $E_T = E + H$, GW$_e$-h/annum
E_B	Total biogas energy output per day, kW$_h$-h/day
e_B	Unit methane production value, kW$_h$-h/day/person

EV	Reactor input from agricultural crop waste, kg/day
FM	Fuel price of natural gas-biogas mix, €/kW_h-h
G_1	Daily biogas production from solid waste, m^3/day
G_2	Daily biogas production from waste water treatment, m^3/day
G	Daily total biogas production, m^3/day
H	Total annual thermal energy production of CHP, GW_h-h/annum
I	Total installation cost for biogas reactor and ancillaries, €
I	Unit installation cost for biogas reactor and ancillaries, €/kW_e
m	Fraction of annual operating cost to annual fuel cost, dimensionless
N	Night-time average electricity price, €/kW_e-h
NG	Natural gas unit fuel cost, €/kW_h-h
NS	Annual net savings of the trigeneration system, €/annum
P	Peak-demand electricity price, €/kW_e-h
P_c	Cooling power output of absorption machines , kW_c
P_e	Electric power output of CHP, $CHPE\eta$ x P_f , kW_e
P_h	Thermal power output of CHP, $CHPH\eta$ x P_f , kW_h
P_f	Thermal power input (based on LHV)) of the fuel to the CHP, kW_h
PES	Primary energy savings percentage (According to EU 2004/8/EC Directive), dimensionless
PES_{RCHP}	Primary energy savings percentage (According to Rational Exergy Management Model, REMM), dimensionless
R	Average electricity price to natural gas price ratio, dimensionless
$RefE\eta$	Reference value for partial power generation efficiency of CHP, dimensionless
$RefH\eta$	Reference value for partial thermal generation efficiency of CHP, dimensionless
SCO_2	Savings from CO_2 emissions, ton
T	Total annual heat and cold production of trigeneration, GW_e-h/annum
T_E	Exit temperature at a point where power generation ends, K
T_f	Adiabatic flame temperature of the fuel, K
T_i	Application temperature, K
t_d	Annual total operating hours: $t_{ow} + t_{os}$, h
t_{ow}	Total operating hours in winter season (including autumn shoulder season), h
t_{os}	Total operating hours in summer season (including spring shoulder season), h
t_o	Daily operating hours, h/day

T_{suph}	Thermal supply temperature, K
T_{supc}	Cold supply temperature, K
T_{ret}	Return temperature, K
T_{ref}	Environment reference temperature, K
V	Number of cows in the farm stock, dimensionless
Y	Simple pay-back period, year
y	Calendar year, dimensionless

Greek Symbols

η_I	First-law efficiency, dimensionless
η_{Iabs}	First-law efficiency of the absorption system, dimensionless
η_b	Boiler First-Law efficiency, dimensionless
η_L	Ancillary loss factor of power generation in a tri-generation system, dimensionless
η_{IT}	First-Law efficiency of the ice tank during charging, dimensionless
η_{ITD}	First-Law efficiency of the ice tank during discharging, dimensionless
η_T	Total First-law efficiency of CHP unit (CHPEη +CHPHη), dimensionless
ψ_R	Rational exergy management efficiency, dimensionless
ψ_{Rbase}	Base Rational Exergy Management Efficiency, approximately 0,20 for boiler, chiller, and grid power combination in conventional systems, dimensionless
ψ_{RCHP}	Rational exergy management efficiency, dimensionless
ε	Unit exergy, kW/kW
ε_{sup}	Supplied exergy, kW/kW
ε_c	Unit exergy of cold produced (@7^{o}C), kW_h/kW_h
ε_{des}	Destroyed exergy, kW/kW
ε_e	Unit exergy of electricity, kW_e/kW_e
ε_h	Unit exergy of heat produced (@90^{o}C), kW_h/kW_h

Subscripts

c	cooling
e	electric
h	Heat
i	Type of fuel
o	Operation

s	Summer
w	Winter

Abbreviations

ABS	Absorption chiller
AD	Anaerobic digester
ASHRAE	American Society for Heating, Refrigerating and Air-Conditioning Eng. Inc.
BG	Biogas
CBECS	Commercial Building Energy Consumption Survey
CHP	Combined heat and power
DHW	Domestic hot water
DCW	Domestic cold water
DOE	US Department of Energy
GHG	Greenhouse gas
GSHP	Ground-source heat pump
HE	Heat exchanger
HVAC	Heating, ventilating, and air-conditioning
LHV	Lover heat value
NG	Natural gas
ORC	Organic Rankine cycle
PB	Peaking Boiler
PV	Photo-voltaic
PVT	Photo-voltaic-heat
PVTC	Photo-voltaic-thermal-cooling
PHVT	Photo-thermal-voltaic-heat
REMM	Rational Exergy Management Model
TES	Thermal energy storage (IT: ice tank)

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Dr. Özgür Erol and Asst. Emre Koç, Graduate Student Doğa Can Bayram from Başkent University have largely contributed to the project development and building modeling.

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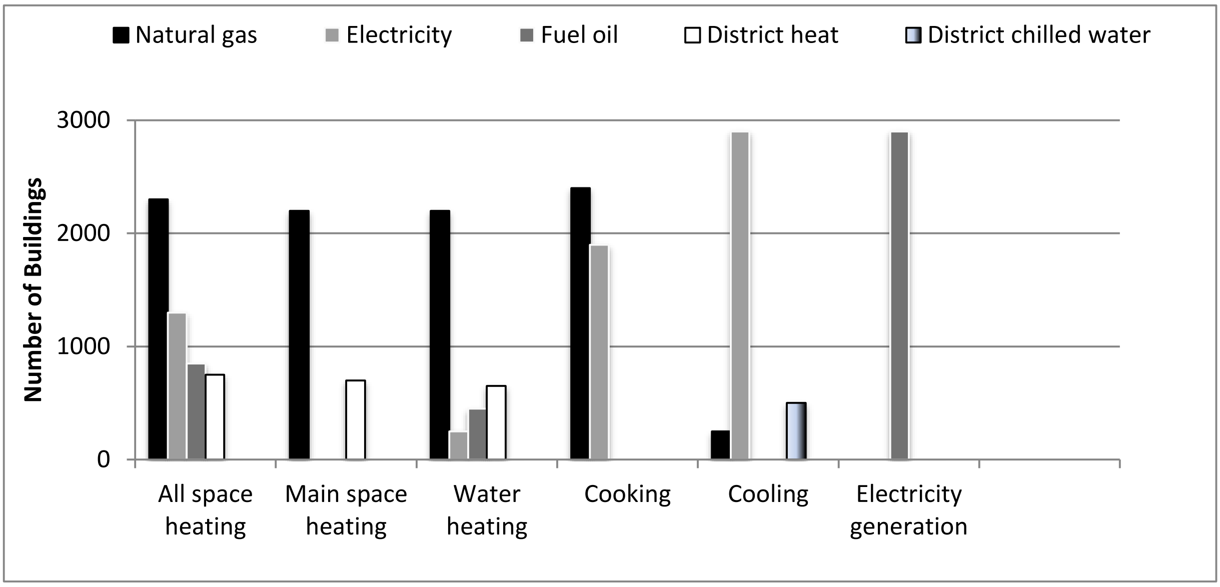

Fig 1. Fuels and energy end uses in large hospital buildings 2007 [2].

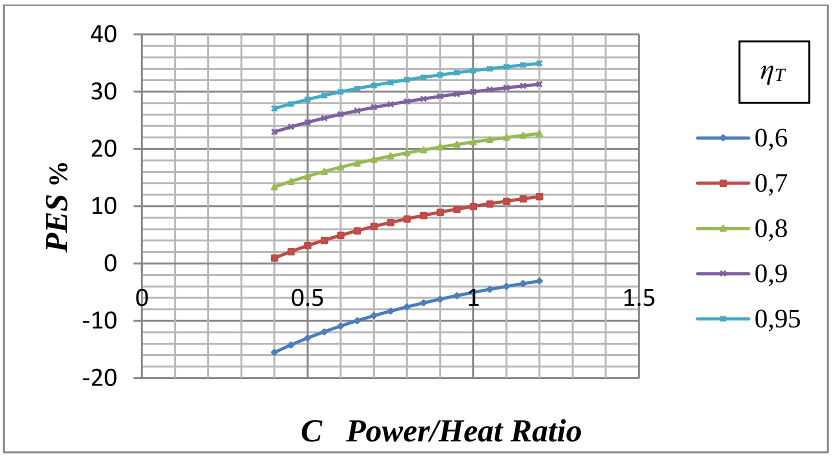

Fig. 2. Variation of the *PES* value with *C* and η_T according to [10].

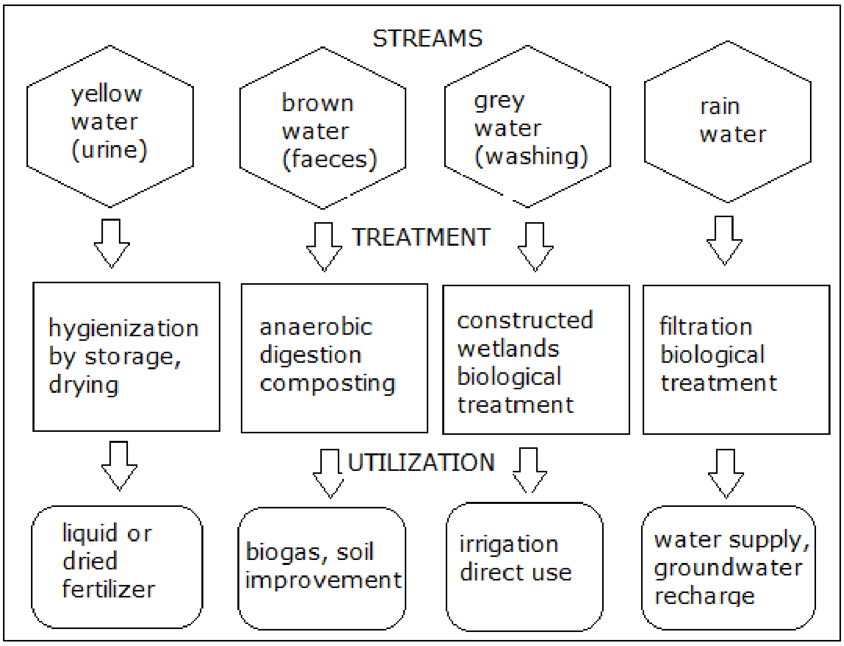

Fig. 3. Treatment and utilization options for three separated wastewater and waste [25].

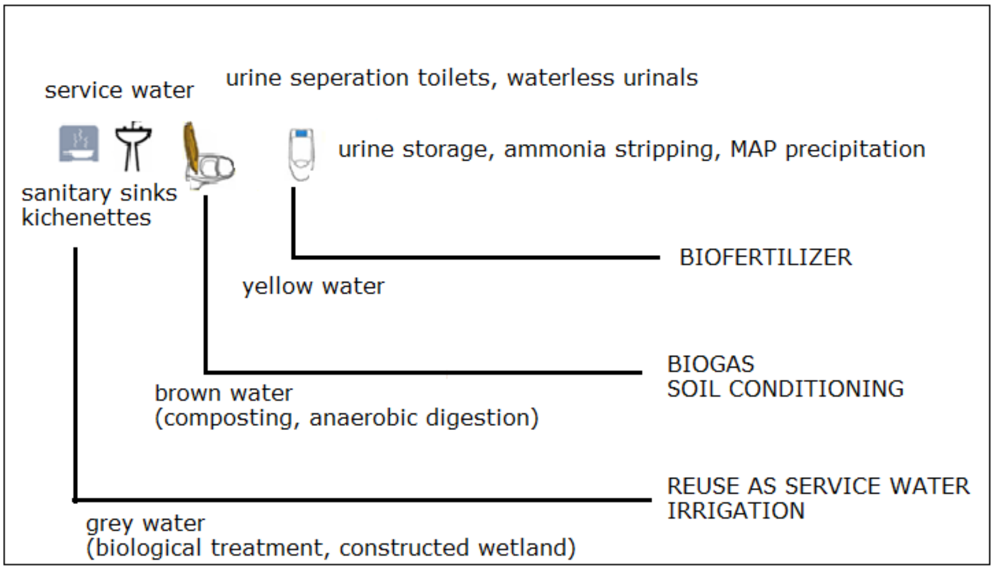

Fig. 4. EcoSan system [26-b].

Fig. 5. Turgut Özal University Hospital Building [28].

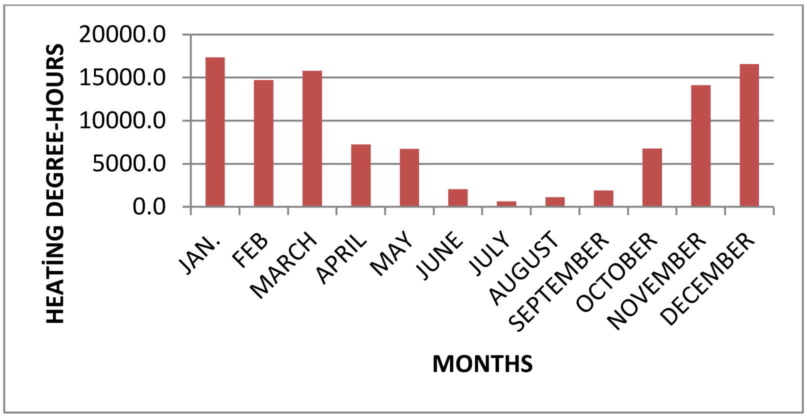

Fig. 6. Total number of monthly heating degree-hours of Malatya [29].

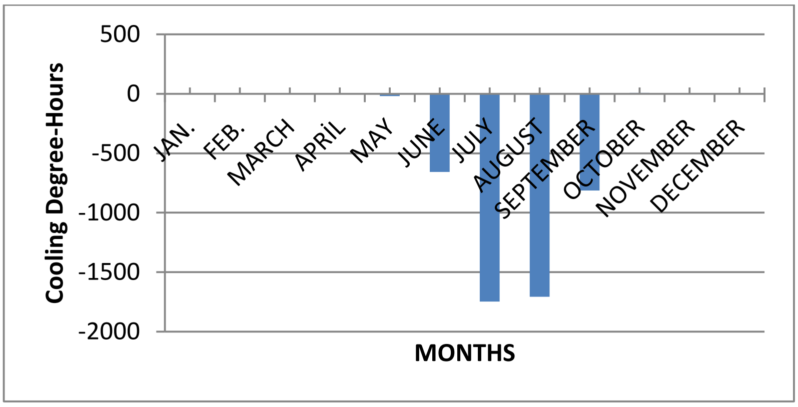

Fig. 7. Total number of monthly cooling degree-hours of Malatya [29].

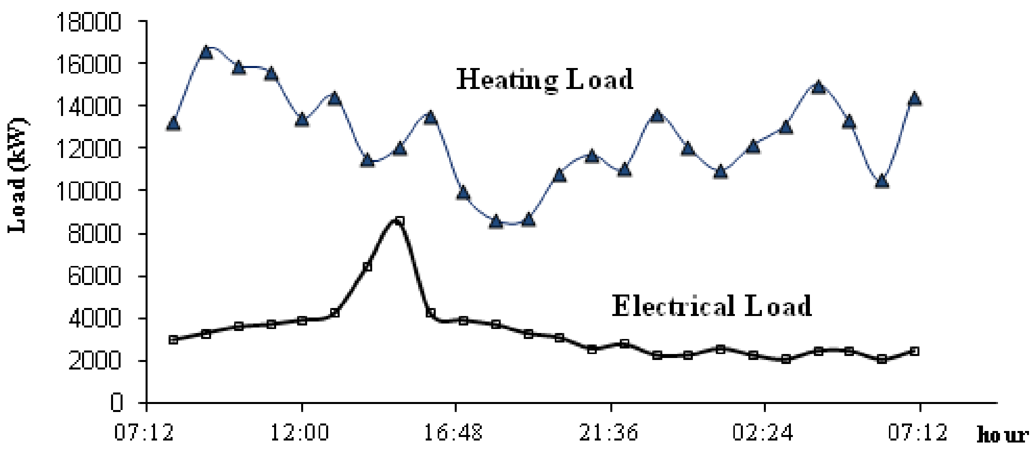

Fig. 8. Typical hourly heating and power load predictions in a 24-hour period [28].

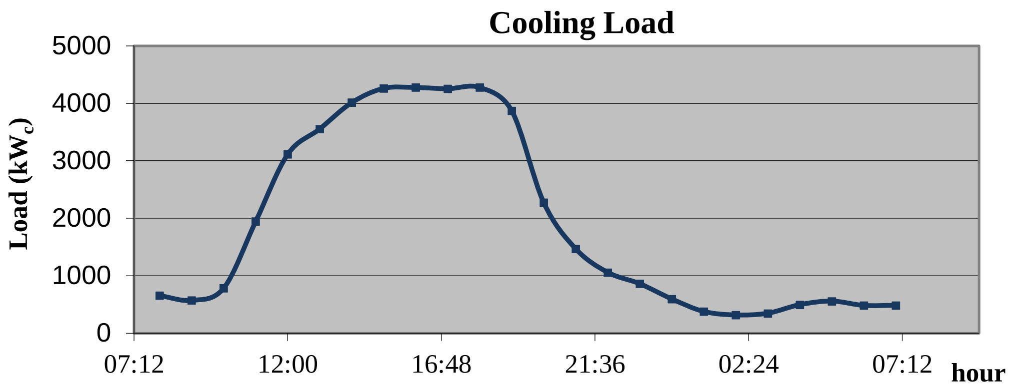

Fig. 9. Typical hourly cooling load predictions in a 24-hour period [28].

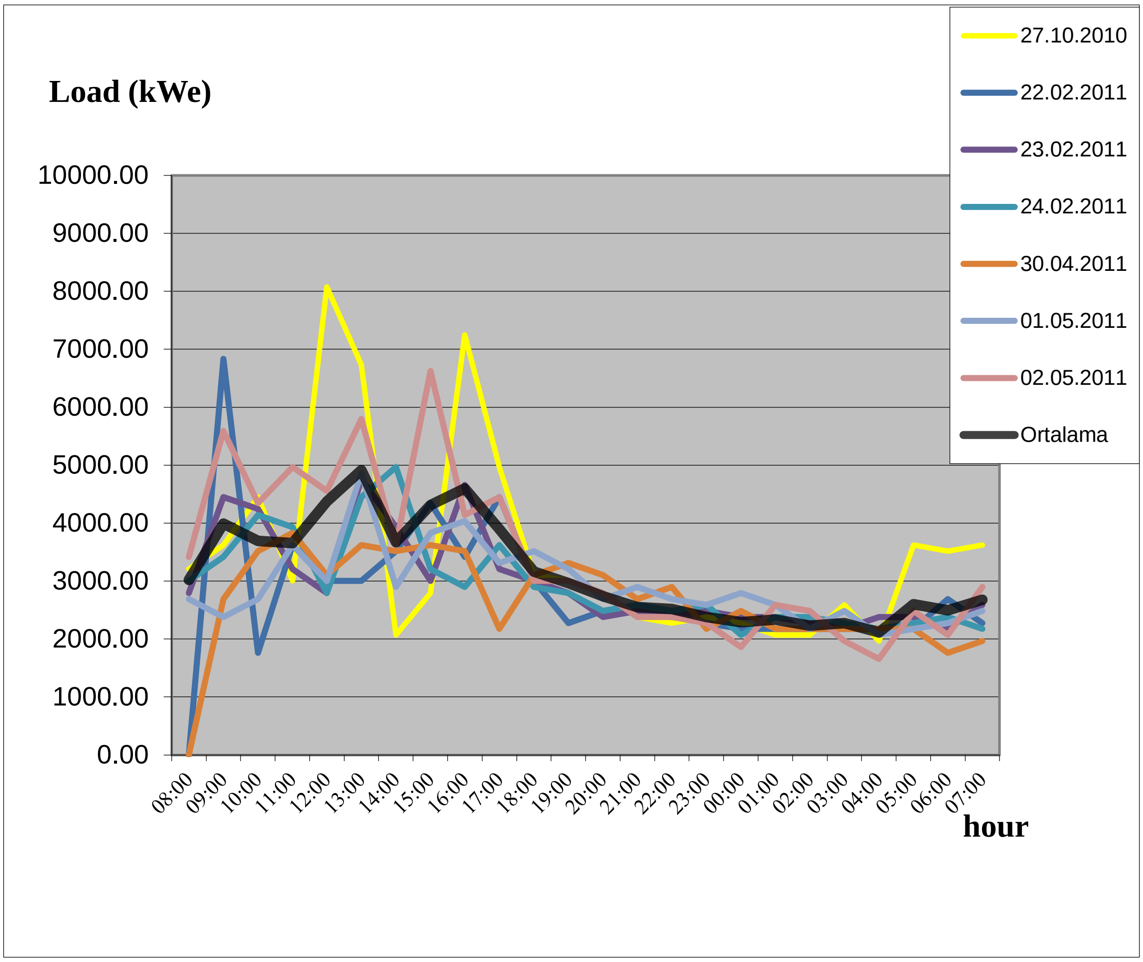

Fig. 10. Actual hourly electrical power loads in different days [28].

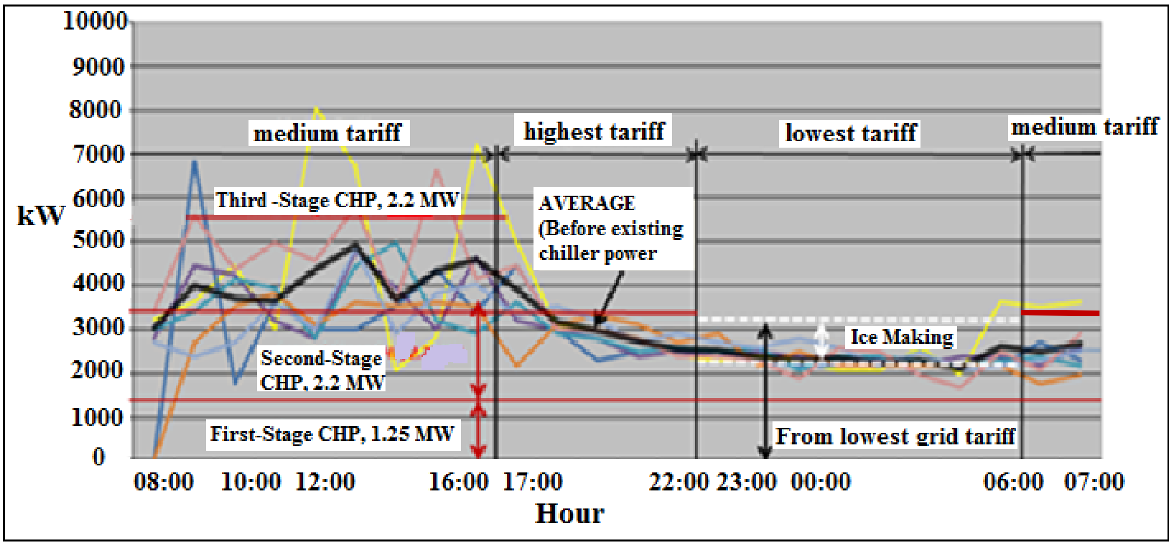

Fig. 11. Optimal operational scheme of the cascaded trigeneration engines [28].

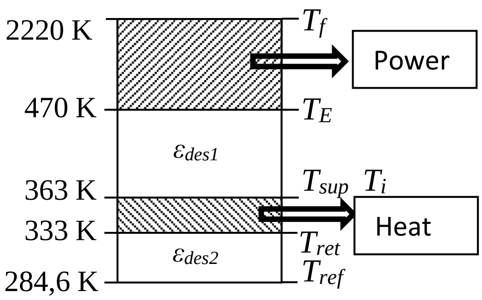

Fig. 12. Exergy flow bar for the CHP Unit [12].

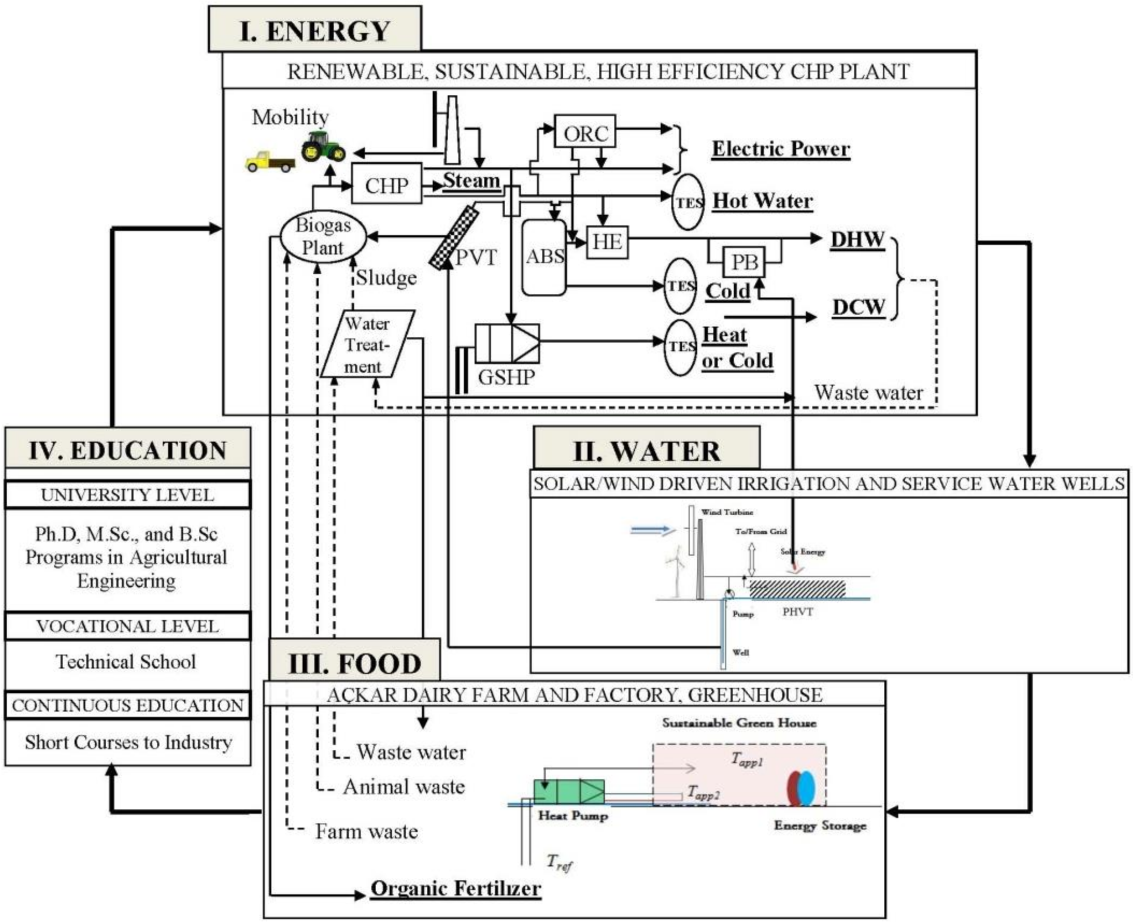

Fig. 13. Eco animal farm and organic dairy concept [36].

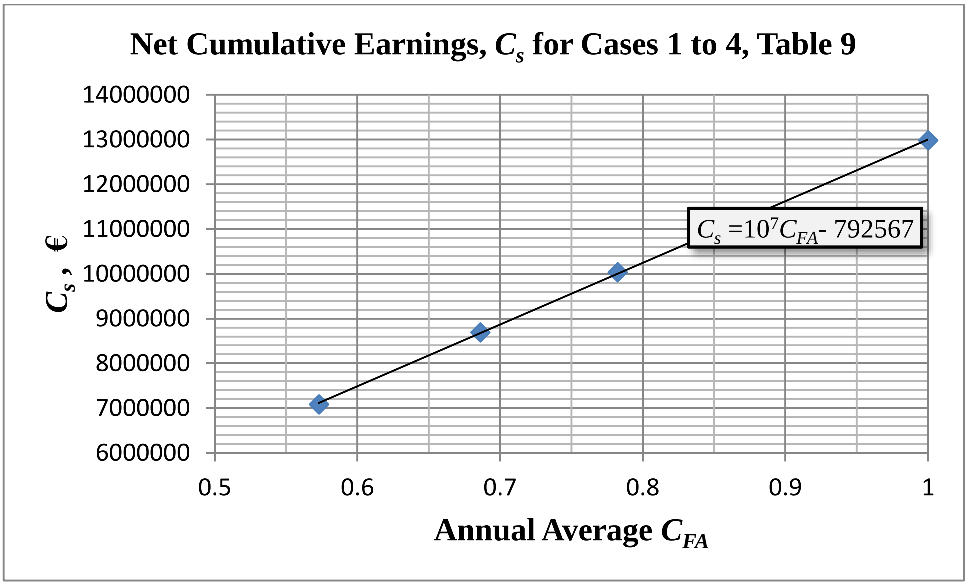

Fig. 14. Change of Total Cumulative Earnings with the C_{FA}: 2,2 kWe Biogas Stage 2.

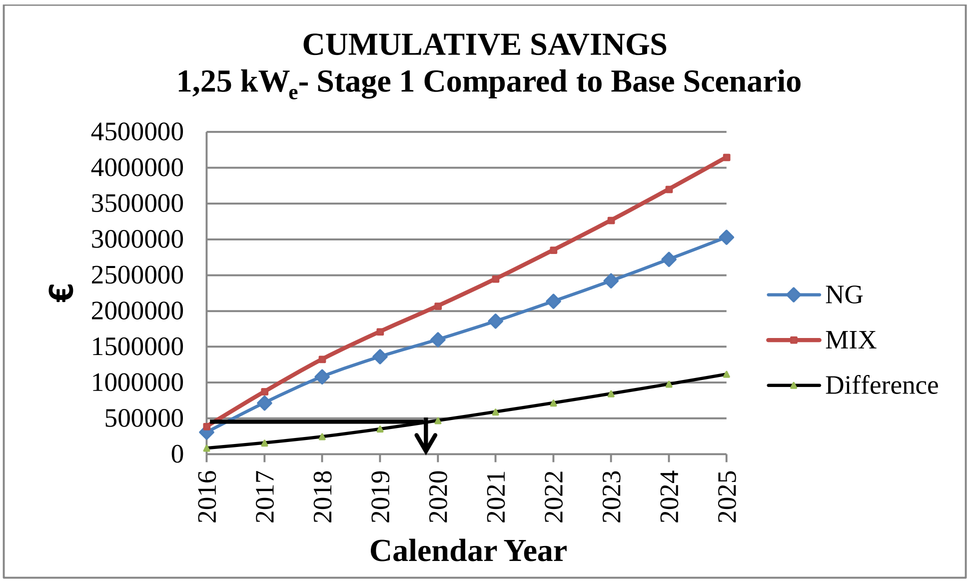

Fig. 15. Pay-Back Period of the Biogas Production in Stage 1.

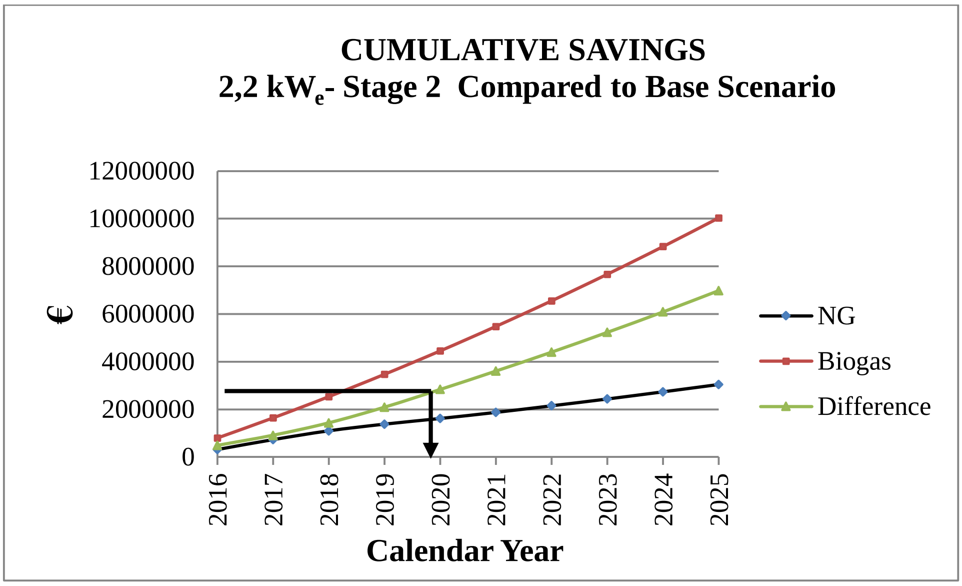

Fig. 16. Pay-Back Period of the Biogas Production in Stage 2.

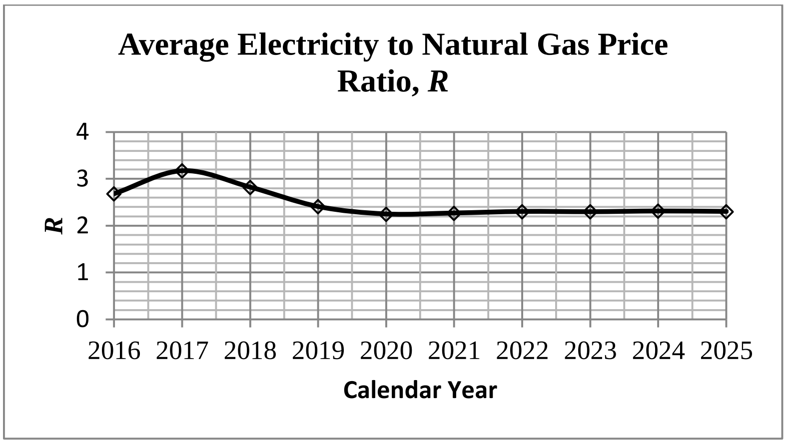

Fig. 17. Predicted Annual Change of *R* value over the years between 2016 and 2020.

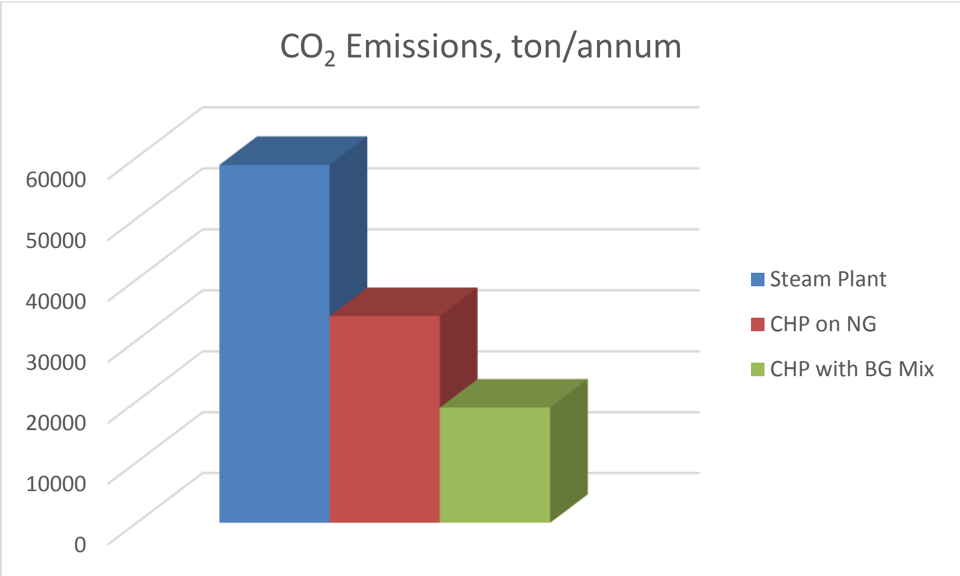

Fig. 18. Graphical CO_2 Emissions Comparison of Existing Power Plant, Base Scenario, and the Biogas Mix Scenario. Annual Base.

Table 1 Typical composition of biogas.

Methane, CH_4	55 -75 %
Carbon Dioxide, CO_2	25 - 45 %
Carbon Monoxide, CO	0 - 0.3 %
Nitrogen, N_2	1 - 5 %
Hydrogen, H_2	0 - 3 %
Hydrogen Sulphide, H_2S	0.1 - 0.5 %

Table 2 Daily biogas production per person from human faeces.

Wet mass (kg)	0,12
Dry matter mass (kg)	0,035
Organic matter mass (kg)	0,030
Biogas (mol)	0,58
Biogas volume (L)	12,99
Methane (mol)	0,377
Methane volume (L)	8,445
Carbon dioxide (mol)	0,203
Carbon dioxide volume (L)	4,547

Table 3 Capacity Factors, C_F and other features of the biogas mix/biogas trigeneration systems in Stage 1 and Stage 2.

	FEATURES								
	WINTER		**SUMMER**			**Annual Average**			
COMPONENT	$\boldsymbol{C_{Fw}}$	$\boldsymbol{t_{ow}}$ **h**	$\boldsymbol{C_{Fs}}$	$\boldsymbol{t_{os}}$ **h**	$\boldsymbol{t_o}$ **h**	$\boldsymbol{C_{FA}}$	***CHPEη***	***CHPHη***	***C***
1,25 MW_e CHP (Stage 1)	0,9	5320	0,85	2880	8200	0,8824*	0,37	0,46	0,8
2,2 MW_e CHP (Stage 2)	0,80	3536	0,75	1920	5456	0,7824**			
Absorption M. (Stage 1 and 2)	-	-	0,75	2880	2880	0,70	COP_{abs}= 0,65 Single-effect 2,5 MW_c***		
Ice Tank 8 MW_c-h	-	-	Operates 120 cycles per year. Overall efficiency, η_{IT} = 0,85 (Charging- discharging)						

* [0,90x5320+2880x0,85]/8200 ** [0,80x3536+1920x0,75]/5456 ***Attributable to biogas is (1,7+0,23) MW_c.

Table 4 Methane production capacities of the hospital complex-Stage 1, E_B.
e_B = 0,076 kWh-h/person/day [35]

SOURCE	**PERSON or NUMBER**	E_B kW$_h$-h/day (Rounded)	**COMMENTS**
In-patients	900	68	E_B = 900 x 0,076
In-patient-companions	90	7	one companion in ten patients, residing 24 hours
Visitors	150	11	2 visitors per in-patient, stays two hours on average
Organic waste from restaurants and cafes	3	450	each serving 400 persons
Outpatients with companions	2000	25	Spend four hours on average
Outsourced local organic waste		10000	Mainly apricot waste, a locally grown produce
Nurse	600	46	24-hour average population
Medical Doctors	300	23	24-hour average population
Other employees	1200	91	Including lab technicians, ambulatory services etc.
TOTAL		10721	Only 4% from humans

Table 5 1,25 MW_e NG engine calculations.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
						R	C_f	C_o	AV_w	AV_s	***NS***	C_S	***E***	***H***
		ELECTRICITY COST €/kWe-h			**Natural Gas**	**Ratio**	**Annual**	**Ope-rating**	**ADDED VALUE**		**NET EARNINGS**	**Net Cumulative**	**Electric**	**Thermal***
Calendar	**Peak, *P***	**Night, *N***	**Day, *D***	**Average, *A***	**Cost, *NG***	***A/NG***	**Fuel Cost**	**Cost**	**Winter**	**Summer**	**Annual**	**Earnings**	**Generation / annum**	
Year, *y*					€/kWh-h		€/annum	€/annum	€/season	€/season	€/year	€	GWe-h	GWh-h
2016	0,166	0,038	0,091	0,089	0,033	2,68	814014	56981	827369	350783	307157	307157	9044,6	10505,25
2017	0,174	0,040	0,096	0,093	0,029	3,17	720089	50406	818415	362255	410174	717330	E_T = 19549,85 Energy	
2018	0,182	0,042	0,100	0,098	0,035	2,82	845322	59173	888369	381795	365670	1083000	8682,816	2008,827
2019	0,189	0,044	0,104	0,102	0,042	2,41	1033172	72322	980869	403641	279017	1362017	E_{XT}= 10691,643 Exergy	
2020	0,197	0,046	0,108	0,106	0,047	2,25	1151248	80587	1048247	422918	239330	1601347		
2021	0,205	0,047	0,113	0,110	0,049	2,27	1185576	82990	1085471	439112	256017	1857364		
2022	0,212	0,049	0,117	0,114	0,050	2,30	1212465	84873	1120017	455032	277711	2135075		
2023	0,220	0,051	0,121	0,118	0,052	2,30	1259644	88175	1161868	471699	285748	2420823		
2024	0,228	0,053	0,125	0,123	0,053	2,31	1295578	90690	1199670	487952	301353	2722176		
2025	0,236	0,054	0,130	0,127	0,055	2,30	1344468	94113	1242137	504681	308238	3030414	*includes cooling	

Table 6 1,25 MW_e NG-Biogas mix engine calculations, Stage 1

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
						R	C_f	C_o	AV_w	AV_s	***NS***	C_S	E_1	***H***
		ELECTRICITY COST €/kW$_e$-h			**Fuel Mix**	**Ratio**	**Annual**	**Ope-rating**	**ADDED VALUE**		**NET EARNINGS**	**Net Cumulative**	**Electric**	**Thermal***
Calendar	**Peak, *P***	**Night, *N***	**Day, *D***	**Average, *A***	**Cost, *FM***	***A*/*NG***	**Fuel Cost**	**Cost**	**Winter**	**Summer**	**Annual**	**Earnings**	**Generation/annum**	
Year, *y*					€/kW$_h$-h		€/annum	€/annum	€/season	€/season	€/year	€	GW$_e$-h	GW$_h$-h
2016	0,166	0,038	0,091	0,089	0,024		577950	115590	742373	342092	390925	390925	9044,6	10505,25
2017	0,174	0,040	0,096	0,093	0,021		511263	102253	743226	354566	484276	875201	E_T = 19549,85 Energy	
2018	0,182	0,042	0,100	0,098	0,025		600179	120036	800105	372770	452660	1327860	8682,816	2008,827
2019	0,189	0,044	0,104	0,102	0,030	N/A	733552	146710	872990	392610	385338	1713198	E_{XT}= 10691,64 Exergy	
2020	0,197	0,046	0,108	0,106	0,033		817386	163477	928039	410626	357802	2071000		
2021	0,205	0,047	0,113	0,110	0,034		841759	168352	961679	426454	378021	2449022		
2022	0,212	0,049	0,117	0,114	0,035		860850	172170	993417	442086	402482	2851504		
2023	0,220	0,051	0,121	0,118	0,037		894347	178869	1030341	458249	415374	3266878		
2024	0,228	0,053	0,125	0,123	0,038		919860	183972	1064391	474119	434678	3701556		
2025	0,236	0,054	0,130	0,127	0,039		954572	190914	1101754	490326	446594	4148149	*includes cooling	

Table 7 2,2 MW$_e$ NG engine calculations,

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
						R	***C_f***	***C_o***	***AV_w***	***AV_s***	***NS***	***C_S***	***E***	***H***
		ELECTRICITY COST €/kW$_e$-h			**Natural Gas**	**Ratio**	**Annual**	**Ope-rating**	**ADDED VALUE**		**NET EARNINGS**	**Net Cumulative**	**Electric**	**Thermal***
Calendar	**Peak, *P***	**Night, *N***	**Day, *D***	**Average, *A***	**Cost, *NG***	***A/NG***	**Fuel Cost**	**Cost**	**Winter**	**Summer**	**Annual**	**Earnings**	**Generation/ annum**	
Year, *y*					€/kW$_h$-h		€/annum	€/annum	€/season	€/season	€/year	€	GW$_e$-h	GW$_h$-h
2016	0,166	0,038	0,091	0,089	0,033	2,68	845217,3	59165,2	860319,7	354801,4	310738,5	310738,5	14114,5	10630,4
2017	0,174	0,040	0,096	0,093	0,029	3,17	747692,3	52338,5	851009,2	366288,9	417267,3	728005,8	E_T = 24744,9 Energy	
2018	0,182	0,042	0,100	0,098	0,035	2,82	877725,7	61440,8	923749,8	386130	370713,3	1098719,1		
2019	0,189	0,044	0,104	0,102	0,042	2,41	1072776	75094,3	1019934	408357,9	280421,4	1379140,5	13549,92	1943,322
2020	0,197	0,046	0,108	0,106	0,047	2,25	1195379	83676,5	1089995	427926,2	238866,1	1618006,6	E_{XT}= 15493,24 Exergy	
2021	0,205	0,047	0,113	0,110	0,049	2,27	1231022	86171,6	1128702	444302,3	255810,0	1873816,6		
2022	0,212	0,049	0,117	0,114	0,050	2,30	1258942	88126,0	1164623	460394,8	277949,5	2151766,1		
2023	0,220	0,051	0,121	0,118	0,052	2,30	1307929	91555,1	1208141	477260,8	285916,9	2437683,1		
2024	0,228	0,053	0,125	0,123	0,053	2,31	1345241	94166,9	1247448	493698,1	301738,8	2739421,9		
2025	0,236	0,054	0,130	0,127	0,055	2,30	1396005	97720,3	1291607	510629,2	308510,9	3047932,8	*includes cooling	

Table 8 2,2 MW_e biogas engine calculations, Stage 2.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
						R	C_f	C_o	AV_w	AV_s	***NS***	C_S	E_2	***T***
		ELECTRICITY COST €/kW$_e$-h			**Biogas**	**Ratio**	**Annual**	**Ope-rating**	**ADDED VALUE**		**NET EARNINGS**	**Net Cumulative**	**Electric**	**Thermal***
Calendar	**Peak, *P***	**Night, *N***	**Day, *D***	**Average, *A***	**Cost, *BG***	***A*/*NG***	**Fuel Cost**	**Cost**	**Winter**	**Summer**	**Annual**	**Earnings**	**Generation/annum**	
Year, *y*					€/kW$_h$-h		€/annum	€/annum	€/season	€/season	€/year	€	GW$_e$-h	GW$_h$-h
2016	0,166	0,038	0,091	0,089	0,0033		84522	16904,3	586034,2	311645,5	796253,6	796253,6	14114,5	10630,4
2017	0,174	0,040	0,096	0,093	0,0029		74769	14953,8	608372	325646,3	844295,2	1640548,8	E_T = 24744,9 Energy	
2018	0,182	0,042	0,100	0,098	0,0026		66142	13228,4	631115,6	339688,4	891433,5	2531982,4	13549,92	1943,322
2019	0,189	0,044	0,104	0,102	0,0023	N/A	58510	11702,0	654218,1	353767	937772,8	3469755,2	E_{XT}= 15493,24 Exergy	
2020	0,197	0,046	0,108	0,106	0,0020		51759	10351,8	677638,1	367878	983405,2	4453160,4		
2021	0,205	0,047	0,113	0,110	0,0018		45787	9157,4	701339	382017,6	1028412,3	5481572,7		
2022	0,212	0,049	0,117	0,114	0,0016		40504	8100,8	725288,3	396182,4	1072866,2	6554438,9		
2023	0,220	0,051	0,121	0,118	0,0014		35830	7166,0	749457,5	410369,7	1116830,8	7671269,7		
2024	0,228	0,053	0,125	0,123	0,0012		31696	6339,2	773821	424576,7	1160362,6	8831632,3		
2025	0,236	0,054	0,130	0,127	0,0011		28039	5607,8	798356,6	438801,3	1203511,4	10035143,7	*includes cooling	

Table 9 Impact of Capacity Factors on Cumulative Earnings: Stage 2 Example.

	Case	C_{Fw}	C_{FA}	C_{Fs}	C_{s}, Earnings, €
	1	1	1	1	12982285
Original	**2**	0,8	0,7824	0,75	10035143
	3	0,7	0,686	0,65	8691076
	4	0,6	0,573	0,5	7081493

Table 10 Stage 1 Cumulative Earnings Difference, €.

Year	NG	MIX	Difference
2016	307156,6	390924,5	83768,0
2017	717330,4	875200,8	157870,4
2018	1083000	1327860	244860,2
2019	1362017	1713198	351181,0
2020	1601347	2071000	469652,8
2021	1857364	2449022	591657,2
2022	2135075	2851504	716428,7
2023	2420823	3266878	846055,2
2024	2722176	3701556	979379,6
2025	3030414	4148149	1117735,0

Table 11 Stage 2 Cumulative Earnings Difference, €.

Year	NG	Biogas	Difference
2016	310738,5	796253,6	485515,1
2017	728005,8	1640549	912543
2018	1098719	2531982	1433263
2019	1379141	3469755	2090615
2020	1618007	4453160	2835154
2021	1873817	5481573	3607756
2022	2151766	6554439	4402673
2023	2437683	7671270	5233587
2024	2739422	8831632	6092210
2025	3047933	10035144	6987211

Table 12. Performance Comparison of Existing Power Plant, Base Scenario, and the Biogas Mix Scenario. Annual Base.

Demand Type	**Annual Load GW-h**	**CASES**					
		Existing Steam Plant		CHP System on NG		CHP System on BG mix	
		Fuel Cons. GW-h eq.	CO_2 ton	Fuel Cons. GW-h eq.	CO_2 ton	Fuel Cons. GW-h eq.	CO_2 ton
Power	37273,6	Power from grid	41415,1	169795,9	33959,2	169795,9	18965,1
Heat and Cold	31766,0	57756	17326,9				
Total CO_2 Emission			58742		33959,2		18965,1