American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-5, Issue-4, pp-15-27
www.ajer.org
Research Paper Open Access

Developing a Model for a CHP System with Storage

M. Abunku[1], T.K. Genger[2], P.I. Udenze[3]
[1,2,3](Department of Electrical and Electronics Engineering, University of Agriculture Makurdi, NIGERIA)

ABSTRACT: *A model for a Combined Heat and Power (CHP) system developed using Matlab is presented in this project. The model developed includes sub-models of Internal Combustion Engine (ICE) and generator, electrical and thermal storage systems, and power converters (rectifier and inverter). The model developed is able to simulate the performance of a CHP system when supplying user load. The battery electrical storage system is modelled and used as the electrical storage for this project, and the water storage tank is modelled and used as thermal storage. The project presents the model developed, and the results of the analysis done on the model. The model considered only heat from engine cooling, which is used to heat water to supply the DHW (District Hot Water) needs of the user. The results show that by the addition of storage to the CHP system, the overall system efficiency is increased by 32% indicating that the model developed is reliable, and the project is a feasible one.*

Keywords: *CHP; ICE; battery electrical storage system; thermal storage; DHW;*

I. INTRODUCTION

Recent world focus on the development of sustainable energy production and the reduction of gas pollution (Green House Gas Emissions), has led to the active study and research of Combined Heat and Power (CHP) systems. Combined Heat and Power (CHP) also known as cogeneration, refers to the production of electricity and heat simultaneously. When the production of electricity and heat is done separately by different dedicated systems as obtained in conventional generation, the efficiency in fuel energy consumption is about 35% less than what would be achieved if the electricity and heat are produced by a single system as obtained in CHP systems[1, 9] . Figure 1 uses sample numbers to illustrate the concept of CHP [9].

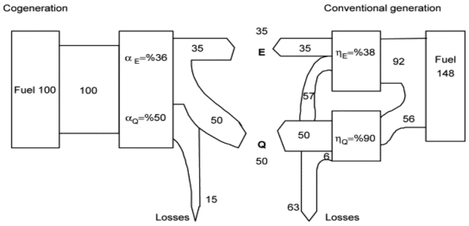

Figure 1: Conventional generation versus CHP[9]

Where α_E is the part of the energy transformed into electricity by the CHP system, α_Q is the part of the energy transformed into useful heat by the CHP system, η_E is the electrical output of a conventional electrical power plant (electricity only), η_Q is the heat output of a boiler (heat only), E is electricity demand, Q is heat demand**[9].** Using the heat produced as a by-product of electricity generation is not a new concept, but due to the significant increase in fuel price, increased awareness in global warming, improvement in the available technology and sensitivity of equipment to power fluctuation, the use of CHP systems has been on the increase [2]. Favorable European Union directives such as Climate Change Levy (CCL) exemptions or reductions, Enhanced Capital Allowance (ECA) on any good quality CHP plant, as well as Feed-In Tariffs (FITs) and clean energy cashbacks also contribute to the rise in use of CHP technologies for energy generation [3]. As a result of these favourable conditions, several countries especially in Europe, US, Canada and Japan have increased their use of CHP for industrial and residential applications. Figure 2 shows the percentage of electricity produced by CHP technology of the produced total electricity in countries such as Denmark(53%), Netherlands (29%), USA (7%) and Canada(6%) [4].

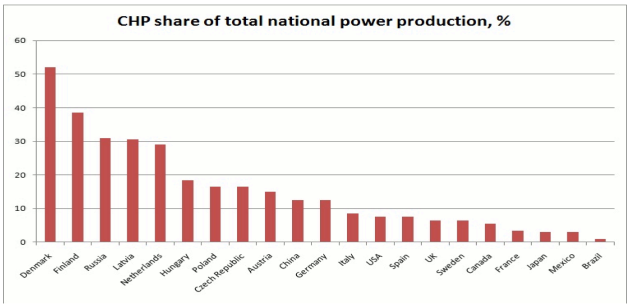

Figure 2: The percentage of total national power generation in countries by CHP [4]

A CHP system consists of a prime mover, such as a gas turbine or steam turbinewhich makes use of an input fuel and produces heat as a by-product of electricity production, and an electricity generating arrangement such as a generator. A CHP system also consists of a heat recovery system. The electricity produced is used to supply electric power, and the waste heat is recovered and used for Domestic Hot Water (DHW) and space heating. In large industries, the recovered waste heat can be used by Waste Heat to Power (WHP) systems that convert waste heat into electricity for driving machines [5]. This improves the overall efficiency of the system. CHP systems have the disadvantage of low flexibility because the adjustment of electricity and heat production (during peak and off-peak periods) cannot be done independently. This means that if the amount of heat and electricity produced at any point in time is more than what is needed, the excess energy is lost thus reducing the energy efficiency of the system [5,6].

To ensure the flexibility of a CHP system and to increase its overall efficiency, there is a great need to create an un-coupled system where the heat produced and not needed at production time can be stored using thermal stores, and excess electrical energy not needed at production time can be stored using various storage means such as batteries, supercapacitors and flywheels [6]. The integration of thermal and electrical storage facilities into the CHP system enables the supply of electricity and heat to be un-coupled from user demand. In addition to increasing the energy saving capacity of the system, uncoupling the production of electricity and heat by the addition of storage can enable a CHP system to operate more profitably. Profitability of the system is increased because the stored heat can be used by the production companies to supply district heating and hot water heating. The excess electricity can also be sold back to the grid for profit [6,7]. This project will develop a model that would be used to simulate the operation and behaviour of a CHP system coupled with electrical and thermal storage, and also analyze the efficiency of the modeled system.

1.1 BENEFITS TO THE INDUSTRY AND SOCIETY

Development of the Combined Heat and Power (CHP) system model with storage can be of great benefit to the energy industry as well as to the society in general. These benefits include:

- Because the CHP system developed is close to where the generated power will be used, power losses due to transmission and distribution of electricity over power lines are avoided.
- Because the system is close to the demand, shorter transmission lines are required thus reducing overall costs.
- Increase in the efficiency of fuel by about 35%, bringing total efficiency up to 85%, compared to conventional electrical or thermal plants.
- Reduction in Green-House Gas(GHG) emissions, air and water pollution.
- Reduction in the cost of space heating and domestic hot water to the consumers, as they get them as a by-product of generating electricity.

1.2 THE APPROACH

This project will focus on the modelling of a CHP system, the efficient storage of the excess electricity or heat produced by the system, and analysing the effect storage has on the overall efficiency of the system. The approach used in this project involves researching about previously developed CHP model examples and examining them in detail. The techniques that will be used in this project are data collation and simulation. The collation technique is used to collect information and data about the various technologies of CHP systems, thermal and electrical storage available. The simulation technique involves using Matlab simulation tool to design, simulate and analyze a model of a CHP system with storage.

1.3 SYSTEM BLOCK DIAGRAM

Figure 3 shows the block diagram of the proposed CHP system with storage to be designed for the project. The CHP unit produces electricity which is used to meet the user's demand. Any excess electricity is stored in the battery. When the load becomes higher than the output power of the CHP unit, the battery then supplies the excess required to meet the load. Heat produced as a result of the production of electricity is recovered and stored as hot water in the thermal storage tank. The storage is used to meet the space heating and DHW needs of the user.

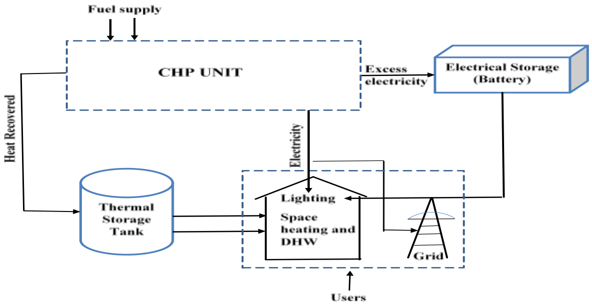

Figure 3: Block diagram of a CHP system with thermal and electrical storage

II. REVIEW OF THE CURRENT CHP TECHNOLOGIES AVAILABLE

Cogeneration or CHP technology refers to the simultaneous production of electricity and heat. The waste heat produced as a by-product of electricity generation is recovered and used for space heating, domestic hot water, and for industrial waste to power systems. CHP systems consist of; a *prime mover* which burns fuel and produces heat and the mechanical power required to drive the generator, an *electrical generator,* and a *heat recovery system*. Fuel cell based CHP systems, however do not have a mechanical prime mover and generator, but have a fuel stack arrangement which produces heat and electricity. CHP systems are classified as follows:

- Internal Combustion Engine (ICE) based CHP systems
- Micro-turbine based CHP systems
- Fuel-cell based CHP systems
- Stirling engine based CHP systems

2.1 REVIEW OF THE TYPES OF THERMAL ENERGY STORAGE (TES)TECHNOLOGIES

- Due to the difficulty in matching generated heat with the required amount at a particular time, a form of Thermal Energy Storage (TES) is needed to work with the CHP system where heat that is not needed at production time can be stored [19].

Figure 4: Whisper Tech stirling engine based CHP unit with 850We and 8kWth [18]

This improves the efficiency of the system as the production of electricity and heat can then be adjusted independently.A good TES should reduce thermal energy losses to the barest minimum while allowing for maximum extraction efficiency of the stored thermal energy [20].There are two types of TES technologies commonly used. These are: sensible heat storage and latent heat storage technologies for space and water heating applications [21].

2.2 REVIEW OF THE TYPES OF ELECTRICAL ENERGY STORAGE (EES)TECHNOLOGIES

Electricity generated especially for renewable sources usually does not provide immediate supply/response as it cannot be easily adjusted to meet consumption needs. Presently, electricity production is highly centralized and electrical energy storage is not used extensively and yet electrical stability of a network rests on the balance between demand and supply. Electrical Energy Storage (EES) refers to the process whereby electrical energy produced from a power plant is changed into a form in which it can be stored and when needed, can be converted back into electrical energy [23]. According to [24], two criteria by which EESs are classified are function and form.

III. Selection Process of CHP system

3.1 OPERATING PRINCIPLE OF CHP SYSTEM

A CHP system consists of an engine and a generator, except for the fuel cell based CHP system which uses a fuel cell stack to generate electricity and heat. The requirements for the selection of a CHP system are that it must be easy and cheap to install and run. The CHP system should be able to meet at least, the base load. Base load refers to the minimum demand of electricity or heat by the user over a 24 hour period [30]. The load profile considered for this project is shown in Figure 5

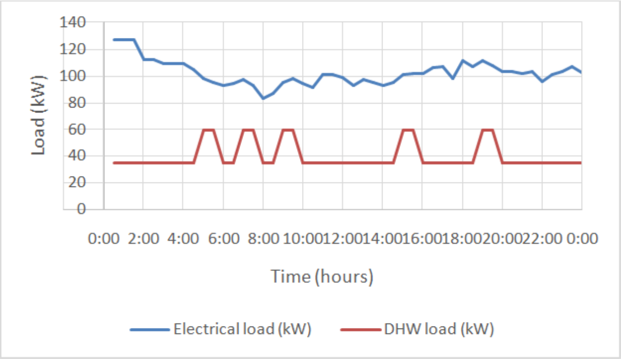

Figure 5: User electrical and thermal load profile

The CHP system should also be power efficient, that is, the overall efficiency of the system should be greater than 70%. The power efficiency of a CHP system is calculated by:

$$\eta_p = \frac{P_e + Q_{th}}{Q_f} X\ 100 \qquad (3.4.1)$$

Where η_p is the overall efficiency of the CHP system in percentage, P_e is the electrical power output in kW, Q_{th} is the thermal power output in kW, and Q_f is the fuel input in kW.

For the purpose of this project, an engine based CHP system is considered. The engine could be an internal combustion engine, a micro-gas turbine, or a Stirling engine. The micro-turbine engine was not used for this project because micro-turbine outputs are usually between 25 to 80kW, which is not enough to meet the base load used for this project (Appendix A). Stirling engine based CHP system was not used for this project because of the fact that the technology is not fully developed yet, and it is not widely used. Consequently, there is a lack of performance data that could guarantee the reliability of the system [8, 9]. The Internal Combustion Engine (ICE) was used for this project because it is a mature and well known technology, it is cheap to install and run compared to other technologies, and it is commercially available to acquire. The main purpose of the engine is to produce mechanical power needed to drive the generator which produces electricity. The mechanical power is gotten by burning fuel inside the engine [31]. Compression ignition engine is considered for the project.

A four-stroke ICE was modelled in this project. The mechanical power output of an engine is given by the formula:

$$\text{Pmech} = \frac{nP_{mi}\,LANk\ X\ 10}{6}\ \text{kW} \qquad (3.4.2)$$

Where Pmech is the mechanical output power of the engine in kW, n refers to the number of cylinders of the engine, P_{mi} refers to the mean effective pressure of the engine in bar, L is the piston stroke in m, A is the area of the piston in m^2 given by:

$$A = \frac{\pi}{4}\ x\ D^2 \qquad (3.4.3)$$

D is the piston bore in mm. N is the speed of the engine in rpm. k is a constant.

An AC generator is connected to the engine to generate electricity. A simple AC machine consists of a wire, mounted on an axle which can rotate about its axis, rotating in a fixed magnetic field. The magnetic field is provided by the North and South poles of permanent magnets. The two ends of the wire are connected to two slip rings which are insulated from one another. The slip-rings have carbon brushes pressed against them. As the wire rotates, it cuts the magnetic flux, thus producing an induced Electromotive Force (EMF). When the external circuit is completed,

The frequency of the AC generator is determined by the engine speed in rpm, and the number of poles p in the rotor. The frequency is given in hertz (Hz). Generator output frequency is given by

$$Frequency\ (Hz) = \frac{p\ X\ speed\ (rpm)}{120} \qquad (3.4.4)$$

So a four-pole generator operating at 1500rpm will produce output frequency of 50Hz, which is the common frequency for the electric power in several countries. Theoretically, the mechanical power from the engine produces an equal electrical power output from the generator, but practically, there are losses in the generator such as I^{2}R losses. Due to these losses, the electrical power output of the generator is given by:

$$P_e = P_{mech} \; x \; \eta_{gen} \qquad (3.4.5)$$

Where P_e is the electrical output power of the generator in kW, P_{mech} is the engine mechanical output power, and η_{gen} is the generator efficiency. The generator efficiency takes into account, the various losses associated with it. The typical generator efficiency is about 90 to 95% [32].

3.2 SELECTION OF APPROPRIATE STORAGE

The type and size of storage is very important because when storage (both electrical and thermal) is added to a CHP system, the overall efficiency of the system is increased by about 30% [8, 9]. Electrical and thermal storage is being considered in this project.

3.2.1 ELECTRICAL STORAGE

Battery storage technology is considered for this project because it is the most widely used electrical storage device. This is due to its high energy and power density, its low cost and availability, and its long shelf life. Table 1 provides a comparison of some significant factors of five commonly used battery types.

To determine the size of the battery (storage) that would be best suited to the CHP system, the energy balance graph of the electrical part of the CHP system has to be constructed, and the battery capacity should be such that it can supply the maximum extra amount of power required at any point in time, and it can also store the maximum amount of excess power produced by the CHP system. The best battery capacity would not lead to waste power and would be able to be charged by the generator. This is given by:

$$P_{excess} = P_{supplied} = C \qquad (3.4.6)$$

Where C is the size of the battery storage in kW, P_{excess} is the maximum amount of excess power produced by the CHP system in kW, $P_{supplied}$ is the maximum amount of power required to be supplied by the battery.Equation 3.4.6 shows that the battery capacity is required to be able to select the right size of CHP to be used. Only one battery cannot be used to supply all the extra power required as no battery has the specifications required, therefore a battery pack consisting of several batteries connected in parallel and series is usually used. Connecting batteries in series increases the voltage of the batteries, while connecting batteries in parallel increases the Ah of the battery bank.

3.2.2 THERMAL STORAGE

Thermal Energy Storage Systems (TESS) are used to store the heat recovered from the exhaust gases and cooling of the engine of a CHP system. Sensible or latent heat storage could be used for thermal storage but for this project, only sensible heat storage is considered. Sensible heat involves storing heat by altering the temperature of the storage medium [20, 21]. Water is the most widely used thermal storage medium because it is easily accessible, and it is cheap to store water at temperatures up to 200°C in pressurized tanks [20, 21]. The capacity or the amount of energy a sensible heat storage can hold depends on the mass and specific heat capacity of the medium. Accurate sizing of the thermal storage is important to reduce loss of heat to a minimum and to increase the efficiency of the overall system, thereby ensuring that the system is profitable to the user.

Similar to electrical storage, the size of the thermal storage should provide a balance between extra power required, and excess power produced by the CHP unit. This is given by:

$$P_{excess} = P_{supplied} = C \qquad (3.4.7)$$

Where C is the size of the thermal storage in kW, P_{excess} is the maximum amount of excess power produced by the CHP system in kW, $P_{supplied}$ is the maximum amount of power required to be supplied by the thermal storage in kW.

IV. ENGINE-GENERATOR SUB-MODEL

SimPowerSystems was developed mainly for the modelling and simulation of power plants, power distribution systems and power electronics. The SimPowerSystems library contains a list of machines that can be used to implement a power system.

The synchronous machine per unit standard block was selected because it best models the generator required for the CHP system. The diesel engine output mechanical power is implemented by using blocks to represent the formula

$$P_{mech} = \tau \; x \; \omega \qquad (4.2.1)$$

Where P_{mech} is the engine's mechanical power in kW, τ is the engine torque in N.m, ω is the engine speed in r.p.m. P_{mech} can be calculated using equation 3.4.2. The datasheet containing the specifications of a commercially available CHP system required for the project was acquired and the values were used to calculate the mechanical power required to drive a generator in order to produce the nominal power of the CHP system being modelled. The mechanical power of the engine was calculated as:

$$\text{Pmech} = \frac{nP_{mi}\,LANk\ X\ 10}{6}\ \text{kW}$$

$$\text{Pmech} = \frac{6\ x\ 6.5\ x\ 0.125\ x\ (\frac{\pi}{4}\ x\ (0.108)^2)\ x\ 1500\ x\ 1\ x\ 10}{6}\ \text{kW}$$

$$\text{Pmech} = 111.6\ \text{kW}$$

111.6 kW is required to drive a generator to produce 105kW of electrical power output on no load, which is the output of the CHP system chosen. To implement the speed control of the engine, the transfer functions of the speed regulator and engine throttle actuator were modeled.

The speed controller transfer function together with the throttle transfer function give the closed loop speed control of the engine where the desired and actual speed are compared and the error used to correct the output speed of the engine, as a synchronous machine is required to get back to rated speed after a disturbance.

The diesel engine block was then connected to the generator block. Visual scopes and load was connected to the engine-generator sub-model. The generator load was simulated using the parallel RLC load block from the elements library of SimPowerSystems.

Three different demand load values were added to the model in order to show a typical load variation on a CHP system. Three-phase circuit breakers from the elements library were used to achieve load change. Figure 6 shows the engine-generator model at this stage.

4.1 BATTERY AND POWER CONVERTER SUB-MODEL

The battery was used as the electrical energy storage for this project. The requirements for the battery is that the size used should be able to supply any extra power required if the CHP cannot handle the load, and there should be no power wastage from the supply. That means the capacity of the battery should be such that supply will match demand. Equation 3.5.1 gives the formula for finding the capacity of battery required to match supply and demand.

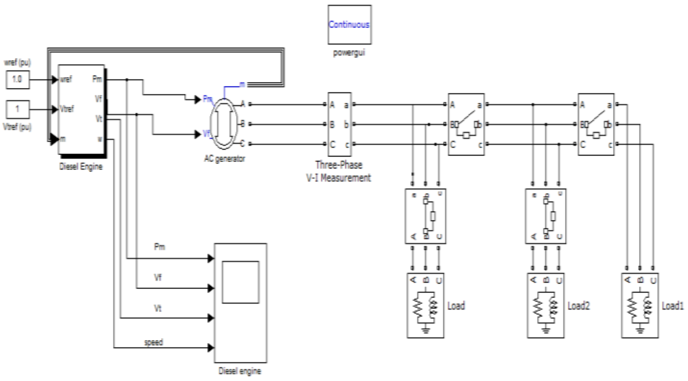

Figure 6: Engine-Generator sub-model

The battery capacity should be able to provide the largest extra power per time (from the load profile), and should also be capable of storing the maximum excess power produced. From the energy balance graph in Figure 10, the battery capacity required is:

$$P_{excess} = P_{supplied} = \text{C}$$

$$22\text{kW} = 22\text{kW} = \text{C}$$

Table 1 gives the major characteristics of the selected Lead-Acid battery to store energy [35]. From Table 1, it can be seen that only one battery cannot meet the storage needs of the CHP system, therefore, a number of battery are connected in parallel and series. Thirty-four 12V batteries are connected in series providing a voltage of 400V. In-order to increase the Ah capacity of the battery to make up the required 20kW, about 3 batteries are to be connected in parallel to provide a battery of 50Ah capacity. The batteries are quite plenty, but due to the low cost of lead-acid batteries compared to other types, the entire battery bank comes up to about $850 which is equivalent to about £500, which is relatively cheap in relation to the number of batteries used.

TABLE 1: MAIN CHARACTERISTICS OF THE SELECTED LEAD-ACID BATTERY [35]

	
Nominal voltage	12V
Capacity	17Ah
Operating temperature	-20°C to +60°C
Weight	6.2kg
Cycle life charge/discharge	500 cycles at 80 to 100% depth of discharge (DOD)
Energy density	40Wh/kg
Charge/discharge efficiency	75%
Price	$25

4.2 THERMAL STORAGE SUB-MODEL

A hot water storage tank was used as the electrical energy storage for this project. Only the district hot water demand of the user is considered in this project. The space heating demands are ignored. DHW load profile is not constant but is relatively easy to predict. There is constant load but with five load peaks over this continuous consumption. The water from the tank is drawn three times at one hour intervals during the morning time, and two draws of one hour intervals during the evening time. The tank is not used from the evening draw to the morning draw. The main requirement for the thermal storage is that the size used should be able to minimize the need to dump excess heat into the environment.

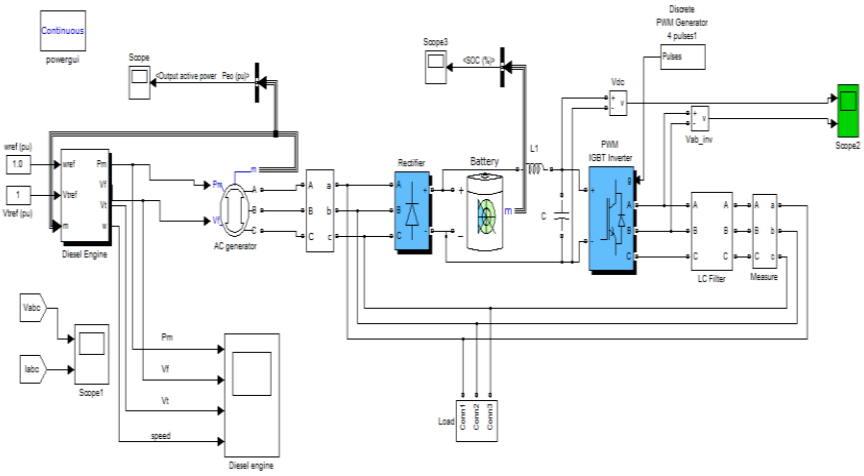

Figure 7: Developed model of a CHP system with electrical (battery) storage

Any heat recovered from the engine should be the right amount to produce enough hot water to meet the user's demand. The thermal sub-model used in this project accounts for any extra heat, such as from a boiler, that would be required if the heat from the engine cannot meet the load.

Simscape is an add-on environment of Simulink which contains thermal blocks which are used to model thermal systems. The hot water storage system consists of a storage tank which stores thermal energy as hot water, and a heat exchanger which heats up the water in the tank. Water from the public water supply flows into the tank at a certain pressure and temperature and heat recovered from the cooling of the engine, heats up this water. The heat from the engine jacket cooling water is typically between 80 and 90°C [8]. The heat in kW from the engine is given by Equation 4.2.2 [37].

$$P_{thermal} = C_v \, x \, \rho_w \, x \, C_w \, x \, (T_u - T_i) \qquad (4.2.2)$$

$P_{thermal}$ is the thermal power released by the engine jacket cooling water, C_v is the water volume to be consumed by the user in a day in dm^3, ρ_w is water density at temperature T_u in kg/dm^3, C_w is the water specific heat in kWh/kg K, T_u is the temperature of the water out of the tank in °C, and T_i is the net water temperature in °C. Assuming the volume of consumption per day to be $1dm^3$ at 60°C, with water net temperature of 16°C, ρ_w and C_w are standard values of water, the thermal power from the engine cooling is 47kW. This means 47kW of thermal power (heat) is produced by cooling the engine in order to provide the DHW demand.

The heat is modelled by an ideal heat flow source from the Simscape thermal sources library. Heat loss from the tank by convection and conduction are also modelled using elements from the thermal library. The tank storage is modelled using a pipe found in the elements library. From the energy balance graph in Figure 15, the capacity of the storage in kW that would be best suited for the system is given as:

$$P_{excess} = P_{supplied} = \mathrm{C}$$

$$12\mathrm{kW} = 12\mathrm{kW} = \mathrm{C}$$

To find the size of the tank that can hold this capacity, the formula in equation 4.2.3 is used.

$$V = \frac{T_{on}\ (Q_{in} - L_{min})}{500\ X\ \Delta T} \tag{4.2.3}$$

Where V is tank volume in gallons, T_{on} is the time the extra burner is on for during its on cycle, $(Q_{in} - L_{\min})$ is the storage capacity in btu/hr, ΔT is the allowed temperature rise in °F. Assuming T_{on} to be 10 minutes, and ΔT to be 10°F, then a 372.28L (81.9 gallons) tank would hold water with stored energy of 12kW. The model of the thermal storage developed is shown in Figure 8. A back up heat source is used to heat up the water when the tank temperature drops below a set point. This heat source (burner) is turned off when the tank temperature reaches a higher set point. That is, the burner only comes on when the heat from the tank is not enough to meet the DHW needs of the user.

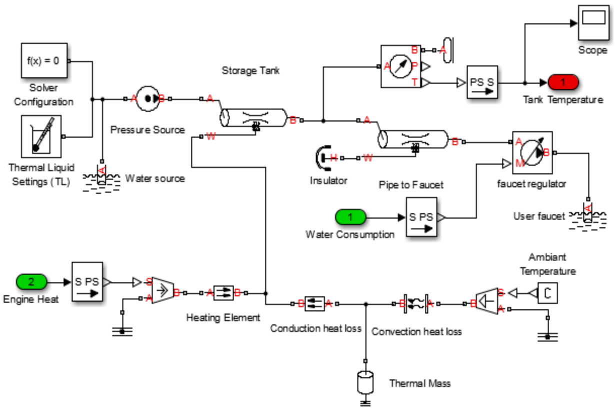

Figure 8: Thermal storage sub-model

V. SIMULATION RESULTS

Matlab uses scopes to show the simulation results. The expected electrical power output of the CHP system is expected to be gotten by

$$P_{electrical} = P_{mechanical}\ x\ \eta_{gen}$$

Typical AC generator efficiency is given as 95%. This means the expected electrical power output is 106kW, this means the CHP system can only meet some of the demand needs of the user as seen in the demand profile. The demand profile of the user for this project is shown in Figure 5. The engine-generator sub-model was simulated and the generator characteristics are shown in Figure 9.The first trace in the diesel engine scope shows the mechanical power driving the generator. The values of the output are in per unit (p u). At the initial load of 87kW, the generator was supplying 65% of its power. At time 3 seconds, the load was switched to a higher load of 95kW which is still within the limits of the generator output. The engine mechanical power to the generator was increased to about 0.95 pu power in order to increase the electrical power output. When a lower load was used, less mechanical power was released to the generator.

The second and third traces of the diesel engine scope show the engine field and terminal voltages respectively. When there is a change in load, both the field and terminal voltages experience a ripple, but are restored back to their nominal values due to the control system implemented. The speed trace shows how the generator returns to synchronous speed after a disturbance, that is, when a load is added, the generator speed reduces because of increased torque but it quickly returns to its nominal speed. The energy balance of the CHP electrical part is shown in Figure 10.

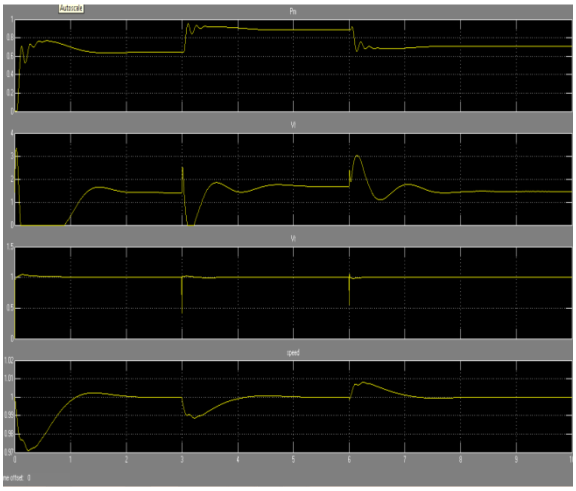

Figure 9: Diesel- engine characteristics

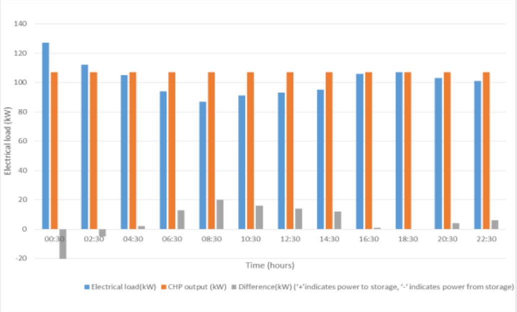

Figure 10: Energy balance of the CHP electrical part

Figure 10 shows that the size of the storage that can provide the power required to meet maximum load and to store maximum excess power from supply per hour is 20kW.

Next, the battery and power converter model was combined with the engine-generator model. From Figure 11, it can be seen that the universal bridge can be used as a rectifier and an inverter.

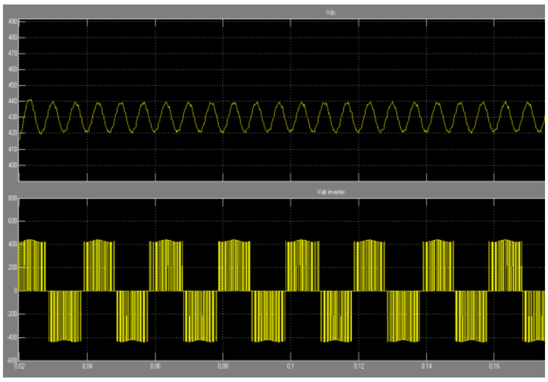

Figure 11: Rectifier and inverter output voltages

The first trace shows the DC voltage output from the rectifier. The second trace shows how the AC voltage that has been inverted from the battery's DC voltage. The use of the universal bridge, reduces the complexity of the overall model considerably.

The load connected to the model was varied as in the engine-generator sub-model, but one of the loads was above the power limits of the generator. Figures 12 to 14 show the results of the simulation. Figure 12 shows the generator voltage and current. The first trace shows the three-phase voltage being supplied to the load. The peak voltage is constant at 565V ($V_{rms}\ x\ \sqrt{2}$). The nominal current value of the CHP system used is given by the generator's rated kVA divided by 1.73 multiplied by rated voltage. With 135kVA, and 400V, the rated current is 195A. The second trace is the current output to the load. When the load is within the generator limits, the current supplied to the load is 195A, but when the generator becomes overloaded, the battery current is added to that of the generator increasing it to about 250A, consequently increasing the power supplied to the load. This means that, to increase the power, current would be increased while voltage is kept constant.

Figure 13 shows how the electrical power of the CHP system increases when the battery also supplies power to the load. When the load changes, the power experiences a ripple then becomes steady. Figure 14 shows the state of charge of the battery during simulation. At initial load which is within generator limits, the generator supplies the load and also charges the battery. The battery is initially set at 40% SOC. When the generator load becomes overloaded, the battery begins to discharge until the generator load reduces within its limits, then it begins to charge again and the cycle continues. From the results shown, the CHP system supplies about 85% of the load with the battery supplying the remaining load. From the results, it can be seen that the addition of the battery to the CHP system reduces the need to use a larger CHP unit which reduces the amount of waste power that would otherwise have been produced.

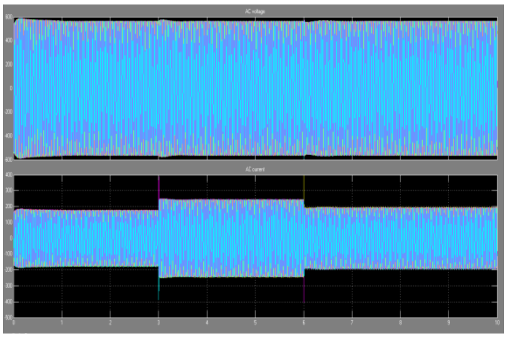

Figure 12: Generator current and voltage

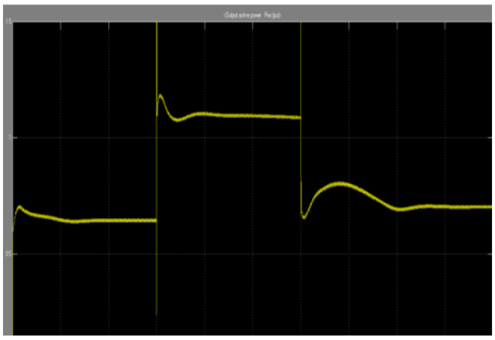

Figure 13: Output power supplied to the load

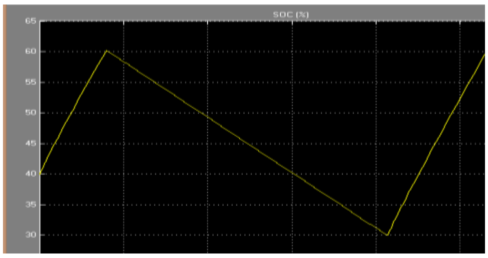

Figure 14: Battery SOC (State Of Charge)

The efficiency of a CHP system is given in equation 3.4.1. The electrical power output of the CHP system without battery is 0.65 pu (Figure 13) which gives 68.25kW, and the thermal power is 47kW. The fuel input to the system is assumed to be constant at 160kW. The calculated overall system efficiency is 72%, which is within the accepted range for a CHP system. When the battery storage is added to the system, the electrical power output of the system is 1.15 per unit (Figure 13) which gives 120.75kW. The thermal power and fuel input remain the same, bringing the overall system efficiency to 104%. The efficiency of the system when electrical storage is added, increases by 32% which agrees with values obtained in real systems [8]. The efficiency of the system is improved because no power is lost thus leading to reduced energy consumption. If the CHP is run without the storage, the CHP system would be required to be large enough to cover 100% of the load, thereby leading to excess power being lost.

The thermal sub-model was modeled using Simscape, which is also an add-on environment of Simulink. The sub-model was modeled and simulated differently from the CHP system with battery storage. This is because the two environments (Simscape and SimPowerSystems) cannot be combined as some component blocks are not compatible. The energy balance of the CHP thermal part is shown in Figure 15.

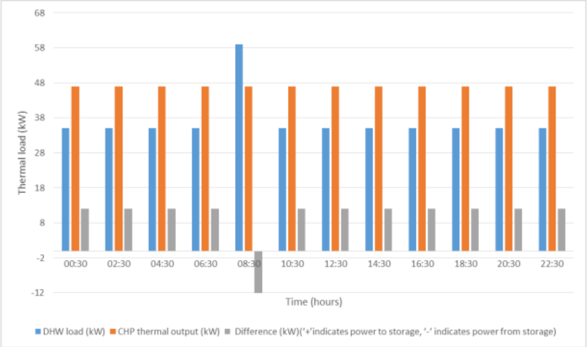

Figure 15: Energy balance of the CHP thermal part

Figure 15 shows that the size of the storage that can provide the power required to meet maximum load and to store maximum excess power from supply per hour is 12kW.
The thermal sub-model was simulated and the result is shown in Figure 16.

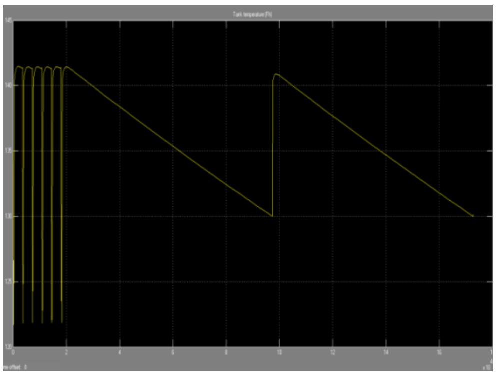

Figure 16: Thermal storage tank temperature in Fahrenheit

From Figure 15, it can be deduced that the CHP system produces enough power to meet about 85% of the user DHW needs, while the thermal storage tank supplies the rest. By the addition of the storage, there is no need to dump excess heat produced to the environment thus increasing the efficiency of the system.

The result shown in Figure 16 shows the storage tank temperature in Fahrenheit. The user draws water from the tank at five different periods for 1 hour each time, and then water is not used for at least 8 hours between the last and the first draws. The tank water temperature supplied to the user is at 60°C (140°F). When the hot water from the tank is drawn, the temperature of the tank reduces to around 50°C (122°C). The water is then heated back to 60°C and the cycle is repeated anytime water is drawn. After a long period of tank inactivity and the tank temperature falls below 50°C, a back-up boiler comes on, and supplies heat to bring the water temperature back to 60°C, waiting for the next water draw.

VI. CONCLUSION

In this work, a model of a CHP system with storage (both thermal and electrical), was developed using Matlab program. The model was first of all developed, and then analysis was done on the model to determine the effect of storage on overall system efficiency. The model makes use of Simulink blocks to model the various parts of the CHP system with storage. The model is useful for carrying out the selection of the right size of CHP system, and storage that would be able to meet a user's load profile. The model is also useful as a tool for assessing and analysing overall system efficiency.

For a CHP system to be used for meeting user demand, the efficiency of the system is to be at least 70%, in order for the user to benefit from its installation. By adding both electrical and thermal storage to the CHP system, the efficiency is increased by about 30%. For this project, a CHP system with electrical power output of

105kW and 47kW thermal power due to only engine cooling is modelled. The results of the simulation of the developed model show how, by the addition of a battery of 20kW and a hot water storage tank with storage capacity of 12kW, the efficiency of the modelled system is increased by 32%, which shows that the model is reliable. The achieved results also indicate the feasibility and acceptability of the project, as well as indicating the importance of selecting the right size of CHP system, thermal and electrical storage in order for the system efficiency to be the best.

Matlab has proven to be a valuable tool for model development and simulation. It is easily accessible and quite flexible compared with the several available software. Matlab gives an opportunity for designers to simulate the actual system before building it physically, therefore reducing time and cost lost to physical testing. This improves the design process greatly.

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ABBREVIATIONS AND ACRONYMS

CHP–Combined Heat and Power;
CCL–Climate Change Levy;
ECA–Enhanced Capital Allowance;
FIT–Feed In Tariffs;
DHW–District Hot Water;
ICE–Internal Combustion Engine;
HPR–Heat to Power Ratio;
WHP–Waste Heat to Power;
HHV–Higher Heating Value;
TES–Thermal Energy Storage;
EES–Electrical Energy Storage;
kWe /P_e–CHP system electrical power output (kW);
kWth /Q_{th}–CHP thermal power output (kW);
PEMFC–Proton Exchange Membrane Fuel Cell;
SOFC– Solid Oxide Fuel Cell;
PAFC–Phosphoric Acid Fuel Cell;
MCFC– Molten Carbonate Fuel Cell;
AFC–Alkaline Fuel Cell;
PEM– Polymer Electrolyte Membrane Fuel Cell;
DC–Direct Current;
AC–Alternating Current;
η_p–CHP overall efficiency (%);
Q_f–Fuel input (kW);
τ–Engine torque(Nm);
ω–Speed (rpm);
P_{mech} –Engine mechanical power output (kW);
n–Number of cylinders of the Engine;
P_{mi}–Mean effective engine pressure (bar);
L–Piston stroke (m);
A–Piston area (m^2);
k–Constant;
η_{gen}–Generator efficiency (%);
$P_{thermal}$ –Thermal power from engine cooling jacket water (kW);
C_v–Water volume to be consumed in a day (dm^3);
ρ_w–Water density at temperature T_u (kg/dm^3);
C_w–Water specific heat (kWh/kg K);
T_u–Temperature of water in tank (°C);
T_i–Net water temperature (°C);
T_{on}–Amount of Time extra burner is on for during its on cycle (minutes);
$(Q_{in} - L_{min})$–Storage capacity (btu/hr);
Δ_T–Allowed temperature rise of tank (°F);
V–Tank volume (gallons);