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Multi-generation Modeling and Building Energy use optimization based on a Natural Gas driven Internal Combustion Engine

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Abstract

Science and technological advancement, environmental pollution, government policies and rising energy costs have long since begun redefining the way power is generated, distributed and utilized. Considering the much higher standards relative to common practices, distributed energy power generation has proven to be a viable alternative to centralized power generation due to the many advantages such as energy generation and control independence, lower greenhouse emissions and significant reduction in transmission losses. This research considers a natural gas-powered internal combustion engine (ICE) with heat recovery and trigeneration capabilities or combined cooling heating and power (CCHP) as well as renewable energy incorporation including solar panels and possibly solar thermal. Research objective is to create an accurate working numerical model that in future can be compared with an experimental model for verification and optimization. TRNSYS software is used to create a numerical model by assembling the components as it would be in real life and running a simulation. In modeling the building, Sketchup and OpenStudio will be used to create thermal zones as in a single-family two story detached house with conventional floor plans. The model will then be imported into the TRNSYS environment for further analysis. Optimization of the system would be primary, and with a targeted energy utilization factor of 95%, this research will seek to provide substantial and convincing data for future installations.

Keywords: *Solar, Power generation, CCHP, TRNSYS, ICE, Natural gas, Heat recovery*

1. Introduction

In this modern age, several factors continually raise the bar on acceptable system operations and performance levels. In the power and energy industry this dynamic shift has been significant. The cost of energy, pollution levels, sustainability, resource conservation and policy restrictions are a microcosm of such factors that encourage substantial optimization. As a result, contrary to the mainstay centralized power generation and distribution, regionalized multi-generation of energy resources for residential and industrial building needs is beginning to expand and attract attention in the United States. It promotes greener energy generation with a negligible carbon footprint by employing the use of hybrid renewable systems, implementing end user energy independence and power control, enhancing fuel efficiency and improving the energy utilization factor (EUF). In this research, the proposed power generation system is a hybrid combination of heating, cooling and power generation (CHCP), where the primary energy source is a natural gas internal combustion engine (ICE) employing extensive heat recovery processes. According to previous studies, by exploiting the huge amount of waste heat rejected by the operating power cycles of the generator the EUF of the system can be improved significantly, with natural gas-powered ICE reaching as high as 81% as against an average of about 38% for thermal power generation systems. (Santo, 2012). Similar research has been done by (Abu-Hamdeh, 2015) and (Taherian, 2017) seeking to optimize the generator size to match residential load demand.

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Several subtle information gaps exist that makes this research imperative. Firstly, research on ICE generators needs to be done and categorized by location and climate type, while including other renewable sources and varying operating conditions. To accomplish this, specifications and performance data from a specific generating unit can be used to simulate power generation and building energy use in the Birmingham area and in addition, extensive heat recovery for space heating and hot water storage has been integrated into the system to achieve assured and greater savings. Renewable energy sources and storage (thermal and electrical) is also incorporated. An emphasis on cleaner and efficient energy was recently brought to light when a small island village in Alaska saved considerable amounts of energy consumed and associated costs by transiting from a majorly fuel oil-based electricity generation to carbon-neutral biomass generation.

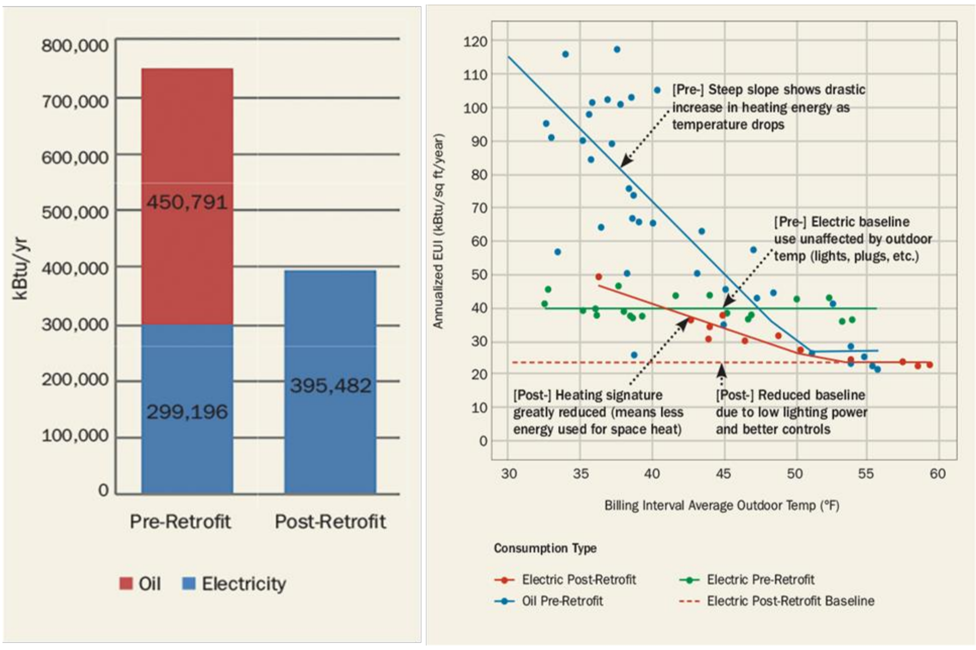


Fig 1: Pre and post retrofit data from Sitka. (Heller, 2018)

Primary design features included reduced load, proper equipment sizing, optimization, and the use of high efficiency pumps and heat recovery ventilators. The energy-efficiency designs in Sitka, Alaska not only eliminated the use of fuel oil but showed how modern buildings can move toward a carbon-neutral, energy-efficient future (Heller, 2018).

Preceding studies have compared hybrid natural gas-powered micro-turbines and central power generation systems, the EUF of the former was reported to exceed 90% as against an average of about 30% for the latter counterpart. This is achieved by exploiting the huge amount of waste heat rejected by operating power cycles. Like the central power systems, conventional steam plants run on the Rankine cycle, which is a significant culprit of waste heat rejection. To compensate for the losses, central combined cycle steam generators only slightly improve the efficiency. It must be noted however that without employing multi-generation functionalities, the natural gas-based electricity generating systems appear to be somewhat costlier than grid electricity use.

Generators, electrochemistry and photovoltaics represents the broad spectrum of power generation methods that have been applied in several systems. Power generation equipment like solar panels are used to capture solar energy while turbines can be run by several different movers such as steam from fossil fuel, nuclear boilers, wind and water current from dams and spillways for hydroelectricity. In recent times environmental concerns amongst other determinants have shaped and somewhat defined the global approach to power generation and its predominant methods. The demand for cleaner energy has led to the development of multi generation power generation that comprise of different energy systems employing optimum renewable energy (RE) utilization. Due to the rising cost of energy for socio-economic development and ever stringent environmentally safe codes and standards, the importance of RE development in these times cannot be overstated.

2. Literature Survey

2.1. Distributed Energy Power Generation (DEPG)

Distributed Energy Power Generation goes by several different terms like Distributed energy resources (DER), On site generation (OSG) or District/decentralized energy. They are small to medium scale systems that serve as an alternative to the customary centralized power generation and distribution system. They are regarded as an advancement to the customary central base station power technologies and are deployed in compact systems able to generate and supply power on a district or regional basis. Although it has been notoriously associated with high initial capital costs per kilowatt, accelerated research and development in this area has brought about better designs and highly optimized solutions that can generate and distribute energy in the most efficient way possible. Hybrid renewable energy sources are frequently employed and several multi generation systems are integrated into single units that can serve the power needs of residential, commercial and regional buildings alike. There are several technologies associated with DEPG with each having its merits, demerits and applications.

2.2 Combined Heating and Power (CHP)

Many definitions of Combined Heat and Power (called cogeneration) have appeared in scholarly literature. As defined by Clarke Energy Cogeneration is the simultaneous generation of work and useful heat from the same primary energy source. Work shall mean either mechanical or electric energy.

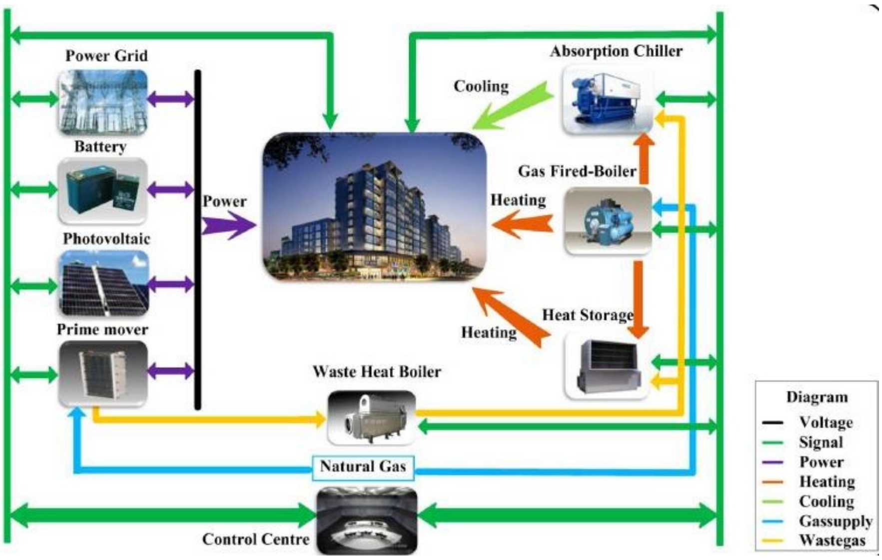


Fig 2: Schematic of a CHP system (Gu et al., 2014)

Substantial measures are required to reduce the emission of greenhouse gases and the avoidance of a fast depletion of fossil fuels. Many sources mention that the amount of heat wasted during electricity production and industrial activities is enough to cover a substantial part of the demand for heat. According to a 2008 IEA model of cogeneration in G8 countries, expansion of cogeneration technology in France, Germany, Italy and the UK would increase primary fuel savings by almost 200% in 2030. In the United States, The Department of Energy is attempting to stimulate cogeneration and have instituted a target of 20% CHP generation capacity by 2030. (Ene.Field, 2017)

3. Methodology

A numerical model was run using TRNSYS Simulation studio to obtain time step performance data of the design as suggested by (Fumo & Chamra, 2010) and emphasized by (Chahal, 2016) in papers advocating for the use of numerical analysis for realistic residential building energy modelling. TRNSYS can analyze transient systems as well as thermal and electrical energy system modeling. Dynamic Numerical Modeling and associated calculations can be done using this package.

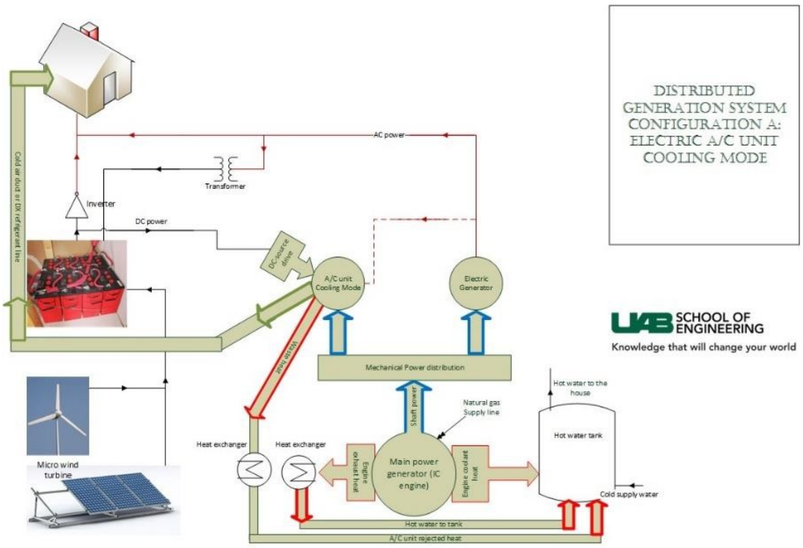


Fig 3: Initial DPEG System Configuration

To initiate, a simple power generation system based on an ICE was modeled to serve as a control or base-case for assessment purposes. Other features were thereafter added to the system sequentially. The primary energy source is a natural gas-powered ICE. Initial calculations were based on a core power output of 9KW, with a 1.5 ton mini-split heat pump (HP) system which will be used for cooling and heating purposes and finally a 7.2 kWh battery bank however during the course of this research some changes were made between the initial and final configuration as shown in figures 3 and 5. Currently the generator unit has a maximum power output of 8KW AC with coefficient of performance (COP) target at 2.5 and a Power Factor of 0.98. In the numerical modeling, the building was modeled as a single-family two stories detached house with conventional floor plans. Several modifications and iterations were carried out to determine optimum configuration set ups. The project was also developed further with Open Studio (OS) to improve the accuracy of the results.

3.1 Building Model Description

A key component to the computer model of the power generation system is the residential conditioned and occupied space. To accurately represent the real-life system a small two-story single-family house was modelled with SketchUp (Trimble Inc. 2018) and TRNBUILD.

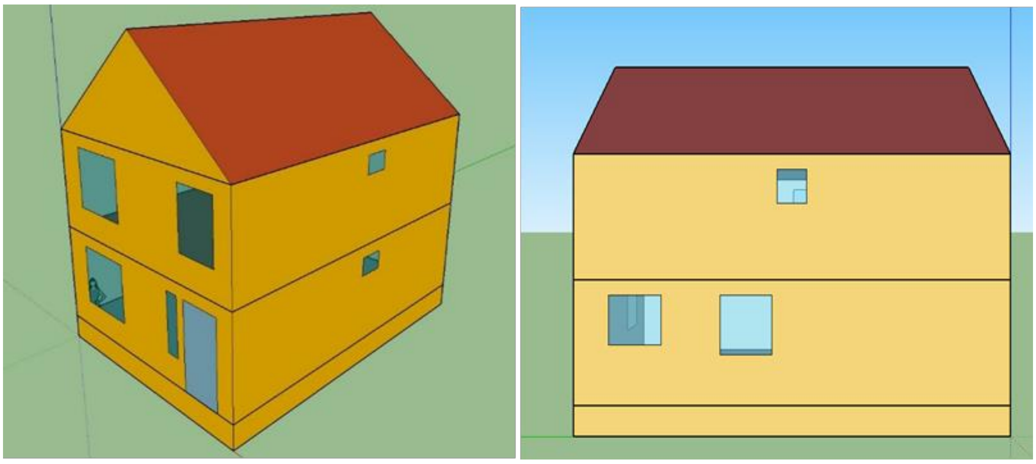


Fig 4: Building Model in SketchUp

SketchUp is used for building design and construction. It’s use also includes programming, diagramming, design development, detailing and documentation of building features. In other to use the Sketchup file on the TRNSYS model a plugin was utilized to make the file compatible.

Figure 4 shows the isometric and side views of the house 3D model. It is a two-story house with a footprint of about 600 square feet. The building is split into two thermal zones corresponding to the first and second floors, enabling independent temperature control for each floor. In addition, distinct features such as the attic and crawlspace were incorporated to adequately represent the building style in the local community. The wall, floor and roof sections along with the material properties for the ceiling, doors and windows were also defined to match the conventional trends in construction materials used for single-family homes.

3.2 TRNSYS Model Description

A TRNSYS project is typically setup by connecting components referred to as “types” graphically in the Simulation Studio. Every component is defined by a mathematical model in the TRNSYS simulation engine which dictates its operation and energy balance within the model. It also has a set of matching proformas which is a black-box description of any component as it contains information about inputs, outputs, parameters, etc. The Simulation Studio generates a text input file for the TRNSYS simulation engine. That input file is referred to as the deck file. (Specialists, 2017)

At the core of the model is a natural gas ICE set to run at about 60 percent power output. The exhaust gas, oil cooler and cooling jacket water both flow into individual sensible heat exchangers that facilitate heat transfer for hot water storage. The storage capacity is neglected in the heat exchanger models. Exhaust gases from the ICE is split using a flow diverter to serve the hot water tank (HWT) and space heating. A bypass heat exchanger facilitates heat transfer between cold unconditioned air coming from the building and hot gases, while thermostats are used to initiate or cut of the heat flow within a temperature band of 21ºC to 23ºC. The exhaust gases are also set to bypass the hot water tank in a situation where additional water heating is not required. Similarly exhaust gases are bypassed and dumped into the surroundings when additional space heating is not required and a dry fluid cooler (radiator) is used as a backup cooling system for the jacket water. An 8 by 3 Solar Photovoltaic (PV) array with 330W modules serve as the renewable energy source. A generic inverter and charge regulator considers load demand from the building model while controlling the charging and discharging of a standby 8 by 3 720Wh battery bank. The size of the battery bank was determined by running the model with the control criterion that excess generated energy can be sufficiently stored for later use.

Table 1 and 2 below show the input and output parameters for the major components. The input parameters are fed to receiving components from the output of other components, external data files or equation data solvers.

Tab. 1: Major Components’ Input Parameters

ICE	HWT	HP
Intake air temperature	Inlet Recycle temperature	Return air temperature
Intake air temperature	Inlet Recycle temperature	Return air temperature
Desired output power	Inlet Recycle flow rate	Return air humidity ratio
Jacket fluid temperature	Inlet Recycle temperature	Return air %RH
Jacket Fluid flow rate	Inlet Supply temperature	Return air flow rate
Oil Cooler temperature	Inlet Supply flow rate	Inlet Pressure
Oil Cooler flow rate	Top Loss temperature	Fan pressure rise
Aftercooler temperature	Bottom Loss temperature	Outside air temperature

Tab. 2: Major Components’ Output Parameters

ICE	HWT	HP
Exhaust Temperature	Outlet Recycle Temperature	Outlet air temperature
Exhaust Flow Rate	Outlet Recycle Flow Rate	Outlet air humidity ratio
Jacket Water Outlet Temp.	Outlet Usage Flow Rate	Outlet air %RH

Jacket Water Flow Rate	Outlet Usage Temperature	Outlet air flow rate
Oil Cooler Outlet Temp.	Table text	Outlet air pressure
Oil Cooler Flow Rate	Table text	Total cooling rate
Electrical Power	Table text	Sensible cooling rate

4. Results and Discussion

It is important to note that the primary tool for this research, TRNSYS simulation studio is highly flexible in terms of what type of system can be modelled, nevertheless with this advantage in adaptivity comes the higher risk of researchers easily mixing up parameters and that can lead to runtime errors, loss of result repeatability and data reliability. Therefore, one of the primary goals of this research was to obtain a working model with accurate, reliable and repeatable data based on specified conditions. Some of the trends are explained accordingly.

The building that was modeled was split into two thermal zones, one for each floor. The setpoint for the two zones is set to 22ºC with a dead band of 2ºC. To achieve this the supply fan from the cross-flow heat exchanger used for exhaust heat recovery is set to supply heated air when the temperature drops below 21ºC, while the air source heat pump supplies cool air when temperature goes above 23ºC and supplementary heating when temperature goes as low as 17ºC. The system was able to maintain an average annual temperature of 21ºC for both zones. Figure 6 shows the current temperature distribution of the model.

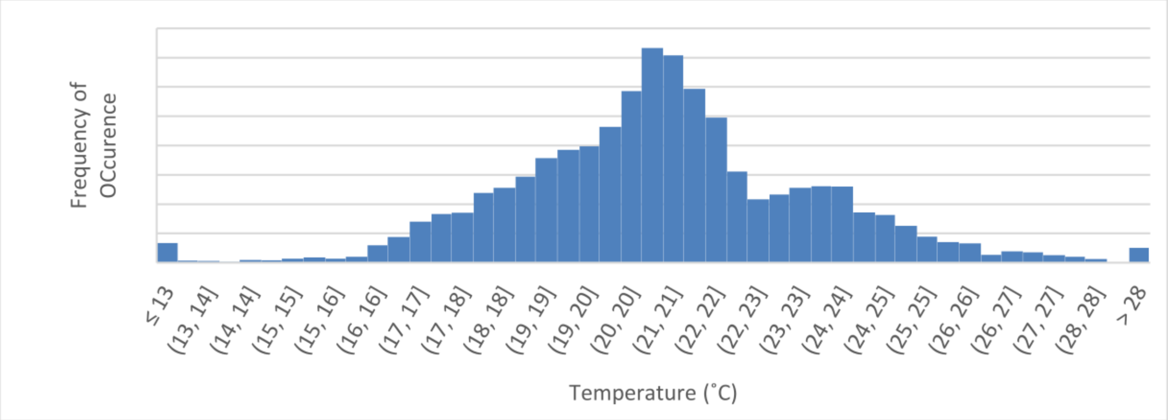
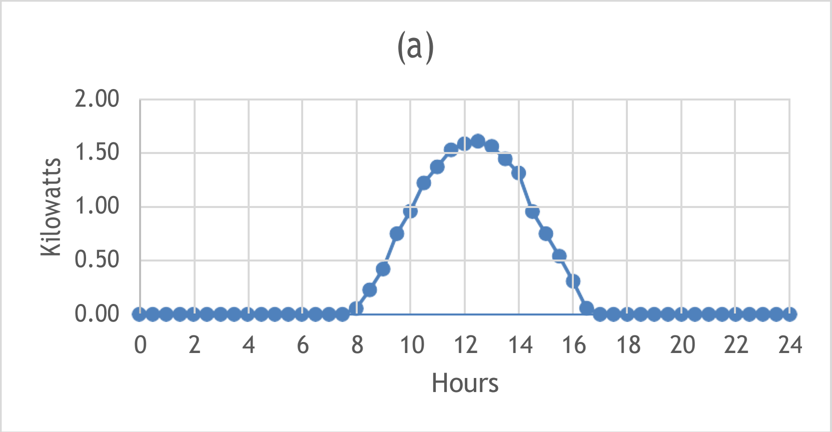


Fig 6: Temperature distribution for first floor

The data in figure 6 shows that in 8760 hours of the year, the set temperature bracket of 20ºC to 24ºC was met 65% of the time. The unmet hours for low temperatures ≤ 16ºC and high temperatures ≥ 26ºC are insignificant as can be observed above. It must be noted that many of the unmet hours are unoccupied unmet hours.



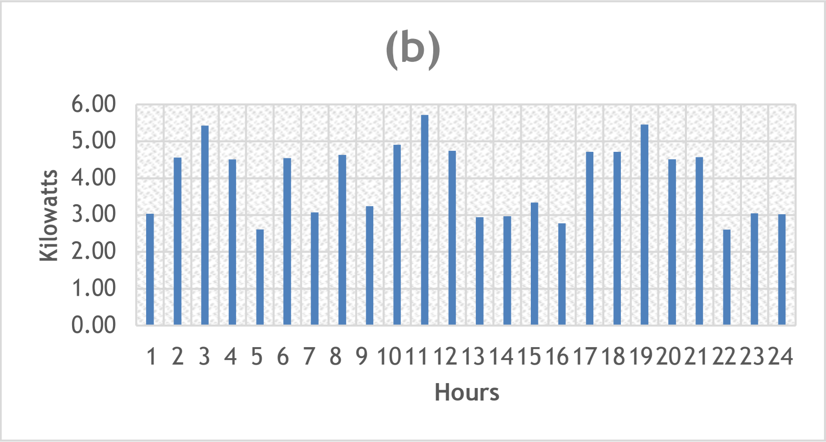


Fig 1: (a) Solar PV generation and (b) Building Energy Use

Figure 7 shows data harvested from the power systems. A familiar trend for the solar PV generation can be observed in (a) while the building energy use over 24 hours is shown in (b). An 8 by 3 solar array with 330 W rated modules was modelled and its annual generation stood at 11900kwh, a value considerably close and only 6% greater than that generated by the National Renewable Energy laboratory PV performance tool that estimated an annual generation of 11200kwh (Laboratory, 2018). The heat transfer between thermal fluids and heat exchangers which represents heat recovery throughout the year currently stands an 36000kwh. This is achieved by strategically placing heat exchangers to recover and utilize heat that would otherwise have been lost to the process or environment.

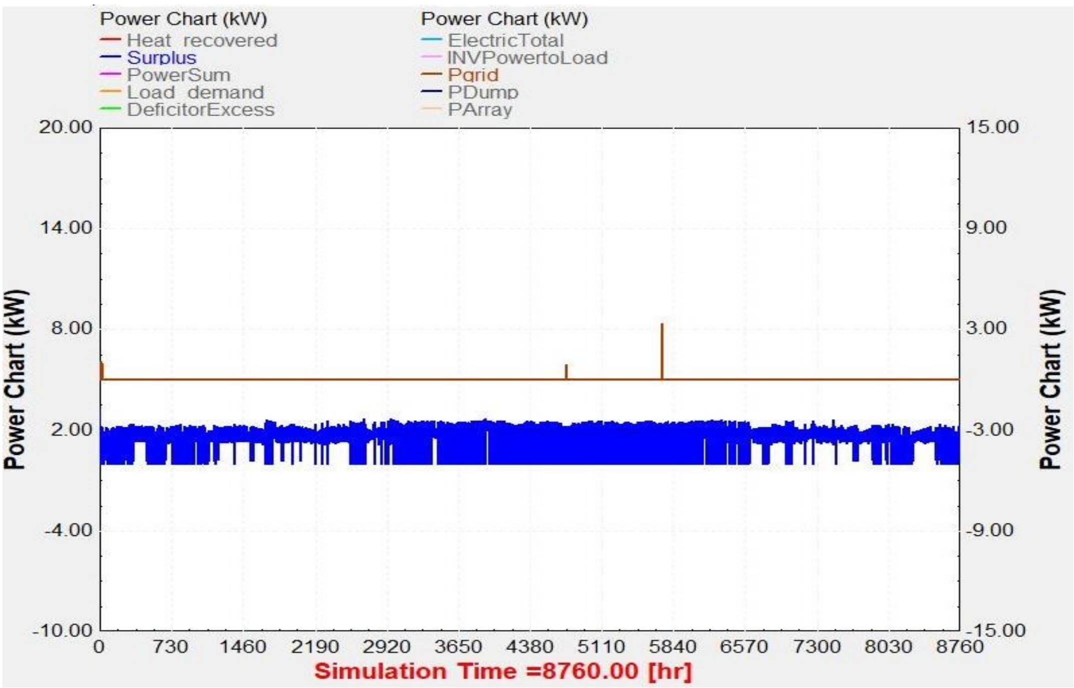


Fig 8: Energy Use and Production Monitor

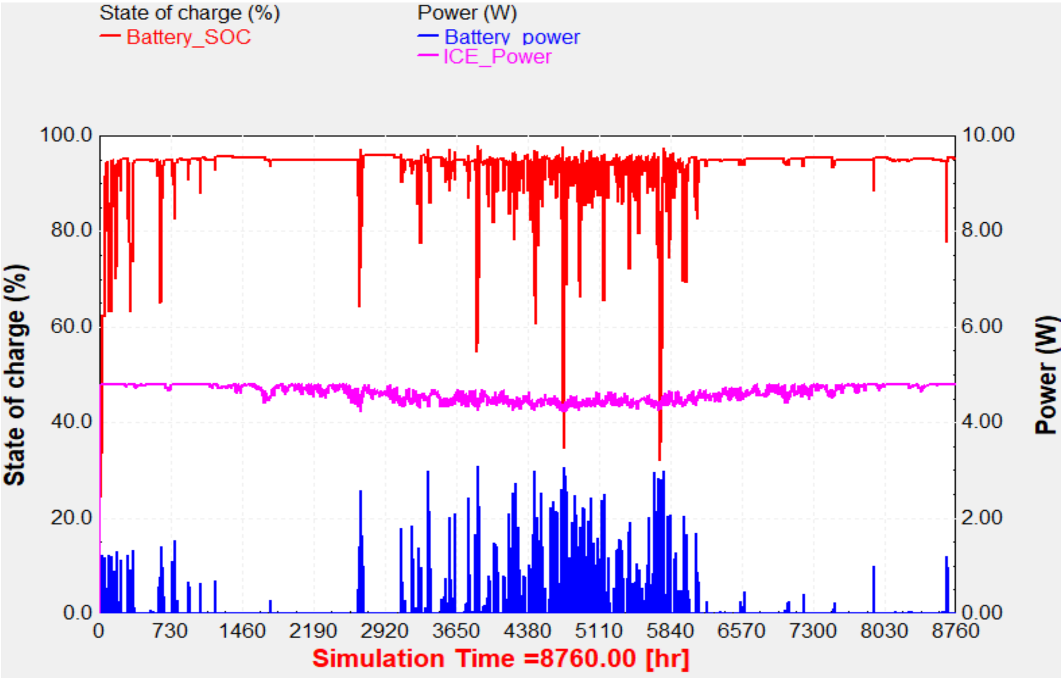


Fig 9: Battery Bank and ICE Energy Monitor

Figure 8 is a TRNSYS chart showing the energy balance of the multi generation model. The charts are plotted on the left and right axis and have been separated accordingly in the legend. Surplus represents the excess energy produced by the current model. This is important especially considering the generator is only running at about 60%. Excess energy can therefore be employed in charging a larger battery bank or sold back to the grid in locations were policies allow such actions.

The energy model is almost totally off-grid as the energy taken from power utility “Pgrid” is nil almost throughout the year. Figure 9 on the other hand shows a plot of the battery bank state of charge (SOC) on the left axis. The fluctuations arise as the battery is charged and discharged according to load demand signals sent to the inverter/regulator. It also shows the right axis plots of battery power and ICE generation. The battery SOC is plotted as a percentage, battery power represents the energy sent to charge the battery to maintain SOC above a set low limit of 35%, to prolong the life of batteries. Finally, the ICE power shows the energy generated from the ICE, shown for relative comparison purposes. The ICE has a power rating of 8KW, however for this research it was set to run hovering around 5KW. This translates to lower fuel burn rates and therefore lower fuel cost.

5. Conclusion

Distributed hybrid power generation is leading a new era in the energy sector and opens avenues to the use and integration of heat recovery and cleaner energy in the mainstream power sector. This research has successfully modeled such a system using several software packages. Birmingham, Alabama was the design location and the model was run for 8760 hours (an entire year). Heat recovery and solar energy was expansively used, the building conditions and main equipment operations were analyzed, and the results are compliant and reasonable with what is required for a typical family house. The current model’s energy use is relatively low, and all building needs have been adequately accounted for. Consequently, energy cost is expected to be low, as there is near zero energy pulled from the grid as well as a considerable energy surplus from the ICE, heat recovery and solar PV multi generation systems. Furthermore, the base model is very flexible and can easily be applied to different locations and building types. The adaptable feature of the model avails researchers the opportunity to carry out further optimization and development in the future.

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