

A Feasibility Study of a CHP System in a Commercial Facilities: Sizing and Parameters Analysis

Md Javed Hossain^{a*}, Shuva Mitra^b, Raihan Uddin Ahmed^c

^aAssistant Professor, Stamford University Bangladesh, Dhaka-1217, Bangladesh

^{b,c}Lecturer, Stamford University Bangladesh, Dhaka-1217, Bangladesh

^aEmail: javed@stamforduniversity.edu.bd

^bEmail: svm2787@gmail.com

^cEmail: raihanahmed95@stamforduniversity.edu.bd

Abstract

The focus of this report is to design a CHP system using energy demand load profile for a food distribution center. This study has investigated energy requirements in food industry. The main distinction of this report is to carry out economic and environmental analysis of a CHP system. Case studies based on food industry demonstrates that the CHP system is able to run continuously at optimal efficiency and operational costs of the CHP system can be effectively reduced in both electric and heating cost.

Keywords: CHP; CO₂; trapezium; turbine; CCL; kWh; Heat energy; Electrical energy; Quality Index (QI); GHG.

1. Introduction

The consumption of both electrical and heat energy is rising rapidly over the last few [1] decades where global energy demands have not yet been fully realized due to the lack of sophisticated technologies and sufficient energy resources so the world is facing severe energy crisis and it is expected to increase in the forthcoming years. Nowadays, the global power and heat generation are majorly done using conventional energy sources though such energy reserve is very much limited and expected to end within few decades. So, renewable energy resources [2-4] is increasingly being requested for as an alternative sources of energy generation because these are everlasting and eco- friendly and it has been drawn more and more attention in recent years to abridge the gap between energy demand and supply.

* Corresponding author.

Combined heat and power generation (CHP) system would facilitate for restructuring [5] the modern power system. In addition it helps to reduce CO₂ emissions to a large extent. Nowadays decentralized CHP is a pivotal research topic for heat and power energy supply of residential buildings because of their high efficiency [6]. Small scale business and commercial facilities have been transformed to a new heights with [7] development of CHP state of art technology especially CHP in gas turbine technology. A CHP has been implemented in this report for a food distributed center and the report is divided into six sections and finally a conclusion has been drawn.

2. Energy requirements in food industry

The demand of energy used in the food industry is continue to increasing with increasing world population and the food industry is the prime consumer of energy. Calculating the exact amount of energy requirement in the food sector is really very hard task but the total energy consumption in food industry is 17 % of the EU's gross [8] energy consumption in 2013.

Energy is used in food industry in three phases, initial phase is Agriculture which includes crop cultivation and animal rearing accounted for one third energy requirements. The middle phase is very crucial because it requires almost half of the energy. It has three stages such as industrial processing, logistics and packaging. In the industrial processing among traditional preservation methods, canning, freezing, and drying are considered the most energy-Intensive processing operations. Finally, slightly more than 5% energy required for the disposal of food waste. The renewable energy is being pursued all over the world as an alternative source of energy yet to be found the contribution of renewable energy in food industry is nominal compared with fossil fuels account for almost 79% of the energy consumed [8].

Huge amount of electrical energy is required for lighting and motoring equipment, energy required for making low temperature hot water which is used for washing rinsing fresh harvest before to packaging and energy required for keeping food at a desirable temperature during storage. One of the promising improvements in the food industry is that nowadays mechanical, electromagnetic, light, electrical, and other forms of energy are being used to facilitate reactions, such as inactivation of microorganisms while conventional process merely thermal energy was used [9].

3. Energy analysis of this site

3.1 Annual Energy Consumption

In order to calculate the annual energy consumption, area under the both load curve need to be calculated. Formula of calculating area of trapezium stated in equation (I) has been used in excel to determine the daily consumption of both heat and power.

$$\text{Area of trapezium} = \frac{a+b}{2} h \quad (I)$$

Where, a= base, b=base and h=height

Daily heat and electricity consumption have been calculated using Microsoft excel sheet and the daily heat and electricity consumption are 50.256MWh, 32.125MWh respectively.

Annual heat consumption of the site = daily heat consumption * 365 days = 50.256MWh * 365 = 18343.440MWh

Annual electricity consumption of the site = daily electricity consumption * 365days

= 32.125MWh * 365 = 11725.625MWh

3.2 Total energy cost

Total energy cost of the site can be calculated two ways firstly by considering the (CCL) climate charge levy secondly without considering CCL. First, total oil requirements needs to be calculated to estimate to energy cost.

$$\text{Annual heat production by boiler} = \frac{\text{Total MWh} \times 365}{\text{Boiler Efficiency}} = \frac{50.256 \times 365}{0.8} = 22929.3 \text{ MWh} = 82545.48 \text{ GJ}$$

$$\text{Total oil required} = \frac{\text{Annual Heat Produced by boiler}}{\text{Heating value of oil}} = \frac{82545.48 \text{ GJ}}{43 \text{ GJ/tonne}} = 1919.66 \text{ tonne}$$

Including CCL:

Annual cost for heat energy = Amount of oil used for heating * unit price of oil

$$= 1919.66 * 610.9 = 1,172,720.294 \text{ GBP/annum}$$

Total electricity consumption = 11725.625MWh

Total electricity cost = Total electricity consumption * unit cost of electricity = 11725.625*1000kWh*0.0999

$$= 1,171,389.438 \text{ GBP/annum}$$

Total energy (including CCL) cost = Heat energy cost+ Electricity cost

$$= 1,172,720.294 + 1,171,389.438 = 2,345,109.732 \text{ GBP/annum}$$

Excluding CCL:

Annual cost for heat energy = Amount of oil used for heating * unit price of oil

$$= 1919.66 * 598.5 = 1,148,916.51 \text{ GBP/annum}$$

Total electricity consumption = 11725.625MWh

Total electricity cost = Total electricity consumption * unit cost of electricity

$$= 11725.625 * 1000 \text{ kWh} * 0.0972 = 1,139,730.75 \text{ GBP/annum}$$

Total energy (excluding CCL) cost = Heat energy cost + Electricity cost

$$= 1,148,916.51 + 1,139,730.75 = 2,288,647.26 \text{ GBP/annum}$$

3.3 Environmental Impact

Yearly CO₂ emission by oil combustion = Total heat consumption in kWh * Oil combustion emission factor

$$= 22929300 * 0.266 = 6099193.8 \text{ kg CO}_2 = 6099.194 \text{ tCO}_2$$

Annually CO₂ emitted by electricity = Total electricity consumption in kWh * Electricity mix emission factor

$$= 11725625 * 0.5 = 6097325 \text{ kgCO}_2 = 6097.325 \text{ tCO}_2$$

3.4 Tabular summery

Table I summaries the all the energy calculation of this food industry and calculates corresponding cost of them.

Table 1: Summary Of Energy Analysis

Name of Calculation	Parameters	Value of Parameters
Total energy demand of the site	Heat energy	18343.440 MWh
	Electrical energy	11725.625 MWh
Energy cost including CCL	Heat energy cost	1,172,720.294 GBP/annum
	Electrical energy cost	1,171,389.438 GBP/annum
	Total cost	2,345,109.732 GBP/annum
Energy cost excluding CCL	Heat energy cost	1,148,916.51 GBP/annum
	Electrical energy cost	1,139,730.75 GBP/annum
	Total cost	2,288,647.26 GBP/annum
CO ₂ Emission	Annually CO ₂ emission by oil	6099.194 tCO ₂
	Annually CO ₂ emission by electricity	6097.325 tCO ₂

4. Implementation of CHP

4.1 Possible CHP technologies

There are three options of sizing of CHP system by considering heat load demand curve such as base heat load, maximum heat load where heat damping is the main concern and intermediate heat demand. Actually a suitable CHP is chosen in accordance with the meeting the heat and electrical demand of this site. In this case study, for given site heat demand curve base heat load CHP is the best suited because it's economical merits. Operating schedule of CHP system is shown in Figure 1. If the existing boiler is replaced by CHP then the base heat load for mentioned CHP system would be $1665.7\text{kW} \times 0.8$ or 1332.56kW where the boiler efficiency is 80%. So near 1332.56 kW of heat demand of CHP needs to be selected.

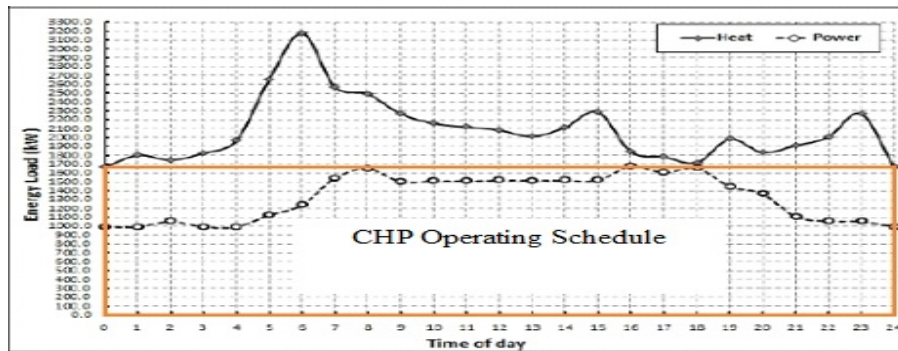


Figure 1: Operating schedule of CHP system

According to Natural Gas U.K. Range Guide 2013, there are many possible CHP technologies. For example, if model ENER-G 1560 has been selected which provides 1662kW heat and 1558kW power output. This model has to be operated at base load but most of the time heat will be damped. It would be costly because of over size and heat damped as well. So this model is not suitable for this specific site. Product reference ENER-G 1560 500NOx with 1719kW heat and 1558kW Power and ENER-G 1280 500NOx with 1413kW heat and 1284kW power are having the same problems. On the other hand, if ENER-G 850 500NOx is considered for this site is not large enough to provide sufficient heat and power to this site because it provides only 948kW heat and 847kW of electricity.

4.2 Suitable CHP technologies

By considering all determining factors for selecting CHP, CHP model ENER-G 1160 500NOx is the best suited model for this site which provides the 1303kW heat 1162kW power output. From load profiles of this food industry is shown in Figure 1. heat demand required is 1332.56kW when CHP mode of operation is considered as a base heat load and ENER-G 1160 500NOx is the closest demand. There are no chances of heat damping as it is considered as base heat load and it is operated for 8760 hours in a year except for stoppage and maintenance only. Selected CHP would be the cheapest since the ratings of this CHP is very closest to the heat demand of this food industry. Moreover, it can be able to export some electricity to the grid.

5. CHP sizing and analysis

5.1 Selected CHP

As mentioned earlier ENER-G 1160 500NOx is the best suited CHP system with the base load as mode of

operation which maximize the profit. This model would be efficient and cost effective. It provides 1303kW heat 1162kW of electricity.

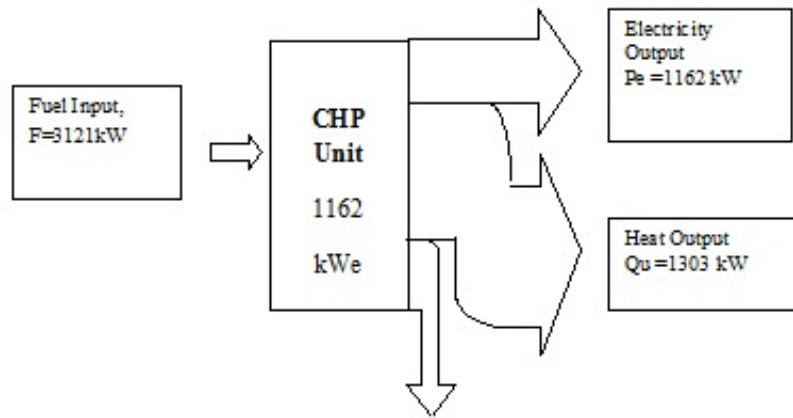


Figure 2: Selected CHP with product reference ENER-G 1160 500NOx

5.2 Specification of selected CHP

Table II provides the all information of selected CHP for example engine type of this CHP is AOE 12V4000L62 and fuel input (HHV) is 3121 kW.

Table 2: Specification of selected CHP

Specification	Quantity or name
Product reference	ENER-G 1160 500NOx
Electrical output kWe	1162kW
Engine Manufacturer	MTU
Engine type	AOE 12V4000L62
Aspiration type	Turbocharged
Output brake kWb	1200
Output jacket water kWth	660
Output exhaust gas kWth	643
Total heat output kWth	1303
Fuel input (LHV)kW	2822
Fuel input (HHV)kW	3121
Maximum operating temperature	78 degree Celsius
Generator type	PE734C-312
Generator efficiency	96.8%

5.3 Energy saving by selected CHP

Energy saving by selected CHP can easily be calculated from the following formula. If CHP is replacing the boiler, CHP (having product reference ENER-G 1160 500NOx) can save 2.893MWh energy for the same amount of energy used by the site. Energy Savings = Input fuel energy required for CHP- (Fuel energy is needed by boiler for producing heat energy + Electrical energy used from grid)

$$= \text{Fuel input of CHP/ kW} * 8760 - \left(\frac{\text{kW} * \text{operating hours}}{\text{boiler efficiency}} + \text{kW} * \text{Operating Hours} \right)$$

$$= 3121 * 8760 - \left(\frac{1303 * 8760}{0.8} + 1162 * 8760 \right) = 2.893 \text{ MWh}$$

5.4 Cost saving by selected CHP

Capital and maintenance Cost Calculation:

$$\text{Capital cost} = 4929x - 0.151$$

$$= 4929 * 1162 - 0.151 = 1697.90 \text{ USD/kWe} = 1180.042 \text{ GBP/kWe} \quad [1 \text{ USD} = 0.695 \text{ GBP}]$$

$$\text{Maintenance cost} = 0.0752x - 0.264$$

$$= 0.0752 * 1162 - 0.264 = 0.0116 \text{ USD/kWh} = 0.008 \text{ GBP/kWh} \quad [1 \text{ USD} = 0.695 \text{ GBP}]$$

With CCV:

$$\text{Annual fuel cost} = \text{Fuel input/kW} * \text{operating hours} * \text{unit cost}$$

$$= 3121 * 8760 * 0.02467 = 674476.813 \text{ GBP/annum}$$

$$\text{Maintenance cost} = \text{kWe demand of CHP} * \text{operating hours} * \text{unit cost}$$

$$= 1162 * 8760 * 0.008 = 81432.96 \text{ GBP/annum}$$

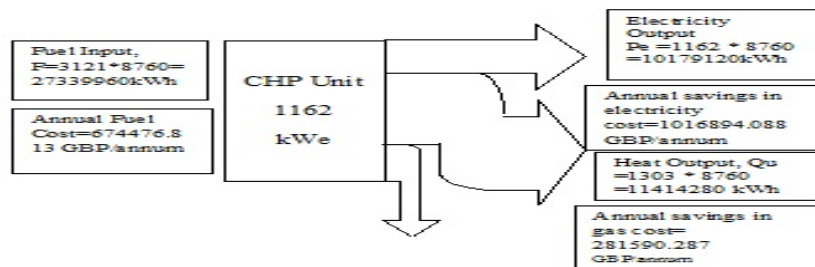


Figure 3: Economic calculation with energy balance diagram

Electricity Output by CHP = Total kW_e * operating hours

$$= 1162 * 8760 = 10179120 \text{ kWh}$$

Electricity cost savings = Total generated electrical energy * unit cost of electricity

$$= 10179120 * 0.0999 = 1016894.088 \text{ GBP/annum}$$

Heat Output = Total kW heat * operating hours

$$= 1303 * 8760 = 11414280 \text{ kWh}$$

Gas cost savings = Total heat generated * unit cost

$$= 11414280 * 0.02467 = 281590.287 \text{ GBP/annum}$$

Annual Profit = (Total electricity cost savings + Total heat generation cost savings) – (Total CHP fuel energy cost + Maintenance cost of CHP)

$$= (1016894.088 + 281590.287) - (674476.813 + 81432.96) = 542574.602 \text{ GBP/annum}$$

Electricity export = 95kW * 8hrs in day*365 = 277.4MWh/year

Electricity surplus savings = 277.4MWh * 25GBP/MWh = 6935 GBP/annum

$$\text{Payback Period} = \frac{\text{Capital Cost, GBP/kW}_e * \text{Total kW}_e}{\text{Annual Profit} + \text{Electricity Surplus}} = \frac{1180.042 * 1162}{542574.602 + 6935} = 2.50 \text{ years}$$

Without CCL:

Annual fuel cost = Fuel input/kW * operating hours * unit cost

$$= 3121 * 8760 * 0.02339 = 639481.664 \text{ GBP/annum}$$

Maintenance cost = kW_e demand of CHP * operating hours * unit cost

$$= 1162 * 8760 * 0.008 = 81432.96 \text{ GBP/annum}$$

Electricity Output by CHP = Total kW_e * operating hours

$$= 1162 * 8760 = 10179120 \text{ kWh}$$

Electricity cost savings = Total generated electrical energy * unit cost of electricity

$$= 10179120 * 0.0972 = 989410.464 \text{ GBP/annum}$$

Heat Output = kW heat demand * operating hours

$$= 1303 * 8760 = 11414280 \text{ kWh}$$

Gas cost savings = Total heat generated * unit cost

$$= 11414280 * 0.02339 = 266980.009 \text{ GBP/annum}$$

Annual Profit = (Total electricity cost savings + Total heat generation cost savings) – (Total CHP fuel energy cost + Maintenance cost of CHP)

$$= (989410.464 + 266980.009) - (639481.664 + 81432.96) = 535475.849 \text{ GBP/annum}$$

Electricity export = 95kW * 8hrs in day*365 = 277.4MWh/year

Electricity surplus savings = 277.4MWh * 25GBP/MWh = 6935 GBP/annum

Payback Period = $\frac{\text{Capital Cost, GBP/kWe} * \text{Total kWe}}{\text{Annual Profit} + \text{Electricity Surplus}} = \frac{1180.042 * 1162}{535475.849 + 6935} = 2.52 \text{ years}$. Payback period increased without Carbon Change Levy (CCV) by $\frac{0.02}{2.50}$ or 0.8%. Figure 3. illustrates the economic calculations with the help of energy balance diagram and Figure 4 depicts the some hour of the day can export power the grid.

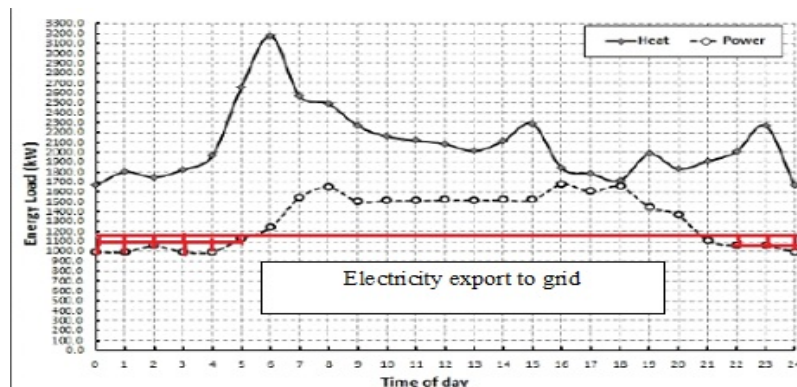


Figure 4: Electricity export to the grid

5.5 Measuring Factors for Good Quality CHP

Quality Index (QI) and electrical power efficiency (η_e) are the threshold criteria for determining the good CHP under normal operating condition.

Quality Index (QI) is very crucial while sizing the CHP as it reflects energy efficiency and environmental performance of the scheme. For upgraded and new CHP system the minimum requirements of is $QI > 105$ needs to be obtained.

Quality Index (QI) is calculated by the following formula:

$$QI = X\eta_e + Y\eta_h \quad (II)$$

where,

X = Power supply coefficient, related to the alternative power supply option.

Y = Heat generation coefficient, related to the alternative heat supply option.

From quality index chart, value of X and Y are easily determined since it is less than 1MWe system. So the QI equation for this system is

$$QI = 249\eta_e + 115\eta_h \quad (III)$$

$$\text{Power Efficiency, } \eta_e = \frac{P_e}{Q_{CHP}} = \frac{1162}{3121} * 100 = 0.3723 = 37.23\%$$

$$\text{Heat Efficiency, } \eta_h = \frac{Q_h}{Q_{CHP}} = \frac{1303}{3121} * 100 = 0.4125 = 41.25\%$$

$$QI = 249\eta_e + 115\eta_h = 249 * 0.3723 + 115 * 0.4125 = 140.14$$

So, the Quality Index (QI) this site is well above the threshold. And power efficiency (η_e) must be greater or equal to 20% in order to meet requirements to be good quality CHP. The electrical efficiency measured by the total electrical energy output divided by total fuel input in the system.

Power Efficiency, $\eta_e = \frac{P_e}{Q_{CHP}} = \frac{1162}{3121} * 100 = 0.3723 = 37.23\% > 20\%$. So the given system have been fulfilled the power performance criteria. This CHP system is qualify for government financial support (CCL, Capital enhanced allowance, ROC, etc) as it maintains all standard for being good quality CHP.

5.6 Cost of unit of CO₂ emission

Unit cost of CO₂ emission reduction (£/kgCO₂ saved) has been calculated in the following calculations.

CO₂ emission reduction = (CO₂ emission by boiler + CO₂ emission by power station) - CO₂ emission by CHP system

$$= (6200194 + 6191276) - (3121 * 8760 * 0.2) = 12391470 - 5467992 = 6923478 \text{ kg CO}_2$$

Annual savings from CHP system including CCV = 542574.588 GBP/annum

$$\text{So Unit cost of CO}_2 \text{ emission reduction} = \frac{542574.588}{6923478} = 0.0079 \text{ GBP/kgCO}_2 \text{ saved}$$

Table III depicts all the calculation regarding the CO₂ emission.

Table 2: CO₂ emission details

Description	Measurements
CO ₂ emission by boiler	6200194 kg CO ₂
CO ₂ emission by power station	6191276 kg CO ₂
CO ₂ emission by CHP system	5467992 kg CO ₂
CO ₂ emission save	6923478 kg CO ₂
Unit cost of CO ₂ emission save	0.79 /kg CO ₂ save

6. Discussion and analysis

Table IV and Table V provides the information about the CHP plant characteristics and return calculations respectively.

Table 2: CHP plant operating characteristics

Parameters	Value of parameters
Fuel input	3121 kW
Heat output	1303 kW
Electricity output	1162kW
Losses	656 kW
CHP daily operating hours	24hrs
Availability	100%
Maintenance cost	81432.86 GBP/annum
Electrical efficiency	37.2%
Thermal efficiency	41.74%
Overall efficiency	79%
Capital cost	1180.042 GBP/kWe
Boiler efficiency	80%
Annual operations hours	8760
Gas combustion emission factor	0.2 kg/kWh

It is really worth mentioning the return of this investment in only 2.5 years

Table 2: CHP plant operating characteristics

Calculation	Parameters	Value of parameters
Energy savings	Total gas input	27339960 kWh
	Displaced boiler fuel energy	14267850 kWh
	Energy savings	2.893MWh
CHP plant operating cost	CHP fuel cost (CCL)	674476.813 GBP/annum
	Maintenance cost	81432.96 GBP/annum
	Total CHP plant operating cost	755909.773 GBP/ annum
Cost savings	Gas cost save	281590.287 GBP/annum
	Electricity cost save	1016894.088 GBP/annum
	Annual profit	542574.602 GBP/annum
Return	Capital cost	1371208.804 GBP/anm
	Electricity export	6935 GBP/annum
	Payback period	2.5 years

7. Conclusion

Some key aspects need to be considered while selecting any CHP system such as technical, commercial or business and environmental consideration. Above mentioned CHP is the best suited for all respect because it is well performed CHP systems. Moreover, it reduces energy input to a large extent in contrast with conventional boiler for the same amount of energy supplied to the system. In addition, it is really worth noting that return of this investment will be given only 2.50 years. Finally, this CHP helps to reduce the GHG emission to a great degree once CHP has been opted for this food industry. In recapitulate, with considering all the merits I would recommend it in company's board and I strongly believe that investor will go for it.

References

- [1] F. Blaabjerg, C. Zhe, and S. B. Kjaer, "Power electronics as efficient interface in dispersed power generation systems," *IEEE Transactions on Power Electronics*, vol. 19, pp. 1184-1194, 2004.
- [2] J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galvan, R. C. PortilloGuisado, M. A. M. Prats, et al., "Power-Electronic Systems for the Grid Integration of Renewable Energy Sources: A Survey," *IEEE Transactions on Industrial Electronics*, vol. 53, pp. 1002-1016, 2006.
- [3] Z. Liang, R. Guo, J. Li, and A. Q. Huang, "A High-Efficiency PV Module-Integrated DC/DC Converter for PV Energy Harvest in FREEDM Systems," *IEEE Transactions on Power Electronics*, vol. 26, pp. 897-909, 2011.

- [4] N. R. Tummuru, M. K. Mishra, and S. Srinivas, "An Improved Current Controller for Grid Connected Voltage Source Converter in Microgrid Applications," *IEEE Transactions on Sustainable Energy*, vol. 6, pp. 595-605, 2015.
- [5] O. A. Shaneb and P. C. Taylor, "An evaluation of integrated fuel cell and energy storage systems for residential applications," in *Universities Power Engineering Conference (UPEC), 2009 Proceedings of the 44th International, 2009*, pp. 1-5.
- [6] M. Pielke and M. Kurrat, "Potentials for asset optimizations in low and medium voltage networks through grid oriented feeding of distributed generation," in *2008 IEEE/PES Transmission and Distribution Conference and Exposition, 2008*, pp. 1-7.
- [7] R. Dettmer, "Wind of change [gas turbine based CHP]," *IEE Review*, vol. 46, pp. 21-24, 2000.
- [8] F. Monforti-Ferrario, J. Dallemand, I. P. Pascua, V. Motola, M. Banja, N. Scarlat, et al., "Energy use in the EU food sector: State of play and opportunities for improvement," 2015.
- [9] O. Rodriguez-Gonzalez, R. Buckow, T. Koutchma, and V. Balasubramaniam, "Energy Requirements for Alternative Food Processing Technologies—Principles, Assumptions, and Evaluation of Efficiency," *Comprehensive Reviews in Food Science and Food Safety*, vol. 14, pp. 536-554, 2015.