2021

Energy Efficient, Cost-Effective Power and Co-Generation Technologies: Techno-Environmental Analysis

Praveen Cheekatamarla
Oak Ridge National Laboratory, USA, cheekatamapk@ornl.gov

Ahmad Abu-Heiba

Kyle Gluesenkamp

Tim Laclair

Energy Efficient, Cost-Effective Power and Co-Generation Technologies: Techno-Environmental Analysis

Praveen CHEEKATAMARLA[a]*, Ahmad ABU-HEIBA[a], Kyle GLUESENKAMP[a], Tim J. LACLAIR[a]

[a]Oak Ridge National Laboratory, Building and Transportation Sciences Division
Oak Ridge, Tennessee, USA
(865-341-0417, cheekatamapk@ornl.gov)

* Corresponding Author

This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

ABSTRACT

Development of energy solutions for addressing grid resiliency and energy efficiency while lowering greenhouse gas emissions is critical in today's energy scenario. Chemical energy provides on demand power. Cogeneration technologies offer numerous benefits in meeting the growing energy demand while lowering the impact on environment. Utilization of waste heat from prime movers in conjunction with energy efficient heat pumps and renewable photovoltaics is an attractive approach. Efficient utilization of available resources to support current and future building energy needs targeting grid resiliency, energy and environmental security via co-generation approaches is the focus of this study. A detailed techno-environmental analysis of hybrid system configurations consisting of conventional and emerging technologies utilizing natural gas, electric grid, and renewable power resources along with heat recovery systems and heat pump technologies are analyzed and presented. The key objective is to present integrated system configurations and thermodynamic analysis of various co-generation systems suitable for providing building energy. Design solutions targeting low carbon footprint and high energy efficiency are presented.

1. INTRODUCTION

Recent increases in wind and solar energy generating capacity have done much to reduce the reliance on carbon fuels, but an important complementary strategy is using available resources including fuels more efficiently. Growth in energy demand is certain. For instance, according to Energy Information Agency (EIA) ("Energy Information Agency," 2019), nearly 50% increase in world energy usage by 2050 is projected, led by growth in Asia. 33% of vehicles coming out of assembly lines are expected to be electric by year 2040 ("International Energy Agency," 2020); 66% of world's 9.5 Billion population will be living in urban areas by 2050 ("United Nations," 2018). Given the climate urgency, and this demand growth, sustainable technologies are needed in meeting the energy needs responsibly. Bridging technologies enabled by renewable fuels (e.g. biogas, renewable hydrogen, renewable methane, ethanol, etc.) and low carbon fuels are necessary while we work towards our long-term vision of 100% renewable, carbon-free electricity. These available resources can fulfill immediate needs but will require enabling technologies to utilize them as cleanly and efficiently as possible with fewer greenhouse gas emissions.

Currently available energy efficient technologies are still languishing, mostly impeded by cost, reliability, lack of education, policy assertiveness, retrofitability and incentives, etc. Deeper penetration of such technologies (e.g. DERs, CHPs, Heat Pumps) into energy markets is required as they are considered deployable technologies and are within reach to make a significant difference in primary energy consumption while improving energy resiliency. As shown in Figure 2, taken from EIA ("Energy Information Agency," 2019), 65% of the primary energy is unutilized or lost in the traditional "electric power sector" and this is 2019 data!, 22 years after Kyoto protocol, 5 years after Paris accords. Cogeneration and utilization of on-site energy via nano CHP/micro-CHP/distributed energy resources (DER) are attractive options in bridging the gap until we achieve 100% renewable, carbon-free energy production for consumption in the residential and commercial buildings. These technologies have a complementary role in future electric systems, although energy storage and demand side response are considered to be the key differentiating factors in addressing grid resiliency (Allan *et al*., 2015, Vahl *et al*., 2013, Huda and Zivanovic, 2017). Operational system balancing strategies (Manfren *et al*., 2011), energy policy for addressing grid resiliency (Bouffard and Kirschen, 1982, Colmenar-Santos *et al.,* 2008) and environmental aspects will dictate the penetration of such technologies and their deployment levels in the next generation electric system (Foley *et al*., 2010).

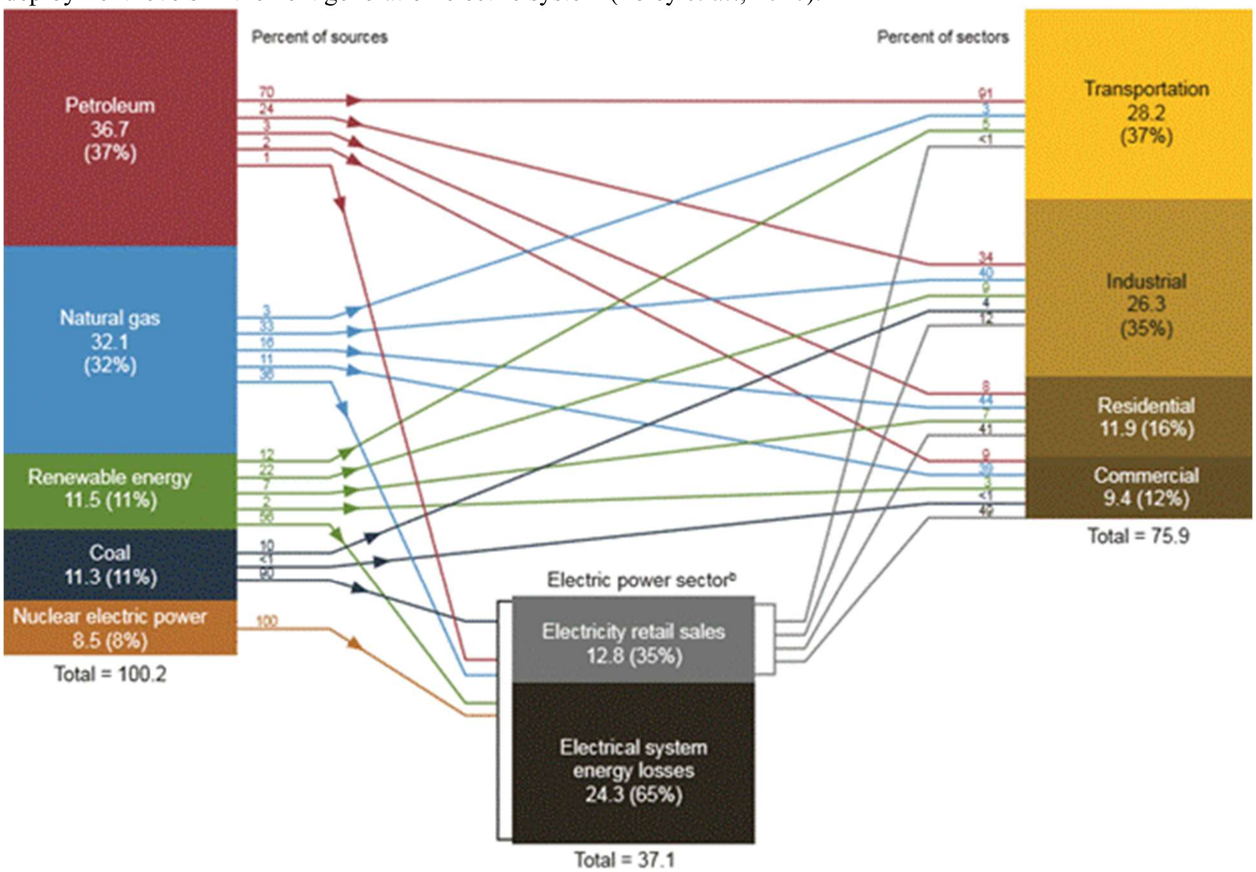

Figure 1: U.S. Energy consumption by source and sector

In this context, this paper presents an analysis of different hybrid system configurations for efficient energy utilization in buildings by studying the influence of design and operational parameters on the primary energy consumption, and environmental impact. Different energy efficient technologies such as fuel driven cogeneration systems, hybrid power systems and integrated heat pumps in lowering the primary energy consumption are analyzed. Configurations including primary movers such as fuel cells, heat engines, and their combinations with heat pumps are systematically analyzed and discussed. The focus was on the energy and environmental analysis and the economic assessment of each configuration has been excluded.

2. APPROACH/METHODOLOGY

The main methodology involved modeling of the cogeneration system using thermodynamic process simulation software package ChemCAD® (Version 7.1) to assess the electric and thermal output for a given load demand and fuel supply. Process flow diagram and the simulation model utilized for this study is shown in Figure 2. The model consists of three major unit operations: (i) a simplified generic prime mover with defined electrical and thermal recovery efficiency, (ii) a heat recovery system in the form of hot water storage tank and an optional heat exchanger to support further heat transfer, and (iii) electrical heat pump consisting of compressor, expansion valve, and condenser, evaporator coils. Primary energy sources consisted of the central power plant/electrical grid, natural gas, and optional Photovoltaic (PV). The impact of different configurational aspects was studied in the case of residential scale buildings consuming 30 kWh/day of combined thermal and electrical energy.

The primary design variables consisted of:

- Kilo-watt power rating of the prime mover (PM)
- Coefficient of performance (COP) of the electrical heat pump system
- Electrical grid efficiency
- Daily operational hours of the PM
- Electrical efficiency of the PM

The influence of these design parameters was studied for different configurations to calculate the primary energy efficiency, and carbon intensity. Primary energy efficiency is defined as the energy consumed by the building vs. energy consumed at the source. Carbon dioxide footprint of each configuration was calculated based on the carbon intensity of the electrical grid and the CO_2 produced via natural gas consumption by the prime mover, assuming 100% conversion. All the assumptions made in this analysis are presented in the table below.

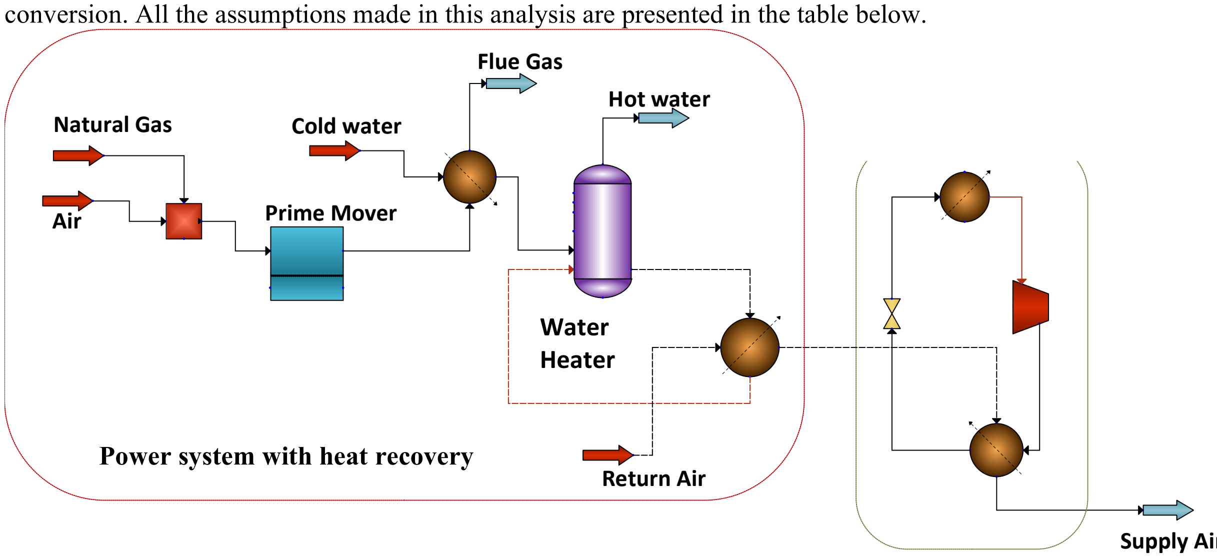

Figure 2: Thermodynamic simulation model adopted for evaluating cogeneration system to assess electrical and thermal outputs. Also shown is the electrical heat pump system in conjunction with the cogeneration system.

Parameter	**Value**	**Component**
Electrical efficiency of the PM	25 – 50%	Prime mover
Electrical efficiency of the grid/power plant	30 – 60%	Grid
Waste heat recovery efficiency	80%	Prime mover
Waste heat energy stream temperature	150°C	Prime mover
PM operational hours	3-24 hours/day	Prime mover
Daily electrical energy consumption	18 kWh	Building
Daily total thermal energy consumption	12 kWh	Building
Daily space heating energy demand	6 kWh	Space heating
Daily water heating energy demand	6 kWh	Hot water
Efficiency of the hot water storage tank (energy loss)	20%	Hot water tank
COP	1-5	Heat Pump
Carbon dioxide intensity	0.2 – 0.7 kg/kWh	Grid
Natural gas site delivery efficiency	92%	Fuel
Natural gas higher heating value (HHV)	36.6 MJ/m^3	Fuel
PV, kilo Watt capacity	0 – 0.5 kW	PV

Carbon dioxide emission for each configuration was calculated according to equation 1, where the efficiency of power source (η_{PS}) and its power level (P_{PS}) were taken in to account while achieving complete fuel conversion in the thermodynamic model shown in Figure 2.

$$CO_{2,ton/yr} = \left((\frac{P_{PS}}{\eta_{PS}}) * 365 * 24 \right) * \left(HHV_{fuel} \right) * \frac{44}{10^6} \quad (1)$$

Primary energy efficiency (η_{PE}) was calculated according to equation 2, where $kWh_{bldg.}$ is the total daily energy consumption of the building in kWh (30 kWh), while kWh_{Grid} is the daily building energy supplied by the grid, η_{Grid} is the electrical efficiency of the grid, PM_{fuel} is the total daily fuel consumption by the PM (in m^3), HHV_{fuel} is the fuel's higher heating value, Site $factor_{fuel}$ is the fuel delivery efficiency to the building.

$$\eta_{PE} = \frac{\left(kWh_{bldg}\right)}{\left[\frac{kWh_{Grid}}{\eta_{Grid}} + \frac{PM_{fuel} * \ HHV_{fuel} * 0.2778}{Site\ factor_{fuel}}\right]} \quad (2)$$

3. RESULTS AND DISCUSSION

As described above, the impact of different design variables and power configuration on energy efficiency and carbon footprint was studied. The influence of electrical power rating of the prime mover (PM) on overall energy balance was investigated in a configuration where the waste heat from the PM was utilized for water heating while space heating energy was supplied by a vapor-compression cycle based electrical heat pump with a COP rating of 3.0. PM's electrical efficiency was assumed to be 30% while that of the electrical grid was assumed to be 33%. As shown in Figure 3, the PM's power rating was scaled up to 1 kW while calculating the yearly electrical grid purchases and primary energy consumed to support the daily energy requirement of 30 kWh. Also shown is the total annual carbon dioxide emissions in supporting the building's energy load while accounting for on-site emissions associated with the PM as well as a carbon intensity of 0.63 kg/kWh of the electrical grid. It can be noticed that the utility purchases decrease as the PM capacity is scaled up to 1 kW at which point excess electricity of 1.46 MWh/year is produced in addition to meeting the annual electrical demand of 10.95 MWh. However, excess thermal energy increases significantly as the PM's power output increases. Total primary energy consumption is the lowest for the 0.25 kW system where the excess thermal energy is the lowest and the carbon dioxide emissions are ~4.5 tons per year, compared to 6.9 tons per year from an all electrical grid powered residential building (i.e. no PM on site), which accounts to ~ 35% reduction in CO_2 emissions.

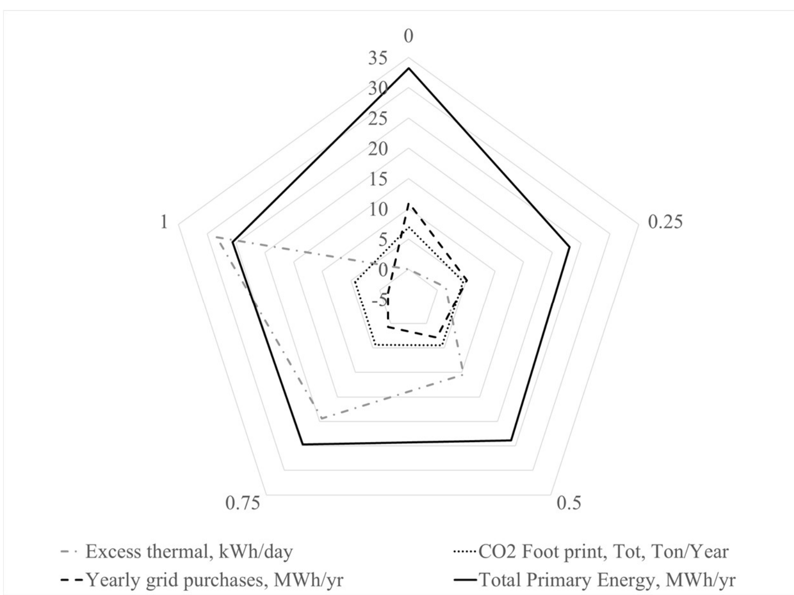

Figure 3: Influence of PM's power rating on grid purchases, primary energy, and carbon footprint. Waste heat utilization for water heating only. Space heating via heat pump.

The configuration described above was further studied by changing the COP of the heat pump. The power rating of the prime mover was fixed at 0.5 kW with 30% electrical efficiency and operating continuously while rest of the configurational, energy, and efficiency values were maintained the same. As can be seen in Figure 4, annual electrical grid purchases decrease as the COP increases from 1 to 5, effectively increasing the primary energy efficiency from

39% to 48% while also lowering the total annual carbon dioxide emissions from 5.3 to 4.4 tons per year. It has to be noted that the only variance in these configurations is the COP of the space heating device while the onsite PM supplies 12 kWh per day of electrical energy and the generated waste heat from the PM is utilized in meeting the water heating loads with an additional 10 kWh per day of excess unutilized thermal energy. This analysis provides insights into the positive influence of COP improvement on the overall energy efficiency of the system considered.

The influence of electrical grid efficiency and its carbon dioxide intensity were also studied for the above configuration by assuming the COP of the space heating device at 3.0 while utilizing the 0.5 kW prime mover operating continuously at 30% electrical efficiency. As shown in Figure 5, the primary energy efficiency of the hybrid power configuration with the 0.5 kW prime mover onsite increases with increase in the electrical grid efficiency.

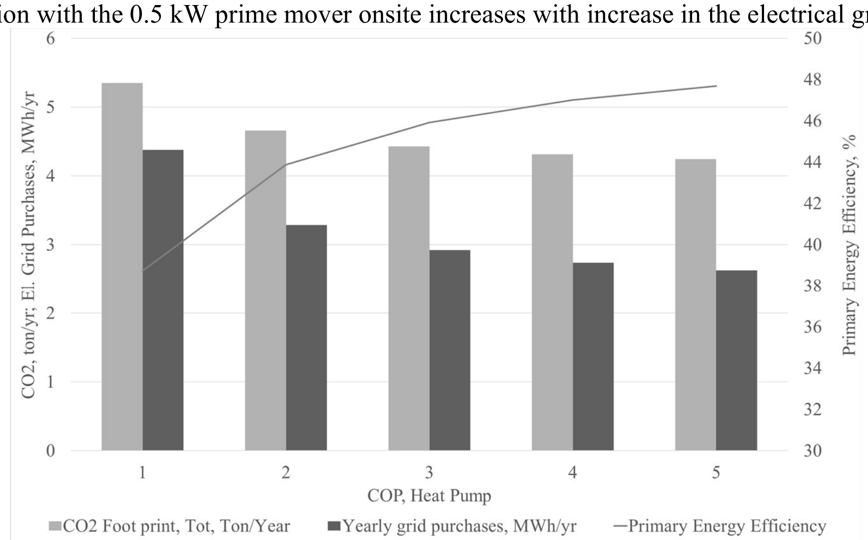

Figure 4: Heat Pump COP impact on grid purchases, primary energy, and carbon footprint. Waste heat utilization for water heating only. Space heating via heat pump.

However, the positive influence of the cogeneration system onsite diminishes as the electrical grid becomes more efficient. For instance, the hybrid cogeneration system's primary energy efficiency is ~ 49% if the electrical grid is 40% but the efficiency gain shrinks if the electrical grid efficiency increases to 50% where the primary energy efficiency is ~ 53%. The positive impact of the cogeneration system completely disappears if the electrical grid efficiency increases to 60%.

Similarly, the presence of the hybrid cogeneration system onsite is more beneficial in terms of total carbon dioxide emission reduction if the electrical grid is less than 50% efficient. As the carbon intensity of the electrical grid decreases from 0.69 (at 30% grid efficiency) to 0.21 kg/kWh (at 60% grid efficiency), the combined carbon intensity also decreases but is effectively higher compared to a 60% efficient electrical grid.
The electrical efficiency of the cogeneration system configuration assumed in the above analysis was 30%, which plays a significant role in the observed lower primary energy efficiency and higher carbon intensity when installed in an application being serviced by a highly efficient electrical grid, for instance 60%. Hence, the influence of prime mover's electrical efficiency was also studied in detail by repeating the efficiency assessment at different values in the range of 25% to 50% in conjunction with a 60% efficient electric grid with a carbon intensity of 0.21 kg/kWh.

Figure 6 displays the primary energy efficiency and effective carbon dioxide intensity of the 0.5 kW prime mover operating at different electrical efficiencies while utilizing waste heat for water heating applications only. Space heating energy is supplied by the grid powered heat pump while operated at a COP of 3.0. As can be seen, the primary energy efficiency with this cogeneration system is effectively higher when compared with the 60% electrical grid if the PM's electrical efficiency is above 35%.

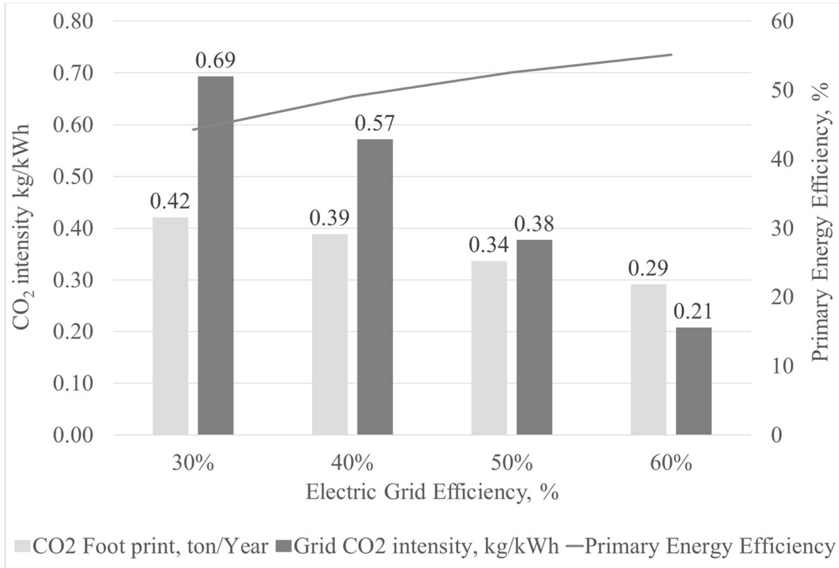

Figure 5: Electrical grid efficiency impact on primary energy efficiency and carbon footprint while utilizing a 0.5 kW prime mover on site.

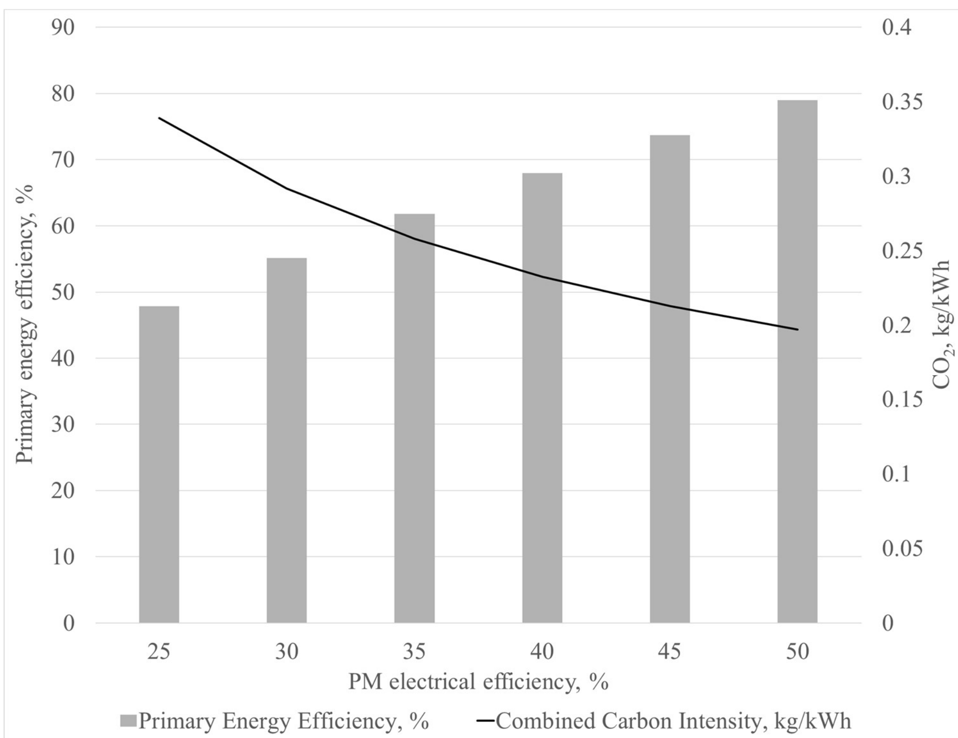

Figure 6: Influence of 0.5 kW PM's electrical energy efficiency on energy and environmental benefits compared to a 60% efficient electrical grid.

The analysis presented so far assumes continuous operation of the prime mover in meeting the thermal and electrical energy demands of the building. A fuel cell (FC)-based cogeneration system fits such a criterion where continuous operation of the system improves reliability compared to intermittent operation.

An internal combustion engine (ICE)-based cogeneration system offers similar advantages as discussed above. However, a cost-effective engine will have a higher electrical power rating compared to the nominal 0.25 to 1 kW power range assumed above. Hence, a 2 kW engine based cogeneration system with an electrical efficiency of 30% was analyzed by considering varied operational hours per day, as shown in Figure 7. Excess electrical energy is produced if the cogeneration system operates for 12 hours per day while the carbon dioxide footprint decreases by greater than 35% compared to an electrical grid supply at 0.63 kg/kWh carbon intensity. The primary energy efficiency however is significantly higher compared to the assumed value of 33% for the electrical grid.

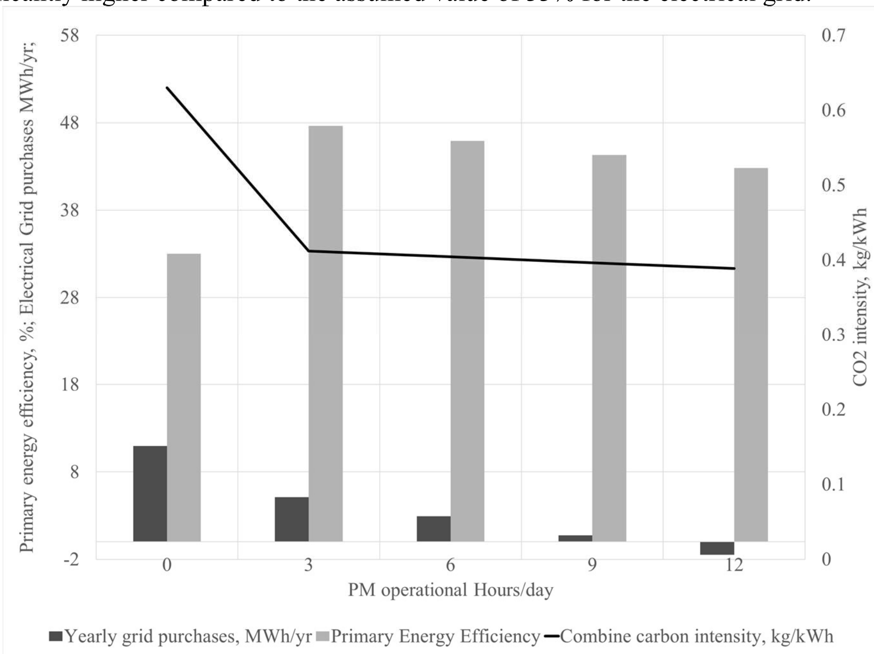

Figure 7: Influence of daily operational hours of a 2 kW PM on carbon intensity and primary energy efficiency.

The analysis was further extended for different configurations with and without cogeneration system and/or heat pump. As shown in Figure 2, two configurations are possible: (a) waste heat from the prime mover is used for water heating only and any excess thermal energy is unutilized or (b) all of the available waste heat from the PM is utilized for water heating and space heating (supplemented by a heat pump).

Figure 8 displays the primary energy efficiency and carbon dioxide footprint of five different configurations including an all-electrical grid supply (33% efficient at 0.63 kg of CO_2 per kWh electricity produced). The PM considered in this analysis assumed an electrical efficiency of 30% while the COP of the heat pump (if utilized) was assumed as 3.0. The second configuration involved a 0.25 kW cogeneration system where the waste heat was utilized for all thermal needs while supplemented by electrical grid (e.g. using resistive heating with 100% efficiency or COP of 1.0). The third configuration shown in the figure did not consider any cogeneration system, but all the thermal needs are met by a heat pump system. The fourth and the fifth configurations utilized all available waste heat from the PM while supplemented by an electrical heat pump. As can be noticed, the configuration with heat pump alone can increase the primary energy efficiency to 44%. A 0.5 kW PM supplemented by a heat pump can achieve a net primary energy efficiency of 51% while utilizing a 33% efficient electrical grid.

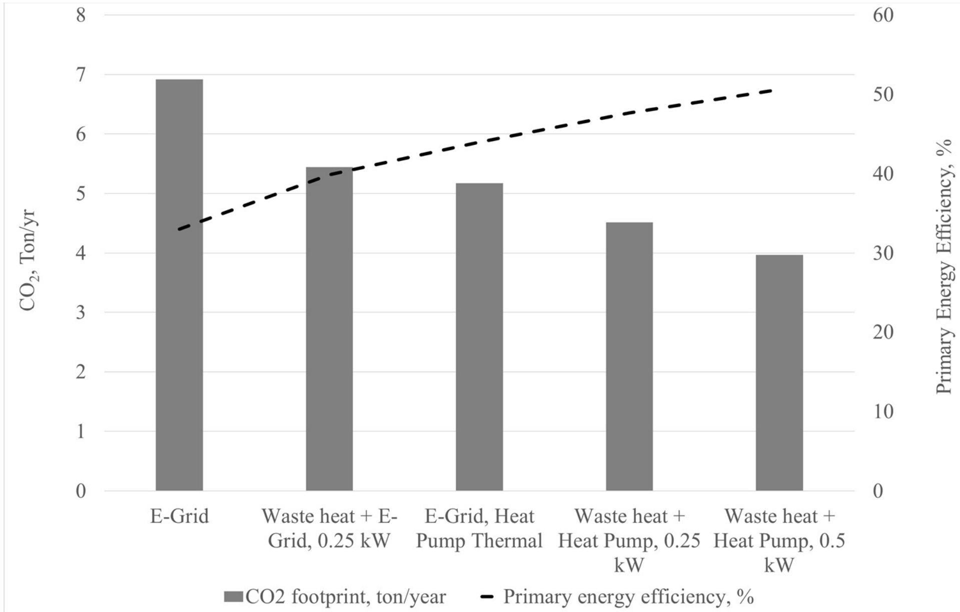

Figure 8: Influence of design configuration on primary energy efficiency and carbon dioxide footprint

The impact of combining renewable PV with the cogeneration system was also analyzed by assuming an average of 4.5 hours per day of solar PV utilization at its full potential. Case studies involving both fuel cell and ICE based cogeneration systems (PM efficiency of 30%) were conducted without heat pump in meeting the needs of a residential building consuming 25 kWh/day of total energy including 10 kWh/day of thermal energy. As shown in Figure 9, ICE based cogeneration system operating at different power ratings and operational hours per day in conjunction with 0.5 kW PV can effectively decrease the primary energy consumption by greater than 55% while decreasing the carbon dioxide emissions by greater than 34%. Similarly, fuel cell-based configurations presented in Figure 10 can lead to significant reductions in primary energy and carbon dioxide emissions. For instance, a 0.5 kW FC cogeneration system along with 0.25 kW PV can decrease the primary energy consumption by greater than 70% while achieving 48% lower carbon dioxide emissions.

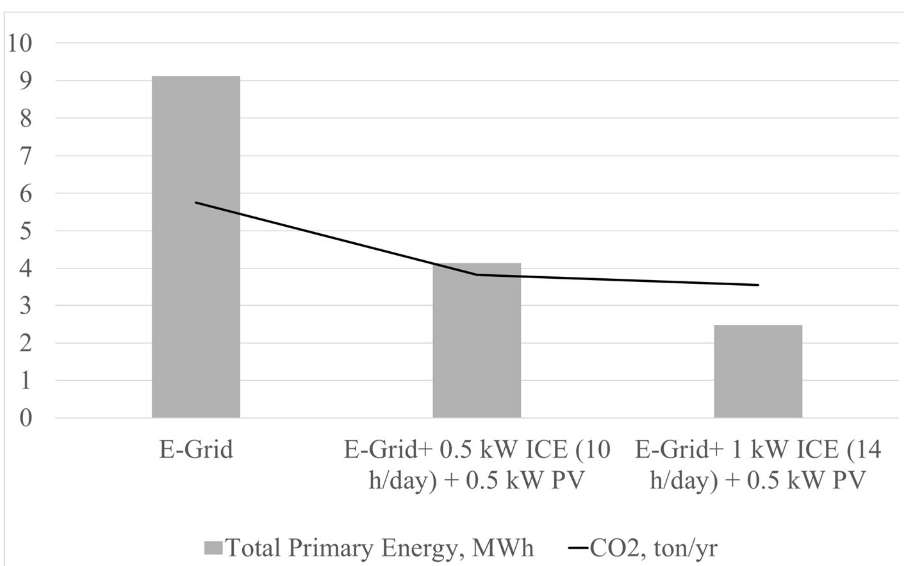

Figure 9: ICE based cogeneration system along with PV: Influence of configuration on carbon footprint and primary energy

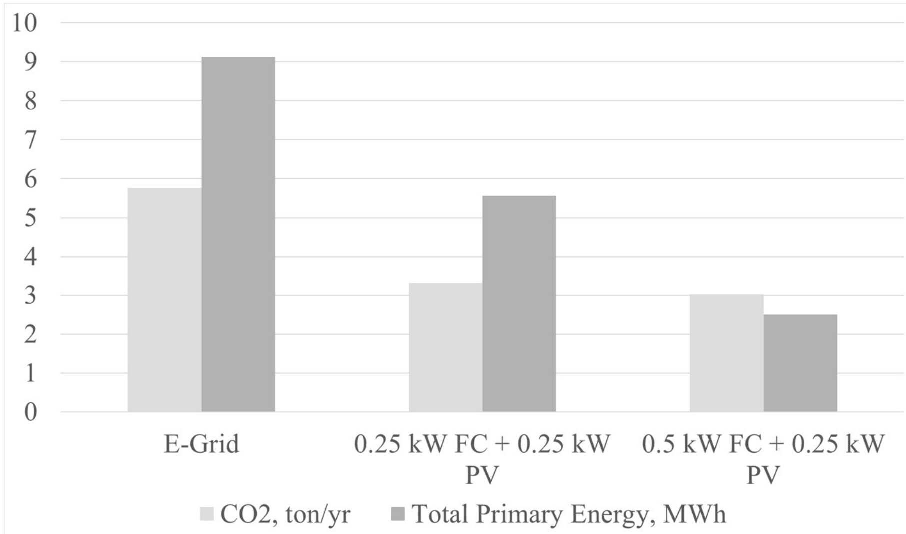

Figure 10: : FC based cogeneration system along with PV: Influence of configuration on carbon footprint and primary energy

6. CONCLUSIONS

Implementation of hybrid power configurations in a cogeneration architecture consisting of prime movers such as fuel cells and internal combustion engines and their combinations with heat pumps and PV were studied for residential building applications. Different design parameters including the power rating, electrical efficiency, COP, and electrical grid efficiency were analyzed to identify the impact of such configurations on energy efficiency and environmental benefits. It has been shown that currently available technologies can significantly lower the GHG emissions while improving the primary energy efficiency. Such configurations have the capability to complement higher electrical grid efficiencies with lower carbon intensities while improving the energy resiliency and sustainability due to their compatibility with natural gas as well as gaseous and liquid renewable fuels. The benefits of higher primary energy efficiency and lower carbon intensities associated with a 30% efficient prime mover in an onsite cogeneration system diminishes as the grid's electrical efficiency increases beyond 50%. However, if the electrical efficiency of the prime mover is maintained beyond 35%, the effective primary energy efficiency of the cogeneration system is always higher than the electrical grid efficiency. The combined primary energy efficiency of a cogeneration system consisting of a PM with electrical efficiency of 50% and in conjunction with a heat pump (COP of 3.0) serviced by 60% efficient electrical grid can reach ~ 80%.

NOMENCLATURE

η_{PS}	Efficiency of power generator (local power source)	(%)
η_{grid}	Efficiency of the electrical grid	(%)
P_{PS}	Capacity of power generator	(kW)
$CO_{2,ton/yr}$	Carbon dioxide emissions per year	(metric ton)
CHP	Combined Heat and Power	
COP	Coefficient of performance	
DER	Distributed Energy Resource	
EIA	Energy Information Agency	
HHV_{fuel}	Higher heating value of fuel	(MJ/m^3)
kW	Kilo-Watt	
kWh_{grid}	Grid supplied energy to the building	(kWh)
kWh_{bldg}	Daily building energy demand	(kWh)
MJ	Mega Joules	
PM	Prime Mover	
PV	Photo Voltaic	

REFERENCES

Allan, G., Eromenko, I., Gilmartin, M., Kockar, I., & McGregor, P. (2015). The economics of distributed energy generation: A literature review. *Renewable and Sustainable Energy Reviews*, *42*, 543-556.

Bouffard, F., & Kirschen, D. S. (2008). Centralised and distributed electricity systems. *Energy policy*, *36*(12), 4504-4508.

Colmenar-Santos, A., Reino-Rio, C., Borge-Diez, D., & Collado-Fernández, E. (2016). Distributed generation: A review of factors that can contribute most to achieve a scenario of DG units embedded in the new distribution networks. *Renewable and Sustainable Energy Reviews*, *59*, 1130-1148.

Energy Information Agency (2019, Aug.) U.S. Energy Consumption by Source and Sector. Retrieved from: https://www.eia.gov/todayinenergy/detail.php?id=41093

Energy Information Agency (2019, Oct.) Electric Power Annual 2018. Retrieved from: https://www.eia.gov/todayinenergy/detail.php?id=41433

Foley, A. M., Gallachóir, B. Ó., Hur, J., Baldick, R., & McKeogh, E. J. (2010). A strategic review of electricity systems models. *Energy*, *35*(12), 4522-4530.

Huda, A. N., & Živanović, R. (2017). Large-scale integration of distributed generation into distribution networks: Study objectives, review of models and computational tools. *Renewable and Sustainable Energy Reviews*, *76*, 974-988.

International Energy Agency (2020, June) Global EV Outlook 2020. Retrieved from: https://www.iea.org/reports/global-ev-outlook-2020

Manfren, M., Caputo, P., & Costa, G. (2011). Paradigm shift in urban energy systems through distributed generation: Methods and models. *Applied Energy*, *88*(4), 1032-1048.

United Nations (2018, May). Retrieved from: https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html

Vahl, F. P., Rüther, R., & Casarotto Filho, N. (2013). The influence of distributed generation penetration levels on energy markets. *Energy policy*, *62*, 226-235.

ACKNOWLEDGEMENT

This research was supported by the DOE Office of Energy Efficiency and Renewable Energy (EERE), Building Technologies Office and used resources at the Building Technologies Research and Integration Center, a DOE-EERE User Facility at Oak Ridge National Laboratory.