Co-location of CHP units for High Power Charging of Battery Electric Vehicles

A comparison of the fuel efficiency for AC and DC coupled systems

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Abstract— **This paper proposes the co-location of gas reciprocating generator sets with High Power Charging (HPC) stations for Battery Electric Vehicles (BEVs), to offer a low carbon source of heat and power which could help to meet national government transportation and heating strategies while minimizing the impact that HPC systems will have on the power network. Three different Combined Heat and Power (CHP) connection configurations are considered to determine the most fuel-efficient per forecasted utilization rates of the HPC station. The use of variable speed generators connected directly to the dc bus of the HPC station can offer improved fuel-efficiency performance compared to fixed speed, especially under part-loading conditions, however, the sizing of engine-generator sets based on expected utilization rates of the HPC station has the most influence on fuel efficiency.**

Keywords—battery electric vehicles, charging systems, combined heat and power, variable speed engines, fixed speed engines.

I. Introduction

There is a growing consumer sentiment and demand for Battery Electric Vehicles (BEVs) which is gradually being met with innovative products from new and existing vehicle manufacturers [1]. However, the success of this nascent industry will equally depend on the availability and convenience of charging infrastructure. The deployment of charging systems has proven challenging for both municipal authorities (MA) and private charge point operators (CPO) [2]. The challenges are both technical and economic; the low utilization rates in the early years of deployment make private financing particularly difficult and the trend towards HPC systems creates a grid integration challenge that leads to higher installation expenses.

Concurrently, MA's and national governments are actively pursuing low carbon forms of heating for industrial, commercial and residential consumers [3]. The use of CHP systems offers consumers a local source of electricity and heating that can be up to ~80% efficient [4]. There is an opportunity to integrate the design and location of CHP systems with the need for BEV charging infrastructure, if implemented effectively this integrated energy solution could reduce the carbon content of the electricity that is used to power our transportation infrastructure by utilising the waste generation heat and a reduction in the electrical transmission and distribution losses from existing centralized power plants. Furthermore, integrated economic benefits may be recognized that could allow both the CHP system and HPC infrastructure to utilize the same land, electrical infrastructure and share the operational costs.

To recognize these benefits, engineering assessments are required to forecast the expected loading conditions of the CHP units per the arrival rates and utilization of BEV's; provide local grid support; and to ensure the CHP sizing matches the local thermal demand for the building or District Heating Network (DHN). Additionally, an electrical integration question exists: considering HPC systems are likely to operate on a dc network [5] with a centralized ac/dc converter, should a CHP unit electrically interface with the dc charging network or with the ac grid? For gas reciprocating engines, a connection to the dc charging network decouples the generator from the ac grid frequency and permits it to operate at the optimum speed and fuel consumption for any loading condition.

This paper presents the results of an energy efficiency model that makes use of existing literature and fuel efficiency curves for gas reciprocating engines to compare the energy efficiency of CHP units that are either directly connected to the dc HPC network as variable speed engines or to the ac grid as fixed speed engines. Three utilization models are presented – low, medium and high utilization rates – to assess the fuel efficiency performance of the CHP units under varying load conditions.

II. High Power Charging Systems

The highest power rating available for existing BEV chargers is 50kW dc, although this technology is rapidly changing. Testing of 150kW public chargers with the ability to increase the power rating to 350kW have already been deployed, and a network of 400 such systems is planned for Europe in 2018 [5]. These HPC systems create a 'refueling' service that is like the existing consumer experience and it opens the potential for the electrification of other transportation infrastructure such as buses, trucks and ferries.

A. Network Integration & Topologies

Due to the power transfer rates, these HPC systems utilize dc voltages up to the LVDC voltage limit of 1500 V_{dc} but most likely between 800-1000 V_{dc} [6]. Despite the high voltage levels, the charging cables must be able to withstand current of up to 350A which requires the use of an active cooling system to limit the weight of the charging cable [7]. Each dc charger is connected to a centralized ac/dc converter which interfaces the dc charging network with the MV ac grid. Considering the power levels of the HPC systems, a network can reach a capacity of 1-2MW and therefore an MV grid connection is the most practical technical solution, however, this may limit the spatial locations for HPC systems and/or increase the installation costs. Alternatively, the use of CHP units could provide local power support and minimize the impact on the local ac network which would open more deployment opportunities for HPC systems. Fig. 1 below illustrates the charging topology for HPC systems and three potential connection scenarios for CHP units considered in this paper.

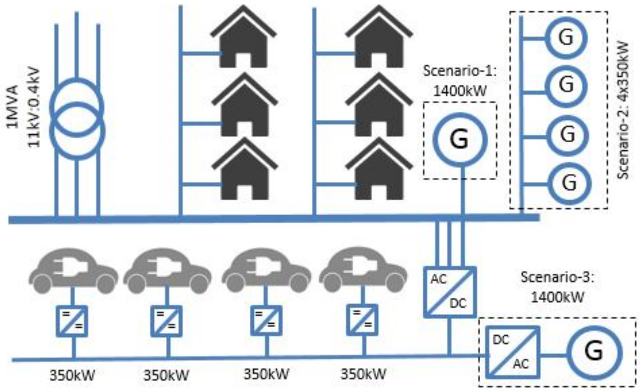

Fig. 1 HPC system topology with ac grid interface and possible connection options for CHP units.

B. Battery Charging Behaviour Model

The primary operational aim of HPC stations is to service the charging requirements of vehicles by rapidly maximizing the energy transfer rate at any moment in time. However, as demonstrated in [8] and in Fig.2, the battery of a BEV does not charge linearly over its complete SoC range. Generally, a constant power charging regime is adopted until the battery reaches a SoC of at least 85-90%, at this level the charging system changes to constant voltage charging with a gradual reduction in current and power transfer. This paper proposes that HPC stations will avoid charging beyond the constant power threshold to maximize the energy transfer rate and therefore a constant power charge of 350kW for each charger is adopted in this paper's system model.

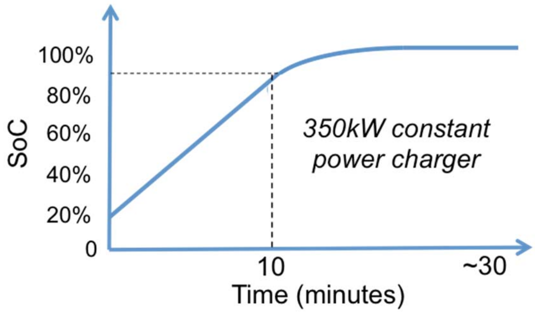

Fig. 2 Battery charging behavior model: constant power charging between 20%-90% SoC

C. Utilisation Rates & Arrival Models

To compare the fuel efficiency of fixed speed and variable speed gas reciprocating engines in a HPC station application, it is necessary to develop a system utilization model that takes into consideration arrival rates of BEVs and the arrival SoC of each vehicle's battery. There are a number of probabilistic models that address BEV charging system planning but few focus on the expected arrival rates at an HPC station [9], [10], [11]. HPC stations will experience different arrival patterns depending on their location: an urban location may experience daily peak usage at commuting hours but a highway/motorway station may experience higher usage over the weekends or holidays.

A 350kW charger can service an 80kWh battery capacity EV from a starting SoC of 20% to a SoC of 90% in under 10 minutes. This service rate is equivalent to existing gasoline service stations and therefore the utilization and arrival models for existing fueling stations would be appropriate data to use in this scenario. However, in the absence of operational data, it is assumed that an urban located HPC station experiences peak usage between the hours of 6am-9am and 3pm-6pm, which is in line with the driver commuting statistics reported in [12] and modeled in [13].

Three utilization models were developed for this paper; low, medium and high utilization scenarios. The models use a uniform distribution for BEV arrival rates during eight separate three-hour periods of the day. Table 1. presents the assumed number of vehicles serviced during each three-hour period and which are assigned random arrival times within each period. Furthermore, each BEV was assigned an arrival battery SoC that was uniformly distributed between 20%-60% SoC. With these values, it was possible to develop the charging profiles which are presented in Fig.3, Fig.4 and Fig.5.

Time	Low	Medium	High
00:00-03:00	8	8	15
03:00-06:00	15	15	30
06:00-09:00	30	60	90
09:00-12:00	15	30	45
12:00-15:00	15	30	45
15:00-18:00	15	45	60
18:00-21:00	30	60	90
21:00-00:00	15	30	45

Table 1 Assumed BEV's serviced in each period per low, medium and high utilization rates with peak usage times between 6am-9am and 3pm-6pm.

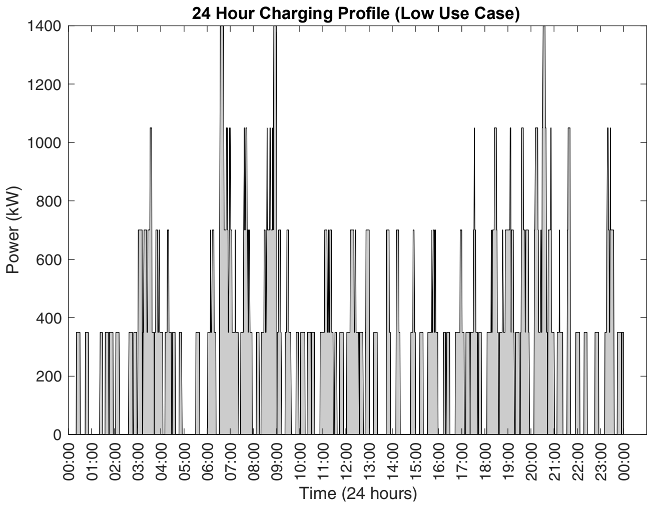

Fig. 3 Low use case loading profile.

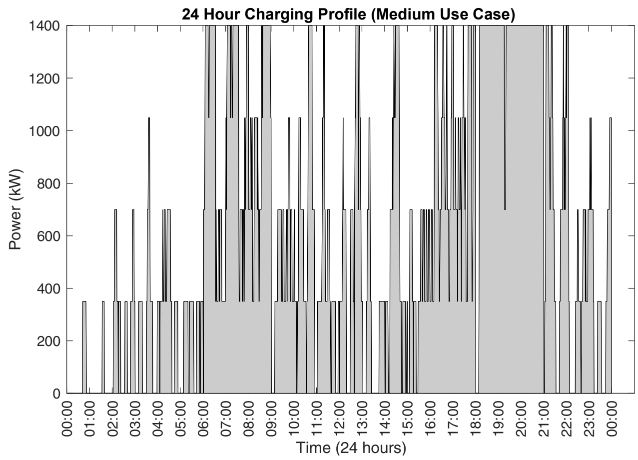

Fig. 4 Medium use case loading profile.

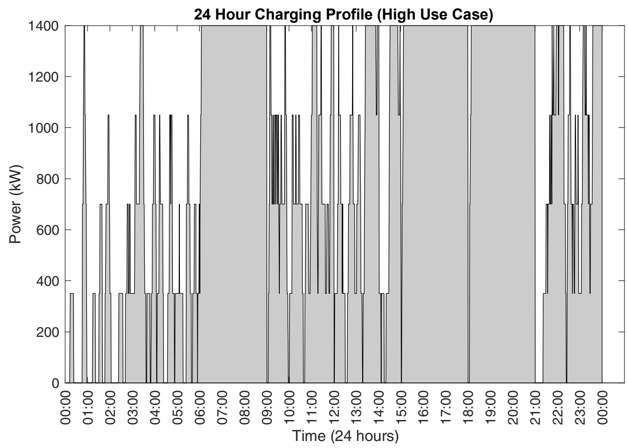

Fig. 5 High use case loading profile.

III. Combined Heat & Power

The use of Combined Heat and Power (CHP) systems as part of an integrated energy solution is not new. It has been adopted as an efficient use of fossil fuels for power generation in Scandinavian countries for decades and has recently seen a renaissance in the UK and internationally, as governments make a concerted effort to decarbonize heating and electricity production [14].

CHP systems can take many forms and sizes, however, they are generally associated with small to medium scale distributed generators (1kWe-10MWe) such as diesel or gas reciprocating engines, gas turbines and more recently the use of fuel cells [14]. Larger, centralized thermal power plants such as coal and nuclear can also operate as heating plants but are generally subject to higher installation costs due to their distance from population centres and the associated heating loads.

The most common urban area CHP systems utilize gas reciprocating engines that can range from a few hundreds of kilowatts up to multi-megawatts and are generally installed for onsite building or campus generation and thermal loads or connected to a wider district-heating network (DHN). Gas reciprocating generators are more appropriate for sub-10MW applications compared to gas turbine solutions and for that reason only gas reciprocating engines are considered within this paper [15].

The great majority of gas reciprocating engines, acting as distributed generators, operate at a fixed speed, where the connected generator is electrically synchronized with the national/regional grid frequency. Although more recently the use of variable speed gas and diesel engine-generator sets (gensets) have been investigated and the fuel efficiency benefits documented for small-scale building level systems and larger marine power system applications [16], [17]. It is therefore worth considering the use of variable speed gensets for distributed generation applications, especially in conjunction with intermittent renewable generators or highly varying loading profiles.

A. *Fixed Speed Gas Reciprocating Engines*

Conventional gas reciprocating gensets operate at a fixed rotational speed, which is determined by the generator topology and grid frequency. The engine maintains a fixed speed regardless of the electrical load on the generator. This is appropriate for base-load power generation applications or for peaking plants where maximum power output is required for set periods of time. However, under part-loading conditions, particularly under 50% loading, the fuel efficiency of the gensets drop markedly. This is illustrated in Fig. 5 and extensively modeled for commercial engines in [18].

B. *Variable Speed Gas Reciprocating Engines*

A variable speed reciprocating genset enables the engine to operate at its optimum speed and therefore fuel consumption for a specific loading condition. This is achieved by either decoupling the generator output from the ac grid using power electronic equipment or by varying the magnetic field on the generator rotor exciter for doubly fed induction generators (DFIGs).

Diesel powered variable speed gensets have been considered and deployed in microgrid applications to dynamically respond to intermittent renewable energy generation and in diesel-electric transportation systems [17], [19]. However, little research exists on the use of large (>1MWe) variable speed gas reciprocating engines and their associated efficiency improvements under part-loading conditions compared to fixed speed gensets. Tecogen, a commercial manufacturer of 100kW variable speed gas reciprocating engines claims high efficiency values and a 'turn-down' ability to 10% of rated electrical load [20], [21]. A sophisticated simulation model of a 28kW gas reciprocating CHP system for a building is presented in [16], with the electrical efficiency of both the fixed speed and variable speed systems presented in Fig. 6.

For the most part, small-scale variable speed reciprocating gensets tend to use Permanent Magnet Synchronous Generators (PMSG). However, larger gas reciprocating gensets use conventional synchronous generators (SG) due to the cost, weight and supply chain monopoly of rare earth metals. Much research and development exists on variable speed generation within the wind industry as it is an operational necessity to convert variable rotational speeds to match ac grid power quality and effective solutions exist for PMSGs and DFIGs [22]. For utility scale gas reciprocating generators, there is little desire to operate generator units at part loading and therefore limited research exists within this area. It is therefore necessary to extrapolate from the existing studies that focus on smaller scale gas and diesel variable speed generators and make some assumptions on the behaviour of larger (>1MW) variable speed gas reciprocating engines.

IV. AC VS DC CONNECTION EVALUATION

A. Connection Arrangements

The analysis within this paper relies on the modeling results in [16] and the research conducted in [18] in order to create an electrical efficiency curve for a medium to large scale variable speed gas reciprocating genset. In this paper, three different CHP connections scenarios were considered, as depicted in Fig.1: a direct dc coupled 1400kW variable speed genset, a 1400kW fixed speed genset connected to the ac network and 4x350kW fixed speed gensets connected to the ac network.

The performance of CHP units can be assessed using either their Heat to Power Ratio (HPR) or the Electric Heat Rate (EHR). The HPR is the ratio of useful heat output to electric power generation and the EHR is the rate of electric energy output to the fuel energy input [18]. In this analysis, the EHR is used to assess the total fuel consumption in kWh required to meet the BEV charging demand for the three loading profiles presented in section-II.

B. Derivation of Efficiency Curves

To perform this energy efficiency analysis, it is necessary to derive the EHR curves for the percentage loading of each CHP unit configuration. The EHR is represented by the number of kWhs of fuel required to produce one kWh of electricity. The research conducted in [18] specifically assesses the EHR and HPR for commercial gas reciprocating generators for part-loading conditions below 50%. This paper uses the generalized part load performance function [18]

$$f(x) = c \times a \times x^{b} \tag{1}$$

to create the EHR curves for the fixed speed 1400kW and 350kW gas reciprocating generators shown in Fig.6.

Capacity Coefficients	350kW Fixed Speed	1400kW Fixed Speed
a	227.9	227.9
b	-1.182	-1.182
c	11000	10000

Table 2. Capacity coefficients for the HER performance of fixed speed gas reciprocating generators.

The net electric efficiency results reported in [16] for a fixed speed and variable speed 28kW gas genset are used to estimate the EHR curve for the 1400kW variable speed gas generator. The EHR curves of the 28kW system are presented in Fig.6 and the percentage relative difference between the EHR of the fixed speed loading curve and the variable speed loading curve is applied to the 1400kW fixed speed EHR curve to form an estimated variable speed EHR for the 1400kW genset.

The electric output from the 28kW variable speed genset includes the efficiency losses of the back-to-back converter and therefore these losses are incorporated in the overall net electric efficiency. However, when the 1400kW genset supplies power to the dc grid only, the genset performance will be slightly higher as the electric generation does not require inverting for export to the ac grid. In this situation, it is assumed that the inverter has a flat efficiency of 95% and this has been reflected in the overall energy efficiency analysis.

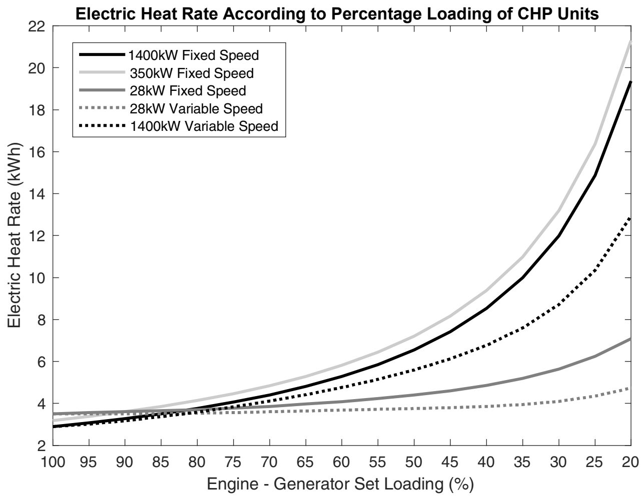

Fig.6 EHR curves per the percentage loading condition for 28kW, 350kW and 1400kW gas reciprocating gensets.

V. Results & Discussion

Using the loading profiles presented in section-II, the model steps through the 24-hour period in 1-minute intervals. At each interval, the percentage loading condition is used to calculate the EHR for that time step and CHP unit type. The energy consumed during each of the 1-minute intervals is summed for the entire 24-hour period to compare the fuel efficiency for each of the CHP unit configurations. The results of this analysis are presented in Fig. 7 and Table 3.

As expected, in all three CHP configurations, the average electrical efficiency over the 24-hour period is relatively low compared to centralized gas turbine electric efficiencies. As a comparison, a Combined Cycle Gas Turbine (CCGT) can offer up to 55-60% electrical efficiency and in some cases the power plant can connect to a DHN for use of the waste heat [23]. The electrical transmission and distribution losses in the UK are reported as 8% on average [24] and therefore approximately 47-52% of the primary energy fed into a CCGT plant would reach a BEV battery. This energy efficiency is still significantly higher than the figures reported in Table 3 for a distributed gas reciprocating genset.

The benefits of co-located CHP systems are achieved through integration utilizing the same land, electrical infrastructure and operating costs. To assess this, a more detailed economic analysis should be conducted that looks beyond just the energy efficiency. This may include the avoided network upgrade costs to accommodate an extra 1.4MW worth of electric vehicle chargers, the capability of gas reciprocating engines to offer ancillary grid services and the use of waste heat from the engines for heating or cooling buildings.

Despite the variable speed genset offering improved efficiency compared to the fixed speed systems, both require high utilization rates to reach maximum electrical efficiencies. These CHP systems are unlikely to service just the demand from the HPC station and therefore the electrical efficiency over a 24-hour period will be slightly higher than the figures reported in Table-3, but as the average loading condition increases the efficiency difference between fixed speed and variable speed becomes smaller.

Overall, from the simplified modeling of this paper there is little benefit in connecting CHP gas reciprocating gensets to the dc charging network as variable speed generators. Greater fuel efficiency benefits can be recognized by carefully sizing the CHP gensets per the forecasted load on the network. For example, the four separate 350kW fixed speed gensets consume the least energy in the low use case scenario as the single 350kW genset can operate at its maximum efficiency, which has a lower EHR than the 1400kW gensets operating under part-loading conditions. Assuming similar economics, this suggests a 350kW genset is the most appropriate configuration for new HPC stations that are likely to experience low utilization rates initially. The stations can then be upgraded to a larger genset when the utilization rates justify an efficiency increase.

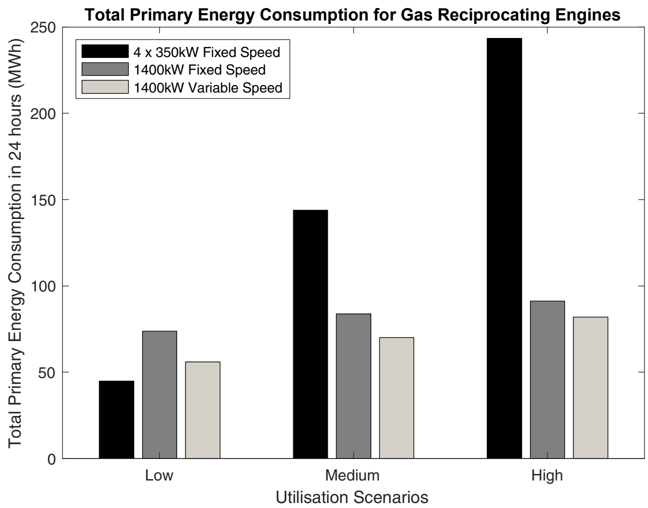

Fig. 7. Total primary energy consumption (natural gas) used in the operation of gas reciprocating engines for the charging of BEVs at an HPC station.

CHP Units	**Low**			**Medium**			**High**		
	E_g	E_e	$\eta_{e\%}$	E_g	E_e	$\eta_{e\%}$	E_g	E_e	$\eta_{e\%}$
1.4MW (fix.)	73.9	7.7	10	83.7	15	18	91.3	22	24
1.4MW (var.)	53.2	7.7	14	66.6	15	23	77.9	22	28
4 x 350kW	44.9	7.7	17	143.9	15	10	243.5	22	9

Table 3. Energy consumption of gas (Eg) in MWh, electric energy generation (Ee) in MWh, net electric efficiency (η_e) for each CHP configuration and low/medium/high use case charging profiles.

VI. CONCLUSIONS

This paper has highlighted the opportunity to co-locate CHP systems with HPC stations to recognize potential installation and operational efficiencies from the desire to decarbonize both the transportation and heating sectors simultaneously. Three different gas reciprocating genset configurations were considered and it was found that regardless of the improved electrical efficiency rates that variable speed gensets can offer compared to fixed speed systems, they must both operate close to maximum power output to recognize adequate electrical efficiency rates. The use of modular 350kW gas gensets, which are each rated to the power output of the BEV charger, offer the highest efficiency in low use case scenarios and therefore careful forecasting and modeling will be required to accurately assess the HPC station utilization rates and the resulting size of the CHP system. To fully assess the practical capabilities of this integrated energy system, a techno-economic analysis should be conducted that takes into consideration the thermal demand profile for the waste heat from the CHP systems and a power network impact study that examines the effect of HPC stations on the network, with and without local distributed generation support.

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